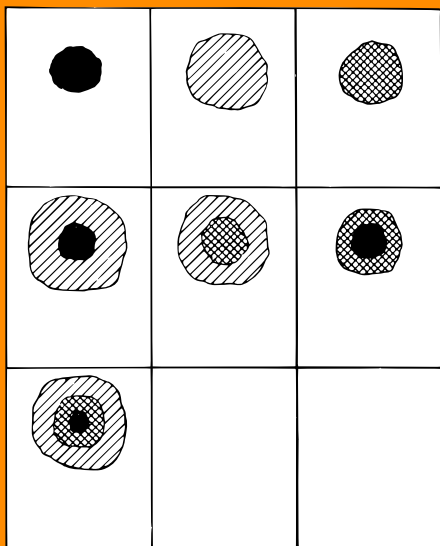I. V. KUZNETSOV and M. E. OMEL'YANOVSKII (Eds.)

Philosophical Problems
of
Elementary Particle Physics

ACADEMY OF SCIENCES OF THE U.S.S.R.
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Translated from Russian by
A. Sen and R.N. Sen

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FOREWORD

Elementary particle physics is a rapidly evolving branch of modern physical science. It lies at the forefront of research into the structure of matter. The attainment of a deeper essence of things – or new level of structure of matter – has been accompanied by the abandonment of many earlier views and the development of new ones. This process of reassessment of physical concepts in order to establish their conformity with the manifestation of objective reality at its deepest level poses important physical problems. In particular, it raises problems pertaining to the laws governing the development of physical theories, the relationship between the whole and the part (the "elementary" and the "nonelementary"), and new aspects of the broad concept of structure. Throughout its growth there arises the problem of the peculiarity of space in the universe of elementary particles. Here the characteristics of discreteness of space previously left in the shade come to the forefront and call for philosophical interpretation. The statistical nature of many of the major laws of the physics of the microuniverse and the ever-increasing role of the probability category in elementary particle physics call attention to new aspects of the problems of chance and necessity, as well as causal relationships of phenomena.

The study of microprocesses has brought to light previously unknown features of physical experimentation which are of considerable philosophical significance. The revision of ideas resulting from the penetration into the world of elementary particles has also raised the problem of the role of visualization and models in the cognition of deep levels of reality. Refinement of the methods of theoretical physics in the course of research into microprocesses has led to the discovery of an unexpected correlation between the theory of elementary particles and information theory. The discovery of a connecting link between these two theories makes it possible to draw important gnoseological conclusions concerning the role of abstract mathematical concepts in the cognition of deep levels of structure of matter.

Such are the problems discussed in the present book, which is the fruit of joint efforts of philosophers and physicists. Use is made of the material of the Theoretical Conference on Philosophical Problems of Elementary Particle Physics held by the Scientific Council on Philosophical Problems of Natural Science in April 1962.

The authors and editors are keenly aware of the controversial nature of some of the views expressed in this book. This is indeed understandable: the development of the fundamental problems of elementary particle physics is very far from complete, and therefore many of the statements are inevitably of a highly tentative nature. But it is precisely in order to help this branch of science make further progress that a wide exchange of views on the philosophical problems of elementary particle physics is necessary.

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The papers collected in this book differ to some extent in type of exposition, reflecting the stylistic peculiarities of each author. The editors thought it unnecessary to eradicate these peculiarities.

The fact that this book is the first of its kind in the literature explains, to some extent, its inherent defects.

Although the book treats very difficult problems, the authors and editors have taken pains to ensure that its content be accessible to a wide circle of readers. They hope that this effort has not been unsuccessful and that the book will attract the attention of all those who are interested in the progress of modern science and in the philosophical problems with which it is faced.

The editors express their deep gratitude to I. V. Dostova for her scientific and administrative work on the book.

Translators' Note

Most of the Russian authors give in their articles citations from statements of non-Russian scientists taken from Russian translations.

Wherever the original citation could be reliably ascertained, the original text and reference were cited by the translators. This was, unfortunately, impracticable in a number of cases where the cited text had to be retranslated from the Russian; such cases are recognizable by the Russian title in the non-Russian source reference given in the respective footnote.

GENERAL PROBLEMS

THE CORRELATION BETWEEN PHYSICAL THEORIES AND THE DEVELOPMENT OF CONTEMPORARY ELEMENTARY PARTICLE PHYSICS

I. V. Kuznetsov

Physics today is passing through a period of unusually rapid development in which many of its fundamental concepts and theories are being radically revised. At the forefront and pointing toward the unknown lies the branch called elementary particle physics. It is precisely here that the scientist is most often called upon to reassess concepts which had seemed to him firmly established but a short time earlier.

The physics of elementary particles now possesses a vast amount of empirical data. Present-day elementary particle theory has been able to explain a considerable range of phenomena. Progress has been particularly significant in the study of the interaction of electrons and photons (quantum electrodynamics). On the whole, however, the theory lags substantially behind experiment. It does not cover the profusion of factual data that have accumulated, does not answer the important questions facing it, and does not represent an integral, closed and internally consistent discipline. The difficulties facing the theory are so great that the need for a fundamental revision of the physical concepts is universally recognized. The problem is one of searching for "crazy" ideas which break decisively with earlier views. The new variants of elementary particle theory proposed in recent years by certain scientists are subject to criticism precisely because they lack the boldness and decisiveness required to attain this goal.

Philosophical analysis of the general paths of development of physical science and study of the regularities in the progress of physical theory from one qualitatively distinct stage to another are of very great importance in this context. The transitions between stages occur where new and strikingly different principles which explain a wider range of phenomena are contrasted with earlier theoretical principles.

Twentieth-century physics has already passed through many such stages. They are demarcated historically by the formulation of Planck's quantum theory, Einstein's theory of relativity and the quantum mechanics of de Broglie, Schroedinger, Heisenberg and Dirac. Everyone knows the revolution in physical ideas that resulted from the trainsition from each stage to the next. However, the detailed mechanism of transition from one theory to another (from the standpoint of the correlation between elements of their conceptual structure) is still little studied. Yet investigation of this question could be very useful in helping us to understand how the transition to a new stage in the theory of elementary particles is to be accomplished in our times. The results of such an investigation would undoubtedly be of considerable heuristic significance.

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The revisions carried out at the beginning of each of the above stages were deeply and truly revolutionary in character. The new theories decisively and uncompromisingly refuted the old ones. And yet new and old were organically related to each other. While refuting the old, the new theories still rested on them. Whatever was confirmed by experiment in the old theories was assimilated by the new. This situation obtains not only in twentieth-century physics but generally throughout the history of physical science. This is understandable. An essential element in the relation of succession between old and new theories is a law of scientific cognition without which progress of the science becomes impossible.

In the following an attempt is made to consider the various forms of correlation and succession among physical theories belonging to qualitatively different stages of development. The stress will be on analysis of these forms with reference to the contemporary theory of elementary particles.

Every physical theory is an organized system of concepts including important and less important ones, fundamental and derivative ones, and so on. As physics develops, the conceptual apparatus of the theory changes. Thus physical theories dating to before the end of the nineteenth century contain such concepts as absolute time, absolute simultaneity, absolute space, and so on. These concepts are already absent from modern physics. If we compare the classical electron theory and the present elementary particle theory we see that the latter contains concepts such as spin, isotopic spin, lepton and baryon charges, strangeness, chirality, parity, combined parity* and so forth which are absent from the classical theory and which account for the differences of principle between the old and the new. In turn classical electron theory differed from Maxwellian electrodynamics in such fundamental concepts as discreteness of the electric charge, electromagnetic mass, Lorentz force, and so on.

The conceptual system of quantum physics differs radically from the classical one owing to the concept of the quantum of action, the introduction of which marked the beginning of a completely new stage in the development of physical science. It led to the formulation of other new concepts, including quantization of energy, space quantization and wave-particle duality.

It may be, as many theoreticians maintain, that the new stage in the development of physics will be associated with the introduction of the fundamentally new concept of an "elementary length" or "space-time quantum". At present this remains a matter for the future. However, it is clear that a fundamental revision of the conceptual system of physics involving the introduction of concepts without immediate analogues in the system of the present stage is necessary.

When we consider the relationships between theories which have arisen at different stages in the development of physics, we cannot help noticing the fact that these theories inevitably contain similar concepts which reflect the existence of common physical properties in qualitatively dissimilar objects. Such, for example, are the concepts of mass, momentum, angular momentum, energy and Hamiltonian of a dynamical system which occur in theories which refute each other dialectically in the course of development of physics. Moreover, these concepts are equally important in the

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* [CP: the term "combined parity" was introduced by L. D. Landau, Nucl. Phys. 3, 254, 1957.]

old and the new theories. This does not mean that concepts common to the refuted as well as the refuting theory are passively or mechanically transferred from one theory to the next without undergoing any change at all. On the contrary, most often they are modified in some way in conformity with the newly-discovered features of the general property which they reflect. In the last analysis, however, their physical essence remains the same.

This point is clearly illustrated by the concept of mass. Integral and undivided in prerelativistic theory, this concept later revealed diversity in unity. Instead of a simple uniform mass, we now know of a proper mass or rest mass, the so-called "bare mass", and the mass of motion. Though dissimilar in origin, they are identical with regard to general role in physical processes, position in laws of conservation and meaning as measures of inertia. A somewhat analogous statement could be made concerning the concept of momentum in classical and quantum physics.

The process of transfer of ideas from one theory to another is thus far from being as simple as might seem at first glance. When a new theory is being developed it is more often than not impossible to tell in advance whether earlier concepts will be applicable in the new region. It is chiefly the differences that stand out here. Now these differences tend to be so considerable that occasionally one is even led to feel that nearly every element of the conceptual system of the old theory is completely inapplicable in the new region. Which of the old concepts – and in what form – have a right to survive in the new theory only becomes clear gradually. This was the situation prevailing, for instance, in the first stages of development of thermodynamics, which operated with concepts absent in mechanics (temperature, quantity of heat, heat capacity, entropy and so on) and which, so it seemed, decisively severed all connections with the conceptual system of mechanics. The deep internal bond uniting the conceptual systems of thermodynamics and mechanics was uncovered only by statistical physics which formed over a considerable period of time.

A somewhat similar situation obtained in the history of optics. The wave theory, which in its time replaced geometrical optics, introduced its own concepts (wave surface, phase, amplitude, interference and so on) and created a special conceptual system alien to geometrical optics. The interpenetration of the conceptual systems of the two theories, the presence in these theories of many common elements, was discovered in the course of a long process of development.

The process of creation of new theories associated with the incessant probing of man's intellect ever deeper into the essence of things results in the intensive production of concepts absent at earlier stages. And while in this process a significant number of early concepts is eliminated, giving way to the new, there is a definite tendency for the total number of concepts to increase systematically in later theories. Not only are the concepts refined, made deeper and broader, etc., but with every succeeding theory their number becomes larger and larger. In this respect it is very instructive to compare, say, classical electron theory with modern elementary particle theory. The classical theory uses a comparatively small number of concepts – mass, electric charge, radius – to characterize an elementary object. In the modern theory, by contrast, the same object is characterized today by such additional concepts as spin, magnetic moment, wave-particle dualism, pair production, annihilation, and lifetime.

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In the classical theory an elementary object is delineated far more poorly than in the modern theory. The new theory represents the same object as being far more richly endowed in properties and relations to other objects. The earlier theory therefore appears more abstract than the modern one. The general dialectic law which indicates that scientific knowledge moves from the abstract to the concrete by progressively sketching a more accurate sample of reality is operative in the development of physics as well.

However fundamentally new theories may differ from old ones their conceptual systems always contain important common elements. These are transferred from one theory to the next.

The necessary transfer of concepts which reflect the presence of common physical properties in objects studied by different theories represents one form of linkage between old and new theories. A distinction can be drawn between several types of concepts common to different theories: a) "continuous" concepts appearing in all systems, past, present and future: these include, for instance, the concepts of energy, mass, charge and so on; b) concepts present in a more or less broad but nevertheless restricted group of theories immediately succeeding each other in the historical development; c) concepts which are present only in two or several adjacent theories.

This form of linkage between physical theories is illustrated schematically in Figure 1 for the relations between classical mechanics, relativistic mechanics and quantum mechanics. A few concepts common to all three, common only to two adjacent ones and present only in one are distinguished. Of course, the diagram makes no claim to exhaust all concepts occurring in each theory, nor even to represent all the common ones which act as links. It merely illustrates the principal features of such relationships between theories.

The core of every physical theory is a set of laws of nature which it sums up. Rather than being arbitrarily assembled, these laws constitute a well-defined complete structure the elements of which are organically related and each causes the other. Because of the completeness of its inherent system of laws, every physical theory appears logically closed. This is shown, in particular, by the following circumstance. When a physical theory is developed in sufficient detail it gradually covers an increasingly large number of newly-discovered facts, interprets them and identifies the laws which govern them. The theory grows in width. But it so happens that not every empirical fact can be "assimilated" by the existing theory, i.e., be absorbed into its framework and explained on its basis. Certain facts may prove completely foreign to the theory and remain outside its limits, without constituting sufficient ground for creating a new theory. The theory, so to speak, "repels" the alien fact and continues to extend its sphere of influence away from the latter. For example, the equality of the inertial and gravitational masses, a fact which has long been known, was essentially alien to the system of laws of classical physics. It was in general a foreign body for physical theory, which continued to by-pass it until the advent of the general theory of relativity. It was then brought into the system of laws of this theory, which differs in essential respects from the classical system.

The discovery of facts not assimilable by the existing theory, while it does not furnish a basis for revision of the old theoretical system or

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construction of a new one, explicitly demarcates the limits of the theory
and shows that it is logically closed.
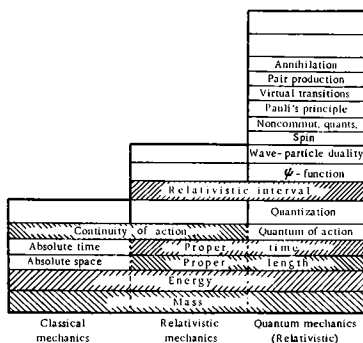
FIGURE 1

Logical closure expresses the high degree of development of a theory
and shows that it covers important aspects of a certain specific fragment
of reality with sufficient thoroughness. But it is this very closure of the
system of laws which is responsible for a very important characteristic
of the development of physical theory: the fact that it progresses by jumps.

Progress in theoretical physics cannot take place by continuous indefin-
ite addition of new knowledge to a previously discovered set of laws or by
purely superficial accumulation of new concepts and laws without modifica-
tion of the essence and structure of the original system. Assimilation of
steadily mounting empirical data can take place within a given framework
only up to a certain point in time. Sooner or later, as the history of phys-
ics shows, the scientist is faced with the necessity of decisively breaking
the frame. Further advances in theoretical physics will be possible only
with a fundamentally new system of laws which must in turn be closed.
This transition from one system of laws to another, with its attendant rear-
rangement of the structure and content of knowledge, truly represents a
j u m p in the development of the science. From this standpoint the history
of physics appears as a succession of different systems of laws constituting
distinct closed entities.

Theories are qualitatively dissimilar as to essence and character of the
corresponding systems of laws. Thus the specific character of classical
mechanics is determined by Newton's laws while that of electrodynamics is
determined by Maxwell's equations; the character of, say, nonrelativistic
quantum mechanics is controlled by the system of laws expressed in de
Broglie and Schroedinger's equations as well as by the commutation

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relations for quantized quantities. These theories display well-defined closure owing to the integrity and completeness of the systems of laws inherent to them. Present-day elementary particle theory, by contrast, is not similarly closed precisely for the reason that it still lacks an integral system of fundamental laws.

Among the laws which express the essence of physical theories a special position is occupied by the laws of conservation. The specific character or qualitative distinction between theories is manifested not only in the principal laws of motion but also in the laws of conservation inherent to each. Thus modern elementary particle theory is characterized by such conservation laws as that of spin, isotopic spin, strangeness, parity (except in weak interactions) and lepton and baryon charges. Such laws were completely unknown in the classical theories.

For all the distinctions between systems of laws of motion and conservation in different physical theories, the latter have much in common. Theories belonging to different stages of development of physics necessarily contain similar laws. There are even a number of all-pervasive laws which are common not merely to "adjacent" theories immediately succeeding each other, but to all physical theories in general. Such, for instance, are the law of conservation and transformation of energy and laws of conservation of momentum and angular momentum. It is well known that the law of motion for the electromagnetic field which is expressed by Maxwell's equations also occurs in the Lorentz electron theory, as well as in modern quantum electrodynamics, while the laws of motion summarized by the so-called canonical equations apply to classical mechanics, electrodynamics and quantum mechanics.

Owing to the fact that the different physical theories which follow each other historically contain identical laws – of motion as well as of conservation – an important form of succession is established between these theories. The community of laws in old and new theories is yet another form of internal correlation between the latter.

The linking of physical theories by laws, either common to all theories, common to a group of close theories or inherent merely to adjacent theories, may be represented by a diagram similar to the one given in Figure 1.

With the advent of the theory of relativity, requirements that laws be invariant under certain transformations began to play an increasing role in theoretical physics.

Physical theories corresponding to qualitatively distinct stages of development differ not only in their system of concepts and laws, but also in the transformations under which these laws are invariant. Thus the laws of classical mechanics are invariant under Galilean transformations and the laws of relativistic mechanics under Lorentz transformations. Specific to Maxwell's electrodynamics is the requirement of invariance under the so-called gauge transformations of the electromagnetic potentials. The laws of quantum electrodynamics satisfy new requirements of invariance – gauge transformation of the second kind, charge conjugation transformation, Salam–Touschek transformation and Pauli–Gürsey transformation. The differences between the systems of transformations satisfied by the laws of the various theories express the specific characters of the theories proper and the fact that they cannot be reduced to each other.

In spite of these distinctions, and in addition to meeting the invariance requirements specific to each theory, the laws inherent to different theories always satisfy invariance requirements common to both old and new theories.

Although the differences of principle between the laws of classical mechanics and those of relativistic mechanics reside in the fundamental contrast between Galilean and Lorentz transformations, these laws have this in common that both are invariant under translations of the space coordinates, translations in time and rotations in space. The laws of classical electrodynamics and those of quantum theory of elementary particles are both invariant under Lorentz transformations, gauge transformations of the electromagnetic potentials, and so on. Similarly, as in the case of the laws of classical and relativistic mechanics, both are invariant under translations of the space coordinates, time translations and rotations in space.

The fact that the laws of the different physical theories satisfy a number of common invariance requirements despite the presence of forms of invariance which are specific only to each is of very great significance. The invariance of the laws of motion of different objects under the same transformations represents a special form of correlation between physical theories.

It should be mentioned that the requirements that the laws of physical theory be invariant under various transformations are related to special requirements of symmetry. In this connection we must state that the study of symmetry has been assuming an increasingly important role in modern physical science.

The development of physical theory is characterized by a highly significant trait which cannot be overlooked. The number of requirements of invariance, the number of conditions of symmetry imposed on the laws and concepts of physical theory, increases unceasingly with progress in physical science. As theoretical physics develops the scientist is called upon to deal with an ever increasing number of invariance requirements and symmetry principles. In general this proves that as the frontier of knowledge penetrates more deeply into matter science reveals greater and greater asymmetry in the internal structure of the material objects under investigation. This was pointed out by Yu. V. Sachkov. That this is so may also be seen from the fact that an elementary particle in modern physics includes such characteristics as spin, chirality and so on. These bear witness to a definite selectivity of certain directions in the particle and therefore to a definite degree of asymmetry. This distinguishes the sample particle from its counterpart in classical physics, which is characterized by the most complete symmetry.

The next step in the cognition of the structure of matter will doubtless be associated with the appearance of new features of asymmetry.

Requirements that laws be invariant under corresponding groups of transformations are not merely a way of verifying the formal correctness of given equations as expressions for laws. These requirements play a very important heuristic role in the search for laws of motion when the latter are still unknown. For illustration we shall take the nonlinear theory of elementary particles developed by Heisenberg and his group. The form of the principal equation (law) of the new theory was determined from the requirement that it be invariant not only under spatial and Lorentz rotations

but also under specific Pauli-Gürsey and Salam-Touschek transformations characteristic of the modern theory of elementary particles.

An expression of the internal bond between physical theories is the fact that the principal laws of motion present in all can be derived from a general form of variational principle identical for all theories (for classical mechanics and electrodynamics as well as for quantum mechanics and modern elementary particle theory). This circumstance is a manifestation of the identity of the general and the particular in the historical development of physical science.

The general is embodied in the universality of the variational principle, in its form and essence as a principle of extremal action. The particular or special is embodied in the Lagrangian function characteristic of the given set of phenomena, given in terms of physical quantities specific to the theory studying these phenomena. In one case this is the ordinary classical coordinates and momenta, in another the electromagnetic field strength and in a third the operators characterizing the state of the particle of matter or quantized field.

It is important to note that the form of the Lagrangian function is determined from the set of all invariance requirements characteristic of the given theory.

In considering the relationships between the conceptual systems of physical theories which appear consecutively in the historical development of physics we must mention yet another extremely important form of linkage. However revolutionary the break in scientific views leading to the creation of a new physical theory, the principal laws of the latter are always such that they tend asymptotically to the laws of the older theory in the limit. In other words, the laws of the old theory are a special limiting case of the laws of the new, to which the earlier laws tend for the appropriate value of some characteristic parameter present in the new theory. This view, first formulated by Niels Bohr for the relationship between his quantum theory and classical mechanics, was named the correspondence principle. Subsequently the correspondence principle was generalized into the form in which it is formulated above, and it assumed the significance of a fundamental law governing the development of physical theories*. The correspondence principle is supported by data from all fields of physical science. Asymptotic passage acts as a link between, for instance, the laws of wave and geometrical optics (this is formally accomplished for the condition that the wavelength tend to zero: $\lambda \to 0$), the laws of quantum and classical statistics (for $T \to \infty$), the laws of relativistic and classical mechanics (for $c \to \infty$) and the laws of quantum and classical mechanics (for $\hbar \to 0$). The correspondence principle is likewise fully operative in the region of modern elementary particle theory.

The linking of physical theories by the asymptotic passage of one set of laws into the next is illustrated in Figure 2. The law giving the energy dependence of the mean number of particles with given energy in classical statistical physics (solid curve 1) and Fermi-Dirac statistics (dashed curve 2) is represented graphically. Although we are dealing here with one particular case, the general characteristics of such links are clearly apparent.

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* For further detail see Kuznetsov, I. V. Printsip sootvetstviya v sovremennoi fizike i ego filosofskoe znachenie (The Correspondence Principle in Modern Physics and its Philosophical Significance). Moscow, 1948.

On the whole, as we can see, the laws belonging to the two theories are fundamentally different, and the two types of curves markedly dissimilar. In the region of phenomena specific to the new theory, the laws of the latter are particularly dissimilar from the laws of the old. In Figure 2 this corresponds to the region closest to the y-axis; here the two curves diverge completely. As the conditions prevailing in the earlier theory draw near, the laws of the new progressively converge toward the laws of the old theory. In Figure 2 this corresponds to the region farthest from the y-axis, i.e., between the right-hand side of the figure; here the two curves tend to merge: the laws of the new theory tend asymptotically to those of the old one.
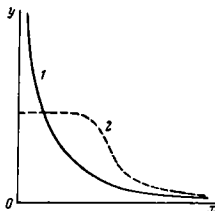
The full force, the full significance of the correspondence principle is felt at the point where the new and old theories are most conclusively dissimilar and where fundamental transformation of the physical theories is taking place. It is here that the inevitability of the passage, in the limit, between old and new laws becomes nontrivial and assumes deep significance of principle.

The correspondence principle operates wherever fundamental transformation of physical theories is taking place. It expresses the final result of the transformation — a regular consecutive linking of old and new theories. But the significance of the correspondence principle does not end with identification of the character of changes in theoretical views, however important this might be on the philosophical plane. The correspondence principle is also important because once recognized it can serve successfully as a tool for building new theories. Since the time when it was first discovered, broadly interpreted and generalized, its methodological role in the development of physical theories has increased steadily.

The correspondence principle proved a real "magic wand" not only in the construction of the first quantum theory of the atom by Bohr but also in the development of present-day quantum mechanics. But even when it has not been taken into account from the first as a tool for building new theories, its influence has manifested itself inevitably and independently of the will of the researcher in the final result of the work: new and old laws are always mutually related in the way it prescribes.

The correspondence principle has played a very important heuristic role in the theory of elementary particles as well. It was used, for example, to help establish the physical meaning of a number of newly introduced concepts. Taken together with the condition of covariance, unitarity and causality, the correspondence principle is sufficient for setting up the so-called scattering matrix which now occupies a central position in modern quantum electrodynamics.

All attempts at progress in the theory of elementary particles are inevitably founded on the application of the correspondence principle. This applies, in particular, to attempts to create a theory of elementary particles based on ideas of quantization of space (introduction of an "elementary length") and nonlocality of interaction.

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It may be asserted that when the new elementary particle theory is born — apparently in a form radically different from the present theory — the correspondence principle will have scored yet another great victory.

We have considered many forms of linking between old and new theories, all of which have actually been realized in the process of development of modern physics: 1) the transfer of concepts from earlier to new theories (resulting in the presence of identical elements in the conceptual systems of different theories); 2) the transfer of laws from some theories to others (resulting in common elements in the systems of laws of different theories); 3) the invariance of laws belonging to different theories under identical types of transformations (resulting in a certain similarity of structure between the systems of laws of different theories); 4) the fact that the fundamental laws of all theories are derivable from a universal variational principle (resulting in the analogy of the mathematical apparatus of the theories); 5) passage, in the limit, of new theories to old ones under proper conditions, or correspondence principle (earlier theories appear as particular cases of new theories).

The existence of such relationships between physical theories is evidence of the regular nature of the development of scientific knowledge. These relationships disclose the inner mechanism by which grains of absolute truth are accumulated in one of the most important fields of modern natural science. Therein lies their philosophical significance.

Owing to this regularity the development of physical theories possesses an internal logic which exerts a truly compelling force on the scientist attempting the creation of a new theory. This force is no less compelling than the empirical facts under the stimulation of which the scientist first embarks upon his attempt. In constructing his new theory, however revolutionary it might be, the physicist cannot break completely with the earlier system of concepts — nor, for that matter, can he ignore the earlier system of laws, the fundamental invariance requirements known from the earlier theory and the necessity of recovering the earlier laws as a limiting case in the new system.

The reason for this lies neither in the sluggishness of the scientist's mind nor in a subjective desire to adapt the new to the old. Rather it is an indubitable fact that the c o n t e n t of man's knowledge, verified by experience, is i n d e p e n d e n t of his will, intellect or cognition. It represents the objective truth, subject neither to man nor to humanity. Scientific theory is the r e f l e c t i o n of objective reality in a definite system of concepts and laws. This is why the scientist is not in a position to modify the content of the theory arbitrarily.

When the scientist encounters a fact which cannot be fitted into the framework of an existing theory it means that he is faced with a qualitatively distinct region of reality in which special laws hold sway. But objective reality is one in material essence; all its phenomena merge into each other and are organically related. No insurmountable barriers of principle lie between them. As a result the theories in which they are reflected are, unavoidably, intimately associated with each other. In this way physical science takes on unity and integrity. And this unity of physical science is caused by the material unity of nature.

It is no accident that the problem of the correlation between physical theories failed to arise prior to the discovery of the material unity of qualitatively different phenomena of the physical world. The belief was once

prevalent in physics that nature is divided into absolutely separate regions each of which is represented by its own invariable "imponderable substation". Correspondingly the branches of physical science existed in isolation and had nothing in common. The development of physical science in consecutive steps led to the disclosure of the intimate interrelation between natural phenomena and to the collapse of ideas envisioning invariable "substations", with resulting elimination of the partitions between different branches and theories of physics.

Contemporary physics sketches a sample of nature in which all phenomena appear organically related, yet highly contrasted as to complexity, physical characteristics and inherent laws. This is why the idea of a correlation between theories has begun to play such an important role in present-day physics.

When consciously applied to the construction of physical theories the above forms of correlation take on the significance of assumptions within a m e t h o d of theoretical physics by means of which new truths are discovered concerning nature. From this viewpoint too their philosophical analysis is a very timely problem.

Far from being sudden, the discovery of the indicated forms of correlation was spread out in successive steps over the history of physics. Thus the correlation associated with the requirement that various systems of laws be invariant under similar transformations was recognized and assigned methodological significance only after the development of the theory of relativity. The correspondence principle was discovered in the process of development of Bohr's atomic theory. The existence of a universal variational principle was revealed only when the equations of mechanics, electrodynamics and relativity theory, as well as the laws of quantum mechanics and modern elementary particle theory, had been expressed in the corresponding form.

Further progress in physical science will probably lead to the discovery of new and possibly even more important forms of correlation between theories.

CERTAIN ASPECTS OF THE CONTEMPORARY DEVELOPMENT OF ELEMENTARY PARTICLE THEORY

V. B. Berestetskii

The theory of elementary particles is developing in a very peculiar way. For a fairly long period the impression one gains is that there has been no serious progress and no change whatsoever in the principles of the theory. Later it appears, however, that very important shifts have actually taken place in the principal concepts during this period, with cardinal changes in the formulation of the problems, in the methods and even in the attitude toward the aims of the theory.

We will consider a characteristic trait of this development which stems from the relationship between phenomenological description and theoretical explanation.

Let us begin with an example dating back to the beginning of the history of modern physics, i. e., to the foundations of celestial mechanics. Kepler's laws give a phenomenological description of the motion of bodies in the solar system: these move in conic sections. Newton's laws explain these motions: accelerations are caused by attraction to the center. Such is the universally accepted point of view. Is it absolutely irreproachable? Exaggerating deliberately in order to stress later the characteristics of modern elementary particle theory, we might answer in the negative. It might be asserted that Newton's laws give us no more information concerning the motion of planets than Kepler's laws. Two descriptions are given of the same phenomenon, in differential form in one case and in integral form in the other. The two forms are equivalent.

Of course, the Newtonian system of mechanics is broader than Kepler's laws. But it must be clearly understood that the main part of this system is its kinematics. By kinematics we will agree to mean what is meant by this term in the modern theory, i. e., all the information concerning the behavior of a system which can be obtained without considering a concrete form of interaction, i. e., law of force. This includes, in particular, all conservation laws. Let us note that although in mechanics the laws of conservation are derived from the Newtonian equations of motion, we know that their significance is far broader than these equations. They remain valid in the region of phenomena where the Newtonian equations are no longer applicable. They are related to symmetry properties of space and time more profound and more fundamental than the concrete equations of motion. If in the two-body problem, for example, the entire kinematic part is eliminated only the problem of radial motion remains. It may be written down in differential form after choosing the law of force, and may be written directly in integral form. There are no grounds for preferring either, though the former seems to be an explanation and the latter merely a description.

Our second example is the quantum mechanics of the free particle. Here the analogue of Kepler's laws is de Broglie's waves and the analogue of Newton's equations the Schroedinger equation. These, however, are equivalent and represent the quantum-mechanical description of the motion of a particle in integral or differential form. Again, we note that de Broglie's waves represent the more profound concept. They are retained in the relativistic region where Schroedinger's equation is inapplicable. When the forms of the relativistic equations are required, these are chosen such that de Broglie's waves be a solution of these equations.

The profound physical significance of quantum mechanics resides chiefly in the establishment of a new kinematics based on the uncertainty relation (just as the basic content of relativistic mechanics involves a new kinematics based on the relativity principle).

Let us turn to the two-body problem in quantum mechanics, i. e., to the problem of scattering. After elimination of the kinematic part it reduces to finding the phases or amplitudes of partial waves. For this it is necessary to know the law of force (e. g., Coulomb's law) and solve Schroedinger's equation for radial motion, which gives Rutherford's formula. This is the explanation of the phenomenon of scattering. Its phenomonological description consists simply of specifying the amplitudes. Here too, however, one might depart from the ordinary point of view and say that specification of the amplitudes is simply another (integral) formulation of the law of interaction. It is important to note that knowledge of the amplitude also solves a second fundamental problem of quantum mechanics, that of the quantum levels of the system. Rutherford's quantum-mechanical formula contains Balmer's formula for the levels of the hydrogen atom.

The foregoing would be of little interest if the second approach — investigation of the scattering amplitudes — had not proved more fruitful than the first in application to new problems. The problem of obtaining the forces (potentials) arose at the dawn of the development of nuclear physics. It proved to be complex and unrewarding, however, and development proceeded along the lines of phenomenological study of the scattering amplitudes. Elementary particle physics has developed in a similar way, but here, as has recently become apparent, description with the help of amplitudes can claim to be a method of constructing a theory of interaction of elementary particles.

For thirty odd years relativistic quantum theory (i. e., the theory of elementary particles) developed as a field theory. Field theory is based on the fact that kinematic quantities (of the wave function type) introduced in quantum mechanics are given the same dynamical significance as force fields (e. g., electromagnetic). Quantum electrodynamics was constructed on these principles. It was natural to believe that all of elementary particle theory could be formulated in this way. Except for electrodynamics, however, field theory achieved no serious success, although it did exercise an important influence on the subsequent development of the theory. Although field theory formally possesses a system of equations these are impossible to solve in practice; moreover, it has not even been possible to establish in principle whether this system corresponds to any real solutions. The position of field theory has become even more uncertain upon the discovery that the number of elementary particles is very large. Now it is impossible to assume, as in quantum electrodynamics where only electrons and photons are present, that every particle corresponds to its own field.

With a large number of particles and strong interaction between them any direct connection between particles and fields in general disappears. Thus at present even a formal system of field equations cannot be said to exist as it is not known how many and what kinds of fields need to be introduced. Attempts have been made to construct schemes with a minimal number of fields or even with one field (Heisenberg) but these attempts have not so far produced any real results.

It is interesting to note that there exists a region in which field theory might be used successfully – or so it seems – namely the region of weak interactions. Indeed, Fermi's theory of beta decay, proposed in 1934, has withstood the test of time and in modified form describes various particle decays. However, upon closer scrutiny it is found that the real consequences of the theory of weak interactions mean nothing more than a notation of the scattering amplitude. Unlike quantum electrodynamics, in which it is possible to calculate the amplitude with arbitrary accuracy, in the theory of weak interactions it is in principle impossible to go beyond the first approximation in which the concepts of Lagrangian interaction and amplitude are identified. This is due to the fact that the smallness of the forces of interaction is not sufficient for a solution of the field equations; a further requirement is the so-called property of renormalizability without which the field equations in reality become devoid of meaning.

The theory of weak interactions is therefore essentially a phenomenological theory, although formally it is written down in differential form.

We note that this process of "sliding" of the theory into phenomenological description occurs in other fields of physics as well. In nuclear physics, for instance, frequent use is made of Schroedinger's equation with complex potential (calculation of inelastic processes), energy-dependent potential (optical model) and so on. Of course this is a phenomenological description – even though the differential form is chosen for it.

The same phenomenological description obtains in a variety of applications of Newtonian mechanics. For example, when the forces of friction are introduced these forces do not express the real law of interaction of bodies. Also, of course, introduction of the forces of friction into, say, the equation for oscillations of a pendulum (differential form of phenomenological description) is in no way superior to simply introducing damping into the amplitude of the oscillations (integral form).

Let us return to the physics of elementary particles and more specifically to the theory of strong interactions. The most important advances were made here owing to more detailed analysis of the kinematics (and here field theory played an important heuristic role). It may be asserted that profound changes (such as were introduced by the theory of relativity and quantum mechanics) did not take place. However, considerable development occurred. New types of symmetry were established, new laws of conservation and corresponding quantum numbers were revealed. Such concepts as internal parity, charge parity, isotopic and baryon quantum number made their appearances. These quantum numbers regulate the character of the transformations of the elementary particles.

Important generalizations were made from the principle of identity. Simple properties of amplitudes noticed in field theory led to the establishment of a new principle which was named the principle of crossing symmetry or principle of universality. It establishes the connection between the amplitudes of different processes in which particles and antiparticles take part.

In electrodynamics an example of such a connection is the simple relation between the amplitude of photon scattering by an electron and the electron-positron pair annihilation amplitude.

The general structure of the amplitudes – more specifically, the number of amplitudes required to describe a given set of processes – and the nature of the variables on which it depends was worked out in detail. It was found that knowledge of the amplitudes gives a complete description of the particles and in particular the presence of bound states (i.e., stable "composite" particles) and resonances (i.e., unstable formations). In cases where it is possible to introduce the concept of the spatial structure of a particle (e.g., charge distribution) knowledge of the amplitude makes it possible to find this structure.

At present attempts are being made to construct a theory of elementary particles which would contain the amplitudes without such concepts as field or other analogous "primary" concepts. The idea of constructing such a theory was first proposed by Heisenberg as early as 1943 and more concretely developed by Gell-Mann and Landau. At first glance this approach seems purely phenomenological. There are many particles, many processes of transformation of these, and to postulate a definite amplitude for each process would be a thankless task with too large an arbitrariness. In actual fact, however, it turns out that the general principles of quantum theory and of the theory of relativity impose such severe restrictions on the form of the amplitudes that there may be no more (and perhaps even less) of this apparent arbitrariness left than when the form of the distance dependence is chosen in Coulomb's law.

For example, the simple law of diffraction scattering which seemed natural for high energy particles is difficult to reconcile with these principles. Theoretically a more complex type of scattering, equivalent to diffraction on a body which becomes virtually broader and more transparent as the energy of the diffracting particles increases, would appear more natural.

It is thus possible that seemingly phenomenological quantities (amplitudes) will actually become the fundamental concepts of the theory. The theory will have no "differential" form (similar to Newton's or Schroedinger's equations), yet with a small number of initial principles it will in a unified way cover a broad region of phenomena of strong interaction among elementary particles.

CERTAIN FEATURES SPECIFIC TO THE QUANTUM THEORY
OF ELEMENTARY PARTICLES

V. Ya. Fainberg

The interaction of relativistic (as well as nonrelativistic) elementary particles takes place at such small distances and in such small intervals of time that it eludes direct experimental verification. What we observe with our macroinstruments is merely the final result of the interaction under well-defined macroconditions (e. g., on a photographic plate). We must then extrapolate into the unknown, create abstractions adequate to the actual processes and attempt to construct on this basis a mathematical theory of the process. The language of the theory and its fundamental ideas will obviously have to be highly unusual as well as necessarily nonclassical; this is not because we are unable to peep "inside" the phenomenon, or for lack of the corresponding microinstruments ("Maxwell's demons") but simply because the properties of relativistic particles and the specific features of quantum conditions are unusual. The language of the theory must reflect these specific features and the peculiar relationship between microphenomenon and macroinstrument, as well as the consequent specific features of the act of cognition proper. (The essence of the microphenomena, so to speak, seeks to shield itself from cognition by means of a "protective wall"– the finiteness of the quantum of action – but since, in the last analysis, the macroinstruments themselves consist of microparticles, such partitions can be broken through by man's knowledge, penetrating ever deeper into this essence.)

Most of the philosphical problems connected with the development of the quantum theory of elementary particles arise owing to specific features of the quantum conditions, their profound dissimilarity from the classical laws of motion and the difficulty of creating space-time models of phenomena.

The qualitatively new character of the quantum conditions, which led to a breakdown of the old classical ideas and their replacement by new ones, ultimately stems from the finite quantum of action discovered by Planck in 1900. This discovery of the discrete nature of action has had, and will yet have, far-reaching consequences not only for physics and many allied sciences but for the development of dialectic materialism.

Philosophical analysis of the latest discoveries in the field of quantum physics must necessarily include among its aims the application of the well-known assumptions of dialectical materialism to these discoveries (i. e., dialectical materialistic interpretation). However, the chief aim in our opinion should be to extract from these discoveries those new elements which enrich and give creative impetus to our ideas concerning the nature of the most "elementary" (for the given level of knowledge) laws of nature and concerning the nature of human cognition itself – and which are thus significant for a broader field of knowledge.

Wherein lies the peculiarity of the quantum conditions and of the principal ideas which follow from them?

Quantum theory consists of two parts: fully finished nonrelativistic quantum mechanics; the continuously evolving relativistic theory of elementary particles, which can by no means be termed "finished" (free from internal contradictions).

Since the relativistic theory of elementary particles represents a natural generalization and development of nonrelativistic quantum mechanics into the region of high energies, the two theories must be considered as an unbroken unity. From this it follows that the peculiarity of the relations of the relativistic theory cannot be understood unless one bases oneself on the fundamental conclusions of nonrelativistic quantum mechanics. It is therefore natural to begin with an analysis of the nonrelativistic theory and to seek later to discover what new elements are introduced into this analysis by the relativistic theory.

The philosophical problems of nonrelativistic quantum mechanics have been discussed in numerous works by Soviet as well as foreign physicists and philosophers. The debate is still continuing today (particularly concerning attempts to give a new interpretation of the mathematical apparatus, the validity of which is not contested).

We will not seek to extend these discussions or to analyze attempts at various interpretations. New contributions can be made here only by generalizing fundamental results obtained in the relativistic theory.

As to the interpretation of nonrelativistic quantum mechanics, the most lucid account of this is given, in our opinion, by V. A. Fok*.

We shall briefly consider the three fundamental characteristics of the relations revealed by nonrelativistic quantum mechanics, stressing their profound dissimilarity from the classical laws. All of these characteristics, as already mentioned, are due to the finiteness of Planck's constant h.

Let us recall, in particular, that simply from the fact that $\Delta S \gtrsim h$ (S – action) one automatically obtains Heisenberg's uncertainty relation** $\Delta p \Delta q \gtrsim h$ (since $\Delta S \sim \Delta p \Delta q$).

First characteristic. A microparticle does not have a trajectory. The relativity*** and restricted region of application of such classical concepts as p and q (and others) are revealed. This leads to the relativity of the division of matter into field and matter and to wave-particle duality in the reflection of the properties of microobjects in the language of classical concepts. The essence of this duality resides in the fact that for the first time we have come up against the impossibility of describing (or even imagining) the process of propagation of an "elementary", "indivisible" quantum object in space and time, either as the motion of a particle or as the propagation of a wave. A quantum object is neither the one nor the other.

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* See Fok, V. A. Ob interpretatsii kvantovoi mekhaniki (The Interpretation of Quantum Mechanics), in a collection of papers entitled "Filosofskie voprosy sovremennoi fiziki" (Philosophical Problems of Modern Physics). Moscow, 1959.

** It is often stated incorrectly in the philosophical literature that the uncertainty relation is a consequence of Schroedinger's equation. In reality it arises independently of Schroedinger's equation as soon as we apply the postulate that every physical quantity can be represented by an operator. Schroedinger's equation represents a different postulate which helps to clarify the real meaning of this relation.

*** The reference is to physical relativity which reflects the objective relationship between phenomena and the concepts which describe them.

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In addition a quantum object possesses such properties (nonreducible to classical ones) as nonlocalizability, the identity of particles of a given kind and the presence of spin.

On the other hand, the restricted applicability of classical concepts (p and q in particular) to microobjects reveals the need for a less relative (most absolute for the given level of knowledge) characterization of the states of individual microobjects. Such a characterization is represented by the ψ-function, which determines the probability of a given behaviour of a microobject under specified macroconditions.

The s e c o n d c h a r a c t e r i s t i c which follows from the finiteness of h is a new element in the interrelation and interaction of microobject and classical macroinstrument (as a necessary instrument of cognition). Nonrelativistic quantum mechanics has shown that it is impossible to abstract oneself completely from the means of observation when characterizing the state of microobjects. A microparticle will behave differently (from the standpoint of p and q) under different macroconditions and depending on the nature of the measurement. The essence of the problem can be grasped only by correctly interpreting the meaning of the ψ-function. Does this quantity refer only to the results of measurement or does it characterize the objective state of the microobject before (or after) measurement? These are essentially questions relating to the nature of cognition of the essence of microobjects from their macroscopic manifestations.

The ψ-function does not depend on the final stage of measurement and is therefore an objective characterization of the individual quantum object. On the other hand, it also reflects the peculiarity of the interaction of micro- and macroobjects, defining the probability for a given result of measurement, i. e., the statistics of the distribution of the results of measurement of a given physical quantity. Before measurement it would be meaningless to speak of the distribution of an individual particle over, say, the momenta and coordinates, since the concepts p and q are not simultaneously suited to the characterization of the state of a microobject. The other point of view – which lays unrestrained stress on the fact that the ψ-function refers only to the results of measurement and that it is therefore meaningless to speak of the objective state of the microobject before measurement – tacitly admits the possibility of extrapolation of the classical concepts p and q to the behaviour of the microobject before measurement, beyond the region of their applicability.

Here, as strange as it may seem, two opposing interpretations converge: the point of view of the Copenhagen school, that the influence of macroconditions on microobjects is uncontrollable and that of the partisans of "causal interpretation", who maintain that we are a s y e t unable to trace the movement of microobjects because we have still not recognized (in the nonrelativistic region!) all of their characteristics. Neither interpretation can be called consistent. This is also shown by the subsequent development of nonrelativistic quantum mechanics into the relativistic quantum theory of elementary particles.

The t h i r d c h a r a c t e r i s t i c is the fundamental role of probability laws in the region of microphenomena. From the finiteness of h and the uncertainty relation it follows that a single individual particle can, from the standpoint of the classical characteristics (p and q), "possess" an entire spectrum of values. From this it follows that statistical description of microphenomena in the language of classical concepts is inevitable and that

formulation of the causality law in the language of these concepts is impossible in principle. It is formulated in the language of a quantity which is not directly observable – the ψ-function.

In nonrelativistic quantum mechanics the concept of probability is primary and fundamental.

In nonrelativistic quantum mechanics we encounter for the first time a completely new interrelation between statistical and dynamical relationships. In classical physics the statistical relations among a large set of particles repose on dynamical laws of motion for an individual particle. Quantum mechanics revealed that more general probability relations lie at a deeper level at the base of the dynamical laws of motion[*]. Does this mean that in an even deeper sense the quantum relations cannot be governed by dynamical (though nonclassical) laws? In principle one cannot say this and such a possibility cannot be disproved by any considerations lying outside physics.

However, to all appearances the subsequent development of quantum physics refutes such a possibility. Later we shall seek to demonstrate this on the basis of the relativistic quantum theory of elementary particles.

In conclusion it may be stated that the finiteness of the quantum of action h reveals the restricted applicability of macroconcepts (p, q and others) to microobjects in the region of nonrelativistic velocities ($v \ll c$) and reflects the new quantum nature of the latter; the need arises for new concepts characterizing the state of individual microobjects (ψ-function). From the standpoint of these concepts a microparticle "possesses" an entire spectrum of possible values of p and q. Hence the inevitability of a probabilistic behaviour of a microparticle under specified macroconditions. The probability laws become primary. In this sense it may be said that accidental (probabilistic) relations lie at the base of the dynamical ("necessary") laws.

Thus the quantum-mechanical description is an example of the brilliant resolution in the nonrelativistic region of energies) of the contradiction between the quantum nature of microobjects and the idea of the existence of classical instruments (or, in more general form, between the former and classical ideas concerning space and time). The essence of this contradiction lies in the fact that we cannot introduce the concepts p and q if we are to look at all bodies from the quantum-microscopic standpoint, i.e., if we are not to assume the existence of classical objects of infinite mass and infinitesimal size.

We will now attempt to set down the new elements introduced into the fundamental characteristics of nonrelativistic quantum mechanics mentioned above by further development of this branch and its generalization into the region of high (relativistic) energies. Our concern will be with the present relativistic theory of elementary particles. In its most complete development this theory should explain both the existence of and the transformations among the various elementary particles (the number of which already exceeds thirty and continues to increase!). The most striking experimental fact distinguishing relativistic quantum concepts from nonrelativistic ones is the multiplication and transmutability of interacting particles as well as the existence of an intimate connection among the quantities which characterize such interactions. A relativistic quantum theory of elementary particles

[*] In other words, in contrast with classical relations no refinement of earlier observations will lead to a single-valued prediction of the result of measurement (see Fok, V. A. Ob interpretatsii kvantovoi mekhaniki, Op. cit., p. 165).

should be the mathematically closed theory of such phenomena. Its mathematical apparatus should synthesize relativistic (the new constant c enters organically) and quantum (constant $\hbar$) ideas.

The trouble is that at present no such theory exists. More precisely, however, one might say that it was launched long ago (in the thirties), is continuously developing and, despite all (possibly seeming) internal contradictions, must inevitably lead to the creation of a coherent relativistic quantum theory of elementary particles. Judging by the latest advances we do not have long to wait. This is witnessed by many facts. In the first place, there are already at present two principal approaches to the solution of problems facing the relativistic theory. While it is true that both are based so far on specified charges, masses and spins of known elementary particles, there are hopes that this restriction will soon be overcome. The first approach is relativistic field theory, which starts from the assumption that there exists a second quantized probability amplitude, i.e., rests on the method of second quantization and the dynamical equations for Green's functions. Quantum field theory has been most successful in the region of electromagnetic and weak interactions (at not excessively high energies). The question of the applicability of quantum field theory to the region of strong interactions and high energies still remains open. Whether the difficulties inherent to it are of a fundamental nature is at present unclear. It may be that it is based on excessively detailed and internally contradictory assumptions.

The second approach, which has been intensively developed in recent years (particularly in application to strong interactions), is the so-called axiomatic approach or S-matrix method. Its fundamental idea is to be dealing in the theory with physically meaningful quantities only, or with the matrix elements of the S-matrix for real particles ($p_i^2 \equiv p_{0_i}^2 - \vec{p}_i^2 = m_i^2$) only. This approach has likewise been associated with a whole series of advances in the relativistic quantum theory of elementary particles. Considerable hopes have been placed in it. How deep is the difference between the two approaches will become clear in the near future. It is not excluded that each (one-sidedly) projects some characteristic features of the "true" theory of elementary particles and has its own region of applicability.

We have presented these lengthy considerations in order to stress the fact that a theory of elementary particles exists, though in unfinished form. Moreover, so far the two approaches display no qualitative divergence between their predictions and experiment. Most of the fundamental predictions of the modern theory of elementary particles have been confirmed by experiment.

All this is evidence that the ideas underlying the modern theory of elementary particles are correct. Analysis of new features of this theory which distinguish it from nonrelativistic quantum mechanics should help delineate the trends of development of the theory and of our ideas concerning microphenomena.

All of the fundamental traits of the relativistic theory listed below follow in some form or other from the nonconservation of the number and nature of relativistic particles in the process of interaction*.

First feature. The relativistic quantum theory of elementary particles discloses the even deeper relativity and restricted applicability of

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* Thus (unless otherwise stated) these features are not related to any particular mathematical formulation of the theory (to, say, the first or second approach).

classical concepts as well as of a number of fundamental concepts of non-relativistic quantum mechanics; at the same time it reveals the need for a more absolute (independent of conditions of measurement and, therefore, objective) characterization of the state of interacting relativistic particles.

In the first place, the state of such particles cannot be represented by the ψ-function of a specified number of particles even with a relativistic formulation of the equation for ψ.

The ψ-function of nonrelativistic quantum mechanics thus becomes meaningless in the high-energy region.

How is the state of elementary particles characterized in relativistic quantum theory?

It follows from the multiplication and intertransmutation of particles that these represent a system with an infinite number of degrees of freedom.

Each degree of freedom can be associated with a quantity characterizing the probability of transition with a specified number of particles of a definite kind (in the initial and final states). Such quantities are called elements of the S-matrix or transition amplitudes.

In relativistic quantum theory of elementary particles the state of interacting particles is therefore characterized by an infinite set of interrelated transition amplitudes. The aim of the theory is to find these amplitudes.

When one goes to the nonrelativistic limit, i.e., for $c \to \infty$, then, roughly speaking, out of all this set there remain those amplitudes which correspond to processes with conserved number of particles; further, these amplitudes themselves lose the so-called property of "crossing symmetry", or universality*.

Such specifically quantum properties as nonlocalizability, identity and the connection between spin and statistics receive a natural explanation in the relativistic theory. The relativistic theory brings to light the further relativity of the concepts of field and particle: the last remnants of a divergence between the classical field and the quantum particle (present in nonrelativistic quantum mechanics) vanish. Their profound internal identity is revealed.

From the standpoint of quantum field theory, a particle is a quantum of excitation of a corresponding field. The concepts of particle and field are fused in the single concept of the quantized field. In the interaction of different quantized fields the quanta may be scattered, multiplied, converted into quanta of other kinds. Here the field has the more fundamental role**.

The dialectics of the concept "elementary particle" is particularly well illustrated by analyzing such concepts as point particles, the interaction and the structure of elementary particles. In this theory even a single free particle cannot be localized in a region of space $\leqslant \left(\frac{\hbar}{mc}\right)^3$, where m is the mass of the particle; consequently even in the absence of interaction one cannot speak of "point" particles. Introduction of interaction results in the particles "smearing out" and assuming a space-time structure. Despite the fact that in the relativistic theory, just as in nonrelativistic quantum mechanics,

* On the subject of universality and crossing symmetry see, for example, Berestetskii, V.B. Dinamicheskie svoistva elementarnykh chastits i teoriya matritsy rasseyaniya (Dynamical Properties of Elementary Particles and the Theory of the Scattering Matrix). Uspekhi Fizicheskikh Nauk (henceforth cited as "UFN"), Vol. LXXVII, No. 1. 1962.
** Concerning quantum-field concepts see Frenkel', Ya.I. Zamechaniya k kvantovo-polevoi teorii materii (Remarks on a Quantum-Field Theory of Matter); Blokhintsev, D.I. Elementarnye chastitsy i pole (Elementary Particles and the Field), "UFN", Vol. XLII, No. 1. 1950.

noninteracting particles are characterized by such properties as mass, charge, spin and so on and do not possess an internal structure (internal degrees of freedom), the profound dissimilarity between particles in non-relativistic quantum mechanics and those in the relativistic theory is manifested during interaction. Thus in the latter the concept of structure cannot be separated from interaction: structure is revealed in interaction. It would be meaningless to speak of a structure of elementary particles "by themselves" without considering their interactions. From the standpoint of the ideas of ordinary quantum mechanics this means, roughly speaking, that in order to obtain the correct expression for the scattering of, say, two elementary particles, we must regard these particles as being "smeared" in space-time. In the relativistic theory this result is the direct consequence of the mathematical apparatus of the theory, despite the point character of the interaction of quantized fields. Thus in the foregoing sense the presence of space-time structure in particles not only fails to contradict the special theory of relativity, but follows necessarily from its fusion with quantum ideas.

It is sometimes stated that the theory of relativity requires that elementary particles be regarded as point particles. Assertions to this effect have been made, for example, by Ya. P. Terletskii*. However, as we saw earlier, they run counter to the real situation in the relativistic theory of elementary particles. To infer the need for a revision of ideas about space and time, with the experimental discovery of structure in particles cited as evidence, is, to say the least, premature. Should such a revision prove inevitable, it will in all probability have a deeper basis. In this connection it seems to us that philosophical predictions concerning possible paths of development of science should be made with great caution.

Second feature. As compared with nonrelativistic quantum mechanics, the relativistic theory reveals a deeper interrelation between the states of the microobject and macroinstrument and a yet greater relativity with respect to the means of observation. In nonrelativistic quantum mechanics (second characteristic) relativity with respect to the means of observation is manifested, in particular, in the fact that under certain conditions the electron can have a definite momentum and under other conditions a definite position. Thus to speak of the position (or momentum) of an electron within the framework of nonrelativistic quantum mechanics is meaningful only after the action of a definite macroinstrument on the electron. In relativistic theory even under definite macroconditions it is meaningless to speak of the position of a given electron** if it is interacting with a relativistic particle or if we wish to measure its position with an accuracy of $\ll h/mc$. This follows from the experimental fact of intertransmutability and multiplication in the interaction of relativistic particles.

Here the new element as compared with nonrelativistic quantum mechanics is that, having discovered a certain number of particles as a result of measurement (let us say on a photographic plate), we can say nothing about the number and kind of particles present before measurement: these concepts are not applicable to the characterization of the state of interacting relativistic particles. Thus if in nonrelativistic quantum mechanics it is

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* See, for example, his article in the present book.
** There is a considerable disparity between the momentum and coordinate representations in the relativistic quantum theory of elementary particles.

meaningless to speak of the distribution of particles over the momenta before measurement, in the relativistic theory it is likewise meaningless to speak of the distribution over types and sorts of particles before measurement.

Before measurement a system of interacting particles is characterized by the entire infinite set of transition amplitudes which determines the probability of a certain behavior (in the sense of number as well) of the system under specified macroconditions. This is an objective characterization of the state because it does not depend on the final state of measurement.

We thus see that the penetration of our knowledge into the essence of microphenomena leads to an unusual situation: in s e p a r a t e acts of measurement of the classical manifestations of this essence (momenta, number of particles and so on) we obtain relatively scant information concerning the essence proper and at the same time uncover an ever narrower region of applicability of the classical ideas for the characterization of this essence. The microessence of phenomena is so profound and so diverse that individual macromanifestations can reveal it only partially or one-sidedly; generally speaking, however, the i n f i n i t e s e t of such manifestations gives us the possibility of inferring the objective microessence of phenomena on the basis of theoretical considerations and evolving representations adequate to this essence. These representations become richer and more profound but less obvious.

The t h i r d f e a t u r e. As quantum concepts are developed and extended to the region of relativistic energies (and, therefore, to small space-time intervals) the concept cf probability assumes an increasingly fundamental importance in the determination of the state of a system. Within the framework of nonrelativistic quantum mechanics it was in principle possible to assume that the probabilistic character of the behaviour of microobjects under specified macroconditions was governed by "hidden" parameters, subject to dynamical equations of motion and having an immediate physical meaning but as yet unknown for some reason or the other. The development of experiment and theory actually led to the discovery of new parameters determining the state of interacting relativistic particles. In the first place, however, it turned out that the number of such interrelated parameters was infinite; in the second place, and more importantly, these parameters had a probabilistic meaning and their presence led to a still more pronounced statistical behaviour of microobjects under specified macroconditions.

Thus we see that the most characteristic tendency in the development of the theory, as it is extended to the region of relativistic energies, is as follows: increasingly deep and consistent rejection of the applicability of classical concepts in small space-time regions, increasingly abstract characterization of the state, increasingly limited space-time visualization.

This is manifested particularly clearly in the so-called S-matrix method mentioned earlier, which was successfully developed in recent years. In this method an attempt is made to remove the last remnants of space-time concepts (x, t) from the mathematical apparatus. The theory even rejects the application in a small region of the very concept of probability to the interaction of relativistic particles. This approach leads, in particular, to a unified point of view on complex and elementary particles (including unstable particles and resonances) and may possibly prove capable of solving

the problem of the mass spectrum of elementary particles (the most opti-
mistic view). If this happens then a theory logically closed to a certain
degree* will have been constructed, apparently without fundamental changes
in classical relativistic ideas concerning space and time in a small region.
However, we feel that the contradiction between the quantum essence of
microphenomena and classical (though relativistic) ideas concerning space
and time can be consistently solved only by changing the latter. As to when
this will happen, and in what direction, nothing definite can be said as yet...

In conclusion the following remark is in order. At first glance it seems
as if the development of new space-time ideas in a small region will permit
the creation, in particular, of models of quantum phenomena. In reality
the difficulties involved in the setting up of such a model (all the more so
of a classical model) will only increase, although our knowledge will be-
come enriched by deeper ideas. In this we see a manifestation of one of
the contradictions of human cognition. There is nothing one can do — such
is the essence of objective regularities in nature and the nature of their
expression in the human mind!

* But not "final", as no such theories exist.

THE PROBLEMS OF MODERN ASTRONOMY AND PHYSICS
OF THE MICROWORLD

V. A. Ambartsumyan

The philosophy of science is of considerable significance for astronomy. Definite philosophical views on nature frequently serve as a foundation for setting up and solving many far-reaching problems of natural science, including the science of the universe. If correct philosophical views are held a correct approach to the solution of concrete problems of natural science can also be evolved. In particular it is entirely possible that such an approach would lead to more rapid discarding of preconceived notions resulting from insufficient knowledge of philosophy on the part of the given investigator or from his utilization of a poor philosophy.

By providing a firm foundation for the thesis that matter is inwardly infinite and inexhaustible and the properties of the material world manifold, Marxist philosophy compels the investigator constantly to seek manifestations of new, still unrevealed regularities of nature, and to find deep relationships between phenomena which at first glance seem scarcely related.

The diversity and depth of the relationships between different phenomena of the material world may be illustrated by the one which relates certain regularities of the astronomical universe and the physics of the microworld. Here we will consider only a few aspects of this relationship.

The very existence of elementary particles is of fundamental importance for all fields of natural science. If the material world consists of elementary particles then, obviously, their existence should in some degree be felt in all natural phenomena. The phenomena and regularities studied by astronomy cannot be an exception in this respect.

Let us begin with the simplest example. It is well known that modern astrophysics deals mainly with problems relating to the structure of stellar atmospheres and nebulae and to interstellar space. Further, it bases itself on the information we obtain from these formations: from stars, from stellar atmospheres, from nebulae and from cosmic interstellar masses.

This information reaches us mainly by means of electromagnetic waves, i. e., in the form of light and radio emission. Correspondingly, two fundamental branches of modern observational astronomy, optical astronomy and radio astronomy, have sprung up and attained a high degree of development. Since electromagnetic radiation consists of elementary particles — photons — we may conclude that the information reaches us in the form of streams of elementary particles.

In addition to the electromagnetic radiation of celestial bodies, our observational apparatus also receives streams of high-energy charged particles

(this is particularly true of the observational media in rockets and satellites). The information carried by these particles – protons, ions and electrons – is very difficult to decipher because the magnetic fields present in cosmic space deflect these particles from their original trajectories in a highly random and irregular manner. The study of these particles has nonetheless already yielded interesting data.

A person in the washroom of a moving passenger train would not be able to distinguish the objects passing by because washroom windows are usually made of matt glass. However, the scattered light which penetrates through the matt glass may provide some, occasionally important, information. For instance, a sharp reduction in the light penetrating through the glass would mean that the train has entered a tunnel; isolated flashing gleams immediately afterwards would show how well the tunnel is illuminated by electric lamps.

In the same way it was found that in some solar flares considerable streams of cosmic rays are formed. By combining data on cosmic rays with the information gleaned by radioastronomical methods it was possible to establish that so-called discrete sources of radio emission, i.e., radio nebulae and radio galaxies, are centers of formation of high-energy particles.

If formerly the corpuscular nature of electromagnetic radiation played an insignificant role in the analysis of optical information and radio information, now, as a result of the increased sensitivity of light and radio receivers, and particularly owing to the application of photon counters, this fact has been assuming increasing importance. As to cosmic rays, the information they furnish is obtained entirely as a result of the counting and investigation of individual particles.

Recently astronomers have seriously begun to entertain the hope of obtaining direct information concerning the state of the interior of the Sun and certain other stars by the detection of neutrinos emitted directly from the central regions of these bodies. So far these neutrinos have not been detected owing to their small number, and also because the probability of detection of each neutrino by our instruments is negligible. However, the construction of sufficiently large instruments will doubtless make it possible to find the neutrinos reaching us from outer space. From the philosophical point of view it is very curious to be dealing with the recording of exceedingly rare events of interaction between neutrinos and nuclei of terrestrial matter; equally curious is the fact that information concerning phenomena which until recently seemed inaccessible to direct observation will be obtained from precisely such recording of individual elementary particles.

As all of these circumstances show, not only the astronomical phenomena themselves but even the means by which we obtain scientific information on celestial bodies are closely related to phenomena of the microworld.

The matter in the universe, which is, in the last analysis, an assembly of elementary particles, is collected in various bodies. This seemingly trivial fact gives rise to a great many questions. Matter is collected in stars, planets, nebulae and interstellar clouds. Looking at the relative amount of matter collected in bodies of each type, however, one finds that significantly more than half of all the matter in the observable universe is collected in s t a r s . The latter are self-luminous bodies with a mass of

the order of that of the Sun. The total mass of scattered matter present in the form of nebulae and interstellar clouds is small compared with the total mass of all stars.

Thus most of the matter in the universe is concentrated in stars. In turn, rather than being uniformly distributed in space stars are concentrated in systems called g a l a x i e s which are relatively small by volume but gigantic in stellar population. It can be said with certainty that the o v e r - w h e l m i n g m a j o r i t y o f s t a r s a r e c o n c e n t r a t e d i n g a l a x i e s containing not less than ten billion stars each, i.e., in giant and supergiant stellar systems. In addition to giant and supergiant systems galaxies containing relatively few stars are also known to exist. The faintest dwarf galaxies contain only some hundreds of thousands – or even tens of thousands – of stars. The number of such dwarf galaxies is very large. Yet nonetheless their overall mass is negligible compared with the overall mass of giant galaxies. Thus it is valid to assert that the overwhelming majority of stars are concentrated in giant and supergiant galaxies.

It is known that galaxies generally differ among themselves in the constitution of their stellar population. Despite this in all galaxies the stars have a mass of the order of that of the Sun (for accuracy we note that the average mass of the stars in every such galaxy is slightly smaller than the solar mass). The differences in composition of population between dwarf and giant galaxies, however, are not much greater than the differences in composition of population between two giant galaxies taken at random or between any two dwarf galaxies. This fact is surprising, as certain giant galaxies are millions of times richer in stars than many dwarf galaxies. It indicates that possible star masses are predetermined by more fundamental properties of matter than, say, the size and mass of the stellar system in which the given stars originated.

In particular it is interesting to note that there exists an upper limit for star masses which is very seldom exceeded. This limit is approximately 100 $\mathfrak{M}_\odot$ *.

Also notable is the fact that there is an upper limit for the observable mass of galaxies. The exact value of this limit has not yet been established but it is roughly of the order of 10^{13} solar masses.

We thus arrive at the following questions:

1. Why is matter in the astronomical universe collected predominantly in stars?

2. Why do stars have an upper limit of mass of the order of 100 $\mathfrak{M}_\odot$?

3. Why are stars collected predominantly in giant galaxies?

4. What determines the upper limit of mass of galaxies?

It is natural to believe that these structural characteristics of the universe are determined by the most fundamental properties of matter, i.e., by those properties which are determined by the characteristics of the elementary particles which constitute matter. It follows further that the quantitative characteristics of stars and galaxies should be determined by the parameters of elementary particles, i.e., ultimately by universal constants.

Let us consider the first two questions in greater detail.

Simple theoretical analysis shows that a certain amount of matter left to itself in space should continue to emit energy until it reaches equilibrium. In the equilibrium state the parameters characterizing the given body – and

* $\mathfrak{M}_\odot$ is the mass of the Sun.

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this includes its internal energy — should not change. This means that the body should emit nothing, i.e., its temperature should be zero.

Thus if we wish to speak of rigorous equilibrium states of star masses we should consider the configuration for $T = 0$. In reality, of course, stars have nonzero and occasionally fairly high temperatures. Stellar masses at zero temperature are, of course, imaginary objects. However, the discovery of white dwarfs has shown that there exist star masses the states of which are close to this ideal state, i.e., such that their temperatures can be taken as approximately zero when calculating their mechanical equilibrium.

What does the theory tell us about the equilibrium state of star masses at zero or near-zero temperatures?

The possible equilibrium configurations of star masses has been worked out in fairly great detail in theoretical astrophysics. A vast literature is devoted to it. It is assumed that matter in stellar interiors is highly ionized. This should be the case even for relatively low temperatures in the stellar interior. Generally speaking, therefore, the matter inside a star consists of a plasma containing a high percentage of charged particles.

For a given density and sufficiently low temperature the aggregate of electrons which compose this plasma ceases to satisfy classical statistics. Owing to the fact that electrons are subject to Pauli's principle their behavior is determined by F e r m i   s t a t i s t i c s . The pressure of a Fermi gas at low temperatures is considerably higher than that of a classical gas. It is so high that, essentially, the total pressure in the plasma is almost entirely determined by the partial pressure of the electrons. The latter in turn becomes practically independent of temperature, the only requirement being that the temperature be below a certain "temperature of degeneracy".

The fact that the pressure is independent of temperature and dependent only on the density of the electron gas radically simplifies the calculation of the equilibrium configuration. The theory of the internal structure of such stars is very simple; it was worked out in the thirties by Chandrasekhar and is known as the theory of white dwarfs*.

The point is that the assumption of a relatively low internal temperature inevitably leads one to suppose that there are no sources of energy in the star or that these are very weak. Therefore the luminosity of such a star should be very low and its density high (otherwise the gas would not be degenerate).

Such properties are present in w h i t e   d w a r f s . The prototype of white dwarfs is the companion of Sirius. Its density is known to be roughly 50,000 times that of water. It has now been established that the number of white dwarfs in our Galaxy is very large. It is of the order of many hundreds of millions.

Calculations have shown that only such masses as are smaller than a certain limiting mass, given, in the case of a hydrogen star, by

$$\mathfrak{M}_0 = \frac{K}{m_p^2}\,\mathfrak{M}_\odot. \qquad (1)$$

* See Chandrasekhar, S. An Introduction to the Study of the Stellar Structure. Dover Publications, Inc., New York. 1957.

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(here $k = 16 \cdot 10^{-48} g^2$ and m_p is the mass of a proton), can occur in a state of equilibrium*. Introducing the numerical value of the proton mass into the above, we obtain

$$\mathfrak{M}_0 = 5.75\mathfrak{M}_\odot. \qquad (2)$$

Thus the simplest theory indicates that the mass of a stellar configuration at low temperatures has an upper limit (2). It is interesting to note that this upper limit is significantly higher than the mass of the Sun.

In reality, as was indicated earlier, the upper limit obtained by observation is far greater than (2), i. e., of the order of 100 $\mathfrak{M}_\odot$. However, stars with a mass exceeding $\mathfrak{M}_0$ are no longer white dwarfs, i. e., do not consist of a degenerate gas. Their temperature must be very high and thermonuclear reactions must therefore be taking place inside them. The theory of such stars, though also developed in fairly great detail**, does not have the simplicity of the theory of degenerate configurations and contains much that is unclear. An important point, however, is that according to this theory for masses of the order of 100$\mathfrak{M}_\odot$ the generation of energy by thermonuclear reaction and emission of this energy by the star take place at a very rapid pace, leading to rapid exhaustion of the sources of thermonuclear energy. Such a star is therefore highly luminous and short-lived. Its lifetime must be at most of the order of a million years. When this time has elapsed the star will have expended its sources of energy and its equilibrium will be destroyed.

It is assumed that disruption of equilibrium is accompanied by ejection from the star of part of its mass. Ejection of mass should continue until a value below the limiting mass is reached.

The theoretical value given above for the upper limiting mass of degenerate stellar configurations is thus of decisive importance for processes of evolution of the entire stellar world.

This very important problem illustrates the decisive importance of the laws of the microworld for problems of cosmogony and stellar physics. In particular we may state the following:

1. If electrons, as elementary particles, were not subject to Pauli's principle, the pressure in the plasma would be far lower. In particular if they obeyed classical or Bose statistics then, as calculations show, a low-temperature stellar mass would have no equilibrium state. If left to itself such a mass could continue to contract under the influence of gravity to very high densities far exceeding the density of white dwarfs, even if $\mathfrak{M} < \mathfrak{M}_0$.

2. We see from formula (1) that the numerical value of the limiting mass is determined by the proton mass. If we imagine a world in which protons and, in general, nucleons have a mass a hundred times smaller than in reality then the upper limit for the mass of degenerate stars in this world should be of the order of 57,000 $\mathfrak{M}_\odot$.

3. It is obvious that the theory of the internal structure of the stars should allow one to determine not only the upper limit of mass but also the radius of degenerate stellar configurations. It so happens that if a star consists of

* Formula (1) is essentially the same as formula (66) in Chapter XI of Chandrasekhar's work cited above, but in a different notation. In this new form attention is drawn to the dependence of the limiting mass on the numerical value of the proton mass.

** See Schwarzschild, M. Structure and Evolution of the Stars, Princeton, 1957.

protons and electrons then, for masses smaller than the critical mass but comparable with it, the order of magnitude of the radius is determined by the formula

$$R \sim \sqrt{\frac{\hbar^2}{cG}} \frac{1}{m_p m_e},$$ (3)

where the usual notation for the universal constants is used.

Thus the radius of white dwarfs is determined primarily by such crucial numerical characteristics of the microworld as the proton and electron masses.

For completeness, however, the following remarks must be made.

Above we discussed the equilibrium configuration which can characterize a given mass of matter. But a gravitational defect of matter exists. In other words, mass is not additive in the sense that if the matter in two stars of mass m_1 and m_2 which are in equilibrium is collected in a single star also in equilibrium, then the mass m_3 in the new equilibrium configuration will generally differ from $m_1 + m_2$. The law of conservation of mass remains in force, of course, but the difference $m_1 + m_2 - m_3$ is lost in the form of radiation (photon or neutrino).

Therefore when speaking of the equilibrium configurations of stellar masses it is sometimes convenient to treat the n u m b e r   o f   h e a v y   p a r - t i c l e s – baryons – as the specified parameter, as is done, for example, in the theory of atomic nuclei. The imaginary fusing of two masses into one can take place without changing the baryon number, though an additional mass defect may appear in the process.

The total number of baryons is convenient as a given basic parameter owing to the validity of the l a w   o f   c o n s e r v a t i o n   o f   b a r y o n   n u m - b e r . The number of baryons in a star remains unchanged provided there is no direct outflux of baryons from the stellar configuration.

It is true that the law of conservation of the total number of leptons is also valid. However, when the energy of a star changes, the energy liberated may be emitted not only in the form of photons but in the form of neutrinos or antineutrinos as well; this generally leads to a reduction in the lepton number.

Turning now to the possible equilibrium configurations of stellar matter for fixed baryon number, we find that the possible cases for low-temperature matter are (in addition to cases where only electrons are degenerate) those where the baryon gas is degenerate. Very high stellar densities of the or- der of $10^{15} - 10^{16}$ times the density of water may be observed in such cases. At such high densities the amount of protons and electrons in low-tempera- ture matter is small compared with the number of neutrons and, in other cases, hyperons. Like atomic nuclei such configurations should consist nearly exclusively of baryons. This is how the idea arose of neutron and hyperon stars. The theory shows that they should have a limiting mass of the same order as white dwarfs. The diameters of such "superdense" con- figurations should be of the order of several kilometers[*].

So far no one has observed such superdense neutron or hyperon stars. However, if they exist they cannot be detected by ordinary methods of terrestrial astronomy. But the fact that theoretical physics is capable of predicting the possibility of still unobserved configurations of stellar mass from existing ideas concerning such microparticles as baryons is remarkable from the methodological point of view.

There exists yet another field of astronomy, scarcely developed so far, in which progress on the basis of phenomenological concepts alone without the introduction of microphysical ideas is apparently impossible. The reference is to the phenomena studied by extragalactic radio astronomy.

After radio galaxies were discovered it became evident that their radio emission is related to the existence in these galaxies of vast clouds of relativistic electrons moving in magnetic fields. These electron clouds frequently lie in the immediate vicinity of, rather than within, the corresponding galaxies.

Recent works have refuted the old conception of radio galaxies as pairs of galaxies in accidental collision. Now there can be no doubt that radio galaxies represent a regular stage in the internal development of separate high-luminosity, predominantly supergiant galaxies*. The question arises of the mechanism by which electron clouds of such high energy appear.

An opinion very frequently and persistently stated in the literature is that high-energy electrons in such cases are formed by means of the so-called Fermi mechanism. According to Fermi a gradual increase in the energy of electrons up to very high values may take place when these electrons are scattered by magnetic fields which move in the given galaxy and are related to ordinary diffuse matter. This mechanism was suggested by Fermi to explain the origin of cosmic rays. Now we know that a certain portion of the cosmic rays which reach us originates in the Sun during great explosive flares. We also know that the origin of galactic radio sources and of the enormous amounts of relativistic electrons which they contain is connected with the explosion of supernovae. There is no basis for assuming the existence of special conditions favorable to the operation of the Fermi mechanism in radio galaxies. A different point of view, according to which clouds of relativistic particles in radio galaxies result from gigantic cosmic explosions, has consequently been launched and developed recently. The observational data favor the view that these explosions take place in nuclei of galaxies, which are known to have a negligible volume compared with that of the galaxies themselves**. In our opinion it is possible that the energy of these explosions derives from some rapid nuclear process the nature of which is as yet unknown.

In other words, the Fermi mechanism explains the appearance of relativistic electrons by the interaction of microparticles and macrofields. The new view supposes that the principal role is played by certain microinteractions in which nuclear forces are paramount. Thus the gigantic phenomenon of the radio galaxy is treated as a direct result of microinteractions in the matter of the galactic nucleus.

* See Ambartsumyan, V. A. Nekotorye zamechaniya o kratnykh galaktikakh (Some Remarks Concerning Multiple Galaxies), 1955; O kratnykh galaktikakh (Multiple Galaxies), 1956. Nauchnye trudy, Vol. II, Erevan. 1960.

** See Ambartsumyan, V. A. Problemy vnegalakticheskikh issledovanii (Problems of Extragalactic Research). Voprosy kosmogonii, Vol. VIII. 1962.

The ejection of giant clouds of relativistic electrons and resulting conversion of the given galaxy into a radio galaxy for a certain time is only one of the forms of activity of galactic nuclei. The nuclei of a few giant galaxies manifest other forms of activity as well. Thus in our own Galaxy an outflow of gases from the central region of the Galaxy, reaching a speed of 50 km/sec, is observed. A similar outflow of matter is observed from the nucleus of the giant galaxy M 31 in Andromeda.

The fact that the spiral arms of many close galaxies can be traced right up to the nucleus on large-scale photographs furnishes ground for believing that the outflow of matter from the nucleus is related to the process of formation and development of spiral arms. Thus it is entirely possible that the development of arms is to a significant degree the result of the activity of the nucleus.

On the other hand, in some cases a rectilinear stream with isolated clusters along it is observed to emerge from the nucleus of certain super-giant elliptical galaxies. Sometimes these are clusters of blue light, which distinguishes them from the remainder of the galaxy. Analysis of these phenomena reveals that the clusters observed in the streams should be considered discrete ejections from the nucleus. The luminosity of such clusters exceeds that of many dwarf galaxies. Thus we are probably dealing with the formation of new galaxies out of the nuclei of supergiant galaxies. This gives us reason to believe that the formation of new galaxies is possible even in the present epoch of development of the astronomical universe.

Since galactic nuclei can generate several cosmic formations of different kinds, such as 1) giant clouds of relativistic electrons, 2) spiral arms and 3) young medium-luminosity galaxies, we can already speak of the d i f f e r e n t f o r m s   o f   c o s m o g o n i c   a c t i v i t y of galactic nuclei.

There is reason to believe that not only the mechanism of formation of large clouds of relativistic electrons (radio galaxies) but other forms of cosmogonic activity by nuclei as well are closely related to transmutations of the elementary particles which constitute these nuclei.

We have considered only a few of the examples which prove the direct relevance of the laws of the microworld for the microprocesses taking place in the astronomical universe. Such examples could be multiplied. We have confined ourselves to those which are significant for cosmogony.

It would be a gross mistake, however, to infer that astrophysical phenomena can always be reduced to a simple sum of microphysical phenomena. Qualitatively new effects arise in dealing with such large numbers of elementary particles as are present in the stars and galaxies: 1) statistical regularities which determine the physical properties of matter in stars and nebulae and the thermodynamic and gasdynamic phenomena taking place inside them; 2) effects related to the enormous role of the force of attraction. It is these effects that are responsible for the special character of astrophysical phenomena and make astrophysics completely dissimilar from laboratory physics.

STRUCTURE

PROBLEMS OF THE STRUCTURE OF
ELEMENTARY PARTICLES

D. I. Blokhintsev

At the present time sixteen elementary particles and roughly the same number of antiparticles are known.

Were this list expanded to include the very short-lived particles – "iso-bars" or "resonance states" – the total number of particles now known would reach forty.

Most of these particles are unstable; they decay, ultimately transforming into a small number of stable particles, i. e., electrons and protons, γ-quanta and neutrinos or into the corresponding antiparticles, which are also stable. The elementary particle world is exceptionally rich both with re-gard to the diversity of particles proper and to the forms of interaction and transformation between them.

There now exists a more or less satisfactory systematics of particles and logical classification of particle interactions.

All of these classifications, however, are still very far from presenting a unified picture; the established forms of particles and interactions still remain unrelated.

On the other hand the materialistic physicist can scarcely fail to believe that there exist profound internal causes which determine both the proper-ties of elementary particles and their very existence.

Particles must also possess an internal structure which determines their global characteristics – including those quantum numbers which serve as characteristics of the individual baryons, mesons or leptons.

In this connection I should like to deal at greater length with the problem of the internal structure of particles.

The problem of the structure of elementary particles has had a curious historical development. In the earliest stages of development of electron theory no one really doubted that the electron had a finite size and, there-fore, an internal structure. Moreover the conviction was that this size was determined by the "classical" electron radius

$$a = \frac{e^2}{m_0 c^2}, \tag{1}$$

where m_0 is the electron mass, e its charge and c the velocity of light.

It seemed as if the entire problem consisted of establishing the form of the charge distribution of the electron in a sphere of radius a. However it was soon shown that such naive ideas concerning particle structure led to very serious contradictions with the fundamental principles of physics and
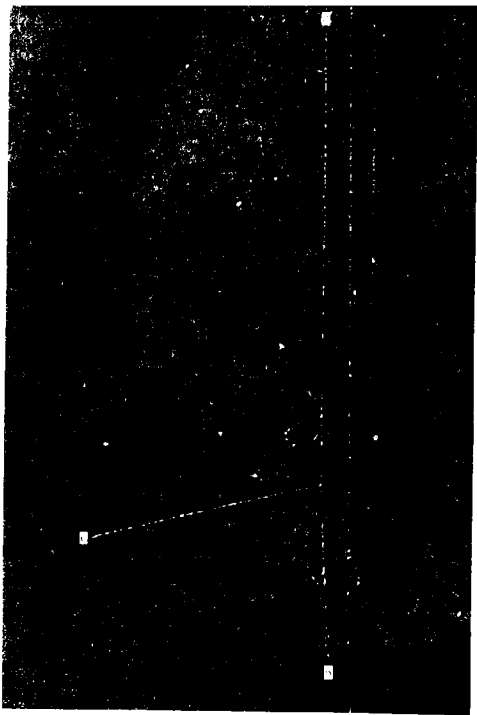
FIGURE 1. Elastic scattering $\pi + p \rightarrow \pi + p$. Photograph taken in propane bubble chamber at the High Energy Laboratory of the Joint Institute for Nuclear Research, Dubna.

a — track of primary π- meson of momentum 6.8 Bev/c; b — track of same π- meson after scattering on hydrogen nucleus in propane; c — track of recoil proton in this scattering

in particular with the principles of the theory of relativity. These models of the electron were therefore discarded. Some believed this to be a temporary departure while others, more formally minded, strongly recommended regarding the electron as a point particle.

It must be stated that the existence of structure in elementary particles is no longer an object of discussion: clear experimental proofs of the existence of such structure now exist, and there are various ways of studying it.

At Dubna one of the methods of studying proton structure has been the investigation of elastic scattering of energetic π-mesons on protons:

$$\pi + p \to \pi + p. \tag{2}$$

Figure 1 shows such a photograph obtained in a propane chamber with a π-meson beam of energy about 7 Bev. The wavelength of such a meson beam is $\lambda = 10^{-14}$ cm.

A typical fact is that the primary π-meson was only slightly deflected from its original direction of flight and the proton recoil was very small.

It follows from the uncertainty relation that such a process cannot be localized in a very small region of space. Indeed, if the momentum transfer from the pion to the proton is q then the dimensions of the spatial region a in which this process occurs are characterized by the inequality

$$a > \frac{\hbar}{q}. \tag{3}$$
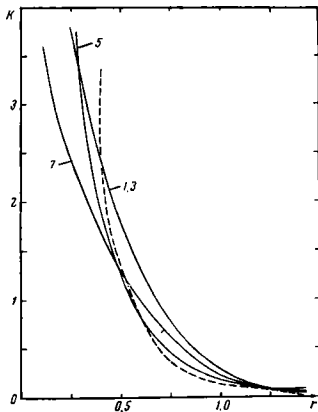
FIGURE 2. Coefficient of absorption K of mesons on nucleon as a function of distance from center of nucleon (in units of 10^{-13} cm)

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An estimate shows that $a \sim 10^{-13}$ cm. This quantity is to be regarded as the characteristic dimension of the pion + proton system.

The picture of the elastic scattering of a pion on a nucleon can be imagined in greater detail as follows: protons very strongly absorb π-mesons; the proton can therefore be treated as a highly absorbent, nearly "black" sphere placed across the path of the pion beam. In this case pion scattering will be the result of the diffraction of the pions by this nontransparent sphere.
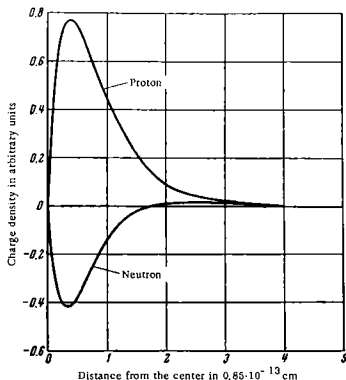
FIGURE 3. Charge density of proton and neutron as function of distance from the center. Charges concentrated at the center proper are not shown

By measuring this scattering it is possible to determine the dimensions of this "sphere" and the effective meson absorption coefficient inside it.

Figure 2 shows this coefficient as a function of distance from the center of the nucleon. One can see that absorption increases strongly toward the center of nucleon and drops sharply at its edges, roughly for $r = 0.5 \cdot 10^{-13}$ cm.

One can thus obtain a more exact idea of the pion structure of the nucleon and of its dimensions.

A second method of studying the structure of nucleons is to investigate the elastic scattering of electrons on nucleons. This method has been successfully developed in the U.S.A. at Stanford University and makes it possible to determine the distribution of electric charge and electric currents within the nucleon. To do this one starts from the formula for the scattering of an electron on a point nucleon and then determines the distribution of charges and currents in the nucleon from the deviations from this formula.

Figure 3 shows the charge distribution in a proton and neutron obtained at Stanford. One can see that a considerable drop in density occurs precisely in the region (near $r = 0.5 \cdot 10^{-13}$ cm) where the sharp reduction in the pion absorption coefficient takes place.

It follows from these measurements that the charge in a nucleon is concentrated in a small domain (of the order of 10^{-14} cm); this points to the existence of a special central region in the nucleon or nucleon "core". The physical idea of the existence of such a core and pion atmosphere has long been considered here at Dubna. These two regions in the nucleon structure are related to the existence of two characteristic lengths: the Compton wavelength of the meson $\frac{\hbar}{\mu c} = 1.4 \cdot 10^{-13}$ cm (μ is the meson mass) and the Compton wavelength of the nucleon $\frac{\hbar}{mc} = 2 \cdot 10^{-14}$ cm (m is the nucleon mass).

Theoretical calculation of the charge density in a nucleon leads to the existence of three regions: the nucleon core ($r \sim 10^{-4}$ cm), the pion atmosphere of the nucleon ($r \sim 10^{-13}$ cm) and the pion "stratosphere" of the nucleon ($r > 10^{-13}$ cm).
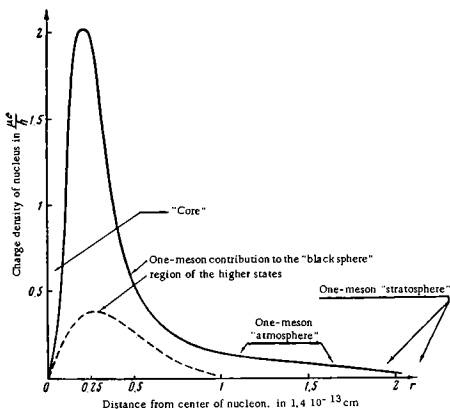
FIGURE 4. Qualitative picture of nucleon (proton). Charge density in proton is calculated theoretically as a function of the distance from the center

The distribution of charge density in a nucleon, calculated by us several years previously, is shown in Figure 4. In its general features it agrees with the latest data from Stanford.

Thus the existence of structure in protons and neutrons is now an experimentally established fact.

It is natural to expect that the structure of the other baryons $-\Lambda^0$-, Σ- and Ξ hyperons – will be similar in its general features to that of a proton or neutron. We have no convincing experimental facts regarding the structure of

π-mesons, K-mesons and so on, but there are certain indirect pointers to the existence of structure in these particles.

However strange it may seem, the particle whose structure is the least known, the electron, has been known for a long time and indeed marks the beginning of the history of the problem of structure of elementary particles.

Several lengths can claim to be characteristic of the dimensions of the electron. If one bases oneself on modern theoretical electrodynamics, which is better developed than any other field theory, one is forced to the conclusion that the size of the electron must be enormous — not 10^{-13} cm as expected in classical physics, but rather 10^{-11} cm (i. e., a hundred times larger!). 10^{-11} cm is the size of the region in which the vacuum around the electron is polarized. This can be put differently: the electron is surrounded by an atmosphere of positrons and electrons extending to distances of 10^{-11} cm. Owing to the smallness of electromagnetic interactions, however, this atmosphere is, so to speak, very rarified. So far there is no direct experiment which permits detection of this electron structure.

However, indirect data referring to very fine level shift in the hydrogen atom indicate that the theory which predicts such an atmosphere in the electron is correct.

At present physicists are eagerly awaiting new information concerning this atmosphere from experiments on electron collisions in opposing beams. The theory of the electron has been developed very completely; it is therefore of great interest to detect deviations from this theory in experiments and to discover new and possibly unexpected facts.

Present-day theoretical views concerning the structure of elementary particles rest on quantum field theory, which was created thirty years ago. Although this theory has advanced considerably since that time and its mathematical methods have been refined, its physical foundations have not been substantially modified.

In conformity with wave-particle dualism every particle, whether electron, proton, meson, neutrino, etc., is assigned a wave field ψ having a definite space-time symmetry.

For this field one can find a linear differential equation which it obeys. Such an equation will describe the motion of free particles. So far as one can judge, the present theory correctly describes free particles at least as long as the possible radioactive particle decay proceeds sufficiently slowly. The main problem consists of the interaction of particles, in the possibility of their interconversion. To take the interactions into account nonlinear terms, containing usually a certain interaction constant — the "charge" (electric, nuclear, etc.) — and the products of the interacting fields, are introduced into the linear equation for the free particle. The number of possible interactions and, therefore, of "charges" is very high, roughly equal to the number of pair combinations of all the known fields (by using symmetries the theory allows a slight reduction of this number). This diversity of fields and their interactions can scarcely be considered a satisfactory feature of the modern theory; moreover it is evidence of the lack of a physical idea which could serve as a basis for understanding the internal unity of the elementary particle world.

The theory of electromagnetic interactions — interactions of electrons, positrons and γ-quanta — has been developed most successfully. Its success

rests on the relative weakness of electromagnetic interactions which is determined by the smallness of the electric charge e of the electron.

It is more convenient to speak of the smallness of the dimensionless constant (so-called fine structure constant):

$$\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}.$$

(4)

The theory of electromagnetic interactions is used as a model for other interactions as well. However, the interaction of nucleons and mesons which is very important in the physics of elementary particles is strong; it cannot be examined by the same methods as were successfully used for the electromagnetic field. In this case the characteristic constant of interaction

$$\beta = \frac{g^2}{\hbar c} = 15$$

(5)

(here g is the nuclear charge) and is two thousand times greater than α. Therefore for strong interactions the following procedure is now followed: it is arbitrarily presumed to be weak, certain quantities important for the theory are obtained and their properties established.

Subsequently only such properties of the physical quantities as would be independent of the assumed weakness of the strong interactions are used. This is the procedure followed in the modern theory of so-called dispersion relations in which only the "analyticity" properties of the scattering amplitudes are employed, based on the law of causality in the microworld. It is further assumed that this law has the same form in the microworld as in the macroworld.

Instead of writing down the formulae describing the interaction of particles it is convenient to represent these interactions by means of diagrams. Figure 5 I represents the interaction of a γ-quantum with a nucleon. The dotted line shows the quantum which can be emitted or absorbed by the nucleon. The solid line with the arrows shows the moving nucleon N. Absorption of the quantum may take place, say at the point A. However, the more complex process represented in Figure 5 II can also take place. The nucleon emits a π-meson (wavy line) at the point A. This meson absorbs or emits a γ-quantum (dotted line) at the point B. After this the meson is absorbed once more by the nucleon at the point C.

It is evident that by this process the nucleon acquires a spatial structure: absorption of the quantum may occur not at the center of the nucleon but in its meson atmosphere. However, we have travelled along a very far-reaching path. The theory admits of the transformation of a meson into a nucleon-antinucleon pair:

$$\pi \rightarrow N + \bar{N}.$$

(6)

and we obtain the right to sketch a yet more complex diagram for nucleon structure (see Figure 5 III). This diagram can be described as follows: at the point A the nucleon emits a π-meson. At B this meson changes into a nucleon (N) and antinucleon ($\bar{N}$) pair. At C the nucleon interacts with the γ-quantum. At D the nucleon and antinucleon annihilate each other and transform once more into a meson. At E this meson is absorbed by the nucleon. This process again contributes to the atmosphere of the nucleon,
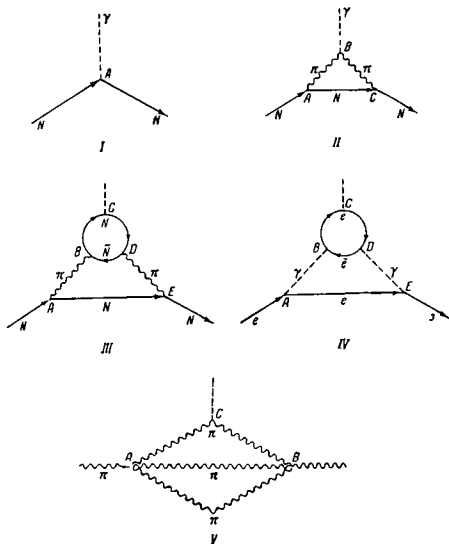
FIGURE 5. Structure diagrams of particles:

I, II and III — for nucleon; IV — for electron; V — for π-meson.

which, as we see, may already contain pairs of nucleons and antinucleons.

Figure 5 IV shows a similar structure diagram for the electron in which instead of the π-meson and the nucleon and antinucleon we have, respectively, γ-quanta and the electron e and antielectron – positron – $\tilde{e}$. Thus the positron-electron atmosphere which we spoke of earlier is formed around the electron.

Figure 5 V shows one of the structure diagrams for the π-meson. The π-meson transforms into three π-mesons at the point A; one of these interacts with a γ-quantum at C. The three pions transform once more into a single one at B.

We might also consider more complex processes which make some contribution or other to the structure of particles.

The extraordinary character of the situation is all too obvious. According to the modern theory, the nucleon "consists" not only of π-mesons but also of pairs of nucleons and antinucleons (N and $\bar{N}$); the electron also has

electron-positron pairs and even nucleon-antinucleon pairs in its "composition"; the meson "consists" of three mesons, and so on. A situation arises which was completely unknown earlier in atomic theory.

Indeed, we are accustomed to the fact that, say a molecule of water consists of atoms of hydrogen and oxygen, atoms consist of electrons and nuclei, nuclei of nucleons... At least we are used to assuming that the part is smaller than the whole; but is a positron-electron pair which enters into the composition of an electron really smaller than this electron?!

If we follow the present theory it seems that particles consist of each other and that the larger can be contained in the smaller.

One should bear in mind, however, that when we now use the word "consist" it is not at all in the static sense in which it was used in classical atomic physics. In using this word we merely wish to stress the fact that in the interaction of one particle (a nucleon, say) with another (e. g. , a photon) certain other particles (mesons, nucleons, antinucleons, etc.) appearing temporarily in the process inevitably participate as intermediate agents.

Thus the modern view on the structure of elementary particles is related to the structure of possible processes and is dynamical.

It is this circumstance which rids us of the difficulties characteristic of the old views, in which the particle was seen as an unchanging object something like a solid charged sphere.

It would be too optimistic, however, to say that this new approach to the structure of elementary particles solves the problem of constructing a coherent theory of the microworld. At present it is already obvious that, basing ourselves on the modern physical theory, we can study only the outermost regions of particle structure. The difficulty is that the modern physicist has no language other than the language of particles, and it would seem as if this language is poorly suited to the description of processes taking place inside elementary particles, in their deepest interior.

Here we might recall that, in addition to particles, the modern quantum theory also operates with the concept of the field ψ; from this point of view particles represent quanta, clots of such a field. One might therefore claim that in studying the internal structure of particles it is possible to drop the particle concept (within a particle) but preserve the concept of the field $\psi\,(x, t)$ at the point x at the instant t.

In spite of all its defects, however, the modern theory is very well cemented together; one cannot discard one of its parts without destroying the remainder.

By returning to the sources of quantum field theory it is easy to show that the arguments x and t of which the field ψ is a function are none other than the coordinates x and time t of the nascent or decaying particle.

In the present view of the quantum field $\psi\,(x, t)$ a corpuscular language is built in from the very first. More precisely this can be described as follows. Let $\psi\,(x, t)$ be, say, a meson field; let us express this field as the sum

$$\psi\,(x, t) = \psi^+\,(x, t) + \psi^-\,(x, t).\qquad(7)$$

where in ψ^+ are collected all harmonic oscillations contained in the spectral resolution of $\psi\,(x, t)$ and having positive frequencies and in ψ^- are collected all harmonics with negative frequencies. Then the point x, t in ψ^+ will denote the point at which the meson is created, and in ψ^- it will denote the point at which the meson is annihilated. In other words, ψ^+ will be the operator of

meson creation at the point x, t and ψ^- the operator of meson annihilation at the same point.

Thus the quantum field language and the corpuscular language are equivalent. This equivalence is particularly evident in old works on quantum field theory.

Therefore one cannot reject the concept of particles without destroying the entire foundation of the mathematical apparatus of the modern theory. At the same time it can be shown conclusively that the particle concept is untenable in cases where the interaction between the particles becomes excessively strong[*].

As a measure of the interaction one can use the mass defect, i.e., the reduction in the particle mass $-\Delta m$ during the formation of a system, or the mass increment $+\Delta m$ in the case of an unstable system. We will regard an interaction as weak if

$$\frac{\Delta m}{m} \ll 1, \tag{8}$$

where m is the smallest of the free particle masses (before they are formed into a compound system).

From this point of view it is reasonable to say, for instance, that the hydrogen atom consists of a proton and an electron, since the mass reduction in the formation of a hydrogen atom constitutes only $2 \cdot 10^{-5}$ the mass of an electron. It is also reasonable to say that the deuteron consists of a proton and neutron, since the mass defect in this case is $2 \cdot 10^{-3}$ of the nucleon mass.

Let us consider, however, an imaginary atom with the nucleon charge $Z = 137$. It turns out that the problem of the motion of an electron in the field of such a nucleus has in general no solution. This mathematical fact, long known, is to be attributed to the fact that in the field of such a strongly charged nucleus the mass defect $\Delta m > 2m_0$ (m_0 being the mass of an electron).

In this case we cannot separate the operators of electron creation ψ^- from the operators of electron annihilation ψ^-. This division of the operators into two types is however, essential. For $\Delta m > 2m_0$ these operators become mixed; this means complete catastrophe and the modern theory is completely inapplicable to such problems.

In the light of these considerations we must recognize as completely untenable all attempts to construct complex models of particles when some particles appear as complex systems consisting of other more "elementary" particles and at the same time allow enormous mass defects.

Such, for example, is the π-meson model suggested by Fermi, according to which the π-meson is a bound state consisting of a nucleon and an antinucleon.

The mass defect Δm permissible here is close to $2m$ (where m is the nucleon mass).

Perhaps such models have a certain meaning only from the standpoint of studying the possible symmetries of systems; a more literal understanding of these models, however, certainly exceeds the "competence" of the modern theory.

There is therefore every reason to believe that the paradoxical nature of the structure schemes of particles given in Figure 5 stems from the fact that we are using the particle language in a region where mass defects are

[*] This aspect of the problem was considered in detail by me in a paper published in "Uspekhi fizicheskikh nauk" in 1957 (see "UFN", Vol. LXI, p. 137).

enormous and the concept of particles is in reality untenable – or, at any rate, very approximative.

These schemes may possibly be analogous to the Bohr orbits in atoms, which only very roughly represented quantum phenomena in atoms. The mechanics of the atom was completely grasped only after the concept of orbits was replaced by the concept of waves.

Modern quantum theory is a "locksmith's tool": for lack of any other we are seeking to use it in the delicate clockwork mechanism of elementary particles.

One must admire the ingeniousness and persistence of the physicists who continue to extract new information concerning elementary particles and their structure by means of this rough instrument.

It is nonetheless evident, however, that we need new physical concepts and, correspondingly, a new language more adequate to the inner nature of particles than that which we now have. However complex and manifold the world of microparticles may seem, we are perhaps lacking only two or three words to express the physical idea required for a complete under-standing of the phenomena of the microworld.

It is clear to us that these words will have to be no less revolutionary than those which led to the creation of quantum theory or the theory of relativity.

THE PROBLEM OF THE ELEMENTARITY OF PARTICLES
IN QUANTUM PHYSICS

M. E. Omel'yanovskii

The dual wave-particle nature of electrons and other microobjects in quantum mechanics is manifested in the interrelations between elementary particles. However, (nonrelativistic) quantum mechanics did not progress very far towards a synthesis of the opposing corpuscular and wave pictures of matter in motion. It was unable, for instance, to predict theoretically the conversion of the electromagnetic field into an electron-positron pair as well as other forms of transformation of elementary particles. It was also unable to predict the remarkable result that to every elementary particle corresponds its antiparticle.

Therein lies not so much the inadequacy as the natural limitation of quantum mechanics, which is to be attributed to the conditions in which it was created and especially to its specific traits. Such limitation is inevitable, for quantum mechanics, like every scientific theory, is incapable of giving an exhaustive interpretation of the infinite diversity of matter and every one of its particles. This limitation was to some extent demonstrated concretely by relativistic quantum mechanics, or quantum electrodynamics, and the quantum field theory which developed from it. The demonstration of this limitation simultaneously marked its elimination by relativistic quantum mechanics and, therefore, a new step toward the cognition of matter.

In quantum mechanics the synthesis of corpuscular and wave pictures of matter referred to substance and to the behavior of its particles. Thus the quantities characterizing moving particles of substance took on the features of wave motion. This gave rise to substance with the field; however, the inverse transition from field to substance could not be accomplished in quantum mechanics: from the standpoint of quantum mechanics fields remained "classical" and the kind and number of particles of substance remained invariable.

Thus in quantum mechanics the synthesis of opposing corpuscular and wave pictures was not carried out in full; it did not refer to fields, and added nothing to physical knowledge of the problem of elementarity: from the standpoint of quantum mechanics elementary particles could be regarded ultimately as immutable – specified for ever – as, say, atoms from the standpoint of classical physics.

While quantum mechanics was taking on its present form of a closed system of concepts, the prerequisites were already being laid for future theories dealing with the transition of field into substance. These problems were worked on by the same scientists who had taken part in the creation of quantum mechanics (Dirac, Heisenberg, Pauli, Fok). Quantum field theory, which is, properly speaking, the theory of elementary particles, was

created. In the new theory, by contrast with quantum mechanics (where wave functions are regarded as functions in multidimensional configuration space), wave functions are treated as wave fields in three-dimensional space; these fields, however, are not the fields with which classical physics deals, but rather q u a n t u m fields, which differ from classical ones in qualitatively new properties.

The essence of quantum field theory, if we look at its mathematical aspect, is the so-called second quantization. The idea of second quantization is as follows: the wave equations are subjected to change and to generalization similar to the transformation accomplished with the aid of the mathematical method (first quantization) by which one passes from the equations of classical mechanics to those of quantum mechanics.

Thus second quantization made it possible to depict mathematically the physical situation in which the continuous wave field is simultaneously a set of discrete particles. If second quantization was once regarded merely as a useful mathematical device unrelated to the physical content of quantum theory, today this point of view has been abandoned. The physical meaning of wave pictures in quantum theory is that the particles represent quanta of the corresponding real fields.

Quantum field theory effected a deeper synthesis of corpuscular and wave pictures of matter than quantum mechanics, collecting in a single unit the concept of field and that of substance. Dirac's relativistic theory of the electron initiated this synthesis; it led to important inferences, among them that there existed a positron, that the conversion of photons into an electron-positron pair and vice versa was possible, that the electron-positron vacuum existed, and so on. Now the following classification of the principal physical fields has been established: strongly interacting fields (these give rise to nuclear forces); fields with intermediate (electromagnetic) interactions; weakly interacting fields (responsible for the spontaneous decay of all elementary particles with the exception of the stable particles, the photons, electrons, neutrinos and protons); ultraweakly interacting (gravitational) fields (disregarded in the modern theory of elementary particles owing to their smallness).

However schematic, our sketch of the ideas involved in quantum field theory makes it clear that this theory is an excellent example of the application of the laws of dialectics. The theory of elementary particles is a graphic demonstration that the principles operative at the foundations of knowledge of matter are the principle of development, principle of unity of matter, dialectic principle of contradiction and other important principles of dialectic materialism. Therefore when investigating the major philosophical problems associated with the theory of elementary particles one cannot do without dialectic thinking.

Such problems include, among others, the problem of the essence of phenomena, the problem of the continuity and discontinuity of matter, the question of the material or spiritual "prius" (origin) of all being. These might seem to be old problems raised many times by philosophical thinking, particularly in connection with ideas of atomism. But now that physics has reached, as many data show, the very foundations of the universe, these problems take on new content; their solution, naturally, does not reduce to mere repetition of old philosophical truths. In elementary particle theory the philosophical problems which have arisen have found their conceptual

expression in the problem of elementarity, to the analysis of which we will now turn.

To the ancient atomists atoms moving in an infinite vacuum were the last foundation, substratum, discrete substance of observable phenomena. For Democritus, for instance, atoms conceivable to the intellect explained the variations in the world perceptible to the senses.

This conception of the atom was adopted without change in the body of natural knowledge as soon as it became a science. For example, Newton's definition of mass as a measure of the amount of matter proportional to its (matter's) density and volume cannot be understood if the concept of atom is not introduced. Incidentally, Newton mentions atoms directly in his famous "31st Query", giving a definition which is often quoted: "... God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles; of such sizes and figures and with such other properties, and in such proportions to space, as most conduced to the end for which he formed them; ..."*

The subsequent development of classical physics strengthened the Newtonian conception of the atom in natural science. Hertz, for instance, regarded the different forms of energy (potential, electromagnetic, chemical, thermal) as the kinetic energy of invisible homogeneous material points. The Newtonian view of the atom was held by Maxwell, the founder of the theory of electromagnetism. The concept of the chemical element, by which, in the nineteenth century, was meant a substance not decomposable by chemical means, served the same purpose as the atom in classical physics. When modern scientists in their investigations apply atomistic theories to the task of explaining the properties and behavior of macrobodies by the properties and behavior of the constituent microbodies, they are using essentially the Democritean principle of the atom.

Thus according to the idea of the atom as substrate and origin of all changes, atoms should be indivisible, qualityless, constant and eternal and so forth. This understanding of the atom is present in some form or other in the old atomistics.

On the other hand, in the history of philosophy ideas of a continuous material substance have developed parallel to ideas of atomism, either in opposition to the latter or supplementing them. If by development of matter the atomists Leucippus and Democritus meant, in the last analysis, a combining and separating of atoms, the great encyclopaedist of ancient times, Aristotle, understood it completely differently. Treating matter as something which enters into the composition of things, something from which things arise, Aristotle requires "form", which transmutes matter as a possibility into real things; that is, according to his conception the appearance of phenomena occurs as a formation of matter.

In the new philosophy, Descartes, one of its creators, denied that the atoms and vacuum of the ancients were the basis of everything that exists. In his view continuous material substance with its attribute of extension is this basis (if one is dealing with the physical world); material substance is infinitely divisible and its moving particles give rise to everything that exists.

The Cartesian conception of the development of matter assumed the place of honor much later, with the emergence of the Faraday-Maxwell theory of electromagnetism and of classical field theory in general. However, the

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* Isaac Newton. The Third Book of Opticks, in: Operum Newtoni (Vol. IV). London, 1782.

physical ideas of Newton — an opponent of the kinetic views of Descartes — potentially contained the concept of field (admittedly as a supplement to his fundamental ideas, and, moreover, in the form of a mathematical predic- tion). We are referring to the forces of gravity — an important concept in Newton's "Principles" — the existence of which Newton formulated mathe- matically in the law of gravitation, while circumventing the question of their possible causes. In the literature Newton's views on gravitation are fre- quently interpreted as implying the necessity of recognizing "action at a distance". Newton himself had his own opinion on this point, but what we wish to stress is something else. From the standpoint of pure mechanis- tics action at a distance without the intervention of any agent seems mean- ingless. But if one reasons rigorously then the idea of contact action (pre- ferred by mechanistics and the old atomism) is, in essence, no different from the idea of action at a distance. Absolute contact between atoms does not exist; otherwise atoms would fuse and matter could not be discrete. It is therefore necessary to endow atoms with forces preventing them from fusing, i. e., forces which act from one atom to another. The development of physics has solved the contradictions which arise by introducing the con- cept of the field.

The development of atomistics — the ideas of which have been dominant in natural science throughout its history — has not consisted exclusively of the search for a substrate or substance representing the last foundation of ob- servable phenomena (though this feature remains to a certain degree in modern atomistics as well, since elementary particles are regarded as the fundamental constituents of matter in the known part of the universe and should in this sense be considered fundamental particles). The development of atomistics also includes the search for solutions of the following problems: is matter fundamentally discrete or continuous, variable or constant? Is it similar to the observable world of phenomena or different from it? (The problem of the substrate of phenomena necessarily becomes concrete in the solution of these problems.)

As to the problem of whether matter is fundamentally similar to or dis- similar from the perceptible world of phenomena, natural science has solved it in the sense that it has confirmed the validity of materialism and dialec- tics. That the microworld (into which the elementary particles enter) and macroworld (which embraces the directly observable phenomena) constitute a single world is shown by the fact that the laws of classical mechanics are a limiting case of the laws of quantum mechanics; it is also shown by other important principles of quantum mechanics, such as the so-called Ehrenfest theorem, according to which the mean values of quantities (coordinates, momentum, etc.) for microscopic systems obey the laws of classical me- chanics. Other evidence of this is those propositions of the principle of complementarity which can be called correct. Finally, and this is the most important point, the identity of the microworld and macroworld can be in- ferred, despite their dissimilarity (more precisely, because of it), from the success of atomic technology and from the fact that man has mastered atomic (nuclear) energy.

Our knowledge of the microworld and its laws will evolve, become more precise, coming closer and closer to its goal; so will, at the same time, our knowledge of the relationships between the micro- and the macroworld; new aspects of the identity of the laws of the micro- and macroworld will unfold in physics, as shown by quantum electrodynamics and other theories

of quantum physics. If one denies the identity of the micro- and macroworld (citing their qualitative dissimilarity) then in the philosophical plane this means, in the last analysis, the adoption of the position of idealism and metaphysics. It is wrong to regard only the macroscopic world of phenomena as real; and to interpret the quantum laws of the microworld as a symbolic representation which merely orders phenomena, as in modern positivism and agnosticism. Again, it is wrong to consider objective only those laws of the microworld which appear in the mathematical scheme of quantum theory, and to interpret the real world of macroscopic phenomena as one inevitably containing a subjective element, in the spirit of Platonic idealism. Both the former and the latter interpretation idealistically distort the image of the world given by modern physics and lead to contradiction with the facts when one solves the problem of correlation between the regularities of the micro- and macroworld.

Thus macrophenomena with their laws and microprocesses with the laws which they obey are equally real objectively and constitute a single material world. In the objective reality of the macro- and microworld there is a higher identity between the two, an identity which physics expresses with increasing accuracy and completeness in its development.

Let us now turn to the problem which is our main task, namely whether matter is fundamentally discrete or continuous.

It is well known that pre-quantum atomistic thought solves this problem by assuming that at the foundations of matter lie structureless (simple) particles which constitute the structure of other more complex formations. This assumption was substantiated to some extent in chemistry. In this branch of science Prout's hypothesis has been realized in some form or other: chemical elements consist of the element hydrogen — only the role of hydrogen is played by the charge of the atomic nucleus, which determines the number of electrons in the atomic shell and the position of the element in Mendeleev's periodic system. From the standpoint of chemical science the chemical element is simple, is an "elementary substance", and so on. From the standpoint of the cognition of matter at its most profound level the "chemical element" is complex and consists of parts, or elements, the number of which is determined by the number of protons in the nucleus.

Although the number of forms of elementary particles is far inferior to the number of forms of chemical elements (the latter now total 102) it is still large enough (the table of elementary particles today contains 32 forms or, if the so-called resonances discovered in recent years are counted, significantly more) for the problem of elementarity to arise again. And it is appropriate to ask oneself here whether this problem can be solved in the same way as for the chemical elements.

In the literature the answer to this problem is often formulated as follows: there is no criterion of elementarity similar to the one used for the chemical elements for the particles considered elementary by modern physics; the future will show whether the history of the criterion for chemical elements will be repeated here, or whether a completely new situation will arise.

To us this formulation seems overly cautious. It is already possible to say that a "completely new situation" has arisen with regard to the problem of elementarity in the microworld, and this applies equally to known elementary particles and particles possibly not yet discovered.

First, a few established facts. One cannot regard stable elementary particles (photon, electron, neutrino, proton) as truly elementary merely

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because they do not decay spontaneously; nor can one regard spontaneously decaying particles as complex: the neutron, for instance, does not consist of proton, electron and antineutrino, although in the free state it decays spontaneously into these three particles. In precisely the same way if one elementary particle produces or absorbs another elementary particle under certain conditions one cannot claim on this basis that the former is "really" complex and the latter "really" elementary: upon acceleration of electrons or protons they emit or absorb photons, and yet the photon is not contained either in the electron or in the proton. I. E. Tamm has stressed that although there exists a variety of different schemes which attempt to segregate a small number of "truly elementary particles and construct out of these all the remaining particles, there still remains an ambiguity in this problem"[*].

In conformity with these data it remains to define the elementary particle as an object which does not consist of other particles. But essentially this definition is a tautology: "an elementary particle is an elementary particle". Such definitions are correctly regarded in the physical literature as unsatisfactory or admissible only as a convention.

Is it possible to give a nontautological definition of the elementary particle? It would seem that the problem of elementarity can be reduced to the existence of a certain series of divisions of matter in which each division (or level) represents the "elementary" stage for the next division and at the same time the "complex" stage for the preceding division. This idea of a hierarchy of elementarity was fulfilled in some form or other in natural science: the Newtonian conception of a hierarchy of systems of particles of successively increasing complexity with the "smallest parts of natural bodies" lying at the bottom of the hierarchy, or the modern conception of the structure of matter (...level of elementary particles — level of atomic nuclei and atoms — molecular level... this division could be continued in the direction of the macroworld and, possibly, microworld).

Could it be that the known forms of elementary particles are only relatively elementary? The fact that the atom or atomic nucleus is r e l a t i v e l y elementary was proved by physics, and the discovery that the atom is divisible and that the atomic nucleus is composed of protons and neutrons was a triumph of scientific cognition. Is the situation the same in the case of elementary particles?

The operations on elementary particles known to modern techniques result not in their breaking up but rather in the formation of other elementary particles. Clearly, new and more powerful means of operation (such devices are being constructed now) may result in our moving beyond the initial stage of elementarity as it is now known to science; however, is there no other way of solving the problem of elementarity?

First, can the relatively elementary be a key to the problem of elementarity?

Let us assume that the series of divisions of matter has an origin on the "elementary" side; it is then necessary to introduce the concept of an object of some degree of complexity. For example, in Newton's hierarchical conception — expressing it in modern physical terms — at the foundation of the structure of matter lie elementary particles; by combining together the elementary particles form particles (systems) of the first complexity, i.e.,

* T a m m , I. E. Sovremennoe sostoyanie problemy elementarnykh chastits (Present State of the Problem of Elementary Particles). Vestnik AN SSSR. No. 10, p. 10. 1960.

atomic nuclei; the latter combine to form chemical atoms, i.e., particles of the second complexity; molecules composed of atoms are more complex, and so on. In this case it would be inadmissible to introduce the concept of an object of some degree of elementarity, as it would merely mean doubling of the terms and would not reach the essence of the problem. The essence of the problem in this case is that the existence of elementary objects is assumed and objects of varying degrees of complexity are regarded as composed ultimately of elementary objects.

Thus the hierarchical conception with an origin looks at matter from the standpoint of the assumption that there exist elementary particles and also particles (systems) of varying degrees of complexity consisting ultimately of elementary particles. In other words, we have arrived at a more complicated variant of the old atomistics (this was clear, incidentally, from the very start of our discussion).

Let us now assume that the series of divisions of matter has neither a beginning nor an end, i.e., is infinite on the "elementary" as well as on the "complex" side; this assumption does not run counter to the data of natural science and corresponds to statement of dialectic materialism concerning the infinity of matter. Let us further assume that the infinity of this series is merely, to recall Hegel, the wrong infinity of an infinite progress i.e., a constantly recurring transition from the elementary to the complex and from the complex to the elementary; in this case the following situation arises. In each division (level) there are complex objects consisting of elementary objects. But the latter are complex objects at a deeper level, i.e., consist, within this level, of elementary objects. But at a yet deeper level the latter are complex objects consisting of ... and so forth a d i n f i n i t u m . Thus in this case the "elementarity" of the objects is merely relative, i.e., is meaningful only within a definite division (level) of matter. This means that if the objects which are regarded as elementary within such a level are taken by themselves (i.e., independently of this division) or from the standpoint of the entire series of divisions as a whole, they will appear as objects having a hierarchical structure; the systems which form this structure will be systems of successively decreasing complexity and the hierarchical series itself will have no end. Summing up, we arrive in this case at the statement that there is no object in general which does not consist of elementary particles.

Thus if one recognizes a hierarchical structure of matter with an origin the problem of elementarity is solved in the spirit of the old atomistics; but if one assumes that the hierarchical structure of matter has no origin, i.e., that "elementarity" is something relative only, then this approach leads to the elimination of "elementary" objects as such.

There exists, however, an approach to the problem of elementarity which does not assume the concept of a purely relative elementarity and also departs from the old atomistics. The infinite series of divisions of matter is not simply the wrong infinity of an infinite progress; it has, as Engels already noted, various nodal points which produce various qualitative forms of existence of universal matter. From this point of view matter is not elementary particles or their collection, nor is it a substance not consisting of elementary particles; matter as a whole possesses simultaneously the properties of the elementary and those of the complex. We feel that this approach will make it possible to find a way of solving the problem of elementarity raised by modern physics. Let us take a closer look at this problem.

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"Complex" and "composite" are in a certain respect synonymous; at least they are actually treated as such in discussions on atomistics and elementary particles. "Complex" in the sense of "composite" is taken from the idea, that is from the observation of macroscopic phenomena, as when a forest, say, is regarded as consisting of a multitude of trees, water in a container of a multitude of drops, sand over a certain area of sand grains, and so on; in certain conditions this conception of the "complex" is doubtless correct.

This notion was applied to the problems associated with matter; hence the concept of "structure" as a distribution of parts (elements) of something. Is this correct when applied to the problems arising from the theory of elementary particles?

For sensory perception or representation the continuous is composite or complex (the concept of "continuity" itself supposes a high degree of abstraction and is foreign to representation; one cannot represent infinity, and the continuous denotes the infinite divisibility of something). Therefore the problem of elementarity and complexity (composition) is the problem of discreteness and continuity expressed in the language of representation. Hegel already called attention to this circumstance. "For anyone foreign to the concept of representation", he wrote, "continuity is easily changed into summation or, more specifically, into an external relationship between ones, ... in which the one preserves its absolute unpliability and the exclusion of other ones."

Later Hegel continues: "Atomistics also clings to this externality of continuity for ones, and it is very difficult for a representation to discard it. Mathematics, on the contrary, rejects the metaphysics which assumed that time c o n s i s t s of temporal points, space of spatial points; it does not admit of such discrete ones"*.

Hegel is doubtless right with reference to the atomistics with which he was familiar and from which modern physics has inherited the problem of elementarity. But modern atomistics, to use Hegel's expression, "does not cling to the externality of continuity for ones", i. e., the solution of the problem of elementarity in modern physics is completely different from its solution in old classical physics.

In as much as the problem of elementarity and complexity is a special kind of imperfect expression of the problem of continuity and discontinuity of matter, solution of the latter means essentially solution of the former.

It is well known that the concepts of the continuity and discontinuity of matter abstractly considered are not employed in the physics of the micro-world. In its propositions quantum physics has synthesized corpuscular and wave representations of matter (which express its discrete and its continuous nature respectively). Correspondingly in quantum theory the continuous and discontinuous appear as aspects of the single essence discussed above.

The same thing must be stated, m u t a t i s m u t a n d i s, concerning the concepts of elementarity and complexity. If in the physics of the macro-world the elementary and the complex could be treated as unrelated and contrasted with each other, i. e., as abstract concepts (and this approach did not lead to confusion), in quantum physics the situation is radically different.

* H e g e l. The Science of Logics.

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In their literal sense the concepts of the elementary and the complex are not applicable to the microworld. Elementary particles are not elementary in the classical sense; they resemble classical complex objects but are not such objects. Elementary particles combine in a superior kind of synthesis the properties of the elementary and those of the complex. Correspondingly the concept "to consist" also loses its literal "classical" meaning with reference to the microworld (i. e., it loses the meaning" to consist of something else").

Even in nuclear physics the concept "to consist" undergoes some modification. The content of the concept "to consist" in the statement that the hydrogen atom consists of a proton and an electron is completely different from its content in the statement that "sand in a bucket consists of sand grains". Whereas an isolated sand grain and a sand grain in a bucket are in no way different from each other, a free proton and free electron differ from the proton and electron in the hydrogen atom: the mass of the hydrogen atom is smaller than the sum of the masses of the proton and electron. Another example: neutrons and protons in an atomic nucleus are not the same as neutrons and protons in the free state; free neutrons decay spontaneously while neutrons in an atomic nucleus are stable (i. e., the atomic nucleus does not "comprise" neutrons and protons).

In the light of these considerations the mass defect cannot serve as a criterion of elementarity. If the mass defect in the formation of a system is smaller than the mass of the particles with which the system is formed, then it can be stated tentatively that the system consists of the particles. As has been remarked in the literature, however, this definition of elementarity does not fit the idea that the π-meson consists of a nucleon and antinucleon (Fermi's hypothesis), since nearly all the mass of the two nucleons is reduced to nothing owing to the mass defect and only a small part of it is left in the form of the mass of the π-meson.

There are grounds for stating, of course, that the nucleon field is more elementary than the meson field because the latter field is formed from the former, or that bosons (particles of integral spin) are complex formations of fermions (particles of half-integral spin); such ideas are being worked out in the literature. What is involved here, however, is essentially the transformation of one thing into something else, rather than the combination of several things: fermions a r e t r a n s f o r m e d into bosons, not bosons c o n s i s t of fermions.

The concept "to consist" undergoes a particularly significant change when applied to resonances, which are elementary particles with unusually short lifetimes (shorter than 10^{-20} sec). For example, one of these particles, the nucleon resonance $N*$, can be formed from a nucleon and a photon and can decay into a nucleon and a π-meson; however, this by no means indicates that this particle "consists" of a nucleon and photon or nucleon and π-meson.

Thus when applied to elementary particles the concepts of elementarity and complexity assume a meaning which is completely different from that attributed to these concepts by the old classical atomistics. The most important concept is the "transformation of one thing into something else"; in the light of this concept the problem of elementarity is stated and solved in a way which differs entirely from the approach of classical atomistics (in which transformation meant the combination and separation of certain constant elements).

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It remains to state the foregoing thoughts on elementarity in more compact form.

When applied to electrons, protons, mesons and other elementary particles the problem of elementarity and complexity does not have the meaning it had in old atomistics. In the microworld the concepts of elementarity and complexity loose their invariable abstract character and become instead "fluid", interrelated and, therefore, possessed of concrete meaning. The proton, for instance, like all the other elementary particles, is neither elementary nor complex; it is simultaneously the one and the other, i.e., the proton possesses simultaneously the properties of the elementary and those of the complex.

This conception of the elementarity and complexity of the proton – and other elementary particles as well – means that elementarity and complexity are true of the proton not as a "thing-in-itself" and irrespective of the conditions under which its transformations take place, but rather in uninterrupted relation to these conditions (they are determined by experimental devices in the investigation of the transformations of elementary particles). In no experiment have elementary particles behaved exactly like elementary objects or complex systems; they – the particles – are similar to elementary objects only in special cases, under certain conditions of transformation; they are similar to complex systems under other conditions. Thus in particle collisions with energies smaller than 100 MeV the proton behaves like an elementary particle, but in collisions with significantly higher energies it decays into hyperons and K-mesons, i.e., behaves like a complex particle. In this sense the concepts of "elementarity" and "complexity" lose their absolute character and become relative.

Seemingly one could say that this conception of elementarity is no different from the conception of "elementarity" discussed above, in the sense of pure relativity: the atom, for example, is indivisible in chemical transformations, i.e., appears elementary within the limits of chemical phenomena. However, a statement which presupposes the purely relative elementarity of an object necessarily requires, as we saw, its complement; namely the statement that an object which behaves as an element under certain conditions is itself complex, i.e., the atom – to return to our earlier example – is a complex object consisting of an atomic nucleus and an electron shell.

The situation is entirely different in the case of the proton and other elementary particles. By itself, not only is the proton not elementary, but is also not complex; These properties of the proton are meaningless outside of the conditions of proton transformation. In other words, the concept of the "complexity" of the proton is meaningful only when the energy (of corresponding value) in its collisions is mentioned (by contrast with, say, the atom, to which the concept of "complexity" can be applied without reference to the energy of ionization). This circumstance distinguishes the "elementarity" and "complexity" of the proton, the electron and so on from the "elementarity" and "complexity" of atomic nuclei, atoms and so on. This kind of relativity of "elementarity" and "complexity" in those material objects which are called elementary particles in modern physics is, ultimately, a manifestation of the dual nature of the elementarity – complexity inherent in elementary particles. The problem of the "elementarity" and "complexity" of objects is somewhat similar to the problem of the identity of location of two events occurring at different times and the problem of the simultaneity

of events occuring in different places. According to classical mechanics identity of location is relative and simultaneity is absolute, i. e., not relative with respect to the frame of reference. The theory of relativity rejected the idea of the absolute nature of simultaneity starting from its first principles; in the theory of relativity the relativity of simultaneity as well as the relativity of spatial lengths and time intervals follows from its recognition of the internal identity of space and time.

If elementary particles can be "complex" it is permissible to assume that elementary particles have structure. Hofstadter's experiments prove that the nucleus is not a point particle and actually has structure. This structure, however, does not carry the same meaning as "structure" in pre-quantum physics. According to modern ideas, the structure of the proton includes a series of shells of other virtual particles: virtual nucleons and antinucleons, virtual hyperons and K-mesons, virtual π-mesons. In general, every elementary particle is surrounded by a system of shells of other virtual particles which make up its structure. That other particles enter into the "composition" of a given elementary particle in the virtual state rather than in real form means, strictly speaking, that the concepts of "structure", "consist" and so forth have a completely nonclassical meaning in the theory of elementary particles. The mutual transmutability of elementary particles is a fundamental feature of modern atomistics and leads to a new understanding of elementarity and complexity, structure and so on.

Werner Heisenberg maintains that there is "no fundamental difference between 'elementary' and 'nonelementary' microparticles"[*]. Where we can agree with Heisenberg and where he is deeply wrong is evident from our discussion of the elementarity of particles.

In conclusion, let us consider the following statement by A. L. Zel'manov concerning the universe (though it may not seem directly pertinent to our theme). According to Zel'manov, three conceptions of the universe are to be distinguished in cosmology. The following expressions may be adopted tentatively for these: "the universe on the whole", "the universe as a whole" and "the entire universe". The first, according to Zel'manov, denotes the whole without reference to its parts; the second, the whole in its relation to the parts and all the parts in their relation to the whole; and finally, the third conception denotes all the parts without reference to the whole. To confuse these concepts could lead to very serious misunderstandings[**].

In our opinion Zel'manov's statement concerning the relationship between the whole and its parts (with reference to the universe) applies to any object regarded as a whole. Thus from the standpoint of the relation between the whole and its parts the elementary particle, for example, is similar to the second conception of the universe.

The relationship between the whole and its parts is similar to the relationship between the complex and the elementary or the continuous and the discontinuous. The whole is not simply make up of parts; it is a dialectic unit with its parts.

[*] See R e i c h e n b e r g, H. Aus der Physik der Elementarteilchen. Physikalische Blätter, H 3, S. 110, 1963. (In this article a brief exposition is given of a lecture by Heisenberg entitled "Introduction to the Theory of Elementary Particles", delivered at the University of Munich in 1961.)

[**] See Z e l' m a n o v, A. L. K postanovke kosmologicheskoi problemy (On the Formulation of the Cosmological Problem), Dopolnenie (Supplement), pp. 82—83. Trudy vtorogo s'ezda Vsesoyuznogo astronomo-geodezicheskogo obshchestva Moscow, 1960.

CONSERVATION PRINCIPLES AND THE PROBLEM OF THE STRUCTURE OF MATTER

N. F. Ovchinnikov

Every physical theory has conservation principles among its fundamental laws. These principles are the foundation of finished theories as well as the starting point of emerging theories. Conservation principles can be defined as requirements that certain quantities which enter into the system of concepts of a given theory be constant. Further, the conserved quantities can be expressed in a variety of mathematical forms and can have different physical contents.

In the present article when we use the term conservation principles we mean equally conservation of things, conservation of properties and conservation of relations. Therefore the conservation laws known in the physics of elementary particles, which express the conservation of properties (electric charge, spin, isotopic spin, baryon charge, lepton charge, strangeness and so on) constitute merely a partial class of conservation p r i n c i - p l e s . Henceforth we will call all conservation laws operative in elementary particle physics conservation principles. Our aim here will be to give a brief characterization of these principles while tracing the logical necessity for introducing given conserved parameters into the theory as knowledge concerning the laws of motion of elementary particles and the structure of matter develops further and further.

The classical conservation principles – conservation of mass, energy, momentum and angular momentum – are fulfilled in the physics of elementary particles. These principles are of a general character and their validity in the elementary particle region is evidence of the profound unity of nature. Here we will be concerned with the specific conservation principles characteristic exclusively of microparticle physics. These conservation principles are indeed the basis of the specific laws of motion of the fundamental particles of matter.

The most important property of elementary particles is electric charge. Electric charge is subject to a special kind of conservation principle. We will seek to trace the process by which the principle of electric charge conservation was established.

There exists a group of electrically charged particles:

Electron — Positron
Mu-minus-meson — Mu-plus-meson
Pi-minus-meson — Pi-plus-meson
K-minus-meson — K-plus-meson

Proton — Antiproton
Sigma-minus-hyperon — Antisigma-minus-hyperon
Sigma-plus-hyperon — Antisigma-plus-hyperon
Xi-minus-hyperon — Antixi-minus-hyperon

Every particle in this group conserves the charge corresponding to it.
As long as a particle does not decay into other particles the electric charge
corresponding to it is attributively associated with the particle. Further,
the absolute value of the charge is identical for all particles. If the numeri-
cal value of the proper masses of the different particles forms a spectrum,
then the electrical charge of all the particles listed above assumes only two
values: +1 and -1. The operation of the principle of electric charge conser-
vation displays certain peculiarities. We will now consider these peculiari-
ties historically.

The idea of electric charge conservation was proposed as early as the
mid-eighteenth century by Benjamin Franklin. "Electrical matter", wrote
Franklin in 1749, "must consist of extremely small particles, for they are
capable of penetrating ordinary substances of the density of a metal with
such ease and freedom as to encounter no perceptible resistance"[*]. Frank-
lin, who believed in the conservation of matter (conservation of atoms in
classical atomism), naturally transferred this idea to "electrical matter".
This electrical matter, in Franklin's view, is of a single kind. But the
empirical facts are such that an object which has received electrical matter
is in a certain respect opposite to an object which has not. Franklin pro-
poses calling the former positively charged and the latter negatively charged.
While he does not explicitly formulate the principle of conservation he ac-
tually applies it in a form which one might term "Lomonosovian": however
much electrical matter be lost from one body, as much appears in another.
This principle enabled Franklin to explain many of the electrical phenomena
known in his time. For example, conservation of electrical matter under-
lies the explanation of the fact that oppositely charged bodies neutralize
each other upon contact; in this process, according to Franklin, uniform
distribution of electrical matter is reestablished in the bodies.

The discovery of the law of interaction of electric charges by Coulomb
in 1785 led to the necessity of admitting two kinds of electricity — positive
and negative. The "dualistic" theory was in opposition to Franklin's unitary
theory. A conservation principle was also present in it: each of the two
forms of electrical matter is never created and never vanishes, and the
two can only neutralize each other[**]. This theory, which assumes two kinds
of electricity, excited doubts for a long time. Partisans of Franklin's
theory (Olintus Gregory, Thomas Young et al.) called attention to the fact
that experiments furnished no basis for definitely preferring either theory,
and that mathematically the two were equivalent. The conservation princi-
ple understood as the impossibility of destruction and creation of substance
is difficult to reconcile with a theory postulating two kinds of electricity,
because in the latter theory the neutralization of two oppositely charged
bodies is difficult to interpret: how can one rationally grasp the mutual
destruction of two substances? The "dualistic" theory of electricity, it

[*] Quotation from K a p i t s a , P. L. Nauchnaya deyatel'nost' Veniamina Franklina (The Scientific Activity
of Benjamin Franklin). UFN, Vol. LVIII, No. 2, p. 172. 1956.

[**] See C o h e n , J. B. Conservation and the Concept of Electric Charge, in "Critical Problems of the History
of Science", p. 368. Madison. 1959.

seemed, was in contradiction with the principle of conservation of material substances. Yet one could not abandon the principle of conservation in the theory of electricity. This principle was obviously the basis on which the theory was developed. Its rejection would have led to the collapse of both theories.

Nonetheless, the development of physics unavoidably resulted in the recognition of two kinds of electricity. It is important to note that purely mathematical arguments played a definite role here. Already in the early nineteenth century it was evident that the "dualistic" theory of electrical phenomena was mathematically more symmetric than the unitary theory. In 1830 Thomas Thompson wrote that while the concept of two electric fluids is merely a mathematical hypothesis, this hypothesis makes it possible to "reduce all known facts to a simple and clear system which enables one to predict the result of any combination of experiments with electricity"[*]. The unitary theory required the introduction of supplementary hypotheses.

The contradiction between the necessity of accepting the "dualistic" theory and the principle of conservation of material substances alarmed the nineteenth century scientists. In creating a consistent theory of electromagnetic phenomena they sought to resolve this contradiction. To take an example, Michael Faraday, who understood the need for resolving the difficulty, would rather have rejected the "dualistic" theory of electrical phenomena than doubted the validity of the principle of conservation of "electrical substance". He steadily sought for but, by his own admission, never found an experimental fact which might definitely support the theory of two kinds of electricity and refute the unitary theory[**]. James Clerk Maxwell stressed that, like ordinary matter, electricity should be conserved. But we cannot "imagine", wrote Maxwell, "two substances annihilating each other"[***]. Yet both Faraday and Maxwell operated with the concepts of positive and negative charges. These concepts are organically contained in the theory devised by the creators of classical electrodynamics.

How can one resolve the contradiction between the conservation principle understood as conservation (in the given case) of electrical substance and concepts of opposite charges (which seem to lead inevitably to the idea of the collapse of this principle)? E. Mach proposed a solution of his own. He had thoroughly grasped the fact that the idea of conservation runs through all laws of physics. On its strength he even asserted that no special discovery of the law of conservation of energy had occurred in the nineteenth century, since conservation principles had long been known. On the other hand, he saw that the substantial conception of conservation does not agree with the theory of electrical phenomena as it was being developed. Mach perceived a solution conformable to his own epistemological inclinations in the following device: regard conservation principles as mere manifestations of the principle of "economy of thought".

The theory of electricity, however, developed along different lines. The contradiction was resolved by the discovery of new forms of conservation in the actual nature of things. The mathematical development of electromagnetic theory rested on the principle of energy conservation. "Having taken upon ourselves the task of discovering the laws of electricity, we see that we have no readily available means of investigation other than the one and

[*] Ibid., p. 370.
[**] See Michael Faraday. Experimental Researches in Electricity.
[***] Maxwell, J.C. A Treatise on Electricity and Magnetism, Art. 36, p. 39. Oxford. 1873.

only principle of conservation of energy"*. But the principle of conservation of energy is a universal conservation principle operative in all regions
of physics. The specific character of electromagnetic processes is indeed
determined by the law of conservation of electric charge.

In the mathematical apparatus of the theory the law of charge conservation necessarily came out in an algebraically symmetric form at variance
with the usual substantial conception of the idea of conservation. But here
mathematics led physicists along the right path. This path ultimately led to
the discovery of a fundamentally new and previously unknown form of the
law of conservation.

Electric charge is an attribute-property of elementary particles. In
this respect the principle of electric charge conservation, if one takes into
account its absolute value, can have the attributive form of its action, as
is the case for the proper mass of particles. However, in contrast with the
proper mass, this attribute-property has mathematical symmetry – there
exist charges of opposite sign. The quantity mass and, correspondingly,
the law of mass conservation are additive. Mass can be added and subtracted but cannot take a negative value**. With the introduction of the concept
of electric charge into physics, fundamentally new quantities of opposite
sign were brought into the science. The properties corresponding to these
quantities can be called the charge properties and the corresponding conservation principles charge conservation principles.

The contradictions which alarmed Faraday and Maxwell were overcome
by the discovery of this new form of conservation principle. The foremost
nineteenth century physicists could not make up their minds to take such a
step in the treatment of their discoveries; yet the development of electromagnetic theory was actually controlled by this form of the conservation
principle, a form contained in the mathematical apparatus of the theory.

As a result of the interaction of oppositely charged elementary particles
a new structure (atom, mesoatom, positronium and so on) may be formed
at the given level. Being the part of a whole the elementary particle loses
its individuality here. Its charge, as an attribute-property, ceases to belong exclusively to the particle and, dissolving into the interaction with
other particles, acts as a basis for new properties characterizing a new
object as an entity. When speaking of electric charges one should point out
that the laws of electrodynamics for such structures are fulfilled with a
restriction. For example, in an atom formed as a result of a definite interaction among electrically charged particles, the laws of quantum processes come into operation. But the laws of quantum physics stil require
the elementary particles as relatively distinct structural parts of a whole.
In complete processes of particle transformation, however, a fundamental
alteration of the particle takes place. Such transformations involve deep
levels of matter the laws of motion of which have not yet been discovered by
modern science. The mechanism of neutralization, for example, is not
understood. All we know is that charges do not vanish from nature; they are,
so to speak, virtually conserved. The possibility of a broad class of such
processes of particle transformation with conservation of the electric charge
is guaranteed by the presence of a large number of neutral particles:

* Max Planck. Das Prinzip der Erhaltung der Kraft, 2nd ed. Leipzig. 1908.
** At least this is true in the modern theory. Negative mass is discussed only as a possible concept. See,
   for instance, Bondi, H. Negative Mass in the General Theory of Relativity. In: Noveishie problemy
   gravitatsii (Latest Problems of Gravitation), p. 309. Moscow. 1961.

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                      Photon
                   Pi-zero-meson
               Neutrino — Antineutrino
           K-zero-meson — Anti-K-zero-meson
               Neutron — Antineutron
     Lambda-zero-hyperon — Antilambda-zero-hyperon
      Sigma-zero-hyperon — Antisigma-zero-hyperon
        Xi-zero-hyperon — Antixi-zero-hyperon
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Electrically neutral particles can be formed in transformations where the initial particles include particles with electric charges of opposite sign. Inverse processes again give rise to initial electric charges. An example is the Fermi process: $n \rightarrow p + e^- + \tilde{\nu}$, where a neutron decays into a proton, electron and antineutrino. The inverse reaction is $p + e^- + \tilde{\nu} \rightarrow n$, where a proton, electron and antineutrino convert into a neutron. In the latter reaction the positive charge of the proton and negative charge of the electron, as in the case of proper mass, do not vanish from nature forever. They are conserved in an implicit, hidden (from us) form in the neutrino, having entered into a deeper level of matter. From the direct reaction of neutron decay it follows that charges are generated anew in this reaction, passing from implicit to an explicit open form. All this points to processes occurring at great depths in nature and betokens the discovery and investigation of as yet unknown submicroscopic levels of matter. Modern elementary particle physics is approaching such a discovery.

The latest stage in the development of elementary particle physics is characterized by the discovery of new attribute-properties which obey conservation principles of the charge type. After the principle of electric charge conservation the next to be discovered was the principle of conservation of the spin of elementary particles.

The concept of ordinary spin was first introduced as early as 1925 by Goudsmit and Uhlenbeck in order to explain the fine structure of spectral lines and their splitting under the influence of a magnetic field. Pauli wrote about this unusual property of particles even before the investigations of Goudsmit and Uhlenbeck. In late 1924 he put forward the hypothesis of the characteristic double-valuedness of the properties of the electron, a double-valuedness which cannot be described classically. Subsequently it was suggested that the electron has a proper angular momentum. The concept of spin was provided with a theoretical foundation by Dirac in 1928 and developed by Pauli. Planck's constant h was chosen to be the unit of measurement of spin (it is known that Planck's constant has the dimensionality of angular momentum). In h units the spin of elementary particles can be either $\pm 1/2$, unity or, finally, zero.

The spin of a particle is an attribute-property and has a completely definite fixed value. It is usually stated that spin is a quantum property or, alternatively, a quantum number. Changes in this property can only take place in jumps accompanied by a qualitative transformation of the particle itself. The spin of a given particle can be neither decreased nor increased. A particle in an external field has a completely determined spin orientation. It preserves this orientation and can change it only in jumps. The presence of spin in the electron accounts for the splitting of spectral lines in a magnetic field (so-called multiplets). This multiplicity of spectral lines is

produced by splitting of the principal energy levels of the atomic electrons under the influence of the magnetic field. Here the number of newly obtained sub-levels, or, correspondingly, the number of lines in the multiplet produced under the influence of the magnetic field, is determined by the number of possible spin orientations of the particle with respect to the direction of the magnetic field.

According to quantum mechanics the number of possible orientations of the angular momentum (we recall that spin is the proper angular momentum) is determined by the requirement that the projections of the angular momentum vector on a chosen direction (direction of the magnetic field) be quantized so as to be integers. If the angular momentum is l in the general case, then the possible angular momentum projections assume a series of integral values from $-l$ to $+l$. For example, if $l = 2$ then the projections of such an angular momentum vector assume the values -2, -1, 0, $+1$, $+2$. In the general form this is written briefly as follows: the number of projections of the angular momentum is $2l + 1$ (law of space quantization).

There is a definite relation between the angular momentum vector and the energy level in the atom. Owing to this relation to each change in the angular momentum produced by the external magnetic field corresponds a definite change of the energy level. The set of such changes constitutes splitting of this level resulting in splitting of the spectral lines.

If one takes into account the proper angular momentum of the particle (its spin), then a particle of spin s can have, according to the law of space quantization, $2s + 1$ different states corresponding to the different orientations of its spin in space. Again, according to this law, a particle of spin $1/2$ can have only two such states with two orientations, either in the direction of the field or in the opposite direction*. The spin of so oriented particles is $+1/2$ and $-1/2$. If there is no external magnetic field these two states have the same energy and become indistinguishable. The inclusion of a magnetic field forms, as they say, a doublet — the electron can be in one of two possible states.

The idea of isotopic spin arose in the course of research into the interaction of nuclear particles. An analogy was drawn with the behavior of a particle of spin $1/2$ with respect to a magnetic field. Investigation of the structure of the nucleus led to the discovery of the so-called charge independence. In other words, it was found that the magnitude of the interaction between the protons and neutrons constituting a nucleus does not depend on electric charge. The forces of interaction between proton and neutron, proton and proton, neutron and neutron are equal. The charge independence of nuclear forces provided Heisenberg thirty years back with the basis for drawing this analogy. Heisenberg suggested considering the neutron and proton as two different states of the same particle, the nucleon. Just as electrons form a spin doublet under the influence of the magnetic field, so a neutron and proton form a charge doublet and differ from each other only in the presence or absence of electric charge.

Were we to abandon electric charge, a proton and a neutron would be indistinguishable nucleons, just as electrons are indistinguishable without an external magnetic field. Heisenberg succeeded in developing this analogy

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* The number of different states in the given case is $2s + 1 = 2$ for $s = 1/2$.

with ordinary spin and giving it mathematical form. He introduced the concept of isotopic spin. The term "isotopic" stresses the analogy in another respect – like isotopic chemical elements, a proton and neutron have somewhat different masses.

Here, however, the analogy with isotopes ceases. Isotopes of chemical elements differ in mass and have the same electric charge on the nucleus, while the proton and neutron, though doubtless differing in mass, also differ in electric charge. The proton has a positive charge, the neutron no charge at all. To extend the analogy of protons and neutrons with isotopes we have to find some other common property; only the presence of some common property analogous to charge could allow us to class them as a single form of particles (despite the slight difference in mass), as in the case of the isotopes of chemical elements. A completely new property – isotopic spin – is such a property. Now the isotopic spin of a nucleon, like the spin of the electron, is one-half. The analogy with spin is also manifested in the similarity of the mathematical apparatus. This similarity will be clarified by the following. As for a doublet of particles with ordinary spin, the number of terms in a family with isotopic spin of $1/2$ is also two. Indeed, denoting the isotopic spin by I, we have in the given case the number of terms in the family $2I + 1 = 2$. Isotopic spin characterizes the entire group of particles, or, in other words, the entire charge family. In the case of nucleons the family consists of two particles, a proton and a nucleon.

Although isotopic spin differs from electric charge as the specific property of particles, it is related to it. This relation makes it possible to give a special characterization of every particle separately. For the charge family such a characterization is provided by the so-called "projection" of the isotopic spin I_z. Now the I_z of a given particle is equal to the difference between the charge of the given particle and the average charge of the entire family: $I_z = e - e_{av}$ (where e is the charge of the given particle and e_{av} the mean charge of the family). It is easy to show that the isotopic spin of a neutron is $-1/2$ and that of a proton $+1/2$.

After Yukawa advanced the idea of the meson character of nuclear forces, the British physicist Kemmer drew attention to the fact that the concept of charge independence can be extended to π-mesons. This means that π-mesons, like nucleons, should have a definite value of the isotopic spin.

It is well known that π-mesons form a charge family consisting of three particles or, in other words, a triplet: π^+, π^0 and π^-. This means that the isotopic spin I characterizing the entire charge family is unity. We recall that the number of terms in a family is $2I + 1$. For $I = 1$ the number of terms in the family is precisely three. The average electric charge of the π-meson family is zero. If we know the average charge of the π-meson family we can obtain the value of the isotopic spin I_z for an individual particle. As in the case of nucleons, the isotopic spin of an individual π-meson is equal to the difference between the charge of the particle and the average charge of the family. But the average charge of the given family is zero and therefore the isotopic spin I_z is equal to the charge of the particle. The isotopic spin (more precisely, I_z) of a π^+-meson is one, the isotopic spin of a π^0-meson zero and the isotopic spin of a π^--meson minus one. In other words the value of the isotopic spin of π-mesons is identical with the value of their electric charge. It should be pointed out that the average value of I_z is zero for any charge family. As a result the isotopic spin (more precisely

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the component I_z) characterizing a particle appears as a special kind of charge.

Isotopic spin has the characteristic traits of an attribute-property of a particle. Like electric charge and spin, isotopic spin is a rigorously defined and conserved quantity inherent in nucleons and π-mesons. The magnitude of the isotopic spin of a given particle is conserved attributively for every given particle as long as it does not undergo qualitative transformations. If such transformations take place then, when these transformations are due to charge-independent interactions, the total isotopic spin of these particles is also conserved. Consequently the principle of conservation of isotopic spin is valid. This principle, however, is operative in a limited sphere; more specifically, it is fulfilled in the region of interactions where charge independence is valid. Such interactions include, as we saw, the π-meson interaction. On the other hand, in the case of, say, electromagnetic interactions, where the electric charge is significant, the concept of isotopic spin is inapplicable. Therefore the principle of isotopic spin conservation is not of a general character.

Starting from 1947, when tracks of so-called V-particles were discovered, the list of elementary particles was unexpectedly increased by new particles. Subsequent investigation of the properties of V-particles revealed that one was dealing with a diverse group of previously unknown particles with unusual or strange properties. Such "strange" particles now include K-mesons, with a mass of 966; and the hyperon group (particles with a mass greater than that of nucleons).

The extraordinary character of these particles resides first in the fact that their time of production corresponds to the time of strong interactions ($\sim 10^{-23}$ sec.) but their time of decay is, strangely enough, completely different – i. e., it corresponds to the time of weak interactions ($\sim 10^{-8}$ sec.). Secondly, these particles are created only in pairs. Single creation of such particles is never observed although all conservation laws known previously admit of such single creation. Furthermore, single creation of these particles should be more probable than multiple production. Yet not one case of single creation of these particles has been detected. Pais and certain other physicists have suggested that this fact is the result of the operation of a special new exclusion principle – nature forbids single creation of strange particles.

Physics is familiar with many other exclusion principles. The p e r p e - t u u m m o b i l e is in principle impossible. It is well known that the exclusion of the p e r p e t u u m m o b i l e follows directly from the fact that the law of conservation of energy is operative in nature. In quantum mechanics the Pauli exclusion principle – no more than one electron can exist in the same quantum state in the atom – is operative. It is well known that the Pauli exclusion principle is a consequence of the law of spin conservation and, more generally, a consequence of the general symmetry properties of the wave function ψ. In spectroscopy there is an exclusion principle according to which optical transitions are impossible between states with the same parity (Laporte's rule). This exclusion principle follows from the law of parity conservation. One might say that every exclusion principle

is related to the operation of a corresponding conservation law. And, conversely, every conservation law imposes a restriction on the infinite possibility of nature and leads to the exclusion in principle of certain seemingly conceivable phenomena. Conservation principles impose a stamp of necessity on the statistical flow of natural processes.

In the case of strange particles the Pais exclusion principle points to the presence of a specific conservation law the consequence of which is this exclusion of single particle creation. The law of conservation of strangeness is this new, previously unknown conservation law.

The concept of strangeness was introduced during the classification of new particles. When an attempt was made to find common traits between these particles and those already known it was natural to seek to apply to them the idea of charge independence. As it turned out charge independence makes it possible to collect the strange particles in charge families (multiplets) similar to those of the nucleons and π-mesons. This means that the new particles have an isotopic spin (I). We recall that the number of particles in a charge family is $2I+1$. If the charge family is composed of a single particle the isotopic spin of this particle is zero. If there are two particles in the charge family the isotopic spin of the family is one half. If the charge family consists of three particles the isotopic spin of the family is unity.

Isotopic spin and the law of isotopic spin conservation gave rise to the possibility of detecting the unity of new and previously unknown particles. However, the attempt to collect the new particles in charge families analogous to the families of nucleons and π-mesons met with difficulties.

It was natural to suppose that hyperons, which are heavy particles, form doublets as do the nucleons and, therefore, have an isotopic spin of one-half. K-mesons, like the π-mesons, should form a triplet of isotopic spin one – or so it seemed. Strangely enough, the newly discovered particles refused to fit into this analogy. The Λ^0-hyperon of mass 2181 has no particles of similar mass which might be classed in a family of lambda hyperons. This family evidently consists of a single term. This means that the isotopic spin of this family is zero and not one-half as in the nucleon family. When classification by isotopic spin was being carried out the particles known experimentally were the Σ^+-hyperon of mass 2325 and the Σ^--hyperon of mass 2341. If these particles with electric charges of opposite sign have an isotopic spin there must exist a third particle in this family, i.e., a neutral Σ^0-hyperon. If this is so then again, strangely, the isotopic spin of the Σ-hyperon family is unity and not one-half as in the nucleon family. Finally, it was definitely established that there exists a Ξ^--hyperon. Here two possibilities arose. One could suppose the existence of two more hyperons – one with a positive electric charge and a neutral one – and thus the Ξ -hyperon family would form a triplet. Or there existed only one more particle, a neutral one, and the family of Ξ hyperons, like the nucleon family forms a doublet. The experimental facts then available tended to favor the latter view. The assumption was made that the Ξ-particle family consists of two terms and has, therefore, an isotopic spin of one-half.

K-mesons are particles analogous to π-mesons in that their mass also lies between the electron and the nucleon masses. It was therefore natural to suppose that K-mesons form a family of three particles as do the π-mesons. However, the K-mesons did not fit into this analogy. In this respect K-mesons proved to be more closely analogous to nucleons, for they form

a doublet, i.e., family of two particles: K^+-meson and K^0-meson. The isotopic spin of the K-meson family is therefore one-half. True, K-mesons display yet greater strangeness than the hyperons, since the K^0-meson, as it turns out, is itself a mixture of two different neutral particles: K_1^0 and K_2^0. However, we will disregard this complication and confine ourselves to the family of K^+- and K^0-mesons.

It should be stressed again that far from all the particles belonging to the above families had been discovered at the time when attempts were being made to classify the new particles. The success and scientific value of any classification is determined by its ability to predict objects as yet unknown. We saw that the classification of new elementary particles by isotopic spin required the existence in nature of a neutral Σ^0-hyperon, a particle not on the list of particles then known. The Σ^0 particle was discovered experimentally soon afterward. At the time of classification the Ξ^0-hyperon was also unknown. The classification of particles by strangeness led to the prediction of another particle, the anti-Σ^--hyperon. In 1961 this particle was discovered experimentally at Dubna. In all these cases the principle of isotopic spin conservation played a heuristic role. This law was the principal methodological guide employed in the classification of new particles and in the prediction of the existence of new particles on the basis of this classification.

The principle of isotopic spin conservation furnished a basis for collecting new particles in charge families. True, these families differed in a strange manner from the nucleon and π-meson families. Nonetheless, as we saw, the corresponding value of the isotopic spin was found for each family.

This value of the isotopic spin had to be related to the value of the average electric charge of the entire family. It was this relation which had led to the determination of the value of the isotopic spin projection for nucleons and π-mesons as a characterization of individual particles. We recall that the average charge of the π-meson family consisting of three particles is zero. Here the projection of the isotopic spin I_z is simply the average charge of the particle $(I_z = e)$. The average charge of the nucleon family is $+1/2$. The isotopic spin of the neutron is $-1/2$ and that of the proton $+1/2$.

It turned out that the average electric charge of hyperon families is not identical with the average charge of the nucleon family. For the Λ^0-hyperon, which forms a singlet family, the average charge is identical with the charge of the Λ^0-particle itself, i.e., zero. The average charge of the singlet Λ-family is displaced by $-1/2$ (see table) with reference to the average charge of the nucleons. For purposes of mathematical convenience this displacement is generally doubled. The doubled value of this displacement for the Λ^0-family is minus one.

The family of Σ-hyperons consists of three particles (Σ^-, Σ^0 and Σ^+). As for the Λ^0-particles, the average charge for this family is zero. The doubled value of the average charge displacement is minus one, i.e., identical with the corresponding value of the displacement for the Λ^0-family (singlet). The Ξ-hyperon family consists of two particles (Ξ^0 and Ξ^-). The average charge of this family is $-1/2$. The displacement of this average charge relative to the average charge of nucleon family is minus one. The doubled value of this displacement is -2.

The displacement of the average charge of the K-meson family is determined with reference to the average charge of π-mesons. The π-meson

Table of strange particles (after Gell-Mann)

Particle	Isotopic spin	Strange-ness	Charge −1	−1/2	0	+1/2	+1
Nucleon	1/2	0			n°		p^+
Antinucleon	1/2	0	$\bar{p}$		$\bar{n}^\circ$		
Lambda	0	−1			Λ°		
Antilambda	0	+1			$\bar{\Lambda}^\circ$		
Sigma	1	−1	Σ^-		Σ°		Σ^+
Antisigma	1	+1	$\bar{\Sigma}^+$		$\bar{\Sigma}^\circ$		$\bar{\Sigma}^-$
Xi	1/2	−2	Ξ^-		Ξ°		
Antixi	1/2	+2			$\bar{\Xi}^\circ$		$\bar{\Xi}^+$
Pion	1	0	π^-		π°		π^+
K	1/2	+1			K_1°, K°, K_2°		K^+
Anti-K	1/2	−1	K^-		$\bar{K}^\circ$, K_1°, K_2°		

family $(\pi^-, \pi^\circ, \pi^+)$ has an average charge zero. The K-meson family (K°, K^+) has an average charge $+1/2$. The displacement of the average K-meson charge with reference to the average π-meson charge is $+1/2$. The doubled value of the displacement of the K-meson charge is therefore $+1$.

These operations with the determination of the average charge displacement may seem purely formal at first glance. However, once it was discovered that the displacement of the average charge is conserved in processes of particle transformation, it became a significantly new characterization of particles. In other words, the discovery of a displacement of the average electric charge of hyperons and K-mesons with reference to the average charge of nucleons and π-mesons was followed by the discovery that this displacement was of a regular nature. The magnitude of the average charge displacement in this case obeys a special conservation law. Gell-Mann and, independently, Nishijima, who were the first to analyze these displacements, arrived at the conclusion that this quantity, subject to a new

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conservation law, makes it possible to explain the strange behavior of the new particles. The doubled value of the displacement of the average electric charge of a family was called strangeness and the corresponding conservation law the law of conservation of strangeness.

Everything that has been said concerning the strangeness of particles can be applied analogously to antihyperons and anti-K-particles. Naturally, in the classification of antihyperons the starting family is the family of antinucleons (antiproton and antineutron) with an average electric charge of minus one-half. Owing to this the antihyperons have a strangeness of opposite sign to that of hyperons. If, for instance, the strangeness of the Λ^0-hyperon is minus one, the strangeness of its antiparticle $\tilde{\Lambda}^0$ is plus one. For anti-K-mesons the displacement of the average charge, reckoned, as for K-mesons, from the average charge of π-mesons, is zero.

The principle of strangeness conservation makes it possible to explain, in particular, the exclusion of single creation of strange particles. Ordinary particles do not have strangeness. If strange particles are produced as the result of reactions with ordinary particles single particles cannot appear in such reactions as this would violate the law of conservation of strangeness — the strangeness quantity would have appeared out of nothing. However, since strangeness can be negative and positive in sign, two strange particles with opposite signs of the strangeness can appear in reaction with ordinary particles. For example, a Λ^0-hyperon of minus one strangeness and a K^0-meson of plus one strangeness can be formed in the interaction of a π^--meson and a proton: $\pi^- + p \rightarrow \Lambda^0 + K^0$. The total strangeness of a Λ^0-hyperon and a K^0-meson is zero. The law of conservation of strangeness permits this kind of reaction.

The law of strangeness conservation explains yet another unusual or strange property of the new particles. Research shows that strange particles are formed in strong interactions within the time interval characteristic of these interactions, i.e., of the order of 10^{-23} sec. There is, however, a principle of reversibility of reactions according to which a particle created in strong interaction must also decay in a process of strong interaction. For example, the Λ^0-hyperon could have decayed into a proton and a π^--meson. According to well-known laws of conservation (of mass, energy, spin, electric charge and so on) such a reaction is possible. And this decay reaction should have taken place within a nuclear time interval, namely within 10^{-23} sec. In reality, however, particle decay takes place differently: most surprising of all, it takes place more slowly than expected, i.e., within 10^{-8} sec. That the seemingly possible decay reaction of the Λ^0-particle is forbidden can now be attributed to the fact that such a reaction violates the law of conservation of strangeness. The exclusion of this kind of decay, as we saw, follows directly from the law of conservation of strangeness which is operative in the region of strong interactions. The stability or permanence of particles is determined directly by the action of the conservation law. But how can one explain the fact that the decay of strange particles still takes place, though more slowly than is characteristic of strong interactions? The decay of strange particles is evidence that there exists a region in which the law of conservation of strangeness ceases to be valid; the possibility of transformation of a given isolated strange particle into ordinary particles arises only when this law is violated. What is this region of violation of the strangeness conservation law like? Could it be that the law of conservation of strangeness, which is operative in the strong interaction

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region, is violated in the region of electromagnetic interactions? No
There can be no such violation in the operation of the law of conservation
of strangeness in the region of electromagnetic interactions. The concept
of strangeness is related to the concept of isotopic spin, and the concept
of isotopic spin is related in turn to the average value of the electric charge
of the particle family. We saw that the magnitude of the strangeness char-
acterizes the displacement of the average electric charge of the family of
hyperons and K-mesons with reference to the average electric charge of
nucleons and, respectively, π-mesons. But in electromagnetic processes
the law of conservation of electric charge is, naturally, operative. All
this leads us to infer that the law of conservation of strangeness is obeyed
in the region of electromagnetic interactions.

One possibility remains — that the law of strangeness conservation is
violated in the region of weak interactions. Additional evidence in favor
of this is the decay time of strange particles. Thus the law of strangeness
conservation explains both the exclusion of single creation of strange parti-
cles and their unusually slow decay time. As it happens, the region of
weak interactions is one where not only the law of conservation of strange-
ness but also the law of parity conservation is violated.

The concept of parity can be introduced into the system of concepts of
classical physics*. But parity conservation assumes the importance of a
principle only in quantum physics. The concept of parity can be illustrated
by the simplest of mathematical functions. The function $y = x^2$ is an even
function because when we replace x by $-x$ the function retains its sign. The
function $y = x^3$ is an odd function because when we replace x by $-x$ the func-
tion changes sign. To take another example, the function $y = \cos x$ is an
even function because $y = \cos x = \cos(-x)$; the function $y = \sin x$ is an odd
function because $y = \sin x = -\sin(-x)$. It is easily seen that the concept of
parity is related to the mirror reflection of the function or with symmetry
relative to right and left-hand systems of coordinates. In the above exam-
ples we are speaking of functions symmetric with respect to the y-axis.

In quantum mechanics the motion of an elementary particle is expressed
by the Schroedinger equation which determines the wave function $\psi(x, y, z)$.
One might ask whether the ψ-function is even or odd with respect to mirror
reflection. It turns out that wave functions which describe the motion of
particles can be both even and odd. One can introduce a special character-
ization of the odd- or evenness of a wave function and, therefore, of the odd-
or evenness of the corresponding particle.

Let $\psi(x, y, z)$ be the wave function of a particle. Let us take the mirror
reflection, i.e., change the signs of the coordinates. We obtain the new
function $\psi(-x, -y, -z)$. If mirror symmetry is present (i.e., symmetry
with respect to right- and left-hand systems of coordinates), then the
particle described by the wave function $\psi(x, y, z)$ should not differ from the
particle described by the wave function $\psi(-x, -y, -z)$. According to the
principles of quantum mechanics, the wave functions of particles can differ
only by some constant factor a: $\psi(x, y, z) = a\psi(-x, -y, -z)$. If we carry out

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* The ideas of this section have been taken from the article "Nesokhranenie chetnosti pri slabykh vzaimodei-
stviyakh elementarnykh chastits" (Nonconservation of Parity in Weak Interactions of Elementary Particles),
written in collaboration with N. F. Nelipa ("Voprosy filosofii", No. 1, 1959).

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another reflection then $a\,\psi(-x,-y,-z)=a\cdot a\,\psi\,(x,\,y,\,z)$. In other words $\psi\,(x,\,y,\,z)=$ $= a^2\psi(x,\,y,\,z)$. Since we have returned after the second reflection to the original particle a^2 must be equal to unity, i.e., $a=\pm1$. The quantity a is called the parity of the particle.

The parity of a particle does not vary with time in all its transformations. If the parity is +1, i.e., if the ψ-function does not change sign upon mirror reflection, then this property of not changing sign is conserved. If the parity is —1, i.e., if the ψ-function changes sign upon mirror reflection, then this property of changing the sign is also conserved. In other words the parity of a system of particles is the same before and after reaction. Here it should be borne in mind that the parity of a group of particles, unlike other quantities subject to conservation laws, is equal to the product, rather than to the sum, of the parities of the individual particles.

Let us consider, in this connection, the so-called $\tau-\vartheta$ puzzle which led to the discovery of the violation of the law of parity conservation in weak processes.

Among the K-mesons there are some particles which are close in mass and lifetime. These particles were called τ-and ϑ-mesons:

τ has a mass of ~966 and lifetime of 10^{-8} sec;

ϑ has a mass of ~964 and lifetime of 10^{-8} sec;

However, they decay differently:

$$\tau^+ \to \pi^+ + \pi^+ + \pi^- \quad (-1)^3 = -1;$$
$$\vartheta^+ \to \pi^+ + \pi^0 \quad (-1)^2 = +1.$$

The difference in the decay modes poses a dilemma: either τ and ϑ are different particles — but then it is incomprehensible why their masses are nearly identical and their lifetimes identical; or τ and ϑ represent the same particle — but the law of parity conservation breaks down.

This raises the problem of verification of the law of parity conservation. The idea of verifying the law reduces to the following. With reference to mirror reflection there exist two types of quantities. Some quantities do not change sign, others do. Energy and momentum do not change sign; the scalar product of the spin and momentum $(s\cdot p) = sp\cdot\cos\vartheta$ changes sign (pseudoscalar). In this respect these quantities are similar to ψ-functions some of which change sign under mirror reflection while the rest do not.

In order to observe experimentally the effect produced by the pseudoscalar $(\vec{s}\cdot\vec{p}) = sp\cdot\cos\vartheta$ it is necessary to fix the position of one of the quantities which constitute the pseudoscalar. In experiments with Co^{60} a radioactive substance was placed in a strong magnetic field. This guaranteed a definite orientation of the spins of the cobalt nuclei. To reduce deviations from this orientation owing to thermal displacement of the atoms the radioactive cobalt was cooled to a temperature close to absolute zero. As a result of the reaction $Co^{60} \to Ni^{60} + e^- + \nu$ it was observed that electrons fly out predominantly in one direction with reference to the spin orientations identical with the direction of the magnetic field. Fewer electrons fly out in the direction of the magnetic field than in the opposite direction.

These results can be explained graphically. Let us consider the two limiting cases of electron emission by oriented nuclei (Figure 1). The upper left-hand side of the figure represents the case where the number of electrons emitted in the direction of the field is exactly equal to the number of electrons emitted in the opposite direction. In the upper right-hand

side of the figure the electrons fly off only in the direction H of the magnet-
ic field. Let us take the mirror reflection of both phenomena. Since in a
mirror the direction of motion of the electrons is replaced by its reverse,
we see that in the right-hand side of the figure the phenomenon and its mir-
ror reflection are not identical. In the left-hand side, however, there is
complete identity of the phenomenon and its mirror reflection. If this iden-
tity were to be supported by experiment we would have a confirmation of
parity conservation. Because the case shown in the right-hand side of the
figure was confirmed experimentally the inference was made that parity is
not conserved. In reality the experiment dealt not with the limiting cases
but rather with a certain intermediate phenomenon. Nonetheless the fact of
anisotropic flight of the electrons was established, and a basis was provided
for speaking of the breakdown of the law of parity conservation in the region
of weak interactions.

   The principle of parity conservation obliges us to undertake a special
examination of the concept of symmetry. The discovery of symmetry

FIGURE 1

principles goes back to the origins of sci-
entific knowledge. The teachings of the
ancients concerning the harmony of the
universe, the primary geometrical elements
of the world, the number as essence of
things are samples of the earliest insights
into the symmetry of nature.
   The concept of symmetry contains two
contradictory moments. It assumes, first,
a regular displacement of the object or
its parts, and, secondly, conservation of
the object or its parts in conformity with
this displacement. In the physics of ele-
mentary particles mirror symmetry (the
inversion transformation) consists of
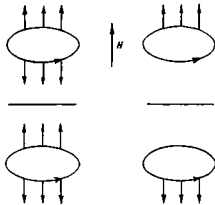
c o n s e r v a t i o n of parity upon t r a n s i t i o n from a right-hand coordinate
system to a left-hand one. The concept of symmetry becomes meaningless
if there is no motion, say, from a right-hand coordinate system to the left-
hand one. It is also inapplicable in the case where the corresponding para-
meter is not conserved upon such transition, as is the case for parity in the
region of weak interactions. Only the existence of a definite group of m o -
t i o n s and, simultaneously, c o n s e r v a t i o n of definite parameters in the
process of these motions can provide a basis for speaking of symmetry.
   In the analysis of the symmetry properties of ordinary space translation
(transfer), rotation and inversion (mirror reflection) proved to be the most
important forms of motion. Each of these forms of motion — or, in other
words, operations — forms a group in the sense of the mathematical theory
of groups. One can speak about, say, the group of translations, the group
of rotations about a fixed axis, and so on. Group theory provides the mathe-
matical apparatus for developing the theoretical side of the science of
symmetry.
   Now that we have given a general characterization of the symmetry prin-
ciples it is necessary to stress their extreme generality. All subjects of
cognition — things, properties and relations — contain symmetries within

themselves as a fundamental trait, a trait which often determines all other features of these objects. Manifestations of symmetry are found in such things as atoms, molecules, crystals. The discovery of symmetry principles characteristic of these objects constitutes the foundation for knowledge of their structural and genetical regularities.

In elementary particle physics, in addition to the symmetry of things, an important part is played by the symmetry of properties and the symmetry of relations. Here, as we saw, one is dealing with, say, the symmetry of charge properties. Physics is seeking the original principles required for the development of the theory in the laws of symmetry of these fundamental properties. Space and time can be regarded as important relations between things in their internal and external ties. Space symmetry and time symmetry represent a symmetry of relations. This is the form of symmetry which is connected with the most general principles of conservation.

The concept of symmetry, as we noted earlier, necessarily contains conserved elements. Now the number of conserved elements, or parameters, is determined by the form of the symmetry. On the other hand, a given conservation principle may prove to be connected to a certain conbination of forms of symmetry. Such is the case, for instance, of the so-called TCP theorem known as the Lüders-Pauli theorem. Originally each discrete transformation – mirror symmetry P, time symmetry T, charge symmetry C – was attributed only its own independent conservation principle, or, to use the term current in the special literature, its own independent invariance. However, a profound connection was subsequently established between these three types of symmetry. It was found that certain of the conservation principles corresponding to each of these symmetry transformations can break down. Thus the breakdown of the law of parity conservation in the region of weak interactions was discovered. At the same time a certain combination of these symmetry transformations gives a new conservation principle. Combined parity, which corresponds to the combination of mirror symmetry P and charge conjugation C, is conserved in the region of weak interactions. In the given system of concepts the most general conservation principle, according to the Lüders-Pauli theorem, corresponds to the product of all three symmetry transformations C, P and T. Thus, as in the given case, symmetry types are related to conservation principles in a complex form. For all their organic interrelation this gives us the right to examine the differences between the conservation principles and symmetry types.

In the most general form symmetry as a general regularity of nature can be formulated as follows: any motion is necessarily related to conserved elements of nature. To each change corresponds a definite conservation and to each conservation a definite change.

Symmetry is expressed in the sphere of logical thinking as well. The symmetry of concepts is manifested in the principle of duality, which is operative in geometry, in the theory of sets, and in topology and which, finally, is generalized in modern logics. This principle can be formulated generally as follows: the validity of a proposition is conserved if the concepts in this proposition are replaced by other concepts symmetric to them.

As it is a universal feature of nature, symmetry is manifested in regularities of abstract mathematical form, occasionally amazing in the harmony and elegance of the relations obtained. For this reason the laws of

symmetry of nature can also be approached from the outset by purely mathematical paths. The forms of symmetry display inexhaustible diversity, and therefore we are not always able to perceive their profound unity — we may even fail to recognize symmetry in certain of its varieties. In searching for natural laws and seeking to penetrate deeply into the structure of matter, however, one is unavoidably led to the discovery of forms of symmetry. At first these forms may seem to be the regularities of empirically determined numbers or, correspondingly, geometrical forms. An historical example of this may be found in the study of atomic structure. Even before the creation of a consistent modern atomic theory the amazing series of numbers — 2, 8, 18, 32, ..., — corresponding to the lengths of the periods in Mendeleev's system was the object of particular attention. Subsequently this series was explained in the quantum laws of atomic structure and associated profound forms of symmetry. Modern elementary particle physics is constantly seeking new forms of symmetry. These new forms may be the key to the creation of a rational systematics of elementary particles and to the understanding of their structure.

The cognition of nature and its laws involves cognition of its structure. To cognize the structure of an object means first and foremost to decompose its wholeness, to find the parts of the object and to study these parts as such according to their properties. This decomposition is characteristic of the first stage of cognition. Cognition of the parts of a whole and investigation of their properties provides the necessary material for further and deeper cognition. The category of structure assumes, further, cognition of the process of formation of a whole from its parts. Reproduction of this process in scientific thinking is possible only through knowledge of the relationships of the parts within the whole. This corresponds to the stage of creation of the theory and discovery of the fundamental laws of the region of nature under investigation.

In the cognition of nature space-time relations come to the forefront and material objects are seen as things with a space-time structure. The types of structure, however, are manifold. In the process of creation of a theory the elements of a wide variety of structures can act as elements or parts of the whole. Owing to the universality of the category of structure these structures can be structures of things, structures of properties and structures of relations. Each of these structure classes can have its own subclasses. This leads to a broader abstract understanding of structure the content of which is expressed in abstract mathematical forms which go beyond the limits of known space-time relations. In the process of penetration into increasingly fine and varied structures the crucial moment is the intersection of structures. This intersection of structures forms the most stable conserved elements of nature. The discovery of these elements gives us the possibility of constructing a theory and provides us with the basis for discovering the regularities of the development of cognizable natural objects.

The deeper we penetrate into the essence of a given type of structure, the finer the intersections which are drawn into the theory. If at first the constancy of properties is treated as a result, so to speak, of the absolute structurelessness or rigidity of the fundamental elements, subsequently it is found that this constancy of the properties is a product of the dynamical

stability of the internal structure of these elements. The constancy of properties, their conservation, stems from the constancy characteristic of any structure in general. This constancy is realized concretely in the constancy of the properties inherent in the elements of the intersection between types of structure.

The discovery of the diversity of structural types and, correspondingly, of the diversity of their intersections, is a result of modern science. The first attempts at penetrating into the structure of matter are associated with the idea of the decomposition of the whole into its parts. Therein lies the characteristic trait of atomism, which pictures its essential task as the discovery of the unified discrete structure of all objects but is not concerned with discovering the hierarchy of structures. Every object, irrespective of its structure, is reproduced directly out of absolutely primary elements. In the fully developed form of classical atomism structure as such, i.e., the relation of parts within a whole, consists of the laws of mechanics. The whole can be a minute particle of dust, or it can be the entire universe. Here we have a "Theory" with capital T, enveloping the entire universe*. The discovery of the diversity of types of structure is in our opinion evidence of the impossibility of creating such a "Theory". It is of course possible to find general relationships and regularities in different kinds of structures, but this type of relationship constitutes a special kind of superstructure or structure of structures. A theory which would express such a superstructure could not be a theory of the physical type. The initial elements of such a theory would be so diverse that they could be expressed only in theories of the philosophical type.

Classical atomism was the first in the history of natural science to propose a conservation principle which can be classed as conservation of things in the system of categories of thing, property and relation. In its attempt to reproduce theoretically the process of construction of higher structures from primary conserved atoms, classical atomism progressed toward the discovery of a new class of conservation principles, namely the conservation of properties. Such properties of macroscopic bodies as gravitational mass, intert mass and electric charge were regarded as resulting from the corresponding properties of atoms. Modern atomism is forced to account for the hierarchy of structures and must take into consideration the fact that not every property of the more complex formation can be explained directly from primary elements. Structure creates new properties not present in its component parts. And, correspondingly, not every property of the original structure need be a property of the more complex structural formation. As it penetrates into the structure of the atoms and investigates the properties of elementary particles physics discovers specific properties not present in the atom; at the same time an understanding of these properties is a necessary condition if one is to reproduce in the theory the objective process of formation of atomic structure and explain regularities of intraatomic motion. This is a general feature of atomism as a scientific theory. The search for elementary structures and for their conserved properties is a general feature of atomism, classical as well as modern.

Like classical atoms, elementary particles have certain fixed attribute-properties. The stability of elementary particles is due to the conservation

* See Markov, M.A. O sovremennoi forme atomizma (Modern Atomism). Voprosy filosofii, No.4, p.125, 1960.

of these properties. Certain of these properties were discovered in the period of classical atomism in the form of properties of the "invariable" atoms. An example is the proper mass of elementary particles, which is analogous to the mass of classical atoms since both have a definite fixed value, for definite kinds of atoms in one case and for definite kinds of elementary particles in the other.

Modern elementary particle physics has discovered many new particles in recent years. The discovery of new particles continues. In order to understand the regularities of the relationships between particles and to impose order on the empirical material, theoretical thinking begins with a search for attribute-properties. Naturally, the process of cognition moves from the external to the internal. This search is methodologically of the same nature as Democritus' attempt to find the constant properties of the atoms (size, form, situation) or the attempt of Newton and of all of classical physics to regard the fundamental properties of discrete particles of matter (inertia, electric charge) as attributively inherent in these particles. In a paper on the classification of elementary particles by the well-known physicist R. Sachs the following statement is made: "The classification is carried out in terms of a single quantum number called the "attribute" which is not given a specific physical interpretation"[*]. This quotation illustrates the fact that the search for new regularities in elementary particle physics begins with a search for quantities which are conserved and attributively related to the particles. It is important to note that the quantity "attribute" of which Sachs speaks is just as much conserved as proper mass or electric charge. The lack of a detailed physical interpretation of the newly discovered quantity is characteristic only of the initial stage in the development of the theory. Later its nature will be revealed and, in particular, it may become clear that its attributive character is only relative. But in order to begin this investigation – one which will lead in the future to the discovery of new regularities – it is necessary to find the attributive parameters of the particles; this is the only approach which can yield reliable scientific results.

Attribute-properties are related to the structure of the object. If the structure of an object is not yet known the object will appear as a simple set of properties. In this case the properties merely indicate the presence of structure, the specific character of which remains to be investigated. At this stage of cognition, when the structure is still unknown but its properties are already known, the nature of these properties cannot be studied to any depth. To understand the nature of a given property means to uncover its relationship to the corresponding structure.

The structure of material objects is always relatively constant or stable in time. Stability is a characteristic trait of structure in general. This stability objectively determines the constancy of the attribute-properties. In cognition the conservation of attribute-properties is evidence of the stability of the corresponding structure. If we were to trace the relationship between property and structure in the real picture of the structure of matter we would see that there exists a chain of interrelated structures which form qualitatively different levels of matter. Were we to represent these levels graphically in the form of concentric rings, the radial lines symbolizing transition from one level to the next would lie across the boundaries

[*] Sachs, R.G. Phys. Rev. Vol.99, No.1573. 1955.

separating one level from another (Figure 2). This boundary is realized by the attribute-properties. Every specific boundary is characterized by corresponding properties inherent to it. The specific traits of the properties are determined by the specific traits of the neighboring levels and corresponding structures. Assuming that a scientific theory which reflects the regularities of a given level of matter is being built, a knowledge of the structure of the underlying level could be important for this theory. The structural properties of the underlying level can be taken as the initial elements of the theory and the elements themselves can be regarded as indivisible and absolutely stable.

Of course, knowledge and consideration of the structure of an underlying level of matter can lead to deeper knowledge of the stable internal relationships of the higher structure. The discovery of intraatomic structure provided a deeper understanding of intramolecular relationships. If, as in the given case, the structure of the underlying level is cognized, a more concrete understanding of the details of the mechanism of the higher structure is the result. However, the point of departure of the cognition of any structure is associated with the search for the attribute-properties of its component elements. Further, it is not only possible but frequently necessary to detach oneself from the structure of these elements even if this structure is already known and studied in another region of science. In giving a dynamical picture of the structure of the solar system classical celestial mechanics detaches itself from the structure of the planets and regards them as indivisible objects (material points) possessing completely determined (in magnitude) attribute-properties: inertia and gravity.

FIGURE 2

The search for attribute-properties and the attempt to place them among the foundations of the theory are general traits of all sciences studying the structure of the given class of objects. These traits are also present in sciences which deal with the latest and, at a given time, indivisible level of matter. In such cases, as in modern elementary particle physics, there is no other way to effect a theoretical penetration into the deeper structure of matter. The way to cognition of this deeper structure lies across the attribute-properties of elementary particles because these properties stem from this structure and lie at the boundary which separates this finer structure from the neighboring higher structure. The next step in cognition should consist of breaking through this boundary. But before doing this, and in order to do this, it is necessary to investigate the attribute-properties which constitute this boundary. The principles of conservation of electric charge, spin, isotopic spin, strangeness, parity and so on which have been discovered in elementary particle physics betoken a breakthrough into a deeper structure of matter.
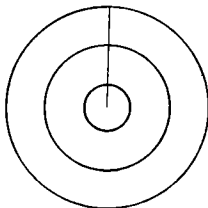
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THE PROBLEM OF THE SPATIAL STRUCTURE OF ELEMENTARY PARTICLES

Ya. P. Terletskii

One of the most striking confirmations of Lenin's brilliant prophecy concerning the inexhaustibility of the electron was doubtless provided by Hofstadter's experiments on the scattering of fast electrons on atomic nuclei and the associated experimental discovery of the spatial electromagnetic structure of nucleons. The inward inexhaustibility of matter – a fundamental postulate of dialectic materialism – has been confirmed in many other ways and has been adopted permanently by modern physics in the form of the concept of the inexhaustibility of elementary particles. However, the experiments which proved directly that two of the thirty odd known elementary particles are not point particles and have a spatial structure made this concept fully concrete and graphically convincing.

Thus one of the basic ideas of modern elementary particle physics, one which should underlie the theory of elementary particles, is the idea of their finite spatial dimensions and of spatial structure.

This idea, however, is in contradiction with certain concepts and consequences of relativistic quantum theory, the only theoretical base available so far in the region of elementary particle physics.

In all the well-known forms of quantum mechanics particles are regarded as point particles. This view is reinforced by the difficulties of ascribing finite spatial dimensions to elementary particles in the relativistic theory. When introduced into the relativistic quantum theory the assumption of finite particle dimensions leads to the negation of the basic ideas and formulas of quantum mechanics. It also meets decisive objections from the theory of relativity.

The difficulties presented by relativistic quantum mechanics have even led certain theoreticians to believe that elementary particles are fundamentally point particles. Although this belief was already subjected to well-deserved criticism in 1949 by S. I. Vavilov from the standpoint of materialistic philosophy*, and despite the results of recent experiments by Hofstadter, the concept of elementary particles as point particles is still vigorously defended. Sometimes the suggestion is even made to define elementary particles as objects which do not have spatial structure. The source of this "punctal" conception is apparently a boundless faith in the unshakability of the principles of quantum mechanics and certain ideas of the theory of relativity.

True, some theoreticians maintain that, owing to the introduction of a form factor associated with the scattering amplitude, it is as if modern relativistic quantum theory regarded elementary particles as objects having

a spatial structure. However, within the limits of quantum field theory this form factor is merely a means of describing the results of macroscopic experiments with actual point objects. It is also asserted that particles are treated as spatially structured because they are represented as point centers surrounded by a "cloud" of virtual mesons, nucleons and so on. This "cloud", however, consists of v i r t u a l particles. The latter appear in the modern theory as mere mathematical symbols and are not identified with any real object. Thus, in reality, underlying modern quantum field theory is the point conception.

Another conception is, however, possible. It is based on the fact of the real spatial extension of elementary particles and admits of departures from the principles of quantum mechanics and from certain conclusions of the theory of relativity within spatial regions lying inside elementary particles (and, possibly, in their immediate vicinity). It encounters no objections from materialistic philosophy, and the possibilities to which it gives rise are well worth analyzing.

Which propositions of the existing theory must be modified in order for one of its fundamental postulates to be that elementary particles have spatial structure? Or, in a narrower formulation, how must the existing theory be modified to allow for the organic introduction of a new constant of elementary length?

The objection of the theory of relativity against the spatial extension of elementary particles is based on the well-known theorem which excludes perfectly rigid bodies and signals propagated at velocities exceeding that of light. It is assumed that if, by definition, an elementary particle is indivisible, then its spatially distinct parts can be bound together only like parts of a perfectly rigid body. As such binding is forbidden by the theory of relativity, elementary particles cannot have a spatial extension, i. e., must be point particles.

Thus the theory of elementary particles seems to be faced with a dilemma: either the theory of relativity is correct and elementary particles are point particles, or particles have spatial extension and the theory of relativity is wrong.

The flaw of the above arguments is that in reality perfectly rigid bodies and faster-than-light signals are forbidden not by the actual theory of relativity but by the relativistic theory of space and time and by the p r i n c i - p l e o f c a u s a l i t y. Thus the incompatible propositions are not the theory of relativity and the spatial extension of particles, but rather extension, the principle of causality and the relativistic theory of space and time.

True, a fairly widespread view is that the content of the theory of relativity is equivalent to the content of the postulates on which it is based. It is sometimes suggested that the l i m i t i n g c h a r a c t e r of the velocity of light is such a fundamental postulate. In this case the exclusion of faster-than-light signals is seen not as a consequence but rather as a fundamental proposition inseparable from the content of the theory. At the same time the principle of causality is regarded as organically and inseparably related to the content of the theory of relativity. The inconsistency of this view resides in the fact that all of the actually usable apparatus of the theory of relativity (Lorentz transformations, covariance, four-dimensional world, tensors and so on) can be derived from a different system of postulates without using the assumption of the limiting character of the velocity of light and even, generally, without using the postulate concerning the constancy

of the velocity of light in vacuum. As for the exclusion of faster-than-light signals and perfectly rigid bodies, it can be obtained as a mere theorem following from the principle of causality and the Lorentz transformations[*].

According to a more widely held view, the content of the theory of relativity resides in the new physical ideas concerning space and time that are mathematically expressed by the Lorentz group and consequent four-dimensional geometric ideas of Minkowsky. The postulates of the theory of relativity are only sufficient, but far from necessary, assumptions from which the entire mathematical apparatus of the theory can be obtained. Therefore the fundamental postulates can also fail to express the true physical content of the theory. In particular, the principle of causality which follows from the postulate concerning the limiting character of the velocity of light is merely a supplementary physical hypothesis not related to the essence of relativistic ideas concerning space and time.

In the theory of relativity understood in the sense of the Lorentz group, "perfectly rigid" objects and perturbations propagated at velocities exceeding that of light are possible. This is evident even from the fact that so-called particle-like solutions, which represent, actually, rigid and spatially bounded agglutinations of the field, are possible in nonlinear relativistically covariant field theory; in these agglutinations, moreover, field perturbations are propagated at velocities greater than that of light.

This type of relativistically covariant theory, however, is refuted on the basis of the principle of causality, i.e., the proposition that the temporal sequence of causally related spatially disconnected events cannot be changed by choosing a system of reference, i.e., that causally related events cannot be separated by a space-like interval. The validity of this proposition is established by considering examples which illustrate the absurdity of its converse. It is absurd, for example, that the time sequence of two such spatially disconnected events as the firing of a gun and the arrival of the bullet at the target be reversed. From similar arguments the principle of causality so understood is regarded as an absolute physical law.

In seeking to introduce an elementary length into the theory certain authors have proposed dropping the principle of causality within elementary particles, i.e., at distances of the order of 10^{-13} cm, and considering it valid for large (macroscopic) scales. However, it is easy to show that two events related by a spacelike interval can be separated by a space interval as large as desired by choosing a suitable system of reference. Thus a process taking place with disruption of causality in an interval of 10^{-13} cm can be related to a significantly larger (already macroscopic) space interval in a different system of reference. Consequently the restrictions imposed by the principle of causality cannot be removed by such simplified treatment of the limits of its applicability. A more profound analysis of the proposition known as the "principle of causality" in modern physics is obviously required.

When speaking of spatially disconnected causally related events it is usual to represent them by analogy with the gun-target example, i.e., one is necessarily regarded as the cause and the other as the effect. Further, the cause is necessarily identified with the earlier event and the effect with the later event. Thus causal conditionality is unconditionally related to the direction of flow of time.

* See Terletskii, Ya.P., Konspekt lektsii "Paradoksy teorii otnositel'nosti" (Summary of Lectures on "Paradoxes in the Theory of Relativity"). Moscow. 1962.

Is it permissible, however, to apply a conception of causal conditionality taken from macroscopic experience to elementary processes of the micro-world at intervals of the order of 10^{-13} cm? Yet it is well known that all the laws of motion of the microworld without exception are absolutely reversible in time. That is, for elementary processes the two directions of flow of time are absolutely equivalent. Consequently, as in classical statistical mechanics, the direction of flow of time is distinguished exclusively by the macroscopic process of increase of entropy, which is due to the historically-produced surrounding macroscopic situation and not to the laws of microscopic motion.

It would obviously be more logical to regard the causal relationship of spatially disconnected events occurring in elementary processes as a m u - t u a l c a u s a l c o n d i t i o n a l i t y which does not necessarily presuppose the identification of one event with the cause and of the other with the effect. For such elementary acts the separation of cause and effect may be regarded as conditioned and produced only by the external macroscopic environment.

From this point of view the principle of causality, the statement that time sequence of causally produced spatially disconnected events is invariable, merely designates a law of macroscopic nature which distinguishes a definite direction of flow of processes in time or, as they say, d i r e c - t i o n o f f l o w o f t i m e. But the directionality of flow of macroscopic processes in time is explained exhaustively by the law of increase of entropy or the second law of thermodynamics. Thus from the standpoint of microscopic reversibility of elementary processes there is no reason to regard the principle of causality as a special absolute physical law, and it can be replaced by the second law of thermodynamics (or regarded as a consequence of the second law).

It is not difficult to see that processes which violate the principle of causality violate in equal degree the second law of thermodynamics. It is easy to show, for example, that any signal transmitting information, i.e., negative entropy, will violate the second law of thermodynamics if it is propagated at a velocity exceeding that of light. An absolutely rigid electron would also violate the second law at intervals of the order of 10^{-13} cm. Therefore the introduction of elementary length into the relativistic theory will also come into conflict with the second law, obviously at intervals comparable with this length.

If the second law of thermodynamics had been absolute, i.e., an inviolate law of nature, the restrictions which follow from it would have the same absolute character. The second law however, is a macroscopic statistical law which can break down in fluctuations, which are particularly large in phenomena occurring at small intervals. Consequently, both departures from the second law and processes which take place with its violation (such as the transmission of influence at velocities greater than that of light) are possible. Further, no restrictions are imposed on the space interval between two events connected by a faster-than-light signal or a perfectly rigid connection. For the second law can be violated at any distance. At large distances its breakdown is merely less probable than at small ones. This removes the contradiction which hampered us from adopting the possibility of the breakdown of the principle of causality only at intervals of the order of 10^{-13} cm.

Consequently when the principle of causality is treated correctly the contradictions between the theory of relativity and the spatial extensions of elementary particles disappear. In the region of elementary particle theory "hard" particles, rigid form factors, perturbations moving at velocities greater than that of light and even particles of imaginary proper mass faster than photons are possible. Particles of negative mass, similar to those which were obtained in Dirac's theory and which were also forbidden by the principle of causality, are also admissible. All this is possible, however, insofar as the violation of the macroscopic second law of thermodynamics (i. e., in fluctuations) is admissible*.

Thus we see that rich possibilities can be opened up for elementary particle theory by abandoning a dogmatic stand on the absolute nature of the rule which is called the "principle of causality", and according to which of two causally connected events occurring at spatially separate points, one is necessarily the cause and the other the effect, and, further, the time sequence of cause and effect cannot be changed by the choice of a system of reference.

Thus elementary particles in the relativistically covariant theory can have finite spatial dimensions and a spatial structure, while possessing the property of indivisibility into smaller independently existing parts. Such concepts, however, are difficult to correlate with the orthodox apparatus of quantum mechanics, which was constructed on the concept of point particles. Attempts to introduce spatially extended particles have always led to serious difficulties which could be removed only by departing from the fundamental postulates of quantum theory.

The difficulties presented by the theory of extended elementary particles are entirely regular. For now, in addition to the already known universal constants c and h, it is necessary to introduce a new universal constant, the elementary length l_0, into the theory. Every introduction of a new universal constant has always led to a sharp break with old ideas and rejection of familiar concepts. If the introduction of l_0, as we have shown, does not contradict the principle relativistic covariance related to the constant c, it comes into acute conflict with the principles of quantum theory in their orthodox formulation. Does this not indicate that the time has come for a significant revision of the formulation and content of the principles of quantum theory?

The introduction of the new constant of elementary length into the theory would become simpler if the formulas of quantum theory were seen merely as rules belonging to a special kind of statistical theory which implicitly accounts for the relationship with objects not recorded in ordinary experiments (hidden parameters). The constant h could then be regarded as a quantity characterizing the "thermostat of hidden parameters" which produce the quantum statistical character. The constant h would then lose its character of absolute universal constant as the state of this "thermostat" can change upon transition into other regions of the universe.

In this case at small intervals of the order of 10^{-13} cm the quantum statistical laws can in general change qualitatively, assuming dynamical features. That is, the theory of elementary particles can become a theory of

* The second law can also be violated on a cosmic scale when the gravitational energy becomes comparable with the proper energy of the system (see Ya. P. Terletskii. K termodinamike gravitiruyushchikh sistem (On the Thermodynamics of Gravitating Systems), in the collection "Tezisy dokladov na Pervoi nauchno-metodicheskoi konferentsii po termodinamike" (Theses of Reports to the First Scientific-Methodological Conference on Thermodynamics). Moscow, 1962.

the quasi-classical type. Thus in this theory there would be no need to account for the uncertainty relation, though at the same time this relation would remain necessary for intraatomic and intranuclear phenomena.

From the physical point of view there can be no objection to a theory in which instead of the ordinary uncertainty relation, a relation of the following form, say, would be valid:

$$\Delta p \cdot \Delta q \geqslant \hbar F (\Delta q),$$

where

$$F \rightarrow 1 \ \text{at} \ \Delta q \gg l_0;$$
$$F \rightarrow 0 \ \text{at} \ \Delta q \ll l_0,$$

where l_0 is the constant of elementary length. But such a theory would be quasi-classical at small distances and quantum at large distances.

This situation is natural for any theory which explains the quantum statistical character not by a dogmatic position on the absolute character of the principle of complementarity but rather by the introduction of a "thermostat of hidden parameters". Just as in the theory of Brownian motion nondifferentiability of the trajectory holds only in the approximate variant of the theory valid for relatively large intervals of time, so in quantum theory, which stems from ideas concerning hidden parameters, the nondifferentiability of the trajectory disappears upon transition to very small intervals of time. But nondifferentiability is related to the uncertainty relation, and therefore for very small time and space intervals the uncertainty principle ceases to be valid.

It is natural to take as one's "thermostat of hidden parameters" a system consisting of particles of imaginary proper mass moving at velocities greater than that of light. Such particles cannot be detected by ordinary experimental devices similar to those which are used to record ordinary particles of positive proper mass and energy[*]. Therefore in ordinary experiments these particles actually behave like hidden parameters.

In 1960 we proposed a theory based on the idea of the existence of an "imaginary thermostat" consisting of particles moving faster than the speed of light[**]. The point of departure in this theory is the concept of a certain classical field subject to nonlinear equations which permit particle-like solutions in the form of stable agglutinations of the field. Upon statistical examination of the possible solutions of this kind one finds that the centers of gravity of the particle-like agglutinations move in conformity with the laws of quantum mechanics, if one assumes that the thermostat with which the field is interacting is at an imaginary temperature. Further the laws of quantum mechanics are valid only at intervals exceeding the dimensions of the particle-like agglutinations. Within these agglutinations, i.e., within the elementary particles themselves, the laws of the classical field are operative. The structure of the particles is obtained as a definite distribution of the field within each particle.

The program of a theory of hidden parameters organically containing the spatially structured character of elementary particles and at the same time not in contradiction with orthodox quantum field theory at large (compared with the elementary length) distances can therefore be drawn up without giving rise to contradictions.

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[*] However, one can prove that in principle particles of negative and imaginary proper mass can be recorded by devices working at negative temperatures (see "Le Journal de Physique et le Radium", Vol. 23, No. 11, p. 910, 1962).

[**] See "Doklady AN SSSR" (henceforth cited as "DAN"), Vol. 133, Nos. 2 and 3, 1960.

It is well known that the introduction of hidden parameters for the purpose of explaining the quantum statistical character conflicts very seriously with the conception of the universality and absoluteness of the principle of complementarity and the uncertainty relation (von Neumann's theorem). In admitting hidden parameters we are therefore unavoidably rejecting the uncertainty relation at some level within the elementary particles, i.e., we are virtually returning to the classical ideas.

To many such a return is absolutely unacceptable, for they are used to considering the ideas of quantum mechanics as something essentially new, something which has replaced the old classical ideas. However, physics is now developing at a very rapid pace; what was new thirty years ago is hopelessly outdated today and greatly in need of radical change. The theory of hidden parameters proposes a return to the classical ideas on a new basis i.e., it maintains that the new shift of ideas should come as a negation of a negation. For quantum theory came as a negation of classical determinism. The new theory should come as a negation of the indeterminacy of the concept of complementarity i.e., as a negation of a negation.

This pattern of development in science is evidenced everywhere but particularly so in physics (corpuscular, wave and again corpuscular theory of light; kinetic, phenomenological and again kinetic theory of heat; Galileo's principle of relativity, Lorentz' immobile ether and again Einstein's relativity, and so on). Do the defenders of orthodox quantum concepts have any philosophical or physical ground for believing that the law of negation of negation is not applicable to the development of quantum theory? Clearly only a blind faith in the stability of familiar ideas upholds the belief in the immutability of the concept of complementarity. It is the only argument against the application of the law of negation of negation to the theory of elementary particles.

A CRITERION OF RELATIVE ELEMENTARITY

B. Ya. Pakhomov

"The greatest problem of all in the face
of the variety of particles is to discover
what is the criterion of elementarity."

A. Salam*

By an elementary particle is generally meant a microparticle which does not consist of other particles. From this point of view the atom or atomic nucleus is not elementary; it has been found that they consist of a definite set of elementary particles. The neutron, for example, possesses the ability to decay into a proton, an electron and an antineutrino, yet it cannot be regarded as c o n s i s t i n g of these particles. The existence of an electron in a neutron is not possible; it is not allowed by the laws of modern atomic physics (and in particular by the uncertainty relation), which have been verified on a vast amount of experimental material. Here we see a particularly clear manifestation of the dialectic character of microworld phenomena and of the impossibility of the metaphysical approach to the study of microparticles: the fact that a microparticle decays into other microparticles is not sufficient grounds for stating that it consisted of these microparticles before decaying. Thus in the atomic world there is a set of particles — photon, leptons, mesons, nucleons and hyperons — which are equally elementary although related by mutual transformations.

And yet one has the impression that the existing definition of elementarity already fails to correspond to the present level of knowledge, and that physics has a l r e a d y advanced beyond the limits of this conception of elementarity. Twelve to fifteen years ago it was easier to speak of elementarity. At that time it was really possible to believe that the particles then known, the photon, the electron, the π-meson, the neutrino, the proton and the neutron, were the "bricks" with which all the rest was built, though even then the role of the μ-meson as a "brick" was not understood. Now that over thirty elementary particles related by complex intertransmutations are known, it is perfectly obvious that they cannot be fitted at all into a framework of ideas in which they are seen as the "bricks" with which everything else is made — now too many particles, aside from the μ-meson, fall outside of this framework. The conception of elementary particles which supposes them to be merely the "bricks" of which everything consists has proved to be far narrower and poorer than the real content of the elementary particle world.

* [We have been unable to find the source of this quotation. The only similar remark in the reference on p. 83 is that "it would be truer to say that we do not know at present of a convincing criterion of elementarity" — Trans.]

The complex processes of intertransmutation, creation and annihilation of particles which are regulated by definite laws and "selection rules" (far from all imaginable intertransmutations are accomplished in reality) lead the mind involuntarily to two assumptions.

Perhaps the elementary particles now known cannot generally be ranked together. The marked steplike or cascadelike character of decay processes, the steplike character of conservation laws, valid in some processes and not valid in others, the ability of certain particles to be identical under some processes and not identical under others (proton and neutron, for example) – are not all these evidence that some particles are more elementary than others?* Does not Salam's remark, placed at the beginning of the present article, mean that the problem of elementarity must essentially be solved anew and that the earlier solution is already unsatisfactory? The various hypotheses of "fusion", according to which not all of the elementary particles now known are truly elementary, can perhaps be regarded as a theoretical expression of such doubts.

Already in very ancient times one of the first philosophical ideas was that the ability of bodies to transmute among themselves is proof of the existence of a single substratum; everything is built out of this substrate, and its different states are everything that exists. This thought was made into the foundation of the concept of matter as a single source of all things.

Our task does not include an examination of the development of the concept of matter. The important point here is that the ability of microparticles to transmute among themselves gave rise perfectly naturally to the idea of the existence of some single basis, or, if one pleases, fundamental principle, of all elementary particles. Can not all known elementary particles be treated as various states of a single primary matter? Such was the program planned, from slightly different points of view, by the outstanding physicists of our century and in particular by Heisenberg.

If this is so the definition of elementarity given at the beginning of the article immediately requires significant correction: elementary particles cannot consist of other elementary particles, which are members of the same family, but all consist of something different and more elementary and in this sense are only relatively elementary.

A profound analogy can perhaps be drawn with the concept of the chemical element: all molecules consist of atoms but atoms do not consist of atoms and in this sense all atoms are equally elementary (a fact which is reflected by the concept of the chemical element). Atoms in turn are composed of common structured elements (which explains their ability to transmute into each other) and, from this standpoint, are only relatively elementary. Some may be regarded as simpler and others as more complex with respect to structure and to the method of combination of whatever it is they consist of.

The outstanding recent achievement of elementary particle physics has been the breakthrough into elementary particles – the discovery of the complex internal structure of nucleons and, later, of other elementary particles. The internal structures of elementary particles are dissimilar; this fundamental fact obliges us to analyze critically the concept of elementarity once

* See Salam, A. "Elementary Particles". Contemporary Physics 1, 337, 1960.

again, this time from a new point of view, for microparticles are unques-
tionably only relatively elementary.

However, when one applies oneself carefully to a critical analysis of
elementarity from the different standpoints of the "fusion" hypotheses and
unified field theory, one is led to the view that they are (to a certain extent)
contradictory. The possibility of constructing all elementary particles in
the same way from a primary field implies that all elementary particles
without exception are qualitatively similar and have the same affinities.
The idea that some of the known elementary particles are more elementary
than others (particularly when the "fusion" hypotheses are taken into ac-
count) implies that elementary particles are internally dissimilar and of
different kinds and that they are divided into groups associated among them-
selves by different affinities. This can be expressed graphically with the
help of a schematic diagram (Figure 1).

As the aim of scientific investigation has always been to reflect reality
such as it is objectively, and not such as one would wish it to be for mathe-
matical or esthetic reasons, one might justifiably ask whether the ele-
mentary particle world is really in "one" inner nature and properties. Are
there no facts to show that elementary particles are internally dissimilar
and of different kinds, that there is not one unified family but several?

The construction of all particles in an identical manner from a unified
field is possible if their internal similarity is truly profound, impossible
if there is internal diversity. The conception of universal unity in dialec-
tical materialism is substantially different from ideas concerning universal
unity in metaphysical materialism. From the standpoint of dialectical ma-
terialism the material unity of the universe is the unity of qualitatively dif-
ferent kinds of matter and forms of motion of the latter; thus intertransmu-
tations (unity) are seen as fundamental qualitative changes (dissimilarity).
From this standpoint the problem can alternately be formulated as follows:
is the microworld a single form of motion of matter or is it, in turn, the
contradictory unity of qualitatively different forms of matter and qualitatively
different forms of motion of the latter? It is in this sense that the problem
of the existence of internal dissimilarities in elementary particles will be
taken in the present article.
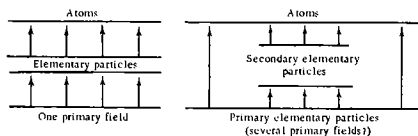
FIGURE 1

As we see it the problem of the criterion of relative elementarity should
be solved from the following point of view: if all microparticles are relat-
ed to a single qualitatively distinct form of motion of matter, they may be
regarded as equally elementary (relatively elementary, of course). If there
are several qualitatively different forms of motion of matter, the more ele-
mentary particle will be the one associated with fewer qualitatively different

forms of motion and the more complex particle the one which includes the greater number of forms of motion. The applicability of this criterion to the determination of the relative complexity of social life and biological processes, biological and chemical processes or chemical and physical processes is evident. It is hardly surprising that the first sign by which one can detect the presence of qualitatively different forms of motion of matter is the character of the interaction inherent to these forms. The uniqueness of an interaction is directly related to the uniqueness of the laws which govern the given form of motion of matter; this fact has already been proved sufficiently well by the historical experience of the science. Finally, the well-known irreducibility of one qualitatively distinct form of motion of matter to another implies that the forms of motion are relatively independent of each other. Related to this is the relativity of rest – the conservation of a given form of motion for a known variation of the other forms of motion*.

Using these features, let us assail the world of elementary particles. It has long been known that there are three essentially different types of interaction in the elementary particle world: electromagnetic, strong and weak interactions (not counting a fourth, the gravitational interaction). The electrons in the atomic shell are held by the positively charged nucleus owing to electromagnetic interaction. But how are the positively charged protons, which can only be repelled by electromagnetic interaction, held in the nucleus? Obviously, so physicists decided about thirty years ago, forces of attraction o t h e r t h a n electromagnetic are at work between protons and neutrons, forces, moreover, substantially stronger, though operative only at short distances (Figure 2).**

The study of nuclear forces has uncovered very interesting facts. The nuclear forces active between two protons, two neutrons or a neutron and a proton are identical (charge independence of nuclear forces). This gives us the right to treat particles different with respect to electromagnetic interactions as identical with respect to nuclear forces (proton and neutron). In addition to short range, a distinguishing characteristic of nuclear forces is the property of saturation.

What we see here is a manifestation of the typical features of the qualitative difference between form of motion: difference in the character of the interaction (a quantitative difference associated with the difference in the inner nature of the forces themselves), difference in the character of the regularities (the law of nuclear forces has still not been found in exact form), the relative independence of different forms of motion (relative independence of nuclear and electromagnetic interactions, manifested, in particular, in the charge independence of nuclear forces).

There is yet another interesting fact. The annihilation process $e^+ + e^- \leftrightarrows 2\gamma$ is obviously electromagnetic; the process of annihilation of a nucleon and antinucleon is known, but the reaction $e^- + p^+ = 2\gamma$ is impossible. Why? The latter contradicts the law of conservation of the number of heavy particles and of the number of light particles but, of course, conservation laws express only the features of the internal nature of particles. Both the proton

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* On this problem see K e d r o v , B. M. O sootnoshenii form dvizheniya materii v prirode (Relationship between Forms of Motion of Matter in Nature), in the collection "Filosofskie problemy sovremennogo estestvoznaniya" (Philosophical Problems of Modern Science), Moscow, 1959; and also "Osnovy marksistskoi filosofii" (Foundations of Marxist Philosophy), Ch. III, § 2, Moscow, 1962.

** The physicists in question were I. E. Tamm and D. D. Ivanenko, and later H. Yukawa.

and the electron have an electric charge, and the proton has precisely the same charge as the positron annihilating with the electron; yet they are incapable of mutual annihilation. While similar in one respect, in the ability to carry electric charge, they are significantly different in another. Their internal nature is on the whole significantly different.
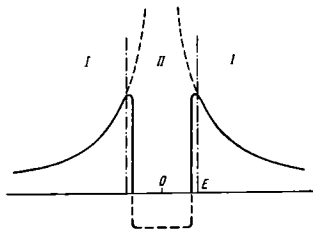
FIGURE 2. Variation of the nature of the interaction between two protons as a function of their distance

I — region where electromagnetic processes are important; II — region where nuclear forces are important (protons are attracted mutually despite forces of electromagnetic nature $OE \sim 10^{-13}$ cm).

Let us attempt to go further. It is significant that all decays of unstable particles (with few exceptions) take place owing to the so-called weak interaction. "It is surely remarkable that all the weak processes have the same strength and it is probably significant. Nature is trying hard to tell us something, but so far we have been unable to decipher the message"[*]. The quantitative identity of the force of weak interaction for a wide variety of different particles is certainly evidence of the unity of the weak interaction, just as the identity of electric charge for all particles is evidence of the unity of the electromagnetic interaction for different particles. At the same time, comparison of the weak interaction and other particle interactions brings out the nonuniformity and qualitative contrast between the processes of the microworld.

While the characteristic time of strong interactions is estimated to be 10^{-23} sec, and that of electromagnetic interactions 10^{-21} sec, the characteristic time of weak interactions is 10^{-9} sec! The colossal quantitative difference(12-14 orders of magnitude), in view of the well-known law of dialectics, is already enough to imply a profound qualitative difference. A well-known precedent is the difference between chemical and nuclear reactions (energy difference of 6 orders). Here the qualitative difference is due first and foremost to the difference in the nature of the material structures responsible for the processes, and, correspondingly, to the difference in

[*] Gell-Mann, M. and E.P. Rosenbaum. "Elementary Particles", Scientific American, 197, 72, 1957. [It should be pointed out that the quotation from the Russian translation (UFN 64, 404, 1958) differs substantially from the original. The Russian has "... perhaps very deeply significant" instead of "...probably significant", and "...tell us something very important", instead of "...tell us something". —Trans.]

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spatial scales (roughly of the same order of magnitude). In chemical processes nuclear structure is not affected at all, and in nuclear reactions chemical bonds are too weak to exercise any influence. Owing to all these circumstances, chemical and nuclear reactions are relatively independent and subject to different laws.

However, there are also direct facts which confirm that the weak interaction differs from other interactions not only quantitatively but also qualitatively. The first is the fact that the weak interaction stands by itself as a special, peculiar type of interaction. It is well known that the theory of weak interactions is as unique as the theories of strong and electromagnetic interactions; thus the success of the one is measured relatively independently of the success of the other (the theory of electromagnetic interactions is well developed, that of weak interactions satisfactorily developed, and that of strong interactions even less developed). The pronounced contrast between the conservation laws of the different interactions is striking: strong interactions obey the law of conservation of isotopic spin, which is only partially applicable to electromagnetic interactions and completely inapplicable to weak interactions. The law of parity conservation, mandatory in strong and electromagnetic processes, breaks down in weak interactions[*].

The relative independence of the weak interaction and the other interactions comes out unambiguously, which is not surprising if we recall the difference of 12–14 orders. One such fact is the stability of the neutron under strong interactions (a neutron inside the atomic nucleus behaves as a stable particle) and its instability under weak interactions, manifested when the neutron does not participate in the strong interaction, i.e., is a free particle. If we recall that the majority of unstable elementary particles owe their decay to the weak interaction, we may suppose that all of these, like the neutron, become stable when the strong interaction is "turned on". This is precisely the kind of fact which led Salam to believe that the same particles are more elementary (are identical) under certain processes and less elementary (display differences) under others, and that with respect to a definite type of interaction some particles are more elementary than others[**].

One of the most general laws of cognition is transition from cognition of the character of interactions to conclusions concerning internal structure. This has been true in the cognition of the microworld, starting from the recognition of the atomic structure of electricity and Rutherford's classic experiments, and ending with modern research on the structure of elementary particles. Obviously, such transition is a law of cognition only because such is the general pattern of nature itself: the character of interactions and the properties of things are determined by their internal structure. In turn it can be assumed that the internal structure of a thing is determined by the properties of structural elements and the nature of the interactions of these elements.

An insufficiently clear understanding of the dialectics of this dependence (precisely of its dialectics – the presence of qualitative critical points, transformation into opposites, and so on) leads to paradoxes. One paradox, for

* See Marshak, R.E. and E.C.G. Sudarshan. Introduction to Elementary Particle Physics. Ch. I, §3. Interscience, New York. 1961.
** See Salam, A. Op. cit.

instance, is noted by Salam: "If the electron is indeed a charged sphere (an assumption which, as Salam notes, explains its mass and size – B. P.), why does it not explode on account of the electrostatic repulsion of various parts of it?"* The dilemma seems insoluble, yet approaching the problem dialectically one can pertinently ask: why, really, in representing the electron as a structured particle, must we assume that its structural parts themselves have charge and are electrostatically repelled, i. e., have all the properties of the whole? Wouldn't it be more correct to assume that electric charge and electrostatic attraction and repulsion are integral properties of the electron which its structural elements do not necessarily have? On the philosophical plane this has been known from acnient times. The following modern examples can be cited. The phenomenon of life is an integral property of the organism but is not extended to the structural elements of the living cell or to the molecules, despite the fact that the interaction of molecules is of great aid in understanding the origin of the integral property itself. Another example of an integral property, i. e., one which is present in the whole but lacking in its parts, is thinking.

Thus the possibility of a given type of interaction is unquestionably dependent on the internal structure of the particle. However, the photon has only one interaction (electromagnetic) and the neutrino only the weak interaction. Could their structures be of the same type, qualitatively identical (especially if one takes into account the fact that the interactions themselves differ in strength by twelve orders and are distinct as to the laws they obey)? Doubtful. More likely we are dealing with qualitatively different material structures, forms of matter and forms of motion not reducible to each other.

The neutrino has only one interaction while the electron has two (weak and electromagnetic). Can one assume that the material structure of the electron is qualitatively uniform, unified? Hardly, especially if one takes into account the fact that the electromagnetic radius of the electron is of the order of 10^{-11} cm while the characteristic length associated with weak interactions is of the order of 10^{-17} cm, and also the difference in the time and energy scales of these processes as well as, of course, the specific traits of their regularities. More likely in the case of the electron we are dealing with the unity of qualitatively different material structures, forms of matter, and forms of motion. But then the electron must be a more complex particle than the photon or neutrino, which can be regarded as more elementary than the electron.

From this point of view particles having all three types of interaction, as the π-mesons, for example, are still more complex. For in their structure they must have a region responsible for electromagnetic interactions, one for strong interactions and one for weak interactions, differing from each other in energy relations, space-time scales and character of the interaction (Figure 3). In this connection it would be interesting to determine whether there exists a particle specific to strong interaction (specific in the sense in which the neutrino is specific to weak interaction, i. e., a particle which has only the strong interaction). Is not the ω-meson, which decays into three π-mesons within 10^{-22} sec, i. e., apparently in strong interaction, such a particle? It would also be interesting to determine, on the other hand, whether there exist in nature particles which have only electromagnetic

* Ibid.

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and strong — or strong and weak — interactions. Should it be found that there are no such particles, the mutual relationships between types of interactions would perhaps be clarified.

At this stage in the investigation of the structure of elementary particles physicists accustomed to precise means of expression speak of the investigation of the electromagnetic structure of particles, a structure which happens to be spatially nonuniform. One can apparently speak of "strong"

ν	γ	?
1	2	3
e μ	?	?
1+2	2+3	1+3
π p n K Λ Ξ Σ		
1+2+3		

●   Structure responsible for weak interaction

⊛   Structure responsible for strong interaction

⬭   Structure responsible for electromagnetic interaction

FIGURE 3

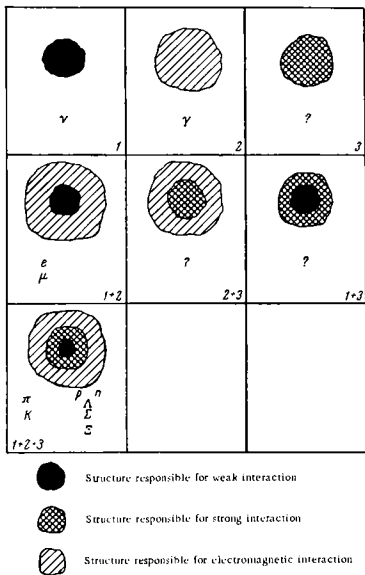and "weak" structures of elementary particles. Because they are responsible for strong and weak interactions these structures must be studied by way of these interactions.

When accounting for the relative independence of processes associated with qualitatively different forms of motion, one can assume that the corresponding structures are also relatively independent and different, therefore, in nature.

In his time de Broglie proposed a hypothesis according to which the photon is regarded as consisting of two "fused" neutrinos. Is not the criterion which has been suggested undermined by this? We note first of all that a classification of particles based on the possibility of different types of interaction represents particles capable of only one interaction as essentially not susceptible of comparison with respect to degree of elementarity. Which is more complex, the photon which has only the electromagnetic interaction or the neutrino which has only the weak interaction? In our opinion the problem is not so much that the criterion itself is insufficient, as that our knowledge concerning the internal nature of elementary particles is insufficient. When physics penetrates further into the microworld and reaches the sub-microscopic level it will doubtless be possible to discover the origin of microscopic properties and establish the internal relationships linking the three types of interaction; however, this will hardly mean a r e d u c t i o n of some forms of motion to other forms.

Let us return to the "fusion" hypotheses. Two particles fuse and as a result we have something new, with new integral properties not present earlier. But then what is the nature of the process of "fusion"? It must be highly specific — one cannot so easily get rid of the qualitative uniqueness of the photon as compared with the neutrino. Qualitative diversity cannot be removed in this way; it can only be supported and to a certain extent explained. In particular, should the development of fusion hypotheses prove successful one can expect to have to deal with the existence of several qualitatively different types of fusion.

If particles are classified according to their capability for different types of interactions, the difference in the number of the particle families becomes in general more clear. Particles with a uniform structure (i. e., having one type of interaction) do not, of course, display outstanding variety: one photon, two neutrinos with their doublets, the antineutrinos. Particles with two types of interaction, which have a more diversified and complex structure, can be constructed in a greater variety of ways, and we truly have a two-member family, the electron and the μ-meson with their antiparticles. We call attention to the fact that all other properties of the electron and muon are so nearly identical that their deep internal affinity is undebatable.

Particles having three types of interaction can be constructed in even greater variety, with their triplet structure; it is apparently no accident that the family of π-, K-mesons, nucleons and hyperons is so numerous. One immediately notices the profound affinity between the "strong" particles and at the same time the deep gap separating them from leptons. The "strong" particles fit comfortably into the systematics proposed by Gell-Mann and Nishijima, but this systematics does not extend to leptons. In the case of the "strong" particles physicists can tell why there are so many of these particles and predict what particles may yet be discovered; however, there are as yet no such predictions for leptons. The concepts invented in order to reflect the properties of "strong" particles — isotopic spin, strangeness do not apply to leptons. A specific law of conservation of the baryon charge is valid for "strong" particles whereas leptons have their own special conservation law (conservation of lepton charge).

It is universally known that the behavior of elementary particles belonging to different families is described by completely different equations. This is not surprising, for the behavior itself is substantially different

from particle to particle. It will not be surprising at all if it turns out that the internal structure of particles in general is not subject to any single equation common to all particles – that it is impossible to construct all particles in the same way from some unified field; nature is materially one but it is not fond of monotony.

SPACE AND TIME

A PHILOSOPHICAL EVALUATION OF MODERN IDEAS
CONCERNING THE PROPERTIES OF SPACE AND TIME
IN THE MICROWORLD

S. T. Melyukhin

So far there exists no fully-developed physical theory of space and time in microphenomena. The theory of relativity, which was based on a generalization of classical electrodynamics and of some experiments in the realm of microphenomena, characterizes the properties of space and time primarily in the region of macroscopic processes and tells us very little about their features in the microworld. Modern elementary particle theory also fails, at least so far, to give a complete picture of space-time relations in this region. Nevertheless modern ideas concerning space and time in the microworld already contain a number of philosophical problems of fundamental significance for all understanding of the microworld.

In the present article an attempt is made to analyze the philosophical significance of modern ideas on space and time in the microworld, and also to establish the correlation between their general and their specific properties.

Space and time are the principal forms of being of matter; they are inseparable from its existence. Their fundamental properties are determined by the laws of motion and interaction of material objects and must therefore be derived from them. The concepts of space and time are among the most general concepts and cannot be defined in a formal-logical way (by supplying a broader concept). Definition is possible only by indicating the relationship of space and time to matter as substrate underlying all changes, and also by establishing the relationship between space and time and such general properties of matter as motion and interaction. We can then define space in its most general form as that form of being of matter which expresses the extension of all objects and systems existing in the universe. By extension here is meant the property of a body to occupy a definite volume, a properly conditioned by the s t a b i l i t y o f t h e b o n d s between different material formations in the structure of this body. Extension characterizes the stability of coexistence and distribution of the elements in the structure, which is conditioned by the character of the internal bonds in the system. Time is that form of being of matter which expresses the duration of existence of material objects and events, as well as the order of succession of states and cause-effect relationships in all existing phenomena. Duration expresses the continuity of existence of an object, the order of its stay in proper being, including the succession of certain of its states by others.

The spatial extension of material objects is a function of their interaction. In any solid, liquid or gas, definite form or dimensions are the result of

interactions between the elements composing the given object, and between this object and other surrounding objects.

This interaction is the union of opposite processes (attraction and repulsion, absorption and emission of quanta of different fields, association and dissociation of structural elements in the system). If only the forces of repulsion and emission were to prevail, the body could not exist in stable form and would decay into a countless multitude of microobjects, which would tend to move away from each other to the greatest possible distance. On the other hand, if only the forces of attraction were to prevail, microparticles would fuse and the dimensions of the body would decrease by a factor of 10^{-14} (or possibly more), because the union of the opposing forces of attraction and repulsion is apparently also valid in the structure of elementary particles. Thus in the case of definite spatial extension of a body, one finds r e l a t i v e   s t a b i l i t y of distribution of the elements in its microstructure. Without stable internal bonds bodies would not have stable spatial properties.

Differences in the extension of bodies are also due to interaction and are physically detected owing to the finiteness of the rate of propagation of interactions. Since, according to the theory of relativity, this speed cannot exceed the speed of light in vacuum, a certain time is always required for a change in matter in some region of the system to cause a corresponding change in other regions. The separation of these changes in time expresses, from the physical point of view, the extension of the bodies; the greater the interval of time between changes, the greater this extension. Were the rate of propagation of interaction infinite, all changes would take place simultaneously i n   a l l   s y s t e m s and differences in their extension would not be detectable in interactions.

It follows from this that the essence of spatial relations and the space-time metric must be derived from the stable bonds in the system, and that precisely a consideration of these bonds should be the physical basis on which to construct a geometry of space of the corresponding systems. In the microworld, where the bonds and interactions of microparticles differ substantially from the bonds of macroscopic bodies, the space-time metric should also be different.

Looking ahead somewhat we note that elementary particles have exceedingly stable internal bonds. For this reason it is entirely likely that their space-time properties also possess great stability and, possibly, a certain discreteness, which is reflected in the idea of space-time quantization.

To understand the specific character of space and time in the microworld, it is first necessary to consider the very important properties of space and time inherent in all states of matter at all possible scales of existence of matter.

From the standpoint of philosophical materialism, the first major property of space and time is their objectivity, their independencé from human cognition or any cognition at all. This is a concrete expression of the principle of the material unity of the world, according to which there is nothing in the world aside from moving matter, its various forms, manifestations and properties, as well as the various expressions or states of these properties.

Another very important feature of space and time is their continuity. The continuity of time is a natural consequence of the indestructibility of matter and motion. Matter, the basis of all changes occurring in nature,

has always existed and will go on existing. It cannot be created from anything, nor can it vanish; it can only change from one state to another. Its motion and interaction are also uncreatable and indestructible. This continuous existence of matter, its constant motion, is reflected in the continuity of time. Before a material system can pass into a given state referring to a definite instant in time, it must pass through all the pre-existing states and corresponding instants in time. All changes and inter-actions in matter take place in conformity with the principle of c o n t a c t a c t i o n, which is a natural and necessary consequence of the law of con-servation of matter and motion, and also of the principle of causality. "Skipping" definite states and instants would imply a breakdown of these laws and is therefore impossible.

The continuity of space is closely related to the continuity of time. The propagation of interaction and variation of the states of matter by the con-tact-action principle implies that to any change, however small, in the structure of matter corresponds a small change not only in time but also in space. A change occurring in time but not in space is not possible. This results from the fact that in every motion a change takes place in the in-ternal as well as external bonds of the system, which necessarily include spatial relations. Even if we assume that the body is at rest and does not change position with reference to the surrounding objects, even so its vari-ation is not only temporal but also spatial. Firstly, the state of rest is relative, and a body at rest with reference to the immediate environment is moving with reference to more distant bodies in cosmic space. Secondly, a body at rest never ceases to interact with other bodies. This interaction is effected by means of the quanta of the, say, electromagnetic or gravi-tational fields. In absorbing and emitting the given quanta the body ex-changes, so to speak, a certain part of its constituent matter with other bodies, and thus the given matter undergoes spatial change.

Thirdly and finally, in a body at rest the motion of its component mi-croobjects – molecules, atoms, elementary particles and so on – never ceases.

The above applies equally to all moving bodies. Thus every change takes place not only in time but also in space, and the continuity of time entails the continuity of space. The discreteness of space-time properties is a relative property, while their continuity is absolute, inherent in all states of matter.

Among the general properties of space one of the most fundamental is its three-dimensionality, which expresses the extension of bodies in three mutually perpendicular directions.

The concept of many-dimensional space is widely used in mathematics, but it must be mentioned that its meaning is completely different from that of the concept of ordinary space. Here the concept of space is frequently used not only to express the extension of bodies and the distances between them, but also to characterize the relationships between the properties of bodies when all these properties are combined in the concept of an n-dimen-sional space and corresponding values of the properties as points in this space. Let us assume, for example, that we are investigating a mixture of several gases and the values of the temperature T, pressure P, density ρ of each gas, percent content C_1, C_2, and so on. The relationship between these quantities can be represented in the form of tables or graphs. Ano-ther possible mode of description, however, is one in which the set of

quantities T, P, ρ, C_1 and C_2 is defined as a five-dimensional space and the values of the corresponding properties of the gas are expressed in the form of points in the given five-dimensional space. The geometric analogy is made use of here to explore the relationship between the properties of the system under investigation because the relations between them are similar to spatial relations.

The concepts of momentum, configuration, Hilbert and other spaces are introduced in physics to describe the interactions of elementary particles. Such spaces are many-dimensional. Here, in addition to the three usual coordinates which characterize the positions of the particles, such other properties as momentum or isotopic spin are taken to be the fourth or fifth coordinate. This mode of description makes it possible to use geometrical methods to investigate a wide variety of phenomena. However, this kind of abstract space should not be identified with real space. The use of the concept of space here is, strictly speaking, somewhat artificial, for the same concept is being used to characterize properties of bodies completely different from spatial extension.

All known forms of matter – cosmic systems of various orders, macroscopic bodies, molecules, atoms, elementary particles and fields – are three-dimensional structures; the three-dimensionality of space, moreover, is the necessary condition of their motion and interaction. There are no grounds for believing that material objects having a different number of dimensions exist at other scales in the microworld or cosmos.

Let us now consider some of the fundamental properties of time.

One of the most important properties of time, its one-dimensionality, is related to its irreversibility and asymmetry. This character of time is closely related to the irreversibility of cause-effect relations, which follows in turn from the inviolability of the laws of conservation of matter and of its most important properties. The reverse flow of time, from future to past, would be possible only if the cause-effect relationship of events could be inverted, i.e., if the effect could precede its cause. But then all laws of conservation of matter and of its properties, as well as the principle of causality itself, would be violated.

However, the steadfastness of these laws is confirmed by all the achievements of science and technology, and therefore the idea of a reverse flow of time has no objective bases.

The irreversible change of time from past to present holds in every space reflection of events.

This proposition is, however, not universally recognized. Certain authors admit of the possibility of time reversal in microprocesses in the belief that time may have mirror symmetry in the microworld, as does space. From the formal standpoint this assumption is based on the fact that in Schroedinger's equation – as well as in the equations of classical mechanics – the sign of time can be changed but the equations retain the same form, i.e., are invariant under time reversals. This reversal has been objectivised and transferred to real time.

The idea of time reversal has also been used to explain the properties of the positron. Thus analyzing Dirac's relativistic equation Feynman puts forward the view that the positron is an electron moving backward in time[*]. This gives a satisfactory description of the properties of this particle.

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[*] See Feynman, R. P. Theory of Positrons. Phys. Rev., Vol. 76, No. 749, 1949.

The fact that results agreeing with earlier experimental data are obtained from a hypothesis does not in itself prove that the given hypothesis is valid. There are many cases in science where phenomena were sometimes successfully described by a hypothesis which was later rejected. In the thirties, for instance, Dirac suggested that the creation and annihilation of electron-positron pairs could be explained by postulating an unobservable background of electrons of negative energy, the "holes" in which would correspond to positrons. Although this hypothesis led to results in agreement with the experimental data, at present it can no longer be regarded as satisfactory. The problem is that the existence of this kind of background requires that particles obey Pauli's principle and Fermi statistics. Processes of annihilation and creation of pairs by photons are also possible in the case of π-mesons and certain other particles which have integral spin and obey Bose-Einstein statistics. As Pauli's principle is not applicable to them, there can be no such unobservable background for these particles. Yet meson creation and annihilation is completely analogous to processes with electron-positron pairs. Hence it follows that the idea of a background is not the only possible description with respect to electrons and positrons. Evidently we are dealing here with the more or less accidental coincidence between the mode of explanation and the results of the described event, whereas the event itself is of a completely different nature. This applies in even greater measure to Feynman's hypothesis, which cannot be considered satisfactory because reversal of time and of the cause-effect relations leads to violation of the fundamental laws of nature.

The irreversibility of cause-effect relations in any given phenomenon does not mean that causes and effects cannot become interchanged (in their action) over significant time intervals and for different phenomena. Such reversibility is very often observed in systems with feedback. For instance, in a cybernetic system functioning on the basis of feedback, changes in the control device A can cause a change in the operating device B. The latter sends a signal concerning its state to the control device, and this device emits a new command signal corresponding to the situation. Here the cause and effect become interchanged. A gives rise to the change B and B conversely influences A, and so on. But in all such cases the cause and effect are interchanged only for more or less significant intervals of time and in different phenomena. The control device is not the same after reception of the signal, it changes, and the same occurs in the case of the operating device. In reality, different causes and effects of phenomena developing in time are changing place here. But for the same phenomenon the interrelation between cause and effect is always irreversible, in conformity with the principle of causality and the laws of conservation.

What physical significance does the possibility of changing the sign of time in the equations have in this case? It is the peculiar reflection of the possibility of reversible processes in a system. If a system goes through the states 1, 2, 3, 4, ... 10 and so on in its evolution, the possibility of reversing the sign of time in the equation is equivalent to recognition of the fact that the system can go through the same sequence of states but in the reverse direction – 10 ... 4, 3, 2, 1.

Reversible processes are frequently encountered in nature; examples are evaporation and condensation of liquids, the intertransmutation of particles. In all these processes, however, reversibility is not complete, but necessarily contains a certain element of irreversible change. This is due

to the fact that every system is open and emits energy into space, owing to which there is a change in its state. Further, matter is infinite in depth, and every system consists of an infinite set of elements of matter of highly diversified nature. The number of possible combinations and associations of these elements is infinite and cannot be fully realized in any finite interval of time.

It should also be borne in mind that every microparticle or other material system fits into a system of still higher order in which the flow of time proceeds owing to irreversible changes in a direction from past to future. This "external" time exerts, so to speak, an influence on processes in the microstructure of matter and gives rise to irreversibility of time in this region as well.

Thus every phenomenon in nature is asymmetric in time. Irreversibility is a very important property of time at all levels of structural organization of matter, because it follows from the fundamental laws of existence and interaction of matter.

A very important property of matter and of its forms of being is their infinity in the quantitative and qualitative senses. The quantitative infinity of matter is expressed in the presence in it of an infinite number of properties and relations, in the inexhaustible complexity of its structure and also in the possibility in principle of its infinite division. The latter means that matter is continuous; as the substance of all changes it exists and displays its properties in any space and time scale, however small or large. Between any two points on the number axis one will always find an uncountable set of other points and corresponding real numbers, the totality of which forms the spatial continuum. To every infinitesimal volume of space can be juxtaposed a certain element of matter, and such an element will always be found, because matter with its properties is the only existing reality. This does not mean, of course, that matter displays the same properties upon unrestricted division. Every concrete property, like every concrete form, is finite. Starting from certain scales quantitative changes lead to qualitative ones, when earlier specific properties lose their significance and the transition to objects with totally different properties is complete. The infinity of matter in depth is therefore qualitatively nonuniform and supposes various levels of structural organization.

On a cosmic scale the quantitative infinity of matter is reflected in the fundamental openness of all systems existing in nature and in the unlimited extension of matter in the direction of increase of scale. The real volume of matter in the universe can be represented by the infinite set of arbitrarily large units of volume. However large the dimensions of a material system are, one will always find a system or set of bodies of still higher order which will include within itself the first system as one of its elements. All existing systems are open and the various emissions which appear in them are capable in principle of being propagated over any distance however large. In this connection we should point out the untenability of assertions made by certain cosmologists to the effect that the metagalactic space surrounding us is closed. In no material system are there forces capable of retaining all the emission (electromagnetic, gravitational, neutrino and other forms) which arises there so as to enable the emitted quanta to return to the initial region after a certain time. On the contrary, the

qualitative inhomogeneity of the distribution and structure of matter has the result that a definite part of the emission is necessarily propagated beyond the confines of the given system, exercising an influence on other systems in yet larger spatial scales. Closed spaces are only a mathematical abstraction; they cannot be realized physically. The infinity of the universe is indeed expressed in the fundamental openness of all systems and in the possibility of unlimited propagation of the emissions arising in these systems to ever larger regions. This infinity, moreover, is far from being "wrong", as maintained by certain authors. Denial of the infinity of the world at all space and time scales would be more "wrong", more in contradiction with logic and physical principles. The so-called "wrong" infinity (a concept introduced by Hegel) is a uniform quantitative infinity which presupposes external repetition of the same properties and laws of motion of matter at all scales, i.e., which absolutizes all concrete qualities. Such repetition is not realized in nature since the infinity of the world is qualitatively nonuniform. But it would be totally wrong to repudiate the quantitative infinity of matter in space on the basis of the concept of "wrong" infinity.

The quantitative infinity of matter is inseparably related to its qualitative infinity. The latter is expressed in the fact that there exists in the world an uncountable number of qualitatively different levels of structural organization of matter, at each of which matter possesses specific properties and obeys particular laws. Quantitative infinity is also expressed in the possibility of unlimited transformations of matter from one state to another in the course of time.

Several levels of objects are known at the spatial scales accessible to modern measuring devices: elementary particles, atoms and molecules, macroscopic phenomena, cosmic systems of various orders.

Quantum relations, which presuppose discreteness of action and many important properties of microparticles, prevail in the microworld. In the region of macroscopic phenomena of the everyday world the changes in inorganic bodies are subject to the laws of classical mechanics, thermodynamics, optics and so on, while at the scale of giant cosmic systems qualitatively new laws, expressed in the general theory of relativity and in the cosmology based on it, become operative.

Moreover, the qualitative difference between levels is also determined by the character of the operative forces. In atomic nuclei the principal forces controlling their qualitative stability are the π-meson forces; the stability of atoms, molecules and also solids and liquids is determined for the main by electromagnetic forces, whereas the stability of cosmic systems is determined by gravitational forces.

It can be assumed that qualitatively new laws and properties of matter, different from the known ones, will be discovered at other scales (smaller than 10^{-13} cm and greater than 10^{27} cm), and that the number of corresponding levels can be as great as desired. It would therefore be wrong to extrapolate specific laws or properties of matter to all possible scales. Thus there are no grounds for extending the conclusions of the theory of relativity to scales smaller than 10^{-13} cm, as is sometimes done, and defining it as the theory of every space and time. At smaller scales space-time relations may be such that the theory of relativity is not applicable to them. Inferences drawn from extrapolation are always of probabilistic value; further, the greater the extrapolation from the direct experimental data (or

from the content of the general laws of being which have been confirmed by all the data of science), the smaller-the validity of conclusions drawn from the extrapolation.

With respect to space, qualitative infinity is expressed in the difference between the metric properties of space at different scales, in its dependence on the character of the bonds and laws operative under the given conditions. In particular there can be differences in the curvature of space, in the relationship between different elements of geometric figures; in the microworld the spatial dimensions of a number of microobjects may be discrete, and so on.

With respect to time, quantitative infinity is expressed in eternity and unboundedness in past and future, as well as in the possibility of infinite division of all intervals, which is conditioned by the continuity of time as an absolute form of existence of matter.

But it would be wrong to represent the eternity of the world as an infinite monotonous duration, perfectly uniform at all its stages in the character of the changes which take place. The world has not always been in the state in which we now observe it. In any cyclic process in the cosmos there is an element of irreversible change. Therefore in the course of time qualitative transformations of matter from some forms to others — and corresponding modification of the functional form of the specific laws of nature which characterize their constants and parameters — are in principle possible*. In this unlimited character of the qualitative transformations of matter we see the expression of the qualitative infinity of time.

The infinity and diversity of the world should not furnish grounds for purely speculative conclusions such as the statement that, starting from certain scales, all properties and laws of motion of matter which we observe in the world surrounding us vanish completely, and that at these new scales the concepts of space and time are not applicable, the law of conservation of energy does not operate, and so on. It is necessary to distinguish between the particular and the universal properties of matter, the specific functional laws and the universal dialectic principles of being which have no functional or mathematical form and are not restricted by definite parameters or constants. If the former are operative only at definite scales, the latter are manifested wherever matter exists, for they express the internal content of its existence.

Of universal significance are the principle of causality, the law of conservation of matter and motion, the dialectic laws of development (of unity and the struggle of opposites, of mutual transition of quantitative and qualitative changes), the law of negation of negation, which expresses the relationship between cyclicity and progression in development. Also universal are the principles of dialectical materialism, which characterize the relationships between the finite and the infinite, the continuous and the discontinuous, the essence and the phenomenon, the form and the content, the possibility and the reality, and so on.

The existence of such general laws has a significance of principle for the understanding of the world, as it allows the establishment of a direct connection between the various levels of structural organization and assists in transition from the known to the unknown. Analogously, if we know the

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* For greater detail see Melyukhin, S. T. O dialektike razvitiya neorganicheskoi prirody (The Dialectics of the Development of Inorganic Nature), Ch. IV, Moscow, 1960.

properties of space and time at accessible scales we can move on to the investigation of their essence in other spheres of the microworld and cosmos as well.

The union of different levels of structural organization of matter is manifested not only in the existence of general properties and relations, but also in the functional similarity of many specific laws of motion with a limited sphere of operation. Many dissimilar phenomena in nature are described by analogous mathematical relations, sometimes completely identical in form. On the other hand, there exists a profound connection and unity between the laws of the microworld and of macroscopic phenomena. The equations of quantum mechanics and those of the theory of relativity go over, in the particular case, into the equations of classical mechanics. Owing to this correspondence of the laws there exists a connection between micro- and macroscopic phenomena and therefore between the properties of space and time in the two regions in question.

Thus continuity, three-dimensionality, quantitative and qualitative infinity and objectivity are very important properties of space which should be valid in the microworld as well. Unidirectionality, irreversibility, continuity, quantitative and qualitative infinity and objectivity are very important properties of time for all forms of matter.

Let us now consider the specific properties of space and time.

Among the specific properties of space we must first mention its h o m o - g e n e i t y, which means the absence in space of any privileged point or system of reference. When moving inertially in a space free of material bodies, material objects do not change mass, momentum and other properties. To the homogeneity of space corresponds the law of conservation of momentum.

Space is i s o t r o p i c, there are no selected directions of up, down and so on. The properties of bodies moving inertially do not depend on the direction of motion.

Owing to the uniformity and isotropy of space, all the laws of nature in all i n e r t i a l systems function in the same way, leading to analogous consequences irrespective of the direction of motion of the system. To the isotropy of space corresponds the law of conservation of angular momentum.

Homogeneity is also inherent in time, with conservation of energy as the corresponding law. By itself the flow of time cannot alter the energy of a system. Energy, momentum and the other properties of bodies can in principle change and do in fact change constantly, but the cause of this is neither space nor time as such but rather various internal and external forces.

Under the influence of external and specific internal bonds in material systems, certain predominant directions may arise in space, violating its isotropy. This can be illustrated by anisotropic crystals, in which the index of refraction of light, heat conductivity, elasticity, resistance to shear and other properties are different in different directions.

Homogeneity of space and time, as well as isotropy of space, should hold in the microworld as well, as here the laws of conservation of energy, momentum and angular momentum are rigorously valid.

Symmetry and asymmetry for different types of material objects are specific properties of space.

In the microworld spatial symmetry is characteristic, for instance, of electromagnetic and strong interactions with participation of neutral π-mesons. The mirror symmetry of bonds and interactions of microobjects is reflected in the concept of parity, which expresses the character of the change of the particle wave function for space reflection of all its coordinates and reversal of the signs. Parity is assumed to be +1 when the wave function does not change sign for reflection of all the coordinate axes; to this corresponds the even state of the system. However, if the wave function changes sign under reflection parity is −1 and the corresponding state is termed odd. Parity conservation in microparticle interactions means physically that the laws of the given interactions and form of all the processes do not change upon mirror reflection of the coordinates and replacement of right by left.

In weak interactions, however, as in the decay of β-radioactive nuclei and certain elementary particles, the law of parity conservation is violated.

Parity nonconservation and the resulting inequivalence of right and left in weak interactions are conditioned by yet unknown peculiarities of structure or internal bonds in the decaying microobjects, just as in the case of macroscopic bodies the asymmetry of form is determined by differences in the character of the molecular bonds in the body in different directions. But this should not be understood as the asymmetry of space itself. "Empty" space, or, more precisely, space containing electromagnetic fields, passes over into iteself upon mirror reflection of the coordinates and does not change properties. Parity is also conserved in nuclear interactions.

L. D. Landau has proposed the idea of combined parity, which relates reflection in space to transformation of microparticles. Upon operation of combined parity the signs of all coordinates are reversed and a simultaneous transition takes place from particles to antiparticles[*]. In the case of truly neutral particles, such as photons or neutral π-mesons, where particle and antiparticle are identical, combined parity reduces to simple space inversion and the law of parity conservation is observed. However, charged particles transform into their antiparticles upon combined parity and parity is not conserved for them. Thus in nature instead of simple spatial symmetry we have a more complex form of symmetry which assumes transition from particles to antiparticles as well as space reflection. In such inversion the laws of nature do not change and the mirror reflection is similar to the original. Therefore the idea of an antiworld should not be understood to mean that in this region of the universe "everything should be the opposite" of our world. The only fundamental difference is that here macroscopic bodies consist of antiparticles whereas all processes and laws of motion are a mirror reflection of the corresponding processes in our region of the universe.

Let us proceed further. From the special theory of relativity it follows that the spatial dimensions of bodies are not invariable but can contract in the direction of motion of the body according to the formula $l = l_0 \sqrt{1 - \frac{v^2}{c^2}}$.

* See L a n d a u, L. D.   O zakonakh sokhraneniya pri slabykh vzaimodeistviyakh (Conservation Laws in Weak Interactions). ZhETF, Vol. 32, No. 2. 1957; see also on this question the collection "Novye svoistva simmetrii elementarnykh chastits" (New Symmetry Properties of Elementary Particles). Moscow, 1957, introductory article by I. M. K h a l a t n i k o v.

For macroscopic bodies this change has not been recorded experimentally so far. Nonetheless there can be no doubt now as to the objectivity of this effect, for it stems from the same fundamental propositions of the theory of relativity as gave rise to the conclusion, repeatedly confirmed by experiment, that the mass and duration of processes is variable. Variation of spatial properties also takes place in mutual collisions between microparticles.

The general theory of relativity has established that the metric properties of space and time depend on the distribution of the gravitating masses and are different from the properties of Euclidian space. The presence of gravitating masses can produce a special "distortion" of the light rays and deceleration of the rhythm of processes and corresponding march of time. In a Euclidian space free from gravitating masses the path of a light ray would nowhere change its direction. But Euclidian space is an abstraction which is very close to reality in cases of practical importance but is nonetheless nowhere fully realized. In Euclidian space there should be no matter at all — neither particles of substance, nor various fields. But in the absence of matter, which includes the electromagnetic field, there can be no space, since space is a property of matter and does not exist without it. Every real space is necessarily different from Euclidian space, and the degree of this difference is characterized by the curvature, which increases with the strength of the gravitational fields.

In systems with a sufficiently large mass and mean density of substance the field strength and gravitational potentials may be so considerable that space has positive curvature. From the physical point of view this means that it is possible for a significant part of the emission formed in the system to be retained by the gravitational field and, in the course of time, to return to a region close to the initial one. This condition, however, does not extend to all of the emission produced, and therefore the closure of space is relative and incomplete. The gravitational field strength decreases in direct proportion to the square of the distance from the center of the system, and therefore at a sufficiently large distance, in the peripheral regions, it may be insufficient to retain emission within the confines of precisely the given system or its parts. Owing to this the system interacts with other surrounding systems, producing changes in their state. Space of positive curvature is an idealized abstraction which is nowhere realized. Every actually existing system or set of systems is open to external interaction.

Is there curvature of space in the microworld? In principle there are no grounds for doubting that elementary particles are capable of creating gravitational fields and thus altering the metric properties of space-time. Physically, however, such change can be detected only at scales not smaller than $10^{-9} - 10^{-10}$ cm, provided the curvature of space can be determined from the character of photon propagation. Upon further reduction of the scale photons cease to exist as such, since they take on such short wavelengths and such high energies that their transmutation into electron-positron pairs becomes possible.

In principle electromagnetic field quanta are capable of changing direction of motion, energy and frequency of oscillation in interactions with particles. At sufficiently high energies they can also create oppositely charged particles. Consequently, if one were to form an opinion concerning the curvature of space from the character of motion of the quanta, one must conclude that the space in the vicinity of microparticles has significant

curvature provided the concept of curvature in its macroscopic sense is applicable here.

Significant change in the metrical properties of space is possible in the structure of atomic nuclei at scales of 10^{-13} cm. The atomic nucleus is the region of concentration of the enormous energy of interaction between microobjects. Nuclear forces of attraction are 200−300 times greater than the energy of electrical repulsion in nuclei of the type of helium, sulfur, etc. Nuclear forces have a small range of action and do not extend beyond $3 \cdot 10^{-13}$ cm. It can therefore be stated that the space of the nucleus is closed with respect to the nuclear field, although it is open for electromagnetic and gravitational interactions as these fields can extend to great distances. This fact indicates the existence of a difference of principle between the mechanism of generation and propagation of electromagnetic and gravitational forces, on the one hand, and of nuclear forces, on the other hand. One might venture to suppose that starting from certain sufficiently large distances space is closed for electromagnetic and gravitational forces as well, although open for forces of another nature. In principle this possibility agrees with the law of transformation of quantitative changes into qualitative ones with respect to the structure of material systems and the metric properties of space, although there are no confirmations of it in modern physics, which admits a p r i o r i of the possibility of infinite propagation of electromagnetic and gravitational interactions.

We will now consider a few specific properties of time. The special theory of relativity indicates that the rhythm of processes in bodies varies with the rate of motion in conformity with the formula $t = t_0 \sqrt{1 - \frac{v^2}{c^2}}$, where t is the time in the moving system and t_0 the time in a system at rest. This variation was first verified experimentally in observations on meson decay in cosmic rays. After their appearance, in the interaction of cosmic particles with nuclei, mesons traverse a distance which increases with their velocity. Here the increase in the path length is only insignificantly conditioned by the increment in the velocity of the meson. It is chiefly due to the increase in the lifetime of the particle.

Is this change absolute, i. e., does it extend to all possible forms of matter? At present it is theoretically extrapolated to macroscopic phenomena, and on this basis it is inferred that the march of time in rockets moving at close-to-light velocities must slow down compared with terrestrial time.

At present there exists no basis for doubting that this is possible, since all kinematic laws of motion at close-to-light speeds are common to microparticles as well as to macroscopic bodies.

However, it is completely unclear whether one can speak of such retardation of time at extremely small scales many orders smaller than those which are characteristic of the most elementary particles. One cannot rule out the possibility that many of the laws and concepts with which the theory of relativity now operates will prove inapplicable at this level. To illustrate let us consider the following analogy. Let us imagine that a certain living organism is in a state of anabiosis in which all its biological processes are extremely slow. Can it be said that time in such a system goes by more slowly than in a normally functioning organism? Obviously not, because,

the slowdown of the biological processes notwithstanding, atomic oscilla-
tions in the molecules of the body in question, as well as the interactions of
elementary particles in the atoms, proceed with the same periodicity as in
surrounding bodies, and the rhythm of time, from the standpoint of physics,
is determined precisely by the character of given, rigorously periodic
changes in the microparticles. If all microparticle oscillations and interac-
tions were to slow down, as is the case at close-to-light velocities or in the
presence of a powerful gravitational field, one would be able to speak of a
deceleration of the march of time in the given body. At present the periodicity
of change of state of microparticles is used as a standard of the uniformity
and rigorous constancy of the march of time.

But this view contains many hazy points. Microparticle interactions are
processes occurring within a scale of $10^{-7} - 10^{-13}$ cm, whereas time is a
universal form of being of matter. And we are not at all certain that a law
established for certain processes at known spatial scales should be valid
at all other scales. The laws would be universal in character if the world
had been qualitatively uniform in structure. In reality, however, the struc-
tural infinity of the world has a higher nonuniformity, owing to which every
s p e c i f i c law has a limited sphere of operation. Therefore it is entirely
possible that at a different level of structural organization of matter it
would be necessary to choose some periodic processes other than atomic
oscillations as one's standard of the uniformity of time. Many conclusions
drawn from the theory of relativity would then prove applicable only at the
spatial scales accessible to modern measurement, but it would not be possi-
ble to regard this theory as the theory of a l l space and time, as is some-
times done. Already, it is being suggested that processes the rate of change
of which exceeds the velocity of light are possible in the microworld. Should
this hypothesis be confirmed, it would mean that physics is drawing close to
phenomena which obey regularities completely different from the laws of the
theory of relativity. It would again confirm a regularity repeatedly observed
in the development of scientific knowledge, that increasingly deep probing
of the essence of phenomena leads to demarcation of the sphere of applica-
bility of old theories on the basis of the discovery of more general laws.

Further, according to the general theory of relativity the duration of
processes and rhythm of changes also depend on the gravitational field
strength. Near gravitating masses time passes more slowly, a statement
which is confirmed, in particular, by the phenomenon of shift of lines at
the red end of stellar spectra, e. g., in white dwarfs, the surface of which
is a region of high gravitational potential. Experiments based on the reson-
ance absorption [sic!] of γ-radiation by nuclei, a fact established by Möss-
bauer, have shown that reduction of the frequency of quanta under the influ-
ence of gravitational fields takes place even in the microstructure of sub-
stance. It is entirely possible that the rhythm of processes in the micro-
world depends not only on gravitational but also on other types of interac-
tion, e. g., nuclear.

It should be remarked, however, that the duration of existence of micro-
objects means something entirely different from the duration of being of
macroscopic bodies. The latter can retain their properties unchanged over
a fairly large interval in time, remaining, as though, in the selfsame state.
Elementary particles behave completely otherwise. Electrons, protons,

neutrons and other microobjects do not persist for any long time in the selfsame state, but undergo continuous internal transformation. For example, according to modern ideas the proton is continuously "splitting" into a neutron and positive π-meson which subsequently combine once more to form the original: $p \rightleftarrows n + \pi^+$. In exactly the same way the neutron dissociates temporarily into a proton and negative π-meson: $n \rightleftarrows p + \pi^-$. Every microparticle spends about 20% of its life in this dissociated state[*].

In analogous manner the electron constantly creates virtual photons and immediately absorbs them again. In every given, sufficiently small, interval of time the particle is "one thing and no longer that thing", behaving like a union of opposites. Therefore stability of particles has a very relative meaning. When we say, for instance, that electrons can exist in a stable form for a very long time, we do not mean that a certain given electron is the same as it was one or a hundred years ago. Since a particle is continuously creating virtual quanta and interacting with fields, stability has a certain integral, rather than differential, character. It refers to the internal form, to the law of organization of the given microobjects, which are relatively stable in time, while the elements of matter composing the microobjects may undergo constant change.

The virtual quanta created by the particles have a definite energy the value of which is determined by the time interval between creation and absorption of the quantum: $\Delta E \cdot \Delta t \geqslant h$. However, it does not therefore follow that the law of conservation of energy is violated here. The energy of virtual quanta apparently stems from the energy of the field associated with the particle. It depends on the time of existence of the quantum. Such a relation is a completely new phenomenon with no analogue in classical physics. It shows that the fundamental properties of microobjects are statistical averages in time. This means that if the time interval is continuously reduced, different values of the properties, and even, possibly, different microobjects, will be obtained every time.

Thus, to conclude what we have been saying, we can state that all the fundamental effects of the variation of the space-time properties which were established by the theory of relativity are manifested in the microworld. But in addition to this quantum theory points to the existence of new, previously unknown specific features of space-time relations in the microworld. Microparticles do not simultaneously have exact values of the coordinates and momentum: $\Delta q \cdot \Delta p \geqslant h$, which indicates that their localization in space is characterized not only by discreteness but by a certain continuity; the effective dimensions of particles are a function of their interactions. Spatial symmetry is closely related to charge symmetry, to the transition from particles to antiparticles; in the structure of nuclei space is closed for nuclear forces; the concept of curvature of space takes on a completely different meaning in the microworld compared with the region of macroscopic phenomena; the sequence of flow of time is irreversible in the microworld as well; the duration of processes depends not only on the velocity but also on the bonds of the particles — and in particular, in the case of neutrons, on intranuclear interactions; the fundamental properties of particles are statistical averages in time. The probing of elementary particle structure

[*] See Sokolov, A. A. and D. D. Ivanenko. Kvantovaya teoriya polya (Quantum Field Theory), p. 516, Moscow-Leningrad, 1952.

will doubtless bring out new specific properties of space and time. The idea of quantized space and time proposed by many modern physicists is an attempt to express these new specific properties.

The hypothesis of space-time quantization arose from attempts to overcome the fundamental difficulties of the theory of elementary particles owing to their infinite proper mass and energy. Already in classical electrodynamics calculations of the energy of the electromagnetic field produced by the electron led to values devoid of physical meaning. The field energy increased continuously as one approached the center of the electron, becoming infinite for a point electron. In quantum electrodynamics this difficulty was manifested in a new form. It was noted above that the electron continuously creates virtual photons the energies of which depend on their lifetimes. The smaller the time of existence of the quantum and, therefore, the distance which it moves away from the electron, the greater its energy. When the distance and lifetime tend to zero the energy of the quantum, and therefore that of the electron which creates it, tends to infinity, which has no meaning physically.

So far no satisfactory way of resolving this difficulty has been found. Usually the difficulty is removed by taking into account in the theory only those values of the proper energy and mass of the electron which follow directly from experiment and simply eliminating as fictitious the additional infinite values. This operation, called mass renormalization, has no theoretical basis but has proved justified on practical grounds.

The hypothesis of the discreteness of space and time in the microworld was introduced even before the idea arose of renormalizing the mass to remove the infinities in quantum theory; it is still attracting serious attention owing to its great physical and philosophical significance. In 1930 V. A. Ambartsumyan and D. D. Ivanenko proved that the infinite self-energy of the electron can be reduced to a finite amount by assuming that space and time in the microworld have a certain discrete, or quantized, structure[*]. In this case elementary cells of space can characterize the dimensions of elementary particles. With a quantized structure of space it becomes completely unnecessary to reduce the space scales when calculating the energy of a particle, since it is postulated from the first that space quanta characterize the minimum possible scales at which physical processes can take place. In this case the proper energy of the electron does not increase indefinitely but assumes a finite value. In order for the electron to have an energy corresponding to its mass as determined from experiment, its spatial dimensions should be roughly 10^{-13} cm. This value corresponds to several objective data. Thus the classical electron radius $\frac{e^2}{mc^2}$ is roughly $2.8 \cdot 10^{-13}$ cm. The de Broglie wavelength of a nucleon of binding energy 7–8 MeV $\lambda = \frac{h}{p} \approx$ $\approx 2 \cdot 10^{-13}$ cm. The so-called Compton wavelength of the meson and of the nucleon is also close in value: $\frac{h}{\mu c} \approx 10^{-13} - 10^{-14}$ cm. The proton radius determined from experiment is $7 \cdot 10^{-14}$ cm and the region of impact of fast nucleons is of the order of 10^{-13} cm.

[*] See Ambarzumian, V. A. and D. D. Iwanenko, Zur Frage nach Verneidung der unendlichen Selbstzurückwirkung des Elektrons, "Zeitschrift für Physik", B 64, S 533, 1930.

This length is also characteristic of a number of electromagnetic processes. In the effect of meson creation by photons, for example, the photon wavelength is roughly $10^{-13} - 10^{-14}$ cm. Further reduction of the wavelength becomes unlikely, since the photon transforms to particles of substance. Thus from many data it follows that the "dimensions" or "size" of elementary particles is close to 10^{-13} cm. From this arises the possibility that there exists a quantum of time which characterizes the minimum time within which physical changes can take place in an elementary particle as a whole. It is given by*

$$\tau_0 = \frac{10^{-13}\,\text{cm}}{3 \cdot 10^{10}\,\text{cm/sec}} \approx 3 \cdot 10^{-23}\,\text{sec}.$$

The given quantities should characterize not only elementary particles proper but also the regions of strong interaction between them. Let us consider the collision between two high-energy protons. The least time of collision will be the time within which any significant change takes place in the state of the particles. Had elementary particles been perfectly rigid spheres with sharply defined dimensions, their collision time would have been as small as desired. But perfectly rigid bodies cannot exist in nature since in such bodies the forces of interaction would have to be transmitted at infinitely high velocities, which is in contradiction with the theory of relativity. All the more reason not to regard elementary particles as perfectly rigid. They have wave properties and are inseparably related to various fields. The collision of two particles is accompanied by interpenetration of their fields; significant change in the states of the two particles cannot take place at scales smaller than the elementary length and time interval. The same must be said for processes of intertransmutation of particles.

The elementary length l_0 and the quantum of time may be related to the quantum of action h, as noted by the British author B. Abramenko**. Let us assume that l_0 is equal to the effective cross section of the proton for the scattering of fast electrons:

$$l_0 = 1.5 \cdot 10^{-13}\,\text{cm}$$

and

$$\tau_0 = \frac{l_0}{c} = \frac{1.5 \cdot 10^{-13}\,\text{cm}}{3 \cdot 10^{10}\,\text{cm/sec}} = 0.5 \cdot 10^{-23}\,\text{sec}.$$

Associating a certain spherical volume with l_0 and multiplying the quantity obtained by τ_0, we obtain the "space-time quantum" $v_{lr} = \frac{4}{3}\,\pi l_0^3 \tau_0 = 7.1 \cdot 10^{-62}\,\text{cm}^3 \cdot \text{sec}$. Let us further suppose that this space-time volume is filled with matter of nuclear density $\rho \approx 10^{-14}\,\text{g/cm}^3$. Its energy will be $v_{lr} \cdot \rho \cdot c^2 \approx 6.4 \cdot 10^{-27}$ erg, roughly the same quantitative value as Planck's constant $h = 6.6 \cdot 10^{-27}$ erg $\cdot$ sec. It is possible that the identity obtained by Abramenko is not accidental and that it has definite physical meaning.

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* It is assumed that the rate of propagation of interaction in an elementary particle equals the velocity of light.

** Abramenko, B. Physical Space and Time. The British Journal for the Philosophy of Science, Vol. 9, No. 34, p. 106. 1958.

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In the modern theory the idea of universal length is introduced in order to remove the difficulties involved in the infinite self-energy of particles. Since the assignment of finite dimensions to particles runs counter to the requirements of relativistic invariance of the equations of motion, the assumption of several elementary spatial cells, at the scales of which the propositions of the theory of relativity are considered inapplicable, is introduced. Space is treated as a special cubic lattice of discrete elements[*]

In the nonlinear quantum field theory developed by Heisenberg and his school, the elementary length is also treated as one of the most important constants of nature together with electron charge, Planck's constant, and the velocity of light[**]. In the field theory of matter elementary particles are regarded as various excited states of a nonlinear spinor field. The elementary length appears as a constant in the equation expressing the self-interaction density of the spinor field.

Heisenberg's ideas represent a further development of hypotheses of space-time discreteness already introduced and developed successively in the thirties by Ivanenko, Snyder, Silberstein, Born, March et al[***].

In Born's conception the minimum length corresponds, according to the uncertainty relation, to the maximum value of the momentum. In view of this Born introduces the concept of the space of momenta of constant curvature.

The supporters of the hypothesis of space and time quantization are always stressing the fact that the geometry of space in the microworld must be non-Archimedean, which excludes the possibility of unlimited division of space and time[****].

What real physical meaning can all these considerations have, apart from the fact that they assist in removing the difficulties of the infinite values of the energy and mass of particles? It would appear that they really express the presence of a definite discreteness in space-time properties of elementary particles. Discreteness is in general a very characteristic feature of the microworld. Many properties of particles — spin, electric charge, magnetic moment, parity and others — have completely defined, discrete values. The concept of a composite mechanical system is not applicable to elementary particles; they have a special type of integrity which distinguishes them from all other material objects. In all the composite systems surrounding us, from cosmic formations to atomic nuclei, the energy of internal bonds between the component elements of the system is many times smaller than the energy $E = m_0c^2$ corresponding to the rest mass of the system. Such systems split into elements for an energy of action many times smaller than $E = m_0c^2$, though with reduction of the size of the system the strength of the cohesion between elements increases, with a

 [*] See S o k o l o v, A. A. and D. D. I v a n e n k o. Kvantovaya teoriya polya (Quantum Field Theory), p. 594, 1959.
 [**] See the collection "Nelineinaya kvantovaya teoriya polya" (Nonlinear Quantum Field Theory). Moscow, 1959.
 [***] A review of the various hypotheses on the problem of space-time quantization may be found in the following works: S v i d e r s k i i, V. I. Filosofskoe znachenie prostranstvenno vremennykh predstavlenii v fizike (Philosophical Significance of Space-Time Ideas in Physics), pp. 285—300, Leningrad, 1956; K u z n e t s o v, B. G. Printsip otnositel'nosti v antichnoi, klassicheskoi i kvantovoi fizike (The Principle of Relativity in Ancient, Classical and Quantum Physics), pp. 205—230, Moscow, 1959; A r o n o v, R. A. O gipoteze preryvnosti prostranstva i vremeni (The Hypothesis of Space-Time Discontinuity), Voprosy filosofii, No. 3, 1957.
 [****] Archimedes' axiom has the following meaning: whatever be the segments A and B one can always find a number n such that B when divided by n is smaller than A: B/n<A.

corresponding increase in the binding energy per unit mass of the component elements.*

As for elementary particles they do not break up into the supposed elements even when the energy of action on them is hundreds and thousands of times greater than the corresponding rest energy. At such energies the only effect is the creation of a host of other particles — electron-positron pairs, mesons and so on. The probability of splitting does not increase with increase of the energy of action; instead, there is only an increase in the number of particles created, each of which has elementarity of the same type as the primary particles. This shows that the complexity of elementary particles is entirely different from the complexity of all other known forms of matter.

Above it was pointed out that the extension of material objects is a function of their interaction, and that a fundamental change in the character of internal bonds should entail a change in the spatial properties of the material formations. The enormous energy of internal bonds of elementary particles suggests that it is possible that they have discrete internal dimensions, characterized precisely by a quantity of the order of 10^{-13} cm. In this region protons, neutrons and other microparticles are localized as integral formations of matter. Generated particles have roughly the same dimensions. The relative discreteness of the spatial dimensions of particles can be related in a definite way to the discreteness of the spin, electric charge, magnetic moment and other properties of particles.

However, one cannot absolutize this conclusion concerning the quantum properties of space and time and deny the possibility of the existence of material processes of any kind at smaller scales. Matter and its fundamental forms of being are not only discrete but continuous. Some authors, unfortunately, permit such absolutization in the belief that it is meaningless in general to speak of material motion at smaller scales. The point of view has been expressed by Poincaré, March, Snyder, Abramenko, Weyl and certain authors. It is usually assumed here that space is also finite at cosmic scales because it everywhere has positive curvature. Thus Abramenko writes: "Weyl once put forward an idea that the non-Euclidicity of world space may mean that it has not only outer, but also inner limits. We shall now reverse argument with reference to time. The limitation of time in the small to some indivisible quanta τ_0 may mean the existence of outer limits; that is, the existence of the longest time interval possible, instead of infinite time, which would be just another logical consequence of renouncing the Archimedean axiom...

"If the Archimedean axiom is not applicable to our physical world, and its spatial and temporal dimensions are finite, the world's content is characterized not by its volume or other dimensional quantity, but by the number of its quanta or spatio-temporal physical points; i.e., by a dimensionless quantity or a pure number, in accordance with the view advocated as early as twenty-five centuries ago by the Pythagorean school"**. And the author calculates the number of possible space-time quanta in the world.

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* This is due to the fact that upon transition from cosmic systems to macroscopic bodies, molecules, atoms and atomic nuclei, qualitatively new (electromagnetic and nuclear) forces whose energy is far greater than the energy of gravitational forces come into play.

** A b r a m e n k o, B. Physical Space and Time. The British Journal for the Philosophy of Science, Vol. 9, No. 34, p. 107, 1958.

He assumes the radius of the universe to be $3.4 \cdot 10^9$ light years, which corresponds to a volume of $8 \cdot 10^{83}$ cm^3. The duration of finite time should be $6 \cdot 10^{17}$ sec, and thus space-time volume will contain roughly 10^{101} cm$^3 \cdot$ sec. Assuming that the value of a single space-time quantum is 10^{-61} cm$^3 \cdot$ sec, the number of such quanta in the whole world should be about 10^{162}. The so-called cosmic number N, or number of elementary particles in the cosmos, determined by Eddington is 10^{80}. "Perhaps there is a definite relation between these two numbers; the latter is the square root of the former, and this connects the atomistic structure of matter with the discrete quantum structure of space-time"[*].

Such juggling with numbers, which is characteristic of the representatives of the Cambridge school, can scarcely have any value as serious proof. The so-called "radius of the world" $- 3.4 \cdot 10^9$ light years $-$ is a completely arbitrary quantity; indeed, modern radio astronomy methods have already led to the recording of emission from galactic clusters thirteen billion light years away, and there is no scientific basis for doubting the possibility of further unlimited expansion of the scale. Moreover, careful measurement in recent years of the mean density of matter in the metagalaxy points to the conclusion that space in the region of the universe surrounding us has negative curvature and is described by Lobachevskian geometry[**]. It is open, thus admitting the possibility that the various kinds of radiation developed in it are propagated to larger and larger regions of the universe.

Characteristically, the authors usually absolutize the idea of quantization of space and time without giving it any logical foundation or physical interpretation, postulating it simply as a means of removing the difficulties of the infinities. Perhaps the only exception in this respect is the work of B. G. Kuznetsov,. who attempts to illustrate physically the proposition of space-time discreteness. Kuznetsov starts from a hypothesis introduced in 1949 by the Soviet physicist Ya. I. Frenkel', namely that the motion of elementary particles is not a simple translation of the self-same particle from one place to the other, but rather a process of periodic and continuous vanishing of the particle in one cell of space and appearance in another, i.e., a regenerative motion[***]. The fundamental properties of particles then become statistical averages in time.

Kuznetsov bases the physical explanation of space-time quantization on this hypothesis. He writes: "Let us imagine a spatial cell of minimal dimensions of the order of 10^{-13} cm. In it there has appeared an elementary particle of definite form. Subsequently, within 10^{-24} sec, the given particle vanished, transmuting into a different type of particle. This transmutational process makes it possible to distinguish one elementary time interval $(10^{-24}$ sec) from the next one. It also makes it possible to distinguish one spatial cell $(10^{-13}$ cm) from another". However, we "cannot distinguish the right half of a spatial cell from the left by means of a moving particle. A particle which moves from the right half of a spatial cell to the left will not be found"[****].

  * Ibid.

  ** See Fok, V. A. Teoriya prostranstva, vremeni i tyagoteniya (Theory of Space, Time and Gravitation), p. 463. Moscow, 1955. [Translated into English. Pergamon Press.]

  *** See Frenkel', Ya. I. Ponyatie dvizheniya v relyativistskoi kvantovoi teorii (The Concept of Motion in Relativistic Quantum Theory). DAN, Vol. 64, No. 4, 1949; also, by the same author, K voprosu o edinoi teorii polya (The Problem of a Unified Theory of Fields). UFN, Vol. XLII, No. 1, 1950. Kuznetsov, B. G. Evolyutsiya kartiny mira (Evolution of the World Picture), pp. 341–342. Moscow, 1961.

"The impossibility of a mathematical subdivision of the three-dimensional volume will not be an arbitrary assumption if it is related to the absence of real physical processes allowing one to distinguish one part of the matter filling this volume from another part"[*].

"Elementary space cells have a right and a left-hand side, but not right and left parts. The definite sign of the spin suggests spatial orientation of the particle, but within the volume which it occupies there are no physical objects with reference to which the space can be divided into parts. This means that space in an elementary cell can be infinitely divisible but that to this divisibility corresponds no real physical process; we can imagine a distance smaller than 10^{-13} cm and a time smaller than 10^{-24} sec, but there will be no physically distinct regions or time intervals corresponding to these scales"[**].

Such considerations are interesting but vulnerable in many places. First of all, the very idea of a constant vanishing and regeneration of particles in different cells of space, their transition from being to nonbeing and back, is problematic. There are no reasons to postulate categorically the absence of any physical processes between vanishing and generation of the particle at the space-time scales corresponding to these processes. In the world all phenomena take place in conformity with the principle of causality and the laws of conservation of matter and its most important properties. In the disappearance of a particle in one cell of space the matter composing it would have to pass over into a qualitatively different state; the existence of the given matter would not cease even for one instant, howsoever small. There would also be no interruption in its motion.

On the other hand, particles cannot be created from nothing independently of other causes. Consequently, between the appearance and the disappearance of the particle there would have to be definite changes of matter and definite physical processes. These would take place at corresponding space-time scales, smaller than 10^{-13} cm and 10^{-24} sec. Before definite changes can take place in the particle as a whole, there must be changes in the elements of its structure. Denial of such intermediate processes would be equivalent to assuming i n s t a n t a n e o u s transitions of particles from one qualitative state to another upon their disappearance in some cells of space and appearance in others; this implies an infinite speed of propagation of interaction. Since this is impossible the idea of particle transmutation is not in itself a sufficient basis for the idea of the discreteness of space and time.

Physically the fulfillment of the principle of causality and the laws of conservation of matter and of its principal properties means that all changes in material objects and in their mutual relationships must be c o n t a c t - a c t i o n processes, gradual and continuous, with a finite speed of propagation of matter and energy from one region of space to another.

The principle of contact action must also hold in all stepwise quantum transitions in the microworld. The apparent simultaneity of transition seems such only when the real process is approximated roughly, considered in too large a time scale. However, were we able to reach the fine microstructure of quantum transitions or elementary particle transmutations, we would see that these phenomena obey the laws of conservation and the

* K u z n e t s o v , B. G. Printsip otnositel'nosti v antichnoi, klassicheskoi i kvantovoi fizike (The Principle of Relativity in Ancient, Classical and Quantum Physics), p. 215.
Ibid., pp. 217—218.

principle of causality; owing to this the propagation of interactions in the given regions takes place as a contact-action process at a finite speed. Therefore all transitions take place within definite time intervals, and not instantaneously. The time of existence of a definite microparticle which appears and subsequently disappears again may be discrete, but not time as a u n i v e r s a l f o r m o f b e i n g of all forms of matter existing in nature.

In this connection we cannot agree with the view, occasionally expressed in the literature, that the quantum character of the properties and interactions of microparticles also conditions the discreteness of time irrespective of the form of matter to which the time refers.

It should be stressed that the properties of space and time must be derived not from themselves but from the properties and interactions of moving matter. Therefore the problem of whether space and time are continuous or discontinuous reduces in the last analysis of the problem of whether matter itself, as the substance of all phenomena, is discrete or continuous. Absolutization of the idea of quantization of space and time is equivalent to assuming ultimate structureless "bricks" of matter representing the lower limit of complexity. Naturally, the recognition of structure in these microobjects implies the possibility of changes in matter at smaller space-time scales.

The idea of structureless microobjects, however, is internally contradictory from the physical and philosophical points of view. Objects of this kind should have no internal bonds, since recognition of the latter would imply structure, which is always a definite type of internal bond. But objects devoid of internal bonds cannot have external ones, as the latter are always determined by the former and cannot exist without them. For example, all the external electromagnetic, gravitational and nuclear bonds of microparticles are determined by their internal bonds or structure, which is their material foundation. Objects devoid of internal and external bonds could not manifest their existence, would not have any properties (since properties are always the result of interactions) and would not be capable of combining together in more general systems. Matter would have no structural organization, and its development would be impossible. This means that microobjects without structure and internal bonds are in principle impossible, although, of course, this structure can be highly varied owing to the qualitative infinity of matter.

Modern physics has obtained many proofs of the structural complexity of elementary particles. Evidence includes the intertransmutability of particles, the great variety of their properties, the constant interaction with various fields and also indirect experimental data. Experiments on the determination of the structure and size of the proton through scattering of high-energy electrons on hydrogen nuclei show that the proton is a highly complex formation at the center of which lies a dense nucleus or "core" surrounded by a cloud of positively charged π-mesons. The neutron may have an analogous structure, with a core surrounded by neutral π-mesons. Thus from the standpoint of modern physics there is no reason to deny the possibility of there existing material processes at scales smaller than 10^{-13} cm and 10^{-24} sec.

However, the problem does not even lie in these quantities. One can assume that the elementary length and the quantum of time have far smaller

values, unattainable so far to modern physics. M. A. Markov points out
that there may be different "critical" lengths and corresponding time inter-
vals. For the nucleon, for instance, this length is roughly 10^{-17} cm, or,
if we take into account the gravitational radius of the electron, 10^{-58} cm[*]
But whatever the value of the elementary length, the idea of the discreteness
of space and time cannot be absolutized. The considerations presented
above remain valid in such cases as well. To these might be added the fol-
lowing arguments.

In classical physics this material medium was taken to be the ether, but
with the advent of the theory of relativity the hypothesis of the ether was
abandoned and the concept of field introduced into physics in its stead. The
electromagnetic, gravitational and nuclear fields are the precisely such
forms of matter which are the carriers of the various forces and which
guarantee the combination of particles and macroscopic bodies in more
general systems. The field is a material system with an infinite number
of degrees of freedom. It is continuously distributed in space, and inter-
actions in fields are transmitted according to the principle of contact action.
True, the field simultaneously possesses the properties of the discrete,
since upon absorption and emission by particles of matter it manifests it-
self as a set of discontinuous formations, or quanta. In space, however, it
is continuously distributed, and the presence of a field can be detected at
any point in its sphere of influence.

Furthermore, aside from the excited states of the field to which the
quanta correspond, there exist special vacuum states in which the proper en-
ergy of the field is close to the absolute minimum, the zero value. Vacuum
fields are continuous. Thus the union of the discontinuity and continuity of
matter is a natural result of the universal bond between bodies, and at the
same time is a necessary condition for this bond. Were matter discrete the
interaction of its component elements and the formation of different systems
would be impossible. This proposition is fundamental; it (and not only the
experimental data) makes it possible to detect the errors in the assumption

The assumption that there exist ultimate discrete elements of matter and
forms of its being leads to insuperable difficulties when one seeks to under-
stand the interactions between them. Here one is necessarily faced with
the problem of how the given discrete elements of matter are interrelated
and combined in more general systems. The assumption that they are every-
where close to each other and in contact is inapplicable, as it leads to re-
cognition of the continuity and compactness of matter, which is in contra-
diction with the original premises. On the other hand, if it is assumed
that the discrete elements of matter are separated by definite distances,
the problem arises of how the forces of binding are transmitted from particle
to particle. The assumption that these forces are transmitted by themselves,
without any material substrate, leads to recognition of m o t i o n w i t h o u t
m a t t e r, which is clearly inadmissible, as it leads to idealism and contra-
dicts the principle of the material unity of the world. It remains to assume
that these forces are transmitted by some form of matter which fills up
the space between particles. This matter must be continuous, since to as-
sume its discreteness would again raise the question of the nature of the
interaction between discrete elements, and thus the old problem arises
in the same form.

[*] See M a r k o v, M. A. Giperony i K-mezony (Hyperons and K-Mesons), pp. 316–317, Moscow, 1958.

of the ancient philosophers that matter is made of actually infinitesimal discrete elements. At the same time it permits a critical approach to attempts at absolutization of the idea of the discreteness of space and time.

The union of discontinuity and continuity is manifested not only in the character of the distribution of material particles and fields but also in certain properties of microobjects. The energy of an electron in an atom can only have completely definite discrete values, and changes stepwise, whereas the energy of a free electron can change continuously, increasing or decreasing by any value however small. The rest mass of particles also has completely definite and discrete values, but with increasing velocity of the particles the overall mass is capable of increasing continuously.

Every solid body has discontinuous dimensions and outlines in space, yet at the same time it creates electromagnetic and gravitational fields which are continuously distributed and capable in principle of manifesting their influence over any distance however great.

Union of discontinuity and continuity also holds in the spatial being of the elementary particles themselves. It is well known that the size of elementary particles can be determined only from the effective cross sections obtained in the scattering of some particles on others. But the magnitude of an effective cross section depends on the velocities of the colliding particles, their mass, and the presence of electric charges. Correspondingly the particle sizes determined by experiment may differ widely in different cases; they are a function of the interaction. This is due to the fact that particles are not microscopic copies of hard spheres and that they do not have clear, sharply-defined boundaries. Every microparticle is inseparably connected with the corresponding field, which is as it were the outward manifestation of the internal essence of the particle. The field merges into the particle to a certain extent, and it is impossible to determine with absolute accuracy where the field proper ends and the particle begins. For example, the size of the proton is $7 \cdot 10^{-14}$ cm, but this quantity characterizes the region of distribution of the π-meson field, which is an organic part of the proton structure and inseparable from it. The density ρ of distribution of matter in a nucleon might be characterized by a diagram (see figure).

The same can be said for the other microparticles. Owing to this even for particles of finite rest mass the discreteness of spatial dimensions is a

highly relative and arbitrary concept, as it is complemented by continuity. This applies in even greater measure to time.

In the philosophical literature the idea of the discreteness of space and time is substantiated from the standpoint of the law of transition of quantitative changes into qualitative ones, which assumes that the world is structurally nonuniform. At a certain stage quantitative changes tending toward increase or decrease of the scales of the principal forms of being of matter must lead to fundamental changes in their metric properties. But certain authors apply the idea of qualitative changes not only to the specific properties of space and time but even to their fundamental properties — extension and duration — in the belief that at a definite stage of quantitative change these properties lose their meaning, transforming into something qualitatively new. A similar idea is

developed, for instance, in the work of V. I. Sviderskii. He believes that beyond 10^{-13} cm and 10^{-24} sec "such fundamental concepts of macroscopic space as distance, time interval, and so on lose their earlier meaning"[*].

In precisely the same way at cosmic scales the operation of the law of transition of quantitative changes into qualitative ones means that, starting from certain scales, the properties of space and time change so sharply that it becomes impossible to speak of a further infinite increase of distances.

"Therefore, as we see it, one cannot speak at the level of abstract infinity of the number of atoms in the world, or of the number of gravitational masses, or of the unlimited possibility of increasing or decreasing space-time scales (meters, hours and so forth). All these quantities, in view of their specific qualitative nature, must be finite"[**].

Qualitative negation doubtless holds in the case of specific properties of space and time, which are fundamentally altered upon transition from one level of structural organization of matter to another. However, in our opinion this does not apply to the universal properties of matter and its fundamental forms of being, which should be manifested at all levels of structural organization. Extension and duration are those fundamental properties of space and time without which they lose their content. These universal properties are indeed the basis of quantitative changes, and due to them the law of transition of quantitative changes into qualitative ones holds at any space-time scale. Space and time have no general properties other than extension and duration capable of assuming any quantitative value. If we assume that at a certain stage extension and duration cease to be inherent in space and time, the law of transition of quantitative changes into qualitative ones loses the basis of its operation, since henceforth there will be n o t h i n g to change to quantitatively. It is precisely the universal properties of matter and its fundamental forms of being that always constitute the basis of those quantitative changes which, at certain stages, upon transition from one level of structural organization to another, lead to fundamental changes in the particular, specific properties.

As to the propositions that the number of atoms, stars, gravitational masses and other specific qualities in the universe is finite, again, they cannot be substantiated by referring to the law of transition of quantitative changes into qualitative ones. If by means of this it is stressed that the universe does not everywhere consist of the same atoms, stars or other bodies with known properties, this is in principle correct. The world is nonuniform in structure, and there is no reason to claim that the same bodies that are encountered in the regions surrounding us must exist everywhere. However, from this it does not follow that the number of atoms, gravitational masses and, all the more so, space-time scales is finite. For the qualitative infinity of the world is not single-valued and completed, nor is it characterized by a completely definite number (otherwise it would not be an infinity). It contains a set of other infinities of different orders, that is, the world can have an infinite set of atoms, gravitational masses, etc., an infinite set of material objects of a completely different kind, a similar set of objects different from these, and so on. If we designate the set M as infinite, then the set M^n, M^{n^n} or $M^{\frac{1}{n}}$ and so on will be infinite (where

* S v i d e r s k i i , V. I. Filosofskoe znachenie prostranstvenno-vremennykh predstavlenii v fizike (Philosophical Significance of Space-Time Ideas in Physics). p. 299.

** Ibid., p. 272.

n is any definite number). All these sets will be equivalent. As *n* increases the hierarchy of sets can be continued indefinitely, and each of these will be covered by the concept of the infinite. The quantitative and qualitative infinity of matter presupposes the possibility of there existing w i t h i n it a set of infinities of various orders, each of which characterizes a set of qualitatively dissimilar objects.

If, however, we assume that this cannot be and that the infinity of the world is a certain unique one which excludes the possibility of there existing within it infinite sets of dissimilar objects, this means that we understand it to be a completed infinity. But were it such it would cease to be an infinity and would assume the properties of a finite set, which is in contradiction with the original premise.

These considerations lead us back to a problem long controversial in science, namely whether the infinite divisibility of matter (and by the same token the infinity of space and time) is actual or potential*.

Speaking of the world as a whole, its infinity in space and time cannot be considered potential insofar as the world is not becoming infinite but is already so. However, although actually infinite, the world is changing, passing over from one state into another. This change affects all properties of the systems, including the space-time ones. The possibility of such changes suggests that the infinity of the world is, simultaneously, also potential, containing in itself the processes of formation and qualitative transition. Thus it is a union of the actual and the potential, that which is completed and that which is limitlessly becoming, the real and the possible. The infinity of the world is not something static and unchanging; instead, it presupposes the limitless variation of matter in space and time.

The infinity of matter in depth is closely connected with space-time infinity in the cosmos. To show this, let us divide in our imagination the infinite volume of the universe into an uncountable set of arbitrary units of volume, e. g., cubic centimeters [sic!]. Now let us seek to distinguish in one cubic centimeter the largest possible number of volumes. It is easy to show that there are as many of these as there are cubic centimeters in the entire universe. These infinite sets are equivalent, and a one-to-one correspondence can be established between their elements. The number of volumes in 1 cm³ is actually infinite. At the same time, since matter is constantly changing and passing over from one qualitative state into another – which applies to all its structural elements – the infinity of matter in depth is simultaneously potential. It also represents a union of opposites, that which is completed and that which is in the process of becoming, the real and the possible – and that is why it is infinite.

Reduction or increase of the space-time scale must surely entail qualitative changes in all s p e c i f i c properties and laws of motion of matter; universal properties and dialectical laws, however, should be conserved, for they follow from the very fact of the existence of matter in various forms and express the most general aspects of its being.

* A quantity or set of quantities is considered actually infinite if it is completed in the sense of its realization and exists objectively as something given and already accomplished. For example, in set theory the set of points and corresponding real numbers on a segment of finite length is considered actually infinite. A potential infinity is a set of quantities which is capable of increasing indefinitely, becoming larger than any previously specified set of quantities. It is infinite not in the sense of its final, completed realization, but rather in the sense of the possibility of an unlimited further increase in which any specific set of quantities, however large, is exceeded.

And so, in conclusion, the following may be added to our earlier conclusions. Space-time properties can be discrete and finite only for certain forms of matter; therefore discreteness is a relative property. Other forms of matter, and in particular the field, are continuously distributed in space. Changes in all forms of matter can take place at scales as small as desired, and only by contact action. Therefore an absolute universal property of space and time is their continuity, owing to which change in matter is possible.

SPACE-TIME QUANTIZATION IN ELEMENTARY PARTICLE THEORY

I. S. Shapiro

When one looks at the history of the development of physics in the last hundred years the conclusion suggests itself that scientific progress was conditioned by the joint action of two diametrically opposite tendencies. On the one hand, progress would not have been possible but for the appearance of brilliant hypotheses which altered the old ideas profoundly. On the other hand, a certain constructive role was played by "healthy conservatism", or the reluctance to change the fundamental propositions of a physical theory as long as there is any hope of finding a way out of the difficulties without substantially changing the foundations.

Our remark would be trivial were it really possible to establish whether the possibilities of the old theory have been entirely exhausted.

The trouble is that this becomes clear at a later date, i. e., only after the new theory, profoundly dissimilar from the old, has been confirmed by experiment. So far, at least, the unsuitability of propositions belonging to old physical views has never been proved in any other way. This circumstance is due in large part to the fact that experimental data are practically never so complete as to allow a u n i q u e solution of the "inverse problem", recovery of the true appearance of the physical theory corresponding to the known aggregate of facts. In reality the research physicist finds himself in a situation somewhat reminiscent of that of a general who must guess the intentions of his enemy from fragmentary and occasionally contradictory reconnaissance data.

That is why the great discoveries in physics have nearly always been due to the intuition of scientists who, convinced of the deficiency of the old views, introduced new and sometimes very daring hypotheses. Thus, although the need for changing fundamental theses which have outlived their usefulness to physics can hardly ever be proved, it is important to "feel" this need, for without it the desire to look for something new cannot arise.

I believe that in any exposition of the ideas covered by the general term space and time quantization an analysis of the difficulties facing the modern theory is particularly necessary, the reason being that only a few tentative steps, with so far no guarantee of success, have been taken in the new direction. Thus we will be dealing with exploratory research the outcome of which is still uncertain.

The crisis in the theory of elementary particles today is associated with difficulties which we can class in two groups.

The first group of difficulties is due to the fact that we are not able to solve the equations of the quantum theory of interacting fields.

The difficulties in the second group stem from the fact that we can see no principles in the modern theory by which to explain the diversity of the known elementary particles and establish the connection between the various types of particle interactions.

Such classification of the difficulties is surely somewhat arbitrary, and it is possible that some of the difficulties in the second group would vanish if we were able to solve the equations of the quantum theory of fields. How do these equations differ from the equations of the so-called classical theory of fields, from, say, Maxwell's well-known equations for the electromagnetic field?

The equations of classical theory are a system of a f i n i t e number of partial differential equations. Very many of the properties of such systems of equations are now known to us, and a very broad class of such equations can be solved, using, where necessary, sufficiently advanced computers. The equations of quantum theory of fields, however, are a system of an i n f i n i t e number of partial differential equations. The properties of such systems of equations are still so poorly studied that even the theorem concerning the existence of a solution has not been proved. In other words, so far we are not certain that this sytem of equations is not internally inconsistent. All that we have learned to do can be reduced to two possibilities.

First, we can solve these equations in those cases where the particles do not interact with each other (free fields). But this is of little interest physically, since real particles are always encountered in interaction.

Secondly, we believe that we can sometimes solve these equations in cases where the interaction is small. An example (the only one so far, unfortunately) of solution by the method of perturbation theory is provided by quantum electrodynamics (interaction of particles with the electromagnetic field). Electromagnetic interaction is characterized by a small dimensionless parameter (the so-called fine structure constant) $\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}$, where $e = 4.80 \times 10^{-10}$ (CGSE) is the elementary electric charge, $\hbar$ the quantum constant and $c = 3 \times 10^{10}$ cm/sec the velocity of light in vacuum.

As α is much smaller than 1, it is reasonable to try to solve the system of equations of quantum electrodynamics by the method of successive approximations, i.e., first obtain the solution for free fields and subsequently correct it by accounting for those quantities which contain α in the first power, in the second power, and so on. One might expect that, owing to the smallness of α, those terms of the perturbation series which contain higher powers of α would be small compared with the lower nonvanishing approximations. Contrary to these expectations the following approximations proved to be not only not small, but even infinite, which is completely meaningless. True, in electrodynamics physicists learned to remove such infinities with the help of the so-called renormalization of the mass and charge. First, however, these methods do not follow systematically from the equations themselves — they are artificial importations into the theory. Secondly, the procedure of renormalization breaks down in other cases where, seemingly, perturbation theory should be as applicable as in the electrodynamics of the electron. This applies, in particular, to the so-called weak interactions responsible for the decay of elementary particles.

As we do not possess the exact solution of the equations of quantum electrodynamics, we are not yet in a position to make final judgments concerning

the origin of the infinities mentioned above, i.e., as to whether they are the consequence of the use of the perturbation method, or evidence that the original system of equations is incorrect (inconsistent).

In this connection mention should be made of the interesting inferences which can be drawn from attempts to sum the perturbation series theory. From certain (natural) assumptions, the following paradoxical conclusion follows from the theory: starting from equations which presuppose the existence of interaction between particles, we obtain a solution in which the interaction vanishes completely (the detailed investigations along these lines are due to L. D. Landau and I. Ya. Pomeranchuk). If rigorously proved such a result would imply that the equations of the quantum theory of fields are inconsistent.

If one adopts this point of view it becomes necessary to modify the original system of equations. However, the trouble is that the considerations underlying the equations of the modern quantum theory of fields are so fundamental that one cannot modify these equations significantly without profoundly altering those general physical concepts by which we have been guided so far. To clarify this point I will now consider the so-called nonlocal theory of fields – an approach close in spirit to the idea of quantization of space and time.

The modern quantum theory of fields is based on the principle of so-called local interactions. This means, for example, that the interaction of an electron with the electromagnetic field at a certain instant in time is determined only by the field strength at that point in space at which the electron is localized at the given instant. In this sense elementary particles are treated in the modern theory as points devoid of any dimensions, since otherwise the interaction would be determined by the field strength in the entire r e g i o n of space occupied by the electron. Nonlocal theory of fields starts from the assumption that elementary particles cannot in general be localized at a point in space at a given instant in time. To give a graphical illustration, this means that the particle is "smeared" over a certain region of the four-dimensional space-time continuum. This idea arose because the above-mentioned infinities appear in the theory owing to interaction at small distances.

The nonlocal theory of fields was investigated intensively in this country by M. A. Markov, and he was the first to indicate one of the difficulties of principle presented by this conception. The problems of nonlocal theory, such as we understand them today, reduce in general to the following. It seems that in the "smearing" of a particle we encounter a violation of relativistic causality, due to admission of the possibility of propagation of signals at a rate exceeding the rate of propagation of light in vacuum (if one admits of the existence of such signals, events which took place, say, yesterday in Leningrad may prove to be dependent on events which will take place the day-after-tomorrow in Moscow; in other words, the "future" may influence the "past"). True, it should be borne in mind that the violation of causality referred to above occurs at very small distances (necessarily less than 10^{-13} cm) inaccessible to direct observation and susceptible of study only by means of indirect experiments.

Thus we are dealing with violation of microcausality. However, as to how microcausality should be understood, we know practically nothing. From nowhere does it follow, in particular, that the causal links at such small distances must appear the same as the causal links between two events

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in the macroworld. It is important, however, that whatever theory is suggested be protected from violations of m a c r o c a u s a l i t y. Unfortunately, at present we have no completely satisfactory mathematical formulation of the conditions of fulfillment of macrocausality for experimentally observable quantities which could be calculated from a given theory. Such quantities are the probabilities, or more precisely, the amplitudes of the probabilities for different processes. But the amplitudes of the probabilities for processes taking place with elementary particles do not depend explicitly on the time and space coordinates (they are functions of the energies and momenta of the colliding and scattered particles, mutual orientations of the spins, and so on). Therefore it is far from simple to determine how the impossibility of "faster-than-light" signals in the macroworld is manifested in such quantities.

Thus we arrive at the following situation:

a) if we do not allow the appearance of "faster-than-light" signals in the small, we are thereby guaranteeing their absence at macroscopic distances;

b) generally speaking, it is not proved that the assumption of the existence of such signals in the small will lead necessarily to violation of macrocausality;

c) at present there is no sufficiently clear-cut criterion which would make it possible to determine effectively whether the presence of faster-than-light signals in the small in one or the other concrete variant of the theory will lead to violation of macrocausality.

Thus it follows from all we have been saying that the appearance of faster-than-light signals (in the small) in the nonlocal theory is an unpleasant fact but, possibly, not a "criminal" one. A more serious problem, at least for the present state of our knowledge, is the fulfillment of the so-called requirement of unitarity.

The requirement of unitarity consists of the following:

1) the sum of the probabilities of all possible processes should be unity;

2) processes with different initial or final states should not interfere with each other.

In the formalism of the quantum theory of fields the reality of such a physical quantity as the energy of the system is also closely related to the requirement of unitarity.

A requirement of unitarity formulated directly for experimentally observed quantities is apparently an essential condition for any physical theory and can scarcely be evaded. Unitarity means, roughly speaking, that no physical object can vanish without trace. If, for instance, a π-meson decays and vanishes, a μ-meson and a neutrino will appear in its place. Unfortunately so far in no known variant of nonlocal theory has fulfillment of the requirement of unitarity been proved. Furthermore, in nearly all the examples of nonlocal theories known to us there were negative probabilities, which is obviously unsatisfactory.

To conclude this brief sketch of the problems associated with the first group of difficulties (the problem of the elimination of infinities), mention should be made of an attempt to circumvent these difficulties – the so-called method of dispersion relations. This is not the proper place to launch into a description of the essence of this method. I will merely mention that its fundamental idea is the construction of a theory in which only experimentally observable quantities, the amplitudes of the probabilities for various processes, will occur. The advantage of such an approach is, in particular,

that the difficulties associated with causality and unitarity are trivially absent. At present this method, which has been developed along new lines by Mandelstam, is being actively pursued by many theoreticians.

Unfortunately, the application of the dispersion relations method is running into great formal difficulties: so far it has not been possible to write down a complete system of equations even for the simplest types of interactions.

All the above-mentioned attempts to circumvent the difficulties involved in the infinities share one trait in common – the difficulties of the second group (i.e., the impossibility of describing the spectrum of elementary particles) are present in them to the same degree as in the orthodox quantum theory of fields.

At the present time about thirty "long-lived" elementary particles are known*. In a certain sense sixteen of the particles are truly dissimilar in their properties, since fourteen have "twins" (antiparticles). These sixteen particles display an astonishing grouping by mass, and the properties of particles having close masses are very similar. Even more amazing is the similarity of the weak interactions responsible for the decay of the particles. These and certain other (see below) regularities are often called the symmetry properties of elementary particles. Up till now it has not been possible to establish the nature of these symmetry properties. In other words, we are not able to predict the properties of elementary particles basing ourselves exclusively on theoretical considerations: The local and nonlocal theories, as well as the method of dispersion relations in its present form, require the introduction of mass, spin (proper angular momentum) and other characteristics as given parameters.

Naturally, the following question arises: are the difficulties of the first and second group related, or are they to a considerable extent independent? There is no agreement on this point. Many physicists apparently adhere to the view that these two groups of problem are related in roughly the same degree as are all things in general in the universe. It is considered likely that the difficulties of the infinities can be eliminated without substantial progress having been made in the understanding of the origin of the symmetry properties. This is a perfectly legitimate standpoint, but not necessarily the only possible one. Another possibility is that the difficulties in the two groups are intimately related. In other words, there exists only one theory free from infinities – precisely the one which automatically predicts the observed symmetries.

If one takes this point of view as a working hypothesis, the search for a new theory becomes closely related to the problem of changing our ideas concerning space and time in the microworld. This is because the symmetries of space-time are the origin of the symmetries of the objects of the quantum theory of fields, and at the same time the structure of space at small distances plays a very important role in the problem of elimination of the infinities. One of the ways of changing our ideas concerning space-time in microregions is the idea of quantizing space.

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* The completely stable particles are the photon, neutrino, electron and proton. The remaining particles are unstable, but their lifetimes are large compared with the times characteristic of processes of particle creation in collisions.

The scope of this article does not permit our listing all works on the quantization of space and time, although their number is relatively small. The most important of these is Snyder's work (1947). His basic idea is that the space coordinates can assume only a discrete series of values: $x, y, z = \pm l_0, \pm 2l_0 \ldots$ and so on, where l_0 is a certain elementary length. What is the physical meaning of this assertion, and what is the formalism corresponding to this idea? These questions are best answered by drawing a parallel between quantum mechanics and classical physics.

It is well known that the foundation of quantum mechanics is the so-called uncertainty principles. Their meaning resides in the fact that there exist physical quantities which cannot simultaneously be measured accurately. Examples of such quantities are the coordinate and the momenta, the components of the angular momentum, and so on. This circumstance is reflected in the apparatus of the theory in the fact that the product of two physical quantities becomes noncommutative. For example, the components M_x, M_y, M_z of the angular momentum obey the relation $M_x M_y - M_y M_x = h \sqrt{-1}\, M_z$, where h is the quantum constant. From these relations it follows that the values of the component of the angular momentum observed in experiment can only be integral or half-integral, i.e., M, say, is 0, $\pm h$, $\pm 2h$ and so on, or $\pm h/2$, $\pm 3/2\,h$ and so on. In the modern local quantum theory of fields the space coordinates x, y, z of a particle commute among themselves, i.e., can be measured simultaneously with perfect accuracy. Snyder suggested that the space coordinates of a particle do not commute among themselves and that they obey a relation of the same type as that written down above for the angular momentum, but with l_0 substituted for h (where l_0 is a certain elementary length, which has the meaning of the minimal distances admissible in the theory). If we set $l_0 = 0$ we obtain the ordinary theory, in which the coordinates of the particle commute among themselves. As the commutation relations for x, y, z are identical with those for the components of the angular momentum, it is evident that the spectrum of possible values of the coordinates is also discrete. Since time and the space coordinates, according to the theory of relativity, enter into all formulae symmetrically (with only one difference, namely that time behaves as a spatial coordinate multiplied by the imaginary unit, i.e., by $\sqrt{-1}$), commutation relations analogous to the above (but without the imaginary unit in the right side of the equation, which gives time a continuous spectrum of values if the space coordinates are discrete) hold between time and the space coordinates in Snyder's theory.

The important achievement of Snyder is that he demonstrated the possibility of constructing a relativistically-invariant apparatus with a discrete spectrum of values of the coordinates. The physical meaning of Snyder's idea is that, in accordance with the above, it is impossible to measure simultaneously and accurately all three space coordinates of a particle (just as in ordinary quantum mechanics it is impossible to determine simultaneously the values of all components of the angular momentum). Measurement of one coordinate, x, say, "hampers" the accurate measurement of the coordinates y and z. In this sense Snyder's theory is nonlocal since its fundamental postulate is that it is impossible to localize a particle (since one cannot accurately measure all three space coordinates of the particle at a given instant of time).

Snyder's idea was not developed further for a fairly long time. Recently a number of interesting results along these lines was obtained by Yu. A. Gol'fand and V. G. Kadyshevskii. However, the possibilities of the theory based on Snyder's idea remain unclear. First of all it must be mentioned that the discrete Snyder space does not, apparently, lead to the required symmetry properties. In this respect the transition from continuous to discrete space introduces little that is new. The investigation of the other problems (infinities, the problems of unitarity) has not been completed as yet.

Even more radical than Snyder's hypothesis is the idea of a finite space-time proposed by Coish (1959). According to this idea, which seems perfectly absurd at first glance, space and time in the microworld are des-cribed not even by a discrete, but by a f i n i t e set (in particular, this means that space consists of a large but f i n i t e number of points). What is attractive in this hypothesis? First, in such a theory infinities are triv-ially absent, as all integrals pass over into finite sums. Secondly, the very fact of the finiteness of the number of points leads to the appearance of a whole series of new symmetry properties of space-time; it is remark-able, further, that the symmetry properties of elementary particles that are generated by this are identical with the most important symmetry prop-erties observed experimentally.

It was noted earlier that the properties of space condition a series of physical regularities even in the local theory. Thus the laws of conserva-tion of momentum and energy owe their existence to the homogeneity of space and time (i. e., to the fact that the internal properties of physical ob-jects do not change when bodies are transferred from one point in space to another, and the physical laws do not change their form with time). Con-servation of angular momentum and, therefore, the appearance in particles of such a characteristic as spin (proper angular momentum), originates in the isotropy of space (invariance of the internal properties of physical bodies under rotations in space).

In elementary particle physics, as noted earlier, several of the symme-tries and conservation laws observed cannot be explained by the symmetries of the ordinary space-time continuum. First and foremost among these are:

a) the quantization of electric charge (the charges of all particles are multiples of the elementary charge of the electron);

b) the existence and conservation of the so-called baryon charge (owing to which decay of a proton into a positron and photon, for example, does not take place);

c) the existence and conservation of lepton charges (owing to which the decay of the μ-meson into an electron and a photon is, apparently, forbidden);

d) the law of so-called combined parity (L. D. Landau) according to which the mirror reflection of a particle is its antiparticle (this law was established experimentally in the beta-decay of the neutron, atomic nuclei and the μ-meson);

e) the remarkable universality of the form of weak interactions responsi-ble for the decay of particles (which consists of the fact that, as apparently indicated by experiments, they are all vectors).

As shown in the above-mentioned work by Coish and in a work by the author (1960), the symmetries listed above appear automatically in the theory exclusively due to the f i n i t e n e s s of space. It is also important to note that the expressions obtained in the theory with finite space for the various kinds of quantities have formally the form required by Einstein's special theory of relativity. In principle this makes it possible to guarantee the relativistic invariance of the theory "in the large".

At the same time it is significant that it is i m p o s s i b l e to introduce m e t r i c relations (i. e., the concept of distance) in finite space. Owing to this in a certain sense the problem of "faster-than-light" signals does not exist, since there is no possibility of introducing such a concept as the velocity of a signal. In other words, in the scheme under consideration it is assumed that the concept of length, i. e., of distance between two points, loses all meaning in the microworld. This circumstance is also attractive; it is worth stressing that such a result cannot be obtained in the continuous space-time manifold.

I think it would be appropriate to quote Riemann in this connection: "The problem of whether the assumptions of geometry are valid down to infinitely small distances is closely related to the problem of the intrinsic cause of the appearance of metric relations in space. This problem, clearly, also belongs to the realm of the study of space, and in considering it one should bear in mind our earlier remark, namely that in the case of the discrete manifold the principle of metric relations has been incorporated in the very concept of this manifold whereas in the case of the continuous manifold it must be looked for elsewhere. Hence either the underlying reality which gives rise to the conception of space constitutes a discrete manifold, or one must try to explain the appearance of metric relations by something external — the forces of constraint to which the real entity is subject"*.

We know that the thought expressed in the concluding works of this brilliant statement has been realized in macrophysics in the general theory of relativity. Perhaps the first possibility indicated by Riemann, discrete space, is also fated to be realized, but this time in the region of phenomena of the microworld.

Earlier it was noted in connection with Snyder's idea that the discreteness of space implies the impossibility of localizing particles. The transition from a discrete but infinite manifold to a finite one may be reduced, first, to the fact that the functions considered on the discrete manifold are periodic. In this sense the conception of finite space is no "crazier" than Snyder's idea of a discrete but infinite space. At the same time the essential difference between the conception of finite space and Snyder's theory is that in the latter the possibility of exact measurement of any one of the coordinates is admitted, whereas the impossibility of attaching the metric to even a one-dimensional finite space implies the impossibility of absolutely accurate measurement of any microparticle coordinate in general.

Thus in a theory with finite space, infinities are absent and a series of new symmetry properties corresponding to the experimentally observed properties of elementary particles appear automatically. However, prospects for further development of this theory are still completely unclear. First of all the dynamical principles which constitute the main core of any

* Quoted from the collection of articles entitled "Ob osnovaniyakh geometrii" (Foundations of Geometry), pp. 323- 324, Moscow, 1956.

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theory of elementary particles have not been formulated (and this is no easy task). The possibility is not to be excluded that in formulating them we will meet some of the "traditional" difficulties (such as the problem of unitarity) which proved catastrophic for other theories.

It is evident from our discussion that it is very difficult to say today what path the development of elementary particle theory will take. From the methodological standpoint the problem of the theory of elementary particles is somewhat reminiscent of the situation in which physicists found themselves when creating quantum mechanics: the laws operative in the microworld are devoid of macroscopic visualizability, and therefore it is very difficult to "guess" the first principles of the theory on the basis of the experimental material. At the time quantum mechanics came into being, however, physicists held within their grasp clear-cut experimental data in qualitative contradiction with the ideas of classical mechanics and electrodynamics (discreteness of the atomic energy levels). In this sense the situation in elementary particle physics is essentially different. Despite the wealth and diversity of experimental facts in this field, no direct contradiction with the ordinary local quantum theory of fields can be perceived so far. Therefore it is still not clear whether a revision of our space-time ideas in the small is at all necessary, or whether the required completeness and logical consistency of the theory can be attained without profoundly altering the foundations.

It is important to stress, in any event, that the investigations connected with the conception of finite space are still at the opening stage and there is still very far to go till the creation of a theory the qualitative conclusions of which can be compared with experimental data. At the same time we should not be intimidated by the novelty and unusualness of the initial idea, as the historical development of physics over the last fifty years has taught us not to consider impossible that which in reality is merely unfamiliar.

THE PROBLEM OF SPACE AND TIME IN ELEMENTARY PARTICLE PHYSICS

R. A. Aronov

The problem of space and time occupies a central position among the philosophical problems of the physics of elementary particles. Many of the difficulties facing elementary particle physics are related to this problem.

J. P. Vigier has pointed out the existence of two opposite conceptions in elementary particle physics: type "A" theories and type "B" theories. * In type "A" theories elementary particles are points and their internal properties are described in an abstract isotopic space which differs in its metric properties from ordinary space and time. In type "B" theories elementary particles are extended and space and time "inside" elementary particles do not differ in their metric properties from ordinary space and time, but new forms of motion of matter qualitatively different from the interactions between elementary particles exist "inside" the elementary particles.

Each conception has advantages and disadvantages. The advantage of the first conception is that it assumes qualitatively different spatial proper-ties (though in an abstract isotopic space). That of the second conception is that it assumes qualitatively different interactions and the spatial exten-sion of elementary particles, now already proved by numerous experiments.

A defect which the two conceptions share is the following spurious dilem-ma: the properties of elementary particles are due either to the peculiari-ties of the interactions or to the properties of space and time. In type "B" theories the properties of elementary particles are conditioned by a specif-if interaction at a deeper level of matter in the sub-microworld. But how-ever much the interactions of the sub-microworld differ from those known to us, the metric of space and time remains the same. In type "A" theories this spurious dilemma arises owing to the concept of elementary particles as points and an erroneous interpretation of Noether's theorem. The con-cept of elementary particles as points necessarily gives rise to illusion No. 1, that space and time act as receptacles of matter and that they are independ-ent of its interactions. Erroneous interpretation of Noether's theorem**

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* See Vigier, J.P. Nekotorye metodologicheskie voprosy teorii elementarnykh chastits (Certain Meth-odological Problems of the Theory of Elementary Particles). Voprosy filosofii, No. 3, p. 119, 1961.
** Noether's theorem deals with the fact that the laws of conservation in the motion of a material system are closely related to its properties and to the properties of space and time. In view of this they can be de-rived theoretically from each other. But one cannot tell, from the mere fact that these properties are re-lated to each other and can be derived theoretically from each other, which are the determining ones and which the determined in objective reality. In Noether's theorem itself there is nothing which tells us whether any kind of subordination is at all present between these properties. Nor, therefore, can one de-rive from Noether's theorem the conclusion which is drawn from it in theoretical physics.

gives rise to illusion No. 2, that the properties of space and time condition the properties of motion and interaction of material objects: "All phenomena taking place in space and time must, so to speak, adjust to these forms of existence of matter"[*].

In one way or other, space and time do not depend on the interactions of material objects both in type "A" theories and in type "B" theories. This statement, as is easy to show, is not purely physical, but goes beyond the limits of physics into the realm of philosophy. Its methodological unsoundness is obvious. And yet theoreticians adhering to both approaches lean on it to a substantial degree, both in attempts to explain new facts and in the search for the future theory of elementary particles. We will illustrate this with the situation which arose in physics in connection with parity nonconservation in weak interactions.

The stupifying impression which the discovery of parity nonconservation in weak interactions made on physicists was in large part due to the basic premise of the theoreticians, that space and time do not depend on the interactions of material objects and condition the properties of these interactions (parity conservation was derived directly from the homogeneity and isotropy of space)[**]. The same basic premise led to the appearance of two competing attempts to explain parity nonconservation, the hypothesis of I. S. Shapiro (anisotropy of space in the small) and the hypothesis of L. D. Landau and Lee and Yang (conservation of "combined parity"). The former attributes parity nonconservation to the asymmetry of space and the latter to the asymmetry of elementary particles. The hypothesis of Landau and Lee and Yang stems directly from the idea that the properties of space are identical in any of its parts and in any interaction, and also that the properties of space condition the properties of interactions. Therefore, according to this hypothesis, parity should not be conserved in any interaction, and in any interaction the mirror reflection of a particle should be an antiparticle. And yet parity is not conserved only in weak interactions, but is conserved in nuclear and electromagnetic interactions, and the mirror reflection of a particle here is the particle and not the antiparticle. Thus a contradiction results.

It is evidence that the basic premises are erroneous, that space cannot condition the properties of interactions and be identical in all its parts and in all interactions. Once the hypothesis of Landau and Lee and Yang are freed from these seemingly obvious basic premises, the contradiction is removed. One then finds that the hypothesis of conservation of combined parity does not at all exclude Shapiro's idea, and that essentially it consists of the following: space is mirror symmetric wherever symmetry with respect to charge conjugation holds, and mirror asymmetric wherever symmetry with respect to charge conjugation is absent. That is, this hypothesis is in reality evidence of the existence of a definite dependence of the properties of space on the properties of material interactions. Analysis of any other facts and ideas in modern physics suggests the same thing[***]. This analysis reveals the falseness of the basic premises of theoretical

[*] S o r o k i n , V. S. Zakon sokhraneniya dvizheniya i mera dvizheniya v fizike (Law of Conservation of Motion and of the Measure of Motion in Physics). UFN, Vol. LIX, No. 2, p. 329. 1956.

[**] See S a l a m , A. Elementarnye chastitsy (Elementary Particles). UFN, Vol. LXXIV, No. 1, p. 157. 1961.

[***] See "Nekotorye voprosy filosofii" (Some Problems of Philosophy), No. 1, p. 44. Kishinev, 1959; "Fizika v shkole" (Physics in the School Curriculum), No. 3, p. 11. 1961.

physics, namely that space and time do not depend on the interactions of material objects, and therefore there exists a dilemma: the properties of elementary particles are due either to the peculiarities of the interactions, or to the properties of space and time. No such dilemma exists. The properties of elementary particles are due both to the peculiarities of the material interactions and to the properties of space and time, because the peculiarities of material interactions and the properties of space and time are interrelated. Space and time are an attribute of matter and cannot be identical in all their parts and in all interactions. Such is the conclusion which follows from analysis of modern physics, and such is the dialectical-materialistic conception of the interaction of space, time and the motion of matter.

It opens up favorable possibilities for the further development of elementary particle physics, including the possibility of synthesis of the two opposing conceptions: type "A" theories and type "B" theories. Obviously, this does not imply a return to classical ideas concerning space and time or retaining the ideas concerning elementary particles as point particles. The contradiction between type "A" theories and type "B" theories can be resolved only on the basis of the idea that "motion is the essence of time and space"*, that qualitatively different interactions condition qualitatively different properties of space and time.

This approach is associated with the idea of the existence of space-time boundaries, with the idea of the discontinuity of space and time. It has all the advantages of the type "A" and type "B" theories in elementary particle physics, and lacks their defects. It even satisfied Bohr's humorous criterion, since it involves rejection of the classical concept of the continuum. True, the hypothesis of the discontinuity of space and time meets with a number of mathematical and physical difficulties. However, the history of the development of this hypothesis from Riemann's time to the present shows that these difficulties are not insurmountable**. At the same time it is becoming increasingly obvious that the outlook for further development of theories based on the space-time concepts of the theory of relativity is unpromising. This was pointed out by Einstein. "I am increasingly inclined to believe," he wrote, "that further progress with the theory of the continuum is impossible, as the Riemann metric suggests itself here as the only natural concept"***.

The attempt to simply banish space and time coordinates from the theory and pass over to momentum space is likewise of no help, as momentum space is related to ordinary space.

One of the attempts to develop a hypothesis of the discontinuity of space and time is the idea of a finite space-time, recently introduced by H.R. Coish and I.S. Shapiro. The idea itself, with its great originality, and the results to which it leads are of undoubted interest. A purely discrete model is considered. Space consists of a finite number of points. In it there is a minimal length l_0. And there are no distances smaller than l_0. One finds that the known symmetry properties of space and time and of the elementary particles are realized in this space. Of course, this is still not a complete

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* Lenin, V. I. Sochineniya (Collected Works), Vol. 38, p. 253.
** See Aronov, R. A. O gipoteze preryvnosti prostranstva i vremeni (A Hypothesis of the Discontinuity of Space and Time). Voprosy filosofii, No. 3, 1957.
*** Quoted from the article by L. Infeld, in: Albert Einstein, Philosopher-Scientist, "The Library of Living Philosophers (Evanston, Ill, 1949).

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physical theory. The dynamical principles have yet to be formulated. In it there is not only much that is unusual — much that is simply unintelligible. Let us take the following example. As was clearly demonstrated by V. G. Kadyshevskii[*], an auxiliary space R of a finite number of points is constructed in the theory. From this space the transition is effected to the real space R', which is also assumed to be a space of a finite number of elements, with a minimal length l_0. This transition is effected in such a way that $l = z l_0$, where z is infinitely large. In order for l to be finite it is necessary that l_0 be zero. But what does the fact that the minimal length of the space R equals zero mean? It is assumed that this means that the space R is continuous. This would really have been the case if the set of points in the space R had been of the power of the continuum. But in reality it is finite or, at best, denumerable. Thus, in this theory much remains unclear.

But even this is not the most important point. The most important point is that this is a purely discrete model in which the qualitatively different metric properties of space and time in the sub-microworld are interpreted as an absence of metrical properties. The hypothesis of Coish and Shapiro is directly affiliated to the ideas of Riemann. Therein lies its strength as well as its weakness. Riemann considered two mutually exclusive possibilities — the purely continuous and the purely discrete model, and demonstrated that in the former case the metric properties of space are determined by material interactions and "in the case of the discrete manifold the principle of metric relations is incorporated in the very concept of this manifold"[**]. But in reality both the metric properties of space and its discreteness are conditioned by the specific material interactions of the sub-microworld, and therefore to them cannot correspond a purely discrete model. This is why the idea of a finite space-time, which rests on this second possibility, must be considered only as a first step toward the future synthesis of the two possibilities.

The hypothesis of the discontinuity of space and time is based on the fact that in the world there exist qualitatively dissimilar types of interaction. All are interwoven in a complex pattern. However, there exist space-time regions in which one or given type of interaction is the determining one. Outside this region it plays a secondary accessory role and a different type of interaction is dominant. Thus, according to the hypothesis of the discontinuity of space and time, the boundary separating the region in which electromagnetic interactions are dominant from that in which nuclear interactions are dominant occurs at distances of the order of $10^{-13} - 10^{-14}$ cm; the lower boundary of the region of strong interactions, which separates it from the region in which weak interactions are dominant, lies at distances of the order of 10^{-17} cm. Beyond this boundary weak interactions, which differ essentially from the other types of interaction, condition qualitatively different properties of the space and time (metric properties, symmetry properties and so on), i. e., here, as M. A. Markov remarks, "a fundamentally new world of physical phenomena is revealed... we are dealing with a further change of our ideas concerning space and time, in that interpretation of these ideas which was formed in the process of

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[*] See Kadyshevskii, V. G. K teorii diskretnogo prostranstva i vremeni (A Theory of Discrete Space and Time), DAN, Vol. 136, No. 1, 1961

[**] Riemann, B. Sochineniya (Collected Works), Moscow-Leningrad, 1948, p. 291.

macroscopic human activity and which becomes unsuitable in the other re-
gion of physical phenomena"*.

   And therefore the minimal length l_0 is a spatial boundary in the micro-
world separating qualitatively dissimilar space-time regions. Extrapola-
tion of classical ideas on space and time to distances smaller than l_0 is in-
admissible not because there are no distances or time intervals there but
because beyond this boundary space and time have qualitatively different
properties.

   Thus the basic premise of modern elementary particle physics —
that the properties of space and time do not depend on the interac-
tions of material objects — and the dilemma which follows from it — the prop-
erties of elementary particles are due either to the peculiarities of inter-
actions or to the properties of space and time — are not adequate to reality
and therefore cannot assist in the further successful development of elemen-
tary particle physics. It is our own profound conviction that further success-
ful development of elementary particle physics is possible only if based on
a dialectical-materialistic conception of the interrelation of space, time
and the motion of matter and on the hypothesis of the discontinuity of space
and time.

* Markov, M. A. Giperony i K-Mezony (Hyperons and K-Mesons), p. 301. Moscow. 1958.

QUANTUM PHYSICS AND THE TRANSMUTABILITY
OF ELEMENTARY PARTICLES

M.E. Omel'yanovskii

If one assumes that the qualitative diversity and changeability of the phenomena of the observable world are not illusory, cognition of the observable world should presuppose motion of the substance which is its base. This applies equally well to continuous substance (the material elements of the Ionian thinkers, the matter of Aristotle, the matter of Descartes, the ether and field of classical physics) and discrete substance (the atoms of the ancients, Newton's hypothetical simple perfectly rigid particles, the material points of Hertz). In ancient atomism the diversity and change of the observable was explained by the fusion of moving "indivisibles" and decomposition of bodies into the original particles. On the other hand, the evident repetitions and relative constancy in nature would be impossible if bodies consisted of an infinite number of infinitesimal parts.

Thus ancient atomistics already saw motion as an inseparable property of matter, although it treated motion — as well as matter — one-sidedly from a standpoint most concretely expressed in the mechanical views of classical physics.

The development of classical physics, despite additions and innovations, did not alter the mechanistic view of motion of the ancient atomists. Newton was a supporter of ancient atomism, and in perfecting the concept of particles composing a body he did not go beyond the mechanistic view of motion. It might seem that the discovery of the law of conservation of energy and the creation of classical field theory and statistical physics could destroy the idea that invariable and forever specified particles moving in space are the foundations of the universe. However, the physicists who discovered the law of conservation of energy and created the classical theory of fields and statistical physics thought otherwise. The views held by the great physicists of the nineteenth century (Helmholtz, Maxwell, Gibbs, Boltzmann and others) responsible for the classical period of development of physical science are well known; these views were along the lines of classical atomism.

At the same time it must be recognized that such a situation was unavoidable: the classical period of physics did not yet have the experimental material required to restate the problem of the motion which takes place at the foundations of matter in a spirit completely different from the mechanistic tradition. This material was gathered much later. On the basis of experimental data of which no one in the nineteenth century

had even dreamed, the theory of relativity and the development of quantum theory prepared the necessary prerequisites for a solution of this problem which tends toward the idea of the transmutability of elementary particles.

A theory of the development of matter in correspondence with the experimental data on the transmutability of elementary particles has long been worked out by philosophy. Advanced philosophy, which has always provided natural science with leading ideas (atomistic view, conservation of motion and matter of Descartes, Lomonosov, et al., Kant's nebular hypothesis, and so on), now, in dialectical materialism, provides science with a concept of development in its most profound and complete form.

First of all, the following two features of the dialectical view of motion and the development of matter must be stressed.

Firstly, motion, the development of phenomena and processes in the world, is a struggle of opposites, the division of a unity into mutually exclusive opposites and their reciprocal relation. Lenin in his fragment "On the question of dialectics" (K voprosu o dialektike) defined the splitting of a single whole and the cognition of its contradictory parts as the essence of dialectics. Each contradictory aspect of a unit develops into its own opposite, and the opposites merge into each other; this resolves the contradiction in question, giving rise to a new phenomenon, the process with the contradiction inherent in it. Without the union of opposites there is no developing phenomenon, no process; without the struggle of opposites there is no development, no transformation of the given phenomenon into a new one.

Secondly, development as unity of opposites implies that the unity of opposites is relative, whereas the struggle of opposites is absolute.

The dialectical conception of the development of phenomena is compatible neither with subjectivism, which transforms the world into a chaos of empty changes, nor with metaphysical ideology in general, which perpetuates constancy and rest in some form or other.

Does the dialectical conception of development cover the data on the transmutability of the elementary particles which, according to the ideas of modern physics, lie at the foundation of known matter? The following discussion will be entirely devoted to this question.

Once more we stress that, according to the experimental data of present-day physics, transmutability is an essential property of elementary particles. Motion is the means of existence of matter; further, motion is not only change of position but also change of quality — the experimental data on elementary particles provide a surprisingly conclusive confirmation of this crucial proposition of dialectical materialism and endow it with new content.

Such elementary particles as, say, photons can be created in quantum transitions in atoms, in the accelerated motion of charged particles, in the decay of the π-meson and certain other particles, in the annihilation of electrons with positrons and, in general, of particles with their antiparticles. They can also be absorbed, or "disappear", in interactions with molecules, atoms and nuclei; they can be scattered by other particles and form so-called pairs (electron-positron). Photons themselves exist only in motion at the speed of light; their "stopping" means their absorption or transformation.

All other elementary particles are likewise capable of transformation and indeed do transmute into each other under appropriate conditions;

this has been proved experimentally, but we will not quote the data[*]. We will only mention two points which have a bearing on the discovery of the law of universal transmutability of elementary particles. Firstly, this law in its particular form was essentially contained in Dirac's theory, which gave a synthesis of quantum and relativistic ideas for the electron. Secondly, the starting point of the experimental demonstration of this law was the discovery of the positron (1932) and its conclusion the discovery of the antiproton (1955). The discovery of the positron led to the discovery of the transformation of the electron-positron pair into photons and back. The discovery of the antiproton (and later the antineutron) overthrew the assumption, which had a certain foundation (smacking of classical atomism), that the existing heavy elementary particles (proton and others) always remain heavy particles and cannot transform into lighter particles (and conversely light particles always remain light particles).

Transmutability is characteristic of all known elementary particles, the transformations of which obey definite laws of conservation. It is asserted that the laws of conservation limit the possibilities of transformation of elementary particles. In practice this assertion stresses the fact that the transformations of elementary particles into one another are not the chaos of all possible transformations but r e g u l a r transformations.

The laws of conservation ensure transformations of elementary particles agreeing with their general and specific nature. We are led to conclude that the transformation of elementary particles and the conservation in this process of definite quantities are two aspects of one and the same thing. In the laws of conservation, some of which were discovered long before modern physics, we see that which is constant, that which is conserved in the transformations. Before attempting a closer look at the relationship between conservation and transmutation in elementary particle physics, we will consider this question in a historical perspective.

The notion of change (in bodies) based upon the fusion and separation of discrete primary particles presupposes the conservation of the number of such particles (they can only change their configuration and relationship with each other). In keeping with this view, conservation of matter in its transformations was conceived ultimately as the conservation of the number of such particles, i.e., the development of uncreatable and indestructible matter was reduced to the motion (behavior) of discrete primary particles.

This mechanistic view of the development of matter, dominant in classical physics, could not be shaken by quantum mechanics. It was possible to assume that fundamental particles (the form and number of which, according to quantum-mechanical ideas, do not change) move in accordance with the laws of quantum mechanics (such mechanistic ideas in the "quantum" manner are current in the modern philosophical literature abroad).

The mechanistic view of the development of matter led to a mechanistic treatment of such a fundamental conservation law as that of energy. Helmholtz, who shares the honor of discovering this law with Mayer and Joule, treated the law of conservation and transformation of energy, in the spirit

* See M a r k o v, M. A. O sovremennoi forme atomizma (The Modern Form of Atomism). Voprosy filosofii, No. 3 and 4, 1960; T a n i m, I. E. Sovremennoe sostoyanie problemy elementarnykh chastits (Present State of the Problem of Elementary Particles). Vestnik AN SSSR, No. 10, 1960; T e r l e t s k i i, Ya. P. Vzaimoprevrashchaemost' elementarnykh chastits (Transmutability of elementary particles), in a collection entitled "Filosofskie voprosy sovremennoi fiziki" (Philosophical Problems of Modern Physics). Moscow, 1959.

of mechanistics, as (in particular) proof of the reducibility of all physical processes to mechanical motion. Engels critically analyzed this mechanistic treatment of the law. He identified the transmutability of forms of motion as the essence of the discovery of Mayer, Joule and Helmholtz and combined the laws of conservation of energy and matter into a whole. These ideas of Engels found application in the physics of the present era.

In modern physics — especially in connection with the discovery of the transmutability of elementary particles — the conservation laws of classical physics were enriched in content and assumed certain new aspects; also, new conservation laws were discovered. The new contribution of modern physics to the understanding of the laws of conservation consists of the following: invariability, constancy or conservation is now considered in organic relation to the development of matter, and this development is understood as a transformation of the various forms of matter into each other (modern physics does not furnish any evidence for the idea that physical changes are reducible to the motion of certain perpetual constant elements).

According to modern ideas the interactions of elementary particles obey the following conservation laws, which fall into two classes.

Exact conservation laws, which include: the laws of conservation of energy, momentum and angular momentum, electric and nuclear charge and lepton number, and conservation of combined parity. These laws are valid in all interactions of elementary particles (strong, electromagnetic and weak) and are not violated in any of these; this is why they are called exact.

Inexact, or approximate, conservation laws, which include: the laws of conservation of parity and strangeness (violated in weak interactions) and the law of conservation of isotopic spin (violated in weak and electromagnetic interactions).

The development of modern physics shows that conservation laws are not absolute. Each of these, as is becoming more and more clear, is valid not generally but rather under certain conditions the determination of which implies cognition of a new level of development of matter and of the laws belonging to this level. Therefore the laws of conservation change in content and form, becoming more specific and profound; likewise, the class to which they belong also changes.

Thus before taking on its present form the law of conservation of nuclear charge underwent certain modifications. This law, which says that the transmutation of the nucleons which constitute the atomic nucleus into leptons and photons is impossible, had the following form: in particle transformations the number of protons remains constant before and after interaction, or, symbolically,

$$N_p = \text{const}.$$

After the discovery of the neutron, the antiparticles and the hyperons (and of their decay reactions), the law of conservation of nuclear charge assumed its present form:

$$N_p + N_n + N_\Lambda + N_\Sigma + N_\Xi - (N_{\bar{p}} + N_{\bar{n}} + N_{\bar{\Lambda}} + N_{\bar{\Sigma}} + N_{\bar{\Xi}}) = \text{const},$$

where N denotes the number of particles, and p, n, Λ etc. the proton, neutron, various hyperons and correspondingly their antiparticles.

Let us consider yet another example. The laws of conservation of energy and momentum, which in classical physics led, so to speak, separate lives, merged together in the theory of relativity, assuming new facets and changing into a law broader than the classical ones. The concepts of energy and momentum changed correspondingly: they emerged from their "classical" independence to form two internally related aspects of the same essence (mathematically expressed in the concept of the four-dimensional energy-momentum vector). The rest mass, a concept unknown to classical physics, made its appearance and is now of great significance in the theory of elementary particles. Correspondingly, mass and energy proved organically related to each other, which led to important theoretical and practical conclusions.

In view of the ideas expressed above, the law of conservation of parity is of special interest. The quantum concept of parity is inseparable from the principle of mirror symmetry, on which we shall dwell for a while later. The law of parity conservation was considered an exact law until the experiments proposed by Lee and Yang. The violation of this law in weak interactions gave rise to serious difficulties. Attempts at resolving these led to L. D. Landau's hypothesis and to a new exact conservation law, that of combined parity.

Skipping ahead for a moment we might state that every conservation law currently known to be exact may change (and will change under appropriate conditions) into an approximate one, but this will be the prerequisite and grounds for discovering a new, broader and more specific exact law. That is, the difference between the concepts of exact and approximate conservation laws is relative and these laws are related by transitions. It could not be otherwise, as the various conservation laws discovered by man are actually the various manifestations of a universal law of conservation of matter and motion.

The conservation laws which are obeyed by the transformations of elementary particles express the uncreatability and indestructibility (conservation) of ever-developing matter at the deepest level now known. The uncreatability and indestructibility of developing matter is one of the preconditions for its objectivity and reality; therefore the conservation laws discovered and to be discovered by natural science repeatedly confirm the objective reality of the developing world, and in turn natural science, as it brings the conservation laws to light, rests upon recognition of the objective reality of the developing world, i. e., on the recognition that an external world exists and develops independently of human understanding.

Modern physics did not confine itself to studying the connection between conservation and transformation as applied to fundamental particles. In its concepts and propositions pertaining to the transformations and interactions of elementary particles, it shed light on the basis of this union and discovered a mutually determinant connection between the conservation laws and the so-called symmetry principles. Many forms of symmetry had been discovered by classical physics (certain of these were known even before the existence of science) where, however, they often did not play a significant role in the study of phenomena and their laws. In modern physics, on the other hand, not only were previously unknown forms of symmetry discovered, but it was found that there was a close connection between symmetries and conservation laws, and that the former were of great significance in physical theory. In the symmetry principles of modern physics (and of

elementary particle theory), if one approaches them from the philo-
sophical standpoint, the profound truth of Lenin's words is clearly seen:
"Dialectics in its proper sense is the study of contradiction in the v e r y
e s s e n c e o f o b j e c t s : not only are appearances transitory, mobile,
fluid, demarcated only by conventional boundaries, but the e s s e n c e of
things is so as well"*.

The symmetries in elementary particle theory are precisely the "con-
tradictions in the very essence of objects", "translated" into the language
of modern physics; these we shall now consider.

Above it was noted that conservation laws and symmetry principles are
related. A definite symmetry entails a definite conservation law; a given
conservation law leads to a corresponding symmetry; or, if a definite
symmetry principle is known, it must lead to a definite conservation law
and vice versa, although the path connecting symmetry and conservation
law is not always simple, and to find the link between them requires much
experimental and theoretical work. The connection between symmetry
principles and conservation laws points to the deeper content of conserva-
tion laws and determines the great heuristic role of symmetry principles
in the understanding of laws of nature. Let us take a closer look at the
philosophical problems involved here.

Symmetries in nature are expressed mathematically by transformations
of the space and time coordinates. The equations which express the laws
of nature should be invariant under such transformations. The invariance
of these equations under transformations of a given kind leads to a given
conservation law. The symmetries and the relations between them known
to modern physics do not exhaust the wealth of symmetries and relations
present in nature. Let us consider a few of the most important symme-
tries.

S y m m e t r i e s o f c l a s s i c a l p h y s i c s . In classical mechanics
we have the transformations of displacement, shift of the time origin, ro-
tation, space inversion, time inversion and the Galilean transformations.

Transformations reflect symmetries; for example, the transformations
of space inversion reflect the symmetry of right and left, or mirror sym-
metry; the Galilean transformations reflect the symmetry of rest and of
uniform rectilinear motion, and so on. Symmetries leads to conservation
laws (the conserved quantities are the invariants of the corresponding trans-
formations); thus the invariance of physical laws under spatial displace-
ments leads to the law of conservation of momentum, and that under time
translation leads to the law of conservation of energy. Every symmetry
does not lead to a conservation law in classical physics, e. g., the symme-
try between right and left. The law corresponding to this symmetry appears
in quantum theory. It is the law of parity conservation.

S y m m e t r i e s o f t h e t h e o r y o f r e l a t i v i t y . This theory does
not simply borrow the symmetry principles of classical physics. It intro-
duces new symmetries, or new invariances, corresponding to regularities
which cannot manifest themselves within the region of applicability of clas-
sical theories. As a result in the theory of relativity the classical sym-
metry principles change at the corresponding points. Thus the Lorentz
transformations express not merely the symmetry between rest and uni-
form and rectilinear motion (as do the Galilean transformations in classi-

* L e n i n , V. I. Sochineniya (Collected Works), Vol. 38, p. 249.

cal mechanics), but also the symmetry between space and time, which is foreign to classical physics. In the theory of relativity the physical laws are invariant under rotations of four-dimensional space-time (the latter transformations decompose into spatial rotation and the Lorentz transformations).

Symmetries of quantum theory. This theory introduces new symmetries corresponding to the regularities of the microworld which it discovered and about which pre-quantum physics could not have any idea. Such are the symmetry between particle and wave, charge symmetry, or the symmetry between particles and antiparticles, and isotopic spin invariance. Manifestations of profound symmetries are the laws of conservation of nuclear and lepton charges and the law of conservation of strangeness. Quantum theory even subjected the symmetry principles of pre-quantum physics to profound revision, a remarkable example of which is the new ideas on symmetry between right and left.

The discovery of the quantum symmetries meant that physics began to study the contradictions at the very foundations of matter. In modern physical theory symmetries have assumed considerable heuristic significance and play a particularly important role in its development. Suffice it to recall that the discovery of symmetry between particle and wave determined, so to speak, the principal axis of quantum ideas: it is well known that the laws of quantum mechanics are invariant with respect to symmetry between particles and waves, i.e., quantum mechanics reflects this symmetry (just as the theory of relativity reflects the symmetry between space and time). Analogously, the discovery of the positron and other antiparticles was a consequence of the recognition of the invariance of physical laws under Lorentz transformations and with respect to symmetry between particle and wave.

Of great interest, however, is an approach to the problem of symmetry which is emerging more and more clearly in modern physics and which, from the philosophical standpoint, becomes completely clear in the light of the dialectical principle of contradiction. In this respect the discovery of parity nonconservation and its interpretation provide us with the required bearing.

We will not go into details of the quantum concept of parity. It characterizes the change in the wave function describing the state of a microparticle upon mirror reflection of the space coordinates (the coordinates x, y, z are replaced by $-x$, $-y$, $-z$). The parity concept makes it possible to express mirror symmetry mathematically in the form of a conservation law. During the period when quantum mechanics was being developed it was found that the concept of parity is a fruitful one, and it was demonstrated that parity conservation is a consequence of the invariance of the wave equation with respect to right-left symmetry. For every state of an atomic system one can determine the "mirror state" which is related to the former state in the same way as any object is related to its own reflection in a mirror.

The law of conservation of parity, or correspondingly the principle of mirror symmetry, held — so it was believed until recently — in all regions of the macro- and microworld. Experimental data on weak interactions, however, raised the problem of mirror symmetry anew. As was shown by Lee and Yang, it follows unambiguously from the experiments on K-mesons that parity is not conserved in weak interactions, i.e., in weak interactions there is an asymmetry between right and left.

Thus the situation was that the law of parity conservation operated in strong and electromagnetic interactions but ceased to operate in weak interactions. In other words, it became necessary to admit that space was uniform and isotropic and at the same time asymmetric with respect to right and left. There was no consistency.

Among the possible ways of solving the difficulties, the hypothesis introduced by L. D. Landau and, independently, by Lee and Yang is of great philosophical interest.

In order to consider this hypothesis and its consequences, which are important for the problem of symmetry in nature, it will be necessary to dwell on the question of the symmetry between particles and antiparticles.

It was once believed that there existed a pronounced asymmetry between positive and negative electricity, not manifested in electromagnetic phenomena but with roots extending to deep, as yet undiscovered laws affecting elementary particles. The first decisive blow to this belief was the discovery of the positron, which is the direct opposite of the negative electron. Now (after many theoretical investigations and the discovery of the antiproton and other antiparticles) the principle of symmetry between particles and antiparticles, or principle of invariance under charge conjugation, has become one of the leading theses of the theory of elementary particles.

However, it became clear recently that the situation with regard to the principle of charge symmetry is far from simple, and that in a certain respect it is similar to the situation which prevailed with the principle of mirror symmetry. Experiments on beta-decay have shown that in weak interactions not only parity conservation but even invariance under charge conjugation (i.e., the principle of symmetry between particles and antiparticles) is violated. It might appear that a return to the original idea of asymmetry of positive and negative electricity, suitably modified, must now take place.

In reality everything has turned out differently. Landau's hypothesis has provided a deeper understanding of symmetry in nature than was possible before.

In strong and electromagnetic interactions, as shown by experiments, symmetry between particles and antiparticles and symmetry between right and left are independent of each other, i.e., both charge and parity are conserved. As to weak interactions, Landau suggested that in these interactions the above-named conservation laws are not obeyed separately, but that a law called the law of conservation of combined parity, is fulfilled. This law consists of the following: with every particle is associated an antiparticle with mirror symmetric spatial properties; correspondingly the transformations of charge conjugation and space inversion are united in a new transformation called by Landau combined parity; physical laws are invariant under combined parity, i.e., with respect to charge and simultaneously to mirror symmetry. Thus Landau's hypothesis excludes mirror asymmetry of space and charge asymmetry of matter; at the same time, it does not permit the conversion of mirror and charge symmetry into absolute principles.

Thus, essentially, Landau's hypothesis states the problem of the symmetry and invariance of the laws of nature in a completely new way. Those symmetries which seemed exact in reality proved to be approximate; at the same time a new exact symmetry, a unique union of old symmetries that had become approximate, was discovered. One is led to believe that the difference between an exact and an approximate symmetry, and

correspondingly between exact and approximate conservation laws, is introduced by our reflection and has no absolute nature: approximate and exact symmetries are not separate, just as the relative and the absolute are not in dialectics.

From this point of view the concept of symmetry in physics, is, so to speak, a fluid concept. The various symmetries cease to lead separative lives; they are bound together by transitions and cover, in an ever more profound and complete manner, the phenomena and processes of nature and their essence and laws. The discovery of combined parity is an important step toward the establishment of the universal and concrete relationship between symmetries in nature. A more complete solution of this problem by physics will make it possible to determine, in particular, why certain symmetries are of a broader nature than others, why certain symmetries exist in precisely some, and not in other, interactions, and so on — briefly, it will make it possible to clarify the forms of symmetry more completely and, in general, to solve the problem of the correlation and hierarchy of symmetries.

In the perspective of what we have been saying, the following problem is of philosophical interest: is a really unified picture of moving matter expressing both the microworld and the vast expanses of the universe possible?

For dialectical materialism the answer to this question can only be in the affirmative. The world is one, and the true unity of the world resides in its materiality; the world, i.e., moving matter, is cognizable. From these assumptions of dialectical materialism it follows that a world picture expressing ever-developing matter is possible, and that this picture must include knowledge — provided such knowledge has been obtained — of the subatomic and atomic worlds, macroworld and world of cosmic scale, as these worlds, despite their qualitative dissimilarity, are ultimately one and the same world of developing matter.

As far as inorganic nature is concerned, at various stages in its historical development physics introduced the fundamental physical theory which was the most advanced for its time and which, so it appeared, was to lead to a unified picture of the world as then known. Thus the achievements of classical mechanics gave rise to the mechanical picture of the world, according to which natural phenomena were reduced to the motions by Newton's laws of perpetually given particles of substance. The attempt to understand the world in terms of classical mechanics, as the theory of relativity and quantum theory have proved, represents a relative truth valid only within definite limits.

The same lack of success, and for the same reasons, characterized the attempt to construct a unified picture of moving matter based on the classical theory of electromagnetism. Today the problem is to create a unified theory of moving matter based on the theory of relativity and quantum theory. Mention should be made of the following philosophical aspect of the problem, one which applies to any scientific picture of the world.

It is not possible to have a scientific world picture which remains stable and unchanging with the progress of science in details as well as fundamental traits. The modern physicist has, in one way or the other, accustomed himself to this idea; for the dialectical materialist, it was obvious from the start. When the electromagnetic picture of the world was establishing itself in physics abroad in the nineteenth and twentieth centuries, Lenin

wrote the following words expressing his disapproval of the spiritualistic philosopher Ward who attributed to materialism a "mechanical" world picture: "It is, of course, sheer nonsense to say that materialism ever maintained or necessarily professed a "mechanical" and not an electromagnetic or other immeasurably more complex, picture of the world of m o v i n g m a t t e r"*.

Precisely such a vastly more complex world picture, as compared with the mechanical or electromagnetic one, is that created in modern physics. Since it rests on the achievements of relativistic and quantum physics, it may be called the relativistic quantum picture.

At present this picture is only in the process of becoming established, and is very far from being the orderly whole, the unified consistent picture which the mechanical world picture was in its time. This is to be attributed firstly to the absence so far of a unified relativistic quantum theory of elementary particles free from internal contradictions. Instead there are many theories, each applying to certain forms of particles and their interactions (e. g., quantum electrodynamics, despite the difficulties it contains, solves the problems of the interaction of electrons and positrons with photons; the meson theory, unrelated to quantum electrodynamics, investigates the interaction of mesons with nucleons). A discussion of the difficulties and contradictions in modern elementary particle theory would take us far from our present theme. Let us merely stress that the creation of a unified relativistic quantum theory of elementary particles and associated scientific world picture will be of great progressive value, for it will mean that a new step has been taken toward the cognition of the material world.

Among the attempts at creating a picture of the world as moving matter based on quantum physics, one which is of great philosophical interest is the p r o g r a m of a unified theory of matter (we are mainly of the program, as no c o m p l e t e theory exists as yet) which was proposed by Heisenberg and which takes into account, to a certain extent, the corresponding works of Dirac, Louis de Broglie and other scientists.

The great superiority of this program over the mechanical and electromagnetic world pictures, which are now part of history, is that it is based on the idea of the transmutability of all elementary particles, and not on some constant element or invariable substance. Since from the standpoint of this idea, which rests on experimental data, elementary particles represent a unified organically bound whole, the foundation of all physical phenomena must consist of an "Urmaterie" or unified field the quanta of which are elementary particles of all kinds. This field is characterized by a spinor operator wave function, and to combinations of the latter correspond elementary particles. This field is nonlinear, i. e., its equation expresses the fact that this fundamental field interacts not with other fields but with itself to produce elementary particles. Thus Heisenberg's nonlinear fundamental field is a kind of illustration of Engels' philosophical remark: "Spinoza's s u b s t a n c e i s c a u s a s u i expresses interaction very well"**.

According to Heisenberg the equation which expresses the motion (interaction) of "Urmaterie" should be invariant under all the known transformations with which the theory of elementary particles deals. Having found this equation, Heisenberg obtained from it masses of elementary particles and

* L e n i n, V.I. Sochineniya (Collected Works), p. 267, Vol. 14.
** E n g e l s. Dialektika prirody (Dialectics of Nature), Moscow, p. 183, 1955.

the elementary electric charge more or less close to their experimental
values as well as other data on elementary particles.

Despite the definite, chiefly qualitative, positive results of the theory,
the attitude of theoretical physicists toward it, to use I. E. Tamm's ex-
pression, "fluctuates to an extreme degree". It is recognized that the
mathematical foundation of this theory is far from satisfactory. Further-
more, the indefinite metric introduced by Heisenberg and the associated
"negative probabilities" (they are intended to free the modern theory of
elementary particles from divergences, i.e., from the infinite values for
the mass, charge and other elementary particle constants present in the
theory instead of the finite values known from experiment) still leave cer-
tain important points pertaining to this problem unclear, as shown by Tamm.
Finally, Bohr's well-known statement that for a new theory it is "not crazy
enough" throws the methodologically weak point of Heisenberg's theory into
high relief. In the given case Bohr stressed that the ideas of Heisenberg's
theory, the "negative probabilities", for example, are not "wild" enough
to construct a truly new theory.

Heisenberg himself states that his equation may possibly correctly ex-
press the law of nature which applies to matter. However, he continues,
there is still no final solution; it will come only with time, by exact math-
ematical analysis of the equation itself and comparison with the ever-in-
creasing mass of experimental material*.

In our opinion in creating a unified theory of matter one should, firstly,
consider the possibility, among others, of a profound revision of ideas on
symmetry and invariance in the spirit of the considerations presented above;
and, secondly, allow oneself to be guided not only by the methodological
principle (explaining the whole by means of its parts) but also by the dialec-
tically related principle, explain the parts by means of the whole. In parti-
cular one must take into account the presence of gravitational fields, with-
out which it is hardly possible to construct a truly unified theory of matter
in the proper sense of the word.

It must be assumed that the unified theory of matter will positively solve
the problem of the revision of space and time concepts with application to
the scale of elementary particles. The need for such revision is dictated
both by general and by particular considerations, on which it would be in-
appropriate to dwell in the present article. The problem arises of the quan-
tization of space and time, i.e., of the possible discreteness of space and
time. This is a very old problem from the philosophical standpoint. Thus
Democritus assigned an atomistic structure to space and time as well as to
motion: there exist minute parts of space and time, as well as discrete units
of motion, which are not perceptible to the senses and which are conceivable
only through scientific thinking. These ideas of Democritus are little known
to naturalists.

The conception of an abstract, pure discreteness of space, time and mo-
tion, as well as the abstract atomistic conception of matter, fails to corre-
spond to the facts; its one-sidedness was overcome in the history of phil-
osophy and natural science. The dialectical materialistic point of view on
the question of the continuity and discontinuity of space and time is concise-
ly expressed in the following words of Lenin: "Motion is the essence of
space and time. Two fundamental concepts express this essence: (infinite)

* See W. Heisenberg. Physik und Philosophie, Stuttgart, p. 159, 1959.

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continuity (Kontinuität) and "punctuality" (= denial of continuity, d i s c o n-
t i n u i t y). Motion is the unity of continuity (of time and space) and discontin-
uity (of time and space). Motion is a contradiction, a unity of contradictions"*.

Philosophically speaking, the various approaches to a solution of the
problem of quantization of space and time cannot circumvent this remark
by Lenin. Thus Heisenberg postulates a third universal constant (aside
from Planck's constant and the velocity of light, which are already known),
a "fundamental length" of the order of 10^{-13} cm (comparable to the radius
of the lightest atomic nucleus) in a region smaller than which modern quan-
tum field theory is inapplicable, i.e., he postulates a length distances small-
er than which are meaningless. Heisenberg introduces this third universal
constant for considerations of dimensionality in an attempt to resolve the
difficulties of the divergences.

It is hardly possible to solve the problem of the fundamental length by
a purely atomistic and formal method. In our view, its solution requires
that the general theory of relativity and quantum field theory be joined to-
gether, as the problem of the quantization of (real) space and time cannot
be solved outside of, and independently of, the problem of the continuity-
discontinuity of moving matter.

• L e n i n, V.I. Sochineniya (Collected Works), Vol. 38, p. 253.

THE DEVELOPMENT OF THE STUDY OF ELEMENTARY
PARTICLES AS COGNITION OF INCREASINGLY
PROFOUND REGULARITIES OF THE MICROWORLD

A.A. Sokolov

   One of the fundamental problems of the theory of elementary particles
is the study of the real microworld and, first and foremost, of the simplest
forms of particle motion which, to a certain extent, determine more com-
plex phenomena as well.
   All these questions are very intimately related to general philosophical
problems concerning the cognizability of the world around us. Therefore
it is not surprising to find that every important discovery in the realm of
elementary particle physics has been the subject of much methodological
discussion.
   It is well known that the development of classical physics took place
under the banner of the mechanistic world outlook. The mechanistic out-
look reached its most advanced stage of development in the doctrine of Lap-
lace. Laplace maintained that the development of any phenomenon could
be predicted uniquely with any accuracy, at least in principle, by means
of the laws of classical mechanics.
   It should be remarked that, in practice, the first blow to Laplace's idea,
delivered by the so-called H-theorem of Boltzmann, goes back to the period
when the mechanistic outlook was prevalent. According to this theorem the
irreversibility of processes in the kinetic theory of gases is a specific reg-
ularity of aggregates of particles and can in no way be explained completely
on the basis of the laws of elementary motions alone. It should also be
stressed that even the simplest claim of the mechanists, according to which
Newton's laws allow, as it were, ultimate knowledge of the motion of even
the simplest particle and Maxwell's equations allow ultimate knowledge of
the nature of light, proved exaggerated. The discovery that light has cor-
puscular as well as wave properties and the establishment in high-velocity
mechanics of a quantitative relationship between the two dissimilar quanti-
ties, mass and energy, demonstrated that the classical laws were applicable
only within definite limits. All these discoveries obliged many scientists
to revise again their philosophical views on the cognizability of the exter-
nal world. Unfortunately, such revision does not always lead even great
scientists to progressive conclusions. For example, the results of the
physical investigations of E. Mach, are even now playing an exceptionally
important role in, say, the study of the motion of bodies with supersonic
velocities. Yet Mach regarded the limitations of the mechanistic world
outlook as an expression of the subjectivity of our knowledge in general

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(revival of positivism), and he denied the existence of an objective reality beyond the realm of sensory experience. Together with Oswald he fought till the end of his life against the atomistic hypothesis, which he regarded as an artificial contrivance introduced by scientists for the sake of convenience in interpreting phenomena in the microworld.

In precisely the same way, the well-known French mathematician and philosopher H. Poincaré, who formulated many of the propositions of the special theory of relativity independently of and practically simultaneously with Einstein, regarded the discovery of new, previously unknown regularities of the microworld as a "crisis" in physics.

All such erroneous methodological conclusions were subjected to severe criticism in Lenin's well known "Materialism and Empirio-Criticism" (Materializm i empiriokrititsizm), in which Lenin demonstrated that the "crisis" in physics arose simply because the scientists did not know dialectics.

Our knowledge of nature — and nature exists independently of the subject — follows an asymptotic approach to the truth; the appearance of a new theory implies a further development, rather than the downfall of the old theory, a development which provides an interpretation of the finer regularities that sometimes lie outside the field of vision of the old theory.

Lenin's statement concerning the inexhaustibility of the electron actually proved to be the guiding star which set modern physics on the only correct course of development.

The so-called correspondence principle plays an important part in correct evaluation of the scientific significance of physical theories. According to this principle the fundamental results of the preceding theory should as a rule follow from the next at some limit.

For example, for $h \to 0$ the results of quantum mechanics should pass over into classical results. Likewise, for $\beta^2 \to 0$ the results of the relativistic theory should pass over into nonrelativistic ones. We will not be concerned here with the many possible exceptions to this rule. In any case, the correspondence principle helps illustrate the asymptotic approach of the development of the theory of elementary particles to a more exact revelation of the objective regularities of the microworld[*].

When a new theory is being created and does not as yet allow investigation of all phenomena, the correspondence principle can safely be used to extend the results of the old theory to the new theory. Thus, for instance, Bohr's quantum theory made it possible to calculate only the frequency, but not the intensity, of radiation. The latter was determined by Bohr by extension of the classical expression for the intensity of radiation to the quantum region, i.e., with the help of the correspondence principle.

According to the classical theory, light should consist of waves and a beam of electrons should consist of particles having a definite charge and mass.

Subsequently, however, light was found to have corpuscular properties (Einstein's theory of photons) and a beam of electrons wave properties (de Broglie's waves).

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[*] See Kuznetsov, I. V. Printsip sootvetstviya v sovremennoi fizike i ego filosofskoe znachenie (The Correspondence Principle in Modern Physics and Its Philosophical Significance). Moscow, 1948.

With the aid of the wave equation Schroedinger was able to explain not only many regularities of motion of electrons in the atom, but even such typical wave phenomena as the diffraction and interference of an electron beam. Today the development of electron microscopy has even led to the creation of a special science, electron optics.

One of the central problems of quantum mechanics is to establish the connection between the wave and the corpuscular properties of substance. In our opinion this connection can be most fully established with the help of Born's statistical interpretation, the latest development of which involves the introduction of the quantum ensembles (works of D.I. Blokhintsev[*] and K.V. Nikol'skii[**]).

According to the statistical interpretation, we can obtain a wave picture for a quantum ensemble, which may be formed either by many particles being simultaneously in the same state (e.g., beam of noninteracting electrons) or in the repetition of the same quantum state with isolated individual particles.

A pure (or coherent) ensemble is a set of states in which wave functions are added (principle of superposition). It explains the interference, and also the diffraction, of de Broglie waves. In the case of a mixed (incoherent) ensemble, which also has application in classical statistics when intensities equal to the squares of the moduli of the wave functions of the individual states are added independently, one obtains a gaussian distribution with one maximum at the center when the electron beam hits the screen.

The possibility of the formation of a quantum ensemble upon repetition of isolated quantum states was confirmed by the experiments of S.I. Vavilov[***] and those of L. Janossy with fluctuations of individual quanta, as well as by the experiments of V.A. Fabrikant et al. with the diffraction of successively ejected electrons. Since in the latter experiments the arrival of an individual particle on the screen produces the image of a point rather than a diffraction picture, this point provides a significantly more accurate idea of the coordinate and momentum of the particle at the past instant than can be obtained from quantum-mechanical calculations, i.e., from Heisenberg's uncertainty relation.

To make our point clearer, let us consider the following illustration. Generally speaking, whether or not a given radioactive nucleus will decay within, say, an hour cannot be predicted univocally with the help of the quantum theory of fields. However, once radioactive decay has taken place we can determine the lifetime of each decayed nucleus with significantly greater accuracy than is possible from theoretical considerations.

Analysis of these processes suggests, of course, that causal connections in the microworld are complex rather than absent. Further, far from all the causal connections are revealed by quantum mechanics.

Incidentally, we note that the elegance and integrity of Laplacian determinism — which would seem to allow one to determine to the end all the causes of a given phenomenon and to identify, if only in principle, causality

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[*] See Blokhintsev, D.I. Osnovy kvantovoi mekhaniki (Foundations of Quantum Mechanics), p. 54. Moscow, 1949.

[**] See Nikol'skii, K.V. Kvantovye protsessy (Quantum Processes), p. 35. Moscow, 1940.

[***] See Vavilov, S.I. Mikrostruktura sveta (The Microstructure of Light). Moscow, 1950.

with univocal predictability — has actually been strongly overrated in view of the restricted applicability of classical mechanics itself.*

In this connection let us recall Lenin's remark that the fundamental epistemological problem which divides philosophical trends is not whether causal connections can be expressed in an exact mathematical formula but rather whether the source of our understanding of the external world is the property of our mind or an objective regularity of nature.**

We will attempt to analyze the causes which, in the microworld, lead to regularities which are more complex than those in classical mechanics.

It is well known that the statistical regularities of classical physics are obtained by averaging over the hidden parameters, which include, for example, the laws of classical mechanics (dynamical regularity***) that determine the motion of individual particles.

The statistical regularities of quantum mechanics, however, do not rest on similar dynamical regularities, since the behavior of an individual electron is determined by the same wave equations as determine the behavior of a quantum ensemble.

One of the first attempts to substantiate wave-particle dualism, or, more precisely, the uncertainty relation, is associated with the introduction of the so-called principle of complementarity. In this connection it should be remarked that the representatives of the Copenhagen school — Bohr, Heisenberg and others — generally contributed a great deal to the development of quantum theory. However, this does not at all mean that all of their methodological views, including the principle of complementarity, must also be adopted in full.

It follows from the uncertainty relation that one cannot predict accurately the coordinate and momentum of an individual electron with the help of quantum mechanics. Supporters of the complementarity principle made the first attempt to justify this conclusion by regarding it as the result of the uncontrollable, or, more precisely, noncognizable operation of the observer (or observational means) on the electron.

According to the Copenhagen interpretation, two classes of experimental devices exist. One class permits measurement of the spatial coordinates with any accuracy, and the second, measurement of the corresponding momentum component. When an observer uses the first class of devices he exerts the uncontrollable part of the influence on the momentum; when he uses the second he exerts it, instead, on the coordinate. Therefore it is as if there existed a certain finite limit to our knowledge of the microworld. This proposition is even set up as a special principle, by exaggerating which one could say that when the instruments vanish the wave regularities of the microworld should also, as it were, vanish.

Thus the principle of complementarity (i.e., the principle of the limit of cognizability) is an expression not of physical regularities but rather of

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* See Born, M. Vorhersagbarkeit in der klassischen Mechanik, Zeitschrift für Physik 153, 372 - 378, 1958; Svechnikov, G.A. Kategoriya prichinnosti v fizike (The Category of Causality in Physics), p.387. Moscow, 1961.

** See Lenin, V.I. Sochineniya (Collected Works), Vol.14, pp.146-147.

*** Generally speaking even in the classical case dynamical regularities cannot fully explain all the statistical regularities, e.g., the irreversibility of processes (Boltzmann's H-theorem).

a world outlook which, generally speaking, is applicable only to the under-
standing of a certain set of phenomena, and that also within definite limits*.
For instance, the perfectly correct inference was drawn from the comple-
mentarity principle that the statistical regularities of quantum mechanics
are of a special nature, and that, in any case, they must not be reduced to
dynamical regularities. With regard to the interpretation of diffraction of
an electron beam as a result of the uncontrollability of the interaction be-
tween microobject (i. e., electrons) and macroinstrument (i. e., diffraction
aperture), at best this question belongs among those questions which are
noncognizable in principle only at certain stages in the development of
science.

Nor can one claim universality by referring to von Neumann's theorem
as to the justification for noncognizability in principle, since the validity
of this theorem has turned out to be restricted to the region of quantum
theory itself, to which, as to any theory, no absolute significance can be
attached**. This last point is apparently yet to be finally conceded by many
followers of the Copenhagen interpretation.

Now that the first more or less reliable experimental data on the struc-
ture of elementary particles and their interaction with the vacuum fluctu-
ations have appeared, the artificial restrictions placed upon our ability to
cognize the microworld by the principle of complementarity cannot be of
assistance in the further development of science.

In precisely the same way the mechanistic outlook, which played a cer-
tain constructive role in the development of classical physics at one time,
ultimately began to hamper the development of microphysics when set up
as an absolute.

As remarked earlier, within the framework of quantum mechanics it is
more reasonable to base our notions of the wave properties of particles on
quantum ensembles. The latter do not provide an explanation for the sta-
tistical nature of quantum mechanics, but they do regard this nature (al-
though, so far, formally) as the manifestation of some objective regular-
ities of nature, and they do not forbid shifting the finite limit of cognition
of the microworld and of introducing various hypotheses which lie outside
the existing theory in order to explain the statistical nature.

Here it must likewise be stressed that our knowledge of the external
world is not composed exclusively of instrument readings. Man is also
capable of extending the results of his observations in a theoretical way
and establishing the relationship between the various phenomena. Thus it
is not surprising that certain properties of the atom were known to scien-
tists long before their experimental discovery.

In this connection let us recall that even as great a theoretician as Niels
Bohr could be quick to draw a wrong inference based on instrument read-
ings alone; from his investigation of beta decay he concluded that the law
of conservation of energy may be violated in certain microworld phenom-
ena. As opposed to this view, which was fairly widespread in its time,
Pauli demonstrated, by analyzing the problem of beta decay from the more
general standpoint of quantum field theory, that part of the seemingly lost

* See Sokolov, A. A., Yu. M. Loskutov, and I. M. Ternov. Kvantovaya mekhanika (Quantum
 Mechanics). p. 144. Moscow. 1962.
** See Mandelstam, L. I. Polnoe sobranie trudov (Complete Works), Vol. V, pp. 387, 397. Moscow.
 1950.

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energy was removed by some unknown particle (antineutrino) not detectable by the instruments then in existence. It was only recently (over twenty years after Pauli's hypothesis) that the antineutrino, i.e., the particle emitted in the beta decay of a neutron, was finally "caught" with the help of more advanced instruments.

This is further evidence that the only things which depend on the observer or observational means are the rate of approach of knowledge toward the truth and the form of notation of the regularities cognized by us. In themselves the regularities of the microworld cannot depend on such factors.

It is our belief that the future theory of the microworld will not be able to reduce the laws of causality to a law of univocal predictability like that of classical mechanics. However, objective causes of the manifestations of statistical regularities in the microworld will doubtless be found.

The vacuum is beginning to play an important part in the development of the science of the microworld.

On the one hand, given an excitation, the vacuum produces interaction between particles, thereby giving rise to fields (e.g., electrostatic, electron-positron, meson). On the other hand, the vacuum is a system with an unlimited number of virtual particles forming a special kind of reservoir from which real particles are "extracted" (e.g., electron-positron pair) and to which they "convert" as a result of annihilation.

A special kind of polarization of the vacuum, somewhat reminiscent of the polarization of the dielectric in the presence of charges in it, takes place near elementary particles.

Polarization of the electron-positron vacuum leads to a slight increase (roughly by one thousandth) of the magnetic moment of the electron. Vacuum terms (π-meson vacuum) exert a particularly strong influence on the nucleon. Thus most of the magnetic moment of the nucleon is due to the "meson cloud"; the density distribution near the nucleon not only of the magnetic moment but also of the electric charge has already been established comparatively accurately in experiments on the scattering of fast electrons by nucleons (Hofstadter and Wilson). The root mean square radius of the nucleus was found to be $0.8 \cdot 10^{-13}$ cm.

It could be that we do not yet have enough experimental data to construct a theory which would explain the statistical character of the motion of the electron. However, we should seek to solve this problem regardless of the fact that the first concrete attempts along these lines (including the principle of complementarity) have aroused many objections. Even if only from first experiments, we must attempt to understand the mechanism of the given phenomenon, rather than shroud it helplessly in a mysterious veil of noncognizability.

Here it should be recalled that whereas in classical theory the motion of a set of particles (classical statistics) is studied on the basis of the motion of individual particles (dynamical regularity), in quantum mechanics, as opposed to it, the motion of individual particles is judged by that of statistical regularities. We are of the opinion that the key to this problem should be sought in calculation of the effect of vacuum fluctuations on a real electron. When fluctuation impacts from the vacuum are taken into account, even a single electron has an infinite number of degrees of freedom. Therefore in the microworld one can no longer choose, as one can in

classical mechanics, a certain closed system containing a finite number of degrees of freedom for which exact classical equations of motion can be formulated.

A consideration of fluctuations was used by us to study the following concrete problems of quantum electrodynamics.

1. We investigated the photon emission by an electron moving in a magnetic field, e. g., the motion of an electron in a synchrotron with an energy of the order of 1 Bev*.

In this case the electron should begin to emit high-energy light quanta, the reaction of which on the electron should lead to fluctuation excitation of betatron oscillations of macroscopic amplitude. This should result in the formation of a special kind of quantum "macroatom"**, a situation subsequently detected in high precision experiments by F. A. Korolev and his colleagues***.

The theory of this phenomenon can be constructed either with the help of quantum mechanics or with the help of classical theory, provided that in the latter one takes into account the fluctuation impulses received by the electron from the statistically independent photons emitted by it.

We are inclined to see in the identity of the two methods a connection between quantum theory and the theory of fluctuations, where the so-called Markov chains hold. In the example given here the electrons should begin to move according to the laws of quantum theory owing to the fluctuation effect upon them of the actually emitted photons.

2. Developing Welton's idea for the Lamb shift, one can include in the classical equation for the harmonic oscillator further terms describing the fluctuation effect of the electromagnetic vacuum on it. Then the coordinate and momentum become operators satisfying the uncertainty relation.****

With the transition to direct investigation of elementary particle structure in physics and the appearance of the quantum theory of fields, one is again led to consider the problem of wave-particle dualism. The latest experimental data indicate that an elementary particle has a center (the "core" for the nucleon) which interacts with the surrounding vacuum (Hofstadter-Wilson experiments).

In this respect the motion of the electron should be reminiscent of the motion of a Brownian particle or that of an object floating in the sea. The action of fluctuation impacts from the wave is particularly perceptible on minute objects (e. g., a small boat). Therefore we can either predict the probability for the motion of a single boat, in which case its more exact motion can be estimated only for the previous instant in time, or predict

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* See Sokolov, A. A. and I. M. Ternov. K kvantovoi teorii svetyashchegosya elektrona (The Quantum Theory of the Radiating Electron). ZhETF, Vol. 25, p. 698. 1953.

** See Sokolov, A. A., D. D. Ivanenko, and I. M. Ternov. O vozbuzhdenii makroskopicheskikh kolebanii kvantovymi fluktuatsiyami (Excitation of Macroscopic Oscillations by Quantum Fluctuations). DAN, Vol. 111, p. 334. 1956.

*** See Korolev, F. A., O. F. Kulikov, and A. G. Ersov. Quantum Excitation and Radiational Damping of Electron Oscillations in Cyclic Accelerators. Nuovo Cimento, Vol. 18, p. 1033. 1960.

**** See Sokolov, A. A. and V. S. Tumanov. Sootnosheniya neopredelennostei i teoriya fluktuatsii (The Uncertainty Relations and the Theory of Fluctuations). ZhETF, Vol. 30, p. 802. 1956; A. A. Sokolov. K teorii dvizheniya elektrona s uchetom vakuumnykh fluktuatsii (Theory of Electron Motion with Vacuum Fluctuations Taken into Account). "Nauchnye doklady vysshei shkoly (Filosofskie nauki)" (Scientific Reports of the Higher School — Philosophical Sciences). No. 1, p. 120. 1958.

statistically the motion of many boats, which can be verified directly by experiment. An exact graph of motion obtained with Newtonian mechanics (dynamical regularity) can be prepared in advance only for large objects (e.g., a large ship) for which the effects of the fluctuation impacts from the waves are compensated on the average.

Thus in the view which we have developed, the wave properties of an electron beam can be regarded as the statistical dispersion resulting from the action of vacuum fluctuations on the electrons. This dispersion is manifested in various concrete forms, e.g., in the form of diffraction, in the interaction between electrons and macroinstruments.

When fixing the position of an electron the latter should manifest itself as a corpuscle the coordinate and momentum of which can be predicted only with a definite probability which becomes a certainty only for macroparticles. This interpretation of wave-particle dualism, though still extremely tentative, is, in our opinion, worthy of attention. It is possible that the key to the solution of the problem of wave-particle dualism will be found as a result of the development of nonlinear theories in which the structure of elementary particles is taken into account (de Broglie, Vigier, Terletskii et al.).

In this connection it is particularly important to stress that elementary particles can be related to each other and to the vacuum not only by electromagnetic interactions but also by the so-called weak and strong interactions. Electromagnetic interactions determine the binding of electrons in the atom, photon emission by atoms and so on. Their nature has been well studied.

Weak interactions, which are approximately 10^{12} times weaker than electromagnetic interactions, give rise to the spontaneous decay of particles, e.g., beta decay. Their theory was for a long time only qualitative, and it is only very recently, subsequent to the discovery of parity nonconservation, that the many phenomena associated with weak interactions were explained quantitatively as well.

Strong interactions, which are nearly a thousand times stronger than electromagnetic interactions at small distances, give rise, for example, to the nuclear forces. So far there has been no good quantitative theory of these interactions. In part this is due to the fact that in the study of strong interactions the perturbation method (i.e., series expansion in a small parameter) cannot generally be used. But the crucial point in our opinion is that in constructing a theory of strongly interacting particles one cannot separate the individual particles from the vacuum.

The vacuum magnetic moment of the proton is roughly twice as large as the Dirac magnetic moment, whereas in the case of the electron it is a thousand times smaller than the Dirac magnetic moment. Therefore the π-mesons surrounding a nucleon occur in so excited a state that the nucleon represents something intermediate between a real state reminiscent of electrons in an atom and a virtual state producing, say, vacuum polarization.

The newly-discovered resonant states of particles ("resonons") are of particular interest in this respect. These resonant states are produced by strong interaction and represent special combinations of elementary particles and the vacuum which decay rapidly into two or three π-mesons, into a nucleon and a π-meson, into a hyperon and a π-meson and so on.

In this connection one of the most important problems of the theory of strong interactions is to construct a unified theory of fields in which the particles may be regarded as excited vacuum states. The provisional

quantum theories of strong interactions formulated recently fall chiefly into two classes: field and phenomenological.

Among the field theories we should mention first of all the nonlinear wave equations (W. Heisenberg and D. D. Ivanenko), from which certain qualitative results, e.g., the mass spectrum of strongly interacting particles, have been obtained. A certain measure of success was achieved with the phenomenological theories, examples being the theories of dispersion relations (Goldberger, N. N. Bogolyubov et al.) and in particular the theory of double dispersion relations (Mandelstam et al.), in which certain qualitative results pertaining to the theory of scattering of strongly interacting particles were obtained from a number of general principles (causality, unitarity and so on) without the introduction of any specific field interaction between particles.

Finally, highly important results were obtained very recently in the theory of strong interactions based on the so-called Regge poles. Regge's theory represents a further development of the theory of potential scattering of ordinary quantum mechanics. Regge demonstrated that in the theory of potential scattering the poles can lie not only on the real axis but also on the complex plane of orbital angular momentum. In particular, upon application of this theory to strongly interacting particles (Chew, I. Ya. Pomeranchuk et al.) it was shown that the formation of resonons should correspond to the case where the poles in potential scattering lie in the complex orbital angular momentum plane.

Unfortunately the latest experiments have shown that Regge's theory does not give good agreement with experiment when particle scattering is studied in the region of very high energies.

The question of the relationship between the properties of a particle and the observer was raised anew by the interpretation of the phenomena which go by the name of parity nonconservation.

It is well known that definite symmetry laws can be established in the modern table of elementary particles. Thus side by side with the electron we have the positron. Together with the proton and neutron we have antiprotons and antineutrons, and so forth. However, our world is not symmetric with respect to the number of particles and antiparticles. In particular the atoms surrounding us consist of protons, neutrons and electrons. Under terrestrial conditions it is possible artificially to create antiatoms consisting of antiprotons, antineutrons and positrons which can exist for prolonged periods only in isolation from atoms.

At first glance it might appear that every physical phenomenon which takes place in the isolated antiworld should be completely identical with the corresponding phenomenon in the world about us, since, so it would seem, the transition from world to antiworld, which reduces to replacement of all electric and nucleonic charges by their opposites, cannot alter the magnitude of the electromagnetic and nuclear forces operative between particles. In particular the spectral lines emitted by hydrogen and antihydrogen should be completely identical, and spectroscopists should be unable not only to distinguish between them but even to indicate how this distinction could be drawn.

However, in phenomena associated with weak interactions which produce, for instance, antineutron decay, a certain asymmetry compared with neutron decay should be observed. This asymmetry was named parity nonconservation by Lee and Yang.

To explain the phenomena of parity nonconservation a certain asymmetry, not contradicting some general requirements that must be satisfied by any theory of elementary particles, must be introduced into the original wave equations upon transition from particles to antiparticles, i.e., for the so-called charge conjugation or C transformation.

Asymmetry under charge conjugation can be introduced by supposing, for instance, that a neutrino differs from an antineutrino in helicity. It has now been established that the neutrino is left-handed or, more precisely, resembles a left polarized photon, and that the antineutrino is right-handed (variant of the theory of Gell-Mann and Feynman).

Noninvariance of wave equations under charge conjugation ($e \leftrightarrow -e, \vec{r} \to \vec{r}, t \to t$; C transformation) is admissible only in casses where it is compensated either by space inversion, i.e., by transition from a right-hand system of coordinates to a left-hand one ($e \leftrightarrow e, \vec{r} \to -\vec{r}, t \to t$; P-transformation), or by time reversal.

It should be remarked that space inversion is an ordinary geometric transformation easily performed by any observer. As to time reversal, no observer can really carry it out, although for the motion of free particles the corresponding wave equations are invariant under geometric time reversal ($e \to e, \vec{r} \to \vec{r}, t \to -t$).

If emission is taken into account, however, then even in the classical case the theory becomes asymmetric under geometric time reversal, as in the original solution it is necessary to take into account only the retarded potentials which, after this transformation, go over into advanced potentials, owing to which cause and effect become interchanged. This noninvariance is apparently due to the fact that the processes which take place in the nature surrounding us are generally speaking not reversible in time.

In order to evade this difficulty in the classical case, geometric time reversal should be supplemented by the condition that the new retarded solutions which corresponded to the advanced solutions in the untransformed theory be left in the transformed equations.

In exactly the same way in quantum theory the signs of all the temporal (i.e., fourth) components of the vectors must be reversed in geometric time reversal, as a result of which particles with positive energy take on negative energy.

In order for the sign of the energy of the particles, as well as their properties, to remain unchanged in this process, geometric time reversal ($t \to -t$) must be supplemented by a substitution of the operators; that is, the operator of electron annihilation must be replaced by the operator of positron creation and vice versa. We will call geometric time reversal supplemented by the indicated substitution of operators a T transformation. It actually corresponds to Schwinger, or strong, time reversal.

Lee and Yang, as well as L. D. Landau, proposed that the noninvariance of the equations for the polarized neutrino under C transformation be compensated by noninvariance of the equations under space inversion.

To do this they introduced the so-called combined parity:

$$C \neq \text{const}, \quad P \neq \text{const}, \quad CP = \text{const},$$

from which it follows that upon transition from a right-hand system of coordinates to a left-hand one a left-handed neutrino should go over into a right-handed one, i.e., into a virtual state.

To make a right-handed neutrino again real they suggested carrying out another C transformation, with the result that the neutrino would be transformed into a really existing right-handed antineutrino. More precisely, for a C transformation the creation operators of a right-handed neutrino are transformed into the creation operators of a right-handed antineutrino.

They substantiated the noninvariance of the equations for the neutrino under the P transformation in the following way: firstly, they took the two-component Weyl equation which is noninvariant under P transformation for the wave equation of the neutrino, the mass of which is zero; secondly, they assumed that a single mirror reflection of the screw which converts a left-hand screw into a right-hand one completely describes P transformation.

However, this view contains certain internal contradictions. In reality the choice of a right-hand or left-hand system of coordinates depends exclusively on the will of the observer, and therefore space inversion cannot in any way modify the real properties of elementary particles, e.g., cannot change right-handed particles into left-handed ones. In such a transformation only the mathematical description of the original helicity can change.

We will take the following example to illustrate our idea. Let us suppose that observers are flying on a propeller aircraft the propeller of which describes a right-hand screw relative to the velocity (or momentum) of the aircraft. Those who choose a right-hand system of coordinates for their investigations will maintain that the angular velocity (axial vector, i.e., the analogue of the pseudovector $\vec{s}$ of spin) is parallel to the velocity of the aircraft (polar vector). The observers who choose a left-hand system of coordinates, i.e., perform a P transformation from the standpoint of the other observers, will maintain, while describing the same helicity, that the angular velocity is antiparallel to the velocity of the aircraft, although physically the real process which both groups of observers are describing in different mathematical ways is one and the same, i.e., the right-hand screw motion of a propeller (Figure 1).

In order to prevent this contradiction from arising we found it necessary to determine, in each concrete solution with specified helicity, the real rotation to which this solution corresponded, just as in studying circular photon polarization it is necessary to determine the corresponding rotations for the electric field strength vector.

The solution of this problem was facilitated by the fact that the four-component theory of longitudinally polarized Dirac particles had already been developed by us in 1945, i.e., long before the discovery of the phenomena of parity nonconservation[*].

Subsequently we were also able to establish the law of variation of helicity under Lorentz transformations and to show, in particular, that helicity does not change in this process if the rest mass of the particles is exactly zero.

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[*] See Sokolov, A. A. On the Polarization of Electron Wave. Journal of Physics U.S.S.R., Vol. 9, p. 363. 1945.

After the discovery of Lee and Yang our results were immediately applied to the investigation of parity nonconservation[*].

Let us first of all consider the behavior of helicity under P transformation. With only one mirror one can describe P transformations if only parallel polar vectors (the mirror is placed perpendicular to these vectors) or only parallel axial vectors (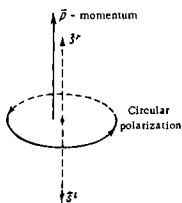the mirror is placed parallel to these vectors) are present. In the presence of parallel polar and axial vectors, i.e., helicities, the P transformation can be obtained by reflection in two mirrors (one is placed perpendicular and the other parallel to the momentum). Then in the P transformation only the mathematical form of description of the helicity, but not the helicity itself, is changed (Figure 2). In this sense we can assume that

$$P = \text{const.}$$

FIGURE 1. Representation of right helicity in the right-hand $\vec{t}'$ and left-hand $\vec{t}'$ systems of coordinates: $\vec{s}$ — axial spin vector; $\vec{p}$ — polar momentum vector

As the wave equation for the four component polarized neutrino is not invariant under Schwinger time reversal $(t \to -t;$ the creation operators of the left-handed neutrino are replaced by the annihilation operators of the left-handed antineutrino), therefore in this theory noninvariance under C transformation is compensated by noninvariance under T transformation, i.e.,

$$CT = \text{const.}$$

The joint CT transformation is sometimes called weak, or Wigner, time reversal. In Wigner time the operators of particle annihilation go over into operators of creation of the same particles, and the value of the helicity does not change.

Characterizing the neutrino and the antineutrino by parallel momenta, and at the same time by opposite polarizations, one can show that a single mirror placed perpendicular to the momentum will describe the T transformation and a mirror placed parallel to the momentum the C transformation (see Figure 2).

It should be stressed that the Lee — Yang — Landau combined parity rules out the appearance of another form of C asymmetry produced by the introduction into the four-fermion interaction (A —pseudovector and V vector) of complex coupling coefficients. In the latter case one obtains an additional term

$$i\,(G'_A G_V - G'_V G_A)\,(\vec{s}_n\,[\vec{p}_e\vec{p}_{\vec{\nu}}]),$$

which is noninvariant under T transformation and for which the right-hand system of coordinates remains right-handed while the neutron spin $\vec{s}_n$ and the momenta of the electron $\vec{p}_e$ and antineutrino $\vec{p}_{\vec{\nu}}$ reverse their signs $(\vec{s} \to -\vec{s},\ \vec{p} \to -\vec{p})$.

* See Sokolov, A.A. Nekotorye metodologicheskie voprosy teorii nesokhraneniya chetnosti (Certain Methodological Problems of the Theory of Parity Nonconservation). Voprosy filosofii, No. 10, p. 76. 1959; Sokolov, A.A. and M.M. Kolesnikova. O rasseyanii poperechno-polyarizovannykh fermionov (Scattering of Cross-Polarized Fermions). ZhETF, Vol. 38, p. 1778. 1960; Sokolov, A.A. Über das Verhalten des Spins von Dirac — Teilchen bei Streuprozessen. Annalen der Physik (DDR), Vol. 8, p. 237. 1961.
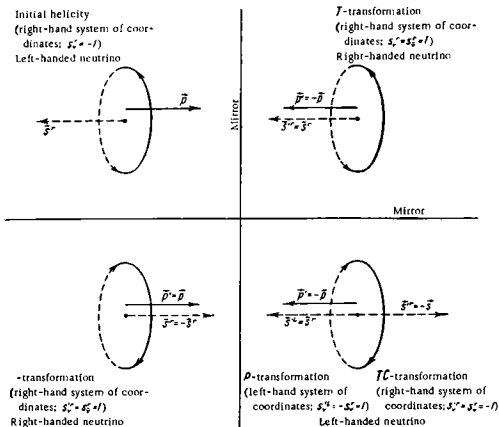
FIGURE 2. Representation of helicity changes in a neutrino in T, C and P transformations with the help of mirrors:

$$\mathbf{s} = \frac{(\vec{s}\ \vec{p})}{p} = \pm 1; \quad s_v \text{—helicity of neutrino}; \quad s_{\bar v} \text{—helicity of antineutrino}; \quad \text{for the initial state}$$

$$s_v^i = -s_{\bar v}^i = -1.$$

However, in the four component theory of the polarized neutrino, this is quite admissible, since according to this theory the latter expression, as well as the neutrino helicity, is invariant not only under P transformation but also under joint CT transformation, when

$$\vec{s} \to -\vec{s}, \quad \vec{p} \to -\vec{p}, \quad (\vec{s}\,\vec{p}) = \text{const}, \quad G \to G^*.$$

Thus in the four component theory the coupling coefficients can be not only real, as in the two component theory, but also complex. In the latter case the phenomena of parity nonconservation can be observed without introducing particles of zero rest mass.

Further, in the four-component theory in addition to the solution that the neutrino is left-handed (v_L), and the antineutrino right-handed ($\bar v_R$) there should be a second solution, namely the neutrino is right-handed (v_R) and the antineutrino left-handed ($\bar v_L$).

Selection of a particular solution can be effected with the aid of a special operator which can be included in the interaction energy[55].

* See S o k o l o v, A. A. Elementarnye chastitsy (Elementary Particles). Moscow. 1963; S o k o l o v, A. A. On the Four Component Neutrino Theory. Physics Letters. Vol. 3, p. 211. 1963.

Recently a second neutrino was discovered, i.e., it was proved that although right-handed neutrinos (or antineutrinos) are formed with the μ^--meson, as well as with the electron, they are not identical (μ^+-mesons, not positrons, are formed in the absorption of a muon antineutrino).*

The results of the latest experiments can be made to fit naturally in the four component theory by referring the muon neutrino to the second type of solution (ν_R' and $\tilde{\nu}_L$). Further, introducing the concept of lepton charge, which like the electric charge, should be conserved in all reactions with elementary particles, we should attribute to e^-, μ^+, ν_L, ν_R', a unit lepton charge (e.g., positive) and to e^+, μ^-, $\tilde{\nu}_R$, $\tilde{\nu}_L'$ its opposite. It then becomes understandable that the decay $\mu^- \rightarrow e^- + \gamma$ should be forbidden.

Should all of this ultimately be confirmed, the applicability of the two component theory noninvariant under space inversion will be severely restricted.

In conclusion it should be stressed that many scientists both in this country and abroad are being led to the conclusion that the regularities of the microworld depend neither on the instrument nor on the observer, i.e., whether consciously or spontaneously, they are taking the road of dialectical materialism.

Bohr himself dwelled with increasing frequency on the objectivity of the regularities of the microworld in his last works, yet until the very last momentum continued to believe that our cognition of the microworld should in principle be limited by the prism of the macroinstrument**. Therefore we cannot agree with V.A. Fok that the only point on which the "Copenhagen interpretation" is open to valid criticism as a positivistic view is the not completely successful terminology introduced by Bohr (e.g., "uncontrollability of interaction", identification of the principle of causality in general with determinism of the Laplacian type, and so on)***.

According to the teachings of Lenin, despite the inexhaustibility of the simplest particle, e.g., electron, our knowledge has an objective nature which approaches the absolute truth asymptotically.

Thus modern science can receive correct guiding principles for its development only from dialectical materialism.

* See Schwarz, M. et al. Observation of High Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos. "Physical Review Letters", Vol. 9, p. 36. 1962; Pontecorvo, B.M. Elektronnye i myuonnye neitrino (Electron and Muon Neutrinos). ZhETF. Vol. 37, p. 1751. 1959.

** See Bohr, N. The Unity of Human Knowledge, in "Essays 1958 - 1962 on Atomic Physics and Human Knowledge". Interscience Publishers. 1963.

*** See Fok, V.A. Ob interpretatsii kvantovoi mekhaniki (On the Interpretation of Quantum Mechanics), in a collection entitled "Filosofskie voprosy sovremennoi fiziki" (Philosophical Problems of Modern Physics). Moscow. 1959.

AN EVALUATION OF THE SIGNIFICANCE OF STATISTICAL
REGULARITIES IN ELEMENTARY PARTICLE PHYSICS

Yu. V. Sachkov

Modern quantum theory, which is the principal theoretical tool of elementary particle research at the present stage and in which are expressed the laws and properties of these "universal bricks", is fundamentally statistical, i.e., the concept of probability is an essential part of it. In quantum theory physical systems and their states are characterized by the probability concept. This concept is necessary for the characterization of the internal properties of microparticles and of their interactions. The development of a consistent treatment of quantum processes is inseparably linked to a thorough analysis of the nature of statistical regularities. Figuratively speaking, notions involving probability constitute the skeleton of quantum theory; on this skeleton rest the formulation and synthesis of the physical ideas which constitute the flesh and blood of the theory.

Concepts involving statistical regularities have led to a new perception of the world in science. If previously scientific thinking started from the necessity of establishing one-one correspondences between elementary world events and viewed such correspondences as the only necessary ones, the incursion of the spirit of probability into physics shattered the belief in this principle. Our world is inexhaustibly rich in events. These events are infinitely varied and minutely interwoven. In such a great multitude of events, could necessity be manifested only as one-one correspondences between the initial elementary events? Is not the statement "one-one correspondence between such events is a necessity only in the simplest cases" closer to the truth?

The new views concerning the necessity which science was called upon to comprehend became established. New things, as is well known, are born in struggle with the old. The birth and consolidation of statistical regularities was a complicated and difficult process. In large part this was due to the widespread predominance of outdated ideas in that science which is meant to assist in the creation and development of sciences and in the evolution of their self-knowledge, namely philosophy, and to the ensuing struggle between the old and the new. In such situations the new frequently establishes itself by means of an especially pronounced rupture of the ties linking it to the past in order to gain freedom of action. Only in this way, apparently, can one account for the fact that many of the leading scientists who laid the foundations of quantum theory came up with a renunciation of materialism and determinism, which are the starting points of classical physics and the foundation of foundations of the theory. The anarchical way of self-assertion however is self-destructive. The new is always faced with a

serious problem, the problem, so to speak, of self-knowledge: who are you, what can you do, of what use are you? The new can impose itself only as a necessity, and this one brings about by analysis of the regular connections with one's antecedents, of the historical process of development. Otherwise, since the problem of self-knowledge always arises in some form or other, one can seek to establish oneself spuriously by means of obsolete ideas. This was the case with a number of physicists who sought to justify statistical regularities on the grounds of the outdated and spurious ideas of positivism.

The means by which statistical regularities can be justified are still unclear in many respects, as evidenced by the keen debate surrounding these questions. Perhaps, the principal positive result of these discussions in materialistic circles has been the recognition that statistical regularities have a specific, distinct character, that they do not reduce to any form of dynamical regularity of individual objects, and that they have a proper objective basis. However, the "moments" of dialectics in the justification of statistical regularities still remain unclear to a large extent. It is not even completely clear what forms of necessity underlie statistical regularities. The general characterization of the class of problems in which they are applicable calls for clearer definition. In what way did they assist in the development of a theory of cognition? The problems associated with the justification of statistical regularities are especially acute in quantum theory. In particular, the following problem is of interest: in what way did quantum theory advance ideas concerning statistical regularities as compared with classical physics? How can one explain the fact that in classical physics statistical regularities were used to express the properties of sets (macroscopic characteristics, which in their very content are characteristics of sets), while in quantum physics they are used primarily to cognize the properties and regularities of individual quantum particles? Statistical methods of research continue to evolve in the present stage of development of quantum theory as well; in this connection the appearance of negative probabilities in nonlinear quantum theories deserves attention. Methodologically it is of great interest to consider the general changes in our ideas concerning statistical regularities.

The following point also deserves mention. Statistical ideas, the core of which is the theory of probability, are finding very widespread application in modern natural science — biology, astronomy, physics, cybernetics and so on. In natural science, however, statistical regularities never appear, so to speak, in pure form; instead they always assume a certain material coloring. Whenever a statistical theory is constructed it is the truly statistical considerations that make it possible to formulate the precise scientific idea which is in the forefront of this theory. In this respect quantum theory can hardly be an exception. From the methodological standpoint it is therefore very important to see which important, truly quantal ideas proved susceptible of formulation in the language of statistics.

In the discussions concerning the justification of statistical regularities the problems were not always clearly stated; sometimes, in fact, problems dissimilar in nature were confused. Yet the problems raised in these discussions were very important ones: they concerned the general prospects for the development of quantum theory, and, chiefly, the fate of statistical regularities in the further development of the physics of microprocesses. Perhaps the sharpest debate was on these problems. Will physics develop

along the lines of statistics and probability? Will there be a "reversion" to regularities of dynamical nature? Or will further sounding of micro-processes necessitate new methods of research, which will lead to the development of new forms of regularities as yet unknown to physics, just as the application of statistical and probabilistic research methods led to the development in science of the idea of statistical regularities?

The most diverse answers have been proposed to these questions. Weighty arguments indicate that the further development of elementary particle theory will take place on a statistical foundation. The foremost evidence for this is the fact that modern elementary particle research is based on the quantum theory of fields. At the same time it is fairly widely believed that physics is destined to undergo a peculiar return to dynamical regularities. Such considerations have been stated persistently by the representatives of the causal interpretation of quantum theory, as it is called. It should be mentioned especially that such views were constantly and very definitely held by Albert Einstein. "One arrives at very implausible theoretical conceptions, if one attempts to maintain the thesis that the statistical quantum theory is in principle capable of producing a complete description of an individual physical system. On the other hand, those difficulties of theoretical interpretation disappear, if one views the quantum-mechanical description as the description of ensembles of systems.

"... I am convinced that everyone who will take the trouble to carry through such reflections conscientiously will find himself finally driven to this interpretation of quantum-theoretical description (the ψ-function is to be understood as the description not of a single system but of an ensemble of systems.

"... If the statistical quantum theory does not pretend to describe the individual system (and its development in time) completely, it appears unavoidable to look elsewhere for a complete description of the individual system; in doing so it would be clear from the very beginning that the elements of such a description are not contained within the conceptual scheme of the statistical quantum theory... Assuming the success of efforts to accomplish a complete physical description, the statistical quantum theory would, within the framework of future physics, take an approximately analogous position to the statistical mechanics within the framework of classical mechanics. I am rather firmly convinced that the development of theoretical physics will be of this type; but the path will be lengthy and difficult" (our emphasis — Yu.S.)*.

In the general evaluation of the prospects of development of the physics of microprocesses the opinion is also stated that the further development of physics will involve the utilization of new, "more probabilistic" concepts. No definite choice has been made, and perhaps at present none can be made without restricting the framework and possibilities of further research. Nevertheless this problem as we see it is worth examining with a view to determining as clearly as possible what the choice of a given path entails and what the latest quantum theories can tell us about such a choice.

The present theme owes its existence to the problems listed above. Of course, only a few of the problems raised can be covered here.

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* Albert Einstein. "Remarks to the Essays Appearing in This Collective Volume", in "Albert Einstein: Philosopher-Scientist", ed. P.A. Schlipp Library of Living Philosophers, Inc., Reprinted in Harper Torchbooks (Science Library), Harper and Brothers, New York.

If we recognize that the class of statistical regularities is specific, it means that, in the given case, necessity has a special objective foundation as well as special forms, the means by which it is expressed in science. In statistical theories these necessities are represented by the distributions of random quantities, by their probability distributions. Knowledge of the distributions and of their interrelations and laws of development in time for all random quantities of the material system under investigation represents complete knowledge of this system within the framework of statistical theory. Correspondingly, a typical, truly statistical problem consists of the determination of certain distributions from other known ones, which includes determination of the variation of distributions in time. Not without reason did N. Wiener succinctly characterize statistics as the science of distribution*.

Probability theory is the mathematical apparatus of statistical theories. More correctly, probability theory constitutes the framework by means of which the fundamental rational content of the mathematical constructions of statistical theories can be exposed and a consistent treatment of these worked out. The content of probability theory also corresponds to the above definition of statistical regularities, since probability theory can be defined as the science of distributions and of their general properties, of those quantities which form distributions, and of those general conditions the fulfilment of which necessarily leads to the existence of distributions.

In statistical theories the distribution category bears a primary character, i.e., cannot be reduced to other more fundamental concepts of these theories. The specific character of distributions as special necessities cannot be brought out by defining the concept of distribution in terms of the concept of necessity. Considering the definition of the concept of probability, A. N. Kolmogorov states that this concept is not susceptible to formal definition in terms of simpler concepts. The classical and frequency definitions of probability express only certain aspects of this concept, although the link with frequency touches its very essence. The fuller content of the concept of probability can be uncovered only gradually in the dialectic process of cognition. Everything we have said about probability applies equally well to the concept of distribution.

The distribution category is primary in the treatment of quantum theories as well: the relationship between quantum concepts and objective reality can be explained fully and deeply only on the basis of this category. In this connection we might mention a very remarkable circumstance: only when the connection between the mathematical apparatus of the theory and the probability distributions had been clarified was it possible to determine the meaning of nonrelativistic quantum mechanics, which had originally been worked out by the method of the mathematical hypothesis. Modern treatments of quantum mechanics (interpretation in terms of the concept of "complementarity", N. Bohr, W. Heisenberg; concept of quantum ensembles, K. V. Nikol'skii, D. I. Blockintsev et al.; standpoint of reality of quantum states, V. A. Fok et al.; causal interpretation of quantum theory) are also based in reality on the concept of distribution as a necessity in quantum theory, although they evaluate the general conditions of its formation in different ways.

* See Wiener, N. Cybernetics and Society (2nd ed. rev.). Garden City, N. Y., Doubleday. p. 199. 1954.

Once it is maintained that the necessity expressed in statistical regularities is represented by distributions and their interrelations, a few additional remarks are in order.

Once more, the true problem of statistical theories is the determination of certain distributions from other known ones, including the variation of these distributions in time. To solve this problem within the framework of the given theory it is necessary to know, aside from the fundamental equations of the theory, the initial distributions of certain random quantities. These distributions are specified on the basis of experiment. In this connection one might receive the impression that the initial distributions are specified exclusively by means of direct statistical treatment of massive experimental material. Far more frequently, however, the situation is completely different, a point fairly thoroughly discussed in works on probability theory[*]. In practice it is only in the first incursion of statistical methods of research into a new region of natural phenomena that one often begins with an empirical treatment of massive experimental material, which serves as the basis for specification of the initial distributions. But here too tremendous difficulties arise. Thus in order to specify empirically exactly the distribution of a random quantity and, therefore, to detect the constancy of frequencies with an accuracy up to a certain very small quantity ε, runs of roughly $n = \frac{1}{\varepsilon^2}$ trials are required. Assuming that, in a certain concrete case, it is necessary to determine statistically a probability with an accuracy of 0.0001, the execution of a number of runs of measurements of about 100,000,000 measurements per run is required. It is obviously very difficult to make progress in the application of statistical research methods with experimental specification of the initial distributions.

Far more frequently, in research into natural processes probability distributions are introduced hypothetically by indirect means. In statistical theories the probability hypothesis is usually introduced on the basis of symmetry considerations, assumptions concerning the equal likelihood of definite outcomes of the investigated process, considerations involving the practical independence of individual runs of events, and so on. Usually the probability hypothesis is also verified by indirect means — on the basis of identity between the principal conclusions derived from the theory concerning the properties of physical systems and the experimental data.

In physics, in the study of gases, the supposition that there exist probability distributions was introduced as a hypothesis on the basis of assumptions concerning a "molecular chaos". The identity between the values of a number of physical macrocharacteristics (pressure, energy and so on) as calculated by statistical methods and their experimental values confirmed the validity of the probability hypothesis in the given case.

In quantum theory probability distributions are obtained by specification of the wave functions. In the general case the wave functions of quantum systems are obtained as solutions of the corresponding equations of motion — wave equations. In order to specify the wave equation of a certain quantum system it is necessary to specify its energy (Hamiltonian).

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[*] See, for example, Kolmogorov, A.N. Teoriya veroyatnostei (Probability Theory), in the collection entitled "Matematika, ee soderzhanie, metody i znachenie" (Mathematics—its Contents, Methods and Significance). Vol. II. Moscow. 1956.

In the quantum case as well the identity of calculated and the experimental characteristics of quantum systems is evidence of the validity of the probability hypothesis.

That this method of specifying probability distributions and verifying their validity (as distinct from specification of massive statistically processed experimental material) is possible is due to the fact that probability distributions and their character and value are largely dependent on the properties of the material systems under investigation. It is not the pure distributions themselves, so to speak, that are of scientific interest, but rather the distributions in intimate natural relation to the various characteristics of the systems and, inevitably, to the physical characteristics of the individual physical systems.

It should be mentioned that when one speaks of distributions one has in mind first and foremost the distributions observed in experimental results or, to use the terminology of probability theory, in runs of trials. The mutual bond between these distributions and the internal properties, composition and structure of the objects under investigation are sometimes left in the shade or directly denied. However, the experience of developing statistical theories shows that they can be used successfully to cognize separate individual objects. An excellent example of this is nonrelativistic quantum mechanics, the theory of the atom.

How can one reconcile such facts with the statement that statistical regularities reflect the properties and interrelations of distributions. For an answer to this question it it necessary to analyze the character and peculiarities of probability distributions. From the general point of view it is evident that probability distributions, their character and peculiarities are largely due to the properties of the material systems under investigation. An important property of probability distributions is the mutual independence of the elements which make up these distributions. Independence means that the state of each element in the distribution, its position in the distribution, does not depend on the state of the other elements of the distribution, or that, in any run of trials, a given outcome of part of the trials will not affect the outcome of the remaining trials. From this it follows that distributions are largely controlled by the structure and properties of the individual objects under investigation and by the regularities of their motion under definite conditions. It is therefore perfectly possible to study, on the basis of a study of distributions, the properties of the individual objects participating in the formation of the distributions.

Even in the simplest cases in which probability theory has been applied (the throwing of coins and dice) the connection between distributions and certain internal properties or structure (symmetry, homogeneity) of the corresponding object is clearly visible. The type of statistics is determined by the internal properties of the corresponding objects, elementary particle spin in the quantum region. In general in quantum theory the problem of studying the properties of individual quantum objects receives the limelight. The distributions themselves are frequently left in the shade, although they are necessary for a truly profound analysis of the content of quantum theory and for correlating its mathematical apparatus with reality.

One must admit, however, that in many respects it is still not clear why it should be possible to characterize individual objects on the basis of statistical, probabilistic concepts. In our opinion the usual explanations of this fact, that in the case of statistical theories not only necessity but also

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chance are taken into account or that the potential possibilities in the be-
havior of the object are expressed in the theories, are not sufficient. Per-
haps it is worthwhile to present the following considerations. In character-
izing an object by means of distributions, statistical theories characterize
it as an element of a definite set, as an element of a certain structural sys-
tem. In the case of dynamical regularities, and primarily in classical me-
chanics, one was restricted to characterization of the object with respect
to the conditions as a whole. Now it is obvious that those properties which
characterize an object as the element of a certain structure express a deep-
er essence of this object than those properties which characterize the ob-
ject outside of the structural systems, with respect to conditions as a whole.
The latter can be clarified by examples. Thus the most complete charac-
terization of a chemical element is obtained by specifying its position in
the periodic system, i.e., on the basis of the regularities of the system
and as an element of this system. At present in biology particular atten-
tion is paid to the study of the cell; in this study those properties which
exercise the greatest influence on the living body as a whole are, naturally,
regarded as essential properties of the cell, while the other properties are
less essential. From the beginning the elementary particle in modern phys-
ics is treated as a structural element of an entire family of elementary par-
ticles. Mathematical objects (and first and foremost numbers: natural,
real, complex) are also regarded as elements of corresponding abstract
structural systems. Analogously, in sociology a person is characterized,
"evaluated", on the basis of his entry and role in a definite "structural
system", as a member of a family, as a member of a certain productive
collective, according to his membership in a definite social stratum or
class, and so forth. A characterization of a person not as the "element
of a certain structure", i.e., outside of social groups, is bound to be ex-
tremely poor.

This approach to the treatment of statistical regularities shows that
they are more fundamental than dynamical regularities. At the same time
it should also be remarked that a set of probabilities represents the sim-
plest dynamical structural system and that more complex structure sys-
tems, such as stable dynamical guidance systems in cybernetics, are now
being subjected to deep mathematical analysis.

Mere analysis of the problems encountered in the substantiation of sta-
tistical regularities is not, however, sufficient for a fully substantiated
answer to the question: will the further development of the theory of micro-
processes be of the type of statistics and probability, or will there be a
peculiar "reversion" to dynamical regularities?

The choice and justification of a given path are conditioned first and
foremost by the nature of the problems which the physics of microprocesses
is at present capable of posing and solving. Without analysis of these actual
problems and of the methods used to solve them, any discussion of the fate
of statistics in the physics of microprocesses is bound to take on a purely
speculative, unsubstantiated character.

If concepts of probability distributions make up the foundation of statis-
tical regularities, it is natural to assume the following: firstly, in statis-
tical theories it is in the language of probability distributions of physical
quantities that the states of physical systems should be characterized —

and problems mathematically stated and solved; secondly, the fundamental equations of every statistical theory should explicitly express the laws of mutual connection between the probability distributions of the corresponding physical quantities, as well as the laws of variation of these distributions in time. And so it is in the early statistical theories of physics. In the mathematical apparatus of quantum theories, however, the formulation of problems is given not in the language of probability distributions but rather primarily with the help of wave functions. In quantum theories physical systems and their states are characterized in the language of wave functions; the fundamental equations are also formulated for wave functions. At the same time the wave functions are fairly abstract mathematical objects and very many people believe that they have no direct physical meaning. Historically wave functions were introduced into quantum theory in a purely formal way and became established in physics only when it proved possible to link them to probability distributions: the square of the modulus of a wave function in a certain representation determines the probability of the corresponding physical quantity. In general the link between wave functions and probabilities justifies their utilization in quantum theory; it was the establishment of this link, and nothing else, which made it possible to endow the entire mathematical apparatus of quantum mechanics with a profound real meaning, an achievement which postdated the development of quantum mechanics.

It should also be noted that there exist quantum systems ("mixed") the states of which cannot be represented by wave functions. In such cases the states are characterized by the so-called density matrices. Once again, the guiding idea for grasping the physical meaning of this characterization is that of probability, and the density matrices themselves are essentially a highly developed special mathematical form of characterization of probability distributions.

The transition from probability distributions to wave functions in the characterization of the states of physical systems contains the fundamentally new element introduced by quantum theory into the ideas of statistical regularities. Wherein lies the heuristic significance of this transition?

First and foremost, the use of wave functions for the characterization of the states made it possible to uncover theoretically the wave-particle nature of microobjects and to relate it to the equations of motion. The presence of wave properties in microobjects is manifested in the phenomena of diffraction and interference and is expressed theoretically in the principle of superposition. Direct characterization of these very important peculiarities of microprocesses by probability distributions is bound to fail, as the superposition of probability distributions, which are everywhere positive, cannot explain the appearance of interference minima. Concepts involving wave functions proved to be more flexible for expressing the regular relationships between the probability distributions of quantities in quantum theory.

As quantum theory developed it became evident that the concept of wave function could also serve as a basis for detecting and expressing other internal properties of microobjects. In the quantum theory of fields the concept of the elementary particle proved to be fairly closely related to the concept of field. The particle began to be treated as a quantum of a definite field. The properties of the various particles were expressed in terms of those of the corresponding fields, which are characterized mathematically

by transformation properties. Every particle and the field corresponding to it are described by a wave function, which has a definite behavior under transformations of the coordinates and time (Lorentz transformations, displacements, rotations, mirror reflections and inversions). Correspondingly the wave function can be scalar, vector, spinor, pseudoscalar, pseudovector, and so on. Since it is by means of the wave functions that the states of the elementary particles are characterized, the very names of the wave functions are evidence of the close connection between the characterizations of the states of the particles and their internal properties. To this one might add that the transformation character of the wave function is uniquely determined by the spin of the particle and by its internal spatial parity, which represent the internal properties of elementary particles. We should also add that the character of the wave function and the form of the corresponding wave equation, which in the given case is the equation of motion, are also uniquely related, which is clear indication that the form of the equation of motion is conditioned by the internal properties of the elementary particles.

It follows from what we have been saying that the transition from the direct characterizations of probability distributions to wave functions made it possible to link the laws of motion to definite internal properties of the physical objects under investigation. As a result it became possible to study the properties and laws of behavior of individual microobjects on the basis of quantum theory, the laws of which are in principle statistical.

In order to see this peculiarity of the probability methods of quantum theory in greater relief, let us consider the historical development of the ideas which physics has held concerning the elementary objects with which it "puts together the world"*. In view of the growing importance of symmetry laws in the study of processes of interaction of elementary particles, we will trace the development of physical ideas concerning the most elementary objects from the standpoint of symmetry.

In classical physics ideas concerning elementary objects were developed chiefly on the basis of classical mechanics. The forms of these objects were expressed by material points, hard elastic sphere, partly inelastic sphere, etc. These objects were allotted definite centrally symmetric forces, manifested in interactions between the objects, and their states were characterized by two quantities — momentum and coordinate. The properties of gases, liquids and solid bodies, i.e., aggregate states of matter, were explained in classical physics on the basis of the properties of the objects and the character of their interactions.

From the standpoint of ideas of symmetry it is important to note that the internal properties of elementary objects in classical physics are isotropic in character. Such notions about the internal properties of elementary objects were valid at least until the development of electrodynamics, i.e., for as long as the study of fields did not make its appearance in physics. It is precisely such objects one usually has in mind when one speaks of the elementary objects of classical physics. These objects contain no special or privileged directions manifested in interactions. In structure they are the simplest objects of physics and, correspondingly, the most symmetric. According to the study of the symmetry of finite objects, the most symmetric material figure is the sphere. Its symmetry is determined by the group $\infty/\infty : m$, which has

* For a review of the development of these ideas see for instance the article of Markov, M. A. "O sovremennoi forme atomizma" (The Modern Form of Atomism), Voprosy filosofii, No. 3 and 4, 1960.

the largest possible number of symmetry elements: an infinite number of axes of symmetry of infinite order intersecting at one point, the center of symmetry, and an infinite number of symmetry planes passing through the center of symmetry*.

The internal properties and structure of an elementary object of classical physics are, as it happens, characterized by spherical symmetry: the changes which were admissible in the form of this object did not destroy its internal symmetry.

As physics developed it was discovered that such notions of the elementary objects were limited. They were sufficient so long as physics, in studying particles of matter, confined itself to purely corpuscular notions and to ideas of action at a distance. The development of the field concept as a new form of matter, and in particular the fact of taking the presence of the field into account in the analysis of the interaction of particles of matter, led to changes in the views held on the internal structure of the elementary objects of physics. These changes were summarized most fully in the theory of relativity. As follows from the Lorentz transformations, the theory of relativity distinguished one of the coordinate axes, the one along the direction of motion of the object. Correspondingly the elementary object became anisotropic in its internal properties, and in the spherical form which was adduced in the discussion of the internal symmetry of the classical object a definite direction was singled out: in the theory of relativity this sphere proved to be, so to speak, "compressed" in the direction of motion. The symmetry of the "compressed" sphere is represented by the group $m:\infty \cdot m$ (sometimes called cylindrical symmetry). The presence of such internal structure in elementary objects is taken into account in transformations of the Lorentz group. The transition from spherical to cylindrical symmetry in the consideration of the internal structure of the elementary objects of physics marks the discovery and incorporation of the asymmetry in their internal structure, where by asymmetry is meant, as usual, the absence of certain elements of symmetry.

Quantum theory introduced further changes into the physical ideas concerning elementary objects. These changes are related first and foremost to the introduction of the concepts of spin and parity as internal properties of elementary particles. It will be necessary to concentrate on these properties inasmuch as they determine the form of the wave function as characterization of the states of particles. Spin and parity express those internal properties of particles which are of an anisotropic, i.e., directed, nature. A very simple, graphic example of this is the fact that the effective cross section of scattering of polarized photons on oriented electrons depends on the mutual orientation of the photon and electron spins.

* Here, as usual, the symmetry groups are denoted by means of the principal symmetry elements which completely determine the symmetry of the corresponding objects. The plane of symmetry is denoted by the letter m, the axes of symmetry by numbers indicating the order of the axis, and the axis of infinite order by the symbol ∞. If the axis of symmetry lies in the plane of symmetry, a dot is placed between the symbols denoting these elements of symmetry to indicate the parallelism of the two elements of symmetry (for instance, the symbol $\infty \cdot m$ means that the axis of symmetry of infinite order lies in the plane of symmetry). If the axis of symmetry is perpendicular to the plane of symmetry, this circumstance is denoted by a colon. If two axes of symmetry intersect at an angle other than a right angle, this is indicated by placing a solidus between the symbols characterizing these axes of symmetry. (For greater detail concerning symmetry see, for example, A. V. Shubnikov. Simmetriya i antisimmetriya konechnykh figur (The Symmetry and Antisymmetry of Finite Figures). Moscow, 1951.)

We will first consider the influence of the spin on the internal symmetry of elementary particles (parity will not be taken into account). This order of treatment corresponds to the historical development of our knowledge of these properties in quantum theory. Since all other internal properties of elementary particles have an isotropic character, it is natural to assume that a consideration of spin will introduce a definite asymmetry into spherical symmetry, which expresses the internal structure of objects with isotropic internal properties. The spin of an elementary particle is its internal angular momentum. Hence it follows that the symmetry which corresponds to the internal structure of an elementary particle when the spin is taken into account is the symmetry of a rotating sphere: $\infty : m$ (axial symmetry). This is also shown by the following. To the spin of a particle is related its proper magnetic moment, the magnitude of which is proportional to the spin. Now it is well known that an elementary magnet has the symmetry $\infty : m*$. This is also shown by other facts, in particular by the fact that in the intrinsic system of reference the electron, with the spin taken into account, also has axial symmetry**.

Thus the internal structure of an elementary particle with spin is characterized by axial symmetry. From this it follows that in the intrinsic system of reference of particles the spin demarcates the axis of symmetry but does not demarcate a definite direction along the axis of symmetry. Intuitively, this is, in fact, the form of a rotating sphere. At the same time we might notice that these directions become distinguishable in the process of interaction. It is perhaps owing to the latter circumstance that one cannot obtain a characterization of the magnetic moments of particles in quantum theory starting from free fields: such characterizations are given only by the theory of interacting fields.

The concept of parity superposes additional asymmetry on those notions of internal symmetry of elementary particles which correspond to taking spin into account. According to modern views on parity, its meaning is that it introduces a distinction between right and left. Consequently, parity, as it were, demarcates the axis of symmetry, i.e., makes it possible to distinguish between one direction along the axis and another. This means that in our conceptions of the internal structure of elementary particles parity liquidates the plane of symmetry, and that now the elementary object is characterized only by an axis of symmetry of infinite order. Such symmetry is characteristic of a rotating sphere moving inertially in the direction of the axis of rotation.

What we have said can be summed up in the form of a chart (see next page).

Of course, far from all historical sequences of data, results, states and so forth are regular: regular relations are underlain by necessity. The sequence of modifications in the physical conception of elementary objects expressed in the following scheme will appear completely regular, or necessary, if:

1) one adopts the correspondence principle, i.e., assumes that knowledge concerning elementary objects develops consistently;

2) one starts from the assumption that knowledge evolves from the abstract to the concrete, i.e., that the earliest conception of elementary

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* See, for example, Shubnikov, A. V. Problema dissimmetrii material'nykh ob'ektov (The Problem of the Asymmetry of Material Objects), p. 31, and the following pages. Moscow, 1961.

** See Levashev, A. E. Elementarnye chastisy (Elementary Particles). Part I. p. 64. Kiev, 1960.

objects was the poorest and that it was enriched with the development of knowledge;

3) one assumes, to follow Pierre Curie, that it is not the presence of definite symmetry elements but their absence — asymmetry — which is more important for a physical phenomenon, i.e., that asymmetry, rather than symmetry, is the cause of phenomena*.

Development of ideas concerning the concept of elementary object in physics, in the light of ideas on symmetry

Physical theories	Characterization of the internal (structural) properties of elementary object	Symmetry groups reflecting internal structure of object	Corresponding geometric form of elementary object
Theories of classical physics (before the development of electrodynamics)	Internal properties of object are isotropic. Object does not contain privileged directions which could be manifested in interactions. Object is the most structureless in physics and correspondingly is the most symmetric with respect to its internal properties.	$\infty/\infty : m$	Sphere
Theory of relativity	In the internal properties of object a direction corresponding to the direction of motion of the object is distinguished.	$m \cdot \infty : m$	"Compressed" sphere
Quantum theory	A new asymmetry is revealed in the internal properties of elementary object, associated with:		
	a) spin	$\infty : m$	Rotating "compressed" sphere
	b) parity	∞	Rotating "compressed" sphere moving inertially in the direction of axis of rotation

It follows from what we have said that the development of the conception of elementary objects in physics might be characterized as the gradual discovery of asymmetry in that geometric form which expresses the internal structure of elementary objects and which originates in classical physics. The modifications introduced by quantum theory into the conception of the elementary object consist of a recognition of the anisotropy of the new internal properties of these objects, which condition the directed character of their interactions. Theoretical expression of the presence of directed internal properties in the elementary objects of physics proved possible only on the basis of statistical regularities, with the use of wave functions.

* See, on this question, Levashev, A.E. Elementarnye chastitsy (Elementary Particles), Part 1, p. 59.

In other words, statistical, probabilistic methods of research afforded the first serious penetration of the internal structure of elementary objects.

Therein lies, generally speaking, the chief value of statistical regularities. This explains the exceptionally widespread utilization or, one might say, eminent position of statistical regularities in modern physics, especially as compared with dynamical regularities.

In the modern physics of microprocesses the line, so to speak, leading to the revelation of the structure of elementary particles is fundamental. If quantum theory reflected, though in fairly general form, the wave-particle structure and a number of other internal properties of micro-objects, the theory of elementary particles is faced with the problem of penetrating yet more deeply into the structure of microobjects, uncovering new elements of asymmetry and reflecting so universal a property of elementary particles as their transmutability.

In the light of the considerations examined above, according to which the evolution of ideas concerning the elementary objects of physics could be characterized in brief as a consecutive transition from symmetry to asymmetry, certain inferences may be drawn concerning the nature of the problem which must be faced for the further development of the physics of microprocesses. This problem is to introduce a new element of asymmetry into our present ideas concerning the elementary particle, i.e., it is necessary to drop the assumption that an axis of symmetry of infinite order is present in it. In other words, our idea that the sphere with few elements of symmetry, the form of which was used to express the internal symmetry of the elementary particle, has a uniform structure will have to be dropped.

The symmetry group ∞ is the group which is the poorest in elements of symmetry in the series of so-called limiting symmetry groups. It is therefore particularly difficult to say to which new symmetry group we will advance, in our knowledge of the elementary particle, if we disregard the axis of symmetry of infinite order in characterizing its internal properties. The easiest answer is, of course, to assume that the axis of symmetry of infinite order will be replaced by a new axis of symmetry the order of which will be a certain finite number. In this case our sphere — the form which we used to characterize the internal symmetry of the elementary object — will be "split" into a certain number of parts.

At the same time, from the general point of view, many other assumptions might be proposed. In particular one could say that our "sphere" is very similar to the good old classical atom. Inasmuch as classical ideas about this form — the atom — proved exhausted from the standpoint of the study of symmetry as well, in the future, when uncovering new symmetry properties of elementary particles, one will have to turn to the form of a different object, the form of the modern, quantum atom. This means that the form of the atom will give us certain explicit considerations in the further study of the structure of elementary particles, just as the form of the sphere helped us, right up to the present time, in finding the quantum properties of elementary particles and first and foremost in finding the meaning of spin and parity.

What we have said, of course, belongs to the realm of conjecture. Without special physical investigation, all such judgments seem highly

unconvincing. However, there can be no doubt that the principal problem in quantum theory is to uncover the structure of elementary particles. It is precisely from the standpoint of comprehension of the structure that it is necessary to undertake an evaluation of the above-mentioned discussions of the fate of probabilistic representations in the further development of the physics of microprocesses. Is it possible to penetrate more deeply into the structure — and obtain the corresponding equations of motion — on the basis of ideas of dynamical regularities? Considerable difficulties stand in the way of an answer to this question. History knows of no such examples. In practice such a statement of the problem is given only in works by representatives of the causal interpretation of quantum theory.

It was the search for a dynamical regularity which led the representatives of this trend to the necessity of unravelling the structure of elementary particles. The model of a particle in the given case is constructed primarily on the basis of ideas concerning the relativistic drop. Here again, however, one meets problems of colossal difficulty. How the states of particles are to be characterized is still not clear. From the general point of view one might venture to suppose that the states of particles in the given case will not be characterized by wave functions, as the meaning of the latter is expressed by means of probability distributions. At the same time, a new characterization of the states must include in itself data on the structure of microobjects obtained by wave functions. In case such investigations are successful, they will lead to an evolution in the very conception of dynamical regularity.

One could suppose, apparently with good reason, that the further development of the physics of microprocesses will proceed on a statistical basis, i.e., ideas of probability and probability distribution will remain prominent. However, the task of penetrating further into the structure of particles requires a further development of the probabilistic ideas themselves. Possibly one will have to pass from wave functions to yet more abstract mathematical means of characterizing the states of physical systems, means which will be even more intimately related to probability distributions. And these distributions, in view of von Neumann's well-known theorem, will not be distributions of quantum-mechanical nature. But it is possible that the very foundations of our ideas concerning probability will undergo modification and expansion, a prospect made likely by the introduction of negative probabilities into the nonlinear quantum theory of fields.

However, there can be no doubt that fundamentally new problems require, in order to be solved, fundamentally new methods of research, which may fail to fit into the framework of known classes of regularities — dynamical or statistical. Therefore for the most qualified answer to the question of the fate of statistics one must dwell especially on a consideration of the methods used in those present-day investigations which are aimed at developing a theory of elementary particles. Today the problem of developing such a theory reduces fundamentally to the problem of developing a natural system of classification of elementary particles based on our knowledge of their several internal properties, or of developing a kind of Mendeleev system for elementary particles. The development of such a system would make it possible to establish the internal interconnections of the various particles, would shed light on the nature of the discreteness of many

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particle properties (mass, charge, spin...), would enable one to draw certain definite inferences concerning the number of particles and, in so doing, perhaps divide them into, so to speak, "fundamental" and "derived" particles, and so on. A number of classification schemes have already been proposed for elementary particles, but all are of an essentially hypothetical nature*.

In developing classification schemes for elementary particles, the general ideas of the quantum theory of fields are taken as point of departure and use is made of data on internal properties obtained from the characterization of particles by means of wave functions. From the methodological point of view it is important to note that in these investigations widespread use is made of the methods of group theory, which are most closely and most directly related to the modern approach to the symmetry of material objects. Since unravelling the structure of elementary particles involves a further unravelling of asymmetry in their internal properties, the utilization of the methods of group theory in the physics of elementary particles is very necessary.

The use of group theoretical methods in the physics of microparticles is based firstly on the fact that they allow one to determine many of the properties of quantum systems without solving the fundamental equations. In quantum physics direct solution of the fundamental equations very often involves colossal mathematical difficulties; occasionally these equations are not even exactly known. In such cases the methods of group theory prove highly valuable by facilitating calculations and enabling the expression of definite properties of quantum systems. In this connection it should be stressed that group theoretical methods make it possible to distinguish the most profound internal properties of quantum systems, properties related to requirements of invariance and symmetry.

The ever-increasing role of group theoretical methods in quantum physics of late has suggested the need for a revision of the foundations of modern quantum theory and of its ideas from the standpoint of group theory. The primary aim here is to examine the possibility of obtaining theoretically quantum mechanical operators starting from the more fundamental propositions which can be studied with the aid of the methods of continuous groups.

Without entering into the substance of such aspirations, from the epistemological standpoint it must be remarked that such a revision of the foundations of quantum theory could prove useful for the construction of a more evolved theory of microprocesses. The history of the development of physics shows that, once the foundations of a new physical theory have been laid and its fundamental equations obtained, one of the tasks of this theory consists of a careful development of its mathematical consequences, accompanied by development of the various mathematical forms of expressing its regularities. As a result not only does the content of the given theory stand more deeply revealed, but the ground is prepared for the development of a new theory. Thus without the work of such men as Euler, Lagrange and Hamilton in classical mechanics, who gave its equations new and more abstract forms of expression, one cannot conceive of the appearance of quantum mechanics. This is clearly seen from the fact that Hamiltonian

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* See I v a n e n k o, D. and A. S t a r t s e v, Klassifikatsiya elementarykh chastits (Classification of Elementary Particles). UFN, Vol.LXXII, No.4, 1960.

formalism plays a tremendous role in the very statement of quantum problems. Analogously one might suppose that the group theoretical approach to the foundations of quantum theory would not only deepen and expand our knowledge of quantum systems, but would prepare the ground for the development of a new physical theory of microprocesses.

Schemes of classification based on the theory of groups view the analysis of elementary particles from the standpoint of revealing their internal structure and make it possible to express the definite asymmetry in the structure of the particles. If successful these attempts will lead to a deepening of our general ideas concerning the regularities of nature, but it must be borne in mind that many authors, in their attempts to evolve a classification of particles, seek to reflect the dynamical picture of their interactions.

To analyze the nature of the statistical regularities of quantum theory it is important to consider the following problem: which of the physical ideas in this theory could be formulated on the basis of statistical, probabilistic concepts? Since quantum theories are fundamentally statistical, it is natural to suppose that such ideas determine the nature of the entire quantum theory. Wherein lies the "piquancy" of quantum theory? And what precisely is its relation to the statistical character?

With the first glance at the mathematical apparatus of quantum theories one is already struck by the presence in them of a new physical quantity, Planck's constant h. The introduction into physics of Planck's constant marked the beginning of the development of quantum theories. This quantity is associated with the most characteristic specific traits of quantum theories; this follows already from the fact that, if one removes h from the fundamental equations of quantum theories by letting it tend to zero, these equations transform into the equations of classical physics. If one considers the position of h in quantum theories and the prominent role the latter play in modern physics, one is perfectly justified in calling Planck's constant, together with O. D. Khvol'son, the "ruler of modern physics".

It is therefore of particular interest to consider the question of the meaning of Planck's constant and its relation to the statistical character of the regularities of quantum theories. This is all the more necessary as Planck introduced his constant into physics while solving the problem of thermal emission on the basis of statistical methods, relying on the corresponding works of L. Boltzmann*.

The introduction into physics of Planck's constant enabled the formulation of physical equations which were simple in form though fundamental in content and the use of which, in association with certain mathematical disciplines already developed by that time (theory of wave equations, theory of operators, and others), led to the rapid development of the quantum theories. To grasp the content of h it is therefore necessary to analyze the fundamental equations in which it was born. Historically the first such equation is Planck's equation $E = \hbar\omega$, where E is the energy and ω the frequency.

In addition to this equation, the fundamental equations which sparked the development of the quantum theories include Einstein's equation for the

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* In this treatment of the problem of the meaning of h, the author is much indebted to L. de Broglie's article "Tainstvennaya postoyannaya h — velikoe otkrytie Maksa Planka" (The Mysterious Constant h— Max Planck's Great Discovery). See de Broglie, L. Po tropam nauki (On the Paths of Science), pp. 139-146. Moscow. 1962.

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photon momentum $\vec{p} = \hbar\vec{k}$ ($\vec{p}$ is the photon momentum and $\vec{k}$ the wave vector) and de Broglie's equation for particles of matter $p = \frac{h}{\lambda}$ (p is the momentum and λ the wavelength). These equations furnish a basis for analyzing the content of the "ruler of modern physics". It is useless to seek for the meaning of this physical quantity outside of these relations, just as it is in general useless to seek the meaning of any physical quantity outside of the fundamental relations in which it appears.

The content of these equations is that they establish the link between the corpuscular and the wave characteristics of matter. The characteristics in the left-hand side of the equation, the energy E and the momentum p, refer to light or to matter as corpuscles; the quantities ω, $\vec{k}$ and λ, on the other hand, are wave characteristics. The meaning of h is that it establishes the link between the wave and corpuscular characteristics of matter and, especially, that it formulates this in a mathematical language. It was the utilization of these ideas concerning the synthesis of corpuscular and wave properties of matter which led to the rapid development of quantum concepts. This evaluation of the meaning of h is in complete conformity with the fact that wave-particle dualism is the fundamental specific trait of quantum theories.

It should be noted, however, that a different point of view concerning the meaning of h, based on an analysis of this constant and on an evaluation of its role in the Bohr-Sommerfeld rules of quantization, was widely adopted in the earliest period of development of quantum ideas. The meaning of this view concerning the content of h is embodied in the statement that h establishes the presence of atomism, or of the quantized character of action, as a special mechanical quantity. Furthermore, in statements of the atomistic character of action was seen the fundamental specific trait of quantum processes, since the quantity h is the embodiment of this specific character. This view concerning the content of h was stressed primarily by the proponents of the matrix variant of quantum theory.

One of the tasks of quantum theory is to determine the discrete internal states of atomic systems. Before the introduction of the concept of wave function these discrete states were determined on the basis of the special Bohr-Sommerfeld quantization rules. These quantization rules are written in the form

$$\oint p\,dq = nh,$$

where q is the cyclic coordinate (the integral is taken over a closed path), p the momentum conjugate to it, h Planck's constant and n a positive integer.

These rules of quantization indicate that the possible discrete internal states of atomic systems are such that the indicated integral is equal to an integral multiple of h. As h has the dimensionality of mechanical action, the inference is drawn from here that h establishes the discreteness of action in quantum processes. Owing to the very small value of h this atomism of action is not at all manifested in the region of macroprocesses. In the region of microprocesses, on the other hand, when all the quantities become very small, the atomistic character of action becomes clear-cut.

The following question arises: can one infer from the relations which express the Bohr-Sommerfeld rules of quantization that the meaning of h reduces to establishing the atomistic character of action as the fundamental specific trait of quantum processes? For an answer to this question

one must evaluate the role and significance of these rules of quantization in modern quantum theory.

The Bohr-Sommerfeld quantum conditions were introduced during the solution of the problem of the structure of the atom: they separated the stable, "nonemitting" electron orbits in the atom from the entire set of conceivable orbits, i.e., those admitted by the laws of classical mechanics. These conditions were introduced into physics as a postulate, and their meaning began to be clarified only with the introduction into the theory of the atom of wave representations. From the standpoint of modern ideas, the presence of discrete internal energy states in atomic systems, to which is linked the quantum condition considered above, is a consequence of wave-particle dualism and is not, in general, a fundamental sign of quantum processes, since not all motions of microparticles are quantized. The problem of quantization is now solved by completely different methods, primarily as a search for proper values of the operators. All this means that the Bohr-Sommerfeld quantum conditions are far from playing a central role in the apparatus of quantum theories; they can be of importance only during the first application of quantum research methods to new regions, when there is no developed mathematical formalism to be applied to the problems of quantization.

It is also important to note the following. Statements claiming that the meaning of h is to establish the atomism of action are in large part determined by the fact that this quantity really has the dimensionality of action. However, if we analyze the content of a given physical quantity only on the basis of its dimensionality, disregarding the fundamental laws in which it appears in physics, we will never understand why physical quantities as different in nature as length and capacity have the same dimensionality. Further, if we seek to grasp the essence of physical quantities by considering only their dimensionality, we will never be able to understand the content of such quantities as electric charge, the dimensionality of which, in the CGSE system, has the form $|M^{1/2} L^{3/2} T^{-1}|$, where M is the mass, L the length and T the time.

Finally, statements that the atomistic character of action is the fundamental specific trait of quantum processes are also colored by a certain mechanistic tinge: in this case quantum processes are actually treated as ordinary mechanical processes, the only difference being that in the quantum case certain mechanical quantities, and primarily action, have a discontinuous character. The Bohr-Sommerfeld theory of the atom actually bore the imprint of such views. The specific character of quantum processes is, however, more complex, and since h expresses this specific character its meaning is more complex than might be inferred from its dimensionality.

Considering the question of the meaning of Planck's constant in the article mentioned above, de Broglie arrives at the following statement: "... Starting from 1923-1924 the development of wave mechanics demonstrated very clearly that the true meaning of the constant h is that it acts as a connecting link between the corpuscular and the wave aspects of elementary units of matter and radiation"*. This development of quantum concepts, continues de Broglie, led to a revision of the content of the rules of quantization on the basis of which, in the earliest period of development

* De Broglie, L. Po tropam nauki (On the Paths of Science), p. 142.

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of quantum theory of the atom, it was inferred that Planck's constant expressed the atomism of action. "The real method of quantization valid in the general case ... ", writes de Broglie, "consists of determining the frequencies of standing waves and is completely unrelated to the existence of discrete quanta in action"*. De Broglie also notes that now, when giving an exposition of quantum theory, the tendency is to limit oneself to "a statement of the role that Planck's constant plays, and no attempt is made to understand its significance"**.

What is the relationship between Planck's constant, or its content, and the statistical character of the regularities of quantum theory? First of all it must be noted that the independent experimental determination, or calculation, of this constant is based on statistical data. Direct experimental determination of Planck's constant requires the application of the above-mentioned relations of Planck, Einstein and de Broglie. These relations contain wave characteristics, wavelength and frequency, the direct determination of which by experiment is always carried out from interference patterns. In the quantum case interference patterns are always formed as statistical distributions of microobjects.

The fact that the independent experimental determination of h is based on statistical data indicates the existence of a profound link between this constant and properly statistical, probabilistic concepts. Perhaps these experiments would have been completely sufficient to prove that the link established by h between the corpuscular and wave characteristics was fundamentally statistical, had it been impossible to refer the wave characteristics λ and ω to individual objects. However, λ and ω are not only characteristics of distributions as a whole, but also important characteristics of individual objects. Therefore for a consistent evaluation of the relationship between h and statistical concepts one is compelled to clarify the problem of the nature of the wave properties of individual quantum objects.

The wave characteristics used to describe an individual microobject — wavelength and frequency — are, strictly speaking, the characteristics of an infinite plane wave. This utilization of the characteristics is based on treating microobjects as the quanta of certain fields. The plane wave is the quantum of the corresponding field. Wavelength is the characteristic of its structure, and, therefore, it is the structural characteristic of the microobject as field quantum. Without the field concept it is impossible to say anything at present concerning the wavelength of an individual particle. Regarding the wave properties of an individual microobject, all one can say is that they are characterized in terms of the wavelength (or frequency) inherent to the microobject and that they are responsible for the remarkable interference of the microobject with its own self and ensuing quantum regularities. These properties are studied from the distributions observed as a result of interactions, and not from ideas concerning the structure of the microobject; they are, so to speak, studied from the outside rather than from the inside. In other words, the mechanism by which corpuscular and wave properties are linked in the individual microobject remains essentially hidden.

The highly schematic considerations put forward above should, in our opinion, prove that underlying the fundamental physical idea of

* Ibid., p. 143.
** Ibid., p. 144.

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quantum theory — the idea of a synthesis of corpuscular and wave concepts of the structure of matter — the concept of probability distributions, i. e. , that Planck's constant is related in a significant way to the statistical character of the regularities of quantum theory: wherever one finds Planck's constant one also finds statistics.

It should also be added that the meaning of Planck's constant is apparently very closely linked to the concept of spin as a special internal property of elementary particles. This is shown by the fact that the spin is measured in units of Planck's constant.

It is natural to suppose that when physics will have penetrated yet more deeply into the structure of microobjects our present ideas of a synthesis of wave and corpuscular properties of microobjects will receive a new and more profound expression. If this is the case one may be able to calculate Planck's constant theoretically from certain new physical considerations. It also means that Planck's constant has a relative character and is not a universal constant guaranteed from restrictions in further investigations into microprocesses, as is now assumed in the overwhelming majority of cases. Only in a few works is the nonabsolute character of Planck's constant mentioned. In particular, de Broglie hopes that a development of ideas of causal interpretation of quantum theory, based upon utilization of nonlinear equations, will lead to revelation of the content of Planck's constant. Let us quote in this connection the concluding words of de Broglie's article: "... Of course, the true meaning of Planck's constant cannot be determined before a firmly based general theory of elementary particles is constructed; this theory will necessarily reveal the deeper meaning of the wave-particle dualism. Its construction will, of course, be long and involved, for the nonlinear equations are an unhandy mathematical instrument, and a description of the various kinds of particles must enable the prediction of a wide variety of characteristics (mass, charge, spin and so on). But sooner or later all these difficulties will be overcome and the real meaning of the constant h will doubtless become clear, and the truly amazing character of Max Planck's great discovery will become even more evident than it is today. Indeed, five years before the birth of quantum theory of light, when no one could even have supposed the existence of the wave-particle dualism, this great physicist, working on the very special problem of black-body radiation, realized the necessity of introducing into physics this universal and fundamental constant h, which expresses in nature the alliance of waves and particles and is doubtless the key-stone of the edifice of our ideas concerning matter and radiation on a microphysical scale"*.

Thus the specific character of quantum processes is embodied first and foremost in the existence of Planck's constant. Erected on ideas of statistics and probability, it appears before the investigator surrounded by the aura of an all-powerful ruler; the glitter of its reputation and the scantiness of our information prevent us from clearly discerning its form. Yet it contains within itself mysterious features the revelation of which could lower it from its present pedestal of universality.

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* De Broglie, L. Po tropam nauki (On the Paths of Science), p. 146.

Statistical regularities introduced into physics the conception of a new form of necessity underlain by probability distributions. In combination with the new experimental data, statistical methods of research enabled the formulation of radically new physical ideas, the quantum ideas, the most complete and consistent expression of which is the quantum theory of fields, the theory of interaction of elementary particles. Quantum ideas were responsible for the first successful breakthrough of science into the region of microprocesses.

The physics of microprocesses has now reached a new boundary and a qualitative modification is once more awaited. What is expected is the development of a, so to speak, proper theory of elementary particles, the task of which would be to explain the mass spectrum of particles, specific interaction constants, the essence of the process of particle transmutation, and so forth. At the same time it is often pointed out justifiably that we are still far from knowing what we wish to obtain from the new theory. So many problems are often put before this future theory that to solve them in a single theory, as M.A. Markov put it, "would mean to discover the exhaustive theory of matter. It would mean that the Universal Theory, or simply the 'Theory', had been found"*. When discussing the question of a new theory it is usually remarked that this theory will be based on the introduction of a radically new and highly original physical idea which is bound to jolt and overturn accepted physical notions. Such views take the experience of the development of physics into consideration and are summed up in N. Bohr's famous remark about the "crazy" idea. At present nothing definite can be said concerning such an idea. From the general point of view, however, one might try to suggest some of the prerequisites for the birth of this "crazy" idea.

Taking into consideration the experience of quantum theory, one might say that the most radical changes will be introduced in physics if the new theory upholds the idea of a new form of necessity. Quantum theory established probabilistic necessity in physics. The idea of probability provides the basis for seeking the objective content of quantum theory and at the same time for applying a developed mathematical apparatus to quantum problems. However, we must stress that the groundwork of the study of probability was laid long before the appearance of quantum theory.

By analogy with the development of quantum theory, remembering that modern physics is developing by the method of mathematical hypothesis, one might conjecture that the foundations of such a "skeletal" mathematical theory have been laid by now. On the one hand, this "skeletal" theory will enable the formulation, within its framework, of the "crazy" idea, and its concepts will act as the guiding thread in the problem of the treatment of the new physical theory. On the other hand, the "skeletal" theory will make it possible to apply the advanced apparatus of modern mathematics to new problems. For it should be recalled that the principal form of expression of regularities in physics is mathematics; it is precisely in modern mathematics that the new forms of expression of the new regularities of the material world should be sought.

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* Markov, M.A. O sovremennoi forme atomizma (The Modern Form of Atomism). Voprosy filosofii, No. 4, p. 125, 1960.

CAUSALITY AND DETERMINISM IN QUANTUM THEORY

G. A. Svechnikov

The discovery and study of the atom, electron, proton and other micro-particles which together constitute what we now call the "microworld" necessarily raised a number of philosophical problems. The most important of these problems concerns the connection between the system of philosophical categories drawn up on the basis of ordinary macroscopic ideas and the system of concepts required for adequate expression of micro-world phenomena. Can the system of, so the speak, macroscopic philosophical categories be applied in its entirety to the region of cognition of the microworld? And if corrections are required, what is their nature?

In the present article an attempt is made to elucidate the specific traits of causal relations in microphysics; what new elements has quantum physics contributed to our ordinary ideas concerning causality, and what is the part played by the principle of causality in the investigation of micro-processes?

The concept of causality is used ambiguously in our physical and philosophical literature. This gives rise to misunderstandings and difficulties which, in discussions of the problem of causality, occasionally turn into a semantic argument. It would therefore be very useful, before turning to a discussion of the problem, to define the concepts of causality and determinism and clarify the relationship between them*.

In the philosophical literature the concept of causality is chiefly used in the sense of a link between cause and effect.

In other cases the concept of causality is identified with the necessary connection between the states of a system, where the initial state of the system necessarily determines its state at any subsequent instant in time. This interpretation of causality is usually called classical determinism.

In some cases, and especially in the physical literature, the principle of causality is identified with the possibility in principle of predicting with absolute accuracy the future state of a system if its state is known at some

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* In the Marxist literature a great deal of work has been done in recent years on the investigation of the concept of causality in physics: see O m e l ' y a n o v s k i i, M.E. Filosofskie voprosy kvantovoi mekhaniki (Philosophical Problems of Quantum Mechanics). Moscow. 1956; the collections of essays entitled "Problema prichinnosti v sovremennoi fizike" (The Problem of Causality in Modern Physics). Moscow. 1960; Z i c h, O., I. M á l e k and L. T o n d l. K metodologii experimentálních věd. Praha. 1959; P o l i k a r o w, A. Zum physikalischen Kausalgesetz. Wissenschaftliche Zeitschrift der Humboldt-Universität, R. XI, Berlin, 1962, and others.

given instant in time. This view of causality is called, somewhat inaccurately, Laplacian determinism*.

The concept of causality is also used in a sense which might be called mathematical determinism. By the latter is meant the case where a differential equation (ordinary or partial) expressing some form of behavior of a physical system has, for definite initial and boundary conditions, one single solution**.

Let us examine the connection between these views. In its profound essence the category of causality expresses the self-activeness of matter, the ability of material things and phenomena to generate other things and phenomena. Cause is the active origin which generates the given thing or phenomenon. Cause can either have the character of an external influence refracted through the internal nature of the thing undergoing this influence, or have the character of an interaction between parts which produces a change in the thing the whole. The principle of causality consists of the statement that all phenomena of actual reality have a cause.

The finite rate of propagation of influences in space (not exceeding the velocity of light) and the impossibility of influencing already completed phenomena are ideas which are of considerable importance for understanding causality in physics.

A causal relation must be distinguished from a relation between states***. If the category of causality expresses the relationship and interaction between different things or parts, the relation between states expresses the relationship between different states of the same thing. If the concept of cause expresses the source of motion and change of a thing, the relation between states expresses the result of motion and change. The category of cause serves to explain phenomena, the relation between states to describe the result of motion. These concepts, though distinct, are organically connected with each other.

To a definite cause acting upon a thing corresponds a definite relation between the states of the thing, and, conversely, a definite relation between the states of the thing presupposes a definite cause. In the relation between states is manifested the character of the causal relation, and, conversely, the causal relation determines the character of the relation between states. Changes in the thing and, therefore, the relation between its states, are determined in the general case both by the nature of the external influences and by the internal nature of the thing. Therefore in the general case the relation between states is both necessary and random.

Classical determinism is a particular case of the relation between states, where this relation has a necessary character, and is possible only when the system does not undergo external influences, i. e. , in the case of

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* This view of Laplacian determinism is historically inaccurate. Laplace himself delimited the problems of objectivity and cognizability of causal relations. See Fil'shtein, E. Laplas, Engel's i nashi sovremenniki (Laplace, Engels and our Contemporaries). "Studia Filozoficzne. Izbrannye stat'i, 1957-1960", No. 1, pp. 47-63. 1962; Svechnikov, G.A. Kategoriya prichinnosti v fizike (The Category of Causality in Physics). Moscow, pp. 129-138. 1961.

** The use of the concept of causality in the sense of mathematical determinism in theoretical physics was pointed out by V.A. Fok in an article entitled "Critique épistémologique de théories récentes" (La Pensée, No. 91, p. 13. 1960).

*** For greater detail see: Svechnikov, G.A. Kategoriya prichinnosti v fizike (The Category of Causality in Physics), pp. 88-105; Krajewski, W. Problem kategorii ontologicznych przyczyny i skutku. Studia filozoficzne, No. 5(26), pp. 3-19. 1961.

isolated, closed systems*. Since there are no absolutely isolated systems in nature, the concept of classical determinism is a limiting, abstract concept applicable only insofar as a system can be regarded in a certain respect as relatively isolated.

Laplacian determinism (in its usual view) expresses the ideal of absolute knowledge, where absolutely exact knowledge of the initial state of a classically determined system and of the law of change of its states permit absolutely exact predictions of the future.

In classical mechanics and Maxwell's electrodynamics Laplacian determinism is identical with mathematical determinism, since the equations of Newton and Maxwell enable univocal prediction of the future state of the corresponding system, provided its present state and the forces or sources of currents and electric charges are known.

In quantum mechanics mathematical determinism differs from Laplacian determinism. Schroedinger's equation, which expresses the behavior of a quantum mechanical system, has a unique solution for specified initial conditions. However, one cannot, in the general case, make univocal predictions concerning the future of this system on the basis of this solution.

In the region of the quantum theory of fields, microprocesses are expressed not by a function but by a field operator which satisfies definite field equations.

The equations of quantum field theory consist of a system of an infinite number of differential equations which modern mathematics has so far been unable to solve. It has not even been proved that such a system of differential equations has a solution.

The field operators which satisfy the equations of the quantum theory of fields, like Schroedinger's wave function, express the probability of certain processes for specified conditions. Thus even if the field equations satisfied by the field operators had a unique solution for specified initial conditions, we would not be able to make univocal predictions concerning the behavior of the quantized field (particles) on the basis of this solution. If mathematical determinism does indeed hold in quantum field theory, then, as in quantum mechanics, it does not generally coincide with Laplacian determinism.

An important question when discussing causality in quantum physics is that of the relationship between necessity and chance, possibility and reality at different levels of material processes. It is essential for understanding the interconnection of dynamical and statistical laws in classical and quantum physics.

We recall that necessity is that which is determined by the internal nature, essence, of an object and therefore cannot be different from what it is. Chance is that which is determined not by the internal nature of the object but by something external with respect to this object and which therefore need not be.

That which is random relative to a given set of things may be necessary relative to a different, sufficiently broad, set of things. Another important feature of the dialectics of these concepts is that they express the union of the internal and the external.

* An analysis of classical determinism may be found in: A u g u s t y n e k , Z. Determinizm fizyczny. Studia filozoficzne, No. 3 (30). pp. 3-65. 1962.

The state of any object, in the general case, is determined both by the internal nature of this object and by the nature of the external influences. An external influence on an object is refracted through its internal structure; the internal nature of an object is manifested in its interaction with external bodies.

A phenomenon is necessary inasmuch as it is determined by its internal nature. A phenomenon is random inasmuch as it is determined by external influences. But since the same phenomenon is determined simultaneously by the internal nature of the object and by external influences, it is simultaneously necessary and random: necessary because it is the manifestation of the internal nature of things and random because it is the expression of the nature of external influences.

Let us see how the role of chance and necessity is modified by transition from the macroworld to the microworld.

First of all, we note that the relative role of chance and necessity can change even in the macroscopic region, when one moves from one system of bodies to another, broader system which contains the first as one of its parts. Let us suppose that we are interested in the motion of a bullet. This motion is necessary insofar as it is determined by the internal property of maintaining the velocity and direction of motion imparted by the shooting (inertial motion). It is random insofar as it depends on the influence of gunpowder gases, the earth's attraction, the resistance of the air, etc. If we consider the broader system containing both gun and bullet, in this system the relative role of necessity is greater, and that of chance smaller, than in the system containing only the bullet. Every influence external for the gun-bullet system is also external for the bullet, but not every influence external for the bullet is external for the broader system. If we extend the system to include the bullet, gun, earth, atmosphere and all bodies in the solar system, we obtain a system with reference to which the role of chance in the motion of the bullet is negligible, and its motion can be regarded as necessary.

The relationship between necessity and chance is also modified by transition from the macroworld to the microworld.

Every microprocess, generally speaking, represents an organic union of mechanical, physical and other phenomena which cannot be destroyed without destroying the process itself. For purposes of study, however, it is sometimes useful to distinguish some form of motion and abstract it from the others. Let us for instance take the spatial displacement of microobjects and separate it from all the other forms of change.

It is easily noted that when one moves from the level of macroscopic bodies to the molecular level the number of random external influences in the mechanical motion of the corresponding objects increases as compared with the number of necessary internal factors. Indeed, every influence external to, say, a flying bullet is external also to its molecules, though not every influence external to the molecule is external to the bullet. If a puff of wind produces a change in the motion of the bullet, this circumstance is reflected in the motion of the molecule of this bullet. If the given molecule, on the other hand, collides with a neighboring molecule, this effect, though external to the molecule, is internal and necessary with reference to the bullet as a whole.

The set of external relations which determine the mechanical displacement of an atom is larger than the corresponding set of relations which

determine the mechanical motion of a molecule; the number of external factors which condition the displacement in space of elementary particles is greater than the number of external factors which condition the motion of molecules and atoms. As one moves deeper into matter the role of the set of random factors in the determination of the mechanical form of motion of the corresponding objects increases. The tendency for the number of random factors which affect mechanical motion to increase as one moves from one level of material processes to other deeper ones is reflected in the increasing role of statistical methods in microphysics. Statistical methods play a more important role in microworld research than in description of the motion of macroscopic bodies.

In the macroscopic region it is possible, under certain conditions, to abstract oneself from the random influences on a body and construct a dynamical theory of its motion. In the microscopic region, however, owing to the smallness of the objects and finiteness of the quantum of action abstraction from random influences is less feasible. For this reason, in order to express the variation of the state of microobjects which are subject to the influence of a vast number of random phenomena, one has recourse to statistical methods.

Let us now consider the role of external factors in conditioning the physical properties of macro- and microbodies. Though the number of external relations increases as one moves from macroscopic to microscopic objects, their influence on the physical properties of these objects decreases.

For example, a piece of ice when heated to 0°C changes into water, i.e., into a different qualitative state, yet in this process the velocity of mechanical motion of the molecules increases but slightly. A sufficiently large external influence can break up a stone into fragments, and convert it to dust, yet in this process the mechanical motion of the molecules decreases very slightly. There are many other external influences which can transform the physical properties of macroscopic bodies with comparative ease but which do not change, or practically do not change, the physical properties of molecules. The internal structure of the molecule refracts the external influences so strongly that it does not allow direct influencing of its physical and chemical properties.

The physical properties of the atom are also determined by the internal interactions of its parts (nucleus and atomic electrons). Thus the atom's ability to enter into chemical combination with other atoms is due to the electrons which occupy the outer electronic shell of the atom. The atomic nucleus is a complex physical system which does not readily yield to external influences. Even more necessary are the physical properties of elementary particles. One cannot break down an electron or proton. Very strong collisions between elementary particles result not in their splitting but in the formation of new particles, i.e., transmutation.

The properties of elementary particles — mass, charge, spin and others — are necessarily related to the existence of the particles themselves. Although the mass of a macroscopic body can be reduced, within certain limits, without affecting the quality of the body itself, one cannot reduce the rest mass of an elementary particle without destroying its quality. Moreover, if for macroscopic bodies rotation about a proper axis is not an inseparable property, for elementary particles the spin can be neither increased nor reduced. Spin, like mass and charge, is a necessary property of elementary particles.

And so as one moves from the macroworld to the microworld one encounters two opposing tendencies: on the one hand, there is an increase in the number of random factors determining the mechanical form of motion of the objects; on the other hand, there is an increase in the role of necessity in conditioning the physical form of motion of matter.

The first tendency is reflected in the increased role of statistical methods for description of the spatial displacements of objects as one penetrates more and more deeply into matter; the other tendency is reflected by the introduction into physics of constants characterizing the necessary properties of microobjects — mass, charge, spin, proper magnetic moment and other properties of elementary particles.

These tendencies, though distinct, affect each other mutually. The use of statistical methods is justified by a definite conception of the internal properties of objects, without which the utilization of statistics would be impossible. In turn, the internal properties of objects are manifested in the behavior of collections which are described by means of statistics.

From what we have said concerning the relationship between chance and necessity, one might expect that every future theory expressing the mechanical displacement of microobjects in space and time will be statistical. However, a theory which expresses certain physical properties of objects in the microworld region may also contain laws of the dynamical type. The simplest examples of dynamical laws in elementary particle physics are the laws of conservation of spin, charge, and so on. If we know, for example, that the spin of a given particle at a certain instant is 1/2, we can say that it will be 1/2 at any subsequent instant in time.

The theory of microprocesses represents a specific fusion of statistical and dynamical laws. Taken separately neither type of law is sufficient to express the processes studied in elementary particle physics. It is only when taken together that statistical and dynamical laws give, within the framework of the corresponding theory, a complete description of the phenomena of the microworld.

A very important task of science is to predict the future. To determine the behavior of a given object in the future, it is important to know the possibilities for its behavior and the conditions for the conversion of these possibilities into reality. Every science, in some form or other, expresses the relationship between possibility and reality in the corresponding region of the real world.

It is well known that for a material point in classical mechanics all such mechanical motions as are compatible with its constraints are regarded as kinematically possible. For a free material point which does not have constraints upon its motion, any displacement of any velocity is possible. But as soon as the material point is correlated with definite external influences, out of the entire set of kinematic (abstract) possibilities only one transforms into a true possibility, all the other abstract possibilities converting into true impossibilities. This true possibility of motion of the mechanical system is actually realized. However, as long as the forces acting upon a mechanical system have not been specified, we can only speak of abstract possibilities compatible with the relations of the system.

The true possibility of a mechanical system is identical with its real motion, and therefore in classical mechanics true possibility and reality

are not distinguishable. Abstract kinematic possibility, generally speaking, differs from true possibility and, therefore, from reality. This distinction between kinematically possible displacements and real motion is expressed in the d'Alembert-Lagrange and Gaussian variational differential principles.

Any one of an infinite set of kinematically possible motions of a classical system can become a true possibility when the system is correlated with definite external conditions. To fixed external conditions corresponds one and only one true possibility of motion of the mechanical system, a possibility which is necessarily realized.

A different situation obtains in the region of quantum physics. To a given microparticle with specified initial state occurring under fixed macroscopic conditions corresponds an ensemble of true possibilities, each of which may be realized if the initial state and macroscopic conditions are repeated a sufficient number of times.

But what is this ensemble?

We can illustrate this by the example of the diffraction of successively ejected electrons. An electron which has just left a source of electrons has the possibility of producing a flash at any point of the bright rings of the diffraction picture. The set of all points of the screen which may be hit by the given electron forms an ensemble of possible hits to which corresponds the ensemble of possible motions of the electron (it does not follow that this motion is necessarily similar to the motion of a material point in classical mechanics).

The ensemble of possible electron flashes is expressed in quantum mechanics by the wave function. Only one possibility is realized in the motion of a single electron: the electron produces a flash at a single point on the screen. In order to realize the entire set of possibilities of the given electron one must either repeat the experiment indefinitely or simultaneously reproduce an unlimited number of identical experiments.

Why is it, one wonders, that for an individual microparticle in a definite macroscopic environment there exists an ensemble of true possibilities, expressed with the help of statistical methods in quantum mechanics, whereas for a mechanical object in a definite macroscopic environment there is only one true possibility, expressed, moreover, in the form of a dynamical law?

When explaining such peculiarities of microphenomena as the motion of successively ejected electrons in a diffracting device, one can make the following conjectures from the microscopic point of view:

1) the conditions of motion and initial states of successively ejected electrons are rigorously identical;

2) the conditions of motion of the electrons are different but their initial states are identical;

3) the initial states of successively ejected electrons are different but their conditions of motion are identical;

4) both the conditions of motion of the electrons and their initial states are different.

If the first conjecture is correct it would mean that the electrons have "freedom of will", "freedom of choice". Absolutely identical electrons moving in absolutely identical conditions produce sparks at different points on the bright bands: from this it should follow necessarily that the motion of an electron is acausal, or, at any rate, acausal within certain limits.

But is it justifiable to assume that successively ejected electrons have absolutely identical initial states and external conditions? The answer is no.

Macroscopically identical external conditions of electron motion may differ from the microscopic point of view. The macroscopic environment of a microobject can be realized in the form of different combinations of microprocesses identical from the macroscopic point of view. To every definite combination of microprocesses taking place within the given macroscopic environment corresponds a definite true possibility of behavior of the microobject. To the set of combinations of microprocesses which can produce the given macrosituation corresponds a set of motions of the microparticle.

By conditions of motion of microparticles should be understood not only the macroscopic body in itself, but also the zero-point vacuum fluctuations of the corresponding field (fields)*. It is possible that the different possibilities of motion of particles expressed by the statistical laws of nonrelativistic quantum mechanics are due precisely to the interaction between the microparticles and vacuum fluctuations.

Attempts to justify this assumption may be found in the works of E. I. Adirovich and M. I. Podgoretskii**, A. A. Sokolov***, K. D. Sinel'nikov**** and others.

A mathematical calculation carried out by Adirovich and Podgoretskii shows that even classical systems manifest certain quantum properties in interaction with zero-point electromagnetic fluctuations. In particular, the influence of zero-point fluctuations leads to the appearance, in classical systems, of a probability distribution of coordinates and momenta partially identical with the results of quantum mechanics. This circumstance permits us to suppose that the interaction of microparticles with the vacuum fluctuations of the corresponding field really plays a substantial role in the microworld, a role not exhausted by small effects like shifts of the atomic levels.

Sokolov and Tumanov demonstrated that the uncertainty relation of quantum mechanics can be recovered by including photon vacuum fluctuations and Planck's force of radiant friction in the equation of motion for the classical electron. However, these attempts to explain the statistical character of quantum mechanics are hypothetical and call for further discussion.

It is also not excluded that there exist, within definite limits, variations of the initial state of the microsystem to which correspond a special set of possible motions of this system.

* This was kindly pointed out to me by M.I. Podgoretskii.
** Adirovich, E.I. and M.I. Podgoretskii. O vzaimodeistvii mikrosistem s nulevymi kolebaniyami elektromagnitnogo polya (The Interaction of Microsystems with Zero-Point Fluctuations of the Electromagnetic Field). ZhETF, Vol. 26, No. 2, pp. 150-153. 1954.
*** Sokolov, A.A. and V.S. Tumanov. Sootnosheniya neopredelennostei i teoriya fluktuatsii (Uncertainty Relations and the Theory of Fluctuations). ZhETF, Vol. 30, p. 802. 1956. Sokolov, A.A. Vvedenie v kvantovuyu elektrodinamiku (Introduction to Quantum Electrodynamics). p. 190, Moscow. 1958. Sokolov, A.A., Yu.M. Loskutov and I.M. Ternov. Kvantovaya mekhanika (Quantum Mechanics). p. 143-146, Moscow. 1962.
**** Sinel'nikov, K.D. O filosofskikh voprosakh sovremennoi fiziki (Philosophical Problems of Modern Physics), in a collection entitled: Filosofskie voprosy sovremennoi fiziki (same title as article). pp. 7-26, Kiev. 1956.

If these assumptions are correct, then to a given macroscopic environ-
ment (which can be produced by various combinations of microprocesses),
upon variation within definite limits of the initial states of a microsystem,
corresponds the ensemble of possible motions of this system expressed by
the wave function.

When the microsystem moves only one possibility is realized, that which
corresponds to the given initial state of the system and to the combination
of microprocesses (which constitute the macrosituation) existing at this
instant.

To justify these ideas one must express them in the corresponding
mathematical form. If a theory constructed in the corresponding manner
gives the same distribution of possible motions of the microsystem as is
given by modern nonrelativistic quantum mechanics, we will know that the
above conjectures concerning the relationship between possibility and
reality are not excluded from the quantum region.

To establish the validity of these conjectures it is necessary that the new
theory of quantum processes constructed on their basis explain or predict
effects not explainable or predictable within the existing theory.

In quantum field theory a microsystem which occurs in macroscopically
fixed conditions, in addition to having the set of possibilities of the quan-
tum mechanical systems, also has the possibilities of transmutation —
creation and annihilation — of particles. The true possibilities of particle
creation and annihilation are expressed with the aid of the method of second
quantization, the essence of which is that elementary particles are treated
as quanta of the corresponding fields. In conformity with the possibility of
transmutation of the elementary particles, the wave functions of second
quantized fields assume the meaning of operators and break down into
operators of particle creation and annihilation, between which commutation
relations are established.

The commutation relations express two facts: first, that if the processes
of particle creation are mutually independent then the processes of
particle annihilation are also independent; second, that the processes of
antiparticle creation and particle annihilation are not related to each other,
just as the processes of particle creation and antiparticle annihilation are
unrelated. The annihilation of a particle at one space-time point and its
creation, generally, at a different point, or vice versa, can be related to
each other.

Thus in classical mechanics the true possibility for a mechanical sys-
tem undergoing definite external influences is identical with the real mo-
tion and is expressed in the form of a law of dynamical type.

In nonrelativistic quantum mechanics a microsystem occurring under
definite macroscopic conditions has a multiplicity of true possibilities ex-
pressed statistically by means of the wave function.

In the quantum theory of fields a microsystem, in addition to having
these possibilities, also has the possibilities of particle transmutation, ex-
pressed by means of the corresponding wave operators.

The fundamental equation of quantum mechanics, Schroedinger's equa-
tion $\left(i\hbar \frac{\partial \psi}{\partial t} = \hat{H} \psi \right)$, makes it possible to determine, on the basis of knowledge
of the wave function $\psi(r, t_0)$ at a certain initial instant, the wave function

at every future instant. But solution of the wave equation does not permit univocal prediction of the motion of a microparticle in the future. It expresses the variation in time and space of the true possibilities of motion of an individual microobject occurring under macroscopically fixed conditions. If in classical mechanics the behavior of a system is expressed immediately by means of quantities which univocally determine the real state of this system, in quantum mechanics the behavior of a microobject is characterized mediately by expressing the regularities of variation of the true possibilities of the microobject. But we can tell the actual motion from the way in which these possibilities of motion change. Schroedinger's equation expresses, in a complicated mediate form, the objective regular relation between the states of the microparticles.

The form of expression of the relation between states in quantum mechanics is such that we cannot, on its basis, judge univocally the transition of a particle from one real state to another; we cannot know the probability that some state will "happen". In order to decide whether the relation between the states of quantum mechanical objects in the finite part of the world is determinate or not, it is necessary to solve the problem of the foundations of statistical quantum mechanics. Since the latter problem has not been solved by modern science, the problem of determinateness of the states of microsystems remains open.

By expressing the objective relationship between the states of a particle or system of interacting particles in a complicated, mediate form, Schroedinger's equation expresses the objective causal relations which produce its motion. The probability or possibility of a given behavior of an object in a given environment is determined, as is stressed by V. A. Fok, "by the internal properties of the given individual object and by these external conditions"; therefore, the variation in time of the true possibilities of a particle characterizes the variation in time of the internal properties of this particle and of its external conditions*. In other words, if we know the wave function we can determine to some extent the variation of the behavior of the microparticle from its internal properties and external influences.

Any change either in the external influences affecting the particle, in its internal state or in both together is reflected in a modification of the wave function, which in turn expresses the change in the true possibilities of the microparticle. Thus,the mathematical apparatus of quantum mechanics automatically accounts for the dependence of the true possibilities for a given behavior on the microparticle's internal properties and external influences. In other words, by specifying the wave function Schroedinger's equation automatically expresses, in a complex, mediate form, the causal relations which produce the motion of the microparticle.

If in classical mechanics the connection between cause and effect (action) is expressed immediately in terms of the quantities which immediately characterize the measure of cause (force) and the measure of effect (acceleration), in quantum mechanics objective causal relations are expressed statistically in terms of the dependence of the probability for a given behavior on the microobject's internal properties and external influences. Not only do the statistical methods used by quantum mechanics to express the motion of

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* Fok, V.A. Ob interpretatsii kvantovoi mekhaniki (Interpretation of Quantum Mechanics), in a collection entitled "Filosofskie voprosy sovremennoi fiziki" (Philosophical Problems of Modern Physics). Moscow. p. 172. 1959.

microparticles not deny the existence of objective causal relations and of regularities of linking of states; they are even the expression of the existence of such relations.

In quantum field theory the state of elementary particles is characterized by the state of the corresponding field.

The probability of a given state of the field is expressed by the wave functional ψ [s], which is a generalization of the wave function of nonrelativistic quantum mechanics. Owing to the fact that the concept of "identical instant in time" is not relativistically invariant, the state of the field is characterized by the state of a field on a space-like surface*.

The functional ψ[s] characterizes the probability for a given state of the quantum field at points on a space-like surface. The magnitude of this probability is proportional to the square of the modulus $|\psi[s]|^2$ of the functional at points on the given surface.

The functional ψ [s] satisfies a certain equation which, in the Schroedinger representation, has the form

$$i\frac{\delta\psi[\sigma]}{\delta\sigma} = \hat{H}_{int}\psi[s],$$

where H_{int} is the interaction Hamiltonian.

This equation expresses the change in the true possibilities of the corresponding field state as one moves from one surface to another in a time-like direction. It is also apparent from this equation that the probability for a given field state on a space-like surface depends on the character of the field itself (form of particle) and the external influences. Any change in the form of particle or external influences necessarily leads to a change in the probability that the corresponding field state will be realized. This is an expression of the causal dependence of the behavior of elementary particles on their internal nature and external influences. It has a more mediate, abstract character than in quantum mechanics.

Thus with its mathematical apparatus quantum physics developed new mediation forms of expressing the causal relations of microsystems and the relationship between their states. These new forms immediately express the dependence of the true possibilities of a microsystem on its internal properties and external influences, as well as the law of variation of these possibilities for a given environment in time

The modern theory of elementary particles is the quantum theory of fields, which is the result of generalization of quantum mechanics on the basis of the theory of relativity.

The quantum theory of fields is tacitly underlain by the idea that the interaction of particles is responsible for processes in the microworld and that this interaction is carried by physical fields (electromagnetic, meson, neutrino, etc.).

To recognize that the interaction of particles or fields is responsible for the corresponding processes in the microworld is to recognize the causal origin of these processes**. In this view the cause which gives rise to

* A space-like surface is the name given to a surface on which any two points are separated by a space-like interval.

** Contrary to the claims of the positivists (E. Mach, M. Shlick, B. Russell et al.), this is evidence of the fruitfulness of applying the concept of cause as an active material agent which produces its effect in modern microphysics.

microprocesses bears the character not of a one-sided influence of one object on another, but of an immanent interaction determined by the internal nature of the interacting particles. The classical idea of cause-force is giving way to the idea of the interaction as cause in the region of elementary particle physics.

The equations of quantum field theory are an infinite system of partial differential equations. Physics is interested primarily in those solutions of the system which express the possibility for given processes generated by field interactions. However, as we saw earlier, modern mathematics cannot even tell us in what cases this system has a solution and in what cases it does not.

For this reason the equations of quantum theory are solved by an approximate method, the so-called perturbation theory. In this theory it is assumed that quantum fields can be regarded as free and noninteracting in the zeroeth approximation. A solution of this simplified problem (unperturbed case) is obtained. The next step is then taken. It is assumed that the fields are, in a certain respect, weakly interacting in the first approximation, as reflected in the fact that the terms expressing this interaction (perturbation) are small compared with the terms of the free field equation. The corrections due to the small change in the terms dropped in the zeroeth approximation are calculated approximately. Thus the first approximation is obtained, and so on.

Tacitly underlying the perturbation method is the idea that causal relations are additive, as reflected in the fact that the effect produced by the sum of the causes is equal to the sum of the effects produced separately by each cause, and that small changes in the cause give rise to a small change in the effect or consequence. When these assumptions are not met the logical foundation for the application of perturbation theory breaks down.

The perturbation method gives good results in quantum electrodynamics. However, a paradoxical situation arises where the results obtained in the first approximation agree with the experimental data, whereas the subsequent approximations lead to infinitely large values for the mass and energy of the particle, as well as for probabilities of the given quantum processes. A procedure of renormalizing the particle masses and charges was instituted to remove these difficulties. This procedure is founded on separation of the total electron mass m into a "bare" mass m_0, which represents the mass of a free electron-positron field quantum, and an electromagnetic mass δm (thus $m = m_0 + \delta m$). Analogously the electron charge e is separated into the bare charge e_0 (of the free electron) and an additional charge δe (due to its interaction with the field). The bare mass and bare charge of the electron are attributed a substantial nature, since they are inherent to the electron "in itself", irrespective of its relationship with other objects. The additional mass and charge, on the other hand, are regarded as the product of the interaction of the electron with the corresponding field. These quantities express the change in the properties of the electron in the process of its relationship with the other objects.

Leaving aside the question of whether it is valid to divide the electron mass and charge into bare and additional, we note that the method of renormalization is not a consistent procedure. On the one hand, it is assumed during the calculations that the additional quantities δm and δe are small compared with the total mass m and total charge e. On the other hand,

as a result of the calculations the electromagnetic mass δm and additional charge δe prove to be infinitely large. It is then assumed that the additional quantities δm and δe should, together with the bare mass m_0 and bare charge e_0, give the finite total mass $(m = m_0 + \delta m)$ and total charge $(e = e_0 + \delta e)$ of the electron. The values of the mass m and charge e are taken from experiment. Subsequently it turns out that in the quantum theory of fields the two infinite expressions for the probabilities of quantum processes appear in such a way that these infinities can be identified with the electromagnetic mass δm and additional charge δe. Thus one has succeeded not in removing the divergence but rather in isolating it by showing that it is not important for calculating the probabilities of certain processes and the mean values of the corresponding physical quantities. The justification given for using this formal and inconsistent procedure is that the quantities obtained in this way for the interaction of the electron and the electromagnetic field (quantum-electrodynamics) are in good agreement with experiment.

When this method is used in the theory of meson interaction, however, it leads to results which are not even in rough agreement with experiment.

In a paper by L. D. Landau and I. Ya. Pomeranchuk it is shown that after renormalization of the charge there is no interaction in the theory (the renormalized charge proves to be zero)*. True, this proof, as pointed out by M. A. Markov, is not entirely rigorous, as particle dimensions which later tend to zero are introduced into the argument (a theory with particle dimensions introduced in this manner is internally contradictory)**. But irrespective of the rigor of this proof, the procedure of renormalization did not fulfill the hope that it would remove the divergences, and it now appears to have exhausted itself.

In 1943 W. Heisenberg proposed an original method for removing the difficulties in quantum field theory in the form of the scattering matrix, or S-matrix, formalism. This method deals with the phenomenological relation between observed quantities, primarily the energy-momentum of free particles but also the discrete eigenvalues for bound states and the phase shift of incident and scattered waves at a sufficiently large distance from the scattering center.

FIGURE 1

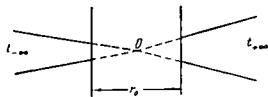We will explain the fundamental idea of this method with the following example (Figure 1).

Let us assume that there are two beams of particles converging at the point O. As a result of the interaction of particles in the vicinity of the

* See Landau, L.D. and I.Ya. Pomeranchuk. DAN, Vol. 102, p. 469. 1955.
** See Markov, M.A. Giperony i K-mezony (Hyperons and K-mesons). Moscow, p. 179. 1958.

point O, scattering, creation of new particles and other processes take place. Owing to the fact that the mechanism of interaction responsible for the corresponding processes is difficult to study, it is excluded from consideration and enclosed in a "black box". It is merely recognized that the interaction of particles in the vicinity of the center O produces a change in the initial state of the incident particles. But this is nothing but a recognition of the causal origin of the change in the behavior of the particles.

The problem is to determine the state of the particles when they leave the "black box" from their state upon entry. Or, in other words, the problem is to find the wave function $\psi_{+\infty}$ in the distant future $(t = +\infty)$ when the particles cease to interact, from the value of the wave function in the distant past $(t = -\infty)$, when the particles do not yet interact.

The operator which transforms the wave function of the distant past into the wave function of the distant future is called the S-matrix, or scattering matrix. Mathematically this is written down as follows:

$$\psi_{+\infty} = S\psi_{-\infty}.$$

The square of the S-matrix expresses the probability that the system of elementary particles will pass from the state described by the wave function $\psi_{-\infty}$ in the distant past to the state described by the wave function $\psi_{+\infty}$ in the distant future.

With the help of the S-matrix we can evaluate the possibility of a certain allowed behavior of a system in the distant future from our knowledge of the possibilities of a certain behavior of the system in the distant past. This complicated mediate expression of the relation between states in quantum field theory is conditioned not only by the peculiar character of human cognition but also by the peculiar character of the objective nature of relativistic microprocesses.

Various methods have been proposed to overcome the difficulties which arise in constructing the S-matrix, but none has so far succeeded in completely avoiding infinitely large expressions for the probabilities of transition from one state of a system to another.

In view of this Heisenberg suggested that, when constructing the S-matrix, one starts from the assumption that at very small distances influences from one particle to another can be transmitted at a velocity greater than that of light. If one assumes that for these rates of propagation of influences from object to object Lorentz transformations remain valid, it must be recognized that for such processes the difference between that which takes place 'before' and that which takes place 'after' becomes less clear-cut. For such processes one can choose a frame of reference in which, for instance, a positron and an electron first annihilate and then collide, i.e., the effect occurs first, the cause later. To admit of this possibility is to deny that macroscopic causality is applicable to the study of quantum mechanical processes, since in the macroscopic region cause always precedes effect (in the case of a mediate influence) or is simultaneous with it (immediate influence). This is why, already in 1954-1956, Heisenberg stated that to overcome the difficulties of elementary particle theory would involve further departure from the idea of causality. "Numerous investigations," he wrote, "have been undertaken in recent years in connection with these difficulties. However, no completely satisfactory solution has yet been found. The only way out of the difficulty seems to be to

assume that, in very small space-time regions of the order of magnitude of elementary particles, space and time have in some peculiar way been obliterated, so that the concepts of 'before' and 'after' can no longer be defined correctly. As far as the structure of space and time is concerned this would not, of course, result in any change, but one would have to reckon with the possibility that in small space-time regions certain processes take place in a direction opposite to that corresponding to their causal order... From this one deduces that atomic physics is tending farther and farther away from the idea of determinism"[*].

However, Heisenberg acknowledged that, at the present time, there did not exist a sufficient basis in elementary particle physics for a final repudiation of the idea of causality[**].

There is a fairly widespread belief among certain physicists that the concept of propagation of influences in the small (at distances of the order of 10^{-13} cm) at faster-than-light velocities is logically compatible in the theory with the requirement of formal invariance of the equations under Lorentz transformations. However, "this view," writes Markov,"is simply a delusion — it is internally contradictory. Indeed, if faster-than-light signals are possible in the small region, the synchronization of clocks is also possible, contrary to the Lorentz transformations, the validity of which is assumed even for this small region. Clarification of these contradictions is merely a question of time and level of experimental technique"[***].

If processes propagated at velocities greater than that of light in vacuum really existed in the microworld, then, from the natural assumption that cause cannot follow effect in real phenomena, we would arrive at the conclusion that Lorentz transformations are inapplicable to such processes. D. Bohm believes, for example, that the transformations may cease to be valid at small distances in the case of faster-than-light velocities. "It is well known from the general theory of relativity", writes Bohm, "that restriction of the possible velocities of light in the gravitational field is quite unnecessary... In any case one can hardly claim that the experimental facts require the same form of covariance to hold for small distances as in the large"[****].

At present, however, there is no adequate basis for abandoning the idea of the existence of a limiting rate of propagation of physical influences equal to the velocity of light in vacuum in the region of microprocesses. The possibility of overcoming the difficulties with the $\mathcal{S}$-matrix divergence without exceeding the bounds of the special theory of relativity is discussed in the works of Soviet scientists. N. N. Bogolyubov and his students are constructing a theory of the $\mathcal{S}$-matrix starting from a number of conditions which include the principle of causality. Causality is formulated by Bogolyubov and D. V. Shirkov as follows: "We must also guarantee fulfillment of the condition of causality, according to which any event taking place in a system can exercise an influence on the march of evolution only in the future, and cannot exercise an influence on the behavior of the system in the past, at a time preceding the given event. We must therefore require that a change in the law of interaction in any space-time region be capable

* Heisenberg, W. Atomforschung und Kausalgesetz. "Universitas", No. 3, pp. 235-236. 1954.
** Ibid., p. 236.
*** Markov, M.A. Giperony i K-mezony (Hyperons and K-mesons), p. 190.
**** Voprosy prichinnosti v kvantovoi mekhanike (Problems of Causality in Quantum Mechanics), Moscow, p. 81. 1955.

of influencing the evolution of the system only in the succeeding instants of time."*

Thus the authors use the term causality to mean a relationship between events such that one event influences the march of the other and the influence of the one on the other can be one-sided as well as reciprocal. The condition of causality which they have formulated is nothing more than an extrapolation of macroscopic causality to the region of microprocesses.

Bogolyubov and his followers stress the heuristic value of this conception of the principle of causality, which, while very severely restricting the theory, leads to a scheme essentially equivalent to the ordinary Hamiltonian method and differing from it only in the possibility of developing the exposition with great mathematical clarity**.

Heisenberg's general scheme for constructing the scattering matrix, which ignores the condition of causality, has produced practically no concrete results***.

In recent years dispersion relations, which relate quantities susceptible of direct measurement, have proved an important theoretical method of elementary particle research. This method is based upon investigation of the mathematical properties of the functions which express physical processes when these functions are continued into the region of the complex variable. The analytic properties of these functions of the complex variable reflect observable physical characteristics. Upon analysis of this method it appears that the continuation of functions which describe real physical processes into the complex region can be performed on the basis of a number of general properties of microsystems. These general properties include causality, which expresses the fact that physical influences are propagated in space over small distances at velocities not exceeding the velocity of light. It is easily shown that the condition of causality underlying the theory of dispersion relations is nothing more than an extension of the macroscopic conception of the link between cause and effect to microprocesses. But is so bold an extrapolation justifiable?

Experiment and theory indicate that the macroscopic idea of the rate of propagation of causal interaction is applicable in the microworld as well, at least for scales of the order of 10^{-13} cm.

Experimental verification of the usual dispersion relations for the scattering of some particles on others has been carried out at the Laboratory for Nuclear Studies, Joint Institute for Nuclear Research (Dubna), as well as a number of laboratories abroad. These studies revealed that "the laws linking cause and effect which are usual to physics remain valid in the new region of physics at least for scales of the order of 10^{-13} cm"****. On the basis of the macroscopic principle of causality it was possible to prove an entire series of important theorems in the theory of dispersion relations and to solve a number of concrete physical problems (M. Goldberger, N. N. Bogolyubov and others).

* Bogolyubov, N.N. and D.V. Shirkov. Voprosy kvantovoi teorii polya (Problems of Quantum Field Theory). UFN, Vol. LV, No. 2, p. 180. 1955.
** See Bogolyubov, N.N., B.V. Medvedev and M.K. Polivanov. Voprosy teorii dispersionnykh sootnoshenii (Problems of the Theory of Dispersion Relations). p. 20, Moscow. 1958.
*** Ibid.
**** Blokhintsev, D.I. Pyat' let raboty Ob'edinennogo instituta yadernykh issledovanii (Five Year's Work of the Joint Institute for Nuclear Research). Atomnaya energiya, Vol. 10, No. 4, p. 318. 1961.

In recent years the overwhelming majority of works on dispersion rela-tions have explicitly rested upon postulating certain properties of the scat-tering matrix (in relativistic problems) or upon assuming certain properties of the potential in Schroedinger's equation (in nonrelativistic problems), rather than upon the condition of microcausality. Implicitly, however, these assumptions apparently contain the idea that even at small distances causal interaction is propagated at velocities smaller than the velocity of light.

Very recently the attention of physicists was drawn to new theoretical methods of studying strong interactions with the help of moving Regge poles.

The new feature of this method is that on its basis one can simultaneously describe the existence of various particles and the dynamical processes of their interaction. This method makes it possible to determine the charac-ter of the interaction of particles from data on their properties; conversely, attempts are made to predict new resonances from the nature of the inter-action.

The consequences of Regge's method, as well as the theory of dispersion relations, are being experimentally verified at present on accelerators.

The question of the nature of the divergences in quantum field theory con-tinues to be the subject of spirited discussion in the physical literature. Certain scientists believe that a revision of the fundamental physical ideas underlying the equations of quantum physics is required; others believe that the equations of quantum field theory correctly reflect reality but that modern science is not capable of solving them correctly.

The physicists who share the first view seek a way out of the difficulties with the divergences by changing the foundations of the theory (nonlocal theories, space-time quantization, introduction of a minimum length, non-linear generalizations of the theory, and so on). As we cannot hope to deal here in any detail with all the various trends, we will confine ourselves to a few remarks concerning attempts to construct nonlocal theories and a uni-fied nonlinear theory of fields.

According to the nonlocal views, all the difficulties associated with di-vergences in quantum field theory arise owing to the fact that in the existing theories particles are regarded as point particles devoid of spatial dimensions. To remove these diffi-culties the idea of particles as extended objects, the dimensions of which can be expressed with the help of certain form factors, is introduced in the nonlocal theories. An extended particle can be regarded either as an absolutely rigid structure or as one capable of deformation under external influences. If the particle is regarded as undeformable it necessarily follows that the propagation of influences at infinite velocities is possible inside the particles.

FIGURE 2

Indeed, if we impart a certain momentum at a definite instant to an ab-solutely rigid particle at the point A (Figure 2), then the point B opposite to it should shift at the very same instant, since otherwise at some instant the particle would be flattened in the direction of the external influence.

The introduction of the concept of an infinitely large rate of propagation of influence inside a particle would lead to recognition of the existence of material processes outside of time. The influence would be propagated in-stantaneously from the point A to the point B. It is precisely here that we
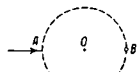
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would be inclined to see the reason for the failure of attempts to construct nonlocal theories on the basis of the concept of undeformable form factors. From this standpoint it seems that the form factors which characterize the particle dimensions should reflect the deformation of the particles under external influences. The introduction of such form factors would imply, as stressed by M. A. Markov, "a phenomenological description of the 'structure' of particles, the possibility in some sense of 'internal motions' of particles, a transition to consideration of the 'internal physics' of the particles, and in particular to a consideration of the possibility of their excited states, and so forth"*.

These form factors can be introduced in such a way that the rate of propagation of influence inside a particle does not exceed the velocity of light. For such signals the Lorentz transformations, and, therefore, the invariance of the temporal sequence of cause-effect relations from one inertial system of reference to another, are valid. Were one to introduce the idea of a rate of propagation of influence inside the particle greater than the velocity of light but still finite, one would have to revise Lorentz invariance in such a way as to preserve the invariance of the temporal sequence of cause and effect in the theory in all inertial systems of reference for these processes as well. Unfortunately, the theory of the deformable form factor has been neither substantiated nor developed coherently.

The most serious attempt to construct a unified theory of elementary particles was undertaken recently by Heisenberg. Although his proposed program for a nonlinear unified field theory is still far from completion and faces an entire series of physical and mathematical difficulties, it would be highly revealing to analyze it philosophically against the background of the question of causality.

Heisenberg starts from the idea that there exists a unified world field, matter. All existing elementary particles represent a manifestation of this world field. The required mathematical apparatus of the theory should refer not to some concrete particle but rather to matter in general. "Particles (elementary or complex) should be obtained as eigensolutions of the field equations"**.

True, Heisenberg himself has repeatedly declared in philosophical remarks that the true foundation of microprocesses is not matter but form, idea, mathematical law. Elementary particles, according to Heisenberg, are obtained as the derivatives of mathematical forms, of mathematical equations expressing laws of nature. The development of quantum physics in recent years seems to be swinging from Democritus all the way to Plato. In Heisenberg's view even Planck's discovery "already contained an indication that the atomic structure of matter should be seen as the expression of mathematical forms in laws of nature"***. In his philosophical pronouncements Heisenberg leaves the scientific ground and passes over to the positions of objective idealism in the Platonic sense.

In his own physical theory of the unified field Heisenberg starts from

* Markov, M.A. Giperony i K-mezony (Hyperons and K-Mesons), p. 191.

** Heisenberg,W. Kvantovaya teoriya polei i elementarnykh chastits (The Quantum Theory of Fields and Elementary Particles), in a collection entitled "Nelineinaya kvantovaya teoriya polya" (Nonlinear Quantum Field Theory). Moscow, p. 224, 1959.

*** Heisenberg,W. Otkrytie Planka i osnovnye filosofskie voprosy ucheniya ob atomakh (Plank's Discovery and the Basic Philosophical Problems of the Study of Atoms), Voprosy filosofii, No. 11, p. 65, 1958.

the following principle: "The fundamental field equations should be nonlinear in order to include the interaction. The particle masses should be obtained as a result of the interaction. Therefore the concept of the "bare particle" is meaningless"*.

Since Heisenberg recognizes the existence of a unified world field outside of which there is nothing, in order to explain the reasons for its changing he must either recognize the existence of a supernatural "force" or postulate the presence of immanent interaction (interaction with itself). Heisenberg chooses the latter solution. In his view the world field, matter, is causa sui, which he imagines as an internal interaction. All processes in the real world are the effects of the interaction of matter with itself. The concept of an internal interaction of matter responsible for all microprocesses admirably expresses the Spinozistic idea that substance is its own cause, the dialectic essence of which was highly appreciated by Engels.

It should be remarked, however, that nothing in Heisenberg's theory has yet been proved rigorously; essentially there is still no complete theory. Heisenberg's remarks can rather be treated as one of the important attempts to construct a unified field theory.

In our country the development of a nonlinear field theory is being carried out by D. D. Ivanenko, the scientist who in 1938 proposed a nonlinear generalization of the field equations based on the introduction of a field operator of the third degree. In France work along these lines is being carried out by de Broglie and his students. What path the further development of modern physics will take is still difficult to predict. Many scientists, however, believe that it will involve a further rejection of our familiar concepts and ideas. But however decisive a revision of modern physical ideas is undertaken, whatever familiar concepts are renounced, the further development of physics cannot take place independently, and outside, of the materialistic principle of causality. When attempting to formulate a unified theory of elementary particles, "the physicist should start", writes Heisenberg, "from the following general propositions: his mathematical interpretation must express the existence of matter in time and space the future state of which is more or less a consequence of the present state, the existence of forces and their variable effects, and effect here appears subsequent to the cause which gives rise to it, and so forth"**.

In these words of the outstanding physicist of modern times, one who very recently denied the applicability of the principle of causality to microworld research, is expressed the tremendous heuristic value of the concepts of causality and relation between states for the development of elementary particle physics.

In modern quantum physics both theory and experiment indicate that the macroscopic concept of the velocity of light as a limit for the rate of propagation of causal action and interaction is applicable even at small scales down to distances of the order of 10^{-13} cm. The question of the rate of propagation of causal interaction at distances smaller than 10^{-13} cm remains

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* Heisenberg, W. Kvantovaya teoriya polei i elementarnykh chastits (The Quantum Theory of Fields and Elementary Particles), in the collection entitled "Nelineinaya kvantovaya teoriya polya" (Nonlinear Quantum Field Theory), p. 224.
** Voprosy filosofii, No. 12, p. 159, 1959.

open owing to the restrictions imposed by the uncertainty relation on the accuracy of simultaneous measurement of the quantity of physical action and its spatial localization.

In revealing the universal property of transmutability of elementary particles, quantum physics brought out two points: the narrowness of the concept of cause as a one-sided action of one body on another, and the necessity of introducing into physics the concept of cause as an interaction of different objects or parts, tendencies, of an entire system*.

Furthermore, analysis of quantum physical concepts shows that, while the role of necessity decreases, the role of random factors in the mechanical displacements of objects in space and time increases relatively as one moves from the macroscopic to the microscopic level of material processes. There is a corresponding change in the relationship between possibility and reality as one moves from the region of classical mechanics to the quantum region. If in classical mechanics there exists one and only one true possibility necessarily realized for every mechanical system correlated with definite external conditions, in quantum mechanics a microsystem occurring under definite macroscopically fixed conditions has an infinite set of possibilities statistically expressed by means of the wave function. In the quantum theory of fields particles have, in addition to the set of possible motions in space and time, the possibilities of qualitative change, or transmutation.

If in classical mechanics the relation between states of a mechanical system is expressed in the form of laws of the dynamical type which permit univocal predictions concerning the state of the system in the future provided its state in the present is known, in quantum physics the relation between states of a microsystem is expressed with the help of Schroedinger's equation which, in the general case, permits only probabilitistic predictions concerning the future of the system. But in the quantum region the role of necessary factors in physical processes increases, as reflected in the laws of conservation of the necessary particle properties (spin, charge, and so on), which represent the simplest form of laws of the dynamical type.

Modern quantum physics has not discarded the macroscopic concept of causality; it has simply made it more profound and more precise. It expresses more precisely than classical physics the dialectical character of the relation between cause and effect and discloses the significance of the concepts of necessity and chance, possibility and reality, for the cognition of the objective causal relations of the microworld.

Both for scientific ideas and for philosophical categories, development consists of a complex transition from an essence of one order to an essence of another, higher order, an essence which more adequately reveals the properties and relationships of things in the real world.

* See Terletskii, Ya.P. Vzaimoprevrashchaemost' elementarnykh chastis (Transmutability of Elementary Particles), in the collection entitled "Filosofskie voprosy sovremennoi fiziki" (Philosophical Problems of Modern Physics). Moscow, 1959.

THE POSSIBILITY OF FURTHER DEVELOPMENT OF A JOINT COORDINATE-MOMENTUM REPRESENTATION OF QUANTUM MECHANICS

A.A. Tyapkin

The development of the interpretation of the e x i s t i n g wave mechanics is exhausted, properly speaking, by cleansing the accepted interpretation of the false superstructure artificially erected on positivistic views.

Unless the mathematical apparatus is deepened and the physical problems solved by quantum theory are broadened, there can be no talk of f u r t h e r d e v e l o p m e n t of our understanding of quantum phenomena.

We believe that further development of the theory of quantum phenomena will consist of a transition from solution of the direct problem, statistical prediction of the results of measurement, to solution of the inverse problem, to obtain, from the results of macroexperiments, univocal information concerning such details of the motion of microobjects in space and time under definite macroscopic conditions as are inaccessible to direct observation.

It must be understood that the construction of a space-time picture of the motion of a microobject under specific macroconditions does not constitute a reestablishment of the traditions of classical macroscopic mechanics, for one can deal with as complex a nonclassical form of motion as desired. From the objective existence of the physical world and its cognizability it follows that no physical theory, present or future, can reject the possibility of constructing a space-time picture of the motion of the physical objects it investigates. Absolutization of the scheme of description adopted in quantum mechanics and its institution as the only possible one impoverishes theoretical physics, reduces it to an applied theoretical construction for calculating the results of measurements, and detracts from cognition of the essence of new phenomena and determination of those peculiarities of motion of microobjects in space and time which are hidden from direct observation. It is precisely the establishment of these peculiarities which will characterize the most important stage in the evolution of the theory of quantum phenomena: the stage which will enable us to grasp their real essence and, by the same token, to fulfill the prerequisites for solving the problems involved in the theoretical explanation of even broader regions of physical phenomena.

The starting point of this stage should be the proof that it is possible to describe statistically the motion of a microobject in space and time before interaction with the measuring instrument. The demonstration of this possibility would moreover be a most convincing refutation of the starting point of positivism in quantum mechanics, namely the denial of the reality of the existence of any properties in a microobject before measurement.

It should also be stressed that the only description of microphenomena one can consider is the statistical one. The fairly widespread belief that

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further development of the theory of these phenomena should take the form of a transition from statistical to deterministic description is profoundly mistaken. It was already demonstrated by von Neumann in 1932 that it follows with certainty from analysis of the regularities known so far that a causal description of the phenomena of microphysics is impossible[*]. The statistical description in use in quantum theory is conditioned not by the method chosen but by the very nature of microobjects, which are always in interaction with the elements of the surrounding macroworld. In this respect we are in complete agreement with D. I. Blokhintsev's affirmation that quantum statistical character is due to the impossibility of isolating microsystems from the macroworld[**].

It should be remarked that the attempt to pass over to a deterministic description is frequently suggested by a desire to obtain a description of the motion of a microparticle in space and time. For example, Einstein's attempt to pass from a statistical to a causal description was to a significant degree dictated by his wish to eliminate the restrictions on the existing theory, which evaded describing reality in space and time before any impending measurement. Indeed, in a letter to Max Born, Einstein wrote the following concerning his relationship with quantum mechanics: "I cannot, however, seriously believe in it, because this theory is incompatible with the fundamental proposition that physics must express reality in space and in time without any mystical interference...[***]". In turn Born also was led to the conclusion that "Einstein''s deviation from modern quantum physics is due not so much to the question of determinism as to his faith in the objective reality of physical being irrespective of the observer[****]".

Once the objective content of the concept of measurement in quantum mechanics is established, one is led to acknowledge that the statistical description of the results of impending measurements of a certain physical quantity is identical with the statistical description of the values which can be assumed by this quantity in the motion of the microobject under specified macroconditions. This means that the square of the modulus of the wave function in the coordinate representation should be treated not only as the probability density for obtaining, in measurement, the values of the coordinate of a microparticle in a specific interval but also as the probability density for a particle really having the coordinate in a specified interval of values. In measuring we do not create a definite value, we merely seize or detect the particle in a certain definite interval of values of the coordinates. The situation is analogous in the case of measurement of the momentum of microparticles.

In this view the necessity naturally arises of combining the information provided separately by quantum mechanics for the coordinates and momenta of a particle and verified in mutually exclusive incompatible measurements. To solve this problem one can start from the very simple assumption that there exists for the particle a definite momentum at every point of its path. This assumption is in striking contradiction with the preconceived notions

  [*] See von Neumann, J. Mathematische Grundlagen der Quantenmechanik. Berlin, 1932.
  [**] See Blokhintsev, D.I. Kritika filosofskikh vozzrenii "kopengagenskoi shkoly" v fizike (Critique of the Philosophical Views of the "Copenhagen School" in Physics), in the collection entitled "Filosofskie voprosy sovremennoi fiziki" (Philosophical Problems of Modern Physics). p. 376. Moscow. 1952.
  [***] Born, M. Albert Einstein und das Lichtquantum. Natur wissenschaften, 42, 425. 1955.
  [****] Ibid.

associated with a widespread view of quantum mechanics, notions which should have appeared dubious when in 1948 R. P. Feynman created the new functional representation of quantum mechanics*. The new formulation created by Feynman, physically equivalent to the ordinary formalism of quantum mechanics, operates with probability densities in the functional space of microparticle trajectories. It was revealed by this formulation that the peculiar character of the laws of the microworld resides not in the fact that the concept of trajectory in space and time is inapplicable to microparticles, but rather in the fact that different trajectories with definite probabilities are possible for microparticles occurring under the same macroscopic conditions (by contrast with the particles of classical mechanics). Unfortunately, the author himself, as well as other physicists, failed to draw sufficient attention to the incompatibility between this new formulation and many of the preconceived notions of the "Copenhagen interpretation". And despite the fact that Feynman's work was published fourteen years ago, in all the universities of the world when expounding quantum mechanics scientists apparently continue to speak without the least hesitation of the inapplicability of the concept of trajectory to the motion of microparticles.

Even in direct discussion of the problems of the interpretation of quantum mechanics, the most important result of Feynman's work continues to be ignored. Thus V.A. Fok denies, as before, the assumption that particles can have momentum and coordinates simultaneously, and justifies this denial by saying that "the practical impossibility of measuring them concurrently, as expressed by Heisenberg's relations, seemed, in the light of this examination, to be some kind of paradox or caprice of nature by virtue of which not every existing thing was cognizable"**. In actual fact the impossibility of simultaneous measurement of the coordinate and momentum of particles does not lead to noncognizability, any more than the arbitrarily assumed impossibility of simultaneous observation of the projections of a body on different planes excludes the possibility of cognizing its volumetric properties.

An even more complete theoretical construction which employs the language of the possible classes of trajectories of microparticles was developed by G. V. Ryazanov***. Again, modern physics has so far failed to draw from this work the necessary inference on currently accepted misinterpretations of a number of postulates of quantum mechanics.

Thus in itself the idea that the particle has a definite momentum at every point in space does not run counter to the data established by science. However, the exploitation of this idea for the solution of the problem stated above encounters serious difficulties. Owing to the special wave properties of microobjects, measurement of the particle momentum is carried out on a macroinstrument without reference to the space coordinate of the particle, while measurement of the coordinate is carried out without reference to its momentum. In conformity with these real possibilities of measurement, in

   * See Feynman, R.P. The Space-Time Approach to Nonrelativistic Quantum Mechanics. Reviews of Modern Physics, Vol. 20, p. 367. 1948.
  ** Fok, V.A. Ob interpretatsii kvantovoi mekhaniki (The Interpretation of Quantum Mechanics), in a collection entitled "Filosofskie voprosy sovremennoi fiziki" (Philosophical Problems of Modern Physics). p. 169. Moscow. 1969.
 *** See Ryazanov, G. V. Kvantovo-mekhanicheskie veroyatnosti kak summy po putyam (Quantum Mechanical Probabilities as Sums over Paths). ZhETF, Vol. 35, No. 1, p. 121. 1958.

the quantum mechanical description the momentum distribution function $f(p)$ is given without reference to the particle coordinates and the distribution function of the particle coordinates $\rho(q)$ is given without reference to the particle momenta. The apparatus of modern quantum mechanics does not contain the function (hidden from direct observation) of distribution over the momenta $F(p, q)$ for a particle situated at the previously specified point q in space, a function which would have been simultaneously the function of distribution function for the coordinates of a particle with specified momentum p. The observed distribution functions $\rho(q)$ and $f(p)$ should, naturally, be connected to the hidden distribution function by the relations:

$$\rho(q) = \int_{-\infty}^{\infty} F(p, q)\, dp; \tag{1}$$

$$f(p) = \int_{-\infty}^{\infty} F(p, q)\, dq. \tag{2}$$

From these relations, making use of the distribution functions given by quantum mechanics, one can find the hidden distribution function of probability density. However, formal calculations of this function (which according to the original intention plays the role of probability density) lead, in the joint coordinate-momentum representation, either to a complex quantity* or to a real quantity capable of assuming negative values**, depending on the form taken for the functions of the noncommuting variables. Although formally the function obtained in this manner acts as the distribution function which leads to the correct values of the observed density distributions $\rho(q)$ and $f(p)$, owing to the incursion into the negative region when describing interference phenomena it cannot be regarded as the probability density for finding a particle at the point q with momentum p.

The statistical approach to quantum theory was considered most thoroughly in a work by D. Moyal. The author of this work starts from the following premise: "The impossibility of carrying out a physical measurement does not forbid us to consider the assumption that there exists a reasonably definite probability that two quantities have specified values"***. At the end of his investigation, however, the author is compelled to conclude that the distribution function $F(p, q)$ which he has obtained "can be negative and therefore is not a true probability"****. Consequently a "reasonably defined probability" is precisely what one cannot obtain with this particular statistical approach to the description of quantum-mechanical problems. One is obliged to operate with "negative probabilities" both in Feynman's representation of quantum mechanics and in the formalism developed by Ryazanov.

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* See T e r l e t s k i i, Ya. P. O predel'nom perekhode kvantovoi mekhaniki v klassicheskuyu (Limiting Transition from Quantum to Classical Mechanics). ZhETF, Vol. 7, p. 1290, 1937; B l o k h i n t s e v, D. I. The Gibbs Quantum Ensemble and Its Connection with the Classical Ensemble. Journal of Physics (USSR), No. 2, p. 71, 1940; D i r a c, P. On the Analogy Between Classical and Quantum Mechanics. Reviews of Modern Physics, Vol. 17, p. 195, 1945.

** See W i g n e r, E. On the Quantum Correction or Thermodynamic Equilibrium. Physical Review, Vol. 40, p. 749, 1932; S t r a t a n o v i c h, R. L. K statisticheskoi interpretatsii kvantovoi mekhaniki (A Statistical Interpretation of Quantum Mechanics). ZhETF, Vol. 31, p. 1012, 1956.

*** M o y a l, D. Quantum Mechanics as a Statistical Theory. Proc. Camb. Phil. Soc. 1958.

**** Ibid.

Thus the peculiar characteristic of quantum mechanical regularities is the appearance of negative probabilities when one attempts to construct quantum mechanics on the pattern of classical statistical physics. This also means that the formal mathematical solutions do not in reality constitute the solution to the problem of constructing a statistical description of the motion of a microobject in space and time under definite macroscopic conditions, before the interference of the measuring instruments (required only for experimental, and not theoretical, investigation of the specified state of motion of the microobject). At the same time, the formal mathematical solution already available for the problem should convince us of the possibility of its complete solution. Further, it should be borne in mind that to concede the impossibility of describing the motion of a microobject in space and time before the interference of measuring instruments would imply the concession to positivism of the most fundamental position in the explanation of microworld phenomena.

The appearance of negative values for the probability density function which describes the joint distribution of noncommuting observables is an indication that some specific peculiarities of quantum physics were not taken into account in the construction of the statistical description. We were able to clarify some of these peculiarities and to obtain an everywhere positive distribution function in a joint coordinate-momentum representation on the basis of analysis of the case of the interference of two states, which is characteristic of quantum mechanics.

Let us consider the simplest one-dimensional case of the interference of a plane wave and a partially or completely reflected wave. The incident wave will be denoted by $\psi_1 = R_1 e^{\frac{iS_1}{\hbar}}$, where $S_1 = -(Et - p_0 x)$; the reflected wave will be denoted by $\psi_2 = R_2 e^{\frac{iS_2}{\hbar}}$, where $S_2 = -(Et + p_0 x)$ and $R_2 \leqslant R_1$. In the absence of a reflected wave $(R_2 = 0)$ the quantum mechanical description of the flux of monochromatic particles with momentum p_0 and constant density $\rho = R_1^2$ does not display any peculiarity. It is only in the presence of the reflected wave that a particle distribution density arises which cannot be explained in the light of classical physics, varying periodically with the coordinate x:

$$\rho_{meas}(x) = \psi(x)\,\psi^*(x) = R_1^2 + R_2^2 + 2R_1 R_2 \cos\frac{2p_0}{\hbar}x. \qquad (3)$$

We will catch particles with the momentum $p_1 = p_0$ with the probability $\frac{R_1^2}{R_1^2 + R_2^2}$ and particles with the momentum $p_2 = -p_0$ with the probability $\frac{R_2^2}{R_1^2 + R_2^2}$. Moreover, quantum mechanics enables calculation of the mean flux of particles at each point x:

$$j(x) = \frac{i\hbar}{2m}\left(\psi^* \frac{\partial \psi}{\partial x} - \psi \frac{\partial \psi^*}{\partial x}\right),$$

which, for the problem under consideration, is constant and equal to

$$j = \frac{p_0}{m}(R_1^2 - R_2^2). \qquad (4)$$

The difficulties involved in constructing a statistical description in a joint coordinate-momentum representation are already evident from this problem. In this representation the function (3) should be regarded

as the probability density for finding particles with momentum p_0 and $-p_0$ at the point x. In this approach, however, a difficulty, that of obtaining the required value of the flux, arises in the region of minimal value $(p_{meas})_{min} = R_1^2 + R_2^2 - 2R_1R_2$. Even if one assumes that only particles of momentum p_0 are present at the minimum of the function (3), the $\frac{p_0}{m}(p_{meas})_{min}$ proves to be substantially smaller than the value of the real mean particle flux (4). In earlier works the statistical description in a joint coordinate-momentum representation was constructed formally regardless of this kind of difficulty; this indeed was the reason for the appearance of negative probabilities. Thus the function of joint quasidistribution, which, for the problem under consideration, has the form

$$F(p, x) = \rho_1'(x)\,\delta(p - p_1) + \rho_2'(x)\,\delta(p - p_2), \tag{5}$$

can be determined directly from the relations (3) and (4), disregarding their incompatibility in this representation. It is easy to show that in this case we obtain

$$\rho_1'(x) = R_1^2 + R_1R_2 \cos\frac{2p_0}{\hbar}x \tag{6}$$

and

$$\rho_2'(x) = R_2^2 + R_1R_2 \cos\frac{2p_0}{\hbar}x. \tag{7}$$

Since $R_2 < R_1$ the function which, according to the original intention, described the density distribution of particles moving in the opposite direction assumes a negative value in that region of coordinates in which the measured particle density (3), after multiplication by the velocity in the backward direction $\left(v = \frac{p_0}{m}\right)$, gives a particle flux smaller than the measured mean flux (4).

It is interesting to note that if we use the obtained quasiprobabilities (6) and (7) to calculate the observed distributions we obtain results completely identical with the quantum mechanical description. The relations for the density (3) and mean flux (4) should obviously be obtained automatically, since it is precisely from these relations, contrary to physical logic, that the quasiprobabilities (6) and (7) were obtained. A nontrivial point is the fact that the obtained quasiprobabilities, after the integration (2), lead precisely to the quantum mechanical probabilities of detecting particles of momentum $p_1 = p_0$ and $p_2 = -p_0$.

Indeed,

$$f(p_1) = c\int \rho_1'(x)\,dx = \frac{R_1^2}{R_1^2 + R_2^2} \tag{8}$$

and

$$f(p_2) = c\int \rho_2'(x)\,dx = \frac{R_2^2}{R_1^2 + R_2^2}. \tag{9}$$

The identity obtained with the complete quantum-mechanical description means that the function obtained for the joint distribution of the coordinates and momenta correctly expresses the fundamental peculiarities of the quantum mechanical phenomenon of the interference of two states.

From analysis of the functions satisfied by negative probabilities it is evident that the cause for their appearance lies in disregarding the existence of states of motion of microparticles which differ with respect to the operations of measurement of the momentum and coordinate. Already from the fact that the flux obtained by multiplication of the minimum value of the

measured density by the velocity in the backward direction is smaller than the required flux, it follows that there must exist states which are not detectable in coordinate measurements. This conclusion follows inevitably provided one believes in the existence of moving microparticles before measurement. At the same time it is precisely in this coordinate region that the quasiprobability ρ_i', which not only appears in the expression for the particle flux but also integrally represents the probability of detecting a particle of momentum p_1, exceeds the measured particle density. Therefore part of the states not detectable by the coordinate instrument make a contribution in the measurement of the momentum. The density of such states will henceforth be denoted by $\rho_p(x)$.

A negative probability enters integrally into the expression for the observed observable probability $I(p_2)$ of detecting particles of momentum $p_2 = -p_0$. Here it reduces the positive contribution of $\rho_2'(x)$, which, in turn, appear as components in the measured density $\rho_{\text{meas}}(x)$. This means that not every state detected by the coordinate instrument contributes in the measurement of the momentum. We will denote the density of such states by $\rho_q(x)$.

The function for the joint distribution now has the form:

$$F(p, x) = \rho_1(x)\,\delta(p - p_1) + \rho_2(x)\,\delta(p - p_2),\qquad(5a)$$

where:
$$\rho_1(x) = \rho_{1,\,q}(x) + \rho_{1,\,p}(x);$$

$$\rho_2(x) = \rho_{2,\,q}(x) + \rho_{2,\,p}(x).\qquad(10)$$

To the operation of coordinate measurement corresponds integration of the function (5a) over the momentum, taking into account only those states having the index q. That is,

$$\rho_{\text{meas}}(x) = \rho_{1,\,q}(x) + \rho_{2,\,q}(x).\qquad(11)$$

Correspondingly,
$$I(p_1) = c \int \rho_{1,\,p}(x)\,dx;$$

$$I(p_2) = c \int \rho_{2,\,p}(x)\,dx.\qquad(12)$$

In the expression for the mean particle flux, on the other hand, all states appear:

$$j = \frac{p_0}{m} [\rho_1(x) - \rho_2(x)].\qquad(13)$$

The function for the density of joint distribution of the coordinates and momenta of particles (5a) is now everywhere positive. This result was achieved by taking into account the fact that the particles occur in four states, which differ either in the direction of the momentum or in the possibility or impossibility of detecting them when measuring the coordinate and momentum. The calculations lead univocally to the following expressions for the density of these states:

$$\rho_{1,\,q}(x) = R_1^2 \left(1 + \frac{2R_1R_2}{R_1^2 + R_2^2} \cos \frac{2p_0}{\hbar} x \right);$$

$$\rho_{2,\,q}(x) = R_2^2 \left(1 + \frac{2R_1R_2}{R_1^2 + R_2^2} \cos \frac{2p_0}{\hbar} x \right);\qquad(14)$$

$$\rho_{1,\,p}(x) = R_1^2 \left(1 - \frac{2R_1R_2}{R_1^2 + R_2^2} \cos \frac{2p_0}{\hbar} x \right);$$

$$\rho_{2,\,p}(x) = R_2^2 \left(1 - \frac{2R_1R_2}{R_1^2 + R_2^2} \cos \frac{2p_0}{\hbar} x \right).\qquad(15)$$

As a particle moves spontaneous transitions from one state to another take place with definite probabilities. In these transitions between states with index q and p are manifested the wave properties of microparticles.

Thus the peculiar character of quantum mechanical phenomena is not that pre-experimental description of the motion of microparticles in space and time is impossible but rather that such description necessarily requires the introduction of states in which the possibilities of measuring coordinate and momentum are taken into account.

SOME METHODOLOGICAL PROBLEMS

THEORY AND EXPERIMENT IN
MICROWORLD PHYSICS

G.B. Zhdanov

   The standpoint of dialectical materialism on the process of human cogni-
tion of the world is best expressed by Lenin's well-known words: "From
living contemplation to abstract thinking and t h e n c e to p r a c t i c e – such
is the dialectical way to cognition of the t r u t h, cognition of objective re-
ality"*. This statement formulates, in an exceedingly brief and clear man-
ner, the organic union of the three principal stages of the process of cogni-
tion: sensory perception of the p h e n o m e n a of surrounding reality, pene-
tration into the e s s e n c e of things with the help of theoretical thinking,
and practical verification of the c o r r e s p o n d e n c e between our ideas and
the objective regularities of the world under investigation. Only by correct-
ly accounting for all three stages of cognition can one hope completely to
overcome the one-sidedness of empiricism and rationalism, which separate
thought from perception and are incapable of giving an exhaustive criterion
of the truth of human knowledge.
   In the process of historical development of any particular science, sen-
sory perception of phenomena travels a long and complex road. The sim-
plest and original form of perception has always been direct o b s e r v a t i o n,
based on a gradual accumulation of the impressions produced by the external
world by direct operation on the human sense organs. In the course of a
long intercourse and interaction with the surrounding world, however, man
steadily perfected his ability to perceive reality. This improvement was
accompanied to some extent by increasingly effective utilization of the five
sense organs with which man has been endowed by nature. Thus as his
experiences accumulated man became more observant; he learned to notice
an increasingly richer and finer variety of features in the objects of his in-
vestigation, to coordinate visual with audile and tactile perception, and so
on. In the field of the natural sciences, however, a far more important
feature of this evolution was the utilization of intermediate means created
by the hands of man which multiplied the ability of the natural sense organs
to perceive natural phenomena: i n s t r u m e n t s. Finally, the next qualita-
tively new stage in sensory perception was the transition from observation
to e x p e r i m e n t. The principal distinguishing characteristic of experiment
as compared with passive contemplation or observation is man's active
operation on the development of natural phenomena with a view to a more
complete and more profound understanding of the latter.

* Le n i n, V.I. Sochineniya (Collected Works), Vol. 38, p. 161.

Since experiment implies the converse influence of man on the external world, it has always been one of the forms of practice, if practice is taken in its most general sense. This kind of human activity represents merely one particular aspect of practical activity, since of all the possible requirements of man it is meant to satisfy primarily one – that of cognizing the surrounding world and understanding the regularities of given form of motion of matter.

Abstract thinking undergoes no less complicated an evolution. It begins wherever abstract ideas, concepts and categories secured by language begin to form in human cognition. At a certain stage in its development abstract thinking inevitably assumes the character of t h e o r e t i c a l thinking. This occurs when man begins to progress from simple perception and description of phenomena and events to their e x p l a n a t i o n, i.e., to cognition of the controlling regularities, to solution of the problem of "how" and "why" observed phenomena and events take place. This aspect of the process of cognition is sometimes regarded as the comprehension of the "mechanism" of phenomena, but in the majority of cases the concept of "mechanism" has a more restricted meaning, since it is connected with the construction of possibly imaginary but more or less explicit models of the process.

An important stage in the development of theoretical thinking consists of arriving at the quantitative, and not merely qualitative, aspects of the process of motion of a given form of matter. This stage, characteristic of all modern exact sciences, is inevitably associated with the appearance of formally mathematical theories operating with mathematical quantities and images.

As the mathematical images and relations used by the theory grow increasingly complex, a branch endowed with some measure of "independence" makes its appearance in the science. This means that the stage of logical interpretation and analysis of observational results and concrete facts – a stage unavoidable for any science – has become so complex that, instead of succeeding, it begins to parallel the development of experiment. This parallelism is stimulated considerably by the need to master, on the one hand, the increasingly complex techniques and methods of experiment and, on the other hand, the constantly evolving mathematical apparatus of the theory. Thus a new type of specialization is born: the division of scientific workers into theoreticians and experimentalists within a single science or even branch of science. Each of these complementary spheres of activity assumes its own specific traits, terminology and difficulties, to the point where representatives of one sphere often become unable to evaluate critically the results and conclusions obtained in the other.

Like every other subdivision of labor in human society, this tendency in the development of the exact sciences has its negative as well as its positive aspects. One of the hidden dangers of parallelism in the development of experiment and theory is, in our opinion, the possibility of considerable lengthening and complication of the "classical" chain of "observation – thinking – practice", although in the normal course specialization is generally intended to reduce the length of this chain in time. In other words, separation of experimental and theoretical research sometimes becomes a habit. This separation may be manifested, for instance, in a tendency for the rate of development of experimental research to lag behind that of theoretical research, or in underestimation of new experimental facts which contradict established "canons" of theoretical science (and, conversely, underestimation

of new theories when these fit poorly into the ideas familiar to the experi-
mentalists). As a curiosity we might recall here that (in a converse situa-
tion) Maxwell decided to publish his work on the electromagnetic nature of
light only after receiving, as was learned later, erroneous information con-
cerning measurements of the constant c which connects electrical and mag-
netic units of measurement in electrodynamics. (According to Maxwell this
constant should be numerically equal to the velocity of light, but at the time
it was very inaccurately measured).

In the following sections of the present essay we will consider, first,
some of the more general features of modern experiment and modern theory,
and, second, certain aspects of the union and interaction of these two fields
of scientific activity.

Modern experimental physics has at its disposal a wide variety of instru-
ments for studying the processes of motion and transmutation of individual
elementary particles of matter. Further, the apparatus has been brought
to a very high degree of resolution in time: already to day methods exist
for directly measuring particle lifetimes of the order of 10^{-16} sec and in-
directly measuring times of the order of 10^{-22} sec. Moreover, by using
particles of very high energy (of the order of one billion electron volts and
higher), physicists have now succeeded in coming close to an experimental
solution of the problem of the spatial structure of elementary particles and
in particular that of nucleons.

One of the most important features of the motion of elementary particles
of matter is its statistical character, which is connected with the contra-
dictory wave-particle nature of particles. For example, we can take the
phenomenon of a particle crossing the so-called potential barrier – the re-
stricted region of operation of external forces. In the simplest (one-dimen-
sional) case an elementary object, just like a wave, can both pass through
the barrier and be reflected by it. At the same time, being an elementary
particle, it can in each individual event either cross (as a whole) or be re-
flected. Both possibilities are realized with a definite probability which can
be predicted by the theory as accurately as desired. In the experimental
determination of this probability (unlike the experiments of classical physics
where repetitions were required either for verification of results, inclusion
of secondary factors or reduction of the error of measurement) a single
experiment is, generally speaking, completely useless. In some cases there
may be two possible processes the probabilities for which differ by many
orders of magnitude, as for rare modes of decay. Here the result of the
experiment, even if repeated many times, may prove to be not wholly de-
finite: "with a probability of, say, 99 % the type of decay predicted by the
theory will not take place". Another very characteristic situation is that
where, say, in the collision of two elementary particles of completely de-
finite energy, one π-meson is formed with a certain probability, two π-
mesons with a certain probability, and so on.

Thus the qualitatively new (as compared with classical physics) nature
of the objects under investigation has led to completely new methods of pro-
cessing the experimental data and to new types of results: only the proba-
bilities for different values of given physical quantities, and not, generally
speaking, the values themselves, are determined. The concept of proba-
bility, and, by the same token, of chance, became an organic feature of

experimental physics. This led to a corresponding generalization of ideas concerning the forms of causal connection between events in quantum theory. The fact that one can speak of generalization, rather than rejection, of the concept of causality is evident from the following considerations. The laws of motion of bodies in the macroworld, i.e., with the participation of a large number of elementary particles, can be obtained by the passage to a limit from the laws of quantum theory assuming Planck's constant h to be zero. But from this one gets that, in the situation where many elementary particles participate in the motion (the usual situation for classical physics), causality must always have an unambiguous, Laplacian character. Great perspicacity was therefore required to declare one century ago, as did Engels, that Laplacian determinism is merely one of the possible relationships in nature, and that chance, for dialectical materialism, is just as objective as causality: its appearance in science is not due to incomplete knowledge of the natural laws, and it expresses not the absence of all causality but simply a special form of manifestation of causality.

In the historical process of cognition of nature by man the role of experiment, in a sufficiently broad sense of the word, was far from always being as great and as obvious as it is today. To a significant extent this was due to the low level of development of the productive forces of society, which at first did not furnish man with means of investigation substantially superior to his own sense organs. As a result, in ancient and feudal societies, the basic stage of intercourse between the thinker and his environment consisted of a process of simple observation or passive contemplation of natural phenomena, not accompanied by any interference in their natural course.

At this natural-philosophical stage of development of science the question of experimentation was not placed "on the agenda" for yet another reason. The existing view of nature, and in particular Democritus' atomistic hypothesis, could not pretend to prove its validity in the sense in which "proof" is understood in modern exact sciences, for which a necessary condition of proof is transition from qualitative arguments to quantitative explanation. The verisimilitude of any given hypothesis could be determined only by guesswork or arguments. Among such arguments a very important role was played by general philosophical considerations and in particular by the consideration that it was inadmissible to adduce categories applicable only to a purely human way of perceiving things and motives underlying human purposeful activity as explanations of non-living nature.

Scientific experiment, as opposed to the more general concept of "experience", covers a completely definite region of human activity involving active and conscious interference in natural phenomena for the sake of acquiring new information concerning the regularities governing these phenomena, or even for the sake of verifying and correcting earlier information. With the development and increasing complexity of experimentation, such "interference" becomes more and more an interaction of man with nature and, subsequently, a transformation of nature by man.

Thus, experiment is that inseparable element of human practice for which penetration into the essence and regularity of observed phenomena is both a condition and a result of investigation. It should be remarked here that every experiment, by virtue of its having originated historically in the development and increasing complexity of observations, contains an element

of observation; it supplements observation of a process by conscious, purposeful operation on its course. On the other hand, by itself conscious operation on a phenomenon becomes meaningful only if the experiment is preceded by analysis of previous observations and experiments and by the formulation of views (possibly not fully definite) on the properties of the phenomenon and its deep essence. Thus the historical onset of the experimental sciences is also organically related to the development of the elements of theoretical thinking.

The categories and concepts created by human cognition for the expression of the objective regularity of nature are historically conditioned and restricted by the peculiarities of the above-mentioned interaction; in this sense they are to a certain extent tinged with a "subjective hue". This restriction is responsible for the fact that at every level of human cognition absolute objective truth seems to us to be a sum of relative truths.

This fact does not imply, of course, that the regularities of nature, and, all the more so, nature itself, exist only insofar as there is interaction between man and nature, as Mach, Avenarius and others tried to "prove" with their "perception complexes", "potential counterterm" and so on. Indeed, when we consider man's interaction with nature in the process of studying nature and for the sake of studying nature, or, which in the given case is practically the same thing, the interaction between subject and object, we must not forget that we are dealing with the interaction between the subject and something occurring and existing outside and independently of this subject.

At first glance it might appear that the interaction necessary for revelation and cognition of the properties of an object already constitutes an element of "dependence" of the object on the subject, in the sense that the properties of the object appear w i t h   r e f e r e n c e   t o the subject and not "in themselves". Properly speaking, this kind of argumentation, in some form or other, is precisely the main "trump" used by the positivists in dealing with the "coordination of principle" between object and subject and associated (but supposed) impossibility of principle of the objective existence of matter.

In reality we are dealing with a mere sophism, already refuted by Engels with his "things-in-themselves" and "things-for-us" in connection with the question of the cognizability of the world. Indeed, the properties of any material object can be revealed by its relation to and reaction with other objects, as well as by its relation to and reaction with subjects possessing consciousness. In the first case the object remains a "thing-in-itself" (relative to consciousness), and only in the second case does it become a "thing-for-us". But this does mean that consciousness can (in principle) express the properties of matter as completely as desired only insofar as man is able, by means of m a t e r i a l   i n t e r a c t i o n s, to convert the various possibilities inherent in things and processes into reality.

Such problems arose with particular prominence in the study of the properties of the microworld. In modern physical experiments involving elementary particles one is generally dealing with observation of processes taking place with one or several particles. These processes, however, take place in an external macroscopic environment the state of which is determined by the design of the instrument and aim of the experiment as a whole. The interaction between microobject and its environment inevitably modifies the state of motion of the microobject and at the same time makes

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it possible to study certain properties of the object. Since the experimenter is frequently faced with the problem of deciding to detect one property rather than another (e. g., measurement of either the coordinate or the momentum), these properties should be regarded as contradictory and mutually exclusive. At the same time, if instead of speaking of one interaction of an object we speak of the set of all its possible interactions, then the same properties (here wave and corpuscular properties) should be regarded as complementary. This is precisely the rational kernel which can be extracted from Bohr's "principle of complementarity" and which, essentially, is a particular case of the already well known thesis of dialectical materialism concerning the union and struggle of opposites in nature.

The impossibility of subdividing interactions in the microworld into important (i.e., those which control the character of the motion of the object) and unimportant ones means that practically every observation is inevitably transformed from passive contemplation of a material interaction between the object under investigation and some other objects into an experiment, i.e., into an interaction consciously prepared and carried out by a cognizant subject. An important feature of this kind of experiment, one repeatedly referred to in V. A. Fok's works, is the presence of basic stages inseparably connected with the structure of the corresponding measuring instruments.

The first stage of any experiment consists of p r e p a r i n g the state of the microobject required by the physicist (in as pure a form as possible) by specifying rigorously fixed macroconditions. This means that the instrument, which is of necessity a macroscopic system, i.e., one consisting of a very large number of elementary particles, is brought at the beginning of the experiment into a state with uniquely determined characteristics of motion of the system as a whole (such as a definite coordinate and velocity of the center of gravity of the system or the absence of systematic streams of charged particles or photons). Thus in one typical experiment on the electromagnetic structure of atomic nuclei (Hofstadter) the instrument includes an electron accelerator producing a beam of these particles of more or less uniform velocity (with regard to magnitude and direction). The second, or o p e r a t i v e, stage of the experiment consists of bringing about a definite reaction between the microobjects under investigation and other micro- (and occasionally macro-) objects. In the above case the second stage is realized during the collision of the electrons from the accelerator and the target nuclei, which results in deflection (scattering) of the electrons by a certain angle. Finally, the third, r e c o r d i n g, stage of the experiment determines the state of the particle after interaction (in this case by a counter which records the passage of the electron in a definite direction).

Thus, as in the experiments of classical physics, the instrument acts as intermediary between the experimenter (subject) and the object under investigation, substantially enriching and expanding the resources of the human sense organs. A qualitatively new feature of the instrument, as far as studying microworld phenomena is concerned, is that it assumes the position of external environment relative to the object under investigation, inasmuch as reaction with the instrument determines the set of possible states of motion of this object. This peculiarity of the measurement of microobjects provided the positivists and idealists with a reason for claiming that, in general, every object studied by quantum mechanics exists, only insofar as it is recorded by an instrument, i.e., only at the instant of

measurement, and that the "traditional idea of materialism" that the object is independent of the subject cognizing it is thus meaningless.

In reality, however, the question is simply that the mechanical properties of microobjects are always manifested dynamically, in the process of material interaction with the environment; man-made instruments are merely a particular form of this environment which allows evaluation of the state of an object from the changes in the state of an instrument with which it has interacted. In other words, as in the case of the sense organs, the principal sophism of the proponents of "instrumental idealism" is that the instrument is regarded not as a bridge linking the cognizing subject and cognizable object but rather as a wall separating them.

As to the mutually exclusive, contradictory character of the measurements which must be carried out to determine, say, the coordinates and momentum of an elementary particle, it is due not to the absence of objective content in these important concepts of classical mechanics but rather to the existence of the contradictory wave-particle nature of the microobjects themselves, to the fact that concepts which are strictly speaking suitable only for noncontradictory description of an idealized object, the material point, are only of limited applicability to these quantities.

Below we will demonstrate that the active role of instruments, in the sense of their operation on the objects under investigation, can also be seen in a different light — that of the technical potentialities of a purposeful transformation of the motions of matter in the process of practical, topical human activity.

The historical development of scientific and especially physical experiment is very closely connected with the development of technology. The most significant moment in this development was the appearance of instruments and their subsequent refinement, quantitative as well as qualitative.

Originally the role of instruments was mainly to help in the very simple measurements required in practical life. Of these the first were the simplest (in conception) measuring instruments, or rather tools, for determining lengths, angles, volumes, weights, time intervals and so on by comparing the object (or phenomenon) under investigation with a sufficiently simple and universally known standard.

Later the increasing accuracy and complexity of the measuring tools led to the appearance of instruments in the true sense of the word, i.e., devices which, on the one hand, raised the sensitivity, resolving power and accuracy of operation of the sense organs (terrestrial telescope, microscope, thermometer) and, on the other hand, qualitatively broadened their range, making it possible to record and measure electric and magnetic fields, invisible radiations, inaudible sounds, unperceivable displacements and oscillations, and so on.

The requirement formulated by Galileo that the description of physical phenomena be based only on concepts having a quantitative measure was of great significance for the progress of instrumental technology. At this stage of development the instrument had already become an important link, or intermediary, between the human sense organs and the surrounding world. In addition to the comparatively secondary function of recording or "storing" the "signals" which arrive from the outside, the chief purpose of the instrument is to transform these signals, quantitatively (amplification) as well as

qualitatively. In the latter case one could say that the instrument processes the information it receives by transforming one form of motion of matter into another.

The expansion of the technical possibilities of measurement which accompanies the evolution of instrument design and technology is merely only of the links in the complex chain of reaction between science and technology. Another very important link is the possibility created by technology of influencing the development of natural phenomena. In the simplest case this influence has the form of a mechanical action on the object under investigation; changing the physical conditions of the environment (pressure, temperature, introduction of electromagnetic fields, etc.) in which the process in question is taking place is slightly more complicated; also possible are artificial influences involving chemical reagents, and so forth.

A significant feature of modern physical experiments is the possibility of creating fundamentally new phenomena and even forms of motion of matter. This generally requires a fairly advanced level of technical development of the apparatus which, in scale and complexity, lies outside the framework of traditional laboratory resources and belongs rather to structures of industrial scale.

Such, for instance, is the role of the accelerators from which are obtained intense, sharply collimated monoenergetic beams of elementary particles of specified kind, such as have not so far been observed in nature and are scarcely likely to be observed under any natural conditions in the future. Another very important region of experimentation is the utilization of nuclear reactors in which the valuable controlled reaction of nuclear fission is realized in a specially calculated and selected mixture of definite chemical elements or even definite specially separated isotopes.

In turn the reactors and accelerators of physics have made it possible to create new substances, such as rare isotopes, transuranian elements, mesic atoms, which are not observed in nature mainly owing to their instability. Equally instructive is the example of the experiments on the formation of new elementary particles (on accelerators), including particles having exceptionally short lifetimes. True, one might protest that all these particles are also formed in a natural manner under the influence of cosmic rays; in the latter case, however, the concentration of short-lived and rare particles is as a rule completely negligible.

Speaking of the direct effect of technology on the nature and aims of scientific experiments, one cannot forget its stimulating role in posing new scientific problems. A striking example is rocketry, which raised a large number of problems in the experimental study of the properties of matter at high temperatures, the search for new types of fuel and new principles of reactive motion, the study of peculiar physical phenomena in the radiation belts of the Earth, and so on.

In the realm of nuclear physics this tendency is also very strong. Suffice it to mention the method of tracer atoms and the study of the influence of different kinds of radiation on inorganic substances and on the organisms of living beings (and particularly the human being). Each of these regions of phenomena either gave rise to essentially new branches of science (radiation chemistry, radiation genetics, and so forth) or produced a major revolution in the means of scientific research for an entire series of important sciences.

The prospects and problems presented to the physicist by technology must not be considered in isolation from their two-way interaction. Indeed, the discovery of new phenomena, or at least of new aspects of already known phenomena, as a result (and occasionally even in the course) of the solution of important scientific problems, opens up fundamentally new paths for the solution of large-scale technological problems. In this connection we might recall the universally acknowledged successes of atomic power, the significance of atomic engines for far-reaching improvement of the means of transport, the first steps in the field of the radiation technology of the synthesis of new polymers, and so on. This reverse aspect of the interaction has often given rise to the appellation "technology of the future" for physics. It should be borne in mind, however, that by itself physics (like chemistry) merely discloses the possibility of developing new branches of technology. The conversion of this possibility into reality is accomplished with the help of an entire range of objective and subjective factors such as economic expediency and material interests of men, socio-political conditions and social relationships. In particular, the tempo of development of the new branches of science and the technical resources they stimulated proved to be one of the most convincing criteria of the superiority of the socialist economy over the capitalist one. This superiority was exemplified most convincingly by the successes in rocketry, but the priority of Soviet scientists and engineers in a number of problems relating to the peaceful application of atomic energy (atom-powered electric stations, atomic ice breakers, etc.) is universally recognized. Another important point is that practical realization of fundamentally new scientific achievements of revolutionary nature is impossible without very close cooperation between scientific and technological workers, the necessary precondition for which is moral responsibility on the part of the scientists for the practical utilization of the fruit of their labor.

The converse influence of science on technology has yet another aspect, the statement of actual problems. Thus the rapid development of elementary particle physics constantly requires the solution of general scientific and technological problems connected with increasing the effective energy and intensity of particle beams, as well as the solution of particular problems such as designing installations which can furnish a very high vacuum in very large volumes.

Our presentation of the principal aspects and trends of the interaction between scientific experiment and technological progress in its general features is not new; indeed, it is valid in some degree for the entire history of science and technology. At the present historical stage, however, these trends have strongly increased, due primarily to the increased complexity and degree of technical equipment of modern experimental installations.

This complexity and the associated high costs and difficulties mean that the resources of individual laboratories, institutes and even entire countries are not sufficient for substantial progress in, for instance, elementary particle physics. Suffice it to mention the example of the Joint Institute for Nuclear Research at Dubna, which combines the efforts of scientists from many countries in the socialist camp, and the European Organization for Nuclear Research at Geneva in which about ten of the main capitalist countries of Western Europe participate directly. The powerful modern reactors, and especially accelerators, have now become plants on a factory scale, and dozens of the largest industrial concerns participate in their

construction; one can therefore speak with complete justification of the industrialization of nuclear and high energy physics.

A second and no less significant feature of the present stage is the rapid tempo of mutual penetration of science and technology and the great effectiveness of the associated basic transformations in various fields. Let us recall with what speed radio engineering methods of molecular and crystal spectroscopy created a completely new branch of physics (literally within some five to ten years), and how, in turn, quantum radio physics created an upheaval in technology by the development of molecular generators of centimeter radio waves.

Just as indicative is the rapid growth of atomic industry stimulated by physics and the colossal range of work on the problem of controlled thermonuclear reactions, the solution of which promises to place at humanity's service practically inexhaustible resources of "peaceful" thermonuclear energy.

What we have said in the present section allows one to understand and evaluate the enormous importance assigned to science in the program for the comprehensive building of communism in the Soviet Union.

So far the prevalence of the cognitive aspect in science has enabled us to regard it primarily as one of the forms of social consciousness and therefore as a kind of superstructure on the social being. Now, however, in the period of the construction of communist society, the operative, revolutionizing aspect of science has begun to play an increasing role, owing to which science is becoming an ever more active member of the direct productive forces of society. One expression of this tendency is the increasingly arbitrary character of the boundary between "pure" and applied science, between "theoretical", i.e., cognitive, research and scientific work which pursues primarily the practical goal of transforming nature and satisfying the growing needs of man – toiler and creator.

Several basic stages can be distinguished in the development of the experimental possibilities for research into the structure of matter at increasingly minute scales. The completion of the first stage, which took place toward the beginning of the twentieth century, was connected with a brilliant victory for atomism – the proof that matter is discrete and composed of individual molecules and atoms of the order of 10^{-8} cm. Already at this stage, the remarkable triumph of the physicists was linked to a significant degree to the mastering of comparatively high energies, i.e., to the application of X-ray and electron diffraction methods of structural analysis. It was found in the twenties that the superiority of these methods over ordinary microscopy (which gives a resolution of the order of only 1 micron, i.e., 10^{-4} cm) is due to the fact that in the former every quantum of the applied radiation carries an energy and momentum many times greater than the energies and momenta of quanta of visible light. According to the quantum-mechanical uncertainty relation $(\Delta p)^2 (\Delta q)^2 \gtrsim \hbar^2$ the localization of any material object is subject to the condition that the smaller the coordinate uncertainty Δq, the greater the intensity of the internal motions associated with this localization and characterized by the momentum uncertainty Δp.

The next significant advance in the direction of the small scales was associated with the planetary model of the atom established by Rutherford in 1913. This victory was made possible solely by the utilization of high-

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energy "projectiles" – α-particles from radioactive elements. Thanks to the fact that the energy of an α-particle is measured in millions of electron volts (and not thousands as for the X-ray quanta), this direct assault on distances on the nuclear scale met with brilliant success.

The following stage in the conquest of matter was associated with the study both of the structure of the atomic nucleus itself and of its transformations. The problem of uncovering the static as well as the dynamic world picture was truly raised for the first time. True, as far as spatial scales are concerned this stage did not bring any significant increase in requirements for accuracy in measurements, since the linear dimensions of the nucleus are not more than one order of magnitude greater than the linear dimensions of its component "bricks", the nucleons. On the other hand, when the question arose of studying the properties of unstable nuclei and their transmutations it seemed as if one would reach, in a number of cases, a tempo of physical analysis completely different from the tempo of ordinary chemical analysis of the atomic composition of matter. By now physicists have studied a great variety of unstable isotopes with mean decay times measured in seconds and small fractions of a second, as well as various excited isomeric states of nuclei with transmutation times of the order of a millisecond.

Finally, the present stage of refinement of space-time accuracy of measurement, which is still far from over, is associated with the study of processes of transmutation of elementary particles of matter and with the statement of the problem of clarification of their structure.

This stage, which is closely connected with the study of cosmic rays and the development of particle accelerators yielding energies close to cosmic-ray energies, was signalized by the fact that experimenters penetrated into the region of energies of the order of one billion ev and higher. Without such energies it would not have been possible to bring about the creation in the free state of the previously hypothetical mesons, the discovery of which was so necessary to verify the newly created theory of nuclear interactions between the principal "constituents" of nuclei, the nucleons. Previously these particles had evaded direct observation by the experimenters, existing, as it were, in implicit – or, as the physicists say, virtual – form. In principle the criterion for the energetically allowed possibilities in a given experiment is very simple. In accordance with Einstein's relation $E = mc^2$ between the energy "supply" and mass of the particle, the production of a free particle with a mass of, say, 273 electrons masses (π –meson) requires the expenditure of at least $273 \times 0.51 = 140$ Mev (0.51 Mev being the electron mass multiplied by c^2 and expressed in energy units).

In addition to the study of inelastic collisions (responsible for the formation of one or more new particles), the simpler and more easily interpreted experiments on elastic collisions, or mutual scattering of particles, were also important for an understanding of structure. Great success along these lines was attained, in particular, by the American physicist Hofstadter, who studied the scattering of electrons with an energy of about 600 Mev on the lightest nuclei of matter, the nuclei of hydrogen isotopes; he was thus able to study the laws of electron scattering on two fundamental types of elementary particles, protons and neutrons.

These experiments indisputably proved the existence of an electromagnetic spatial structure in nucleons – the presence of electric charge and magnetic moment distributed in space in each of these particles.

Another aspect of the study of the structure of nucleons was undertaken by a group of physicists of the Joint Institute for Nuclear Research headed by D.I. Blokhintsev. These physicists made a detailed study of the processes of interaction of π-mesons with the simplest nuclei and with nucleons (protons). They were able to establish that in a number of cases the process takes the form of simple scattering of the bombarding meson on one of the structural elements of the nucleon, the mass of which is close to the mass of the π-meson. With this and other, analogous, experiments it was shown that the nucleon is a complex structure consisting of a dense interior ("core") surrounded by a cloud, or rather cluster, of lighter particles, virtual π-mesons.

At the same time from a number of other experiments it became evident that this structure was different in principle from the planetary structure of the atom discovered by Rutherford precisely because the properties of the virtual particles of the meson cloud in the nucleon are essentially different from the properties of free π-mesons. In a free particle the quantity $E^2 - p^2 = m^2$ (E being the total energy, p the momentum and m the rest mass) is always the same and moreover positive, but in virtual particles it is negative. One can say that the mass m of virtual particles is imaginary and moreover, variable. As a result, a nucleon, which has emitted a virtual meson increases, rather than decreases, in mass and can transmute into an unstable system (isobar) which subsequently decays into a nucleon and a free π-meson.

Facts of this type made it abundantly clear to the physicists that the presence of structure in elementary particles could in no wise be interpreted as complexity of composition in the sense in which this term is understood for atomic nuclei, which are composed of individual and comparatively weakly bound particles, protons and neutrons. On the other hand, in addition to the concept of structure as a certain spatial distribution of the mass and charge of a given particle over its volume (so-called form factor), a new, essentially dynamical, description of structure in terms of the scattering probability of other particles proved very fruitful. The idea is to regard the ability of the elementary particle to exchange momentum with certain other particles, rather than geometric form and size, as its primary property. This description of the structure of particles, which at first glance seems purely phenomenological, is entirely within the spirit of the fundamental ideas of quantum theory. Indeed, this method of describing elementary particles immediately stresses two of their most important peculiarities: first, that their properties reveal themselves only in the process of interaction with other particles; and second, that these interactions bear a probabilistic, nonunivocal character.

The rapid development of experiments on the processes of formation and subsequent transmutations of new elementary particles very soon led to the need for much higher resolutions both in space and in time. Indeed, even such a comparatively stable particle as the μ-meson decays on the average within approximately 2 microseconds ($2 \cdot 10^{-6}$ sec), while most of the other new particles (mesons and hyperons) exist for a far smaller time interval — between 10^{-8} to 10^{-10} sec.

In order to study such short time intervals experimental techniques immediately developed along two parallel lines. On the one hand, ultrarapid electronic devices enabling direct measurement of intervals in the nanosecond region (one nanosecond is 10^{-9} sec) were evolved. On the other hand,

physicists made use of the felicitous circumstance that unstable particles, after "coming out into the open", move in space at velocities close to the velocity of light (as a rule), traveling a distance of the order of even 10-30 cm per nanosecond. Therefore, by observing the decay processes of such particles in Wilson or bubble (liquid) chambers physicists have the opportunity of studying processes realized within time intervals of $10^{-10} - 10^{-11}$ sec. In experiments with photographic emulsions, where spatial accuracy reaches fractions of a micron, even time intervals of the order of 10^{-15} sec or less proved accessible (for example, observations were made recently of the decay of neutral π-mesons, the mean lifetime of which is about $2 \cdot 10^{-16}$ sec).

Still more sensitive, and moreover entirely reliable, methods of measuring negligibly small times were worked out very recently (1961). These methods are based on the utilization of the relation given by quantum mechanics between the uncertainties of the energy and time characteristics of the process of interaction. By analogy with the relation for the momentum and the coordinate, this second relation is written as $\Delta E \cdot \Delta t \gtrsim h$, where ΔE is the uncertainty in energy of the given state of the microobject and Δt, roughly speaking, is the uncertainty in time of the interaction which disrupts the given state. Using this relation physicists discovered an entire series of cases where it is possible to observe the formation and nearly instantaneous (within a time of the order of $10^{-21} - 10^{-22}$ sec) decay of special "quasiparticles" (so-called ρ-, ω-, η-mesons, etc.), obtained as a result of resonance interaction of two or three already known particles (mesons, nucleons or hyperons).

Thus it was discovered that there existed material objects lying on the boundary between the "ordinary" unstable particle with very small energy uncertainty and the system of several interacting particles, which is formed in a vanishingly small interval of time and has such a large energy uncertainty that this uncertainty is already comparable with the energy supply of each of the component parts (taken in the free state). It should be mentioned, however, that in the case of reactions with "quasiparticles", precisely as in the case of "ordinary" unstable particles, one can speak only of the transmutation of certain particles into other, equally elementary particles, and not of the decay of complex particles into simple ones.

Another, fairly unusual, approach to the study of the structure of elementary particles was found to be possible in the last two to three years in experiments with cosmic rays carried out, on the one hand, by a group of physicists of the Physical Institute at Moscow (N. A. Dobrotin et al.) and, on the other hand, by a group of Polish physicists (Y. Gerula, M. Miezowicz et al.).

In the first case the reliability of determination of the energy of the primary particle which interacted with the immobile (and moreover very light) atomic nucleus approached the reliability of accelerator experiments. The data obtained definitely indicate that in a significant percentage of the cases the process of multiple production of particles goes through an intermediate stage of production of a strongly excited clot of the meson field (so-called "fireball", according to the terminology now adopted) and its subsequent decay into five to ten particles. The entire mass of the interacting nucleon does not take part in the initial process of production of the clot; only a fraction of about the mass of the π-meson does so.

In the investigations of the Polish physicists definite indications were obtained that not one but two "fireballs" (as a rule) are produced in interactions in the region of still higher energies (thousands of billions of electron volts, and not hundreds as in the preceding investigations). Despite the provisional character of these results they must be regarded as strong experimental evidence in favor of the existence of a new and highly unstable form of motion of matter, similar in nature (perhaps) to the above-mentioned resonance system of two to three π-mesons.

Thus contemporary physics has already begun to study directly the structure of elementary particles, and as a result the term "elementary" has lost its original meaning. Essentially the concept "elementary" merely designates a certain arbitrary and transient facet of our cognition of the structure of matter (as has indeed repeatedly been the case at previous states of the analysis of matter). However, while at earlier stages physicists successively proved the complexity of the molecule (or crystal), the complexity of the atom and, finally, that of the atomic nucleus, at the present stage it is already very difficult to admit of the existence of the connection between simple and complex to which we are accustomed.

From the quantitative standpoint this new character of the relationship between simple and complex is fairly easy to define: the complex becomes something significantly different from the "composite" (i.e., the simple sum of its parts) only when the energy generated in the process of transmutation of a "complex" particle into the sum of several "simpler" particles becomes comparable with the total energy of the individual products of this transmutation.

For instance, in principle one can construct a model of the π-meson consisting of a nucleon and an antinucleon, the total mass of which (in the free state) is roughly thirteen times greater than the mass of the π-meson itself.

From the qualitative standpoint the situation is more complicated. Until now physicists assumed that the principal characteristic of elementary particles was their ability to interact with surrounding particles and with force fields (electromagnetic, nuclear, neutrino field of weak interactions and so forth). The equivalence of the concepts "other particle" and "force field" follows from the fundamental premises of modern quantum theory, which takes for granted the idea that any force field can be "quantized", i.e., represented as a stream of individual free quanta or particles.

The difficulties which physicists met in the quantitative development of these ideas led them to other approaches to the study of the structure of elementary particles and the law governing their interaction. Perhaps the most interesting of these attempts, from the philosophical point of view, are associated with the introduction of the idea of the discrete structure of space and time. So far, however, attempts to find the "atom" of space, the elementary cell, have been unsuccessful. At least no sign of spatial discreteness has been found at the scale of distances of the order of 10^{-14} cm and higher.

Turning now to a consideration of certain fairly general (from our standpoint) features of the theory of elementary particles of matter, we will first of all take the liberty of departing from the accepted terminology and join

M. A. Markov in calling the particles not elementary but fundamental*. This is required, in particular, by the direct experimental data mentioned above, which favor the existence of structure in these particles and from which one may conclude that it would be unwise to regard elementary particles as simple structureless "bricks" of matter.

The first stage in the construction of a physical theory consists, as a rule, of systematization of the experimental facts. Strictly speaking, this stage is absolutely unavoidable only for theories created by the inductive method. Only then does the theory begin with a simple description of the entire set of experimental data, a description in which the element of classification or systematization increases gradually as the scientist advances from purely external signs and characteristics to signs involving the essense of the observed phenomena. The gradual refinement of the principles of classification of the facts prepares the ground for the transition from description of phenomena to their explanation.

In cases of deductive construction of physical theories the element of classification of the facts plays a relatively smaller role. By dint of successful intuitions the scientist manages to find support among a small number of very important facts which he supplements by appropriate postulates, as in the case of Maxwell's electromagnetic field theory or Einstein's theory of relativity. Still even in this case it would be wrong to deny altogether the role of the process of accumulation and classification of facts, for intuition and erudition always supplement each other to some degree. Similarly, in the seemingly pure inductive construction of theories intuition and guesswork, which are required for comprehending and selecting the most important facts and aspects of the phenomenon and for distinguishing them from secondary relationships, play an important role.

Two more or less parallel and somewhat independent trends are clearly discernible in the branch of theoretical physics which deals with the study of fundamental particles. The one aims at explaining the principal characteristics of the entire known "assortment" of particles on the basis of certain unified, more general premises concerning the physical properties and regularities of motion of matter as a whole. The other, in a certain sense narrower, approach aims at finding the laws of motion and interaction of, perhaps, only a certain class of particles, while regarding their basic characteristics (mass, charge, spin, etc.) as specified and, so far, not liable to explanation. Historically the second trend arose earlier, due largely to the fact that the sharp increase in the variety of experimentally detected types of particles and the discovery of the diversity of their properties are comparatively recent. We will nonetheless begin with a consideration of the former trend and the associated peculiarities of the theory.

By now physicists have discovered and investigated about thirty types of fundamental particles, not counting the ten to fifteen types of "quasiparticles" mentioned above, the nature of which (in the sense of their "elementarity") remains even less clear than that of the unstable particles of the "ordinary" type. Thus the "assortment" of particles which can be created with the help of accelerators is nearly as rich as the selection of various chemical elements in Mendeleev's time, i. e., about a century ago. It is well known that the immense service performed by Mendeleev was to compile the periodic table of the elements, a classification based upon the law

* See M a r k o v, M. A. Giperony i K-mezony (Hyperons and K-Mesons), Moscow, 1958.

which he discovered, namely that there exists a periodic dependence of the chemical (more accurately, the valency) properties on the single main characteristic of the elements — atomic weight. Although it was only much later, in connection with the first successes of quantum mechanics and the discovery of Pauli's principle, that the periodic law received a complete explanation, in its time it played (and continues to play even now) an immense progressive role by helping to determine the existence of regularity in the structure of the chemical elements and providing research scientists with a reliable means of predicting new elements.

Despite their smaller number, the problem of classifying the "physical elements", i.e., fundamental particles, immediately proved to be more complicated owing to the abundance of physical properties (mass, charge, spin, magnetic moment and so on), each seemingly impossible to reduce to other simpler or more "primary" properties.

For a fairly long time now it has been practically obvious that none of these properties, taken in isolation from the rest, can serve as a basis for a reasonable classification of the particles. Such is the situation, in particular, with mass: several admittedly different particles (photon, two kinds of neutrino and antineutrino) all have zero mass, and the enormous relative difference in the masses of, say, the μ-meson and electron fails utterly to correspond to the very small difference in their interactions with all the remaining particles. The same situation holds for the other properties (spin, electric or nuclear charge): the physical quantities corresponding to them (the quantum numbers) can assume a significantly smaller number of possible discrete values than the total number of known particles.

On the other hand, a definite analogy can already be pointed out between the present situation in physics and the "family relationships" of the chemical elements. As is well known, Mendeleev's table divides all the elements into eight groups according to their valency — their ability to enter into some kind of chemical combination. Correspondingly, the fundamental particles can be divided into three fairly well-defined groups according to their ability to enter into three different types of interaction. The first group will contain the neutrino and antineutrino, which participate only in the weak interaction (with an interaction constant of the order of 10^{-12}). The second group will contain the photon, the electron (together with the positron) and both μ-mesons (μ^+ and μ^-), which can participate in electromagnetic interactions (constant 1/137) but not in interactions of the strong (nuclear) type, characterized by a constant of the order of unity. Finally, the last and most numerous group contains all the remaining particles, which participate in weak, electromagnetic and also strong interactions.

A very fruitful concept for the classification of the fundamental particles (at least for the particles of the third group) proved to be the new physical concept of isotopic spin. This vectorial quantity I, formally similar to ordinary spin (the proper angular momentum of a particle), has no obvious physical interpretation. One of its three components (the z-component I_z) is manifested in the fact that to its various values correspond states of nearly the same mass but with different electric charge (thus for the π-meson to $I_z = +1$ corresponds the charge $+e$, to $I_z = 0$ the charge 0, to $I_z = -1$ the charge $-e$, where e is the charge of a positron or proton). Even this correspondence is far from univocal, though it can be made so by introducing another, equally abstract, quantum number, the so-called "strangeness" S.

Isotopic spin proved to be the expression of three previously unknown but apparently very important internal degrees of freedom of the particle, to each of which corresponds a very restricted set of proper values of the quantum numbers (0, ± 1/2, ± 1). Taking the isotopic spin and strangeness together as fundamental quantum numbers, Gell-Mann and Nishijima carried out the first successful (1956) attempt to classify a large number of particles, namely mesons, nucleons and hyperons. This classification might be illustrated in a simplified form by the table below:

I_t \ S	0	+1	−1	−2
0	(?)	(?)	Λ^0	(?)
±½	p, n	K^+, K^0	$K^-, \bar{K}^0$	Ξ^0, Ξ^-
±1	—	—	$\Sigma^+, \Sigma^0, \Sigma^-$	—

Thus by making use of a previously known quantum number (isotopic spin) and introducing yet another number (strangeness), Gell-Mann and Nishijima were able not only to arrange univocally those strongly interacting particles which had been discovered in experiments in the rows and columns of a table, but even to conjecture about the possible existence of several new particles (question marks in the table). Despite the arbitrariness involved in choosing the new quantum number S (in other attempts to classify particles different quantum numbers are introduced), the quantum numbers I and S proved useful not only in classifying the particles themselves but also in explaining certain regularities (conservation laws or selection rules) satisfied by the "reactions" of transmutation of the fundamental particles. Indeed, in all strong interactions of mesons, nucleons and hyperons the total values of each of the four numbers (I_x, I_y, I_t, S) remain constant, whereas in weak interactions of the same particles the rule $\Delta I_t = \pm 1/2$ and the rule $\Delta S = \pm 1$ which follows from it are invariably obeyed. In particular, as is easily seen from the above table, the concept of isotopic spin and its conservation makes it clear why strange particles (K-mesons and hyperons) are always created in pairs in the nuclear interaction of high-energy nucleons and mesons. It is due to the fact that the total strangeness of the entire system of particles should remain equal to zero or, correspondingly, the total quantity I_t should remain constant.

Thus the first successful steps in the construction of a scientific classification of the fundamental particles were made possible by bold mathematical hypotheses concerning the presence of new internal degrees of freedom which, though not susceptible of intuitive physical interpretation, are manifested in a completely definite way in the regularities which govern the interactions and transmutations of these particles.

It is often believed that kinematical ideas and relations play an auxiliary (phenomenological) role in physics, inasmuch as their only purpose is to describe certain forms of motion of matter, the causes of which they do not explain to the same degree as do the dynamical regularities. For a characteristic example one can take Kepler's kinematical laws, which describe the motion of planets in their orbits, and Newton's dynamical laws, which connect, on the one hand, the accelerations of bodies with the

external forces acting upon them, and, on the other hand, the magnitude of the active force (force of gravity) with the mutual position of the two bodies. However, as pointed out by V. B. Berestetskii, from the standpoint of explaining observed phenomena the difference between the two types of regularities in the given case is not so fundamental as might appear at first glance*. In the last analysis, Kepler's laws connect relative velocities of motion of bodies with their relative positions, and Newton's laws relative accelerations with relative positions; in the given case the two groups of laws are equivalent. The more general character of Newton's treatment is due, basically, to the introduction of the further concept of force, which can have any origin, and not only a gravitational one; it may be dependent not only on mutual distances but also on mutual velocities and even mutual accelerations of bodies (the latter would imply a transition to the considera- tion of noninertial systems of coordinates in which the forces of inertia must be taken into account).

At the same time (and this again was pointed out by Berestetskii), what may be required when one moves to new phenomena is not so much a con- sideration of a new type of force as, in the first instance, a revision and generalization of kinematical ideas. Precisely the latter is already achieved in nonrelativistic quantum mechanics, which, operating with Schroedinger's equation, is satisfied essentially by classical expressions for the forces of interaction of material objects. It nonetheless requires a decisive modifi- cation of kinematical ideas and, in particular, discloses the far-reaching connection between the particle momenta and coordinates in the form of the uncertainty relation.

Another example of a basic revision of kinematical ideas in modern physics, one which is important in principle, is provided by the theory of relativity. At first glance it might appear (at least if one confines oneself to the inertial system of coordinates) that the new content of the theory is mainly concerned with kinematics — the laws of transformation of the coor- dinates and velocities upon transition from one system of reference to another. In reality, however, the content of this theory goes far deeper; from it also follow, logically and inevitably, such highly important "dynam- ical" results as the dependence of inertial mass on velocity, the equality of the inertial and gravitational masses, the connection between mass and the total energy of a body and, finally, the more profound view on the causal connection of phenomena from which follows, in particular, the impossibi- lity of the existence of absolutely rigid bodies (the latter point is very signi- ficant when considering the question of the structure of fundamental par - ticles).

Thus the relative character of the space-time relations and properties of material objects, their indissoluble connection with the actual forms of mo- tion of matter, show us how limited and arbitrary is the attribution of a descriptive capacity to kinematical laws and of "explanatory" significant capacity to dynamical laws.

The connection between the forms of motion and interaction of material bodies and their space-time properties is no less strikingly revealed by the fundamental role of the numerous conservation laws in microworld physics. Strictly speaking, this role is not so small even in the classical physics of the microworld. Suffice it to mention the law of energy conservation, the

* See p. 12 of this book.

concrete form of which, in each individual case, is the main guiding line for a rigorously materialistic approach to the question of mutual transitions of one form of motion of matter into another. This law also plays a tremendous role in dicsovering new forms of motion of matter (as was the case for the prediction of the neutrino). An important point is that the law of energy conservation can be derived in a rigorously logical way from a single very general property of time, namely its uniformity (or more precisely from the requirement that the physical laws describing the motion of matter retain their form when the origin of time reckoning is changed).

A similar situation prevails for such very general conservation laws as that of momentum and angular momentum: the former is equivalent to the property of homogeneity and the latter to that of isotropy of space. Extending this situation to the other analogous conservation laws of dynamical quantities, one might say that they are all expressions of certain symmetry properties of space-time.

A very important new fact, one which, in some degree, characterizes a new stage in the development of space-time ideas, is the discovery of "parity nonconservation" in weak interactions. Thus, for instance, the beta decay of atomic nuclei or the decay of a μ-meson (into an electron, a neutrino and an antineutrino) take place asymmetrically in the left-handed and right-handed systems of coordinates (which are mirror reflections of each other). Yet, as has been specially ascertained, this kind of asymmetry is not found in strong interactions, which means that different forms of motion of matter are characterized by different spatial symmetries.

It should be mentioned here that a different, more complex form of symmetry, involving the conservation of "combined parity", remains valid for weak interactions. It appears that the regularities for the corresponding elementary processes remain fully valid if, as one moves from the right-handed system of coordinates to the left-handed one, one also performs the operation of "charge conjugation" — replacement of the particle by its antiparticle. This interesting property is also reflected in the fact that, for example, the spin of the neutrino is always parallel to the direction of its own motion, while that of the antineutrino is parallel to its own motion.

Another fact which shows the diversity and complexity of the space-time properties of fundamental particles is the abundance of "transformation characteristics". Indeed, the wave functions for the different particles may contain a variable number of components which transform in a definite way upon transition from one system of coordinates to the other, and necessarily satisfy in this process the requirements of the theory of relativity. Thus there are particles of the pseudoscalar type (π-mesons) with a one-component wave function which changes sign under mirror reflection, particles of the spinor type (nucleons, electrons) with two-component wave functions, particles of the vector type (photon), and so forth.

A consideration of these peculiarities proved very important in various attempts to cognize the structure of fundamental particles. In particular, it must be considered that particles of the spinor type, which have half-integral spin (in units of Planck's constant $\hbar$) and obey Fermi statistics, may be the structural elements of the other remaining particles, which have integral spin and obey Bose statistics (for which reason they are called bosons, as distinct from fermions, the former type of particle). An interesting attempt to make use of this peculiarity in constructing a half-phenomenological theory of fundamental particles is due to the Japanese

physicist Sakata, who made a thorough examination of a single concrete hypothesis, treating all particles with integral spin as bound states of two particles belonging to the three basic types (protons, neutrons and Λ-hyperons) with their antiparticles.

For an accurate dialectical understanding of the question of which physical regularities are to be regarded as "purely descriptive" or phenomenological and which as significant, it is highly instructive to take up the so-called scattering matrix method. In this method to every particle, or more precisely, to every pair of interacting particles, is assigned a certain set of matrix elements — the scattering amplitudes. Determination of the complete set of amplitudes makes it possible to predict, in a probabilistic manner, all the possible final states of this pair of particles (after their interaction from their specified initial states. It was found that this kind of description of particles was, in general, equivalent to an explanation of their structure, or the so-called form factor. True, in this case, as distinct from the earlier method of studying the form factor in coordinate space (e. g. , in the exposition of the laws of scattering of X-rays on the atoms of crystals), it is more expedient to use momentum space. This means that one is studying not the statistical distribution of the structural elements of the particle in space (statistical form factor) but rather the set of possible momentum transfers in the process of interaction with another particle (dynamical form factor). However, the well known laws of transformation of particle wave functions from the coordinate to the momentum representation (they are used, in particular, when the localized particle is treated as a "packet" of elementary waves) make it possible to establish the deeper internal connection between the two forms of form factors.

Regarding the experimental possibility of studying the structure of particles, the idea of a dynamical form factor has proved to be (despite its seeming abstractness) significantly closer to the direct methods and results of contemporary experiment. Indeed, processes of mutual scattering of particles (and especially elastic scattering) now constitute, in the hands of the experimental physicist, a powerful tool for studying the structure of the fundamental particles and, in the first place, that of the nucleons (let us recall the by now classical experiments of Hofstadter on the scattering of electrons on nucleons).

The method of describing the interactions and motions of fundamental particles with the help of the scattering matrix and of dynamical form factors is somewhat analogous to Kepler's kinematical regularities, though it possesses a fundamentally new quality connected with the uniqueness of the result of the particle interaction.

The next development of the scattering matrix method disclosed the existence of very profound bonds of causal character. Indeed, on the basis of very general and (at first glance) fairly abstract principles, in particular the principle of analyticity of the functions of the basic dynamical variables (energy of interacting particles and the momentum transfer), it was possible to derive rigorously very general mathematical relations between the matrix elements (scattering amplitudes), which were named dispersion relations.

With the help of certain additional, again fairly abstract postulates, and in particular the principle of unitarity of the matrix operators used by

the theory, it was possible to obtain from the dispersion relations a number of important equations connecting a wide variety of processes of interaction of the fundamental particles. Especially important and entirely concrete results were obtained by applying this method to the effective cross sections of interactions occurring at very high energies (work of the Soviet physicists I. Ya. Pomeranchuk and V. N. Gribov).

Despite the formal mathematical character of the postulates at least one — the postulate of analyticity — has a very important physical meaning. As N. N. Bogolyubov was the first to show, this postulate is the concrete expression of the requirement of microcausality of processes of interaction of fundamental particles. On the other hand, the well known success of this method is due to the fact that it proved possible in this theory to sidestep the fundamental physical difficulties associated with the problem of spatial structure of particles.

Indeed, another method of analyzing particle interactions (solution of the equations of motion of quantum field theory) which was intensively developed for many years, met with very serious difficulties of principle. This theory starts, as zeroeth approximation, from the states of free particles, on which is superimposed, as the "perturbation", the interaction of the particles. The latter can be treated mathematically by expansion of the corresponding expressions in series in the interaction constant.

It was demonstrated by the work of L. D. Landau and other Soviet physicists, however, that even in the theory of electromagnetic interactions, where the above-mentioned interaction constant is substantially less than unity (it is 1/137), the idea of point (structureless) particles, though it does make it possible to obtain results in agreement with experiment, suffers from a very important defect. It appears that the original, i.e., unperturbed (it is also called "bare"), electric charge of the interacting particles should be smaller than that observed in experiment by an infinite factor, and therefore should be zero. But then one does not see from where the interaction, which is an actual fact, comes about (provided one does not drop the concept of point particles from the start).

On the other hand, attempts to improve the theory by introducing the idea of extended fundamental particles have also met with difficulties of principle. The main difficulty consists of the contradiction with the theory of relativity: any conception of a definite geometric form (form factor) of the particle leads to the situation where for every interaction of this particle as a whole (and only such interaction is possible if the particle is truly elementary) the signal propagated inside the particle should be transmitted with infinite velocity. At the same time the possibility of infinite velocities of transmission of signals is in contradiction with the principle of causality, assuming that the properties of space and time at small scales (expressed mathematically by Lorentz transformations) are the same as in the macroworld.

A significant number of attempts have been made to overcome this difficulty in principle by revising the properties of space and time at very small scales, even without rejecting the validity of the Lorentz transformations (for which there is, so far, no experimental foundation). An interesting attempt of this kind is considered, in particular, in the book by M. A. Markov cited above. Markov begins his argument from the fact that, despite the novelty of its ideas, quantum mechanics does not lead to violation of the classical principle of causality but merely to violation of the

conditions of its applicability. Indeed, this principle requires that, from specified initial values of the coordinate and momentum (q_0, p_0), one be able to predict univocally their values $q(t), p(t)$ at any subsequent instant in time. Since simultaneous specification of q_0 and p_0 is, in the case of microobjects, devoid of physical meaning, one cannot demand further motion of the particle along the trajectory in the classical sense of this word. On the other hand, quantum mechanics does not exclude the possibility in principle of performing as many accurate, and moreover, repeatable measurements as desired of (only) the coordinate q at instants t as close to each other as one wishes; thus the possibility of motion of the microobject along a continuous trajectory is retained (but only if the particle does not have a definite momentum).

The next possible generalization of ideas concerning the nature of microobjects, according to Markov, consists of assuming the nonlocalizability in principle of the particles, i. e., the presence of a certain region of dimension r_0 over which the particle coordinates will be distributed with a certain probability density $\chi(x)$ even for maximally accurate consecutive measurements on the same particle state. Thus the idea of a certain minimum dimension $\Delta q \sim r_0$ which the quantum-mechanical wave packet associated with the particle can have is introduced. The presence of such minimal "smearing" of the coordinate, combined with the corresponding inaccuracy in principle of time measurement $(\Delta t \sim r_0/c)$, makes it impossible to create experimental conditions where violation of the law of limiting signal velocity $(= c)$ "within" particles (as predicted by the theory of relativity), and associated violation of causality, could be manifested. Such ideas can easily be generalized to an entire group of particles with similar properties, to which is assigned a discrete series of functions $\lambda(t)$ and corresponding series of values of the mass. Using this approach, Markov proposed a new and interesting possibility, that of treating the hyperon family as a special kind of "excited state" of the nucleons, and the family of π- and K-mesons as systems consisting of two baryons (i. e., nucleons or hyperons) each.

The result is the development of an entirely new approach to the classification of the fundamental particles, which, in a number of significant predictions concerning the possible types of particle interaction (including weak interactions), differs markedly from the Gell-Mann and Nishijima scheme.

The ideas of space quantization put forward repeatedly by various authors are somewhat similar to Markov's ideas. In our opinion, however, while retaining the basic notion of a revision of the space-time properties of matter at small scales, these ideas of quantization are for the most part rather formal in character, far removed from concrete peculiarities of motion of microobjects. As a result such attempts have, so far, remained within the framework of abstract schemes not directly related to the experimental facts which could have confirmed or refuted the corresponding theory.

Summarizing the contents of the present section, one might say that the fundamental difficulties which arose in the creation of a theory of interaction of fundamental particles placed the physicists face to face with the necessity of thoroughly analyzing modern ideas on causality and the properties of space-time at very small scales.

Theory and experiment are two tightly linked and complementary aspects of the cognition of the objective world by the thinking subject; therein lies their unity. Experiment deals with immediate or remote perception of reality; however, between simple perception and cognition, understood as the process of more or less adequate expression of reality, a decisive step remains to be taken: the formation of generalizing abstractions in the consciousness of man. Theory deals with the creation of abstractions for the purpose of cognizing the essence of phenomena and the regularities which determine them; without this the process of extrapolation of previous experience to the future would be impossible. In turn, both the creation of abstractions and the extrapolation of experience become meaningless without practice and without experiment in the most general sense of this word, since both are, in some way, the initial and final link in the interaction between the subject and the studied object.

Before considering the concrete forms of linkage between theory and experiment in the field of physics in general and microworld physics in particular, a brief remark is in order concerning two somewhat different aspects of the concept of "theory". One aspect consists of stressing the cognitive aims of science which, at different stages in its development, stand, generally speaking, in varying relation to practice as the applied side of science. In this sense of the word all of elementary particle physics should today be classed as a theoretical science, since its applied significance is felt only insofar as it is one of the important subdivisions of the physics of the atom and of the atomic nucleus.

The other aspect, which is usually the basis for distinguishing between theoretical and experimental physics, consists of stressing those methods of research with which the scientist solves the problems facing him. Theoretical physics, which takes as its point of departure certain fundamental and already known facts and postulates (hypotheses) based, in the last analysis, on generalization or extrapolation of facts, uses for its own purposes a definite logical apparatus which, as a rule, is formulated in terms of appropriate mathematical relations and transformations. Experimental physics, which takes as its point of departure a directly perceptible object of the external world in conjunction with previously obtained (experimental or theoretical) results and ideas, "addresses questions", as it were, to nature itself by performing certain material operations on the object and subsequently recording their result, or simply by bringing about (at the first stage) a definite complex of conditions to guide the natural phenomena in the direction of interest. This subdivision (by research methods) is the basis for the far-reaching subdivision of labor among specialists in the same field owing to which the fully successful combination in the same person of theoretician and experimentalist has now become a great rarity.

We shall now consider the most widespread forms of linkage between experiment and theory in the physics of fundamental particles.

1. The experimentalist "provides" the theoretician with primary, basically descriptive data relating, firstly, to the fundamental properties of already known particles (mass, charge) and secondly, to their transmutations, which are determined by interaction (lifetimes and cross sections, types of possible "reactions" and their relative probabilities, angular and momentum distributions of the products of "reaction", and so on); the characteristics of the latter kind frequently prove important not only in themselves but also for the determination of deeper properties of the

particles (spin, parity, transformation type, statistics, and so on); incidentally, it should be mentioned that, essentially, any property of fundamental particles characterizes first and foremost the ability of the given particle to enter into interaction with other particles and fields.

2. The experimentalist "encounters" (purposely or accidentally) new particles or new types of "reactions" between them; in many cases (e. g. , the particular case of the K-mesons) to distinguish one type of discovery from another is far from simple and requires tremendous efforts on the part of both the experimentalist and the theoretician. The theoretician makes use of these results to develop existing ideas concerning the systematization of particles, the laws governing their motion and interaction and the space-time peculiarities and causal relations manifested in these forms of motion.

3. The theoretician formulates certain incomplete hypotheses (in the form of mathematical relationships between quantities measured in experiment), which are then subject to experimental verification prior to initiation of the next stage of setting-up the structural system consisting of ideas and mathematical relations and covering an entire region of phenomena. Such was the case, for example, in the formulation of the hypothesis of the universal four-fermion interaction, the fundamental laws of which proved applicable to an entire, fairly broad class of weak interactions of particles.

4. The theoretician "devises" certain methods for revising fundamental physical ideas on the nature of elementary particles and formulates (sometimes) completely new ideas more or less abstract in content (as in the case of isotopic spin, strangeness, methods of space quantization); both require, as a rule, the development of new mathematical apparatus adequate to the physical content of the new concepts. An important point (the primary distinction between physics and mathematics) is that all these concepts and ideas are converted from hypothesis into theory, from guesswork to scientific discovery, only when they survive the criterion of practice — comprehensive experimental verification.

Unity and organic linking of theory and experiment do not imply, however, identical linking at all stages of cognition. In this connection it is worthwhile to pause over Heisenberg's well known thesis that any physical theory should contain only directly observable quantities, and that its aim is to establish the relationships between these quantities. A closely related view is that the determination of any physical quantity becomes rigorously scientific and exhaustive when and only when at least one concrete method of direct measurement of this quantity by experiment (such as the scattering amplitudes in the method of dispersion relations) is proposed. The experience of developing elementary particle physics shows, however, that despite the soundness and apparent obviousness of these requirements they can in no case be made into absolute principles or into the major foundations of new theories.

Indeed, a point apparent from our earlier exposition is that abstract-mathematical concepts and hypotheses not susceptible of direct physical interpretation — susceptible only of very indirect (and occasionally even nonunivocal) experimental determination at the given stage of development of the science — tend to be very useful in the development of theories dealing with completely new unexplored circles of phenomena. Such, in particular, were the concepts of isotopic spin, strangeness, parity and many others.

Although at present it is still difficult to say what position these concepts will assume in the future rigorous theory, it is already evident that to require categorical rejection of similar concepts would strongly inhibit the possibilities of development of the science. In the last analysis excessively strict attachment to the observable quantities at each stage of development of science is the result of a positivistic tendency to underestimate theoretical methods of cognition of the truth as the essence of experimentally perceptible phenomena, and to absolutize the purely descriptive function of science, as if the latter were confined to dealing only with the relation between phenomena and not with their causes.

Dialectical materialism treats the union of theory and experiment not in congealed form but in close connection with the process of historical development of science as a whole. A certain parallelism between the development of experiment, which accumulates the new facts, and that of theory, which devises the detailed abstract-mathematical scheme of relationships between objects (or even several alternate schemes simultaneously), may be entirely justified at certain stages of cognition. Despite the partial and temporary gap between one method of developing science and the other, each may, up to a certain limit, progress successfully while preparing the conditions for the decisive qualitative jump which will allow, on the one hand, a completely new clarification of accumulated experimental facts and, on the other hand, the discovery of fundamentally new possibilities of verifying the theory.

It must, of course, be stressed once again that sooner or later this kind of gap between theory and experiment, if allowed to widen, becomes a hindrance to the development of the science. There are, of course, positive aspects to the narrow specialization that calls for virtuoso mastery of the "home-made" methodology, terminology and store of knowledge, for continuous preparation of new "precooked products", which fail to throw new bridges between theory and experiment. One of these is the fact that, as a rule, the introduction of fundamentally new research methods (theoretical or experimental) is in itself enough to permit substantial progress, the discovery of significantly new aspects or peculiarities of the phenomenon in question. However, the extensive and frequently unavoidable mutual trust in the accuracy and reliability of results obtained by theoreticians, on the one hand, and experimentalists, on the other, may ultimately weaken the mutual criticism so beneficial to the development of science as a whole. Similarly, conservative orthodox tendencies involving absolutization of results obtained and confinement to definite research methods may prove to be fetters for the science in the absence of constant, fructifying contact between theory and experiment, unless care is taken to search continuously for new points of contact between theory and experiment.

VISUALIZABILITY AND MODELS IN THE THEORY
OF ELEMENTARY PARTICLES

I.B. Novik

Analysis of the question of visualizability and models is one of the most important methodological problems raised by the development of modern science and, in particular, by that of microworld physics. The method of models is applied both in experimental and in theoretical cognition.

A very considerable scientific and philosophical literature is devoted to this complex question.

On 4-8 January 1960 a special Colloquium was held in Utrecht on "The Concept and the Role of the Model in Mathematics, Natural and Social Sciences". The proceedings of this Colloquium, published in a special number,* indicate the existence of very serious philosophical difficulties in the understanding of modern forms of model construction in scientific cognition. Suffice it to mention that L. Apostel—author of the introductory article of this number—establishes the conclusion that owing to the complexity of modern model construction a general definition of the model is impossible. In his work entitled "Towards the formal study of models in the nonformal sciences" he writes: "As a result of the theory presented in the article in question, we see that we cannot hope to give a unified structural definition of models in the empirical sciences". Further on Apostel stresses that, in describing the functions of models, we can only determine what it means to use a model, but we cannot determine what a model is. Here we see a manifestation, in the field of model construction, of that distrust of general methodological approaches to the investigation of theoretical problems which is so characteristic of positivistic philosophy.

In our literature interesting considerations relating to the nature of the method of models may be found in A.I. Uemov's "Induction and Analogy" (Induktsiya i analogiya), Ivanovo, 1956; V.P. Branskii's "The Philosophical Significance of the Problem of Visualizability in Modern Physics" (Filosofskoe znachenie problemy naglyadnosti v sovremennoi fizike), Izd-vo LGU, 1962; V.A. Shtoff's "The Gnoseological Functions of the Model" (Gnoseologicheskie funktsii modeli), Voprosy filosofii, 1961, No. 12; A.A. Zinov'ev and I.I. Revzin's "The Logical Model as a Means of Scientific Investigation" (Logicheskaya model' kak sredstvo nauchnogo issledovaniya), Voprosy filosofii, 1960, No. 1; I.T. Frolov's "Gnoseological Problems in the Construction of Models of Biological Systems" (Gnoseologicheskie problemy modelirovaniya biologicheskikh sistem), Voprosy filosofii, 1961, No. 2.

The aims of the present article do not include a systematic exposition of the philosophical problems of model construction. We will undertake to analyze philosophically only such aspects of the process of model construction as are, in our opinion, of the greatest value for clarifying the role of models in the development of the theory of elementary particles. Accordingly, three sections have been distinguished in the present article:

1. Statement of the problem.

2. Forms of models in microparticle research.

3. Model construction and certain prospects for the development of the theory of elementary particles.

The method of models is very widely employed in the development of physics.

In classical physics the model was regarded as a pictorial example of the physical object under investigation.

As to the actual concept of visualizability, it was treated under three aspects: as characterization of a mechanical system, as susceptibility to sensory perception and, finally, as habit.

Taking the idea of the picturing of physical concepts to its logical conclusion, William Thompson [Lord Kelvin] said: "It seems to me that the true meaning of the question of whether we understand a given physical problem reduces to the following: can we construct a good mechanical model of it?"*

J. C. Maxwell linked the problem of picturing to that of constructing mechanical models of non-mechanical phenomena, but pointed out the well-defined limitations of such models.

Accurately enough, Maxwell saw the model as a preliminary means by which a physical phenomenon could, to a certain extent, be explained prior to the development of a systematic — or "mature", to use Maxwell's expression — theory. "By expressing everything in terms of the purely geometrical concept of the motion of an imaginary fluid," he wrote, "I hope to achieve generality and accuracy and to avoid the misapprehensions which arise when one attempts to explain causal phenomena by means of a p r e - m a t u r e   t h e o r y" (our emphasis — I. N.)**.

The problem of visualizability is modified in the development of quantum mechanics, appearing as the question of (the possibility of) constructing a classical macromodel of a nonclassical microobject.

In its general form at present this problem is often formulated as the role of visualizable models in the cognition of nonvisualizable microobjects.

In our opinion the problems of visualizability and of model construction do not entirely overlap in modern physics. First of all, we feel, there is a certain difference between the questions of visualizability of microobjects and those of the means of interpretation of these objects and, in particular, visualizability in model construction.

The former question is considered in a work by M. E. Omel'yanovskii, "The Problem of Visualizability in Physics" (Problema naglyadnosti v fizike)***.

* "Arkhiv istorii nauki i tekhniki AN SSSR" (Archives of the History of Science and Technology, Academy of Sciences of the USSR), p. 49, No. VI. 1935.

** M a x w e l l, J. C. Izbrannye sochineniya po teorii elektromagnitnogo polya (Selected Works on the Theory of the Electromagnetic Field). Moscow, p. 17. 1954.

*** See "Voprosy filosofii", No. 11. 1961.

We believe that a characteristic feature connected with generalization of the concept of model is reduction of the element of sensory visualizability in modern model construction.

When the visualizable and the model-representational character of knowledge are rigidly connected, the following argument is arrived at: inasmuch as in modern physical cognition the role of the element of visualizability is decreasing, the significance of models is also decreasing or even disappearing; it follows that in order to strengthen the method of model construction in microphysics one will have to somehow "make the latter more visualizable" in the future.

In this respect it is interesting to analyze a highly characteristic statement by the German physicist G. Geber: "We describe the nature of atomic objects mathematically but are unable to understand it modelwise (modelmässig). This is the meaning of the common assertion that the nature of the objects of quantum mechanics is 'not visualizable' "*.

Later on Geber notes that, possibly, the force of sensory contemplation will develop and we will be able to visualize pictorially microobjects, modelwise.

To a certain extent this approach is related to that of certain theoreticians in the recent past toward the treatment of the uncertainty relation, when it used to be said that at the present time indeterminism was prevalent in physics but in the future, because the force of reason was unlimited, we would find out how causality was manifested in the microworld. In our opinion, setting hope in the future instead of attempting to interpret rationally the contemporary data may be the reverse side of admitting incapacity in the present. An idea of this sort is implicitly based on the illusion that any new element in cognition is transient and that gradually everything returns to the old, familiar forms.

On the whole, we feel, Bohr was right when he stressed that "there can be no question of a return to a method of description which would largely meet the familiar requirements of a pictorial, model representation of the connection between cause and effect"**. However, one cannot agree with the tendency to identify pictorial with model description which is manifested in this statement.

A more expedient approach, in our opinion, and one which is more in the spirit of modern scientific cognition, is to regard the dilemma (expressed in the above thesis of Geber) which contrasts mathematical description and model description as unfounded. Here it should be stressed that the concept of model has been generalized, so that the conception of model is not confined to its treatment in the spirit of classical physics as a pictorial (i. e., mechanical system; it is also treated in the spirit of the contemporary stage of cognition—as a logico-mathematical structure. This approach to the construction of models is founded on an important regularity of the modern cognitive process, related to the increasing role of the category of relationship in the cognitive process. We can understand the nature of microobjects modelwise, but the models themselves are not pictorial, or, at any rate, the concept of visualizability itself requires radical extension.

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* See the collection entitled "Naturwissenschaft und Philosophie", Berlin, p. 30. 1960.
** Bohr, N. Kvantovaya fizika i filosofiya (Quantum Physics and Philosophy), UFN, Vol. LXVII, No. 1, p. 42. 1959.

Thus if the first important feature of model construction in modern physics is the reduction of the element of visualizability, its second feature is the increase, in cognition, of the role of models consisting of logical elements.

The attribution of a relatively independent existence to the logical elements of the model and treatment of these elements as the objects of research have drastically increased the cognitive possibilities of model construction. Thus it is well known that highly significant information concerning the microworld (e.g., the antiparticle hypothesis) was obtained by investigation of a mathematical model of the microworld such as Dirac's equation.

Logical model construction is one of the most effective accelerators of modern physical knowledge. Modern physical understanding does not presuppose a pictorial, mechanical representation of physical processes. We see that not only the concept of model but even the very idea of physical understanding is generalized in contemporary cognition.

To quote N. R. Hanson's felicitous remark, "unpicturity is the price for the 'intellectual advantage' connected with understanding"[*].

It may be inferred from what we have been saying that both the method of construction of models and the concept of model are in need of generalization at the present stage of scientific cognition.

It is possible to formulate a generalized concept of model construction.

Model construction is a method of mediate cognition in which the object under investigation is studied through the mediation of another object which stands in a certain relation to the first and is capable of replacing it at definite stages of the cognitive process[**].

Accordingly, the model is a natural or artificial object which stands in a certain relation to the object under investigation or to any one of its aspects and is capable of replacing this object (i.e., of serving as a relatively independent "quasi-object") and which makes it possible to obtain, when investigated, a certain indirect knowledge of the object itself[***].

Regarding what we have been saying as an important basic principle of any approach to the study of the role of models in modern physical cognition, we can suggest that the situation in the case of the concept of the model is somewhat similar to that which is obtained in the case of the principle of causality. Just as it was concluded from the discovery of new forms of causal dependence that repudiation of this fundamental principle was in order, so from the changes in, and increasing complexity of, the process of model construction it is inferred that modern scientific knowledge is "non-model-like". In reality, however, as is well known, the principle of causality was extrapolated upon transition to the microworld. The same situation occurred with the concept of the model in modern physics; this highly important logical tool has not been removed from the cognitive process, it has been extrapolated on the basis of experience.

The importance of the extrapolated concept of the model in modern physics becomes especially obvious if one turns to a consideration of the gnoseological function of the construction of models.

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 * Hanson, N. R. Patterns of Discovery. p. 122. Cambridge. 1958.
 ** The aim of the present work does not include an analysis of the forms of correspondence between model and modelled object; here it is important to stress the diversity of these forms.
 *** The fundamental difference between model mediation and instrumental mediation is obvious to us, if only because an instrument does not replace the cognized object (does not become a "quasi-object") but rather performs the function of representative of the subject.

If ontologically model construction is the juxtaposing of a new object and one which has already been studied, from the gnoseological standpoint model construction is a form of linking between a theory in the formative stage and one already established; that is, model construction makes it possible to evaluate the unknown in terms of the known.

We will formulate the basic stages of the gnoseological role of models in the cognitive process from the latter point of view.

With this in mind let us again turn to the Maxwellian statement of the problem of physical model construction. Maxwell believed that models based on the analogy with an incompressible fluid made it possible "to conceive visually the laws of attraction and of the inductive influences of magnets and currents"[*]. The gnoseological role of models of this type consists of pictorial representation of new physical phenomena.

The function of a model of this kind is to act as a connecting link between new physical phenomena and the old physical theories. The importance of this function cannot be denied.

However, in the development of cognition the term "model" is also used in connection with a different kind of problem, when the question is one of p a s s i n g from old theories to new ones, rather than of l i n k i n g new facts and old theories.

When a new fact becomes established, the first step is to attempt to interpret it on the basis of the old theoretical ideas by somewhat modifying the latter without admitting new radical assumptions. If this does not succeed it becomes necessary to bring in such assumptions. Here instead of the model-analogue we have the model-hypothesis, which is a preliminary form of explanation of new phenomena which has broken away from the old theory. Model construction of this kind is of particularly great practical value. It is of the greatest significance for the development of elementary particle physics, since here the question is indeed one of the e s t a b l i s h - m e n t of a theory.

In this case the construction of a model is not the result but merely the starting point of logical knowledge. The emphasis is shifted to the second stage, namely i n v e s t i g a t i o n of the constructed model resulting in transition to the formulation of a systematic closed theory of the definite physical object.

The distinction between the two types of model construction becomes particularly evident if one turns to the history of the development of ideas on the atom. When Rutherford's ingenious experiments with the bombardment of thin foils by α-particles led him to the remarkable conclusion that there existed a dense massive nucleus in atoms, he constructed his well-known planetary model of the atom entirely in the spirit of nineteenth century physics, by analogy with the solar system. This is the classical example of the model-analogue, built on an evaluation of the unknown in terms of the known. It should be emphasized that Rutherford assumed no ontological peculiarities in atomic processes which might have distinguished the latter from macrophysical processes, despite the fact that he encountered some very unexpected results in experiment.

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[*] M a x w e l l, J. C. Izbrannye sochineniya po teorii elektromagnitnogo polya (Selected Works on the Theory of the Electromagnetic Field), Moscow, p. 17. 1964.

It is well known that the interpretation of atomic structure in terms of this model led to a contradiction and to Bohr's idea of allowed quantum orbits. The idea of allowed orbits, in which the electron does not radiate energy, characterized new properties of the atom not present in macro-objects. This is the classical example of the model-hypothesis. It is sometimes suggested that the term "model" be dropped in connection with Bohr's work and that this was the first theory of atomic structure. In our opinion, since what we actually have here is a preliminary form of explana-tion of atomic phenomena which were systematically interpreted only later by quantum mechanics, one ought to speak in this connection of a model.

Thus the model is not only a form of linking of old and new theory, it is also a form of transition to the new theory, a preliminary form of inter-pretation of new, as yet unknown physical phenomena not covered by the existing theory.

Our general glance at model construction suffices to show that it is as essential a part of the cognitive process as the distinction between the known and the unknown.

The model is the first, preliminary form of theoretical interpretation of new objects; it often discloses contradictions in the conception of these new objects in the light of the old theory. In view of this it is, as it were, an inquiry addressed to the systematic consistent theory of this new object. It precipitates the further development of theoretical interpretation of the object. Thus it is entirely understandable that this first form should be highly important.

In conclusion, let us formulate the basic stages associated with the gen-eralized treatment of the method of model construction.

1. For the construction of a model it is necessary to have an objective correspondence between model and modelled object, one which is objective, independent of the subject constructing the model and capable of extensive gradations. (This is the "imageness" of the model—owing to the corre-spondence with the object, the model appears as an image of the object.)

2. The model is capable of serving as a relative substitute for the ob-ject to be cognized.

The model serves as a "quasi-object" relatively independent of the ob-ject to be cognized, which acts as an object of investigation at definite stages of research. Having appeared on the basis of the object which is to be cognized, this "shadow-object" is capable of living a relatively independent life. It does not matter whether the model is composed of cer-tain images of sensory-real nature (e.g., "spinor fluid") or of certain logi-cal structures devoid of sensitivity (e.g., Dirac's delta function).

(This is the "objectness" of the model, i.e., its ability to act as an ob-ject of investigation in which information is obtained mediately concerning the model's original.)

3. In the process of model construction the "imageness" and "object-ness" of the model both appear as traits of two essential stages of this process. The former prevails at the stage of construction of the model, the latter at the stage of investigation of the model.

4. The chief heuristic function of model construction is that the model acts as a means of preliminary explanation of those physical phenomena for which no systematic theory has yet been constructed.

Taking these considerations as our point of departure, we will continue in the following sections to analyze the problems of model construction in the light of the present state of microworld physics.

For an answer to the fundamental question of the present article — the question of the role of models in the formation and development of a theory of elementary particles — it is convenient to begin with a discussion of those basic situations in which the term "model" is employed in modern physics.

First of all, models can be divided into two types depending on their role in the cognitive process. Type I comprises the illustrative-methodological models (e.g., one of the principles of accelerator operation is illustrated by means of such a visual image: the movement of a horse galloping around a circus arena is accelerated by the whip stroke of the trainer standing at a certain point on the arena). Type II comprises heuristic models, which act as a preliminary incomplete form of explanation of new physical phenomena, or as the guiding lines for such explanation. We will be concerned mainly with Type II models as the more important of the two.

It is useful to class heuristic models according to the degree to which they express the nature of the modelled object as p h e n o m e n o l o g i c a l (which describe certain features which characterize h o w the physical process takes place but do not explain w h y they take place in this way) and e s - s e n t i a l (which provide a certain preliminary interpretation of the essence and causes of the physical process).

It is also useful to class models according to the character of the ele- ments which act as object of modelling as l o g i c o - m a t h e m a t i c a l and o n t o l o g i c a l models.

A logico-mathematical model is a system of logico-mathematical ele- ments the structure of which is, to a lesser (phenomenological logico- mathematical models) or greater (essential logico-mathematical models) degree, the analogue of the structure of the physical objects.

Ontological models represent basic conjectures concerning the essential peculiarities of certain spheres of physical reality. Acknowledgment of these peculiarities of real being makes it possible to obtain important theo- retical results (an analysis of such a model will be given below).

One should, in our opinion, regard as phenomenological certain classi- ficatory models which grasp definite truths in the relations between phys- ical objects but are not capable of explaining their essence. Such, for in- stance, is the Gell-Mann — Nishijima classification of elementary particles. It was formulated by Gell-Mann in a report at a conference in Pisa in 1955.

This classification covers definite features of microparticles and of their interrelations. In our opinion, however, what we have here is merely a provisional classification of microparticles. Its value is limited since it is being supported in a situation where the law governing the motion and development of elementary particles is still unknown.

If one desires an analogy one can say that here we have a situation simi- lar to the pre-Mendeleevian attempts to classify the atoms (prior to the dis- covery of the law of periodicity) when chemical elements with similar char- acteristics were classified but no single criterion valid also for elements belonging to different groups and having dissimilar characteristics was known.

Of course, Mendeleev's classification of the atoms took on its finished form only after the establishment of the nuclear charges of atoms, which

was already in the twentieth century. Nevertheless, the classification of microparticles under consideration here differs methodologically from the Mendeleev classification of the atoms in 1869 in three significant points.

1. The classification in question does not advance any fundamental correlation of the periodicity type between the three quantum numbers basic to it and the variations in the properties of the microparticles. Owing to this the particles remain as if in a state of one-dimensional juxtaposition (whereas the Mendeleev classification was two-dimensional — vertical and horizontal).

2. We believe that the classification in question (as opposed to the Mendeleev classification) is of no prognostic value, in the sense that it does not require the existence of new particles in the gaps between existing ones.

3. In our opinion, the incompleteness of this classification is due to the presence, in its foundations, of three bases (quantum numbers) the relation among which is not clarified. This is apparently due to the absence in the modern theory of a reliable criterion of elementarity, which can be discovered only at the same time as the essential particle classification.

(It is well known that the Mendeleev classification made it possible to define the chemical element as the set of atoms occupying a definite position in this classification. A definition of microparticles as objects occupying a definite position in the classification under consideration can scarcely be fundamental.)

In view of all these circumstances one can conclude, in our opinion, that the given classification represents a certain phenomenological model of the real link between particles and their classificatory subdivision.

Phenomenological models can be kinematical, related to the characterization of physical processes without accounting for the specific traits of the forces responsible for these processes. One such model in classical physics was the idea of motion as the displacement of relatively invariable spheres (macrobodies) along grooves (trajectories).

This model is not applicable to microworld physics since the motion of microobjects is considerably more complex.

A characteristic trait of kinematical models is that they consider a type of motion without analyzing the forces and internal particle peculiarities which control the given motion.

Dynamical models which are phenomenological in character and which give a characterization of the internal peculiarities of elementary particles on the basis of more or less visualizable analogies are very widely used. Thus the Dirac theory of the electron used a model representing the electron as a point.

In nonlocal theories the electron is treated as a smeared cloud.

In the trend associated with the works of the de Broglie and Vigier school, an important role is played by the so-called "spinor fluid" of de Broglie. This model "substance" is, of course, considerably less visualizable than Faraday's "incompressible fluid".

However, the nature of models of this kind is identical with that of Maxwell's models, which were constructed by analogy with a certain imaginary but relatively visualizable mechanical system possessed of an independent existence (independent of the subject making the model). In modern views concerning nucleons one finds a certain resemblance with the planetary model (the proton "core" — its central formation — and a certain periphery). This is an example of model construction based on a visualizable analogy.

While noting the well known role of such models we should emphasize that, despite their widespread application, they are of very limited significance in the development of the theory of elementary particles.

They play more a systematizing than a heuristic role. However, in recognizing the limited scope of models of this kind we do not mean to deny them a certain role in the cognitive process, since systematization of the data is a necessary prerequisite for the formulation of the very problem requiring interpretation or explanation.

Let us now turn to an analysis of the prospects for logico-mathematical models in elementary particle research.

Before attempting to consider the role of logico-mathematical models we must answer the following question: in what sense and under what conditions can elements of a mathematical apparatus be regarded as a model in physical cognition?

This problem was already dealt with in a general form by Maxwell. In a work entitled "On Faraday's lines of force", he wrote:

"If one wishes to formulate physical conceptions without adopting a special physical theory one must resort to physical analogies. By physical analogy I mean a similarity which happens to exist between the laws of some two regions of science in virtue of which one forms an illustration of the other. In this sense every application of mathematics to science is based on the correlation between the laws to which physical quantities are subject and mathematical laws, so that the aim of the exact sciences is to reduce the problems of natural philosophy to a determination of quantities through operations on numbers"*.

The first inference we can draw from this quotation is that the mathematical apparatus has one fundamental content-significant condition for model formation — an analogy with the corresponding aspects of the physical processes. True, this analogy is of a special, generalized character. It does not reduce to an element-by-element correspondence between model and modelled object. A special kind of isomorphism is operative here — to certain aspects of the physical process corresponds a mathematical expression taken as a whole, not reducible to its elements. Thus, for instance, the structure of Dirac's equation as a whole is the analogue of certain important aspects of the behavior of the electron; therefore by studying this equation we obtain mediative information concerning the electron. We use the term "logico-mathematical model" to denote the essential difference between mathematical models and symbolic ones. This difference is related to the fact that the mathematical language has its own proper logic which is relatively independent of the logic of the physical process and which therefore renders the physical content indirectly, in its own terms. Symbolic models immediately specify the structure of the object being modelled and have no meaning outside of this structure.

We see that the logical aspect of model construction (analogy, isomorphism) can be generalized, or extended, to the elements of the mathematical apparatus.

The applicability of the term "model" to the mathematical apparatus becomes even more apparent when one analyzes the functional aspect of model construction.

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* M a x w e l l, J. C. Izbrannye sochineniya po teorii elektromagnitnogo polya (Selected Works on the Theory of the Electromagnetic Field), p. 12.

We noted that the essential task of the model is to give a preliminary interpretation of a new phenomenon. From this point of view mathematical formalism can develop up to the creation of a systematic physical theory and the decisive experiment. In this case a mathematical model is constructed of a phenomenon the physical nature of which is still not revealed. The basis for constructing models of this kind is not an analogy between known and unknown but rather the mathematical extrapolation called the method of the "mathematical hypothesis".

The second stage characterizing the provisional mathematical model is related to the fact that mathematical formalism can not only provide a computational procedure for the quantitative study of a phenomenon the qualitative nature of which is still hidden, but also characterize the very qualitative nature of a physical object for which there exists as yet no systematic method of quantitative solution of the corresponding equation. In modern physics, for instance, a certain mathematical feature of the equation, nonlinearity, is regarded as the expression of a fundamental qualitative aspect of the microparticles, their capacity for self-action and action upon themselves.

Here the mathematical formalism covers the substantial nonformal feature of the content of microobjects, but the quantitative methods for solving such equations are still highly unsatisfactory.

A fundamental change is taking place in the role and functions of the mathematical apparatus in the development of modern scientific cognition. The mathematical apparatus is now not only a means of characterizing the q u a n t i t a t i v e aspect of physical processes, it is also, to no lesser degree, a means of characterizing their q u a l i t a t i v e aspect. The mathematical peculiarities of the equations indicate the presence of definite physical prototypes. The physical original can be detected from the mathematical "shades".

This change in the function of mathematical formalism — its ability to characterize not only the quantitative but also the qualitative aspect of microobjects — rests on far-reaching methodological foundations.

It is due to the increased role of the category of relationship in modern cognition (a question we have considered in a work entitled "The Categories of 'Thing' and 'Relationship'" — "O kategoriyakh 'veshch' i 'otnoshenie'")*. If the structure of the relationships (which are devoid of real visualizability) is grasped in the model, then the question as to which elements (ontological or logico-mathematical) reproduce this structure in the model does not play a decisive role.

In the light of these considerations we believe that Niels Bohr's well-known thesis on the "nonmodel" character of the physical interpretation of the mathematical apparatus needs to be corrected**. For the question is that in a number of cases the mathematical apparatus is itself the model of the physical phenomenon and, as was noted earlier, the absence of visualizability does not exclude model character of knowledge.

Two types of phenomenological mathematical models can be distinguished. The first type is a procedure for calculation of a certain physical process such as will lead to agreement with the quantities obtained by experiment. The integral characterization of the physical process from the standpoint

* See "Voprosy filosofii" (Problems of Philosophy), No. 4, 1957.
** See Bohr, Niels, Kvantovaya fizika i filosofiya (Quantum Physics and Philosophy), UFN, Vol. LXVII, No. 1, p. 39, 1959.

of its content is not affected. Here we are dealing with phenomenological logico-mathematical models. To this class of c a l c u l a t i o n m o d e l s belongs the procedure of renormalization, which leads in a purely formal way to agreement between the calculated quantities and the finite quantities obtained from experiment, on the basis of the operation of subtraction of the physically meaningless infinities. This procedure can be regarded as a phenomenological mathematical model of microprocesses, since in this procedure there is an absolutely obvious simplification, the real meaning of which is not clarified (we are referring to the dropping of the terms of the series). Later, in the theory of the scattering matrix, which does not employ the idea of the "bare" particle and associated concept of a vacuum of infinite quantities, an understanding of the essence of the operation of renormalization is developed.

Among phenomenological calculation models are the particular solvable ones.

One example in the theory of elementary particles is the method of model calculation proposed by T. D. Lee in 1954. Characterizing this method, V. G. Solov'ev wrote: "Owing to the major difficulties of principle standing in the way of a solution of the equations of quantum field theory, it is of methodological interest to investigate individual models for which exact solutions of the corresponding equations can be obtained"*.

True, in a definitive work entitled "Introduction to the Theory of Quantized Fields" (Vvedenie v teoriyu kvantovannykh polei) N. N. Bogolyubov and D. V. Shirkov arrive at the conclusion that this method has given no results**.

Among phenomenological logico-mathematical models can also be classed the so-called graphical models which do not claim to explain the physical process but merely give a pictorial scheme of the process which is convenient for carrying out calculations.

An example is the "forks" of Feynman's diagrams, which represent schematically the mechanism of interaction of microparticles.

As we have already noted, the mathematical model of the second type, gives a mathematical interpretation of the process as a whole, not only covering its quantitative relations but also characterizing qualitatively certain important relationships of the given process or phenomenon. Essential mathematical models of this kind are the most important for the development of physical knowledge. They represent the first step toward the creation of a new physical model, which assumes its completed form subsequent to the physical interpretation of the given mathematical model.

Just before the beginning of the present century, it was usual in physics for the proposal of a mathematical formula for a process to coincide in time with its physical interpretation (based on a number of assumptions concerning the content of the very essence of the process). The mathematical formula played on auxiliary role with respect to the physical idea.

Thus in founding the theory of radiation Max Planck, in order to justify the experimental formula, advanced (in very cautious form) the idea of the

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* S o l o v ' e v, V. G. Ob odnoi modeli v kvantovoi teorii polya (Concerning One Model in Quantum Field Theory). DAN, Vol. 108, p. 1041. 1956.
** See B o g o l y u b o v, N. N. and D. V. S h i r k o v. Vvedenie v teoriyu kvantovannykh polei, p. 372. Moscow, 1957 (English translation, "Introduction to the Theory of Quantized Fields". Interscience Publishers, New York and London, 1959).

discontinuity of physical interaction which plays a decisive role in modern physics.

The situation in the case of quantum mechanics was different. Here the fundamental mathematical equations originally played the role of mathematical models, since they appeared either prior to the corresponding physical experiments and ideas (thus, the observation of electron diffraction in experiment occurred somewhat later than the original works of de Broglie and Heisenberg), or in combination with incorrect physical interpretations (e. g., Schroedinger's equation and its original physical interpretation by the author).

The mathematical models of the second type characterize in an indirect way the actual qualitative nature of physical processes. These are the essential mathematical models. Dispersion relations occupy an intermediate position between mathematical models of the first and the second type. Since this schema does not advance any systematic physical explanation for the behavior of elementary particles and since it is still far from finished (it contains much that is provisional), it can be called a model. The intermediate position of this model is due to the fact that, on the one hand, it develops a phenomenological calculation procedure which does not make assumptions concerning new properties of the physical processes, and, on the other hand, such essential physical ideas as relativistic invariance, microcausality and unitarity are mathematically realized in dispersion relations.

N. N. Bogolyubov and his students V. V. Medvedev and M. K. Polivanov emphasize the bond between this mathematical calculation method and the experimental material, noting that this method arose from the study of π-meson scattering on nucleons*. Roughly speaking, dispersion relations connect quantities characterizing particle scattering with quantities characterizing their absorption.

Here, in our opinion, the important element is the well-known generalization of the hermiticity concept. The question raised here is that of the relationship between two parts of the scattering amplitude, the hermitian and antihermitian parts. In the work referred to above, the following definition is given: "Dispersion relations are the relations between the hermitian part of the scattering amplitude and a certain integral over energy of its antihermitian part".

Stressing the very general character of these relations, the authors remark that "the only thing which is important for obtaining them is the requirement of microscopic causality, formulated in most works as the requirement that the commutators of the field quantities tend to zero at spacelike separations"**.

Grave difficulties have yet to be overcome in the development of a theory of dispersion relations. Thus, so far the general system of integral equations which should, according to this theory, characterize microprocesses has not been written down.

In a review article I. E. Tamm notes the phenomenological character of dispersion relations, which stems from the fact that they do not go into the mechanism of elementary physical phenomena (collisions), but admits of the possibility of constructing, on their basis, a unified picture for low

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* See Bogolyubov, N. N., V. V. Medvedev, and M. K. Polivanov. Voprosy teorii dispersionnykh sootnoshenii (Problems of the Theory of Dispersion Relations). Moscow, 1958.
** Ibid., p. 7.

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energies of the order of one billion ev*. However, Tamm stresses justifiably that no success of the theory of dispersion relations, in the present or in the future, will be able to solve the fundamental problem — that of creating an integral physical theory based on a limited number of general principles and postulates.

One could say that in dispersion relations the logico-mathematical model is not supplemented by a new ontological model characterizing new features of physical reality.

We believe that while one may note the limitations of dispersion relations, one can in no case cast doubt on the validity of this procedure.

By using the S-matrix, which connects that which took place before the collision to that which takes place after the collision but by-passes the actual internal mechanism of collision, dispersion relations give, as it were, a physical modification of the cybernetical "black box" model.

Indeed, a process can be represented by the following scheme:

Input	"Black box"	Output
(particles before collision)	(mechanism of collision)	(particles after collision)
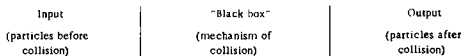
Here we encounter a "cybernetization" of microworld physics. In our opinion, this tendency — provided one recalls its limitations and does not absolutize it — is not only valid but also fruitful, since by exposing the external relationships of microobjects we prepare the ground for the conquest of their internal structure.

The validity of this "cybernetical" approach to microphysics is also justified by a general synthetic tendency in modern scientific cognition, the effect of which is that different sciences equip each other. We will consider this peculiar feature of the development of microphysics in greater detail in the following section.

A mathematical result very often leads to a subsequently proposed physical consequence (which serves as the physical interpretation of the mathematical model) in the form of an integral physical theory.

Thus the presence of positive and negative solutions in Dirac's equation seemed highly unexpected. It was even concluded that the equation was incorrect. Subsequently, however, a physical interpretation of this mathematical result was advanced in the form of one of the most brilliant hypotheses in the history of physics, one which was to have tremendous prognostic value — the idea that to each particle corresponds an antiparticle.

In modern physics the dialectical path of logical cognition from abstract to concrete is frequently manifested as the path from an abstract mathematical model to the physical theory which gives a concrete interpretation of this model and expresses, in the language of physics, the essence of the process hitherto hidden in the peculiarities of the mathematical model. Analysis of this path will be of decisive importance in any consideration of the role of model construction in the future development of the cognition of elementary particles.

* See Tamm, I. E. Sovremennoe sostoyanie problemy elementarnykh chastits (Present State of the Problem of Elementary Particles). Vestnik AN SSSR, No. 10, p. 21, 1960.

It is now universally acknowledged that the present situation in the cognition of elementary particles is characterized by three circumstances.

1. A considerable amount of experimental material which does not lead to explicit contradiction with the existing theory has accumulated. This circumstance, which is specific to elementary particle physics, was emphasized by M. A. Markov.

2. Nevertheless, the fact that the existing theory is unsatisfactory is universally recognized, inasmuch as there is no sufficiently well-founded method of solving the equations which follow from this theory (even the existence of such a solution has not been proved).

3. Another defect of the existing theory is that the particle spectra cannot be obtained from it, i.e., to use I. S. Shapiro's happy expression, it is impossible to bring about a situation where the particles would be the "product" of the theory rather than its "raw material".

This inability to derive the characteristics of the particles from the existing theory is manifested graphically in the lack of a reliable criterion of elementarity. In an attempt to elucidate the general character of the situation in elementary particle research, I. E. Tamm writes: "It is completely obvious that we are now on the eve of a new stage in the development of physics and that the difficulties of principle which come up in the physical theory as man explores the new world of high-energy elementary particles, their interactions and their transmutations will be overcome only on the basis of a revision and generalization of fundamental concepts and ideas; this revision will most probably be no less radical than the one which led to the founding of the theory of relativity and quantum theory at the beginning of the present century"*.

One could say that formally the problem facing microphysics is that of systematizing the entire collection of elementary particles.

In view of this we feel that it would be useful to compare the situation in the case of elementary particles in the nineteen-sixties with the situation in the case of the atoms of chemical elements in the eighteen-sixties.

In the nineteenth as well as in the twentieth century, the problem consists of finding the law relating the objects in a definite sphere of physical reality.

However, the initial data available in the last century on the atoms and those available in the present century on elementary particles are substantially different. In the eighteen-sixties the facts of the transmutations of the atoms of chemical elements was not known. The relationship between atoms was discovered by Mendeleev first and the idea of the transmutation of atoms was subsequently derived from it by indirect means.

The absence of experimental data on the transmutations of atoms impeded the search for a general basis for the classification of the atoms. As a result many schemes covering only the chemical elements in individual groups and not the entire set of known elements were proposed in this period. The fact of the transmutation of elementary particles has not been established experimentally.

This is evidence of the unity of the elementary particles, and therefore methodologically the problem of what to look for can be formulated very clearly—the very fact of the transmutation of elementary particles indicates

the working of a general law relating them to each other and controlling their motion and development.

There can be different concrete approaches to the search for such a law, formulated in an equation.

We believe it would be useful to mention two very important trends in the development of the theory of elementary particles. The first is related to a dynamical, functional, so to speak, "substrateless" (of course, in the sense of the absence of a real substrate, rather than in the sense of a liquidation of any objective substrate) approach to elementary particles.

The basis of this approach is the substrate of objective relationships of the microparticles, and emphasis is laid on investigation of their dynamical properties, i. e., the properties manifested in their interrelations.

The most important problems facing this approach to the microparticles are set forth in a very interesting (methodologically speaking) work by V. B. Berestetskii, "The Dynamical Properties of Elementary Particles and the Theory of the Scattering Matrix" (Dinamicheskie svoistva elementarnykh chastits i teoriya matritsy rasseyaniya)*.

The second approach to the problems of elementary particle theory may be termed the substrate approach. It consists of increasing the complexity of the model of the field as substrate of the microparticles (e. g., by introducing a constant of minimal length) whereas in the former approach an attempt is made to construct a theory of elementary particles which is not based on the concepts of the theory of fields.

In the first approach the model of microparticle interaction is the scattering matrix, i. e., the model here is highly "unpictorial" (it is no fluid — not even a spinor fluid). A set of functions called scattering amplitudes or generalized form factors is used to describe the structure of these interactions.

This approach to the construction of a theory of elementary particles, as well as the second approach, is in the initial stage. As Berestetskii remarked, at present there is no system of equations for determining the scattering amplitudes **.

One could say that both the first and the second approach are at the stage of formulation of the provisional model, which is the first step in the construction of a systematic theory. This circumstance alone already makes it worthwhile to consider these two approaches to microparticles in the light of the problem of model construction.

First of all it should be noted that these approaches do not represent alternatives. On the contrary, they supplement each other: they characterize two distinct but interrelated aspects of the theory of elementary particles. If in the first approach the emphasis is on investigation of external relations between particles, in the second approach an attempt is made to analyze their internal substrate. Both approaches are justified by the experience of the development of physical knowledge.

Thus in the middle of the seventeenth century Hooke and other physicists struggled with the question of the existence (from the standpoint of a real substrate) of gravity. Newton declined to solve this problem but by a stroke of genius disclosed mathematically the structure of the relations operative in the process of gravitation. It is well known that Einstein enlarged our

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* See UFN, Vol. LXXVI, No. 1, 1962.
** Ibid., p. 26.

understanding of these relations but he did not follow Hooke's approach (or substrate approach in our terminology) to gravitation.

Here we must make an important (in our view) terminological point. In the light of dialectical materialism, the limitations of the phenomenological and, so to speak, "essential" approach are not to be regarded as absolute. Absolutization of these limitations is connected with Kant's philosophy, which allows cognition only of phenomena. In neopositivism, which has rejected the rational elements of Kant's teachings and aggravated his subjectivism, the objective existence of "things-in-themselves" is denied in general and, accordingly, phenomenological knowledge is treated as purely subjectivistic — arbitrary in character.

It is common knowledge that such subjectivistic phenomenological attitudes were severely criticized by Lenin, who stressed the dialectical unity of phenomenon and noumenon, manifestation and essence, and demonstrated the inexhaustibility of essence.

If in disclosing the external relations of objects we disregard the nature of their real substrate but do not deny the objective existence of this internal substrate, then we are not admitting any idealism. Furthermore, this approach permits us to rationalize — and accelerate — the process of cognition by supplying us essentially with all the information concerning the cognized object required at the given historical stage of experience. The functional method, by revealing the external functions of a system as being the expression of its objective internal structure, characterizes the concrete mechanism of the dialectical movement of cognition from the external to the internal, or, as Lenin emphasized, the progress of "cognition from external manifestation to substance"*. Therein lies the universality of the functional method.

It is natural for its application to be required in the case of the microparticles.

The functional approach to the theory of elementary particles does not provide, so to speak, "second-rate knowledge"; on the contrary, it is an entirely valid and fruitful, extremely contemporary method of cognizing microprocesses.

This becomes particularly obvious if one applies a slightly old-fashioned term, "the general feature of the spiritual culture of a definite historical stage".

From this standpoint the present era is characterized by development and proliferation of the functional method, inseparably linked to that remarkable event: the appearance of cybernetics.

In our opinion, just as one referred to a "mathematization" of physics at the beginning of the century, we can now speak of a certain "cybernetization" of physics.

Progress in physics is inseparably connected in general with the formalization of physical knowledge. The cybernetization of physics, which clears the way for its further mathematization, can be regarded as a regular stage in this general process.

The "black box" model associated with the functional method of cybernetics may play a certain role in the physics of microparticles. .

Indeed, in the theory of the scattering matrix (which is not based on the apparatus of the theory of fields), as was remarked earlier, the internal

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* L e n i n, V. I. Sochineniya (Collected Works), Vol. 38, p. 148.

mechanism of a system of interacting elementary particles can be regarded as a "black box", the "input" and "output" of which represent the dynamical properties of the elementary particles. For example, the scheme of crossing symmetry called "tetrode" can be interpreted as a form of the cybernetic "black box" model with "input" and "output" (see Figure)*.

While characterizing the substrate approach to the theory of elementary particles we noted that a particularly interesting method was, so to speak, the constant method, i.e., the introduction of a new constant which would make it possible to overcome the difficulties in the existing theory.
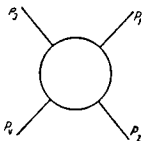
In connection with our theme a certain amount of attention should be devoted to analysis of this method, which provides a manifestation of the essential role of models in the development of physical knowledge.

In the preceding section we spoke of the so-called ontological models associated with conjectures concerning the structure of being. We will now dwell in greater detail on these models in connection with the prospects for elementary particle research.

Certain important features of the construction of models of this type can be discerned by analyzing models of discontinuous space in the microworld.

In 1947 H. Snyder advanced the idea that the coordinates can assume only a discrete series of values (continuous variation of the coordinates is now allowed in physics) whereas time changes continuously.

The idea of space quantization was advanced in the thirties by W. Heisenberg. At that time, however, it had to be dropped, since it would have led to violation of the isotropy of space**. Snyder proved that discontinuity can remain associated with isotropy of space.

The impossibility of simultaneous exact measurement of the coordinates and momentum in the microworld, it is well known, is related to the non-commutativity of the corresponding operators:

$$\hat{P}\hat{X} - \hat{X}\hat{P} = -i\hbar.$$

Snyder suggested that it was also impossible simultaneously to measure exactly all three coordinates, i.e., he effected, as it were, a generalization of non-commutativity: $\hat{X}\hat{Y} - \hat{Y}\hat{X} = -il_0$, where l_0 is the constant of fundamental length.

I. S. Shapiro notes that there is a peculiar modification of nonlocal theory, since the point spreads, and it cannot be localized.

Snyder's fairly drastic assumption did not make a strong impression in physics as it was not clear whether the possibility existed or not of utilizing this assumption in overcoming the difficulties of the theory.

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* See Beretetskii, V. B. Dinamicheskie svoistva elementarnykh chastits i teoriya matritsy rasseyaniya (The Dynamical Properties of Elementary Particles and the Theory of the Scattering Matrix). UFN, Vol. LXXVI, No. 1, p. 36. 1962.

** Here we evidently face an important feature of the cognitive process which involves its consistency: in physical theory it is unthinkable to doubt the universality of certain most fundamental features of space, at least until such time as all ways of overcoming the difficulties while recognizing the universality of these fundamental traits have been exhausted. Extrapolating into the future, from general- logical considerations one cannot completely exclude the possibility that limitations will be discovered in certain of these features of space.

In 1959 the Canadian scientist H. R. Coish proposed that space is not only discrete but is also composed of a finite number of points[*]. This model aroused considerable interest; the divergences could be eliminated on its basis and, moreover, new symmetry properties could be obtained. A significant contribution to the development of this model was made by I. S. Shapiro[**].

From our standpoint it is interesting to conduct a philosophical analysis of the argument in favor of the model of discontinuous space, such as is contained in V. G. Kadyshevskii's "On a Theory of Discrete Space-Time" (K teorii diskretnogo prostranstva-vremeni)[***].

Kadyshevskii uses both physical (discovery of the peculiarity of weak interactions with respect to parity nonconservation) and logical (analysis of the constants to "universality") considerations to justify the assumption of the quantized character of four-dimensional space with a unit of length l_0. Having correctly (in our opinion) noted the universal dialectic of "losses and the compensations for these losses" in the process of cognition, Kadyshevskii applies this general-methodological proposition to the situation in field theory. Indeed, the newly introduced constants give us new information on physical reality but in this process something of the previous physical information is lost. Thus the introduction of the constant c in the theory of relativity "compensates" for the loss of the invariance of distances and time intervals under coordinate transformations which had been accepted in classical physics. The introduction of the constant h compensates for the loss of the possibility of simultaneous exact measurement of the coordinate and momentum of a particle.

We can draw the following inference: if in physics one discovers a limitation on some proposition and part of the previous information is lost, then this situation deserves a search for the "constancy", i. e., the question arises, is there some constant, responsible for this loss of information, which is now to "compensate" for this loss by providing new information concerning physical reality?

In recent years a limitation was discovered by Lee and Yang in one of the fundamental assumptions of physics, the law of parity conservation. Kadyshevskii suggests that the constant l_0 is meant to compensate for parity conservation in weak interactions. Indeed, for $l_0 \to 0$ and $G \to 0$ (i.e., weak interactions are excluded) it has been established very exactly that the law of parity conservation is obeyed in strong and electromagnetic interactions. Kadyshevskii notes that since the "range" of strong and electromagnetic interactions is far greater than the "range" of weak interactions, the degree of parity nonconservation in these interactions is very small and they appear as "classical" interactions in relation to weak interactions[****]. Here the correspondence principle, which indicates limiting passages between physical theories and is of great heuristic force, is introduced.

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[*] See Coish, H. R. Elementary Particles in a Finite World Geometry. Physical Review. Vol. 114, p. 383. 1959.

[**] See in the present book, Shapiro, I. S. "Space-Time Quantization in Elementary Particle Theory", pp. 118-126.

[***] See DAN, Vol. 136, No. 1, 1961.

[****] See DAN, Vol. 136, No. 1, p. 70.

This example illustrates the considerable value and even advantages of negative information*. If it is established that mass is not invariable with increasing velocity, then the classical principle of constancy of mass is treated as a very small change of mass at small velocities (compared with c); if parity conservation is established at intervals of l_n, then parity conservation in strong and electromagnetic ("classical") interactions can be treated as a very small nonconservation of parity at very large intervals (compared with l_0).

Further, starting from the methodological proposition that all world constants are universal, Kadyshevskii analyzes the constants of field theory for "universality".

Such constants as the electric charge, the coupling constant of strong interactions and the particle mass are obviously not universal. As to Fermi's constant G for weak interactions $(G = 1.4 \cdot 10^{-49} \, \mathrm{erg} \cdot \mathrm{cm})$, it is universal in character, since the intensity of weak interactions (if there is no contribution from other forms of interaction) is the same for all particles, and, as emphasized by Kadyshevskii, all particles other than the photon have weak interactions. Eliminating the factors h and c from the constant G, we obtain $l_0 = 7 \cdot 10^{-17} \, \mathrm{cm}$. If one is to analyze this trend in the theory of elementary particles from general-methodological standpoints one must stress the admissibility of this approach.

First of all, this trend is clearly very closely related to certain fundamental facts of microworld physics. Thus, of all the possible types of weak interaction of elementary particles only one type is observed in nature, precisely the one realized in the space of the Coish-Shapiro model. In this process Landau's combined inversion is necessarily valid. Further, since weak interactions are responsible for all decays of elementary particles, one can assume that they are indeed the microcorpuscular forces which guarantee the integrity of elementary particles, i.e., (so to speak) those "which are operative in the particle". The idea of the discontinuity of space, which acknowledges the fundamental character of Fermi's constant, may help disclose the nature of these microcorpuscular forces and may help in setting up the equation for this force-field, the quanta of which may be the hypothetical intermediate vector bosons. Of considerable methodological significance for the justification of such an approach is the actual character of the logic apparent in the development of physical knowledge. Here we have in mind, in particular, the sequence of physical knowledge — movement in the same direction as long as the intellectual potentials of the ideas basic to the given stage of physics have not been exhausted. In this light it is natural to move from the idea of the quantized character of interaction to the idea of the quantized character of space. Furthermore, from the general-philosophical proposition regarding the unity of matter and its attribute, space, one can even acknowledge that the quantized character of material substance inevitably implies the quantized character of its attribute, space. One can say that in models of this kind there is an extension of the idea of quantization to the space-time region.

Naturally, the fate of this model will depend ultimately not on these general considerations but on how successfully it will be able to overcome the

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* We have already noted that the utilization of negative information is a characteristic trait of human consciousness (see the collection entitled "Kibernetika na sluzhbu kommunizmu" (Cybernetics in the Service of Communism), p. 46, Moscow, 1961.

difficulties which arise in the way. Thus, to use Shapiro's words, this trend has so far failed to give us the dynamics of the process. Obviously, the field equation should coincide with the equation of motion under the influence of the forces of this field. This trend also faces methodological difficulties stemming from the problem of the relationship between the finite and the infinite. Shapiro believes that the solution here may be the conception of a world so arranged that the infinite set of its elements is collected in periodically repeated complexes each of which has a finite number of elements. Perhaps such separation of the finite and the infinite provides merely a provisional interpretation of this complex methodological problem.

However, this can in no way be construed as a reproach to the Coish-Shapiro model, since it is advanced for the solution of purely concrete problems. Precisely the same situation prevails at the present stage of development of field theory in connection with the neglect of gravitation, which is, of course, temporary. What is operative here is the regularity of development of physical knowledge described by S. I. Vavilov in connection with an analysis of Newton's work. "Many stages in the history of science", wrote Vavilov, "were accompanied by conscious disregard, for a certain time, of groups of facts and entire regions of phenomena which tended to complicate the problem"*.

It is surely important for the purposes of our article to consider the question of whether or not one is justified in using the term "model" in relation to logical constructions of this kind. For an answer let us analyze the logical structure of such constructions.

First of all, we see that, formally, in such constructions the physical object is "chosen" to fit certain mathematical requirements; it is as if one were seeking that physical object which would satisfy these requirements (in the given case this is obviously the elimination of the infinite number of equations in the system). Here we see the growing role of mathematical "requirement", which characterizes a peculiar form of ascent from the abstract to the concrete — the path from realization of a mathematical requirement to reproduction of physical reality in thought.

Mathematical requirement is surely not subjectivistically arbitrary. On the contrary, it is the objective expression of the newest physical problems and of those real contradictions (e. g., infinity) which arise in the existing theory.

Essentially, in logical constructions of this kind, instead of the sphere of physical reality known today, which has definite properties, we place a different presumed sphere of physical reality with other properties. We see that a peculiar form of substitution function, characteristic of model formation, is operative here. This is the first basis for believing that in logical constructions of this type we are dealing with a model.

The second basis for using the term "model" in relation to these logical constructions is their unquestionable tentativeness, a trait which we regard as the fundamental feature of model construction. These hypothetical constructions represent a certain provisional point of departure for the formulation of one of the possible programs for overcoming the difficulties in elementary particle research and building a systematic theory of this sphere of physical reality.

* Vavilov, S. I. Isaak N'yuton (Isaac Newton), p. 58, Moscow. 1945.

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Evaluating the trend associated with the development of Coish's model, I. E. Tamm writes: "This, however, is not a theory; it is merely the rough draft of a possible approach to the construction of the theory, one, it is true, which completely satisfies Niels Bohr's requirement with regard to degree of 'craziness' "[*].

Obviously, the question here is one of seeking a radical solution—a jump in physical cognition. Originally, of course, this search is not supported by the full weight of argumentation. However, the argumentation may be found in a later stage of development of the theory, provided a systematic theory can in general be constructed on the basis of the given model.

Here we encounter a property of human awareness mentioned by Marx, the ability to penetrate into the upper stories of the edifice of scientific theory even before its foundations have been laid.

"Unlike other architects", wrote Marx, "science not only draws castles in the air but even erects individual habitable stories of the building before laying its foundations"[**].

The point of departure (however "crazy" it might appear) should be obtained eventually from the theory, when the latter has attained maturity, as an argumented result; only then will the theory take on a closed form. Thus if one speaks here of "craziness", one implies, so to speak, a "rational craziness". The "craziness" of logical constructions of this kind resides in a radical break with familiar ideas (the classical example being Planck's quanta).

The rationality of such a construction, on the other hand, consists of two things; first, in the subsequent development of the theory it is systematically justified; second, it is advanced not by a purely arbitrary, statistical, so to speak "mechanical" sifting of hypotheses but on the grounds that it meets certain objective conditions. We feel that it would be useful to formulate the four basic conditions for the selection of models of this kind (ontological according to our classification).

1. A radical ontological model is not proposed arbitrarily; it must meet a definite rationally realized requirement.

In the case of the Coish-Shapiro model this requirement is obviously that it overcomes the infinity in the system of equations which prevents formulation of consistent methods of solving it. In modern physics mathematical "necessity" is assuming the role of an important theoretical factor with an influence on the logic of physical cognition.

2. The radical idea underlying such a model should be necessary and sufficient to overcome the difficulties of the theory. Thus Snyder's model is obviously insufficient, since by itself the assumption that space is quantized does not provide the opportunities furnished by the more radical assumptions of Coish's model. Heisenberg's indefinite metric is likewise, to use Bohr's expression, "not crazy enough". It is very important to note that the assumptions of the initial ontological model should not be "too strong"; this means that the models should not skip over less radical possibilities not yet investigated. Only that part of the earlier information which can no longer be preserved should be repudiated. One can say that the requirement of unitarity and completeness of the physical

* T a m m, I. E. Sovremennoe sostoyanie problemy elementarnykh chastits (Present State of the Problem of Elementary Particles). Vestnik AN SSSR, No. 10, p. 21, 1960.
** K a r l M a r x. K kritike politicheskoi ekonomii (A Critique of Political Economy). p. 46, Moscow, 1953.

theory is valid also for the actual process of searching for a systematic theory; this means that o n e m u s t e x p l o r e i n d i f f e r e n t d i r e c - t i o n s.

Here, of course, no universal recipe can be given. In the last analysis the true model will be that on the basis of which one can build a systematic theory i n c o n f o r m i t y w i t h t h e e x p e r i m e n t a l d a t a.

3. For the development of a radical model it is necessary that the amount of information acquired on its basis be greater than the amount of informa- tion lost as a result of assuming this model. From this standpoint it should be noted that Heisenberg's idea of a unified ψ-field fails, perhaps, to satis- fy this condition inasmuch as it precludes application of the renormalization procedure for removing the infinities but does not provide any alternative; this is obviously the chief difficulty in this approach to the theory of elemen- tary particles.

4. As we noted earlier, the question of what can be repudiated and what assumptions introduced in the initial model must always be solved concrete- ly, in each real situation. However, the entire experience of cognition shows that mystical assumptions, i.e., assumptions concerning transcendental fac- tors inaccessible in principle to reason should not be introduced. Empha- sizing this correctly, J. von Neumann wrote: "There is no doubt that any special phase of any conceivable form of behavior can be described 'com- pletely and unambiguously' in words. This description may be lengthy, but it is always possible. To deny it would amount to adhering to a form of logi- cal mysticism which is surely far from most of us"*.

A characteristic feature of the physical (ontological) model is its organic bond with the corresponding mathematical model.

A mathematical model is a provisional form of radical replacement of the existing mathematical apparatus by an essentially new one.

By a mathematical model is understood new mathematical tools with new structural features, often involving rejection of the "usual" mathematical axioms. Here one must distinguish between generalization of the mathe- matical object itself (the "mathematical thing", so to speak) and general- ization of the axiomatics (relationships of the mathematical objects). The former consists of, say, passage from a constant quantity to a variable one, from it to a function, from a function to a functional. The latter consists of, say, transition to non-Euclidian geometries, transition to a mathematical model in which the operation of multiplication is noncommutative.

The mathematical model of nonrelativistic quantum mechanics is com- posed of two elements — linear operators (new "mathematical things") and the idea of noncommutativity (new mathematical relations). The mathe- matical model used in the Coish-Shapiro approach is substantially differ- ent — here continuous integrals are employed, instead of linear operators owing to the nonsmoothness of the functions and the necessity of dealing with a certain region rather than a point.

It is very important to stress that the essential structural features of the mathematical model are analogues of definite aspects of the physical model, which grasps the nature of a definite sphere of physical reality. Owing to this circumstance it is possible to draw conclusions concerning the physical model from the mathematical model. While objectively the

* v o n N e u m a n n, J. The General and Logical Theory of Automata, in: The World of Mathematics, By James R. Newman. Vol. 4, p. 2070.

content of the scheme of physical knowledge is: physical reality—physical model—mathematical model, in scientific cognition, formally, development proceeds in the opposite direction: from mathematical model to physical model and from there to physical reality. Of course, a "topsy-turvy situation" is not specific only to physics; it is inherent in general in logical cognition, which ascends from the abstract to the concrete on the basis of forms of logical content. The content-significance of a mathematical model resides in the fact that even prior to the construction of a clear-cut physical theory certain important aspects of physical reality are expressed in the corresponding mathematical structures. Moreover, the absence of an adequate mathematical expression for a given physical principle makes it difficult to operate with the latter. Thus in modern physics and in particular in dispersion relations, the mathematical expression for microcausality has been established, but the principle of macrocausality has no corresponding mathematical expression; therefore at present one cannot show in the language of mathematics what violation of the principle of macrocausality means. The following examples will suffice to show the mutual correspondence between the structural features of the mathematical apparatus and definite traits of physical reality. Thus, the utilization of Dirac's delta function is closely connected with the model of the point electron, the non-linearity of the equations expresses the capacity of physical objects for self-action and so on.

Further, speaking of the content-significance of mathematical models in modern physics, it should be noted that an increasingly large role is being played by mathematical criteria through which a certain amount of indirect support can be obtained for theoretical hypotheses prior to decisive experimental verification. An example of such an indirect criterion is the uniqueness of the mathematical approach ("uniqueness of solution", to use Einstein's expression), the uniqueness of the mathematical model, which follows from the given theoretical hypothesis. In justifying the approach used to develop Coish's model (which assumes a finite number of points in the world), I. S. Shapiro uses this criterion as an argument in favor of his theoretical constructions, and stresses that the given mathematical apparatus is closely connected with the model. In general the criterion of uniqueness of this particular approach plays a certain methodological role in the development of physics.

In 1856 in a work entitled "Faraday's Lines of Force" J. C. Maxwell had the perspicacity to write: "A mature theory in which physical facts are physically explained will be constructed by someone who, by questioning nature itself, will succeed in finding the only true solution to the problems raised by mathematical theory"*.

We see that in noting the importance of the "problems raised by mathematical theory" Maxwell emphasized the fact that their only true solution could be found only by "questioning nature itself".

It is obvious that the decisive and highest way to "question nature" is experiment. There can be no doubt that for a decisive verification of any theory one must explore beyond its confines and turn to the actual real being. However, even the most abstract and mathematized theory queries nature, using, so long as the decisive e x p e r i m e n t u m   c r u c i s has not been carried out, such auxiliary criteria of truth as uniqueness of solution and logical noncontradiction.

* M a x w e l l, J. C. Izbrannye sochineniya po teorii elektromagnitnogo polya (Selected Works on the Theory of the Electromagnetic Field), p. 17.

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This statement of the problem, while casting no doubt on the decisive role of experiment in the development of physical knowledge, stresses the high degree of liveliness of physical theory itself, which cannot wait passively until the accelerators, having attained considerably higher energies than today, "make everything clear".

In this context it should, we feel, be emphasized that the development and refinement of the structural elements of the mathematical language and the identification of their assumed physical "prototype" constitute one of the important tasks of modern physics. This task is particularly important in view of the fact that, while previously physics could select its mathematical tools from the realm of pure mathematics (thus at the beginning of the twentieth century the theory of relativity made use of tensor calculus, proposed by the mathematician Levi-Civita in the last third of the nineteenth century), the present stage of physics is characterized by a refinement of the mathematical language stemming directly from the problems involved in developing physical theory and accompanying this development. Examples are the idea of noncommutativity in quantum mechanics, negative probabilities in Heisenberg's unified field theory, etc.

Of course, the prospects for the application of advances in pure mathematics, assuming their physical interpretation, are high. This is shown, for instance, in I. A. Akchurin's article in the present collection with regard to the Bourbaki many-dimensional "kernel space".

The diversity of structures in the mathematical apparatus of modern physics should in our view allow us to raise the question of the diversity of the logical structures; for, as noted earlier, the language of mathematics is not a conventional, purely symbolic system: it has its own relatively independent logic.

We feel that it is admissible to suppose that the peculiar character of the microworld can be expressed in peculiar formal-logical models, connected by a limiting transition based on the correspondence principle to ordinary two-valued formal logic. This approach conforms to the general methodological idea of regarding logical forms as content-significant.

A. A. Zinov'ev has this to say concerning the problem of the universality of logic: "Finally, from the material considered in the present work it follows that the laws of two-valued logic are not refuted by the laws of many-valued logic, nor are the laws of the latter refuted by the laws of the former. Therefore to interpret the nonuniversality of the laws of logic as a division of the world into spheres, in some of which certain logical laws hold true while in others they are repudiated would be to commit the grossest of errors"[*].

Obviously, the correspondence principle is not sufficiently taken into account in the above quotation. Euclidian geometry, for example, does not contradict Lobachevskii's geometry but is a limiting case of the latter; yet one of its axioms (the axiom concerning parallels) is the negation of the corresponding axiom in Lobachevskii's geometry. In any case we feel that one cannot agree with Zinov'ev when he writes: "owing to the ambiguity of the actual concepts of universality and nonuniversality, the categorical character of pronouncements on this question is dubious"[**]. We feel

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[*] Zinov'ev, A. A. Filosofskie problemy mnogoznachnoi logiki (Philosophical Problems of Many-Valued Logic), pp. 101-102. Moscow. 1960.

[**] Ibid., p. 101.

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that it would be appropriate to discuss the question of the possibility of devising logical models for the sphere of elementary particles with axioms different from the axioms of ordinary "macroscopic" formal logic. Let us examine from this point of view the fact of K-meson decay which is so fundamental for the physics of the microworld and, in particular, for an understanding of weak interactions.

In this decay one obtains equations the left-hand sides of which contain equal objects (K^0-mesons), and the right-hand sides unequal objects. Apparently the axiom that two quantities separately equal to a third (or to two equal quantities) are equal to each other does not hold true in this case. If this is so, then the mathematical apparatus which rests on this logical calculus will have fundamental peculiarities. Possibly in such a mathematical apparatus the commutative law of addition will not hold true, and, therefore, the result of addition will depend on the order of the addends. One cannot exclude the possibility of a definite connection here with the "crazy" feature of the Coish-Shapiro model, which is apparently conditioned by the fundamentality of weak interactions to the elementary particle world. This feature is that, in a space with a finite number of elements having the properties of a group, the sum of two positive quantities is often negative. Further, if one takes virtual processes into consideration then in a single particle a multiplicity of others can be found. Apparently, the question "what consists of what?" is either meaningless for the elementary particle world in general or, at least, has a substantially different meaning. The specific character of this sphere of physical reality is so essential that in it the relationship between the part and the whole which holds in the macroworld is transformed in such a way that the fundamental formal-logical axiom — "Whatever includes the including includes also the included" — underlying the entire syllogistics loses its validity.

From this approach to an analysis of these two examples taken from modern microphysics one can infer, we believe, that the problem of the peculiarity of logical calculus in the sphere of elementary particles requires discussion. It is completely obvious that such logical systems generalize, rather than negate, ordinary formal logic.

The visualizability of the model is closely related to the nature of the language of science. Surely this language is not something self-contained (as claimed by the partisans of semantic philosophy), nor is it an "independent substance".

In order to be adequate for the cognized objects, the language of science must develop in conformity with the specific character of the given sphere of reality. Such a content-oriented approach to the language of science brings out its dependence on physical reality and provides the key to understanding the character of its development. We saw from the preceding discussion that one of the important functions of the model in microworld physics is expressed by the following thesis: with the help of models we translate nonclassical phenomena into the language of classical physics. Many authors derive the necessity for using models from the fact that, in the last analysis, the language of classical physics cannot be separated from the scientific picture of the world. That it cannot be "separated" is often attributed to the macroscopic nature of man. Indeed, human sensitivity is macroscopic and, of course, theoretical thinking cannot be isolated from sensitivity. However, the idea that the language of science is inseparably macroscopic tends toward a certain absolutization of the role of sensitivity

in the cognitive process. As we see it, such an idea is, in sum, a modern version of the common illusion which derives various forms of limitation on cognition from the finite possibilities of the sense organs of finite man.

Yet for the mind all layers of reality, from the ultramacroscopic to the submicroscopic, are equivalent. To set the macroscopic scale aside as an absolute frame of reference for the cognitive process is one of the illusions of anthropocentrism. In our opinion there is nothing unnatural in discussing the possibility of the emergence of physical language beyond the confines of Newtonian concepts.

In the evolution of modern physical theory, the phenomenon is first described in mathematical language and then this description is translated into physical language. This is the essence of the method of the mathematical model, or method of mathematical extrapolation. A characteristic feature of this fundamental methodological procedure, in its present concrete-historical treatment, is the fact that mathematical models can be exceptionally diverse but they must, in the last analysis, permit translation to only one classical physical language. If we assume that the peculiarities of elementary particles are related to the regularities of the submicroworld, then we can suppose that a description of elementary particles, before being interpreted in the language of classical physics, will require a preliminary intermediate translation into the language of "ordinary" quantum-mechanical concepts, which describe phenomena on the atomic scale. Independently of whether or not the "final language" of the physical interpretation is classical, it can be inferred from the correspondence principle (the universality of which is determined by the most fundamental of the peculiarities of being) that in any case a translation will be required of the description of elementary particles into the physical language of phenomena on the atomic scale. This translation becomes all the more necessary if the language of the physics of phenomena on the atomic scale takes on a "classical" role.

We can conclude that the final, or classical, language may change with the progress of physics, but the actual qualitative infinity of matter and the actual structure of the cognitive process (seen as the progressive conquest of objective reality by the mind) determine the necessity for "translations" from the language of one layer of reality to that of another. This, in our view, is the essence of the process of mediation in scientific cognition. Logical model construction will play an important part in the development of this process in the future as well. Logical (mathematical) models are free from sensory visualizability, are exceptionally flexible and therefore adapted to this kind of translation. Stages characterized by drastic changes in physical ideas are associated with the construction of models of this kind.

The devising of such a radical natural-scientific model should, of course, be based on certain ontological parameters. Such parameters include the idea of the materiality of the world, which precludes mystical assumptions, and the generalized principle of causality (in the sense of a general interaction rather than a temporary dynamical or statistical relationship between two events). However, increase of the number of such ontological parameters is a dangerous illusion which can delay the development of science. An example of the danger involved is provided by the situation in physics in the late nineteenth—early twentieth century when a rigid coupling of the rational materialistic interpretation of the world and the idea of the

indivisibility of the atom led to grave delusions. Gauss's elegant aphorism plays an exceptional role in the methodology of the development of scientific knowledge: "We must not confuse that which seems to us unnatural with that which is absolutely impossible".

A contemporary example of the delaying influence on science of the absolutization of certain seemingly universal propositions is provided by the situation in the theory of weak interactions before Lee and Yang's discovery. In characterizing this situation Ya. A. Smorodinskii wrote that Wu's experiments could have been carried out considerably earlier had physicists not been convinced that parity nonconservation could not occur in nature.

Obviously, philosophical research cannot prescribe ready solutions for natural science, it can only draw the attention of natural-scientific thinking to certain possibilities in the development of physical cognition. This general consideration, of course, requires further elaboration. However, even in this general formulation one can draw an important methodological conclusion from it. So long as the decisive experiment has not been carried out, one must explore in different directions and not absolutize any single trend of thought. In constructing a set of alternatives a certain part may also be played by philosophical analysis, provided, of course, that it acknowledges the progressive character of scientific development and does not limit itself to a futile return to familiar conceptions. It is important to note that the further development of microworld physics will not be of the order of a simple return to visualizable classical ideas. Thus in one of the most interesting contemporary trends in elementary particle theory, the trend associated with Regge poles (in this country this trend is being cultivated by V. N. Gribov and I. Ya. Pomeranchuk), comparatively simple dependences are obtained in the nonrelativistic theory for the scattering amplitude at high energies. Regge poles are moving poles of the scattering amplitude as functions of the angular momentum (with the condition that nonintegral values of the angular momentum also be taken into account). However, the utilization of a dependence on angular momentum, which is a classical quantity, does not make the Regge pole model classical. Thus in a work entitled "Fermionic Regge Poles and the Asymptotic Behavior of Meson-Nucleon Large-Angle Scattering (Fermionnye polyusa Redzhe i asimptotika rasseyaniya mezonov na nuklonakh na bol'shie ugly) Gribov stresses that: "In this process the asymptotic behavior of scattering, especially in the region of small angles, is comparatively simple, although it has no simple classical description" (our emphasis –I. N.)*.

The ability to explore in different directions, as we remarked earlier, embodies a general trait of the creative activity of human consciousness, to which the idea of passively waiting until high-energy accelerators reveal the secrets of elementary particles in the collision of opposing beams is foreign. By this we do not wish to denigrate the role of experiment but merely to stress the active role of theoretical methods, among which logico-mathematical and ontologico-physical models are of considerable significance.

From our discussion we can conclude that the rising abstraction of physical knowledge and the decline in the element of visualizability by no means

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* ZhETF, Vol. 43, No. 4(10), p. 1329, 1962.

imply the negation of the role of models in its development. On the contrary, the concept of model has become generalized. The model, revealing itself as a form of provisional interpretation of new data, becomes a natural stage on the road to the development of a systematic physical theory, including the theory of elementary particles. This road to cognition is highly characteristic of modern physics — new facts, their dynamical and mathematical expression in a model, and, finally, physical interpretation of the mathematical model in a systematic theory. The proposition of a mathematical model prior to its physical understanding is becoming an increasingly active regularity in the development of modern physics. It would be wrong to regard model knowledge as second-rate knowledge operating (to use U. Ashby's expression) with half-truths, or as a kind of "quasi-knowledge" or (this is R. Braithwaite's expression) "a s - i f thinking"*. Such an approach is a modern form of the gnoseological illusion of common sense, connected in the old philosophy with the division of knowledge into "dark" and "light" and carried to its logical conclusion in the ideas of one modern philosopher who has steadily defended for ten years the thesis that a column is "nevertheless more objective" than its shadow.

The view that it is meaningless in general to speak of models in connection with explanation (which is how, for example, H. Gronewald of Groningen University states the problem in his work "Models in Physics")** is, in our opinion, unfounded.

There are no grounds for denying the heuristic role of the model as a provisional form of scientific explanation which prepares the ground for a systematic theory.

To understand the peculiar character of modern scientific knowledge it is very important to note the widespread use (both in physics and in other sciences) of the following path of theoretical research: from empirical data to logico-mathematical and ontological models, and from these to a systematic theory of the given sphere of existence.

The material presented in this work enables us to conclude that the mathematical apparatus and the physical concepts and ideas are not the only ones to be subjected to generalization in contemporary physics. Also generalized in modern physics are the actual concept of scientific explanation, the methods of research and, in particular, the method of model construction.

The possibility cannot be excluded that the so-called "crazy idea" radically transforms our logical apparatus (perhaps even to a greater degree than our ideas concerning the world).

Figuratively speaking, one might say that the problem lies (possibly) not so much in formulating the "crazy" idea in reasonable language as in "going crazy", thereby radically changing our very conception of the structure of scientific knowledge. An example in favor of this possibility is the fundamental increase in the role of functional knowledge now noticeable in all sciences.

The possibility of a radical revision of the foundations of the logical language has a certain basis in the experience of the history of physics. L. Boltzmann, for instance, noting that "inefficacy of thought habits" is common, admits of the possibility of a change in the laws of thinking***.

* Braithwaite, R. Scientific Explanation. p. 93. Cambridge. 1953.
** See Synthèse, Vol. XII, No. 2/3. 1960.
*** See Boltzmann, L. Ocherki metodologii fiziki (Essays on Methodology of Physics), pp. 121, 124. Moscow. 1929.

And, finally, in view of the general-methodological idea of the unity of the logical and the ontological, it is natural that the generalization of the concepts which constitute physical knowledge be supplemented by generalization of the methods and tools by which this knowledge is attained.

Thus, when discussing the prospects for the development of microphysics, in addition to the two traditional possibilities (refinement of the mathematical tools of the existing theory and advancement of a radically new physical idea) it is useful (in our opinion) to consider a third possibility involving change in the actual methodological structure of knowledge. It should be noted that, in conformity with these new tendencies, which stem from the growing problem of logical language, the forms of dogmatism are also modified. If at the beginning of the century dogmatism was associated predominantly with ontological consideration ("the atom is indivisible"), in our epoch dogmatism is becoming increasingly prominent in the methodological sphere. Such dogmatism is less concerned with what a scientific result represents but is capable of casting doubt on this result on the grounds that it was obtained "not according to the rules".

One can still encounter statements claiming that really logical discussions must necessarily have the form $S \to P$ and casting doubt on the logic of relations with the formula aRb. In our opinion absolutization of causal relations to the detriment of functional relations can also be a considerable hindrance to the development of physics. And there can be no doubt now as to the harmfulness of illusions according to which the abandonment of visualizability (in the sense of ordinary sensory representation of phenomena) is merely a passing episodic "fluctuation" which will be followed by a "sound and completely visualizable equilibrium" in future physics.

We believe that the tendency of the increase in abstraction of physical knowledge, its mathematization and its cybernetization will grow. In view of this one can conclude that abstract-logical model construction is one of the most contemporary and clear-cut manifestations of the liveliness of human consciousness.

In the theory of elementary particles as it is forming today scientific cognition is becoming less and less visualizable as it encounters the mass of "remarkable" peculiarities of real objects. Their expression will require increasingly roundabout and abstract logical tools and procedures, among which abstract models are, we believe, destined to play a growing role.

THE THEORY OF ELEMENTARY PARTICLES AND INFORMATION THEORY

I. A. Akchurin

Today the greatest physicists of our times acknowledge that the creation of the general theory of elementary particles will involve taking a new step the like of which has been seen only three or four times in the history of the "leader of natural science". Moreover, this step will apparently rival in significance those we now associate with the names of Galileo and Newton, Faraday and Maxwell, Lorentz and Einstein, Planck and Bohr, Schroedinger, Heisenberg, Dirac and other founders of quantum theory. That the understanding and explanation of the very general (and yet highly specific) regularities of the behavior of elementary particles will require the creation of an essentially new theory distinct from quantum mechanics or relativity is a truth which, on the whole, is widely acknowledged. Somewhat fewer, but still the majority of scientists believe that modern quantum theory is satisfactory only for physical processes at comparatively low energies — approximately up to one billion electron volts (10^9 ev). Let us recall that the so-called extensive air showers in cosmic radiation are due to particles with energies of 10^{17}–10^{20} ev. On the basis of the reports and discussions at the celebrated Rochester conferences, one may claim that scientific "public opinion" is more or less unanimous in conceding that a theoretical interpretation of the highly unusual and "strange" regularities of the elementary particle world will have to await a new, far more general theory, in which quantum mechanics, the theory of relativity and quantum field theory will merely appear as particular limiting cases.

Whenever this future theory — which is yet to be created — is mentioned, it is Niels Bohr's words concerning the "crazy" idea which, like a flash of lightning, is to illuminate the way to the new theory, that are most often quoted. In these few words is evidently formulated a very interesting and effective heuristic principle. Sometimes, however, they are interpreted at a fairly limited level, namely as the requirement that certain completely extraordinary, in a certain sense utterly "wild" equations of motion of the primitive physical objects be written down.

One point which is somehow lost sight of in this process is that equations of motion — or any equations at all — represent merely a part of any physical theory: a very important one, a very significant one, but nonetheless merely a part of every, even profoundly "mathematized" branch of modern theoretical physics. A no less important part is made up of the fundamental concepts and theoretical ideas of the physical theory: the exact categories which characterize the primitive physical objects and their state of motion and are susceptible of mathematical formalization; the completely definite and univocal scheme of interrelation between these fundamental concepts; their correlation with the old concepts of earlier physical theories, and, finally, with experiment.

Judging by Bohr's last articles and especially by his lectures at the Moscow State University in 1961, he seemed to believe that the most difficult and complex problem in constructing a new physical theory was precisely the devising of a system of fundamentally new, logically consistent ideas, coupled with an objective structure of reciprocal subordination and correlation with experiment. Indeed, Bohr's own scientific results furnish ample cause for reflection on this topic. For he, as is well known, wrote no such relations and equations as perpetually preserve the fame of their authors, obtained no exact solutions and formulas such as are to be found in the manuals next to the appropriate names. His contribution was far more important, immeasurably more difficult. Under his, and, possibly, Max Born's guidance, a brilliant school of young physicists of various nationalities evolved a logically consistent system of concepts capable of expressing the most amazing and intricate peculiarities of the behavior of intra-atomic particles. And if today we have mastered the secrets of atomic and thermonuclear energy, can create substances with required properties and are close to disentangling the physicochemistry of living beings, then this is in no little measure due to the scientist who, by his own account, never feared to refer to himself before his own pupils as a man incapable of comprehending in its entirety the multifarious and inexhaustible character of the phenomena of nature.

Of course, it must be stated clearly that in solving all these highly intricate problems, the great Danish scientist often, too often, formulated his thoughts in such a way as to enable idealists of all shades to clutch at them and interpret them for their own ends.

But while criticizing these errors we must always bear in mind Lenin's remark that "modern physics... is moving toward the only true method and the only true philosophy of science not directly but by zigzags, not consciously but spontaneously, not with the 'ultimate aim' clearly in view but groping toward it..."[*]

Precisely these words, spoken over half a century ago, should determine our attitude to the great Danish scientist. While persistently and consistently criticizing Bohr's idealistic statements — particularly those belonging to the era of the thirties — we have a very great deal to learn from him. First and foremost we can learn to adopt a very serious, fundamental attitude to questions of methodology, to questions relating to the formation of new ideas adequate to experiment and of a logically consistent system of such ideas. Naturally, equations and abstract symbolic relations in general will play a very important role in any future theory, but completely new ideas — concerning the state of motion of physical objects, the reasons for changes in this state — will play just as great a role. The formation of such ideas, as the experience of building the theory of relativity and quantum mechanics shows, is a very tedious, intricate and even worrisome business. Of course, it must not be imagined that these new ideas and new characterizations of the state of physical objects at the elementary particle level will be worked out first, and that the corresponding equations of motion will be written down later. The history of quantum theory shows that the formation of the new ideas which expressed adequately and profoundly the regularities of the behavior of intra-atomic particles was closely interconnected with the discovery of those new mathematical objects (Heisenberg's

* Lenin, V.I. Sochinentya (Collected Works), Vol. 14, p. 299.

matrices and Schroedinger's wave functions) which proved capable of quantitatively expressing the new regularities. But now that several different variants of the equations have already been written for "all" elementary particles, it seems imperative to shift the emphasis to the question of the formation of essentially new physical and mathematical ideas, which are bound to be distinct from quantum mechanical ideas and to play a fundamental role in any future theory.

One thing is apparently certain: the formation of the new ideas and superstructures of a general theory of elementary particles is unthinkable without serious discussion of problems relating to the methodology of modern science and to the philosophical interpretation and assimilation of its latest results. Roughly speaking, one might even say that the future theory of elementary particles will consist, as it were, of two parts: very profound philosophical, or methodological, considerations, which will reveal the content, meaning and relationship to experiment of the fundamental ideas of the theory, and further, an entirely new mathematical apparatus (which we will consider in the following section). The development of new ideas is impossible without the most serious and careful consideration of the philosophical questions of science, without solid philosophical grounding on part of the scientists dealing with these problems. The interest of Max Planck, Albert Einstein, Niels Bohr, Erwin Schroedinger, Werner Heisenberg and other great scientists of modern times in the philosophical problematics of their science is in a certain sense purely "utilitarian" — their own practical scientific work has led them to conclude that the formation of the fundamental ideas of any developing theory, as well as the interpretation of their connection with experiment and earlier ideas, are always due, ultimately, to a creative utilization of the secular experience in dealing with highly complex and difficult abstractions which is stored in the most generalized expression of all human culture, philosophy.

In this connection it is very characteristic that in talking about the outstanding contributions of Bohr to the formation of the system of ideas of quantum mechanics, all his students, who later became very great scientists themselves (Heisenberg, Pauli, Rosenfeld et al.), never mentioned the purely "Socratic" method which he employed in his talks on the subject of any scientific work or in connection with any scientific problem.

In our opinion this method of discussion is another manifestation of Bohr's remarkable ability to feel deeply, and communicate to others, the objective dialectics of the phenomena of the atomic and subatomic world.

In this connection it should be stressed that the elementary particle world is already displaying increasingly profound and unusual features of dialectical contradiction (virtual "particles", "vacuum", "strangeness", parity nonconservation, etc.).

The possibility is not excluded — and the history of quantum theory speaks in favor of it — that the theory of elementary particles will be created not by one man but by an entire group of scientists working on the principle of division of labor: some will deal primarily with methodological problems and others with the development of a corresponding mathematical apparatus. The success of this group will depend a great deal on the extent to which its members are familiar not merely with their own "speciality" but also with the limiting branches of science, especially with the two which have long been regarded as bordering upon every branch of human knowledge, namely philosophy and mathematics.

As a very serious methodological problem we suggest studying the experience of collective scientific creation by many eminent scientists working simultaneously; indeed, it is precisely in this way that such great physical theories of the twentieth century as quantum mechanics and quantum field theory were developed. Similarly, entire collectives — and very strong collectives at that, even "constellations" of collectives — were responsible for creating cybernetics and the leading branches of modern mathematics (the methodological seminar in New Mexico and the Bourbaki group, respectively). And it is entirely possible that the last physical theory created, so to speak, to a large degree "personally" will have been Albert Einstein's theory of relativity. Today and in the future — owing to the qualitative jump in the complexity and profundity of human knowledge — every scientist working by himself, however great his capabilities and talents, will be able to develop only a certain fragment of the theory, only certain of its sections. This is why today, in the period immediately preceding the creation of the theory of elementary particles, the slogan of greater union and efficient cooperation among physicists and philosophers assumes very concrete significance and is of considerable practical importance.

However difficult and complicated the work carried out by Bohr in creating quantum theory, someone will have to perform a similar, and apparently even immeasurably more difficult, feat to develop the general theory of elementary particles...

Thus in the previous section we tried to draw a few "methodological lessons" from the experience of creating the most fundamental physical theories of the twentieth century — the theory of relativity and quantum mechanics. We came to the conclusion that in any future theory of elementary particles, and especially in the period of creation and formation of the latter, problems of gnoseological order and very general ontological assumptions regarding attributes and properties of moving matter would play a very important, indeed decisive role.

In the present section we will consider these same "lessons" drawn from earlier fundamental physical theories from the standpoint of foreseeing the mathematical apparatus which will be used in the future general theory of elementary particles. In this connection it should be underlined that the mathematical apparatus of a physical theory — the fundamental mathematical concepts, the system of their mutual subordination, the abstract symbolic relations which express this system, and, finally, the algorithms for transformation of certain symbolic relations into others — all of these things are related in a completely definite manner to the objective content of this theory.

It is no accident that Newton, in order to create general dynamics, had to develop an essentially new branch of mathematical science for its quantitative formulation — differential and integral calculus. In the language of pre-Newtonian mathematics, which was innocent of limiting processes and which utilized exclusively invariant, constant quantities, formulation of the general principles of mechanics would simply have been impossible. In later years, owing to increasing specialization of human knowledge, there was not a single case of the founder of a new physical theory also being the creator of its mathematical apparatus. Division of labor in science and the colossal growth of human knowledge have converted every

more or less serious scientist into a very narrow specialist. But a certain parallelism between the development of physics and that of mathematics has persisted and continues to be manifested even under these conditions.

To formulate the complete system of equations of the electromagnetic field, Maxwell was compelled to use the apparatus of vector analysis and the theory of partial differential equations, the most important sections of which were developed a very short while before the publication of his fundamental "Treatise on Electricity and Magnetism". Tensor calculus in the form of the so-called "absolute differential calculus" was developed by the Italian mathematicians Ricci and Levi-Civita again only a few decades prior to its utilization as the fundamental mathematical apparatus of the general and special theory of relativity.

Even more instructive is the history of the creation of the mathematical apparatus of quantum mechanics — the theory of self-adjoint operators in infinite-dimensional Hilbert spaces. An interest in these so-called Hermitian operators arose at the beginning of the present century, originally in response to purely internal mathematical requirements related to the development of the theory of integral equations and infinite-dimensional matrices. But no more than two decades later these, which had seemed so very abstract and remote from concrete problematics, proved to be absolutely necessary components, or even, one might say, the fundamental building bricks, of the abstract-mathematical models of intra-atomic processes developed in quantum theory.

If we now raise the question of the mathematical apparatus of the future theory of elementary particles, in its most general form the answer will apparently be as follows: this apparatus, in its foundations, will be very closely related to the most important, most fundamental concepts of modern mathematics — category, functor, diagram, abstract measure, algorithm, and so on. It should particularly be emphasized that these concepts will be an essential part of the formulation of the original, most general principles of the theory; they will not simply be used as an auxiliary means to seek the solutions of certain equations, as is the case, for example, in the application of group theory in quantum mechanics.

This answer is, of course, so general as to fail to give any concrete indication as to the path of development of the mathematical apparatus of the future theory of elementary particles. In a later section of the present article we will give more effective criteria for the appropriateness of various concrete mathematical structures as an adequate expression of "strange" and unusual peculiarities in the behavior of elementary particles. But already from the considerations given above, certain perfectly definite conclusions may be drawn concerning the role of modern mathematics in the solution of the central problem of modern physics.

The most important conclusion is that it is necessary for the physicists to make a persistent and systematic study of mathematics, a science which has been progressing at a fantastic pace and has undergone two cardinal changes in the present century. It is well known that the first of these changes was due to the widespread introduction into mathematics of the methods of set theory and group theory and the axiomatic method. The second change, which began after the second world war and has evolved particularly rapidly in the last decade, is usually attributed to the development of cybernetical calculating techniques, on the one hand, and, on the other, to the brilliant work of an international group of young and talented

mathematicians who adopted the pseudonym of Nicolas Bourbaki (so that today many speak of the process of "Bourbakization").

If one examines the scientific works published in any modern physical journal from the standpoint of the mathematical methods they employ, one find that these methods, in the overwhelming majority of cases, go back to nineteenth, or at best, early twentieth century mathematics. Integration over some contour or other in the complex plane, various matrix relations and transformations, formulas from the theory of special functions — this accounts for 90% of the mathematical baggage of any modern theoretical physicist.

The great American mathematician Marshall Stone, author of a monograph fundamental to quantum theory ("Linear Transformations in Hilbert Space"), writes point-blank in his essay on "Mathematics and the Future of Science" that the absence of progress in the theory of elementary particles is due to the fact that modern physicists do not know modern mathematics*. Of course, such a statement is very easy to make for a specialist in mathematics, while for any nonmathematician it is extremely difficult to take even the first steps toward an acquaintance with "Bourbaki mathematics"; still there is obviously a measure of truth in Marshall Stone's words.

Further progress in theoretical physics is clearly unthinkable without a certain "Bourbakization", a "Bourbakization" which will involve its deepest roots and its most fundamental and profound theorems. For if one takes the edifice of the "leader of modern science" as a whole, its most deep-seated base of mathematical concepts consists of the content of the first six chapters of Dirac's well-known "Principles of Quantum Mechanics" (which, as we may note parenthetically, plays the part of Newton's "Origins" in modern physics). Yet these six chapters are nothing but a "physicized" exposition of the axiomatics of Hilbert space, which was introduced over a half-century back, whereas modern mathematics can supply physics with spaces of a far more abstract, "exotic" and even completely "strange" nature.

One should not forget the immense heuristic value which a correctly chosen mathematical apparatus has always had in physics. Indeed, Newton's dynamics is, first and foremost, Newton's equations of motion, just as Maxwell's electrodynamics is, first and foremost, Maxwell's equations. The mathematical apparatus of differential and integral calculus made it possible to formulate such fundamental physical concepts of mechanics as velocity, acceleration, etc., and the apparatus of vector analysis and of the theory of partial differential equations did the same for such fundamental physical concepts of the theory of electricity as the potential or eddy field, ponderomotive forces, etc. It is the heuristic force of the equations which led Newton to discover the law of universal gravitation, and Maxwell to discover the displacement current and to establish the identity of light and electromagnetic oscillations.

The tremendous heuristic role of four-dimensional formalism in the creation of the special theory of relativity and of tensor analysis in the creation of the general theory of relativity is universally known. Matrices and wave functions (as distinct though equivalent representations of "vectors" in infinite-dimensional Hilbert space) were, as is well known, the

* See Matematicheskoe prosveshchenie (Mathematical Education), No. 4, p. 111, 1959.

initial mathematical objects which served as the heuristic foundation for
the formation of all the fundamental physical concepts of quantum theory —
state, observable, etc. It is therefore entirely natural to expect that the
revelation of the most fundamental physical concepts of the future general
theory of elementary particles will take place in very intimate contact with
the revelation of those new and highly abstract mathematical spaces, which
will prove to be the only ones suitable for the construction of adequate
logico-mathematical models of the motion of matter at the elementary par-
ticle level.

Below, at the end of the present article, we will speak in greater detail
about these spaces; here we will confine ourselves to repeating what seems
to us a very likely hypothesis, namely that in the future theory of element-
ary particles the mathematical ideas of the first six chapters of Dirac's
book will be replaced, apparently, by a "physicized" exposition of the axio-
matics of a mathematical space more abstract than Hilbert space, one out
of the vast number introduced in modern mathematics in the last two to
three decades. Of course, this will be possible only if, firstly, one can
cope more or less acceptably with all such spaces, and, secondly, if one
has some criterion on the basis of which to try to adapt certain abstract
mathematical spaces to the description of the motion of matter at the ele-
mentary particle level while rejecting the rest from the very start.

To attempt to propose such a criterion is the main aim of the present
article, one which will be realized in the following sections. Here we
should like simply to adduce yet another argument in favor of the
"Bourbakization" of theoretical physics, namely that the "Bourbakism" is
highly reminiscent of the style of the school of physicists headed by Bohr — the
physicists who founded quantum mechanics and quantum field theory. A
detailed consideration here would take us too far afield (on this subject see
P. R. Halmos's article "Nicolas Bourbaki"*) but we feel that in the whole
of modern science it would be difficult to find a more striking example of
a living, active, constructive (though spontaneous) dialectic, bursting with
creative flights. The "simple" is seen by Bourbaki in terms of the com-
plex — though the most intricate mathematical constructions on "simple"
mathematical spaces — and, conversely, in the complex they see the very
"simple" — for example, they treat all of modern mathematics as an inter-
weaving of a few basic mathematical structures (for greater detail see the
article by the "many-headed" author himself, entitled "The Architecture of
Mathematics"**).

In every mathematical construction these basic structures — algebraic,
topological and ordering — occur in complex, contradictory interaction; the
extent to which algebraic or topological axiomatics are employed in a given
theory determines that qualitative trait which characterizes this division
of mathematics as functional analysis or, say, the abstract theory of meas-
ure. Clearly, progress in science is always most likely along those lines
which use, in their constructions, the mathematical methods most tho-
roughly penetrated by a creative dialectic. The history of the founding of
the most fundamental theories demonstrates this absolutely unequivocally.
The entire problem is, which of the trends in modern mathematics has
most minutely captured the immanent dialectic of the world and of its own

* See Matematicheskoe prosveshchenie. No. 5, p. 229. 1956.
** Ibid., p. 99.

subject. We maintain that the "Bourbakist" trend is the answer. This specific answer may possibly be inaccurate, or even worse, an error. But one cannot evade solving this problem: if it is not pondered over and discussed, the future founders of elementary particle theory will still have to solve it "pragmatically" by choosing the only mathematical objects which can possibly enable the construction of a systematic, logically consistent theory of the "strange" world of interacting leptons, mesons, nucleons and hyperons.

And now, one last remark concerning the role of mathematics in the construction of the future theory of elementary particles, or, more precisely, concerning the role of the foremost mathematicians of our times in this matter. Here the history of science in the preceding half century supplies us again with extremely instructive examples. How much the theory of relativity owes to the participation of great mathematicians of the early twentieth century (such as Hermann Minkowski, Carl Schwarzschild and Hermann Weyl) from the very beginning of its development is common knowledge. Weyl, who was one of the most powerful geometers in the world, interrupted his purely mathematical research for some time and plunged into "pure" theoretical physics to write his world-renowned book "Space-Time-Matter", which within a very short time went into five printings in the German language alone.

The history of the creation of the mathematical apparatus of quantum mechanics is indissolubly linked with other even greater stars and constellations of the mathematical horizon — David Hilbert, John von Neumann, Marshall Stone, and others. Throughout his life that patriarch of the mathematics of the first half of our century, David Hilbert, continuing the tradition of his predecessors, Gauss and Klein, nourished a deep interest in the affairs and problems of his closest "scientific neighbors", the physicists. He was the first in Germany — and one of the first in the world — to grasp and evaluate the importance of theoretical physics as a new science which had detached itself from its parent (physics) only at the close of the previous century. Not only did he grasp and evaluate this event for himself: he created at Göttingen the most favorable conditions for the development of the new science by inviting the greatest theoreticians of the beginning of the century — Born and Sommerfeld, the future teachers of Heisenberg, Pauli, Weisskopf, Jordan, Fermi, Oppenheimer and other great names of mathematics and mathematical physics.

Not only was he ever ready with friendly aid and reassurance, with qualified mathematical advice, with help in solving problems or even with an assistant's post — Hilbert himself was very actively interested in how matters stood in the most fundamental, most "philosophical" sections of physical science. According to Göttingen tradition, he used to begin work at his own seminars with the following sentence: "Now, gentlemen, who will tell me what is an atom?" The stimulating influence of a mathematician of this caliber could not fail to affect the course of theoretical physics in the most fruitful, positive manner.

Also tremendously important for the development of the mathematical apparatus of quantum theory were such books as "Mathematical Foundations of Quantum Mechanics" and "Linear Transformations in Hilbert Space" by the great contemporary mathematicians J. von Neumann and M. Stone, the works of Garret Birkhoff and others.

And now, if from all these facts some conclusion is to be drawn, it is entirely possible (in our opinion) that an adequate theory of elementary particles will not be created before one of the prominent mathematical seminars is opened by roughly the following question: "Who can tell us what is an elementary particle?"...

We fully appreciate that modern mathematicians have more than enough interesting problems of their own to solve, and that for them to take on physics as well would mean their stretching themselves too far and even trying to "envelop the unbounded". Nevertheless it is absolutely imperative to try to combine modern mathematics with the latest experimental material. For it is precisely from such attempts that the most valuable and amazing of the conquests of man's genius were born in the past — conquests which will remain for all time to come in the gold reserve of world science.

However difficult and tedious David Hilbert's mission in the borderline between mathematics and physics may have been in the twenties, someone will have to carry out a similar, apparently even immeasurably more complex mission in our times...

The moment we maintain that the creation of a general theory of elementary particles will necessarily include the utilization of the latest scientific methods developed in the last decades, we cannot afford to overlook cybernetics, the new scientific trend which is triumphantly stepping across the most varied scientific disciplines and, more often than not, over the "blank areas", over "no man's land". From the standpoint expounded above it is completely natural to expect that cybernetics will make very significant contributions to the business of finding new ways of building an adequate theory of elementary particles. In what concrete way is something we shall try to elucidate in this and later sections of the present article.

In our opinion cybernetics should be treated as the general theory of construction of algorithmizable logico-mathematical models of material objects, related in some way or other to the problems of guidance of goal-directed activity. In each subdivision of cybernetics a basic set of structures or operations, which are regarded as elementary, is specified from the very beginning; then one tries to see how an object or guidance system with the specified (required) properties is built or can rationally be built out of these structures or operations.

The simplest is the model constructed in information theory, in which objects are only distinguished, only denoted — binary elements are taken as the basic structures and then a study is made of how, with the help of sets of such binary elements, one could definitively and uniquely characterize numbers, letters, coordinates, words, functions, propositions, functionals, etc. In the theory of programming the model is more complicated; the operations of a given computer (or of some generalized device) are regarded as the elementary structures, and the problem is to express most rationally the solution of a certain mathematical, logical, linguistic or other problem in the form of a sequence of such operations. In automata theory the model is even more complex: a study is made of what combination and mutual subordination of the specified base elements will ensure reliable

operation of an automatic device with required reactions to a "universe" of possible influences from the external world — to a certain set of situations which the automaton can "encounter". The most complex models in cybernetics are now being studied in the theory of games: the "universe" of possible external and internal situations becomes so vast that no way of sorting or listing them exists; therefore only allowed reactions to a certain situation ("input") are specified, and one is required to find the most rational ("profitable") line of behavior ("strategy") which if adopted would allow one to "cope" with any conflicting situation.

The first logico-algorithmic models of certain objects were constructed during the first half of this century in mathematics: the so-called constructive trend set itself the aim of studying how various mathematical theories and structures would change if one were to reject from the start the very general, non-concrete, diffuse idea of infinity as something opposed to everything finite, and introduce in its place a certain more or less real "model" of infinity — the natural series of integral numbers with its recursive definition of the succeeding element in terms of the preceding one. The constructive trend does not permit that the existence of mathematical objects of any kind be simply postulated — it requires that the method of their construction from certain simpler objects, taken to be the basic ones, always be indicated. In this sense it studies the objectively existing structure of different mathematical objects, the real complexity of their construction is a reflection of certain relations of material reality of great moment for modern science and technology.

Cybernetics has begun to build similar "constructive" models of all natural science and, possibly, of all human knowledge as a whole. And although for this reason its level of rigor is far below that accepted in mathematical science, this level exerts a strong disciplinary influence on such sciences as biology, linguistics, learning theory, etc. In our opinion this level will also prove beneficial in determining what meaning can be attributed in modern physics to the concept of "structure" of the elementary particles and what ideas and conceptions must be excluded from such consideration from the very start. Today the concept of structure in mathematics is totally isolated from intuitive spatial conceptions; it is a highly abstract logical construction satisfying a definite system of axioms. Naturally, this construction and these axioms are not arbitrary products of man's mind; they reveal more profound and more significant aspects of mathematico-geometrical relations in the real world, but these aspects and relations are already highly abstract and essentially non-intuitive.

In the present article we will employ the first and simplest (in structural aspect) subdivision of cybernetics, namely information theory, in an attempt to determine a few quantitative criteria by which to distinguish between those highly abstract objects which can be used to create abstract-mathematical models of processes in the elementary particle world and those which cannot. In order to do so we shall have to give a more or less general definition of the amount of information, present certain highly non-rigorous qualitative considerations relating to the so-called information capacity of various mathematical objects, and formulate a certain ontological hypothesis concerning the nature of the different levels of structure of matter.

Earlier we indicated that the amount of information is, figuratively speaking, the number of "very simple building bricks" — binary elements —

which must be "expended" to create the simplest logical model of the object under investigation, a model in which the object and the details of its structure are only distinguished, merely fenced off from everything that is related to them or that exists simultaneously with them.

In the simplest case, where N different objects (digits, letters, etc.) are given and the probabilities p_i for the occurrence of each of these are the same, in order to specify a particular object one must use at least $\log_2 N$ binary elements. This quantity $I = \log_2 N = \log_2 \frac{1}{p_i} = -\log_2 p_i$ — the number of characteristic binary elements — is taken, by definition, as the quantity of information contained in the specification of one of the equally probable symbols.

Thus one must distinguish between the concept of the quantity of information and the concept of information in general.

In the most general form the concept of information should be associated with the philosophical categories of being, possibility and reality. Whenever there exist several different possibilities but only one is truly realized, only one moves into reality, only one assumes an existence, it is meaningful to speak of the information carried by this realized possibility. It is completely obvious that this concept of information is entirely objective and absolutely independent of whether or not some subject will cognize this information. It agrees with the intuitive meaning of the word "information" and is so broad as to include, for example, the idea of "information" which is "conveyed" by a work of art or literature: for the painter or writer has at his disposal an absolutely inconceivable number of possibilities of choosing certain lines, colors, composition, theme, persons, landscape, etc., or words, figures, subjects, characters, etc. But he always chooses completely definite ones — those which express his thought, feelings, and experience most clearly and profoundly.

It is entirely evident, however, that so general a concept of information would remain a simple tautology unless it provided something essentially new relative to the old categories of being, possibility and reality. This new element, first realized in cybernetics, resides in the fact that, in a whole series of cases, one can introduce an exact qualitative characterization of the "complexity" of the information in question — its quantity. When and only when the objective probabilities (they must be objective — otherwise it would be nonsense) of the various possibilities are known, one can, it seems, introduce an absolutely objective measure of the "structural complexity" of the information, related to the measure of the "improbability" that each possibility will be realized. This measure of the "improbability", so it appears, characterizes the quantity of information carried by the occurrence in reality of precisely the given possibility. The more improbable a certain event, the greater the amount of information its realization contains, and, conversely, the occurrence of an event the probability of which is very high carries very little information. (The "structural complexity" of this information, on the other hand, is very low.) The objectivity of concepts relating to the quantity of information and their independence from the subject are guaranteed here by the utilization of only objective probabilities. This very important requirement destroys not only all sorts of idealistic inventions but also, unfortunately, some fairly interesting and highly promising attempts to establish an analogous

quantitative characterization of the information contained in abstract concepts. Every abstract concept surely has a certain objective meaning independent of man, but attempts to evaluate quantitatively the corresponding probabilities, and also to evaluate, in terms of the latter, the quantity of information "accumulated" when this abstract concept is introduced and used, have so far failed to give definite results.

Returning to the general concept of quantity of information, let us stress that its rigorous mathematical definition, the essence of which was set out above in a purely qualitative, descriptive manner, furnishes absolutely no grounds for any subjective loosening of the thought. Just as the Earth and other celestial bodies were in existence millions of years before the appearance of man, so the earth has been accumulating within itself a vast quantity of information concerning its past for many millions of years, while light waves have been bringing a different kind of information from inconceivably remote depths of the universe concerning the composition, structure, motion and evolution of stars, galaxies and other celestial bodies. Man does not create, he merely cognizes this objectively existing information which, taken as a whole, expresses the peculiar and the unique which characterize the being of every single particle of eternally existing and eternally developing matter.

Owing to the comprehensive work of A. N. Kolmogorov and his students on the so-called information capacity of various kinds of abstract mathematical spaces, it is now possible to grasp the fundamental ontological significance of the concept of the quantity of information*. There is apparently every reason to believe that the specific quality and peculiarity of the various levels in the structure of matter are related to the fact that elementary objects belonging to different levels carry appreciably different amounts of information. Indeed, the state of any elementary object of the macroworld (material point, field strength vector at a given point, etc.) can always be specified exhaustively with the help of a certain element of a Euclidian space of given dimensionality. In 1932 the Soviet mathematicians L. S. Pontrjagin and L. G. Shnirel'man obtained a remarkable result which, in modern terms, may be interpreted as the proof that in a Euclidian space of any finite dimensionality the information capacity of any system of points increases no faster than the logarithmic function multiplied by the dimensionality of the space. The information capacity is the maximum amount of information which is given when one specifies a single definite element of a set of points in the given space, separated from each other by a distance not less than a certain pre-assigned one. The argument of the logarithmic function is the inverse of this specified minimum distance between points.

Pontrjagin and Shnirel'man's theorem has an intuitively clear, transparent meaning: if the points are chosen lying no closer than the distance ε from each other, then it is obvious that we can place not more than $\frac{1}{\varepsilon}$ different points on a segment of unit length, and not more than $\frac{1}{\varepsilon^n}$ in a unit cube in a space of dimensionality n. From the definition of the quantity of information, in order to indicate a definite point in the set of $\frac{1}{\varepsilon^n}$ points (with identical probabilities) with the aid of binary elements, one requires

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* See Kolmogorov, A.N. and V.M. Tikhomirov, ε-Entropiya i r-emkost' mnozhestv v funktsional'nykh prostranstvakh (ε-Entropy and ε-Capacity of Sets in Functional Spaces). Uspekhi Matematicheskikh Nauk, Vol. XIV, No. 2, 1959.

at least the quantity of information (number of binary elements) $I = \log_2 \frac{1}{\varepsilon^n} =$ $= n\log_2 \frac{1}{\varepsilon}$, the result presented above in verbal formulation.

Here it is again important to stress that the information capacity is an absolutely objective property of the given space: whatever ε we choose, the capacity increases only in accordance with the above formula. This growth characterizes in a completely definite way the "internal structure" of all Euclidian spaces, a structure which is objective and independent of our awareness. When one moves to other abstract mathematical spaces the information capacity displays a significantly different character of growth. Thus upon transition to the space of analytic functions it begins to grow as a certain power of the logarithm, and for the space of real functions as a certain power of $\frac{1}{\varepsilon}$. When one moves to yet more abstract mathematical spaces — functional spaces — the information capacity grows as the exponent (exponential function) to the base 2 of $\log \frac{1}{\varepsilon}$ or $\frac{1}{\varepsilon}$.

One can see why the specification of a definite point in the space of functions contains far more information than the specification of a point in ordinary Euclidian space from the following highly nonrigorous considerations. Let us count the total "number" of different functions on the segment 0,1 which take on values also in the interval 0,1 — for an accuracy of ε in the specification of the values of the argument and of the function: one point on the segment 0,1 can determine $N = \frac{1}{\varepsilon}$ essentially different functions, two such points can determine $N^2 = \frac{1}{\varepsilon^2}$ different functions, three points $N^3 = \frac{1}{\varepsilon^3}$ different functions and, finally, all $N = \frac{1}{\varepsilon}$ points of the segment 0,1 can determine N^N distinct functions different from each other — if only at one single point (for an n-dimensional space with its $N^n = \frac{1}{\varepsilon^n}$ points, this becomes N^{N^n} functions). Then the specification of a definite function out of this total "number" of functions will contain the amount of information (by definition, will require the number of binary elements) $I = \frac{1}{\varepsilon}\log_2 \frac{1}{\varepsilon}$, a result in which the first factor must be raised to the n-th power for an n-dimensional space. Analogous arguments for the space of functionals — for the space of all kinds of methods of juxtaposing definite (real or complex) numbers to the functions — give a total number of "different" functionals N^{N^N} and, correspondingly, an exponential growth of the quantity of information with decreasing "error" of specification ε. Purely qualitatively, from the standpoint of tabulation of the functions and functionals, this growth of the quantity of information can be understood to mean that a completely definite function (or functional) is specified not only by its value at a certain point but also by the values of the coefficients of its Taylor series expansion at this point (or by the values of the functional derivatives of the functional at this point). This explains why restriction of the class of admissible functions or functionals by requirements of definite "smoothness" (for example, representability in power series — analyticity) reduces the quantity of information contained in the indication of a definite element of the space of analytic functions or of functions satisfying the so-called Lipshitz conditions.

It is well known that the states of elementary objects in the microworld cannot be specified with Euclidian spaces: quantum mechanics characterizes

the state of particles of atomic dimensions by means of a certain element of the space of functions — a "vector" in the Hilbert space of square-integrable functions. For individual localization of the elementary objects of the sub-microworld — the elementary particles — Dirac was obliged to introduce, in the thirties, the so-called delta function, which turned out to be, in the light of the latest post-war researches of Laurent Schwartz and other mathematicians in the Bourbaki group, an element not of the space of functions but rather of the space of more general mathematical objects, the functionals. The work of V. A. Fok in the thirties and the post-war works of the American mathematician K.O. Friedrichs and of N.N. Bogolyubov proved that the construction of a rigorous mathematical theory of elementary particles — theory of quantum fields — as a system with a variable number of particles in different states (and, therefore, with an infinite number of degrees of freedom) is not possible within the framework of Hilbert space alone. Even the simplest problems involving one field already require its expansion to the space of certain functionals (to the space of so-called generalized functions).

Finally, W. Güttinger and N. N. Bogolyubov and his colleagues were able to show that every recent success in the theory of elementary particles — the development of general procedures of renormalization in the quantum theory of fields (the separation of the finite, experimentally observable parts from the divergent integrals) — are due simply to the establishment in the space of generalized functions of a unique operation of division. The question is that in this space, owing to the so-called divisors of zero — arbitrary functions equal to zero at the origin of coordinates, multiplied by the delta functions which are nonzero, by definition, only at the origin — the operation inverse to multiplication becomes unique only owing to additional externally imposed requirements. This is employed in the theory of renormalizations: it is only by virtue of this that the masses, charges, and other characteristics of elementary particles can be made finite and equal to their experimentally observed values.

Thus in modern quantum theory individualization of the elementary particles is achieved only at the cost of exceeding the limits of Hilbert space, by using far more general spaces of functionals. Since the means of mathematical expression of the regularities of a certain fragment of material reality (macroworld, microworld and sub-microworld of elementary particles) reflect certain very abstract but still highly significant aspects and relations objectively valid in the given fragment, it is logical to assume that the elementary objects belonging to different levels of structure of matter accumulate within themselves significantly different quantities of information.

In this highly nontrivial circumstance may be seen yet another form of manifestation of the dialectical regularity which proclaims the union of the qualitative and quantitative definiteness of all objects in the material world and the inevitability of qualitative jumps at the transitions from certain ranges of quantity variation to others. For it is to the different information capacities of elementary objects belonging to different levels in the structure of matter that is due, in our opinion, the specific qualitative character of each such level and the qualitative peculiarity of the behavior of its objects.

At the level of atomic particles, for instance, a characteristic regularity of their motion — wave-particle dualism — is linked, in our view, to the

.following circumstance: quantum-mechanical particles carry, or can accumulate, so much information that when we apply to them macroscopic categories and concepts, which essentially use Euclidian spaces, they may behave both as waves and as corpuscles. In this, we believe, lies the solution to the riddle of the hybrid, or dual, "centaurian" nature of quantum objects.

Thus one should speak not of the indeterminateness, or indefiniteness, of intra-atomic processes but rather of their excessively great, macroscopically incomprehensible "super-definiteness" — to which is due, in our opinion, the marked statisticity of many quantum mechanical regularities. In this view the marked statistical character of many predictions in quantum theory owes its existence to the fact that the detailed behavior of an atomic object is determined by so large a quantity of information that macrodevices are as yet simply incapable of detecting it all.

This is the reason why, in quantum mechanics, we cannot predict what point on the screen a given electron will strike in experiments on diffraction, at what instant in time a given uranium nucleus will decay, and so on. The question of whether one can, in principle, express by means of "Euclidian information capacities" the quantities of information associated, for example, with the Hilbert space of functions — i. e. , the fundamental question in the discussions surrounding quantum mechanics — is thus formulated as a highly complex but more or less clearly stated mathematical problem. Its solution is a far from trivial matter, and for the time being it is not even clear whether the answer will be positive or negative.

From this "information-theoretic" point of view, however, the objectivity of the statistical regularities of quantum theory becomes absolutely explicit and evident: macroinstruments do not create statistics, they merely reveal it. The thermometer, surely, does not create the Maxwellian statistical distribution of the gas molecules over the velocities — it merely reveals a certain averaged characteristic of motion of the molecules, namely their root-mean-square velocity. Similarly, the macroinstrument usually "extracts" so "limited" a quantity of information from the microworld that it is absolutely impossible to determine univocally from this information the future behavior of the microobject — just as it is impossible to determine the individual trajectory of a certain molecule solely from a thermometer.

In this case the uncertainty relation is interpreted as a theoretically and experimentally confirmed principle which indicates the sphere of applicability of macroscopic concepts in the microworld — that is, the region of phenomena within which "macroinformation" concerning a microobject completely determines its behavior. The uncertainty relation provides, as it were, the rules for moving from "microinformation" to "macroinformation" by showing in which cases the former reduces entirely to the latter and in which cases such reduction is impossible in principle, requiring the introduction of the wave function, hermitian operators and other apparatus of quantum mechanics.

Thus we see that the "information-theoretic" approach permits a somewhat novel view of the basic features of the quantum-mechanical form of motion of matter. Still more interesting possibilities are opened up when this approach is applied to the basic and most fundamental ideals of the modern theory of elementary particles — the quantum theory of fields. Above it was pointed out that when we move from quantum-mechanical problems to the problem of the theory of elementary particles, we must somehow

individualize the particle under investigation — either localizing it by means of a delta function, or treating it as a certain state of a system with an infinite number of degrees of freedom (in the method of second quantization), or seeking to account for its individual characteristics (mass, charge, etc.) with the help of the renormalization method. In all these cases we are obliged to exceed the limits of Hilbert space of functions and to introduce as "working mathematical tool" of the theory an abstract space of greater information capacity — the space of functionals. To what methodological conclusions this idea of an increasing information capacity of the deeper levels of structure of matter may lead us will be the subject of the following section of this article, in which the general considerations of earlier sections will be made more concrete with the help of this idea.

Let us now attempt to give some sort of synthesis of the methodological, mathematical and cybernetical considerations advanced above. In earlier sections these considerations were developed more or less thoroughly but always individually. It should be absolutely obvious, however, that it is their joint application which is of the greatest interest; indeed, utilization of a synthesis of all known heuristic ideas usually gives the most rapid and effective means of solving any problem. Surely what we will ultimately obtain here is again certain heuristic ideas, but ideas of a more special form which will very severely limit the paths research can take toward the construction of a general theory of elementary particles.

As point of departure we can take the ontological idea expounded in the preceding section that the information capacity of elementary, or simplest, objects increases as one moves inward through matter — to elementary objects with characteristic dimensions of 10^{-8} or 10^{-13} cm. Qualitative jumps in the ability of material particles to accumulate given (Euclidian, power or exponential) amounts of information occur at precisely such "linear dimensions".

But once the ontological properties of elementary particles are such that their state can be specified only with the help of objects having an exponential increase in information capacity, it is completely useless to try to construct a complete theory of elementary particles solely with wave functions, no matter what their type and no matter how complex the equations they obey. The features peculiar to the behavior of sub-microworld particles are so special that their expression in a unified, systematic and logically consistent theory is possible only by means of mathematical objects capable of accumulating information exponentially — the functionals.

Therefore, in all general theories of elementary particles — whether it be Heisenberg's unified spinor theory or models of the Sakata type (so-called "Nagoya" model, perhaps the most advanced of all contemporary models of the elementary particles) — all wave functions are to be regarded as functionals; functionals, that is, which become of the function type (i. e., reduce to functions) only at large distances (significantly larger than 10^{-13} cm). At distances of the order of 10^{-13} cm representation of general functionals by ordinary functions ceases to be valid, and "strange" and unusual properties of objects of tremendous (exponential) information capacity begin to appear.

One of the most striking manifestations of the increase in the information capacity of elementary objects as one crosses the 10^{-13} cm boundary is the

appearance, at these distances and at energies sufficient for localization of the microparticles in such spatial regions, of a new large group of symmetry properties associated with isotopic spin invariance, conservation or violation of parity and strangeness, "chirality" transformation properties, the Pauli-Gürsey and Salam-Touschek symmetry groups and others. It is well known that the basic difficulty with all the theories of elementary particles that have been proposed so far is the near-impossibility of explaining the appearance of this new and fairly large group of symmetry properties at a definite spatial or energy limit without straining the theory or introducing arbitrary assumptions. With the information-theoretic approach, on the other hand, all these things can be given a fairly natural explanation: a jump in information capacity always involves the appearance of new symmetry groups; indeed, the symmetry groups which appear in the space of functions are qualitatively different from those in Euclidian space — the symmetry groups in the space of functions are all the more likely to be qualitatively special.

From the purely philosophical standpoint the idea of an increase in information capacity "inward" reveals a very interesting connection with a thought expressed by Heisenberg a fairly long time ago, that the peculiar qualitative character of the microworld is due to the fact that new and more special relationships between the categories of possibility and reality are operative in this region. Heisenberg believes that the equations of quantum mechanics are precisely the equations for the different possibilities (characterized by expansion of the wave function in a certain complete set of states). And it is this circumstance which accounts for the radical difference between the quantum equations and the classical equations, which describe real motions.

This more refined relationship between possibility and reality in the microworld has the following interpretation in our view of the variations in information capacity. Every information is related to certain possibilities — the more such possibilities there are, the greater the information contained in the realization of one of these. Naturally, if we speak of a jump in information capacity as one passes over to elementary objects in the microworld, it implies a similar jump in the "amount" of different possibilities of behavior for the microobjects.

This sharp increase in the "number" of different possibilities of behavior is also reflected in the fact that the microworld regularities formulated so far do not provide rules for excluding all possibilities of behavior in the microworld other than the one actually realized; there are so many possibilities that these regularities which are known so far do not allow us, for instance, to calculate what point of the screen a given electron will strike after diffraction, or at what instant in time a given nucleus of uranium will decay.

This probabilistic character of the predictions will apparently persist in all future theories of microphenomena. The question here, as was pointed out very recently by the young Soviet mathematicians R. A. Minlos*, A. G. Kostuychenko and B. S. Mityagin, is that the abstract measure required for every integration cannot be introduced in every mathematical

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* See Minlos, R.A. Obobshchennye sluchainye protsessy i ikh prodolzhenie do mery (Generalized Random Processes and their Continuation to the Measure). Trudy Moskovskogo matematicheskogo obshchestva. Vol. 8. 1959.

space*. In spaces with too rich a variety of possibilities — and a large information capacity — such as the space of functions, it is by no means always possible to introduce the measure of arbitrary sets required for integration and, hence, for the construction of every theory. And, as a rule, this measure proves to be not uniquely defined (as opposed to length, area or volume in Euclidian space) but rather related to a certain probabilistic distribution.

Thanks to the above-mentioned works, for which the latter two researchers were recently awarded the Moscow Mathematical Society prize, one can now systematically construct the entire system of modern quantum theory starting exclusively from the hypothesis that there is a jump-like increase in information capacity of elementary objects as one moves inward through matter. The ideas and works of A. N. Kolmogorov and his students, which were mentioned earlier, constitute the mathematical basis of this hypothesis. And now the works of Minlos, Kostyuchenko and Mityagin make it possible to bridge the gap between these very general, purely mathematical considerations and the constructions of the American theoretical physicist R. P. Feynman, who succeeded in obtaining all the basic results of quantum mechanics and quantum field theory solely from one idea, that in the motion of a physical object from a certain initial state into a certain final one every possible intermediate state makes a certain statistical, probabilistic contribution**.

If we now regard the set of all states of the physical system under investigation as a certain abstract mathematical space, then the statistical weight factor which evaluates the contribution of each intermediate state is none other than a certain probability measure, the only one possible in spaces of the given information capacity. In particular, in quantum electrodynamics a fundamental role is played by the so-called Wiener measure, a certain random distribution similar to the Gaussian one but continued to the measure for any sub-set of the space of functions.

We mention here (for details the reader is referred to the review article by I. M. Gel'fand and A. M. Yaglom and the bibliography given there***) that with Wiener's measure every basic result in modern quantum theory is obtained in the form of so-called functional integrals, i. e., in a closed and compact form, as distinct from, say, the ordinary theory in which the results are obtained as a rule in the form of an expansion in series (perturbation theory), which immediately raises the very difficult problems of the convergence or of the separation of its infinite terms from the finite and experimentally observed parts, and so on.

Minlos' basic result is that a measure in a certain abstract mathematical space can be introduced by continuing a certain random distribution to Wiener's measure only under the condition that this space be a kernel space, i. e., only if any element of this space can be represented in the form of a sum of a certain system of vectors multiplied by certain numbers — functions of an arbitrary element and basis vectors.

* See Kostyuchenko, A.G. and B.S. Mityagin. Polozhitel'no-opredelennye funktsionaly na yadernykh prostranstvakh (Positive-Definite Functionals on Kernel Spaces). Trudy Moskovskogo matematicheskogo obshchestva, Vol. 9, 1960.
** See Feynman, R.P. An Operator Calculus Having Applications in Quantum Electrodynamics. Phys. Rev., 84, 108, 1951; Theory of Positrons, ibid., 76, 749, 1949; Space-Time Approach to Quantum Electrodynamics, ibid., 76, 769, 1949.
*** See Uspekhi Matematicheskikh Nauk, Vol. XI, No. 1, 1956.

Kostyuchenko and Mityagin proved that this property of being a kernel space is very closely related to its information capacity and is operative only for completely definite powers of growth of the quantity of information (with reduction of the "separation" between points carrying this information). Thus, for a very rich "number" of possibilities of behavior of physical objects, even probabilistic evaluations may prove impossible and certain qualitatively new regularities governing the behavior should appear.

In the case of particles of atomic dimensions, the space of particle states is rigorously "kernel", and therefore in the theory of quantum particles only probabilistic evaluations of their behavior are possible. The space of states in second quantized theory (quantum field theory), owing to the fact that the so-called vacuum fluctuations are taken into account, is no longer rigorously kernel but rather "stepwise" kernel.

The problem here is that at sufficiently small distances from a given particle one can have the virtual appearance of a state consisting of the given particle plus a pair of any other particles, or one can even have such states as are not known to us today. Further, the smaller the space interval (and correspondingly the time interval) of interest to us, the greater the masses of the particles which can contribute, and thus the expansion of the state vector of the physical system in a certain system of basis vectors, which account for all intermediate states, ceases to be valid for definite lengths, which means that the corresponding space also ceases to be kernel. In order to make the space of states kernel again, one must, while choosing the basis vectors, take into account the new intermediate states with pairs of virtual particles of large mass — and in this manner this process of stepwise inclusion of the influence of particles of increasingly large mass will continue to infinity.

All of modern quantum field theory is built on this kind of approximation. In ordinary quantum mechanics the space of possible particle states is assumed to be rigorously kernel and a complete set of intermediate states is formed by the states of motion solely of the given particles. In quantum electrodynamics the effects of the virtual states of the electron-positron and photon vacua — the effects of the possible presence in intermediate states of the given particles plus a certain number of photons and electron-positron pairs — are taken into account. In this way it becomes possible to construct a "nearly closed" theory of long-range electromagnetic forces.

So far all attempts to construct a theory of short-range nuclear forces ended in failure for the very reason that we do not as yet know precisely what space of states of strongly-interacting nuclear particles is even approximately kernel — or, roughly speaking, which hyperons and mesons contribute appreciably in the intermediate states and which virtual particles and their pairs can be disregarded.

The most reliable approach in the theory of strong interactions, the one which makes the least number of hypothetical assumptions, is the so-called dispersion relations. The information-theoretic approach emerges increasingly explicitly in their derivation — the double dispersion relations, for instance, have not been given any rigorous proof so far, and heuristic argumentation (of the type presented above) is substituted for proof: in a sum over intermediate states, only the lightest particles can make an appreciable contribution.

Justification of this assumption, in our opinion, will be possible only in a future "complete" theory of elementary particles, which, let us hope, will have roughly the following idealized features. When the study of any completely new physical phenomena and processes involving particles is initiated, certain, so far unknown, characteristics of the latter are measured, and from these characteristics one decides what information capacity and "kernel property" spaces must have if they are to be used in constructing an adequate theory of the given processes and phenomena. In this way one avoids wandering through the nearly inexhaustible supply of abstract spaces in contemporary mathematics — a fate to which are condemned today the many investigations on problems of principle in the so-called abstract theory of fields (starting with the works of Friedrichs, Van Hove, M. Schwartz, and other scientists).

In these investigations it is demonstrated that Hilbert space is not at all "large" enough for the construction of a rigorous mathematical theory of quantized fields and that it should be replaced by some infinite product of Hilbert spaces (i. e., by a certain more general, and possibly even non-kernel space). But what concrete kind of space is required in, say, the theory of nuclear interactions is a question which can be answered only by adducing information-theoretic considerations.

The theory of dispersion relations has already taken this road — it has abandoned attempts to prove rigorously Mandelstam's idea (double dispersion relations) and instead simply postulates a class of functions among which can be sought the solution to the problem of nuclear interactions at low energies, i. e., as its fundamental postulate it has established the requirement that only abstract mathematical spaces of a definite type, and, therefore, of definite information capacity, be used in constructing the theory.

We are convinced that within a very few years this approach will be universally acknowledged as the only possible approach to the construction of a general theory of elementary particles.

THEORETICAL CONFERENCE ON THE PHILOSOPHICAL PROBLEMS OF ELEMENTARY PARTICLE PHYSICS

V.I. Skurlatov

The theoretical conference on the philosophical problems of elementary particle physics, convened by the Scientific Soviet on the complex question "The philosophical problems of modern science", was held on 25-26 April 1962 in Moscow at the Physical Institute of the Academy of Sciences of the USSR im. P.N. Lebedev (FIAN).

Over 250 physicists and philosophers from the leading scientific institutions and universities of eighteen cities took part in the conference.

In the opening address D.I. Blokhintsev (Joint Institute for Nuclear Research, Dubna, OIYaI) noted that the philosophical problems of elementary particle physics were linked indissolubly to basic problems of philosophy. As the classics of Marxism-Leninism point out, materialism assumes a new form with every new success in natural science. The creation of quantum physics was a very great success of science, one which revealed extraordinary aspects of matter and disclosed the dialectical character of microphenomena. To this day, scientific materialism continues to assimilate and interpret new situations, enriching and developing its own bases. On the other hand, further advances into the interior of matter and in elementary particles have raised substantial difficulties the overcoming of which will require a further "dialectization" of physics. Therefore, not only is dialectical materialism in its creative form capable of acting as a source of new physical ideas and concepts, but one ought to regard it as a special "compass" for physics. If physics "gives birth to dialectical materialism", then dialectical materialism, in turn, should assist in the birth of new physical theories. Blokhintsev stressed that at the present time further progress, philosophical or physical, was impossible without intimate creative cooperation between physics and philosophy.

The conference heard reports by Blokhintsev, M.E. Omel'yanovskii (Philosophical Institute of the Academy of Sciences of the USSR, IFAN), V.B. Berestetskii (FIAN), V.Ya. Fainberg (FIAN), I.V. Kuznetsov (IFAN), A.A. Sokolov (Moscow State University, MGU), A.A. Tyapkin (OIYaI), Ya. P. Terletskii (MGU), N.F. Ovchinnikov (IFAN), I.S. Shapiro (FIAN), and Yu. V. Sachkov (IFAN). The articles written by the speakers for the present book develop the basic ideas of these reports. The discussion centered about the most important methodological problems of modern theoretical physics, among which were wave-particle dualism, the problems of the structure of elementary particles and the connection between the infinitely small and the infinitely large.

It is entirely admissible that the fundamental conception of wave-particle dualism in "old" quantum mechanics will be subjected to re-interpretation

on the threshold of the creation of the newer and deeper theory. By itself quantum mechanics cannot explain why in particular wave-particle dualism exists, and why microparticles appear as discontinuous and finite (corpuscle) and as continuous and infinite (wave) in macroexperiments. Furthermore, other "paradoxes" of quantum mechanics are associated with the wave-particle dualism — the identity of microparticles of one kind, the uncertainty relation, etc. Every one of these "paradoxes" merely indicates the unusual character of the conclusions which follow from the quantum-mechanical formalism.

The fact of wave-particle dualism led to the creation by Bohr of the idea of complementarity. In this idea Bohr allowed for the complementary aspect of the mutually exclusive characteristics of microobjects. The debate surrounding the idea of complementarity is largely due to the fact that it was used in positivistic philosophy.

It is natural that the development of the physics of the microworld and of the theory of elementary particles should have required that the limits of quantum mechanics be exceeded. Formal subjective "solution" of the "paradoxes" had become a hindrance. It is not without reason that de Broglie and Heisenberg transferred the problematics of the "paradoxes" to the "ontological" plane when they encountered the necessity of devising new ideas for the creation of a unified theory of elementary particles.

One promising direction in physics consists of recognizing the inseparable link between the infinitely small and the infinitely large. In de Broglie's "causal" interpretation of quantum mechanics this link is guaranteed essentially by "hidden parameters" owing to which the microobject is instantaneously informed of changes in the surrounding world. In his nonlinear spinor theory of matter Heisenberg arrives at this link indirectly from the "world equation". In an article entitled "Remarks on Einstein's program for a unified field theory", in the chapter on "Relationship to problems of cosmology", he writes that "in the nonlinear spinor theory fields cannot be treated without taking cosmological problems into consideration... a local system cannot be separated completely from the entire world ... Even when the fundamental field equation is relatively simple — and this is assumed in the nonlinear spinor theory — the ground state from which the elementary particles appear upon application of the field operators need not at all be simple. This ground state cannot be designated simply as a vacuum and cannot be assigned all the invariance properties which the field equation possesses. This ground state is not a vacuum but rather a world"*. No less radical attempts to account for the connection between the infinitely small and the infinitely large have been made in the investigations of other physicists. This question is one of the most urgent ones in modern science. It is therefore natural for it to have occupied a fitting position in the conference talks.

Below we will give a summary of the talks in "chronological" order.

The first to speak was B. Ya. Pakhomov (Biisk). He expressed the opinion that one could scarcely embrace the entire microparticle world in a single formula, since microparticles were internally "inhomogeneous" and qualitatively different from one another.

* See the collection entitled: "Einstein and the Development of Physico-Mathematical Thinking". Moscow, pp. 67-68. 1962.

A. I. Uemov's (Ivanovo) talk was devoted to the role of analogy in the construction of the theory of elementary particles. Uemov noted in particular that physicists would become convinced of the practical significance of philosophy only when it played a part not only in analysis and generalization of known results but also in the actual process of obtaining results and in determining the direction and methods of research. While previously philosophers were chiefly concerned with seeking examples to illustrate various propositions of dialectical materialism and rejecting theories which seemed at first glance to contradict these premises, today the focus is on utilization of philosophical knowledge in the development of the natural sciences. In view of this, problems of logic, such as the problem of analogy, have become incorporated as an organic part in the philosophy of natural science.

As recently stressed by Oppenheimer, analogy is a necessary tool of all scientific cognition. Here by analogy is understood a taking over of relations from one system of objects to another. Thus, analogy was repeatedly exploited in the reports. For example, M. E. Omel'yanovskii mentioned the analogy between the elementary particle and the universe. V. Ya. Fainberg proposed that the possibility of taking over given problems of physics to other regions of cognition (e. g., Bohr's taking over of the idea of complementarity from physics to biology, psychology and other sciences) be used as a criterion of their philosophical nature.

Not all analogies are adopted, however. Sometimes one analogy is refuted by means of another. The saying "comparison is no proof" is well known. Sometimes opponents of a certain analogy call this saying to witness. But on the spot they advance another analogy, in the firm conviction that it is valid and even demonstrable.

A final estimation of the value of a given analogy can be given, of course, only by experience. However, the determination of a logical criterion for analogies would be very useful in solving the problem of which analogies are to be preferred irrespective of any subjective predispositions. The establishment of such a criterion in modern logic would involve certain ideas concerning the isomorphism of relations.

Uemov proposed a scheme for proof by analogy, with the help of which he showed that there was no analogy between such different levels of structure of matter as atoms and elementary particles.

In his talk G. B. Zhdanov (FIAN) engaged in a polemic with V. Ya. Fainberg concerning the relationship between the random and the necessary. The well known thesis of dialectical materialism — "chance is a form of manifestation of necessity" — implies that the dynamical regularities of the macroworld are not a random expression of the regularities of the microworld. It is evident from the very fact that averaging of chance at the macroworld level yields certain regularities and a univocal necessity, that the chance which is manifested at lower levels is a definite form of necessity. It is different from dynamical regularity, but still a form of necessity. Thus the growing role of statistical regularities in elementary particle physics, and, possibly, in the deeper physical theories yet to come, cannot serve as a basis for Fainberg's thesis that "necessity is a form of manifestation of chance".

I. S. Alekseev's (MGU) talk was devoted to the question of the part and the whole and their relationship in the microworld. If the atom consists of other objects, namely elementary particles (the whole is greater than

the part), then elementary particles consist of elementary particles (the part is equal to the whole). This fact reflects the specific character of elementary particle physics. Alekseev singled out two trends in the theory of elementary particles. The first, starting from the transmutability of elementary particles, seeks their internal structure in the internal structure of an "original mother", the excited states of which are particles. The second trend is phenomenological, and draws away from structural levels deeper than the elementary particles. The speaker remarked in this connection that even if more profound levels do exist, they might occur beyond the limits which can be reached with the aid of elementary particles. To emphasize the reality of this peculiar "boundary of cognition", Alekseev recalled D. I. Blokhintsev's idea that in the interaction of two very energetic particles it was possible to have the formation of galaxies, supergalaxies, and so on. Therefore the universal constant c implies, apparently, that when the speed of a particle approaches infinity, i. e., when the particle energy tends to infinity, the particle, as it were, "draws along" the entire universe. Hence it seems unlikely that elementary particle research at increasingly higher energies would eventually lead to the discovery of a more profound level of matter, a level of "subelementary particles". At the same time the only means of cognizing an elementary particle is by the action upon it of another elementary particle. But there seems to be no way out at the present time from the vicious circle of transmutability and mutual compositeness. Alekseev expressed the opinion that this circle is due to the position of the macroscopic subject in the objective world and to the active nature of man's expression of reality. In the last analysis the speaker did not propose any hypothesis concerning the conquest of the "boundary of cognition". He noted merely that the difficulties stemmed from the unity of the elementary particle and the universe.

In his talk A. L. Serdyukov (Moscow) stated that an erroneous interpretation of the essence of wave-particle dualism had supposedly become widespread in the philosophical literature; while previously one frequently encountered claims that the particle can change into a wave and the wave into a particle, now one encountered claims that microobjects were neither particles nor waves but a dialectical union of wave and particles, which represent polar opposites. Serdyukov's main argument was as follows: in physics by the word "wave" is meant not a certain material formation but a form of motion. Obviously, a form of motion cannot in any way change into a particle of matter, and a particle of matter cannot change into a form of motion. Hence it is evident that the "dialectical synthesis" of "wave" (continuous) and "particle" (discontinuous) as polar opposites is erroneous. In Serdyukov's opinion, dialectical union is actually valid in wave-particle dualism in the sense that the wave and the particle represent form and content.

Serdyukov's assertion was subjected to criticism by the very next speaker, L. A. Glebov (Institute of History of Natural Sciences and Technology, AN SSSR), in the beginning of his talk. No physicist and no philosopher says that the particle changes into a wave and the wave into a particle. It is also very naive to treat the wave as form and the particle as content. In reality wave-particle dualism implies that, depending on macroconditions, an elementary object manifests itself in certain cases as a wave and in others as a particle.

Glebov dwelt on certain methodological problems of physics. He remarked that the classification of physical theories as phenomenological (descriptive) and true (explanatory) was a relative one, since one and the same theory may be descriptive in relation to certain phenomena and explanatory in relation to others. For example, Kepler's laws are explained by Newton's theory, but Newton's theory taken as whole is descriptive.

Next Glebov dealt with the correspondence principle. He stressed that the correspondence principle was determined by the material unity of the world and that it expressed the necessary connection between the scientific theories which describe increasingly profound levels of matter. However, in Glebov's opinion, the correspondence principle cannot be absolutized, since the case where two different theories give identical results in a certain region is possible.

Glebov made some remarks concerning the principle of complementarity. According to the idea of complementarity, one can study the physico-chemical structure of the organism in biology, but then its vital activity is destroyed and in principle it is impossible to learn how the life process takes place in reality. However, when I. P. Pavlov suggested applying the conditioned reflex in biology, he provided the biologists with an apparatus which, without involving the fundamental functions of the organism, made it possible to advance very far into the essence of biological phenomena. In precisely the same way, one can "circumvent" the principle of complementarity in physics with the help of theoretical thinking, bold mathematical hypotheses and so on.

In conclusion Glebov indicated that the new "crazy" theory would have to explain not only new phenomena, but also, and chiefly, to shed an entirely new light on old phenomena. Thus, Ptolemy's world system described the astronomical phenomena then known, with the aid, however, of a large number of artificial constructions inserted in the theory. In this respect it is reminiscent of the modern theory of elementary particles. Copernicus' world system, on the other hand, explained the same phenomena from a unified point of view, simplifying the picture by means of the "crazy" idea that the earth revolves around the sun. It is possible that the future theory of elementary particles will follow the Copernican trail. But that which, at first, will seem "crazy" in this theory will eventually become as natural as the idea of the earth's revolution around the sun has become in our times.

V. I. Skurlatov's (IFAN) talk centered about the question of infinity. Two and a half millennia ago Zeno of Elea asked: "Will Achilles overtake the Tortoise?" and answered that he would not overtake it if space and time were infinitely divisible. Zeno's argument concerning the impossibility of a counted, finite infinity is irrefutable to this day. For example, in modern mathematics Cantor's infinite series of transfinite ordinals contains difficulties of the same nature as Zeno's infinite number series. The difficulties of modern physics are also related in the last analysis to infinity.

Particular attention in solving the problems of the infinite should be paid to the philosophy of Democritus, which contains a conceptual apparatus which resolves Zeno's "arguments" of the infinite. Democritus regarded the cosmos as a single organic whole, indissolubly linked to every one of its parts, to every "atom". He believed that every atom "feels" instantly the entire cosmos, just as man in his being, in his imagination, instantly embraces the entire world and is therefore a "microcosm". Figuratively speaking, "to destroy" a single atom means to destroy the entire universe.

The unity of the "atom" and "cosmos", of the infinitely small and the infinitely large, is becoming increasingly important in modern science.

In this connection Skurlatov examined at some length the mathematical formalism of quantum mechanics, which, apparently, points to the integrity of the quantum-mechanical description of the universe. It cannot be ruled out that this mathematical formalism, which leads to "non-force" instantaneous interactions, can be endowed with physical content by introducing an "internal" space-time of elementary particles.

In conclusion Skurlatov dwelled upon the problem of the "boundary of cognition" raised by I.S. Alekseev. It is possible that we, as material objects in our own ordinary space-time, can physically penetrate neither into the interior of the "atom", i.e., of elementary particles, nor beyond the limits of the "cosmos", i.e., the metagalaxy. In order to do this we may have to change our present space-time structure. But one thing is certain: the world is not exhausted by the "atom" and the "cosmos". Even if we succeed in creating a unified theory of the "atom" and the "cosmos", we may ask: from where will we deduce the constants and specific relations of our "universal equation"? This question necessarily requires further cognition of the world.

The next speaker, I. P. Bazarov (MGU), claimed that the dialectical materialistic idea of the contradictory nature of motion, evolved following Hegel, by Engels, overcame Zeno's arguments and showed that a body occurred at a given place with a certain probability and simultaneously at a different place with another probability, i.e., the state of motion of the body should be determined by the wave function. Quantum mechanics, having overcome the restricted mechanistic conception of motion in a trajectory in classical mechanics, confirmed the dialectical trajectoryless character of motion and the spontaneous probabilistic behavior of individual microparticles, which is not to be "explained" by force fields, quantum fluctuations or other "hidden" causes.

The contradictory nature of motion is also expressed in the fact that at a given instant a moving body occurs and does not occur at the very same place, i.e., it, as it were, "glances into the future", which exercises a "non-force" influence on its present. In the opinion of the speaker, this influence is expressed in physics in the impossibility of representing the motion of a microobject in isolation from other bodies (means of observation), which leads to wave-particle dualism and so forth. The influence of the future on the present is also necessarily responsible for the probabilistic behavior of the microobject.

In conclusion Bazarov indicated that the non-force influence of the future on the present, which is an expression of the contradictory nature of motion, made it possible to remove the well-known difficulties with the principle of causality in quantum mechanics, disclose the "rational kernel" in Bohr's principle of complementarity, solve easily the Einstein-Podolsky-Rosen paradox and evaluate existing interpretations of quantum mechanics.

The main ideas in R. A. Aronov's (Kishinev) talk will be found in his contribution to the present collection.

In a second talk G. B. Zhdanov considered the relationship between chance and necessity in the microworld and indicated that there was no reason to seek to reduce the statistical laws of quantum mechanics to dynamical laws, since negation of chance contradicted dialectical materialism and led to fatalism.

In the beginning of his talk M. F. Shirokov (MGU) expressed surprise at the fact that debate continues around many problems of modern physics which seemed completely solved, with such eminent scientists as Einstein and de Broglie taking part. Yet, in Shirokov's opinion, there is nothing to discuss, everything is clear. For example, it is clear that the statistical character of quantum mechanics refers to the individual particle and not to the ensemble, that the wave function represents a "record of my information on the state of the microobject", and so forth. All the discussions are due to the philosophical points of view of the numerous scientists and are essentially fruitless. Actually, one need only fuse the general theory of relativity and quantum theory, and the difficulties of modern physics will vanish.

A. I. Kompaneets (IFAN) spoke strongly against the principle of complementarity and denied that Bohr's philosophical evolution was progressive.

I. B. Novik (IFAN) criticized the statements made by Kompaneets and stressed that it was wrong to revert to the nonargumentative criticism prevalent earlier with reference to eminent foreign scientists. This style had caused much damage in philosophical works and had engendered dissatisfaction and even exasperation among scientists. At the present time life required positive philosophical endeavour and creative participation of philosophy in the development of science.

Novik pointed out that the philosophical problems of natural science became particularly significant in times of upheaval in physics. This is due to the fact that when the usual formalism fails to work, physics is obliged to use the language of the general conceptual systems, among which belongs the philosophical system as well. It is thus understandable that philosophical problems should play a very important role at the beginning of the present century, in a period of radical breakdown of ideas concerning the world.

In the opinion of the speaker, an even more fundamental break than ever before is now taking place in the development of physics. This break involves a total collapse of basic physical ideas and a sharp increase in the role of the functional method of investigation. If the beginning of the century saw a mathematization of physics, at mid-century we are witnessing a cybernetization of the physical theories. For example, Heisenberg's celebrated S-matrix is a typical cybernetical scheme with input, output and "black box".

It could be that the way out of the difficulties of modern physics lies in abandoning the "anthropomorphic" Newtonian language, in moving away from the structure of the "black boxes", in the cybernetic approach to physical phenomena. Cognition is unitary; it attains the truth by moving along different directions and covering all the possibilities. We must therefore seek ways of changing our ideas concerning both physical reality and physical cognition.

In this connection a very important question is that of the role of philosophy. Naturally, philosophy cannot replace the natural sciences, and great caution must be exercised when using philosophy in natural sciences, as philosophical premises are very liable to dogmatization. One cannot say that owing to such-and-such philosophical considerations nature must obey certain regularities. Such a tendency was apparent in Ya. P. Terletskii's report in the statement that, owing to the law of negation of negation, quantum physics should be replaced at small distances by a quasi-classical theory. But nature owes us nothing. On the contrary, nature is the touchstone

of our knowledge, of our physical and philosophical assertions. Hence every rational physical idea, however much it might seem to contradict familiar conceptions, must be assimilated by scientific philosophy. For example, should our world prove to consist of a finite number of points, as stated in the Coish-Shapiro theory, there would be nothing to contradict philosophical teachings concerning the infinity of the world. There is nothing mystical about this theory, and it is entirely possible that it expresses an essential aspect of reality. Therefore those who, reasoning undialectically, declare themselves opposed to such theories on the grounds of the "demonic power" which they attribute to superficially assimilated philosophical propositions, are in error.

In his talk M. E. Omel'yanovskii criticized A. L. Serdyukov's attempt to attribute to philosophers a meaningless conviction in the transformation of wave to particle and vice versa on the grounds that it was baseless. Serdyukov apparently had an extremely "peculiar" understanding of where the dialectical essence of wave-particle dualism lay. He obviously refused to allow for the fact that, following S. I. Vavilov, Soviet philosophers regard matter, i.e., substance and field, neither as a collection of particles and waves nor as a mixture of the two; matter simultaneously has the properties of particles and those of waves.

In the beginning of his talk S. F. Shushurin (MGU) paused over the definition of the subject of the philosophical problems of physics. The latter represent general problems of concrete science (physics) and at the same time the practical application of general-philosophical propositions. If until recently, for the main, physics operated upon philosophy, in the sense that concrete physical achievements were used to support propositions of dialectical materialism, today physics provides philosophers with a number of problems requiring creative solution. The first actual problem is that of the character of physical theories. Must a physical theory reduce exclusively to a quantitative theory, and can it be qualitative? Is not the useful and very necessary method of quantitative description (which, of course, must be used to the utmost) merely a tool by which to grasp those regularities over which we build the qualitative picture of the objective world? The point is that one cannot confine oneself to quantitative study of the world, for qualitative knowledge is also necessary; this calls for further development of the ontology of dialectical materialism and the development of a philosophical theory of the structural organization of matter.

The problem of elementarity is important. The conception of an infinite set of different qualitative levels outlined in Omel'yanovskii's talk is highly interesting. However, his attitude toward it was sceptical and (in the present speaker's opinion) his preference for the conception of elementary-structural dualism was not sufficiently justified. Shushurin believes that one cannot deny the possibility of there existing a more elementary level of structure of matter on the grounds that elementary particles can transmute into each other. Molecules transmute into each other, yet there are atoms; atoms transmute into each other, yet there are nucleons. The speaker stressed that the "subelementary particles" apparently lacked a rest mass.

In conclusion Shushurin remarked that the more elementary was ordinarily interpreted as the part of a whole. Therefore the problem of elementarity is closely connected with that of the part and the whole, which has not been sufficiently developed. The part is usually understood in a

destructive sense as something that can be "detached" from an object. This interpretation cannot claim philosophical generality, since in biology, for instance, it is unsuitable. It is apparently also inapplicable in elementary particle physics.

Where can one look for objects more elementary than the elementary particles? Perhaps it would be meaningful to analyze — and re-classify accordingly (e. g., by the number of properties) — the known microobjects. Photons have fewer properties than most other elementary particles, while the neutrino and graviton have even fewer properties than the photon. Therefore, to the speaker, the problem of elementarity is not a completely hopeless one, though it does call for analysis of our ideas concerning the fundamental properties of the structural forms of matter and the regularities of their cognition.

In his talk I. V. Kuznetsov dwelled upon the profound thought concerning the bond between the infinitely small and the infinitely large so strikingly expressed in the Coish-Shapiro idea of a finite number of points in space. This thought throws a clearly perceptible bridge between microprocesses and the properties of the universe.

However, the assumption of a finite number of points in the Coish-Shapiro theory does not necessarily imply the finiteness of material objects in the entire universe and the spatial finiteness of the universe as a whole. The assumption of a finite number of points can be interpreted as follows: individual elementary objects do not exist by themselves; they occur in organic relation with a definite macroscopic complex of other elementary objects, a complex having a large number of such elements but at the same time a finite spatial extension. The microobject should not be considered outside of this set of elementary objects, independently of its coordination with these objects. The relationship with this finite, spatially bounded complex of material objects should explain the properties of the individual elementary objects.

In Kuznetsov's view, that which figures as a "finite space" with a finite number of points in the Coish-Shapiro theory is nothing, but an individual ultra-large cell of the truly infinite space of the universe. It is merely one cell in the infinite extension of the universe, and one can imagine an infinite set of such cells in the universe.

Thus the idea advanced by Coish and Shapiro that our space is finite can be reconciled completely with the premise of the spatial infinity of the universe.

One cannot exclude other interpretations of this idea which could reconcile the finiteness of our space with the infinity of the universe.

At the very least all possible philosophical objections to the Coish-Shapiro theory collapse in this approach. This theory should be explored further and all possible consequences drawn from it in order to determine what it could contribute to the building of a systematic theory of elementary particles.

Next Kuznetsov remarked with regard to I. B. Novik's talk that philosophy was not alone in enjoying the "advantage" of easy dogmatization of its premises, and that both in physics and in other scientific disciplines many concepts were dogmatized. For example, such dogmatization was experienced by the concept of the atom, simultaneity, and the concepts of classical mechanics. Another example of such dogmatization of concepts is provided by the microobject, a concept which has long figured in our

literature, has suffered excessive ossification and delayed the development of elementary particle physics.

Citing de Broglie's formulas, which establish the connection between the corpuscular (energy and momentum) and wave (frequency and wavelength) characteristics of an object, Kuznetsov demonstrated, from the standpoint of physics itself, the unsoundness of A. L. Serdyukov's attempt to refute the concept of wave-particle dualism. Kuznetsov stressed that the term "dualism" bore no relation to the philosophical concept of dualism (e.g., psycho-physical dualism) but simply expressed the connection between two types of characteristics of microobjects. In reality the microobject is evidently neither wave nor particle but some higher, synthesizing third thing.

In his talk A. V. Shugailin (Kiev) protested against Fainberg's claim that no new philosophical problems arose in relativistic quantum theory as compared with ordinary quantum mechanics. Shugailin pointed out that the problem of the union of the wave and particle properties took on a different character in relativistic quantum theory. In quantum mechanics this union was established for an individual "invariant" microobject, but relativistic quantum theory allows the transformation of one particle into other particles and into antiparticles. For example, if the interaction between two microobjects takes place with a very high energy, then microobjects practically devoid of wave properties may arise in this process. In this connection Shugailin noted that relativistic quantum theory dealt with very large values of the momentum and energy, and that for precisely this reason the manifestation of wave properties in relativistic microobjects was insignificant. Shugailin also dwelled on the problem of elementarity, on the philosophical understanding of the categories of part and whole. He emphasized that the problems of elementarity and interrelation between the part and the whole had to be stated anew, allowing for the ideas of relativistic quantum theory concerning the transmutability of elementary particles. One could thus conclude that in constructing the future theory of elementary particles it would be necessary to consider not only the problematics raised by ordinary quantum mechanics but also that raised by relativistic quantum theory. In this process, Shugailin stressed, a very important part would be played by the correspondence principle, which expressed in physics the dialectical correlation between the absolute and relative truth. There can be no doubt but that the correspondence principle is an essential methodological "lever" for the construction of physical theories.

At the beginning of his talk S. T. Melyukhin (Leningrad) defined the elementary particle as a material object in which the binding energy between structural elements was of the same order as the rest mass energy. This distinguishes the elementary particle from all the rest (macroscopic bodies, molecules and atoms) in an essential way. It is precisely for this reason that with increasing energy of interaction the elementary particle does not "split" but rather undergoes a qualitative transformation into other elementary particles having the same degree of elementarity.

Melyukhin criticized those philosophers who, under the influence of incomplete hypotheses, were inclined to shine by their originality and up-to-dateness and to abandon proven philosophical principles, thereby evincing a lack of respect for philosophy.

As an illustration Melyukhin mentioned the superficial assimilation by certain philosophers of a number of physical ideas of Ya. P. Terletskii

(negative masses, i.e., negative energies, faster-than-light signals which transmit information but not energy, and so on), which were proclaimed the last word in science and from which "original" conclusions were drawn concerning nonconservation of energy, motion without matter and so forth. Melyukhin expressed the opinion that in constructing any new theory of elementary particles it was necessary to take into account the "deeply based, established general-philosophical principles".

The main theme of Yu. P. Markov's (MGU) talk was the quantum-mechanical uncertainty relation $\Delta p \Delta q \gtrsim \hbar$. Markov pointed out that in classical physics the uncertainty relation $\Delta p \Delta q \sim D$, where D is the coefficient of diffusion, was valid when considering the behavior of a gas molecule. For a molecule isolated from other particles, i.e., for $D \to 0$, the momentum p and the coordinate q can be accurately determined at the same time. A different situation prevails in quantum theory, where $\hbar$ is a constant. In Markov's view, this reflects the fact that the quantum object cannot even conceptually be represented as isolated from the environ- or macroscopic situation in which the quantum-mechanical process is being studied. Markov defended those hypotheses which claim that the quantum-mechanical object exists only as a result of interaction with the surrounding situation or vacuum. An object exists at all only inasmuch as it interacts with the vacuum, and, moreover, in a discrete way. The real fact of the existence of virtual particles, which reflects the interaction of elementary particles with the vacuum, supports this hypothesis. Allowance for particle interaction with the vacuum automatically leads to the requirement of nonlinearity of the generalized theory of elementary particles.

I. I. Davletshin (MGU) sought to justify the approach to the theory of elementary particles from the standpoint of information theory. He noted that cognition and expression of the real world occurred by way of construction of a model of this world with a certain degree of accuracy, with an element of idealization of the objective. In the process of development we obtain an increasingly adequate expression, i.e., construct models with increasing degree of accuracy. This process must be examined from the information-theoretic cybernetical point of view, since cybernetics deals with the general theory of algorithmizing logico-mathematical models of material objects. Such examination would doubtless be of heuristic value.

Modern theoretical physics has demonstrated that in order to construct a theory of elementary particles it is necessary to go beyond the limits of Hilbert space. This construction must apparently be carried out in the space of functionals, since description in the language of functionals carries far more information capacity per element of space.

In turn, information capacity is closely connected to the kernel property of mathematical space. In the case where the kernel property is rigorously valid for the space of states of a certain object, the evaluation of the behavior of the object is only probabilistic. But the space of states of elementary particles is, strictly speaking, not a kernel space and therefore it is entirely possible that in certain cases (strong interactions) even probabilistic evaluations of the behavior of elementary particles will prove inapplicable.

It should be remarked that the information-theoretic approach to the physics of elementary particles has also been developed in the article by I. A. Akchurin printed in the present collection.

The next speaker, A. R. Pozner (MGU), centered his talk around Bohr's idea of complementarity.

The interest in the idea of complementarity manifested at the conference is due, first of all, to the dialectics of cognition. The elementary particle theories revert somehow or the other to the question which, though born in quantum mechanics, was not solved by it exhaustively enough — the question of wave-particle dualism.

Secondly, the difficulties encountered in the development of elementary particle physics are connected with the devising of definite methodological ideas and the creation of a definite mathematical apparatus. The present stage of development of physics is reminiscent of the initial stage of quantum mechanics when its mathematical and conceptual apparatus (including the idea of complementarity) were being created.

The idea of complementarity was subjected in its time to justified criticism on account of the idea of uncontrollability. However, this idea also contains many rational aspects an analysis of which would be of interest for modern physics. The main point about it is that it stresses the deficiencies of the classical ideas and the need for disregarding them. Secondly, Bohr sought in his conception to account for the contradictory character of microphenomena. Thirdly, the idea of complementarity shows up the need for considering the inseparable connection between microobject and experimental conditions.

Pozner noted that the idea of complementarity had been given a different interpretation in a number of the talks. This recalls the cybernetical scheme proposed by I. B. Novik, where the input was a certain idea and the output its various evaluations (with a "black box" in the middle). The idea of complementarity is, on the one hand, metaphysical and on the other hand, dialectical. In reality a materialistic evaluation is required, since even Bohr himself, in the last years of his life, repudiated many positivistic terms and emphasized that the further development of physics would require generalization of the idea of complementarity.

Also wrong are those (V. Ya. Fainberg) who maintain that the idea of complementarity continues to operate in the same form in the physics of elementary particles. In fact, elementary particle physics has revealed new properties of complementarity distinct from the quantum-mechanical properties (parity nonconservation and so on). It is therefore necessary to generalize the principle of complementarity and to pursue the course of repudiation of the classical ideas.

A. A. Tyapkin began his talk with a critique of the talk delivered by I. P. Bazarov. Tyapkin announced that Hegel had not known of quantum mechanics, and therefore his thesis concerning the fact that a body occurs at a point and does not occur at a point referred to mechanical motion. This Bazarov countered by saying that Hegel had analyzed dialectically in a general abstract form the motion of any body in space and time. The validity of Hegel's analysis was in fact proved by modern quantum mechanics.

Next Tyapkin defended R. A. Aronov's talk concerning the connection between the space-time metric and the properties of interactions. Tyapkin expressed the opinion that this connection should be taken into consideration not only in the construction of the future theory but also in the treatment of the theory of relativity, in order to relate the space-time transformations in the theory of relativity to certain ideas concerning interactions. Here one should consider not just any properties of interactions, but rather only those which bear a general character, since space and time are forms of existence of matter in general and not merely concrete forms of matter.

For example, the increase of mass with velocity applies to all particles we know or will know.

Tyapkin supported Fainberg in his criticism of Ya. P. Terletskii's statement that Hofstadter's experiments proved the existence of a rigid form factor for the nucleon in contradiction with the theory of relativity. But he agrees with Terletskii that reasons for the statistical character of quantum mechanics should be sought, though not in a refutation of von Neumann's theorem. Tyapkin expressed the opinion that the principle of complementarity was an artificial philosophical adjunct to the physical uncertainty principle and that new treatments of quantum mechanics would be able to show what part of it is true and what part false.

The speaker did not agree with M. F. Shirokov that, since everything was supposedly clear, no discussions need be held. On the contrary, the greatest physicists, such as Einstein, Bohr, de Broglie, have argued and are arguing concerning fundamental questions of theoretical physics, which shows that they are dissatisfied with the present stage of physics and that a more profound physical theory must be sought. Where we err is in not conducting enough discussions. This seriously impedes the development of theoretical physics. The time came long ago to found a journal of "Philosophical problems of natural science", yet none exists as yet.

M. E. Omel'yanovskii delivered the concluding address of the conference. He remarked upon the fruitfulness of the conference's labors and the creative atmosphere which prevailed. A characteristic trait of the conference was concrete methodological analysis of the concrete situation in the modern physics of elementary particles. The many profound thoughts expressed in reports and debate would be of aid both to physicists and to philosophers in the further creative development of physical and philosophical problems.

On the whole the conference was an example of creative cooperation between physicists and philosophers. It did not, of course, establish the ultimate truth of the points discussed; however, new problems were raised and old ones illuminated from unexpected points of view. It will doubtless be necessary to return repeatedly to all these problems, and much work lies ahead.

The resolution adopted by the conference was extremely brief and practical: to publish the proceedings of the conference and to hold regular conferences on the philosophical problems of modern physics henceforth.

EXPLANATORY LIST OF ABBREVIATIONS OF U.S.S.R. INSTITUTIONS
AND ORGANIZATIONS APPEARING IN THIS TEXT

Abbreviation	Full name (transliterated)	Translation
AN SSSR	Akademiya Nauk SSSR	Academy of Sciences of the U.S.S.R.
DAN	Doklady Akademii Nauk (SSSR)	Proceedings of the Academy of Sciences (of the U.S.S.R.)
FIAN	Fizicheskii Institut Akademii Nauk (SSSR) im. P. N. Lebedeva	Institute of Physics of the Academy of Sciences (of the U.S.S.R.) im. P. N. Lebedev
IFAN	Institut Fiziki Akademii Nauk	Institute of Physics of the Academy of Sciences
MGU	Moskovskii Gosudarstven-nyi Universitet	Moscow State University
OIYaI	Ob"edinennyi Institut Yadernykh Issledovanii	Joint Insitute for Nuclear Research
UFN	Uspekhi Fizicheskikh Nauk	Advances in Physical Sciences
ZhETF	Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki	Journal of Experimental and Theoretical Physics