Structure of elementary particles and relationships between the different forces of nature

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Usp. Fiz. Nauk 123, 505–529 (November 1977)

PACS numbers: 12.40.Bb, 12.20.Hx, 11.30.–j

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INTRODUCTION

The investigation of the structure of matter, the search for the smallest particles of matter, and the study of their structure and the forces acting between them have always been one of the principal directions of science. Since the world surrounding us consists of very small particles of matter, the properties of these particles and the laws governing their motions and interactions determine the properties of macroscopic bodies and the processes taking place in them. Thus, knowledge of the structure of the elementary "bricks" of matter is the foundation of all natural sciences and the basis for investigating the forces of nature.

Major discoveries in this field lead ultimately to radical changes in technology, to the appearance of new products, and to scientific and technical revolutions. Indeed, the discoveries in the structure of the atom and nucleus made in the first half of the 20th century provided the basis of the modern scientific and technical revolution. These discoveries supplied not only the key to numerous applications but now also form the basis of modern chemistry, solid-state physics, electronics, and many other sciences, which in their turn are the foundation of the most diverse outgrowths of modern technology.

One can also recall the fundamental jumps in our knowledge such as the establishment of the connection between electric and magnetic phenomena, the discovery of the structure of the atom and the discovery of the structure of the nucleus. Recognition of the fact that atoms consist of a positively charged nucleus and negative electrons and that their motion is governed by the laws of the newly created theory of quantum mechanics led to a revolution in not only the whole of our scientific outlook but also in technology. One can now state confidently that quantum mechanics has now been transformed essentially into a branch of engineering whose applications we encounter in numerous branches of technology and even in everyday life. For this is the technology of semiconductors, which is so widely used in radio electronics and without which the creation of the powerful modern computers would be impossible. Then there is the phenomenon of superconductivity, which already has technical applications and will no doubt have a great future. And then there is quantum electronics, which has led to the creation of lasers and masers. The lift of examples could be continued. Discovery of the structure of the nucleus, i.e., of the fact that it consists of neutrons and protons, has led, on the one hand, to a further deepening of our knowledge of the structure of matter, and, on the other, to familiar applications such as nuclear energy, the numerous uses of radioactive isotopes, and so forth.

Besides the determination of the composition of the various elements of matter (atoms, nuclei, etc), fundamental importance also attaches to understanding the properties of the forces that act in nature. The most important example here is Faraday's discovery of the connection between electric and magnetic phenomena, which subsequently found its mathematical expression in Maxwell's equations. This discovery had decisive consequences for the development of science. It led, first, to the creation of the theory of a physical field and, second, to the creation of the theory of relativity. These two theories together with quantum mechanics provide the basis of our modern scientific view of the world. On the other hand, the creation of the theory of electromagnetic phenomena led to innumerable applications. Modern technology and everyday life would now be unthinkable without electronics, radio technology, etc.

We see that every decisive success in our understanding of the fundamental physical laws deepens our knowledge and provides a stimulus for further investigations and at the same time considerably extends the power of man over the forces of nature and leads to numerous applications in technology and industry. It is a truism to say that the achievements of electrodynamics and atomic and nuclear physics now provide the foundation of technical progress and the scientific and technical revolution.

The frontier at which knowledge is now being gained of new fundamental laws of nature has advanced even further. We are now concerned with the structure of

 0038-5670/77/2011-0956$01.10

the elementary particles that make up the atoms and nuclei. Of what do the proton and neutron consist, and what forces act between their constituent parts? These are the fundamental questions of modern physics. A rapidly developing branch of physics—high energy physics, which is also sometimes called the physics of elementary particles—is concerned with these questions and numerous problems related to them.

The recent years have been marked by important progress in high energy physics. In the first place, this has been due to numerous important experimental results obtained at the largest accelerator centers: The Institute of High Energy Physics (at Serpukhov), CERN (Geneva), Fermilab (Batavia), SLAC (Stanford), among others. It must be emphasized that powerful particle accelerators are the main tool for investigating the physics of elementary particles, and therefore progress in the solution of problems in physics is intimately related to progress in the physics and technology of accelerators and broadening of the accelerator basis of high energy physics. On the other hand, the experimental advances have been matched by major successes in the theory of elementary particles, these being associated, above all, with the deeper development of the composite quark models of elementary particles, the use of non-Abelian gauge variants of quantum field theory, and the use in theory of the concepts of vacuum degeneracy and spontaneous symmetry breaking. It is apparent that we now stand at the threshold of a new level of understanding of the phenomena in the world of elementary particles and their inner structure. But one cannot yet say that this level has already been achieved. There remain unsolved problems, both theoretical and experimental, and to solve them we require a further development of the accelerator basis of experimental investigations, the creation of accelerators with superhigh energies, and the concentrated efforts of both experimental and theoretical physicists. If the picture of the structure of elementary particles and their interactions discussed below is confirmed, we shall undoubtedly obtain the key to an understanding of the most diverse phenomena in nature, beginning with global astrophysical problems and ending with problems of the interaction of the smallest particles of matter. There is no doubt but that the clarification of the structure of elementary particles will be as important a step as the discovery of the structure of the atom and the nucleus. As an example, let us mention one of the possibilities discussed in the framework of the composite quark model. Suppose that the quarks, which, according to modern ideas, make up protons and neutrons, have a large mass appreciably exceeding the proton mass; then the mass defect of three quarks in a proton is enormous. Then the energy liberated in an elementary process of combining three quarks to form a proton will in this case be 1000 times greater than the energy liberated in an individual nuclear reaction. Such a possibility arises if the quarks can exist in a free, unbound state. This possibility is not ruled out by the experiments (see also below). Use of the new theoretical principles which we mentioned above and will discuss in more detail below enables us to attack the problem of the unification of the very varied forces that act in the world of particles and thus arrive at an understanding of their common basis. If successful, this unification would be of no less significance than the unification of the electric and magnetic phenomena achieved in the last century by the efforts of, above all, Faraday and Maxwell.

The aim of the present paper is to discuss the fundamental questions in modern high energy physics and the problems now facing it, especially those connected with the composite structure of particles and a possible unified nature of the different interactions.

First of all, we consider the classification of the elementary in the framework of the composite quark model.

CLASSIFICATION OF ELEMENTARY PARTICLES AND THE COMPOSITE QUARK MODEL

A very great number of elementary particles has now been discovered. Some of them are widely known. These are the proton and neutron, which make up the nuclei, the electron, which fills the shells in atoms, and the photon, i.e., the quantum of light. But besides these, many other particles, which differ in their properties and characteristics, have been discovered and investigated. Very important characteristics of a particle are its quantum numbers. The simplest example of a quantum number is the electric charge of a particle. The charge of all hitherto observed particles is found to be a multiple of the electron charge, and particles may be positive, negative, or neutral. Alongside the charge, it has been found necessary to introduce other quantum numbers: the baryon charge, which proton, neutron, and a number of other particles such as the hyperon do have but, for example, the photon, the electron, and the entire group of particles formed by the mesons do not have; the isospin and strangeness, which distinguish particles with the same baryon charge; the lepton charge, which the electron, muon, and neutrino have. In addition, the particles have different masses, spins, and parities.

In this diversity of particles, one can nevertheless find a fairly elegant classification system. First of all, the particles can be divided into three large groups on the basis of their properties. There is, first, the most numerous group of the strongly interacting particles—the hadrons, which include the proton, neutron, hyperons, their antiparticles, and mesons, which may or may not carry strangeness, and a large number of resonances, i.e., short lived particles. These particles interact strongly with forces characteristic of the interaction of the proton and neutron in the nucleus. This interaction has been called the strong interaction, and it is distinguished by the fact that the quantum numbers of strangeness and isospin are conserved in it.

A second group of particles—the leptons, i.e., the electron, muon, neutrinos of both types, and their antiparticles—do not participate in the strong interaction. The most characteristic force for them is the weak interaction, in which all hadrons also participate and which leads to the decay of almost all particles, and also to neutrino reactions. Only the proton, electron, neutrino, and photon are stable. However, the weak interaction leads to comparatively small decay probabilities, and it is therefore possible to obtain beams of unstable particle and investigate the properties of their interaction before they decay. In the weak interaction, strangeness, isospin, and, very importantly, parity are not conserved.

A third group of particles consists as yet of a single particle—the photon, which transmits the electromagnetic interaction. All particles, both charged and neutral, participate in the electromagnetic interaction to some extent.

Besides the conservation laws already mentioned, which differ for different interactions, there are in the modern view certain absolute laws. These are the laws of conservation of energy and momentum, the law of conservation of electric charge, and, with certain reservations, the laws of conservation of the baryon and lepton numbers, which are needed to ensure the stability of matter. It should be noted that the requirements of conservation of the baryon and lepton numbers are not absolute. Moreover, it is assumed in some models[1,2] that the baryon number is not conserved, which means that the proton is unstable, though admittedly with a huge lifetime that does not contradict observations. The assumption that the lepton quantum number is not conserved leads to an interesting phenomenon—oscillations in neutrino beams, which have been considered by Pontecorvo.[3]

The different types of interaction, strong, electromagnetic, and weak, differ as much as do the different classes of particles.

One of the manifestations of strong interactions are the nuclear forces that bind neutrons and protons in the nuclei. The idea of such forces, as forces of a new and previously unknown nature, appeared immediately after the discovery of the structure of the nucleus. It was established that the nuclear forces have a very short range, of order 10^{-13} cm. We may mention in passing that this explains why nuclear forces were discovered several centuries after the well-known long-range forces of electromagnetism and gravitation. At the beginning of the thirties, to explain the short-range nature of the nuclear forces, Tamm, and also Ivanenko, advanced the suggestion that these forces have an exchange nature. Subsequently, Yukawa proposed that the interaction between nucleons is transmitted by the exchange of a new hypothetical particle, just like the electromagnetic interaction between charged elementary particles occurs through the exchange of photons. However, to explain the short range of the nuclear forces, the carrier must, in contrast to the photon, have a fairly large rest mass, approximately 300 times the electron's. The correctness of this hypothesis was brilliantly confirmed by the discovery of the π meson. At the same time, the idea of the existence of new forces—strong interactions—was formulated. Modern hypotheses about the nature of strong interactions will be discussed below.

The first ideas about weak interactions were obtained in 1934, when Fermi showed that to explain the main features of the radioactive β decay of *nuclei* it is necessary to assume the existence of particular forces capable of transforming a neutron in a nucleus into a proton with the simultaneous emission of an electron and an antineutrino. The forces that give rise to the decay must act between four spin 1/2 particles at very short distances. The characteristic strength of these forces at the energies characteristic of β decay is 12 orders of magnitude (i.e., 10^{12} times) less than that of electromagnetic forces. At the end of the forties, when π and μ mesons were discovered, it was established that their decays are also caused by forces comparable in strength with those that lead to β decays, and this suggested that the weak interactions have a universal nature. However, the proof of this universality and the establishment of laws of the weak interactions required an immense amount of investigation, which cannot even now be regarded as completed. The most important stage in the study of weak interactions was the discovery in 1956 of parity nonconservation, i.e., the breaking of left—right symmetry in weak interactions. After this discovery, intense experimental and theoretical investigations led to the establishment of the universal $V-A$ theory of weak interactions. An important hypothesis in this connection was Landau's of the two-component longitudinal neutrino. According to the $V—A$ theory, the weak interactions reduce to the interaction of particular weak currents, just as the electromagnetic interactions of particles are represented by the interaction of their electromagnetic currents. However, in contrast to the electromagnetic current, the weak current is charged. It is constructed in such a way that after the interaction a transformation of particles occurs and their charges are changed. In addition, the weak current consists of two components—the vector and axial-vector, which differ in their spatial parity. An important property of the weak current is the law of conservation of its vector part, which is analogous to the law of conservation of the electromagnetic current. The conservation of the vector current was proposed by Gershteǐn and Zel'dovich.[4]

In 1973, neutral neutrino reactions, which can occur only if there exists a new type of weak current—neutral currents—were discovered. As we shall see below, the discovery of neutral weak currents is an important indication of the unified nature of the weak and electromagnetic interactions.

In the physics of weak interactions, the problem of the violation of CP invariance is also important. The hypothesis of this invariance was suggested by Landau, Wigner, Lee, and Yang immediately after the discovery of parity nonconservation in weak interactions. Under this assumption, the left—right symmetry of the world is restored, the left-handed world of particles now corresponding to the symmetric right-handed world of antiparticles. This hypothesis was widely accepted, but in 1964 decays of neutral K mesons were discovered, and in these decays this symmetry is clearly broken. The problem of the breaking of CP invariance has since remained on the list of unsolved problems of elementary particle physics. Great attention is paid to it in the development of the modern gauge theories of weak interactions.

Very great importance attaches to the study of the most numerous family of particles, the hadrons, and their basic, strong interaction. Numerous facts argue for a composite structure of hadrons. Among these, the most important is the classification of the particles, i.e., the regularities in the distribution of the quantum numbers of isospin and strangeness among the particles with the same spins and parities. It is found that the particles occur in certain groups, which are called supermultiplets. For example, the baryon supermultiplet with spin 1/2 includes not only the well-known proton P and the neutron N but also particles with nonzero strangeness: Λ, Σ^+, Σ^0, Σ^- (strangeness -1) and Ξ^0, Ξ^- (strangeness -2). Mesons, i.e., particles with spin 0 and negative parity, also occur in an octuplet: π^+, π^0, π^-, η (strangeness 0), K^+, K^0 (strangeness $+1$), and K^-, K^0 (strangeness -1). The baryon and meson resonances, i.e., states that decay rapidly into hadrons, are similarly grouped into supermultiplets. For example, there are nine vector (i.e., having spin 1 and negative parity) particles: ρ^+, ρ_0, ρ^-, ω, φ $(S=0)$, $K^{*+}K^{*0}$ $(S=+1)$, K^{*-}, $\bar{K}^{*0}$ $(S=-1)$. This classification of the particles can be described mathematically in the framework of the symmetry group $SU(3)$, which was introduced into particle physics by Gell-Mann and Ne'eman.

The masses of these particles are basically grouped around the value 1 GeV/c^2 (1 GeV is a billion electron volts). For example, for the proton mass we have $M_P c^2 = 0.9383$ GeV, and for the mesons $M_{\pi^+} c^2 = 0.1396$ GeV, $M_{K^+} c^2 = 0.4938$ GeV, $M_\varphi c^2 = 1.019$ GeV. Recently, new particles have been found with higher masses in the range ~2–3 GeV. For their classification, one requires a new quantum number, which has been called charm. These are particles with spin 0 and negative parity: D^+, D^0 (1.86) $(S=0$, charm $C=+1)$, D^-, D^0 $(S=0,\ C=-1)$,[5] and also the family of vector particles J/ψ (3.1) ([6]) $(S=0,\ C=0)$, D^{*+}, D^{*0} (2.01) $(S=0,\ C=+1)$, $\bar{D}^*$, $\bar{D}^{*0}$ (2.01) $(S=0,\ C=-1)$. (The mass in GeV/c^2 is given in brackets.) The arguments for introducing the new quantum number will be considered in more detail below, but we point out here that this new number does not fit in the framework of $SU(3)$ symmetry, and we require a larger group. For this, the group $SU(4)$ has been proposed;[7] it contains the requisite number[3] of quantum numbers additively conserved in strong interactions, i.e., the isospin projection I_3, the strangeness S, and the charm C.

The classification of particles in the framework of a symmetry group, for example, $SU(3)$ or $SU(4)$, is sometimes compared with the classification of the chemical elements in Mendeleev's Periodic Table, which finds its explanation in the quantum-mechanical composite theory of the structure of the atom. In exactly the same way, the classification of the particles finds a natural explanation in the hypothesis that the hadrons have a complex structure and consist of more fundamental particles, which have been called quarks.

In fact, long before the quark hypothesis, Fermi and Yang in 1949 considered a model in which the π meson is a bound state of a nucleon and antinucleon. On the basis of this model, Markov predicted the existence of particles that are excited states in the nucleon—antinucleon system and must decay into π mesons. Thus, the existence of unstable particles, π-meson resonances, was predicted, and these were subsequently discovered in experiments (for example, the ρ and ω mesons mentioned above).

The transition from $SU(3)$ to $SU(4)$ also increases the number of quarks, i.e., of particles, or rather entities (since we are not certain that we can really apply the name "particle" to quarks) that form a multiplet which transforms in accordance with a fundamental representation of the group, in the given case $SU(4)$. We recall that quarks were introduced[8] in the framework of $SU(3)$ in order to understand the observed symmetry in the classification of hadrons in the language of a composite model. The fundamental representation of $SU(3)$ has three dimensions and therefore describes three quarks q_α $(\alpha = 1, 2, 3)$. Its associated contravariant representation describes three antiquarks $\bar{q}^\beta$. From the representation q_α and the conjugate $\bar{q}^\beta$ we can construct new representations of $SU(3)$, including those that classify the observed particles. For this, it is well known that one must ascribe to all quarks and antiquarks spin 1/2 and baryon number $B=1/3$ for q_α and $B=-1/3$ for $\bar{q}^\beta$. This possibility is in fact the basis for constructing the composite quark model, in which the mesons are described as bound states of a quark and an antiquark and the baryons as bound states of three quarks. The quarks and antiquarks have the following basic quantum numbers:

$$\begin{aligned} q_1 &\equiv u\left(Q=\tfrac{2}{3}e,\ S=0,\ B=\tfrac{1}{3}\right), & \bar{q}^1 &\equiv \bar{u}\left(Q=-\tfrac{2}{3},\ S=0,\ B=-\tfrac{1}{3}\right)\\ q_2 &\equiv d\left(Q=-\tfrac{1}{3}e,\ S=0,\ B=\tfrac{1}{3}\right), & \bar{q}^2 &\equiv \bar{d}\left(Q=\tfrac{1}{3}e,\ S=0,\ B=-\tfrac{1}{3}\right),\\ q_3 &\equiv s\left(Q=-\tfrac{1}{3}e,\ S=-1,\ B=\tfrac{1}{3}\right), & \bar{q}^3 &\equiv \bar{s}\left(Q=\tfrac{1}{3}e,\ S=1,\ B=-\tfrac{1}{3}\right). \end{aligned}$$

It is then easy to see that, for example, the proton P, i.e., the particle with baryon charge $+1$, charge $+e$, and strangeness 0, can be constructed from three quarks:

$$P = (uud),$$

and the neutron from

$$N = (ddu).$$

Mesons, which have baryon number 0, can be constructed from a quark and an antiquark, for example

$$\pi^+ = (u\bar{d}),\quad \pi^- = (d\bar{u}),$$
$$K^+ = (u\bar{s}),\quad K^0 = (d\bar{s}),\ \ldots$$

It turns out that this simple quark model, augmented by natural dynamical assumptions, which in different applications have different names, such as the model of quasi-independent quarks, the additive quark model, the parton model, etc. gives a fairly good description

TABLE I.

	Q/e	B	I	I_3	S	C
u	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	0	0
d	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$	0	0
s	$-\frac{1}{3}$	$\frac{1}{3}$	0	0	-1	0
c	$\frac{2}{3}$	$\frac{1}{3}$	0	0	0	1
$\bar{u}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	$-\frac{1}{2}$	0	0
$\bar{d}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	0	0
$\bar{s}$	$\frac{1}{3}$	$-\frac{1}{3}$	0	0	1	0
$\bar{c}$	$-\frac{2}{3}$	$-\frac{1}{3}$	0	0	0	-1

of not only the classification of the particles but also of the dynamics of their interactions. As examples of the most successful use of the quark model, one may mention the calculation of the magnetic moments of the proton and the neutron, and the description of deep inelastic reactions of electrons and neutrinos with nucleons. The picture of a quark as a particle with dimensions much smaller than those or ordinary particles or, as one says, of a pointlike quark, leads in the case of these last reactions to a deep inelastic reaction that is basically like a reaction on a point particle, as was first predicted by Markov. Very interesting rules have been explained by a simple counting of the number of quarks in particles. An example is the relationship between the total cross sections for the interaction of π mesons with nucleons and of nucleons with nucleons.[9] In the first case, a particle containing two quarks (the meson) interacts with a particle containing three quarks (the nucleon). In the second case, both particles consist of three quarks. If the quarks interact in the same way with one another and independently and, in addition, in agreement with Pomeranchuk's well-known theorem, the cross sections for the interaction of a quark with a quark and an antiquark with a quark are comparable at high energies, then the ratio of the probabilities of interactions of a meson with a nucleon and a nucleon with a nucleon, i.e., the ratio of the corresponding total cross sections, is 2/3. A value close to this is observed experimentally. By simple counting of the quark numbers one can also explain interesting features in large angle elastic scattering.[10]

TABLE II.

0^-	$\bar{u}$	$\bar{d}$	$\bar{s}$	$\bar{c}$
u	π^0, η (η')	π^+	K^+	$\bar{D}^0$ (1.86)
d	π^-	π^0, η (η')	K^0	D^- (1.86)
s	K^-	$\bar{K}^0$	η (η')	F^- (?)
c	D^0 (1.86)	D^+ (1.86)	F^+ (?)	X (2.8)

TABLE III.

1^-	$\bar{u}$	$\bar{d}$	$\bar{s}$	$\bar{c}$
u	ρ^0, ω	ρ^+	K^{*+}	$\bar{D}^{*0}$ (2.01)
d	ρ^-	ρ^0, ω	K^{*0}	D^{*-} (2.01)
s	K^{*-}	$\bar{K}^{*0}$	φ	F^{*-} (?)
c	D^{*0} (2.01)	D^{*+} (2.01)	F^{*+} (?)	J/ψ (3.1)

As we have already said, it was found necessary to augment the old quark model with at least one new quark c, the carrier of the new quantum number charm C. We give in Table I the main quantum numbers of the modern four-quark model. It is easy to see that the quantum numbers have been chosen here in such a way that the formula relating the charge to the main quantum numbers, which generalizes the well-known Gell-Mann—Nishijima relation, now takes the form

$$Q=e\left(\frac{B}{2}+\frac{S}{2}+\frac{C}{2}+I_3\right). \qquad (1)$$

The states of particles, both meson and baryon, can now include not only the ordinary quarks but also the new quarks c and $\bar{c}$. In particular, the meson states $\bar{q}^\beta$, q_α, which were previously classified in accordance with representations of dimensions 8 and 1 of the group $SU(3)$, are now described by representations of dimensions 15 and 1 of the group $SU(4)$, i.e., we obtain seven new meson states. A certain amount of information about such states with spin and parity 0^- and 1^- has now been accumulated. We recall that in the framework of the quark model both these states correspond to an orbital angular momentum of the quark—antiquark system equal to zero and they differ only in the manner in which the spins of the quark and antiquark are added. In the language of atomic physics, the splitting between such states is hyperfine. We give the data known about such states in Tables II and III, in which the meson consisting of the quark and antiquark is placed at the intersection of the corresponding rows and columns.

It should be noted that the states F^-, F^+, F^{*-}, and F^{*+} have not (as yet) been observed, and the interpretation of the state $X(2.8)$ cannot be regarded as definitive.

For the new baryon states, the information is as yet not very great (but see[11]), and we shall therefore give no tables for them.

Thus, the classification of the particles and also the other available data, of which we have given only a few examples, persuade us of the fruitfulness of the quark ideas. But a number of problems, of both theoretical and experimental nature, then arise. The first of them is related to one of the deepest principles of quantum theory—the Pauli exclusion principle, according to which identical particles with spin 1/2 cannot exist together in a symmetric quantum state. But for the correct description of the baryon classification (proton, neutron, hyperons, and the resonances) one requires a

TABLE IV.

	1	2	3
u	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
d	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
s	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
c	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{3}{3}$

	1	2	3
u	1	1	0
d	0	0	−1
s	0	0	−1
c	1	1	0

symmetric state. This comes out most clearly in the example of the Ω^- particle with strangeness −3. The quark composition of this particle is sss, and all three identical quarks are in a symmetric state. The way out of this difficulty was found by Bogolyubov, Struminskii, and Tavkhelidze,[12] who suggested that the quarks forming baryons and the Ω^- in particular are different. Thus Thus, one must assume that there exist three species of each of the quarks (q_1, q_2, q_3), the species differing by some new quantum number, for which the name color has become established. Then, for example, the quark composition of Ω^- is $s_1 s_2 s_3$ and the Pauli principle present no difficulties. Moreover, the quarks do then not necessarily have to have fractional charges, as is noted in Table IV. One can consider various possibilities, of which the most popular to are shown schematically in Table IV (in the cells of this table, the quark charges are given in units of the elementary charge). The first possibility is a direct generalization of the quark model and is currently the most popular. The second possibility[12,13] also has a number of advantages and is used in many variants of the theory. The two possibilities lead to the same results for the classification of the particles but, in general, to different schemes of quark interactions.

We now come to a very important question: Why, despite intense searches, have quarks not been observed experimentally? There are different types of answer to this question. First, quarks may have a very large mass. Then they will ultimately be discovered in experiments with future accelerators having superhigh energies. The next possibility is that quarks (with integral charges) are unstable, and this explains the negative result of searches for them. And, finally, there is the possibility which is currently the one most widely discussed, namely, that quarks cannot "come apart." According to this hypothesis, the quarks have small masses but the interaction between them is constructed in such a way that the quarks cannot leave the inner region of the particle. The simplest model of such a situation is a potential with infinite walls. There exist a number of variants of bag models which describe phenomenologically the data fairly well. We shall briefly consider below the possibilities that are considered in quantum field theory for explaining these bags.

We should mention that recently data have been published on an experiment looking for free quarks,[14] or rather, particles with fractional electric charge; the results of this experiment indicate the existence of the charges $e/3$ and $-e/3$. If this positive result, after many years of unsuccessful searches, is correct and confirmed by further investigation, then the first possibility—heavy stable quarks with fractional charges—will have been confirmed. And the strenuous efforts now being made by theoreticians to establish definitely the impossibility of unbound quarks will prove to be unnecessary. The solution of the problem of whether there exist free quarks is fundamental, and we should like to use this opportunity to call upon the experimentalists to make every effort to confirm or refute the results of[14].

In the following exposition, we shall not feel bound by the results of this recent experiment, which undoubtedly requires verification.

Thus, the basis of modern ideas about the structure of hadrons is the composite model with color quarks. As we shall see below, the introduction of color degrees of freedom permits one to solve not only the problem of quark statistics but also consider an attractive new possibility for formulating the bases of the strong interactions of particles.

We have already mentioned a number of consequences of the composite quark model that are well confirmed by experiment. In recent years, it has become clear that for the investigation of the internal structure of particles inclusive reactions, considered for the first time in[15], are of exceptional value.

For the study and understanding of hadron structure, a very important property is the scaling in inclusive processes discovered in nucleon–nucleon interactions with the accelerator at Serpukhov.[16] Scaling and deviations from it were subsequently investigated in a large number of processes. Processes in which electromagnetic and weak interaction participate were also found to be very important.

Let us consider some examples that illustrate the situation. We begin with the annihilation of e^+ and e^- into hadrons, which is studied by means of colliding electron–positron beams. In the framework of the quark model, it is natural to suppose that this process takes place through the exchange of a photon:

$$e^+ + e^- \to q + q. \tag{2}$$

It is assumed at the same time that the quarks can be treated as point particles. The quarks produced in this elementary process must give some hadron state with unit probability since they themselves, at least at the existing energies, cannot appear in a free form. These arguments immediately lead to the conclusion that the cross section of e^+, e^- annihilation into hadrons at high energies has the form

$$\sigma_h = \sigma_0 \sum_q \left(\frac{Q_q}{e}\right)^2, \tag{3}$$

where σ_0 is the cross section for annihilation into a pair of point particles with unit elementary charge, for example, μ^+, μ^-, and the summation is over all species of quarks such that the considered energy is sufficient for production of the particles containing the corresponding quarks. Thus, we obtain the well-known relation for the ratio of the cross sections:

$$R=\frac{\sigma_h}{\sigma_{\mu^+\mu^-}}=\sum_q\left(\frac{Q_q}{e}\right)^2. \qquad (4)$$

We can now give the values of R for the different variants of quark model:

1) $R=2/3$ for the old model with three quarks without color,

2) $R=10/9$ for four quarks without color,

3) $R=2$ for three species of quark with color and fractional charges,

4) $R=3\frac{1}{3}$ for four species of quark with color and with fractional charges,

5) $R=4$ for color quarks with integral charges without charm,

6) $R=6$ for color quarks with integral charges with charm.

The experimental data give for the ratio a value close to 2 in the region of total e^+, e^- energy up to ~4 GeV, which is followed by a sharp rise accompanied by resonance peaks, and then, after 4.5 GeV, a new constant value is established at the level 5 ± 1 up to the currently available energy 7.8 GeV. This behavior of R completely rules out the models without color (possibilities 1 and 2) and agrees best with the model of color quarks with fractional charges. Indeed, in the region of 4 GeV there is a threshold of pair production of charmed particles since the lowest states having this quantum number have masses in the region of 2 GeV (see the tables given earlier). Therefore, up to 4 GeV we expect $R=2$, which agrees well with experiment, and above 4 GeV we should have $R=3\frac{1}{3}$, which, it is true, is somewhat lower than the observed value. This circumstance may be due to the fact that the introduction of the new fourth quark is insufficient and one must introduce even more new quarks with different quantum numbers. Such many-quark models are widely discussed at the present time. In addition, states that are not hadronic in the strict sense, in the first place heavy leptons, may also contribute to the measured ratio R. Indeed, indications of the existence of heavy leptons τ^+ and τ^- with mass ≈ 1.9 GeV, which were obtained for the first time at SLAC in the reaction[17]

$$e^+ + e^- \to e^\pm\mu^\mp + Y,$$

where Y is an unobserved (nonhadronic) state, have recently been confirmed in data from DESY (Hamburg)[18] in the reaction

$$e^+ + e^- \to \mu\ (e) + \text{hadrons}.$$

It seems to be confirmed that there is a heavy lepton τ^+ with mass ≈ 1.9 GeV (and its antiparticle) with heavy decay channels

$$\tau^+ \to \bar{\nu}_\tau + e^+ + \nu_e \quad (\sim 17\%),$$
$$\tau^+ \sim \bar{\nu}_\tau + \mu^+ + \nu_\mu \quad (\sim 17\%),$$
$$\tau^+ \to \bar{\nu}_\tau + \text{hadrons} \quad (\sim 66\%).$$

The last decay obviously contributes to the ratio R and increases it effectively.

Another important feature of e^+, e^- annihilation into hadrons serves as a confirmation of the composite quark model. We have in mind the hadron jets into which the final hadron state is divided at high energies (greater than 5 GeV[19]). These can be pictured qualitatively as follows: The quarks produced in the elementary event (2) divest themselves of hadrons with small transverse momenta relative to the original direction of motion of the quark, so that the hadron state is divided into two jets which fly apart in opposite directions in the center of mass system. The properties of these jets agree with calculations in the quark model. It is very important that the angular distribution of the jets with respect to the direction of the e^+ and e^- momenta is characteristic of a "particle" with spin 1/2. This is evidently a most important fact, which indicates that the entity producing the jet really is a quark.

Thus, the data on the annihilation of e^+ and e^- into hadrons—and we have only mentioned the most important above—support a quark structure of the particles and, very importantly, with color quarks.

Another very important field in which quark ideas can be tested are inclusive deep inelastic reactions of leptons (electrons, muons, and neutrinos) with nucleons. We are here speaking of the reactions

$$e^\mp + N \to e^\mp + \text{hadrons}, \qquad (5a)$$
$$\mu^\mp + N \to \mu^\mp + \text{hadrons}, \qquad (5b)$$
$$\nu_\mu + N \to \mu^- + \text{hadrons}, \qquad (5c)$$
$$\bar{\nu}_\mu + N \to \mu^+ + \text{hadrons}. \qquad (5d)$$

Note that experiments with high energy neutrinos, in particular study of the reactions (5c) and (5d), give very deep physical information about not only the structure of weak interactions but also the structure of particles. These experiments are also of great importance for the searches for new particles. Neutrino experiments with accelerators were first proposed by Markov and Pontecorvo.

The reactions (5a)–(5d) are usually analyzed in the framework of the quark—parton model.[20] Let us briefly recall the main propositions of this model. We assume that a nucleon (like any other hadron) contains above all quarks, which determine its quantum numbers (the so-called valence quarks) and, in addition, a certain number of quark—antiquark pairs, which are present with an appreciable probability since the interaction between quarks is strong. We then assume that the quarks within a hadron are almost free, so that their transverse momentum with respect to the direction of the motion of the hadron is small. At momenta of the nucleon much greater than this small value, one can assume that the momentum of the nucleon P is divided between its constituent quarks (and antiquarks), and that each quark has a certain fraction x of the momentum: $p_q = xP$. The probability that a given quark q has the fraction x is determined by the distribution function $q(x)$. In addition, it is natural to assume that the leptons interact independently with the different species of quark. Then the process of deep inelastic scattering can be imagined as follows: A lepton with initial momentum k interacts with one of the point quarks in the nucleon, which has momentum xP, and acquires as a result of the interaction a final momentum k^1. The struck quark together with the remaining quarks is deexcited with unit probability into some hadronic state. The calculations in such a model become particularly simple, and the momentum fraction x is directly related to observable kinematic variables if we can ignore the quark masses compared with the other energy variables:

$$x = -\frac{\mathbf{q}^2}{2(\mathbf{Pq})}, \quad \mathbf{q} = \mathbf{k} - \mathbf{k}'. \tag{6}$$

Another convenient invariant variable is $y = (\mathbf{p}\cdot\mathbf{q})/(\mathbf{P}\cdot\mathbf{k})$. The characteristic feature of the variables x and y is that they dimensionless, i.e., they are scaled variables. The kinematically allowed range of variation for both variables is the interval (0.1). As an example, we give the expressions obtained for the inclusive differential cross sections for the reactions of neutrinos and antineutrinos (5c) and (5d) on an "averaged" nucleon, i.e., on a target containing an equal number of protons and neutrons.

1) The reaction (5c):

$$\frac{d^2\sigma}{dx\,dy} = \frac{G^2}{2\pi} sx\,[(u(x) + d(x)) + (1-y)^2(\bar{u}(x) + \bar{d}(x))]. \tag{7a}$$

2) The reaction (5d):

$$\frac{d^2\sigma}{dx\,dy} = \frac{G^2}{2\pi} sx\,[(u(x) + d(x))(1-y)^2 + (\bar{u}(x) + \bar{d}(x))]; \tag{7b}$$

where $s = (P + k)^2$ is the square of the total energy in the center of mass system, G is the Fermi constant of the weak interaction, and $u(x)$, $d(x)$, ... describe the distributions of the corresponding quarks in the proton. The most characteristic feature of the cross sections (7) is their scaling since the cross sections, except for the increasing energy factor, depend only on the scaled variables x and y. It should be noted that scaling is well confirmed in the experiments up to lepton energies of 30 GeV. Thereafter, one observes deviations which are of the greatest interest since they may be due, on the one hand, to the production of particles with new quantum numbers, and, on the other, to the manifestation of corrections due to the strong interaction. The actual form of these corrections is very important for testing the validity of different models of strong interactions, in particular the ones we shall consider below.

We should like here to dwell on two aspects of the parton picture and its correspondence with the experimental data. Because the expressions for the cross sections of the neutrino reactions (5c) and (5d) and the corresponding expressions for the reactions of deep inelastic electroproduction (5a) and (5b) contain the same distribution functions $u(x)$, $d(x)$, $\bar{u}(x)$, $\bar{d}(x)$, and the cross sections of the reactions (5a) and (5b) obviously depend on the charges of the quarks, by comparing the two types of reaction one can extract a simple sum rule that enables one to determine the sum of the squares of the quark charges, i.e., $(Q/e)_u^2 + (Q/e)_d^2$, which for a model with fractional charges must be equal to 5/9. The experiment gives a value which agrees with this number. In the first place, this indicates that the standard quark model is not contradictory. However, one cannot yet regard this result as proof of the quarks having fractional charges. In a number of other models, for example, in a gauge model with integrally charged quarks, [1] predictions are obtained for the sum rule that also agree with the experiment. But, of course, the number 5/9 is obtained most naturally in the standard quark model.

The second aspect relates to the bases of the quark-parton model. In accordance with the parton model, the total momentum of all the quarks making up a hadron must be equal to the momentum of the hadron itself. This leads to the simple sum rule

$$\sum_q \int_0^1 xq(x)\,dx = 1, \tag{8}$$

where the summation is over all species of quarks and antiquarks. However, the relation (8) is in crass disagreement with experiment, which gives ~0.5 for the right-hand side. Thus, half of the hadron momentum is not carried by quarks at all, but by something else which feels neither weak nor electromagnetic interactions. This something else has been called gluons, i.e., particles of fields that carry only the strong interaction and "glue" the quarks within the hadrons. However, this interpretation produces very serious difficulties for models of quark bags, which describe the classification of the hadrons and their static properties such as the magnetic moments, the electromagnetic radii, and so forth. Indeed, to obtain the ratio of the neutron and proton magnetic moments $\mu_N/\mu_P = -2/3$, which agrees splendidly with experiment, we use wave functions of the neutron and proton constructed exclusively from quark wave functions with perfectly definite symmetry properties. But the introduction of a strong admixture of gluons, which moreover, as we shall see below, have spin 1, must, it would seem, completely destroy this symmetry. The same arguments apply to other aspects of the hadron classification. Thus, one of the important problems for the modern composite model is to reconcile the strong violation of the sum rule (8) and the fact of good fulfilment of the predictions of the simple quark model for the static properties of hadrons. We should like to emphasize this important aspect as an example of an unresolved problem in the way of our achieving a new level of understanding in particle physics, such as we mentioned in the introduction to the review.

Concluding our discussion of the composite quark model, we mention that the overwhelming majority of the facts support the validity of the standard quark model, in which there are not less than four species of quarks with fractional charges, each in three color states. At the same time, one cannot rule out certain alternative models, for example, the Pati–Salam gauge model[1] with quarks having integral electric charges.

GAUGE THEORIES WITH SPONTANEOUS SYMMETRY BREAKING AND UNIFIED DESCRIPTION OF WEAK AND ELECTROMAGNETIC INTERACTIONS

We now turn to discussing modern predictions and the dynamics of elementary-particle interactions. The formalism for describing these interactions is of course quantum field theory.[21] Until recently, we have had only one example of a well developed theory—quantum electrodynamics, i.e., the theory of the interaction of photons with charged leptons. Quantum electrodynamics has two very important advantages. First, this theory is renormalizable. This means that the mathematical uncertainties which arise as a result of the multiplication at coincident arguments of the generalized functions with which quantum field theory deals can be eliminated in each order of perturbation theory by a redefinition of the charges and masses of the particles. In other words, in this case a program of renormalizations can be carried out in each order of perturbation theory. After the renormalizations have been made, all the perturbation theory calculations are rendered unambiguous and the second advantage comes to the fore—the small value of the coupling constant, or rather the expansion parameter $e^2/4\pi=\alpha=1/137$. The smallness of this expansion parameter leads to a remarkable agreement between the results of perturbation theory calculations and experiments. Attempts to apply the methods developed in quantum electrodynamics to other interactions, namely the strong and the weak, did not lead until recently to significant successes. In the case of the strong interactions, one could attribute this simply to the computational difficulties associated with the larger values of the coupling constant. But in the case of weak interactions fundamental difficulties were found. The four-fermion $V-A$ theory of Fermi, Gell-Mann, and Feynman was found to be unrenormalizable, this being manifested, in particular, in the growth of the neutrino interaction cross sections with the energy, as can be readily seen in the expressions (7a) and (7b) given above. As was first noted by Blokhintsev, this behavior at very high energies comes into conflict with the unitarity condition (conservation of probability). The energy $s\approx 2\pi/G\approx(1000\ \mathrm{GeV})^2$ at which this conflict occurs has been called the unitary limit. It is obvious that at energies of the order of or greater than the unitary limit we can no longer use perturbation theory and, in particular, Eqs. (7a) and (7b); one would have to consider the perturbation series as a whole, which is an exceptionally complicated problem. Despite some successes in this direction (see, for example,[22] and the references given there), we are still very far from a solution of this problem. It was therefore very natural that one should wish to avoid the nonrenormalizability of the weak interactions and, in the first place, the growth of the total neutrino cross sections. This last can be achieved comparatively easily. Namely, if we replace the four-fermion interaction of charged currents $H_{int}=(G/\sqrt{2})J_\alpha J_\alpha^+$, where $J_\alpha=\bar{\nu}_\mu\gamma_\alpha(1-\gamma_5)\mu+\bar{u}\gamma_2(1-\gamma_5)d+\ldots$, by an interaction with a charged vector boson W_α: $H_{int}=gJ_\alpha W_\alpha$, $g^2/M_W^2=G/\sqrt{2}$, then we obtain a theory that is identical with the four-fermion theory at energies $s\ll M_W^2$ and leads to a constant neutrino cross section for $s\gg M_W^2$. However, a theory with a charged vector boson still remains unrenormalizable, which is manifested in particular by the growth of other cross sections, for example, the cross section of the process $\nu\bar{\nu}\to W^+W^-$. If we introduce in addition a neutral vector boson Z^0, then in this reaction too we can construct a mechanism for canceling the increasing terms by the exchange of Z^0. It is precisely this possibility which is realized, as we shall see, in gauge theories with spontaneously broken symmetry. The fundamentals of such theories have already been discussed extensively in the literature.[23] Let us illustrate the essence of the problem with a simple example.

Consider the Higgs model[24] with the Lagrangian

$$\mathscr{L}=\frac{\partial\varphi^+}{\partial x^\mu}\frac{\partial\varphi}{\partial x^\mu}-m^2\varphi^+\varphi-\lambda(\varphi^+\varphi)^2-\frac{1}{4}F_{\mu\nu}F_{\mu\nu}+ +ie\left(\varphi^+\frac{\partial\varphi}{\partial x^\mu}-\frac{\partial\varphi^+}{\partial x^\mu}\varphi\right)A_\mu+e^2A_\mu A_\mu\varphi^+\varphi, \tag{9}$$

where $\varphi=(\varphi_1+i\varphi_2)/\sqrt{2}$ is a complex scalar field, A_μ is a vector field, and $F_{\mu\nu}=\partial A_\mu/\partial x^\nu-\partial A_\nu/\partial x^\mu$. The theory described by such a Lagrangian is renormalizable but it contains a massless vector field. At the first glance one would therefore think it could be used only to describe the electromagnetic interaction. This Lagrangian is obviously invariant under the gauge transformations

$$\varphi\to e^{i\theta(x)}\varphi,\quad \varphi^+\to e^{-i\theta(x)}\varphi^+,\quad A_\mu\to A_\mu+\frac{1}{e}\frac{\partial\theta}{\partial x^\mu}. \tag{10}$$

Thus, we have symmetry under the simplest group $U(1)$. The real and imaginary parts of the field φ transform as follows:

$$\varphi_1'=\cos\theta\varphi_1-\sin\theta\varphi_2,\quad \varphi_2'=\sin\theta\varphi_1+\cos\theta\varphi_2,$$

i.e., there is symmetry under rotation in the φ_1, φ_2 plane and no distinguished direction in this plane. It is obvious that this problem has a solution that satisfies the original symmetry and has a normal vacuum such that

$$\langle 0\,|\,\varphi_1\,|\,0\rangle=\langle 0\,|\,\varphi_2\,|\,0\rangle=0.$$

However, this problem is interesting in that it also has a solution with degenerate vacuum, in other words, with spontaneously broken symmetry. It is well known that the concept of a degenerate vacuum played a decisive role in problems of statistical physics such as superfluidity, superconductivity, and ferromagnetism. The general method of solving problems with degenerate vacuum was developed by Bogolyubov.[25] Following this method, we investigate our simple problem and to

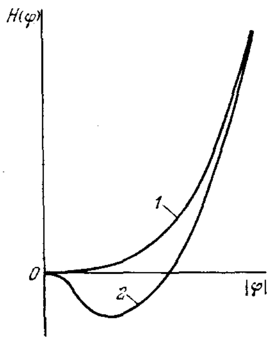

FIG. 1.

this end add to the Lagrangian (9) a small term $\varepsilon\varphi_1$ that breaks the symmetry (10), having in mind the passage to the limit $\varepsilon \to 0$ at the end. In this case, the vacuum expectation value of φ_1 is no longer zero:

$$\langle 0 \mid \varphi_1 \mid 0 \rangle = \eta \tag{11}$$

and we redefine the fields:

$$\varphi_1 = \eta + \chi, \quad \varphi_2 = \psi, \quad \langle 0 \mid \chi \mid 0 \rangle = \langle 0 \mid \psi \mid 0 \rangle = 0. \tag{12}$$

Substituting (12) into (10) with allowance for the small correction, we obtain

$$\begin{aligned}\mathscr{L} = {} & \frac{1}{2}\frac{\partial\psi}{\partial x^\mu}\frac{\partial\psi}{\partial x^\mu} + \frac{1}{2}\frac{\partial\chi}{\partial x^\mu}\frac{\partial\chi}{\partial x^\mu} - \frac{m^2}{2}(\psi^2+\chi^2) - m^2\chi\eta - \frac{m^2}{2}\eta^2 \\ & - \frac{1}{4}F_{\mu\nu}F_{\mu\nu} + e\left(\psi\frac{\partial\chi}{\partial x^\mu} - \chi\frac{\partial\psi}{\partial x^\mu}\right)A_\mu - e\eta\frac{\partial\psi}{\partial x^\mu}A_\mu \\ & - \frac{\lambda}{4}[\psi^4 + 2\psi^2(\chi^2 + 2\chi\eta + \eta^2) + \chi^4 + 4\chi^3\eta + 6\chi^2\eta^2 + 4\chi\eta^3 + \eta^4] \\ & + \frac{e^2}{2}A_\mu A_\mu(\psi^2 + \chi^2 + 2\chi\eta + \eta^2) + \varepsilon\eta + \varepsilon\chi.\end{aligned} \tag{13}$$

The requirement (12) leads in the lowest order to the compensation equation

$$\lambda\eta^3 + m^2\eta = \varepsilon. \tag{14}$$

It is easy to see that in the limit $\epsilon \to 0$ the compensation equation (14) has two solutions: the first $\eta = 0$, which corresponds to the normal vacuum and preserves the original symmetry, and the solution

$$\eta^2 = -\frac{m^2}{\lambda} = \frac{m_0^2}{\lambda}, \tag{15}$$

which is realized if the parameter $m^2 = -m_0^2$ is negative. The appearance of the solution (15) in this case can be readily understood by considering the classical energy H as a function of the value φ of the scalar field. Indeed, writing down the expression for $H(\varphi)$ in the case of a constant field φ, we obtain

$$H(\varphi) = m^2 \mid \varphi \mid^2 + \lambda \mid \varphi \mid^4.$$

Plotting this dependence (see Fig. 1), we obtain qualitatively different curves for the cases $m^2 > 0$ (curve 1) and $m^2 = -m_0^2$ (2). As we see, in the first case the minimum of the energy corresponds to the value $|\varphi| = 0$, i.e., the trivial solution. In the second case, the value $|\varphi| = 0$ also corresponds to an extremal point, but in this case it does not correspond to the minimum of the energy, which occurs at the point $|\varphi|^2 = m_0^2/\lambda$. Therefore, the solution (15) is realized here. In this solution, the vacuum is degenerate with respect to rotations in the φ_1, φ_2 plane, and the choice of a definite direction, which is achieved by introducing the original perturbation $\varepsilon\varphi_1$, breaks the original symmetry (10). Thus, the symmetric problem has symmetric equations but an asymmetric degenerate solution. Let us now see what happens to the fields χ and ψ if the solution (15) is realized. For this, we write down the kinetic-energy terms of these fields, i.e., the ones quadrative in the fields:

$$\frac{1}{2}\frac{\partial\psi}{\partial x^\mu}\frac{\partial\psi}{\partial x^\mu} + \frac{1}{2}\frac{\partial\chi}{\partial x^\mu}\frac{\partial\chi}{\partial x^\mu} + \frac{m_0^2}{2}(\psi^2+\chi^2) - \frac{\lambda}{2}\eta^2\psi^2 - \frac{3}{2}\lambda\eta^2\chi^2. \tag{16}$$

Using the solution (15), we see that the field φ is massless, and the field χ has mass $m_\chi = \sqrt{2}m_0$. The appearance of the massless field ψ is a reflection of a general property of theories with degenerate vacuum, in which there must necessarily exist excitations whose spectrum begins at zero. This general theorem was proved in statistical physics by Bogoloyubov and, in application to quantum field theory problems, by Goldstone. The appearance of massless scalar fields in quantum field theory problems with degenerate vacuum delayed for a certain time the use of this fruitful and attractive concept in elementary particle theory; for whereas zero-mass excitations really do exist in problems of statistical physics and are manifested experimentally, the long-range forces that must be associated with a massless scalar field do not occur in nature. It was a great step forward when the recognition came that this problem can be successfully solved in gauge theories, an example of which we now consider. Indeed, let us consider in addition to the terms (16) the other quadratic terms, which also contain the vector field:

$$\frac{1}{2}\frac{\partial\psi}{\partial x^\mu}\frac{\partial\psi}{\partial x^\mu} + \frac{1}{2}\frac{\partial\chi}{\partial x^\mu}\frac{\partial\chi}{\partial x^\mu} - m_0^2\chi^2 - \frac{1}{4}F_{\mu\nu}F_{\mu\nu} - e\eta\frac{\partial\psi}{\partial x^\mu}A_\mu + \frac{e^2}{2}\eta^2 A_\mu A_\mu. \tag{17}$$

If we now introduce the new field $B_\mu = A_\mu - (1/e\eta)\partial\psi/\partial x^\mu$, we readily see that (17) is transformed to

$$\frac{1}{2}\frac{\partial\chi}{\partial x^\mu}\frac{\partial\chi}{\partial x^\mu} - m_0^2\chi^2 - \frac{1}{4}F_{\mu\nu}F_{\mu\nu} + \frac{e^2\eta^2}{2}B_\mu B_\mu, \quad F_{\mu\nu} = \frac{\partial B_\mu}{\partial x^\nu} - \frac{\partial B_\nu}{\partial x^\mu}. \tag{18}$$

Thus, the massless field ψ has disappeared from the kinetic-energy part of the Lagrangian, and we see instead that the vector field B_μ has acquired the mass $m_B = e\eta$. Physically, this phenomenon, which is now called the Higgs effect, is readily comprehensible. The original massless field A_μ had two polarization states. The massive field B_μ has three such states. It is precisely the unwanted massless scalar field ψ that is needed to produce the additional degree of freedom, while the other scalar field χ remains observable, which is a characteristic feature of all such theories. We have therefore shown that in gauge theories the solution with degenerate vacuum does not contain the undesirable zero-mass excitations, and we have therefore gained the possibility of applying them to actual physical problems. Another important step was the proof by t'Hooft that the degeneracy of the vacuum does not destroy the renormalizability of the theory,[26] despite the fact that the vector fields acquire mass.

We have already noted above that massive particles, both charged and neutral, would be very desirable for creating a renormalizable theory of weak interactions. For this, it will be necessary to use multiplets of vector gauge fields, as first introduced by Yang and Mills.[27] In this case, the gauge transformations (10) are generalized. For example, if the Yang–Mills vector field A^i_μ is a triplet of the group $SU(2)$, and the complex scalar field φ is a doublet, then the gauge invariant Lagrangian is written as follows:

$$\mathcal{L}=\frac{\partial\varphi^+}{\partial x^\mu}\frac{\partial\varphi}{\partial x^\mu}-m^2\varphi^+\varphi-\lambda(\varphi^+\varphi)^2-\frac{1}{4}G_{\mu\nu}G_{\mu\nu}+ie\left(\varphi^+A_\mu\frac{\partial\varphi}{\partial x^\mu}-\frac{\partial\varphi^+}{\partial x^\mu}A_\mu\varphi\right)+e^2A_\mu A_\mu\varphi^+\varphi, \tag{19}$$

where $A_\mu=(\tau^i/2)A^i_\mu$, τ^i are Pauli matrices ($i=1, 2, 3$), and

$$G_{\mu\nu}=\frac{\partial A_\mu}{\partial x^\nu}-\frac{\partial A_\nu}{\partial x^\mu}+ie(A_\mu A_\nu-A_\nu A_\mu).$$

The gauge transformations under which the Lagrangian is invariant are

$$\left.\begin{aligned}&\varphi\to\exp\left[i\frac{\tau^k\theta^k(x)}{2}\right]\varphi=S\varphi,\\&\varphi^+\to\varphi^+\exp\left[-i\frac{\tau^k\theta^k(x)}{2}\right]=\varphi^+S^{-1},\\&A_\mu\to SA_\mu S^{-1}+\frac{i}{e}S\frac{\partial S^{-1}}{\partial x^\mu}.\end{aligned}\right\} \tag{20}$$

One can then carry out the same program as in the simple Higgs example considered above. Thus, in the framework, of a renormalizable theory the vacuum degeneracy enables us to obtain charged and neutral massive vector fields, which can serve as carriers of the weak interaction. Moreover, depending on the method of symmetry breaking, some of the vector fields may remain massless, and one of them can be used to describe the electromagnetic field. Thus, in the framework of a gauge theory with degenerate vacuum we obtain the possibility of a unified description of weak and electromagnetic interactions. This decisive success of gauge theories seems to us most attractive. It suggests that we have achieved a qualitatively new stage in our understanding of the nature of particle interactions. Invoking an historical analogy, we could compare the unification of the weak and electromagnetic interactions with the unification of the electric and magnetic fields in the framework of Maxwell's equations, which led to such fruitful results in the most varied fields of human activity.

The actual schemes for unifying weak and electromagnetic interactions depend on the symmetry group that we choose for the gauge theory. It has now been established that the minimal group in which we can unify the weak and electromagnetic interactions without coming into conflict with the experiments is the group $SU(2)\times U(1)$, which leads to the well-known Salam–Weinberg model.[28] This means that in the original unbroken theory we have a triplet of massless vector fields W^+_μ, W^μ_0, and W^-_μ and also a singlet B_μ. After the program of spontaneous symmetry breaking has been carried through, the charged bosons W^+ and W^- acquire mass, as does also the field superpositions $Z^0=\cos\theta W^0+\sin\theta B$, whereas the orthogonal superposition $-\sin\theta W^0+\cos\theta B$ remains massless and is associated with the photon. The mixing angle θ remains a free parameter of the theory and is called the Salam–Weinberg angle. From the comparison with the known coupling constants of the weak and the electromagnetic interactions, we obtain the following values for the masses of the bosons $W^\pm$ and Z^0:

$$\begin{aligned}M_W&=\frac{1}{2|\sin\theta|}\sqrt{\frac{e^2}{\sqrt{2}G}}\approx\frac{37(\mathrm{GeV}/c^2)}{|\sin\theta|},\\M_Z&=\frac{M_W}{|\cos\theta|}=\frac{74(\mathrm{GeV}/c^2)}{|\sin 2\theta|}.\end{aligned} \tag{21}$$

The existence of the neutral intermediate boson means that the weak interactions entail not only the known charged currents, which lead, for example, to the reactions (5c) and (5d), but also neutral currents, which interact by means of exchange of the boson Z^0. In the framework of the symmetry group $SU(2)\times U(1)$, the neutral current consists of two parts: One corresponds to the third component of the "weak" isospin, which is related to the group $SU(2)$, and the second is proportional to the electromagnetic current:

$$J^0_\mu=J_{3\mu}-\sin^2\theta J_{\mu\,\mathrm{e.m.}}.$$

Now we know the electromagnetic current: It is determined by the charges of the quarks, and we can obtain the third component of the isospin from the charged components corresponding to the known charged currents by using the group relations

$$[I^+, I^-]=2I_3, \tag{22}$$

where

$$I^\pm=\int d^3x J^\pm_0(x),\quad I_3=\int d^3x J_{30}(x);$$

here $J_0(x)$ is the time component of the corresponding current. We know the form of the charged current for leptons, and also for ordinary quarks, which follows from numerous data on decays and neutrino reactions:

$$J^+_\mu=\bar{e}\gamma_\mu(1-\gamma_5)\nu_e+\bar{\mu}\gamma_\mu(1-\gamma_5)\nu_\mu+(\cos\theta_C\bar{d}+\sin\theta_C\bar{s})\gamma_\mu(1-\gamma_5)u, \tag{23}$$

where θ_C is the well-known Cabibbo angle. The first term in the quark part of the current corresponds to strangeness-conserving weak processes, and the second, which is proportional to $\sin\theta_C\approx 0.22$, leads to strangeness-changing processes. We now use the expressions (22) and (23) to calculate the neutral current. The lepton part of the current will then contain the terms $\bar{\nu}_\mu\nu_\mu$, $\bar{\nu}_e\nu_e$, $\bar{e}e$, $\bar{\mu}\mu$, whereas the quark part

$$\begin{aligned}J_3&=\bar{u}\gamma_\mu(1-\gamma_5)u+\cos^2\theta_C\bar{d}\gamma_\mu(1-\gamma_5)d\\&+\sin\theta_C\cos\theta_C[\bar{s}\gamma_\mu(1-\gamma_5)d+\bar{d}\gamma_\mu(1-\gamma_5)s]\\&+\sin^2\theta_C\bar{s}\gamma_\mu(1-\gamma_5)s\end{aligned} \tag{24}$$

contains, in addition to the first two terms, which do appear experimentally in neutral neutrino reactions of the form $\nu_\mu + N \to \nu_\mu +$ hadrons, a third, extremely undesirable term. The trouble is that this term leads to a strangeness-changing interaction of neutral currents, which emphatically contradicts experiment. In particular, if (24) were to hold, then there should be significant probabilities of the decays

$$K^+ \to \pi^+ \nu\bar{\nu}, \quad K_L \to \mu^+\mu^-, \ldots$$

Experimental bounds on the probabilities of these decays completely rule out the existence of strangeness-changing neutral currents of the form (24). If we wish to eliminate such currents, but at the same time keep the form of the charged current (23) for known particles, there is but one way out—the introduction of a new quark c with a new quantum number—charm. To the expression (23) one must then add a new term, which contains a combination of the d and s quarks orthogonal to the one used in (24):

$$(-\sin\theta_C \bar{d} + \cos\theta_C \bar{s})\,\gamma_\mu\,(1-\gamma_5)\,c. \qquad (25)$$

Then if the charged currents commute, the strangeness-changing neutral currents obtained from (23) and (25) cancel each other, and we arrive at a diagonal neutral current that not only contains no contradictions with experiment but gives a good description of the existing data on neutral neutrino reactions. This argument, which is due to Glashow, Iliopulos, and Maiani, [29] shows that in the framework of gauge theories the existence of a fourth quark c is essential in the presence of ordinary neutral currents. We should therefore like to emphasize that the discovery of charmed particles (D mesons) is a real coup de grâce and indicates that, basically, we understand the structure of the elementary particle interactions.

It should be noted that the data on the neutral neutrino reactions

$$\nu_\mu + N \to \nu_\mu + X,$$
$$\bar{\nu}_\mu + N \to \bar{\nu}_\mu + X,$$
$$\nu_\mu\,(\bar{\nu}_\mu) + e \to \nu_\mu\,(\bar{\nu}_\mu) + e$$

agree well with the predictions of the Salam–Weinberg model if the mixing angle has the value $\sin^2\theta \approx 0.35$. This value of the angle leads to the following masses for the intermediate vector particles: $M_X c^2 \approx 62$ GeV and $M_Z c^2 \approx 78$ GeV. Of course, at the present time we cannot assume that this precise model is correct. A great number of models that use different symmetry groups and different numbers of quarks and leptons are discussed in the literature. Some of them are also in good agreement with the experiments but give different masses for the intermediate bosons. Of course, the most decisive indication of the validity of unified gauge theories in general and the particular choice of the model, in particular, would be a proof of the existence of these vector particles and a determination of their masses. This could be achieved either by direct observation of W or Z or by studying the behavior of the weak interaction cross sections at superhigh energies; for since the cross section (7) contains the factor $M_W^4(M_W^2 - q^2)^2$ if intermediate particles are present, this factor will be manifested at energies $s \geq M_W^2$. Since the predictions for the masses of the intermediate bosons in the various models range over the interval 50–150 GeV, both these possibilities require the construction of accelerator facilities with an energy more than 200 GeV in the center of mass system. Let us emphasize once more that the solution to the problem of unifying the weak and electromagnetic interactions is of fundamental importance.

After the formulation of the unified gauge theories of weak interactions, attempts were naturally made to include strong interactions as well in a unified gauge scheme. Here, it has not yet proved possible to achieve such elegant constructions as in the preceding case. However, the examination of various possibilities has led to the formulation of a gauge theory of quark interaction with massless vector color fields (gluons), [30] and this is now regarded as a serious candidate for the theory of strong interactions. We shall consider this possibility very briefly. We know that if quarks exist they have three color states. The simplest group describing the symmetry of these states is the group $SU_c(3)$, where the subscript c indicates the color nature of this group. In this theory, which has received the name quantum chromodynamics, it is assumed that the strong interactions are transmitted by gauge vector color fields, which form an octet representation of the group $SU_c(3)$. These fields are completely analogous to the Yang–Mills fields that we discussed earlier. The Lagrangian of the interaction of these fields and the quarks is then expressed in the very simple form

$$\mathscr{L}_{\text{int}} = g \sum_q \bar{q}\gamma_\mu B_\mu^i \lambda^i q, \qquad (26)$$

where the summation is over all quark species, B_μ^i are octets of gauge fields ($i = 1, 2, \ldots, 8$) and λ^i are the eight generators of the group $SU_c(3)$ in the quark representation (3×3). It is assumed that in this case there is no spontaneous symmetry breaking, so that the gluons do not have mass and the symmetry $SU_c(3)$ is exact.

This model has a number of advantages. First, in the framework of it one can understand why leptons, which are singlets with respect to the group $SU_c(3)$, do not have strong interactions; for a singlet can in no way interact with an octet in such a way that the interaction is $SU(3)$ invariant. Second, this theory is "asymptotically free," i.e., in it the effective coupling constant $\alpha_s(k^2)$ of the strong interaction with the gluons decreases at large values of k^2, which guarantees scaling in deep inelastic processes. And, third, the vanishing of the gluon masses and the nature of their interaction with one another provides hope that in this theory the quarks and gluons are confined within particles. In fact, the requirement of confinement is necessary for the validity of quantum chromodynamics since if the gluon fields were to exist outside particles this would lead to strong long-range forces. However, it has not yet been possible to prove that confinement does occur in quantum chromodynamics, i.e., only singlet states with respect to $SU_c(3)$ are observable. Therefore, to describe a composite model of particles in the framework of quantum chromodynamics phenomenological approaches are used, two in particular being popular. The first may be called the potential approach. In it, it is postulated that at short distances between, for example, a quark and an antiquark the ordinary Coulomb potential is valid with the corresponding constant and logarithmic corrections. But at larger distances the potential increases linearly with the distance to infinity, which creates an insurmountable barrier for the escape of quarks from particles. Such a model with appropriately chosen parameters gives good agreement for the masses of a large number of states.

Another approach is called the bag model. In this approach, the particles have a definite but deformable surface of radius about 10^{-13} cm, the boundary conditions on the surface being formulated in such a way that the surface is impenetrable for colored objects, i.e., for quarks and gluons, but is transparent for color singlets (leptons, photons). In such a model, one can also achieve successes in describing the spectrum of hadrons and their static properties.

The most important problems for the composite model in the framework of quantum chromodynamics is the question of states with nonstandard number of quarks and antiquarks in a particle. For example, nothing rules out the existence of a bag containing no quarks at all but only gluons. On the other hand, one could have bags with anomalously large number of quarks, right up to macroscopic numbers. The problem of gluonium is an important experimental problem. Among the known states, there are as yet no candidates for its role. On the other hand, the problem of the existence of bags with an immense number of quarks—quark stars—is a problem for astrophysics.

In our opinion, the foundations of quantum chromodynamics, both experimental and theoretical, are not yet as firm as for the corresponding unified theories of the weak and electromagnetic interactions. However, the examples we have discussed show that gauge theories are attractive from the most varied points of view.

CONCLUSIONS

Above, we have considered the main conclusions that have now been deduced about the structure of elementary particles and their interactions. It must be emphasized that the level achieved by experiment and theory does not yet permit a final conclusion about the validity of such a picture. Indeed, different alternative possibilities are discussed in theory, some based on quarks and gauge fields, other using different basic assumptions. Therefore, the main problem facing high energy physics is the testing of the basic propositions of the ideas discussed in this review. Above all, this means establishing what is the set of basic particles we confront in nature.

Bearing in mind our discussions, let us summarize what we know, what we assume, and what we should like to discover about the three main groups of particles.

a) Hadrons consist of quarks, of which there must be not less than four species, each in three color modifications. Here, the main problem is whether they are absolutely "captive" or not. It is also very important to establish whether they have the quantum numbers we ascribe to them, and above all whether their charges are fractional. The next question is: Is it necessary to augment the family of 12 quarks with additional new quarks? And, finally, is the proton absolutely stable?

b) Currently, there are ten known leptons: e, ν_e, μ, ν_μ, τ and their antiparticles. Do there exist other leptons, in particular neutrinos corresponding to the heavy lepton τ? To what accuracy are the lepton quantum number and the numbers that distinguish the individual leptons (e, μ, τ) conserved? Here, experiments on neutrino oscillations would be of great value.

c) The family of intermediate particles, which previously consisted of just the photon, has been augmented by the new, as yet hypothetical gauge particles: the weak intermediate bosons W^+, W^-, Z^0 and the eight color gluons. Here the main question is: Do they really exist? With regard to W and Z, we must obtain a direct answer when a center of mass energy greater than 200 GeV is achieved. The question of the existence of the color gluons is related to the validity of absolute confinement. The question could also be answered by the discovery of gluonium. The next question is this: Are just these intermediate particles sufficient, or do more exist? In all schemes that unify strong, weak, and electromagnetic interactions, an appreciably larger number of intermediate gauge fields is required. And, finally, do scalar Higgs particles exist?

We see that the number of members in each of the three groups has increased with the accumulation of experimental data and the development of theory. We cannot say whether there is a limit to this process, or where it may be. As an illustration, we can give the interesting model developed in a cycle of papers (see[2]). In this model, the strong, weak, and electromagnetic interactions are unified in the framework of the exceptional group E_7. $SU(6)\times SU(3)$ is a maximal subgroup of E_7. Its last factor is identified with the color group $SU_c(3)$. The basic representation of the group E_7, which corresponds, by hypothesis, to spin 1/2 particles, decomposes as follows into representations with respect to the subgroup $SU(6)\times SU_c(3)$:

$$(6, 3) + (\overline{6}, \overline{3}) + (20, 1),$$

where the first index designates the multiplicity of the representation with respect to the group $SU(6)$, which distinguishes the particles according to quantum numbers, and the second designates the color multiplicity. Thus, we obtain six quarks in each of three color modifications, their antiquarks (the second term), and 20 leptons, which are color singlets. In this model, it is therefore predicted that the four known quarks are augmented by two new quarks with charge $-e/3$ and that there are, besides the ten known leptons, ten further new leptons, both charged and neutral. With regard to the intermediate vector particles, there must be in this case a great many of them. They include the already familiar W, Z, the massless gluons, and more than a hundred new particles, with very large masses. Only further investigations can show whether or some other model is valid.

With regard to the interaction dynamics of the elementary particles, the diverse problems here touch all the processes that are currently investigated and may be investigated with future accelerators. This applies to all the interactions—strong, electromagnetic, and weak.

For our understanding of the structure of particles and their interactions, fundamental importance attaches to experiments at high and superhigh energies aimed at determining the total interaction cross sections of particles, the differential cross sections, the inclusive spectra, especially at high transverse momenta of the produced particles, and the laws governing multiparticle production and the formation of jets. Of great importance too are experiments to determine more accurately the spectrum of the "old" particles and resonances and to investigate the laws governing the production of new particles. Fundamental information has already been gained and, no doubt, more will be gained in investigations of reactions of electrons, muons, and neutrinos with hadrons and electron–positron annihilation processes. Many fundamental questions in the physics of weak interactions can be studied through the decays of particles. There is, for example, the very important problem of the violation of CP invariance. Of course, it is difficult to foresee the direction of investigations in which the most important results will be obtained. All we can say is that the investigations must be pursued on a wide front.

In conclusion, we should like to express once more our conviction that these future investigations in high energy physics will lead to new successes in our understanding of the laws that govern the structure of particles and their interactions—and ultimately it is these laws that determine all the phenomena in nature.

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Translated by Julian B. Barbour