сообщения
объединенного
института
ядерных
исследований
дубна

D2-85-206

N.N.Bogolubov

COLOUR QUARKS AS A NEW LEVEL OF UNDERSTANDING THE MICROCOSM

1985

D2-85-206

N.N.Bogolubov

COLOUR QUARKS AS A NEW LEVEL OF UNDERSTANDING THE MICROCOSM

Боголюбов Н.Н. Д2-85-206

Цветные кварки — новая ступень познания микромира

Доклад на общем собрании Академии наук СССР, прочитанный академиком Н.Н.Боголюбовым 18 марта 1985 года в связи с вручением ему высшей награды АН СССР — Золотой медали им.М.В.Ломоносова.

Сообщение Объединенного института ядерных исследований. Дубна 1985

Bogolubov N.N. D2-85-206

Colour Quarks as a New Level of Understanding the Microcosm

A talk given at the general meeting of the Academy of Sciences of the USSR held on March 18, 1985 at the ceremony of presentation of the M.V.Lomonosov Gold Medal.

Communication of the Joint Institute for Nuclear Research. Dubna 1985

The future of physics and a successful development of other branches of natural science based on its achievements depend to a great extent on the advance in understanding the intrinsic structure and fundamental laws of the elementary particle interaction.

The origin of matter is a perennial problem of natural science. The ancient view of matter as well as the modern theories of elementary particles rest on the idea of existence of pure elementary fundamental constituents of matter.

About 220 years ago the great Russian scientist M.V.Lomonosov in his papers "Micrology" and "Systems of Physics as a Whole" written shortly before his death tried to create a unified physical picture of the world on the basis of his "corpuscular philosophy" and his seeing of matter which "fills the ocean of the world space" and is governed by the "unbreakable laws of motion" /1/.

The twentieth century marked by the fundamental changes of our notions of space and time, creation of relativistic mechanics and quantum theory, elucidation of the atomic and nuclear structure and practical use of nuclear power, discovery of a unique world of elementary particles and understanding of the unity of all basic forces of nature added a fresh page to the history of the development of ideas on the origin of matter.

The creation of new engineering and technology in close relation with the development of fundamental investigations led to a new level in understanding the structure of elementary particles and atomic nucleus. A new science has emerged — high energy physics utilizing powerful accelerators of particle beams of high energy and intensities, large physical installations, modern electronics and high-speed computers.

A fruitful unification of relativistic and quantum mechanics gave rise to a new powerful branch — quantum field theory which has been for several decades the basis for high energy physics and nuclear physics, theoretical constructions in related branches of physics such as quantum statistics, solid state physics, biophysics, etc.

Efforts of many outstanding theoreticians especially of soviet scientists were crowned with success in formulating a grace and powerful apparatus of quantum field theory.

Based on the idea of renormalization invariance and renormalisation group method the theory of quantized fields succeeded in overcoming the difficulties thought to be insurmountable due to the so-called ultraviolet divergencies, which forced to reconsider critically the way of describing quantum fields interacting at small (even on the microcosm scale) distances.

This theory is based on several general principles such as the relativistic invariance, locality, microcausality, total probability conservation and others playing the role of a system of axioms in geometry.

Involving still new profound ideas like the notions of local gauge invariance, degenerate vacuum and spontaneous symmetry breaking, quantum field theory extends its boundaries thus turning into a powerful universal tool of investigations from the microcosm physics up to cosmological models of the early Universe.

Great advances in treating the fundamental laws of the microcosm have been made in high energy physics during the last decades due to intensive experimental and theoretical investigations. It became clear how significant is the role of the space-time and so-called intrinsic symmetries related with the most important conservation laws in the microcosm.

As a result of the development of this, so to say, symmetric approach, in the theory of elementary particles 20 years ago there emerged a highly fruitful composite quark model of strongly interacting particles, mesons and baryons, which exploits the notion of colour quarks.

The idea of colour quarks — fundamental fermions carrying a specific quantum number called colour and being, as well as leptons, the simplest constituents of matter makes the basis of modern concepts of the world of elementary particles and atomic nuclei.

For the last twenty years the theory of elementary particles uses the language of colour quarks. It initiated many achievements in the high energy physics. Without being aware of colour quarks as fundamental constituents of matter we could hardly advance in understanding the evolution of the early Universe, in realizing a powerful idea of unification of all basic forces of nature: electromagnetic, strong, weak and gravitational.

It is impossible to cover within the framework of one report all the most important steps in the development of the theory of colour quarks which is a central problem and a constituent of many fundamental investigations in elementary particle and high energy physics. In what follows I shall dwell upon some basic moments of the development of the theory of colour quarks and illustrate the most important, in our opinion, results obtained on its basis.

By the sixties the number of the observed strongly interacting particles and resonances, mesons and baryons or hadrons, as they are called now by physicists, amounted to many dozens of states.

Numerous attempts to find the key to understanding the laws in a vast sea of states still called elementary particles and to describe a variety of their properties such as masses, lifetimes, quantum numbers and decay modes, etc., led to the formulation of composite hadron models *(see Illustr.1)*.

A starting-point was in 1949 when Fermi and Yang put forward a hypothesis that the lightest of strongly interacting particles, π-meson, is not an elementary particle but a bound state of nucleon and antinucleon[2]. This hypothesis was soon recognized to be incorrect, however the search for "the most elementary particles" continued.

The next step in the development of the idea of composite particles was to compose a kind of "Mendeleev's table" for elementary particles. Of great importance was the discovery of the so-called unitary symmetry of elementary particles reflecting an approximate independence of dynamic properties of hadrons, belonging to the same family or unitary miltiplet, of a concrete set of quantum numbers: electric charge, isotopic spin, strangeness or "flavour" as is now often called.

When in 1964 Gell-Mann and Zweig introduced a hypothesis of quarks as hypothetical particles which could be used for constructing all the observed strongly interacting particles, mesons and baryons, quarks were treated rather as pure mathematical objects, in terms of which the properties of the unitary symmetry of strong interactions could be described in the simplest way *(see Illustr.2,3 and 4)*. Since quarks carry fractional electric and baryon charges and have never been detected in a free isolated state, they have not at once found a physical interpretation. There were some principal difficulties encountered by the quark model.

First, formation of hadrons from quarks with spin $j = 1/2$ led to the discrepancy with the Pauli principle for the systems of particles with half-integer spins, which plays a fundamental role in quantum mechanics and quantum field theory.

Then, there was still an open question: Why only the systems formed by quark-antiquark pairs (mesons) or triplets of quarks (baryons) are realized in nature and there are no indications to the existence of other many-quark states?

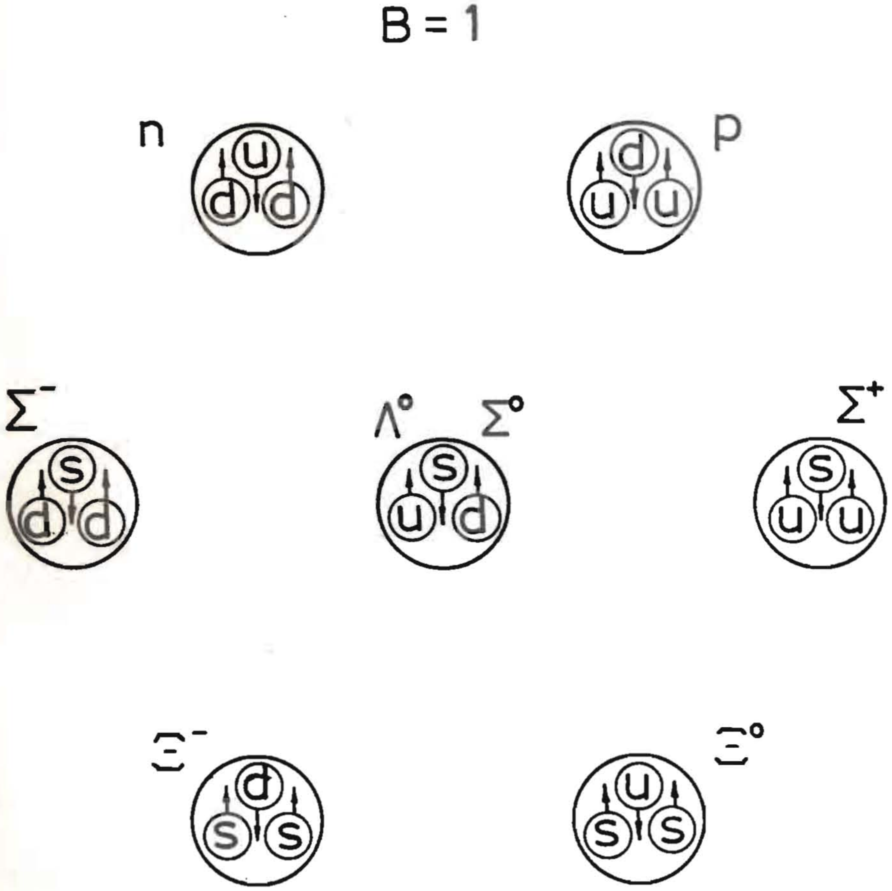
And finally, an explanation was needed to a striking fact why in spite of strenuous experimental searches quarks were not observed in free isolated states. The last problem is known as the problem of confinement.

The analysis of these fundamental problems of the elementary particle physics has driven in 1965 Tavkhelidze, Struminsky and me[5-7] and independently Hahn and Nambu[8] (USA) and Miyamoto[9] (Japan) to a hypothesis according to which quarks have a new earlier unknown quantum number or charge now called the colour.

According to this hypothesis quarks are ordinary fermions and, consequently, are governed by the Fermi-Dirac statistics. However, for each type of quarks with given values of the isotopic spin, electric charge and strangeness (i.e., for each flavour of quarks) there are three unitary equivalent states differing by values of the new quantum number, colour *(see Illustr. 5 and 6)*.

Thus, the general number of quarks constituting hadrons tripled after introducing the colour, though the number of hadrons observed in nature had to be the same. This fact can figuratively be expressed as follows: the observed hadrons, mesons and baryons, in contrast with quarks are colourless. In other words, colours of quarks compensate each other inside hadrons like electric charges of a nucleus and electrons around it compensate each other in atoms of chemical elements. However, this does not mean that colour never manifests itself in experiment *(see Illustr. 7)*.

Octet of baryons ($J=\frac{1}{2}$) ③

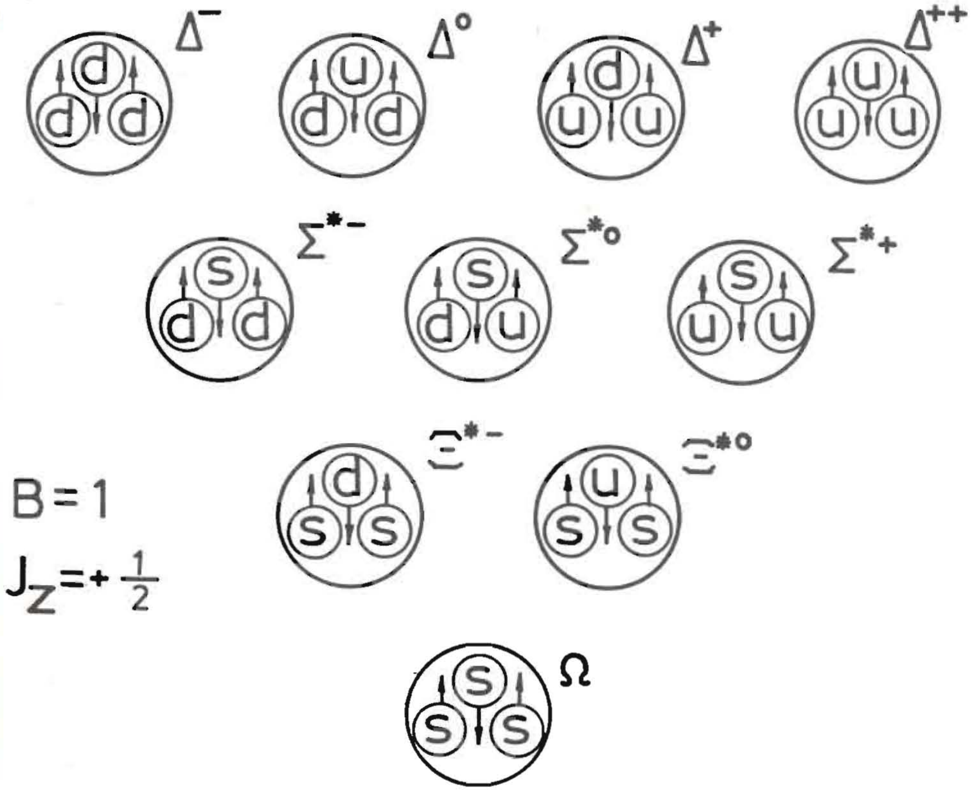


Addition rule of quark spins:

$p(J_z=\frac{1}{2})=\sqrt{\frac{2}{3}}|u^{\uparrow}u^{\uparrow}d^{\downarrow}> - \sqrt{\frac{1}{3}}|u^{\uparrow}u^{\downarrow}d^{\uparrow}>$

$n(J_z=\frac{1}{2})=\sqrt{\frac{2}{3}}|d^{\uparrow}d^{\uparrow}u^{\downarrow}> - \sqrt{\frac{1}{3}}|d^{\uparrow}d^{\downarrow}u^{\uparrow}>$, etc.

Decouplet of baryons with $J=3/2$: ④



$\Delta^{++}(J_z=+\frac{3}{2})=|u^{\uparrow}u^{\uparrow}u^{\uparrow}>$

$\Omega^{-}(J_z=+\frac{3}{2})=|s^{\uparrow}s^{\uparrow}s^{\uparrow}>$ etc.

Discrepancy with the Pauli principle:

Each fermion of a definite type may occupy one and only one quantum state! Are quarks fermions?

Hypothesis of colour quarks (1965)

Colour is a new quantum number allowing to arrange on the lowest energy level up to three quarks with coincident flavours and spin projections without the discrepancy with the Pauli principle for fermions.

Bogolubov
Struminsky
Tavkhelidze
*
Numbu, Hahn
*
Miyamoto

Colour states of quark : $q = (q, q, q)$

Hadrons are composed of quarks with different colours and have no colour themselves (are colourless):

$$\Omega^-(J_z = +\tfrac{3}{2}) = |\, s^{\uparrow} s^{\uparrow} s^{\uparrow} \rangle$$

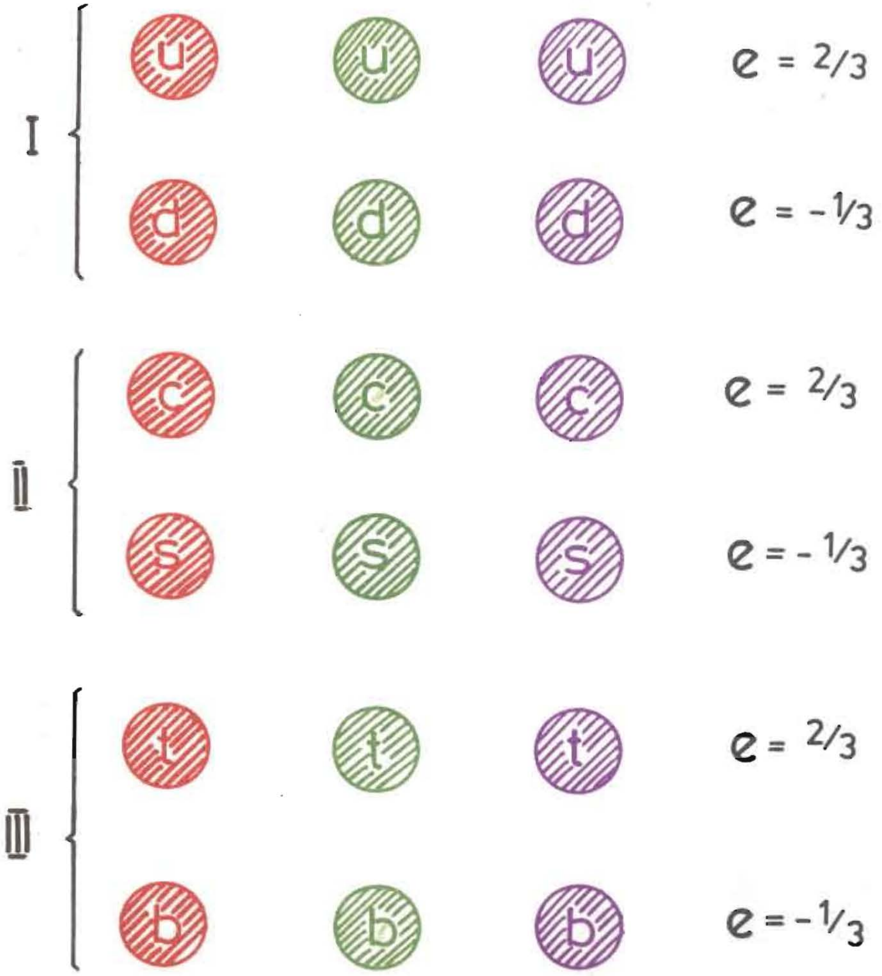
$$P(J_z = +\tfrac{1}{2}) = \frac{1}{\sqrt{18}} \Big\{ 2|\, u^{\uparrow} u^{\uparrow} d^{\downarrow} \rangle + 2|\, u^{\uparrow} d^{\downarrow} u^{\uparrow} \rangle +$$

$$+ 2|\, d^{\downarrow} u^{\uparrow} u^{\uparrow} \rangle - |\, u^{\uparrow} u^{\downarrow} d^{\uparrow} \rangle - |\, u^{\downarrow} u^{\uparrow} d^{\uparrow} \rangle -$$

$$- |\, u^{\uparrow} d^{\uparrow} u^{\downarrow} \rangle - |\, u^{\downarrow} d^{\uparrow} u^{\uparrow} \rangle - |\, d^{\uparrow} u^{\uparrow} u^{\downarrow} \rangle -$$

$$- |\, d^{\uparrow} u^{\downarrow} u^{\uparrow} \rangle \Big\} \text{ etc.}$$

Colour quarks



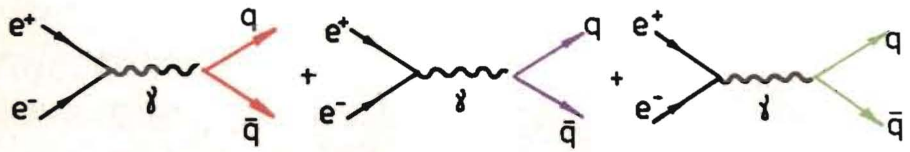
Spin $j = 1/2$. Baryonic number $B = 1/3$.

(Quantum numbers of antiquarks are opposite in sign).

Experimental manifestation of quark colour ⑦

Example: Annihilation of e^+e^- - pairs into hadrons at high energies $E=\sqrt{s}$:

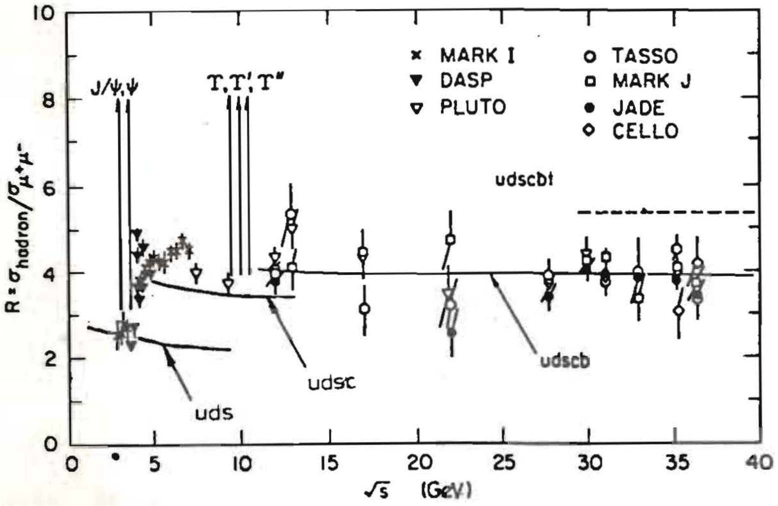
$$e^+ + e^- \to q+\bar{q} \to hadrons$$



$$R(s)=\frac{\sigma(e^+e^-\to hadrons)}{\sigma(e^+e^-\to\mu^+\mu^-)}\sim 3\times\sum_i e_i^2$$

└ sum over flavours

└ number of quark colours



$$\sqrt{s} > 10\,GeV : R=3\times(e_u^2+e_d^2+e_c^2+e_s^2+e_b^2)= {}^{11}/_3$$

udscb

An example of a direct experimental detection of the colour of quarks is the measurement of the total probability of hadron formation in the processes of annihilation of colliding electron-positron pairs at high energies. The theory predicts that this probability is defined by the number of quark colours and values of electric charges of quarks generated in these processes.

The hypothesis of colour quarks is a powerful idea which made it pissible to solve the afore-mentioned fundamental problems of the elementary particle theory and (consequently) to develop consistently the concept of the quark structure of matter.

As has been mentioned above, the absence of quarks in a free state is the basic problem to be tackled. The quark confinement in hadrons is the key problem of the modern elementary particle physics. Obviously it is up to experimenters to make the final steps in handling this problem, nevertheless, some attempts have been made to give a consistent explanation of "the eternal confinement" of quarks in hadrons.

The dynamic quark model developed at Dubna in 1964 was based on the assumption that quarks are very heavy objects bound in hadrons by enormous forces which stipulate a large defect of quark masses on the one hand, and on the other, hinder their escape /5–7/ *(see Illustr. 8).*

Kept by the walls of the potential well the quarks in this model appeared to be effectively free or quasi-independent inside it /10–11/. Such a behaviour generated a concept of the asymptotic freedom of quarks at small distances which is very important in the physics of hadrons.

The dynamic quark model provided a systematic description of the observed static characteristics of elementary particles (magnetic moments, axial-vector constants of weak transitions, and others) as well as of hadron form factors. These investigations initiated the modern quark models of elementary particles.

In the course of development of the dynamic theory of hadrons a great contribution had been made by Nambu /12/ who was the first to introduce into the theory vector fields, carriers of colour interaction, the so-called gluons (from the English word "glue") *(see Illustr. 9).*

By analogy with electrodynamic interaction of two electric charges, interactions of two colour charges mediated by gluons were called chromodynamic interactions and the relevant theory — quantum chromodynamics. In contrast to electrodynamics with the only photon, chromodynamics contains eight gluon fields in accordance with eight different ways of transfer of quark colours. It turns out that gluons have nonzero colour thus being a source of chromodynamic interactions *(see Illustr. 10).*

This important difference from chromodynamics may be due to the existence of forces acting between two colour charges, which do not decrease with distance. In other words, between quarks carried apart at large distances there appears, let's say, a string hindering their flying apart. However, the string can be treated as a result of production from vacuum of a new quark-antiquark pair thus producing two new colourless systems, say, two mesons *(see Illustr. 11).*

Dynamic composite model of hadrons

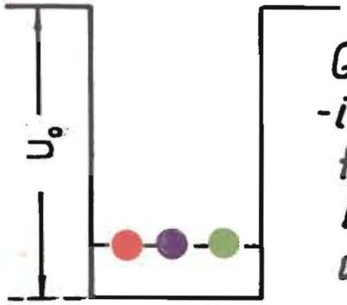
Principle of quark confinement:

The observed states (hadrons) are colourless, objects with nonzero colour (quarks, diquarks, etc.) do not exist in a free state.

„Quark bag model": Dubna (1965)

P. Bogolubov (1967)

Bogolubov
Struminsky
Tavkhelidze



Quarks in a bag are quasi-independent (asymptotically free) at short distances and interact strongly with walls at long distances.

A large mass of quarks M is „eaten away" by immense scalar forces ($M \simeq U_0$) ⇒ the effect of strengthening of the magnetic moment of bound quarks in nucleon.

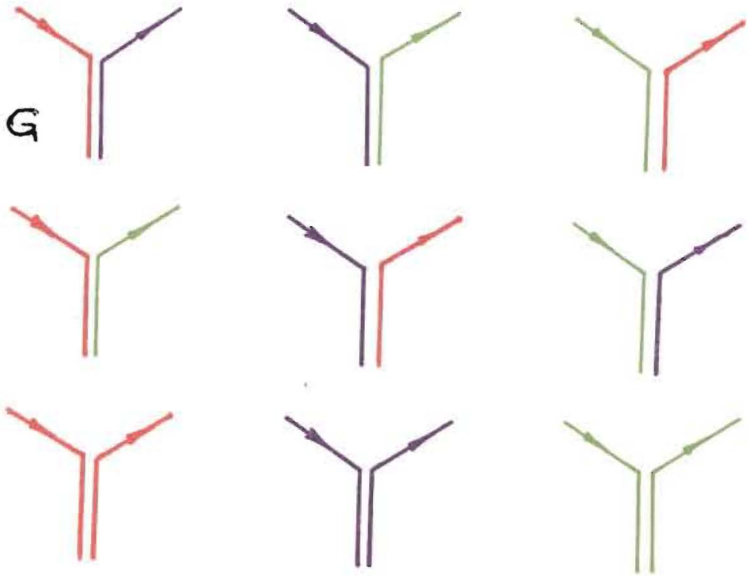
Quantum chromodynamics – gauge theory of nuclear forces

Colour ⇒ charge of the new type („colour")

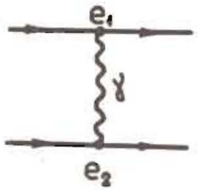
Gluons - vector bosons, carriers of the interaction between colour charges

Nambu (1966)

There are 8 ways of transfer of the quark colour - 8 types of gluons ($3 \cdot 3 - 1 = 8$):



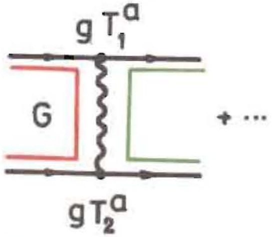
QED



$$U = \frac{e_1 e_2}{4\pi r}$$

e_i are multiple of electron charge e, $e^2/4\pi \sim 1/137$

QCD



$$U = \alpha_s \, T_1^a \, T_2^a \cdot f(r)$$

T_i^a are the generators of the colour symmetry group $a = 1, 2, \ldots, 8$

$$f(r) \sim \frac{1}{r} + C \cdot r$$

Inclusion of the effects of vacuum polarization and other highest quantum corrections:

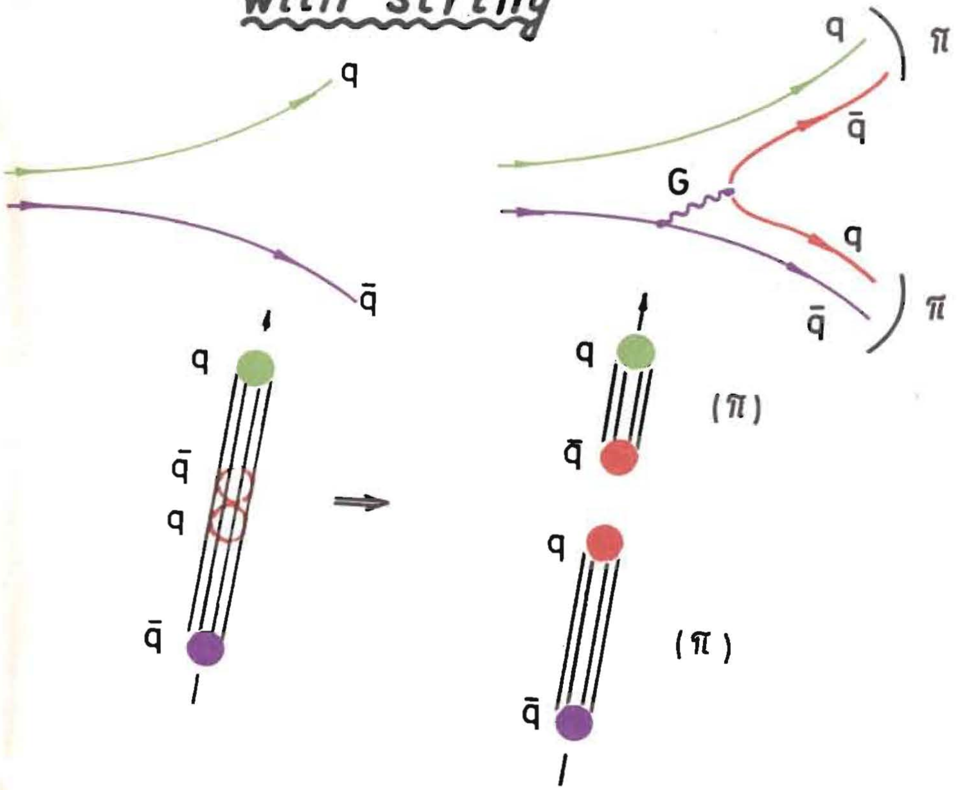
$\alpha_s = g^2/4\pi \Rightarrow \alpha_s(Q^2)$ is the effective QCD coupling constant

Properties of asymptotic freedom

$\alpha_s(Q^2) \sim 1/\ln Q^2$
$(Q^2 \sim \infty)$

Renormalization group method in quantum field theory
Bogolubov
Logunov
Shirkov
(1955 - 1956)

Analogy of nondecreasing chromodynamic forces between colour quarks with string



The „string" connecting quarks „tears" when $\bar{q}q$ fly apart at large distances ($\sim 10^{-13}$ cm); at the point of tearing a new pair $\bar{q}q$ is generated from vacuum, which leads to the emergence of two strings, and as a result of further tearings to the production of a system of hadrons in the final state of the reaction.

It should be noted that quantum chromodynamics which has been developing in the course of the last several years is a result of unification of the hypothesis of colour quarks and colour unitary symmetry with the principle of the Yang-Mills local gauge invariance. In this connection it should be emphasized that according to Grinberg's hypothesis on para-Fermi statistics of quarks /13/ posed in 1964 one cannot introduce a gauge unitary symmetry which is the basis of quantum chromodynamics thus being a physically inadmissible alternative to the hypothesis of colour Fermi-quarks /14/.

It is impossible in a few words to elucidate all the achievements of quantum chromodynamics the development of which marks great progress in the strong interaction theory.

Non-Abelian, i.e., noncommutative, character of colour gauge symmetry and nontrivial topological properties of vacuum field configurations in quantum chromodynamics raise our hopes of a consistent theoretical solution of the problem of confinement.

An important role in quantum chromodynamics is played by the renormalization group methods in field theory developed by Logunov, Shirkov and myself /15–17/. These methods laid the foundation of the proof of the property of asymptotic freedom of quantum chromodynamics and allowed the development of effective methods of calculation of higher-order approximations in perturbation theory. These methods as well as the Wilson operator expansion and dispersion sum rules of quantum chromodynamics provide at present a reliable basis for theoretical calculations of some of the most important characteristics of hadron physics /18–19/.

It is to be noted that the very explanation of laws of the hadron spectroscopy could not be a decisive argument in favour of the existence of quarks. It was necessary to establish a direct dynamic manifestation of the quark structure of hadrons. An adequate way of doing so is to study the peculiarities of interaction processes of particles at high energies, which provide us with the most direct information on the internal structure of elementary particles and atomic nuclei *(see Illustr. 12).*

In 1911 Rutherford, in experiments on the scattering of charged alpha-particles on thin fiols, discovered a dense core in atoms of chemical elements, which led to a new, so-called planetary model of the atom.

The increase in energy of interacting particles that introduces us into the region of still shorter distances allows a deeper insight into the microcosm, very diverse and intricate in its nature.

A specific feature of processes occurring in collisions of two high-energy particles is their essential inelasticity favouring the production of new secondaries. The higher the energy of colliding particles, the larger amount of new particles can be produced in a collision of that type. Diversity and complicated description of the final reaction products at high enough energies make here the traditional research methods inapplicable.

In 1967 A.A.Logunov put forward a new fundamental approach to the study of processes of particle inelastic scattering at high energies.

---

⑫

Quark-gluon structure of hadrons and its dynamic manifestation in particle collisions at high energies

Rutherford's experiments (1911) on the scattering of charged α-particles on thin foils

⇒ detection of a dense core in atoms of chemical elements.

High energies ⇒ multiple production of elements.

Concept of an inclusive reaction

$a + b \to c$ + all the rest $\to c_1 + c_2$ + all the rest and so on.	1967 Logunov and collaborators

Inclusive method allowed one to treat all the channels of the reaction and to provide a model-independent description of many-particle processes at high energies on the basis of general principles of quantum field theory.

This approach is based on the concept of the so-called inclusive measurement or inclusive reaction [20-21].

Instead of tracing all the new particles, this approach is aimed at studying the characteristics of one or several selected secondaries of a given sort but taken over the set of all possible reaction channels.

The inclusive approach provides the consideration of all reaction channels and model-independent description of the most important laws of high-energy multiparticle processes on the basis of fundamentals of quantum field theory.

It is noteworthy that both the hadron inclusive reactions and the reactions of deep inelastic scattering of leprons on nucleons reveal a property of approximate automodelity (self-similarity), universal for the processes of strong, weak, and electromagnetic interactions [22]. The property consists in that all the observables of the corresponding processes turn out to depend only on dimensionless combinations of large kinematic variables: energies, momenta of particles, etc. In a sense, here we have a close analogy with the phenomenon of automodelity in gaso- and hydrodynamics *(see Illustr. 13).*

The phenomenon of automodelity of inclusive and deep-inelastic processes points to the local, point-like (i.e., scale-invariant) interaction mechanism at high energies in complete accordance with the hypothesis of quark-gluon structure of hadrons and with the property of asymptotic freedom of quantum chromodynamics.

Theoretical studies made by me together with Vladimirov, Tavkhelidze, as well as by Logunov and colleagues gave rigorous grounds for the automodel asymptotic behaviour in quantum field theory and established a number of the most important properties of deep-inelastic and inclusive processes [23-24].

For the first time the scale-invariant behaviour of inclusive reactions of hadron strong interaction was experimentally discovered in 1969, immediately upon putting into operation the proton accelerator of the High-Energy Physics Institute at Serpukhov, the most powerful at that time. The scale-invariant behaviour of processes of deep-inelastic interaction of leptons with hadrons was first observed in experiments by the electron linear accelerator at Stanford, USA.

The quark structure of elementary particles in high-energy interaction process manifests itself most clearly in the so-called quark counting rules established in 1973 by Matveev, Muradyan and Tavkhelidze for the asymptotic behaviour of cross sections of wide-angle elastic scattering and hadron form factors as a function of the number of constituent quarks [25] *(see Illustr. 14 and 15).*

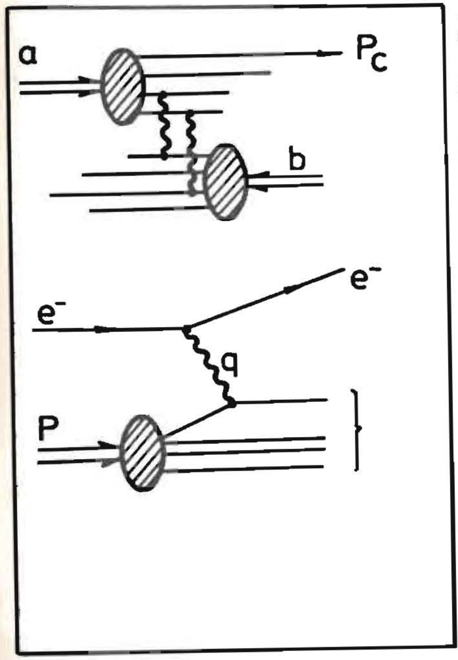
The quark counting rules describe surprisingly well numerous experimental data on electromagnetic-particle scattering thus providing a direct information on the quark structure of hadrons and lightest atomic nuclei.

It is to be noted that in recent years the ideas and concepts of the theory of colour quarks have got still more powerful in the physics of ato-

A universal property of automodelity (self-similarity) of inclusive and deep inelastic processes ⑬

Scale invariance at short distances is a universal property of strong, weak and electromagnetic. interactions.

Experimental detection:



Serpukhov (1969) - inclusive spectra of secondaries,
$x = \frac{|\vec{P}_c|}{E_a}$ is a dimensionless characteristic

Stanford (1968) - deep inelastic scattering on a nucleon,
$x = q^2/2p \cdot q$ - dependence.

A point-like behaviour of inelastic νN-interactions.
Markov (1964).

Bogolubov
Vladimirov
Tavkhelidze
•
Logunov with colleagues

} Proof of the existence of automodel asymptotics in local quantum field theory.

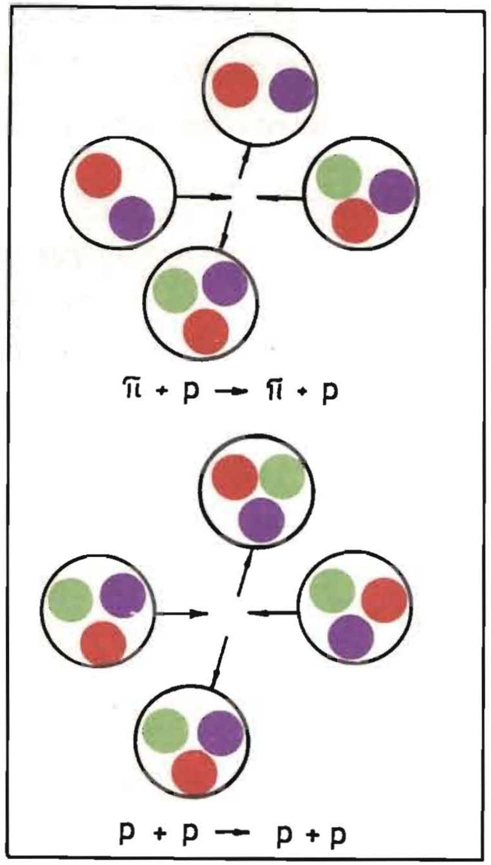
Quarк-counting rules (1973)

A power law for the cross section of hadron elastic scattering at large angles θ and high energies $E = \sqrt{s}$:

Matveev
Muradyan
Tavkhelidze

$$\frac{d\sigma}{dt}(ab \to cd) \sim \left(\frac{1}{s}\right)^{n_a+n_b+n_c+n_d} \cdot f(\theta)$$

n_a, n_b, n_c, n_d are numbers of quarks in hadrons a, b, c, d.



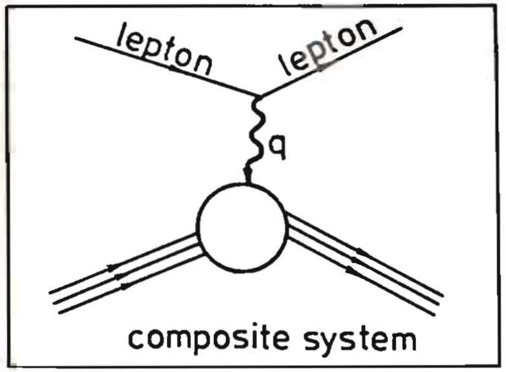
$$n_a+n_b+n_c+n_d = 10$$

$$\frac{d\sigma}{dt}(\pi p \to \pi p) \sim \frac{1}{s^8}$$

$$n_a+n_b+n_c+n_d = 12$$

$$\frac{d\sigma}{dt}(pp \to pp) \sim \frac{1}{s^{10}}$$

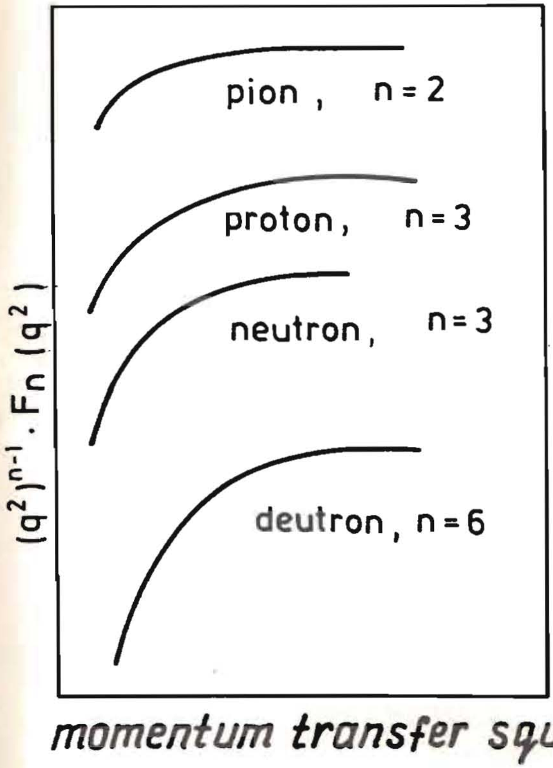
Quarк-counting rule for the form factor of a composite system



$$F_a(t) \sim \left(\frac{1}{t}\right)^{n_a-1}$$

n_a is the number of elementary constituents of the system

$t = -q^2$



$$F_\pi(t) \sim \frac{1}{t}$$

$$F_{p,n}(t) \sim \frac{1}{t^2}$$

$$F_d(t) \sim \frac{1}{t^5}$$

mic nuclei. The main problem here is to explain the nature and basic laws of nuclear forces on the basis of fundamental chromodynamic interactions of quarks and gluons. Recent works have intensively discussed the problem of how the quark degrees of freedom are to be taken into account when describing the nuclear structure and dynamics of short-distance nuclear interactions and have pointed to a possible existence of a new type of highly excited states of nuclear matter specified by a kind of internal colour polarization, the so-called "hidden" colour /26/ *(see Illustr. 16).*

This new field of research now called the relativistic nuclear physics, which makes our knowledge of a complex structure of atomic nucleus more profound, has much been contributed by the theoretical works by A.M.Baldin and intensive experimental investigations he initiated long ago on the beams of relativistic nuclei of the Dubna synchrophasotron, thus establishing, in particular, the range of applicability of the proton-neutron nuclear model /27,28/.

The tendency towards unification of all basic forces in nature, electromagnetic, strong, weak, and gravitational, within a unified theory represents one of the principal laws in the development of modern theory.

An essential role in the course of realization of this fundamental idea was attributed to the concept of degenerate vacuum and the principle of spontaneous symmetry breaking, crucial points in the elaboration of the microscopic theory of superfluidity and superconductivity /29/.

A recent discovery at CERN, Switzerland, of the so-called Z and W intermediate bosons has marked a great success of the Weinberg-Salam-Glashow model providing a unique description of electromagnetic and weak interactions within a unified gauge theory of electroweak interactions.

A next urgent task is the construction of an appropriate theory of Grand Unification that will incorporate also the chromodynamic forces acting between colour quarks and gluons.

Of the most importance, in our opinion, is the question of whether the colour symmetry is an absolutely exact or an approximate law of nature. This, still unsolved principal problem of the elementary-particle theory is tightly related to the problem of quark charges.

Note that even the first works devoted to composite quark models indicated a possibility of choosing integer values for electric and baryon charges of colour quarks. The integer quark charges dependent on their colour state would break the colour symmetry, at least, in electromagnetic interaction of particles.

The investigation of spontaneous colour-symmetry breaking made in the latest works gave rise to interesting and important results concerning the structure of vacuum in gauge theories with colour scalar fields and the existence of light scalar quarks /30/.

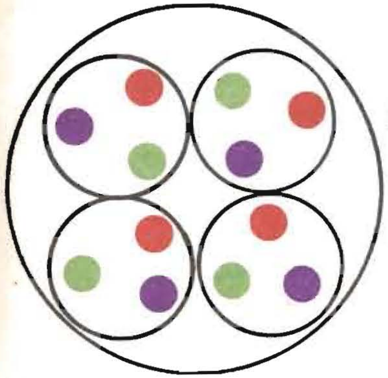
The hypothesis of integer quark charges and the assumption of spontaneous breaking of colour and other gauge symmetries led to the concept of nonstable quarks and was a starting point of the construction of first unified gauge models of elementary particles /31/.

⑯

Quarks in nuclei

The problem is to explain basic laws of nuclear forces on the basis of fundamental chromodynamic forces acting between colour quarks and gluons.

$^4He = ppnn$



A new problem is the search of manifestation of quark degrees of freedom of nuclei („hidden colour")

12 quarks

Experiments with relativistic nuclei

At Dubna (1971) Baldin ⇒ Relativistic nuclear physics is a new field of investigations on the boundary between nuclear and elementary-particle physics.

Study of the quark-gluon structure of atomic nuclei.

It is just the symmetry between quarks and leptons that plays an essential role in constructing the theory of Grand Unification. Reflecting the present-day level of knowledge of elementary particles, the world of quarks and leptons appears in an extremely symmetric form *(see Illustr. 17)*.

Fermion fields corresponding to quarks and leptons are, as a rule, grouped in doublets, the simplest two-dimensional representations of the isotopic-spin group.

Quarks and leptons are arranged by the law of increasing mass. This, obviously, determines also the chronology of their discovery: heavier quarks and leptons to be discovered require higher energies. Information on a possible detection of the most heavy quark, the so-called t-quark, appeared a year ago.

It is very much to the point to ask whether the world of fundamental particles does consist only of known quarks and leptons, or this series will still continue. Further development of high-energy physics is called to answer this, by no means, scholastic question.

It is worth noting a considerable impact on the development of elementary-particle physics produced by the hypothesis of the existence of two types of the neutrino, electronic and muonic, posed by Markov and Pontecorvo in 1957 and then confirmed experimentally /32-33/. At present we are aware of opinions brought on by the data of astrophysics and cosmology that the number of the neutrinos, the lightest neutral leptons, cannot be larger than three-four. Of great interest for theoreticians and experimenters is the Pontecorvo idea on the neutrino oscillations, i.e., on the possibility of transforming neutrinos of different types into each other /33/.

Attempts to construct the theory of Grand Unification lead to the observable consequences of primary importance: predictions of a possible instability of the proton and neutron-antineutron oscillations, the possibility of theoretical interpretation of the baryonic asymmetry of the Universe. Experimental verification of these predictions represents an important problem of the modern elementary-particle physics, an object of intensive studies of many leading laboratories of the world including our country.

As to the prospects of construction of a unified theory of electromagnetic, strong, weak, and possibly, gravitational interactions, it must be stressed that the necessity of a unified description is dictated by the very logic of the development of theoretical ideas on elementary particles and properties of their interactions.

Search of a unified description of the properties and fundamental interactions of elementary particles and their universal constituents, quarks and leptons, is essentially the search for basic characteristics of phenomena of the microcosm. Knowledge of the governing laws has enormous latent possibilities not only for the science but also for the technology and engineering of the future.

It is now hard to say to what extent we approach the solution to this gigantic problem. It is clear, nevertheless, that the progress in this direction is possible only under the very broad development of thorough theoretical

Quark - lepton symmetry

⑰

Doublets of fundamental particles:

Quarks $\binom{u}{d}, \binom{c}{s}, \binom{t}{b}, \ldots$ $m_t \sim 45\,GeV$ CERN (1984)

Leptons $\binom{e^-}{\nu_e}, \binom{\mu^-}{\nu_\mu}, \binom{\tau^-}{\nu_\tau}, \ldots$

Unification of fundamental particles in the framework of unified gauge theories of strong, weak and electromagnetic interactions.

$$\underbrace{SU_c(3)}_{\alpha_s} \times \underbrace{SU(2) \times U(1)}_{e,\; G \simeq 10^{-5} m_p^{-2}}$$

$\underbrace{QCD\text{-}g \quad \gamma, Z^0, W^{\pm}}$ - electroweak interactions

Grand unification of all three interactions at $M \sim 10^{15}$ GeV

Weinberg
Glashow
Salam
(1967)

Experimental results at low energies:

- nucleon decay ($\tau_p \gtrsim 10^{32}$ years)
- ocsillations $n \leftrightarrow \bar{n}$ (period is about several years)
- explanation of the baryon asymmery of the Universe

investigations and experiments on the existing and future accelerators of charged particles as wess as on other large scale physical installations.

REFERENCES

1. Ломоносов М.В. Полн.собр.соч. Изд-во АН СССР, М.-Л.,1950, т.3, с.323.
2. Fermi E., Yang C.N. Phys.Rev., 1949, vol.76, p.1739.
3. Gell-Mann M. Phys.Lett., 1964, vol.8, p.214.
4. Zweig G. CERN Preprint TH-401, Geneva, 1964.
5. Боголюбов Н.Н., Струминский Б.В.,Тавхелидзе А.Н.ОИЯИ,Д-1968,Дубна,1965.
6. Tavkhelidze A.N. In: High Energy Phys.Elem. Particles, Vienna, 1965, p.753.
7. Боголюбов Н.Н., Матвеев В.А., Нгуен Ван Хьеу, Стоянов Д.Ц., Струминский Б.В., Тавхелидзе А.Н., Шелест В.П. ОИЯИ, Р-2141, Дубна, 1965.
8. Han M.Y., Nambu Y. Phys.Rev., 1965, vol.139B, p.1005.
9. Miyamoto Y. Progr.Theor.Phys., Suppl.Extra, 1965, No.187.
10. Боголюбов П.Н. ОИЯИ, Р2-3115, Дубна, 1967; ЭЧАЯ, 1972, т.3, вып.1, с.144.
11. Bogolubov P.N. Ann.Inst.Henri Poincare, 1968, vol.VIII, p.2.
12. Nambu Y. In: Preludes in Theor.Phys. (Ed. by R.Gatto). J.Wiley, New York, 1972.
13. Greenberg O.W. Phys.Rev.Lett., 1964, vol.13, p.598.
14. Говорков А.Б. ЭЧАЯ, 1983, т.14, вып.5, с.1229.
15. Боголюбов Н.Н., Ширков Д.В. ДАН СССР, 1955, 103, с.203; 103, с.391.
16. Логунов А.А. ЖЭТФ, 1956, 30, с.793.
17. Ширков Д.В. ДАН СССР, 1955, 105, с.972.
18. Logunov A.A., Soloviev L.D., Tavkhelidze A.N. Phys.Lett., 1967, vol.24B, p.181.
19. Chetyrkin K.G., Krasnikov N.V., Tavkhelidze A.N. In: Proc. of the Int. Conf. on Neutrino Physics and Neutrino Astrophysics. Bacsan Valley, June 1977, vol. 2, p.189; Красников Н.В., Тавхелидзе А.Н., Четыркин К.Г. ТМФ, 1978, т.35, вып.2, с.373.
20. Logunov A.A., Mestvirishvili M.A., Nguen Van Hieu. Phys.Lett., 1967, vol.25B, p.611.
21. Logunov A.A., Nguen Van Hieu. Lectures at the Int. School on High Energy Phys., Popradske Pleso, Czechoslovakia, 1967; and In: Topical Conf. High Energy Coll. Hadrons. CERN, Geneva, 1968, vol.2, p.74.
22. Матвеев В.А., Мурадян Р.М., Тавхелидзе А.Н. ОИЯИ, Р2-4578, Дубна, 1969; ОИЯИ, Е2-5962, Дубна, 1971; ЭЧАЯ, 1971, т.2, вып.1, с.7.
23. Боголюбов Н.Н., Владимиров В.С., Тавхелидзе А.Н. ТМФ, 1972, т.12, вып.1, с.619.
24. Логунов А.А., Мествиришвили М.А., Петров В.А. Принципы квантовой теории поля и их следствия. "Наука", М., 1977.
25. Matveev V.A., Muradyan R.M., Tavkhelidze A.N. Lett.Nuovo Cim., 1973, vol.7, p.712.
26. Matveev V.A., Sorba P. Lett.Nuovo Cim., 1977, vol.20, p.443.
27. Балдин А.М. Краткие сообщения по физике. ФИАН, М., 1971, с.35; ОИЯИ, Р7-58, Дубна, 1971; ЭЧАЯ, 1977, т.8, с.429.
28. Baldin A.M. et al. Proc.Rochester Meeting APS/OPF, 1971, p.131.
29. Боголюбов Н.Н. Избранные труды по статистической физике. Изд-во МГУ, 1979.
30. Матвеев В.А., Тавхелидзе А.Н., Шапошников М.Е. ТМФ, 1984, т.59, вып.3, с.323.
31. Pati J.C., Salam A. Phys.Lett., 1975, vol.58B, p.333.
32. Марков М.А. Гипероны и К-мезоны. Гос.изд.физ.-мат.лит., М., 1958.
33. Понтекорво Б.М. "Природа", 1983, №1, с.43.

Received by Publishing Department
on May 23, 1985.