# Sixth International Seminar on Problems of High Energy Physics: Multiquark interactions and quantum chromodynamics

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The first Dubna seminar of this series, organized in 1969, was devoted to vector mesons and included a considerable number of papers containing attempts to create a theory of gauge fields: problems of quantization of Yang–Mills fields, their geometrical interpretation, and attempts at phenomenological applications of these theories for the description of experiments. This was the first important meeting devoted to this topic, which was then not yet very popular but is now the main trend of elementary-particle theory [see Usp. Fiz. Nauk 101, 557 (1970)].

Scientific public opinion reached a turning point in the seventies under pressure of experimental discoveries and a number of important theoretical studies. The result was the development of a unified approach to all classes of interactions: symmetries are formulated on the basis of the principle of local gauge invariance, and this completely determines the structure of a dynamical theory.

The second half of the seventies passed under the overwhelming influence of quantum chromodynamics (QCD), which translates into reality the application of the principle of local gauge invariance to the symmetries describing quarks. There is now a strong experimental foundation for this beautiful gauge theory.

QCD claims to make it possible to calculate all aspects of hadronic interactions from first principles, including the parameters of nuclear physics and the properties of nuclear matter. However, the unsolved problems in the description of quark confinement have proved to be so complicated that these claims will evidently remain simply claims for a long time. It is possible that the development of the theory will not take place primarily in a purely deductive manner but that experiment will again have an important say. In this connection, besides the study of hard processes (or small distances of order $10^{-14}$ cm or less), for which QCD claims to give a quantitative description of experiment, chromodynamics of "large" distances, i.e., distances of order $10^{-13}$ cm, acquires special significance.

In the light of the foregoing remarks, it becomes clear why the main topics of discussion at the present seminar included, together with general problems of QCD, problems such as the phenomenological description of quark confinement, the search for quark exotica, the quark–gluon plasma, reactions involving large momentum transfers, relativistic nuclear physics, and the construction of a modern theory of the nucleus on the basis of quantum chromodynamics.

The solution of the problems of perturbative QCD was the subject of a paper by A. V. Radyushkin. One of these problems is related to the choice of the momentum parameter which characterizes the value of the effective coupling constant, whose decrease with increasing momentum transfer makes it possible to use the apparatus of perturbation theory in calculating cross sections for hard processes. So far, no single criterion for choosing this parameter has been found, and the only solution which remains is the calculation of a sufficiently large number of correction terms in $\alpha_s$ and their minimization. In certain important cases, these corrections are found to be so large that this casts doubt on the applicability of perturbation theory.

A second problem of QCD is to take into account corrections from lower powers of the momentum transfer—so-called higher twists. In individual cases, it is possible to include such corrections and to obtain interesting results. Thus, in a paper by D.V. Shirkov it was shown that allowance for the masses of the heavy quarks in the renormalized equation makes it possible to obtain an invariant charge which automatically takes into account the changes that occur at the thresholds for inclusion of the heavy quarks. These effects are important and lead to a decrease of the parameter $\Lambda$ in the subthreshold region.

V.I. Zakharov gave an account of a method of including corrections due to the gluon and quark condensate of the vacuum and considered in particular their influence on the properties of hypothetical gluonium. One of these consequences is a rather large interval of gluonium duality (3–4 GeV).

The problem of quark confinement is one of the most complicated problems in QCD. One of the methods of solving it is to formulate QCD in terms of gauge-invariant objects—so-called loop integrals. A paper by A.A. Slavnov was devoted to the successes in this direction. He proposed a new method of linearizing QCD by means of collective gluon variables. Another method of investigating the equations that are obtained is to go over to a discrete lattice space and to solve them on a computer. The results of such calculations for the four-dimensional Abelian model of Higgs was the subject of a communication by J. Ranft (GDR). In a report by V.N. Pervushin, attention was drawn to the fact

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that the ordinary methods of quantization cannot be applied to the Yang–Mills equations because of the presence of singular solutions. Separation of the regular part and its quantization using the requirement of stability and finite energy of the vacuum lead to equations for the singular part, whose solutions have the form of a confining potential for the quanta of the regular part of the field. The mechanism of color confinement also affects the development of hadron jets. In particular, in a paper by I.M. Dremin it was proposed to determine experimentally the rate of this development by measurement of the spectrum of muon pairs in quark–gluon jets.

A number of papers were devoted to hard processes on nuclei. Thus, L.A. Slepchenko presented a generalization of the quark counting rules in processes involving large $p_T$, using the anomalous dimensions of the distribution function.

Special interest attaches to the use of the nucleus as an analyzer of quark states, in particular, as an instrument for measuring the formation length of a hadron beam. In the opinion of the authors, the study of processes involving large $p_T$ on nuclei has shown (paper by V.V. Abramov) that the formation length grows with the momentum, but much more slowly than what one would expect simply from the $\gamma$ factor.

Spin effects in hard processes have brought and continue to bring many surprises. They have hitherto remained a stumbling block for many models. One of the surprises is polarization of the $\Lambda$ particles in proton–proton and proton–nucleus collisions which rises with increasing $p_T$; attempts to explain this were the subject of a paper by L. Pandrom (USA). In essence, it reduces to a polarization of the $s$ quark, but the mechanism that gives rise to this polarization still remains a mystery. Another surprise is a spin dependence in $pp$ scattering (paper by A.D. Krisch, USA). So far, there have not even been any attempts to explain it.

The phenomenological description of large-distances chromodynamics (bags, strings, multiquark systems, hidden color, the quark–gluon plasma, etc.) has occupied a special place in the programs of recent seminars. In particular, the present seminar included papers devoted to the problems and successes of phenomenological models with a confining potential in the description of the static properties of both ordinary hadrons and hadrons with new flavors, as well as supernuclei. It was shown in a paper by S.B. Gerasimov that a variational approach in the relativistic potential model makes it possible in a number of cases to obtain a marked improvement in the agreement between theoretical calculations and experiment. For baryons with new flavors, on the basis of a model analogous to the Veneziano model it was predicted that the hadronic and radiative widths decrease with increasing quark mass (paper by K. Igi, Japan). As to supernuclei, it was noted that nuclei containing $\Lambda_c$ and $\Lambda_b$ are the most probable, but even their production is strongly suppressed by the kinematics (paper by V.A. Tsarev). A paper by V.M. Dubovik was devoted to the $P$-odd effect in nuclei and the so-called "color enhancement."

One of the main topics of the seminar was the problem of exotic and multibaryon resonances. The existence of such resonances is predicted by many models of large-distances chromodynamics. Information about dibaryon resonances is obtained from three sources: polarization measurements in elastic $pp$ scattering, photodisintegration of a polarized deuteron by a polarized beam, and $\pi d$ interactions. There are at least two candidates in the $pp$ system and two in the $pn$ system. However, each of these sources entails the performance of a phase-shift analysis using an incomplete set of experimental data and is therefore ambiguous (papers by M.M. Makarov and by N. Hoshizaki, Japan).

There exist, however, experimental arguments in favor of dibaryon resonances involving a strange quark in the $\Lambda p$ and $\Lambda p\pi$ systems (paper by B.A. Shakhbazyan). Unfortunately, the statistics here do not make it possible to carry out a phase-shift analysis of the events.

As was noted in a paper by J.J. de Swart (Netherlands), the main difficulty lies in the large number of predicted resonances and the small cross sections for their production. In this sense, the resonance which is preferred is one in the $\Lambda\Lambda$ system, which, as expected, is relatively stable.

As to multiquark states, the seminar included a report (Yu.A. Troyan) of experimental results on the discovery of peaks in the $\pi\Delta$ system with isospin $\frac{5}{2}$ (i.e., of the type $qqqq\bar{q}$), masses 1425 and 1510 MeV, and a small width. It became possible to carry out this work as a result of a unique neutron beam with energy 4–5 GeV and a small energy spread, obtained from the Dubna synchrophasotron by stripping of accelerated relativistic deuterium nuclei.

Apparently, heavier resonances with masses 1690 and 1850 MeV also exist in these same systems. The need for such resonances was felt previously in an analysis of dispersion sum rules (paper by A.A. Grigoryan). There are grounds for believing that some of the resonances which are now well established ($\varepsilon, s, \delta$) are in fact also four-quark resonances (paper by N.N. Achasov).

An interesting explanation of the anomalously large heavy fragments observed is cosmic rays and in experiments using the Berkely accelerator was proposed by S. Fredriksson (Sweden). He regards them as a manifestation of six-quark "deuterons" in a $0^-$ state with mass 2 GeV, produced in particle–nucleus collisions.

Theoretical aspects of multiquark states in nuclei were discussed in many papers and communications (V.A. Matveev, Yu. A. Simonov, V.G. Neudachin, V.V. Burov, and I.T. Obukhovskiĭ). In particular, these authors estimated the admixture of the six-quark state in the deuteron to be in the range 1–14%.

The presence of multiquark states in nuclei should manifest itself in reactions of elementary particles and nuclei with nuclei. One of these manifestations may be a rather large value of the electromagnetic form factors of nuclei, whose rate of decrease with increasing momentum transfer is determined by the number of point constituents (papers by V.A. Matveev, and A.I. Titov).

Another clear manifestation is the cumulative effect—production on a nucleus of a secondary particle outside the kinematic region which is admissible in a collision with a single stationary nucleon of the nucleus. This line of research has traditionally been widely reflected in the program of the seminar; this is not surprising, since Dubna physicists were the first to study the cumulative effect, and Dubna still remains a leading center of experimental and theoretical research relating to this phenomenon. There was special interest in a paper by I.A. Savin on deep inelastic scattering of muons by carbon in the cumulative region of the Bjorken variable, $x>1$. This result is direct confirmation of the existence of the cumulative effect on flüctons similar to Blokhintsev flüctons and is in good agreement with the data on limiting fragmentation of nuclei in relativistic nuclear collisions (papers by V.V. Burov and L.A. Frankfurt).

New experimental data on the production at the seminar (V.S. Stavinskiĭ, G.A. Leksin, and K.Sh. Egiyan). On the whole, these data confirm and refine the previously discovered properties of the cumulative cross sections: nuclear scaling, universality of the spectrum with respect to the variable $x=(\varepsilon-p\cos\theta)/m$, and so forth; however, there are also several new features. First of all, there is a specific $A$ dependence. For heavy nuclei it becomes the behavior $d\sigma\sim A$, and this occurs much earlier for cumulative mesons (when $A\approx30$) than for protons ($A\approx100$). For light nuclei one observes a stronger $A$ dependence, which in all probability is due to the influence of the nuclear surface. The significant influence of the nucleus is also indicated by the different values of the longitudinal and transverse dimensions of the region of formation of a cumulative proton (paper by G.A. Leksin).

The transverse-momentum dependence of the production cross section at 90°, normalized to the cross section at 180° at the same values of $x$, is very interesting. In all probability (paper by A.V. Efremov), this indicates different production mechanisms: Regge dissociation of flüctons in the region of small $p_T$, and hard scattering in the region of large $p_T$.

A large number of new results on the production of cumulative particles over a wide range of angles in beams of relativistic nuclei at Berkeley were presented by A. Sandoval (USA).

The existence of multiquark fluctuations in the nucleus manifests itself not only in cumulative processes. M.G. Meshcheryakov presented the results of precision measurements of coherent production of fast pions in the processes $d+p\to d+\pi+X$ and $d+d\to\pi+X$. A comparison of the resulting spectra with the nuclear-cascade model confirmed the inadequacy of this mechanism and the need for objects in the nucleus that are heavier than the nucleon. The same picture is apparently also the basis for the effect observed using the ISR: the cross sections for production of pions with large $p_T$ in $\alpha p$ and $\alpha\alpha$ collisions are appreciably greater than $4\sigma_{NN}$ and $16\sigma_{NN}$, respectively (paper by W.J. Willis, CERN).

The quark structure of nucleons, QCD, and multiquark states in the nucleus also compel us to look at the nature of the intranucleus forces in a new way. A paper by T.I. Kopaleishvili at the seminar was devoted to the quark aspects of nuclear forces.

The implementation of the program of accelerating nuclei to relativistic velocities makes it possible to expect that collisions of such nuclei may involve production of states with a rather large number of quarks and gluons, which can be regarded as a quark–gluon plasma. At the present time, it seems difficult to say to what extent this picture is valid. In the opinion of some authors (paper by É.V. Shuryak), the plasma phase is now already manifesting itself in processes involving large $p_T$ in the form of a plateau in the effective temperature. It is believed by others, however, that it cannot become apparent up to collisions of heavy ions with energy ≈30 GeV/$N$ (paper by H.I. Miettinen, Finland). Therefore a primary objective of investigations in this direction is to find a sufficiently good indicator of the plasma state of matter. Such evidence would be provided by heavy fireballs in events with maximally large multiplicity, or an anomalously large number of heavy muon pairs or direct photons.

A number of papers at the seminar were devoted to the characteristics of the quark picture of hadron fragmentaton on a nucleus (B.Z. Kopeliovich, N.N. Nikolaev, S. B. Nurushev, I. Ya. Chasnikov, and K. Kinoshita).

Thus, the problem of the quark–gluon degrees of freedom in nuclei has undergone new development in recent years and now undoubtedly offers a major prospect for fundamental research in the field of nuclear physics. The seminar has made it possible to review the past three years and to mark out the course of further research. The proceedings of the seminar have been published (OIYaI 01, 2-81-728, JINR, Dubna).

Translated by N. M. Queen