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THE STRUCTURE OF NUCLEONS AND NUCLEI AND NONPERTURBATIVE QCD

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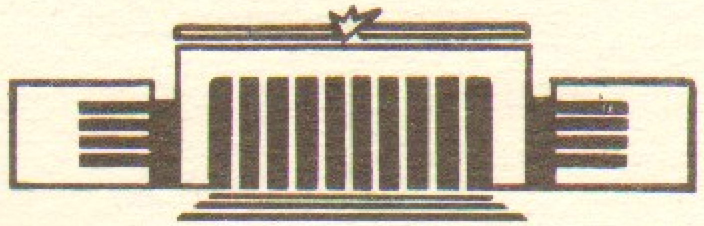

НОВОСИБИРСК

THE STRUCTURE OF NUCLEONS AND NUCLEI AND NONPERTURBATIVE QCD[*]

E.V.Shuryak

ABSTRACT

This talk starts with brief review of current ideas concerning hadronic structure, with the conclusion that original nonrelativistic quark models may be justified. If so, investigations of multiquark system, being of great interest for nuclear physics, can be put much further with modern computational methods. As an experimental test of these ideas we consider nonperturbative («higher twist») scaling violating effects in deep inelastic scattering, both on the proton and nuclear targets.

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1. INTRODUCTION

During the last few years traditional questions of nuclear and soft hadronic physics again became a subject of intensive investigations. The central questions addressed by this studies deals with modifications of the average nucleon parameters in nuclear matter. Another physical problem deals with virtual multiquark systems which appear when two nucleons come close to each other, a configuration relevant for understanding of nuclear forces at small distances.

Obviously, this process was triggered by experimental discoveries, such as the «cumulative effect» [1] in backward direction, «Cronin effect» [2] at large transverse momenta and «EMC effect» [3] in electromagnetic structure functions, to be much discussed at this conference. They all emphasized that at some accuracy level nuclei are not at all just a sum of individual nucleons, but something more complicated.

Another important reason for this activity was inspired by general hope to make contact with the fundamental theory, QCD, and obtain definite answers to all these questions. Unfortunately, with the development of this theory it becomes more and more clear that the roots of the problem are rather deep and we can hardly understand them without insight into «QCD vacuum structure», connected with so difficult problems as colour confinement and spontaneous chiral symmetry breaking. In other words, whatever particular system we study, at some accuracy level we have to face the underlying field theory with infinite number of degrees of freedom.

It does not mean that nuclear physists should just collect data and wait for progress in quantum field theory. The crucial problems of QCD are solving now, therefore conclusions made so far and even current trends are sufficiently interesting and (I hope) fruitful for nuclear physics. Reversing the argument given above one may put it into more optimistic form: the studies of hadronic and nuclear structure can provide more fundamental information, than it was anticipated before. In particular, nuclear matter is a step toward superdense matter in which phase transitions into quark-gluon plasma is expected. Since the latter phenomena should take place at density about one order of magnitude larger, at 10% level we may find many interesting phenomena in nuclei. This is exactly what is observed experimentally, and this is why new generation of essentially more precise experiments are badly needed.

It seems impossible now to review all «QCD-inspired» models and their predictions. It is also rather difficult to cover in so short form more fundamental approaches, such as lattice calculations and QCD sum rules (also there are many recent reviews). Instead, I prefer to concentrate on few key points which seem to be the subject for future investigations in theory and experiments.

2. THE NUCLEON STRUCTURE

Since the pioneer works by Gell-Mann and Zweig [4] we know that hadrons are made of quarks. However, precise meaning of this statement has made curious circle during last two decades. Its original sense was that one can classify hadrons in flavour SU(3) multiplets. However, in quark models developed at sixties quarks were treated in nonrelativistic way. It was assumed that quarks are present in fixed numbers and represent correct set of degrees of freedom (see Fig.1,*a*). Some well known observations supported such nonrelativistic approach, for example it explains why hadrons with «unnatural» parity $P=(-)^l$ are essentially heavier: they are «orbital excitations». Also magnetic moments of baryons are well described with only spin part of the wave function, without any references to orbital motion.

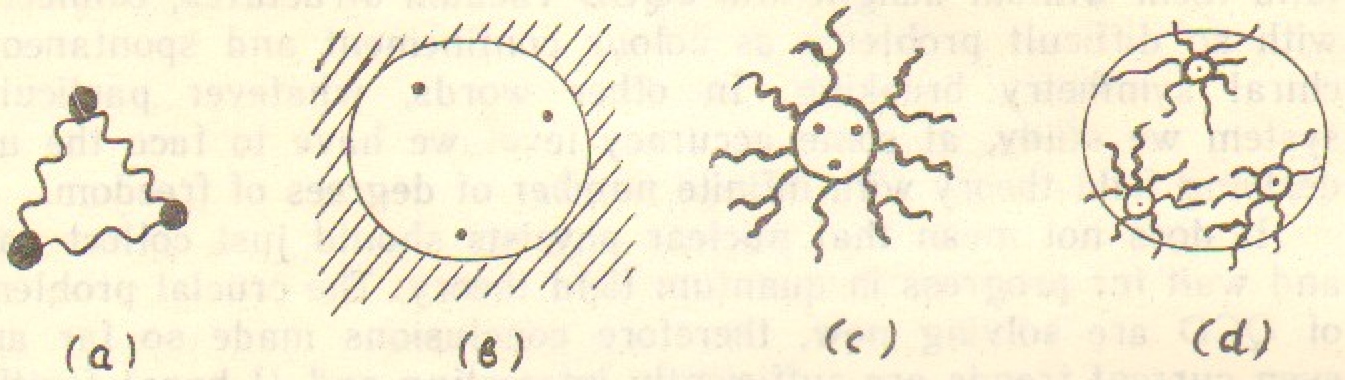

Fig. 1. Schematic pictures of the nucleon structure in various models. (*a*) The nonrelativistic quark model, based on binary forces between quarks. (*b*) MIT bag model, in which quarks are confined in a bubble of perturbative vacuum inside the «physical one». (*c*) Chiral bag model, the wavy lines outside the «little bag» represent virtual pion field. (*d*) The constituent quark model, in which these complicated objects are rather compact and affect the quark condensate (or the pion field).

However, in seventies strong scepticism toward such models has appeared: no apriory reasons was seen for it to take place. Quark masses present in the QCD Lagrangian are very small, about few MeV, and also massless gluons are there. The standard picture of this period was the MIT bag model [5] (see Fig.1,*b*), in which confinement is reproduced in very economic way. Small quark masses were assumed to cause relativistic motion of quarks in the bag, but they also revealed severe defect of this model.

As soon as massless quark is reflected from the (scalar) bag boundary it changes chirality, violating chiral symmetry of the theory. The so called chiral bag model [6] appeared on the stage (see Fig.1,*c*), in which axial charge is conserved on the bag boundary due to the pion cloud outside the bag. The «quark core» or «true bag» becomes in this model much smaller, being compressed by strong pressure from the pion cloud. I will not mention various versions of such models, but just comment, that all of them emphasize that chiral symmetry breaking is numerically more important than confinement, to which I totally agree.

An extreme case in this direction are topological models, e.g. the famous skirmion [7] (which I failed to drow at Fig.1). In this case topologically nontrivial pion cloud is assumed to substitute for quarks. Although such models are interesting theoretically and may reproduce soft nucleon physics, they are not what we are going to discuss at this conference, devoted to deep inelastic reactions. Obviously, at large momentum transfer the skirmion fails, and observed scaling can be reproduced only by pointless fermions, the quarks, in the theory.

In order to make contact with such physics one has to start with short distances, as it is done by the so called QCD sum rules [8] based on Wilson operator product expansion method. For example, one may consider propagation of a quark from a point 0 to close point x and wonder what is the first nonperturbative correction to its free propagation. This question was first addressed by D. Politzer [9] who has considered effect of nonzero quark condensate in vacuum corresponding to diagram shown at Fig.2,*a* and has obtained the following result for «momentum-dependent effective mass»:

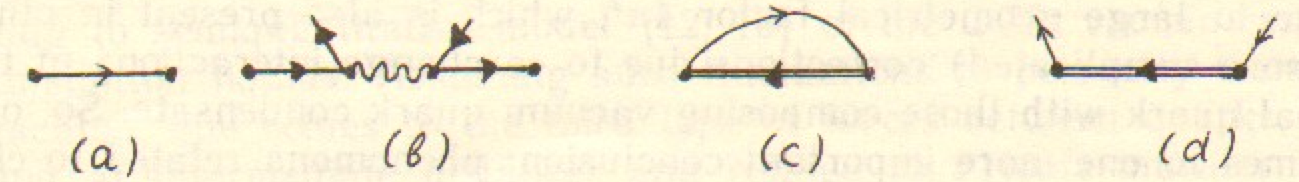

Fig. 2. Corrections to quark propagator (*a*) due to nonzero quark condensate (*b*) according to Politzer. Analogous correction (*d*) exists to *B*-type meson correlator (*c*), and it is much simpler.

$$M_{eff}(q)=16\pi\alpha_s\langle\Psi\Psi\rangle/q^2 \qquad (q\to\infty). \tag{1}$$

Dependence on q and proportionality to the quark condensate looks reasonable, but unfortunately this expression can not have direct physical meaning because it is gauge dependent, as well as the propagator itself. Obviously, one can cure this defect by consideration of gauge invariant «probes», quark-antiquark for mesons [8] and three-quark ones for the baryons [10]. Unfortunately, derivation of corresponding formulae is rather complicated and it is more instructive to consider simplest case [11] in which quark contour is closed by straight line in order to restore gauge invariance. Physically this means that light («dynamical») quark is supplemented by very heavy («static») antiquark, so the system considered is in fact B-type meson. It is trivial to find the corresponding correction for it simply follows from the definition of the condensate

$$S_{quark}(x)=-\frac{\hat{x}}{2\pi^2x^4}-i\langle\Psi\Psi\rangle+\ldots \qquad (x\to0). \tag{2}$$

First of all, this correction becomes relevant at very small distances

$$x\sim r_{chiral}=(-2\pi^2\langle\Psi\Psi\rangle)^{-1/3}\simeq\frac{1}{3}\,\mathrm{fm}. \tag{3}$$

Second, comparing it to fermion propagator with some effective mass one obtains some (conditional) expression for it:

$$M_{eff}(x)=-4\pi^2x^2\langle\Psi\Psi\rangle \qquad (x\to0). \tag{4}$$

Note, that in reaches phenomenological constituent mass value as early as at $x\approx .1$ fermi! Existence of this small scale is essentially due to large geometrical factor $4\pi^2$, which is also present in other (more complicated) corrections due to «exchange interaction» of the trial quark with those composing vacuum quark condensate. So, one comes to one more important conclusion: phenomena related to chiral symmetry breaking show up at distances essentially smaller than confinement forces!

(Unfortunately, nowdays lattice calculations are too «coarse-grained» to study such substructure from first principles, but, surprisingly enough, from QCD sum rules at small distances it turns possible to find correct hadronic masses and other parameters, see [8, 10] and vast subsequent literature.)

It was suggested in my papers [12] that these facts are just manifestation of some substructure inside hadrons, in form of clusters (or «constituent quarks») with dimensions few times smaller than hadrons themselves, see Fig.1,d. (This quasinuclear picture was first suggested long ago [13] on quite different basis, the so called «additive quark model» of soft hadronic interactions.) Therefore, one may probably add one more fundamental problem to our list: that of «constituent quark structure».

Meanwhile, motivated by completely different arguments (successful treatment of heavy quarkonia) the nonrelativistic quark model has again appeared on the stage. Its main ingredient now is spin-colour interaction between quarks of the type

$$V_{int}=\mathrm{const}\cdot(\lambda_1^a\lambda_2^a)\left(\frac{\vec{\sigma}_1}{m_1}\frac{\vec{\sigma}_2}{m_2}\right) \tag{5}$$

where the matrixes λ^a, σ^m correspond to colour and spin, respectively. We remind that these forces reproduce correctly spin splitting of mesons and baryons [14] (which is surprising because the coupling constant found from the fit turns to be large enough for perturbative interpretation to be literally agreeable). Adding to (5) linear confining potential people have calculated impressive set of spectroscopic parameters, including masses of excited mesons and baryons, photon transitions, decay constants etc. About a hundred of reasonable numbers definitely shows, that this old-fasional approach contains some truth in it.

Making one more step toward more fundamental problems the reader may ask the following question: if there exist substructure of hadrons with the typical length of, say, 1/3 of fermi, then what are small-size vacuum fluctuations which create them? A good candidates for this role are instantons, providing qualitative dependence of corrections on the quantum number of a «probe» [15] and even leading to semiquantitative model [12, 16] of the QCD vacuum as an «instanton liquid». Assuming such fluctuations to be really there in vacuum, one comes to the third type of forces between quarks, acting at intermediate distances and related to t'Hooft multifermion interaction with the following spin-flavour structure:

$$\begin{aligned} L_{inst}=&\lambda_{ud}(\bar{u}_Ru_L)(\bar{d}_Rd_L)+\lambda_{su}(\bar{s}_Rs_L)(\bar{u}_Ru_L)+\\ &+\lambda_{sd}(\bar{s}_Rs_L)(\bar{d}_Rd_L)+(R\leftrightarrow L) \end{aligned} \tag{6}$$

(L and R mean here left and right polarized quarks, let me also note that λ_{su}, λ_{sd} is about one half of λ_{ud}). In particular, such interaction produces both very light pion and very heavy η' [12, 16, 17], eliminating the largest «cloud in the sky» for the quark models. One more interesting consequence of these forces may be existence of relatively light and diquark with scalar quantum numbers [17 c].

3. NUCLEONS IN NUCLEI

Instantons are also relevant for the story I am going to tell now. In 1978 Callan, Dashen and Gross and independently myself [18] have suggested some explanation for the origin of the bag constant: colour field suppress instantons, which are known to produce negative shift of the vacuum energy. (Unfortunately, it is still unclear whether this idea indeed works, because it was never made quantitative.) It is important for us now because it has pointed out that hadrons can only retain their known properties if they are surrounded by sufficiently thick amount of vacuum.

At the end of that year I have obtained a letter from R.J. Ellis (then from Los-Alamos), in which he pointed out that in nuclei there is not so much place for unperturbed vacuum fluctuations and suggested that therefore bag constant should be reduced, leading to some increase of nucleon's dimensions. (I replied that he should publish this idea, but he did not, as far as I know.) After EMC effect was observed, it was suggested by a number of authors. My point now is that similar considerations show that quark condensate also should be suppressed in nuclei, which makes nucleons somewhat lighter: at some critical density chiral symmetry is restored, and «constituent» quarks become massless.

The average parameters may be shifted by only few percents, but those sensitive to certain fluctuations may change stronger. For example, particular nucleon configuration in which it is unusually compact occures in nuclei less frequently, because in this case (negative) binding energy is reduced [20].

It is important to note, that such effects also may have «old-fashional» formulation: for example, one may say that nucleon size is increased because nucleons are attracted to each other and therefore stretch each other a bit. Another old-fashional argument suggests an opposite trend: fermi-blocking prevents nucleon from emision of soft virtual pions, therefore its «pionic cloud» should be reduced. (Quite opposite idea put forward in refs [21], predicting plenty of «sea quarks» in nuclei in order to reproduce EMC effect at small x, deal with hard pions.) The profit of using more modern quark language is connected with its greater predictive power, at least we hope so.

4. MULTIQUARK SYSTEMS

Parametrs of virtual six-quark system at short distances is crucial for nuclear physics, because it is responsible for repulsive core of nuclear forces. At this particular point predictive power of more fundamental quark-based approach should be especially great.

Started with spherically symmetric systems with six quarks it was found [22] that the simplest totally symmetric state has the energy higher than two nucleon masses by about 300 MeV, essentially due to the interaction (5). However, later investigations [23] (done now with potential nonrelativistic model in harmonic potential well) have found that this interaction prefers another state with Young table [4, 2], corresponding to two radially excited quarks. Respectively, completely new interpretation of the nucleon core was suggested: it was related to some node of the wave function.

In view of importance of this question it should be addressed at more quantitative level free from various technical simplifying assumptions: selection of certain set of states etc. In the low energy (static) case one can use very flaxible variational methods. (Note, that even in static case there are some interesting problems to deal with: for example, low energy scattering parameters. Another long-standing problem is connected with deuteron: admixture of d-wave found from magnetic and quadrupole moments are essentially different, and it is interesting to see whether the six-quark virtual system can help here.)

Nevertheless, static calculations are not sufficient for many problems. In particular, considering scattering at growing energies one should find that the time for the wave function rearrangement becomes smaller, and such effect is decreasing. Unfortunately, dynamical calculations for so complicated quantum systems are extremely difficult in technical sence. In this connection let me attract attention of theorists working in the field to interesting development of some modern technique, based on Feynmann path integrals instead of traditional Shredinger wave function. Using rather conventional Metropolis algorithm for paths in Euclidean time O.V. Zhirov and myself [24] have tried to solve few traditional multidimentional problems (with known unswers!), such as two-electron atoms and up to four-nucleon nuclei. Althogh it is completely impossible to consider general 12-dimensional quantum problem in Shredinger framework, this method (without any approximations, therefore without much «intellectual efforts») was found to converge to correct properties of the ground states. Unfortunately, applicability of this powerful method of calculations is at the moment restricted: in particular, it can not be used if completely identical fermions are present, as well as it does not allow to use real (Minkovsky) time: in both cases the weight is nonpositive. However, recent works [25] suggest to use Langevin equation in these cases. Although it is difficult to predict precisely what particular problems can be solved by such methods, the question obviously deserves further investigations.

Returning to experiments, let me first mention the well known idea that EMC effect is due to scattering on six-quark system [19]. In order to prove this experimentally one may try to detect «cumulative» proton in deep inelastic scattering on deutron and see whether «EMC» deviations from scattering on the proton are associated with them or with ordinary «spectators». This experiment is rather difficult, but probably with gas target in electronic storage ring it can be done.

Another set of experiments are connected with sigma-hypernuclei lifetimes. This is dynamical rearrangement of quarks in the six-quark system $\Sigma N \to \Lambda N$ and therefore it should be reproduced by «six-quark theorists». More generally, forces between hyperons and nucleons are very interesting. Valuable information can be given by masses of dibaryon resonances, especially of dilambda, predicted by Jaffe to be below strong decay threshold and having therefore noticeable lifetime due to weak decays. I think that this nontrivial point should be seriously checked with high energy «hyperon beams» (up to Ω^- are now available in large numbers!). The qualitaive idea that repulsive core becomes softer by substitution of ordinary quarks by the strange (or even charmed) one is a consequence of (5), and since these forces are generally considered to dominate in hadronic spectroscopy this point should be tested.

Let me add, that «mechanical stability» of macroscopic blobs of partly strange (or charmed) matter was independently suggested many times by different authors (including myself), but it was considered just as simple way to evaluate «asymptotics of Rosenfeld tables of resonances». However, Witten has recently advocated more radical possibility that strange quark mass can be compensated and therefore such systems are absolutely stable (and even compose «dark matter» in galaxies)! Unfortunately, it is hardly possible to check these ideas directly, but trying to put more and more strangeness into nuclei one can at least see whether the tendency is right.

4. HIGHER TWIST EFFECTS

Scaling violation in deep inelastic scattering has attracted much attention during the last decade, considered to be the most suitable place for «QCD test» and measurement of the fundamental parameter Λ_{QCD}. Experiments with high-energy muon and neutrino beams have allowed to reach very high momentum transfer. Unfortunately, unequivocal determination of gluon bremsstrahlung effect and accurate measurements of lambda turns out to be extremely difficult. (Similar complementarity between calculatable and observable effects is standard in perturbative QCD.) The main problem is connected with nonperturbative corrections (or «higher twist» effects in more technical notations), which is not easy to separate from perturbative ones (unless $Q \geqslant 10$ GeV where scaling violation is hardly seen).

The main idea of this section is that instead of trying to get rid of these irritating higher twist effects one should better study them, and that they are extremely important for most crucial questions of hadronic structure, discussed in section 2.

Unfortunately, theory of these effects is very complicated, only few papers deal with them, and they are not easy to understand because of too technical presentation and cumbersome formulae. So, let me try to discuss only main physical points.

In this audience it is useful to emhasize from the start close similarity between this effect and the now popular EMC effect. Indeed, the latter exists because scattering takes place not at an isolated nucleon, but on that affected by surrounding matter. Similarly, higher twist corrections to deep inelastic scattering exist because scattering takes place not on the isolated quark, but on that placed inside the nucleon and affected by quark and gluon fields. The obvious advantage of this effect is that it is based on the solid formalism of QCD, so we may reasonably formulate what fundamental parameters we can obtain from the data. In particular, twist classification means that structure functions can be expanded in powers of $1/(Q^2)$ and the coefficients can be definitely presribed. Writing electomagnetic structure function in the form

$$F_2(x,Q^2) = f^{leading\ twist}(x,\log Q^2) + f^{next\ twist}(x,\log Q^2)/Q^2 + \ldots \qquad (7)$$

one can pass to its «moments» (integrals over x):

$$M_n(Q^2)\equiv\int_0^1 dx\, x^{n-1}\, F_2(x,Q^2)=a_n(\log Q^2)+b_n(\log Q^2)/Q^2+\dots \qquad (8)$$

(Perturbative effects lead to known logarithmic dependence of these quantities, which we now ignore). There exists formulae for coefficients b_n [26—28], in particular, b_2 in schematic presentation looks as follows:

$$b_2=\langle N|\,(\sum C_{AB}\Psi\Gamma_A\Psi\Psi\Gamma_B\Psi+\sum C'_{\alpha\beta\gamma\delta}\Psi D_\alpha G_{\beta\gamma}\Gamma_\delta\Psi)\,|N\rangle \qquad (9)$$

where C, C' are some known numerical constants, Γ are Lorentz-flavour-colour matrixes, $G_{\beta\gamma}$ is the colour field in the scattering point, and D_α is the covariant derivative. Such formulae are not easy to derive and they do not look very attractive, it is true. Fortunately, their physical meaning is not so complicated. First of all, in [26] arguments are given that four-fermion effects are more important here, so we concentrate on them. They appear either because some other quark happen to be close to the struck one and its field affect the scattering (Fig.3,*a*), or because we consider interference of scattering on different quarks (Fig.3,*b*). (Note, that «scattering on diquarks» considered in some works appears only in terms $O(1/Q^4)$!) Anyway, summing over all intermediate states and putting Q to infinity we obtain local operators (9), which up to certain coefficients is just the probability to find two quarks in the same point in transverse plane (in Breit system nucleon is moving with large momentum, therefore it is Lorentz compressed disc!). In «naive» quark models, like MIT bag, this probability is about $1/(\pi R^2)$, where R is the nucleon radius, see details in our work [26] and also estimates by Jaffe [27].

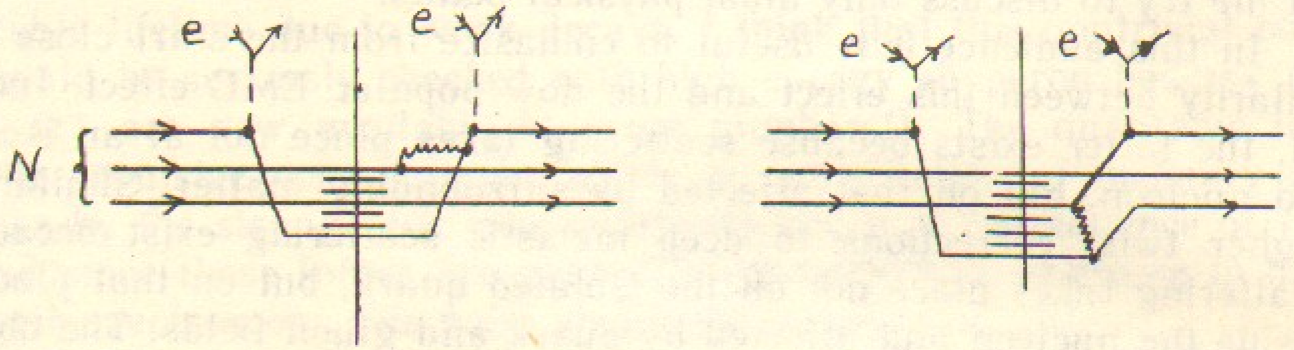

Fig. 3. Schematic presentation of effects producing $1/Q^2$ corrections to structure functions. The dashed lines represent photons, while the wavy lines correspond to hard gluons.

Even rather uncertain data concerning such effects are sufficient to conclude that such estimates are definitely wrong, producing effect an order of magnitude smaller than observed. The proposed explanation [26] is based on compact «quark clusters» or constituent quarks, so that nucleon radius is substituted by much smaller radius of such clusters.

These arguments are probably sufficient to explain why next twist effects are so important. It measures two-quark density in nucleons and nuclei, the quantity of fundamental importance. Average values of operators entering these formulae are as fundamental parametrs of the nucleon as its magnetic moments etc., but much more sensitive to details of its structure. In addition, one may study these effects at momentum transfer of few GeV with electronic beams, that is why they are important for this meeting.

Another aspect of higher twist physics is more directly connected with the EMC effect. First of all, they are of comparable magnitude and one may reasonably ask whether known deviations between EMC and SLAC data are connected with different Q values in these experiments? Assume now, that this problem is resolved and A dependence for a_n and b_n in (8) is separated.

Such information is of great importance for understanding of many questions considered at this conference. For example, two different explanations of the EMC effect, the increase in nucleon dimensions and admixture of six (or more) quark configurations, lead to quite opposite predictions. If the former explanation is right, one may await some decrease in two-quark density, while in the latter case it would be enhanced. Most probably, the second effect will dominate, so we will learn something new about the six-quark system.

6. CONCLUDING REMARKS

Studies of nonperturbative QCD are now going on at high speed. Most difficult problems are still ahead, but also we have already understood a lot. The central point is the «QCD vacuum structure» problem, now attacked from first principles (lattice numerical experiments) and phenomenologically (QCD sum rules). The former approach is potentially important, but its results are not yet accurate enough for many applications. The latter approach is no so well grounded but it has already been used for many successful applications. Its most important conclusion is that for light quark systems the largest nonperturbative effects are those connected with chiral symmetry breaking (and not confinement), and that they show up at surprisingly small distances. This may give some justification to old-fashional nonrelativistic quark models.

Interesting qualitative phenomena are predicted in nonperturbative QCD, in particular deconfinement and chiral symmetry restoration at high density, and extrapolation of nuclear physics data to such densities are of fundamental importance. As an approach toward such densities one may consider short-range nuclear forces. Quark models of hadrons are now in very good shape, and they may be considered as quite reliable basis for many-body calculations. New exciting techniques are now developing in this field, and it may well be that they soon will allow for quantitative results for extremely complicated quantum problems with many degrees of freedom.

Returning to nuclear physics and electron scattering, we may hope to witness in nearest future much more precise measurements of structure functions in «intermediate» region $Q^2=1-10$ GeV^2, capable to single out next twist corrections and even its A-dependence. As I have emphasized above, such information is of great importance for new step in understanding of hadronic and nuclear structure. Many new experiments become feasible with technique developing now. It seems reasonable to concentrate on such simple system as deutron, for which also polarized gas targets can be used. Recording protons (and may be even neutrons) together with scattered electron one may obtain more detailed information on the nature of, say EMC effect, provided data are accurate enough to see such details. Polarization allows to obtain additional information, even in elastic channel (quadrupole formfactor), and new structure functions in deep-inelastic case.

And finally, let me thank the Organizing Commettee for the opportunity to discuss these interesting problems and express a hope that at the next such conference we will hear solutions of some of them.

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**The structure of nucleons and nuclei
and nonperturbative QCD**

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