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MULTIQUARK STATES IN NUCLEI AND THE DEEP INELASTIC SCATTERING

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I. INTRODUCTION

The European muon collaboration (EMC) data[1] on deep inelastic scattering (DIS) of muons on iron and deuterium nuclei and their confirmation by the MIT-SLAC group[2] call close attention of a wide number of physicists. Apparently, the main reason for such an interest was the fact that the results obtained laid a clear emphasis on the unsoundness of the standard nuclear models and the standard methods for the description of nuclear effects in the sufficiently high momentum transfer region, when the multiquark states in nuclei start to play an essential part. The study of them was begun by the Dubna experimenters more than ten years ago in the so-called cumulative processes[3] (i.e., in the nuclear processes far beyond the kinetical region which is allowed by the interaction with one nucleon) and continued at the Dubna, ITEP, Yerevan, Berkeley and FNAL accelerators[4-7]. Already in the first papers[8] on predictions of the cumulative particle production, those particles have been considered as the nucleus fragmentation products connected with its quark-parton structure function[9-10]. The greatest attention is called by the preliminary data of the NA-4 group[11] in CERN on a direct measurement of the carbon structure function in DIS. These data point out the carbon structure function to have a considerable value in the cumulative region $x > 1$ (up to $x \approx 1.4$), which is by many orders of magnitude greater than it is allowed by the Fermi-motion. If confirmed, this result will play an important part in proving the existence of the multiquark states in nuclei.

One sees from fig.1 that the difference from the standard nuclear approaches is observed in three regions:

a) The region of small x, where the ratio of the iron and deuterium structure functions becomes greater than unity. This points to the existence, in nuclei, of an additional sea of $q\bar{q}$ pairs (valent quarks do not contribute when $x \to 0$). This sea is more sufficient in heavy nuclei than in light ones. The physical reason for a formation of such a sea may be different: multiquark states[12,13], pion condensate[14,15], "quark bag percolation"[16], etc.,[17].

b) The region of intermediate x, where that ratio first becomes less than unity, and then again intersects the line $R = 1$ at $x \approx 0.8 \div 0.9$. As has been shown by numerical tests, the region of the second cross through unity depends on what

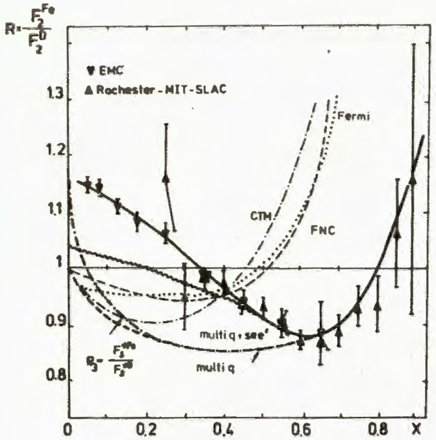


Fig.1. The ratio of the structure functions R(Fe/D). The thin lines are the predictions of the standard nuclear models (the Fermi motion, the coherent tube model (CTM) [29], the few-nucleon correlation (FNC) model [6]). The thick lines are our results for $R_2 = F_2^{Fe}/F_2^D$ (———) and the prediction for $R_3 = F_3^{Fe}/F_3^D$ (—— ·——). The wave line is the prediction of the "swelling nucleon" model [24].

part of the average momentum (in the infinite momentum frame) do the nucleons carry. If this part amounts to 100 per cent (as in any nonrelativistic potential approach), then the cross point lies in the vicinity of $x \approx 0.5$ and moves to the right side with the momentum part decrease. So, the deviations in that region again show the existence of an additional agent with a certain momentum part.

c) Finally, the region $x > 1$, which has already been talked about and which is a direct evidence that in the nucleus there are some objects much heavier then nucleons. The same qualitative peculiarities have also been observed for the ratio of the cumulative pion scattering cross-sections on different nuclei [18].

Our point of view consists in that all these three properties, just as the cumulative hadron production, are consequences of one reason - the permanent creation and desintegration of the multiquark fluctuations (fluctons) in nuclei. It is clear that, qualitatively, this hypothesis in fact explains not only the third one but also the two former new peculiarities, so far as that multiquark compound must certain a gluon sea additional to that of the initial joint nucleons. It is this very sea that gives rise to an additional sea of the $q\bar{q}$ pairs, explaining the increase in the ratio in the small x region. At the same time, the additional seas take away a part of the momentum of valent quarks. That leads, to a shift of the $R = 1$ region to larger x. The question is how it is co-ordinated quantitatively. Will the sea not prove too large, so as to give rise to a discrepancy with the absolute values of the structure functions or even to an inconsistency with the momentum conservation law at all? Do the percentages of the multiquark states in cumulative processes and DIS agree? The aim of our work is

to answer all these questions and to show that the multiquark flucton hypothesis is capable of providing quantitative explanations for all these phenomena and of predicting some peculiar features of the behaviour of the neutrino and muon DIS at nuclei, in particular, the ratio of the structure functions for different nuclei, the difference of the isobar-nuclei structure functions, their A dependence.

An important consequence of the EMC-data disagreement with the standard-model predictions is a distruct to the nucleon-structure information obtained at nuclear targets. Particularly, that applies to the QCD verification and to the determination of the Λ_{QCD} value. Of course, nucleus is not a bit worse (but in many respects still better) than nucleon for the QCD verification because the evolution equations (the renormalization-group or Lipatov-Altarelli-Parisi ones) for nucleus are identical to those for nucleon. However, we are unlikely to intend a correct Λ value if, as usually done, rejecting the region $x > 1$. Therefore, our first problem should be to restore the nucleon structure function using the hydrogen data only. This is treated in Sec.2. Section 3 is devoted to the constructing of the nucleus quark-parton structure function based on the hypothesis of the multiquark fluctuations which is used in Sections 4 and 5 for describing the DIS and cumulative pion production cross sections. Section 6 is dedicated to some of the model predictions and to discussions.

2. THE NUCLEON STRUCTURE FUNCTION

Up to now, there are relatively few good data of the DIS on hydrogen [19]. Here one may call the old SLAC data [20] in the momentum-transfer region $Q^2 \leq 20$ (GeV/c)^2, the new EMC-group data [21] of the muon scattering in the region $Q^2 < 300$ (GeV/c)^2, and the CDHS- and ABCMD-group preliminary data of the ν and $\bar{\nu}$ DIS on hydrogen [19]. In the present work we will not be concerned with fitting the Q^2 dependence of structure functions but are going to dwell upon the region $50 < Q^2 < 300$ (GeV/c)^2, since the experimental R-ratio depends weakly on Q^2 [1], and the NA-4 group data on carbon in the region $x > 1$ are related to this very transfer-interval [11]. In fig.2 the EMC-results of measuring $F_2^{\mu p}$ in this region are represented; in fig.3, the ratio d_v/u_v obained by the CDHS and ABCMD groups. The valent u-quark distribution in a proton is approximated by the expression

$$x \cdot u_v(x) = \frac{2{,}188 \cdot (1 + bx)}{1 + b/g} \cdot \sqrt{x} \cdot (1 - x)^3 , \qquad (1)$$

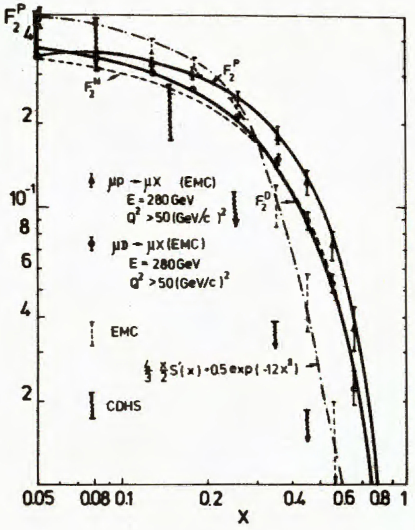


Fig.2. The proton (▲) and deuteron (●) structure functions and the collective sea contribution $(\frac{4}{3}\cdot\frac{x}{2}\cdot s'(x))$ in the six-quark flucton obtained from F_2^{Fe} of the EMC group /30/ (⫶) and the structure function $\bar{q}^{Fe} = x(\bar{u}^{Fe}(x) + \bar{d}^{Fe}(x))$ of the CDHS group /32/ (I).

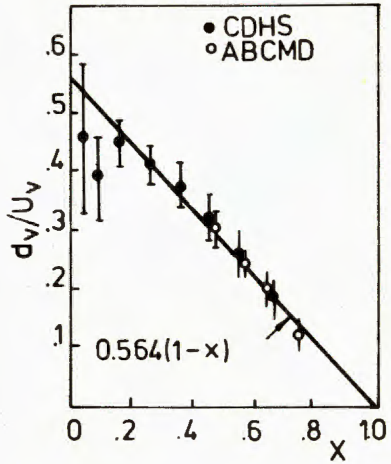


Fig.3. The ratio of the valent d- and u-quark distributions obtained from the neutrino DIS on hydrogen.

which satisfies the normalization condition $\int_0^1 u_v(x)\,dx = 2$ and the d_v/u_v ratio by the expression

$$d_v/u_v = A\cdot(1-x). \qquad (2)$$

Thereupon, the normalization $\int_0^1 d\ (x)\,dx = 1$ leads to a correlation condition:

$$A = \frac{1+b/9}{1+b/11}\cdot 0.562\,.$$

The SU(3)-symmetric quark-sea structure function is chosen in the form $u_0 = \bar{u}_0 = d_0 = \bar{d}_0 = s(x) = c(1-x)^n$. The proton structure function

$$F_2^{\mu p} = \frac{4}{9}\cdot x\cdot u_v(x)\cdot(1+\frac{1}{4}\cdot\frac{d_v}{u_v}) + \frac{4}{3}\cdot x\cdot s(x) \qquad (3)$$

is fitted to the EMC data (fig.2) by the selection of the parameters b, c and n. The sea parameters have been chosen over the small x region (0.05 ÷ 0.35), where $F_2^{\mu p}$ is practically independent of b, and the parameter b over the region x > 0.45. The result represented in fig.2 implies

$$n = 7,\quad c = 0.15,\quad b = 0.15. \qquad (4)$$

The A = 0.564 values, obtained here, are also in good correspondence with the data of fig.3.

The nucleon structure function, constructed from the distributions u_v, d_v and s, has the form

$$F_2^{\mu N} \equiv F_2^S = \frac{1}{2}\cdot(F_2^{\mu p} + F_2^{\mu n}) = \frac{5}{18}\cdot x\cdot u_v(x)\cdot(1+\frac{d_v}{u_v}) + \frac{4}{3}\cdot x\cdot s(x) \qquad (5)$$

with the same parameters (4).

3. THE NUCLEUS STRUCTURE FUNCTION

Suppose that in the nucleus, together with the nucleons, the multiquark density fluctuations, fluctons, are present. Then, the nucleus structure function can be written in the form (still with no account of the Fermi motion)

$$F_2^A(x) = \sum_{k=1}^{A} f_k^A\cdot\frac{1}{k}\cdot F_k(x)\,, \qquad (6)$$

where f_k^A are the flucton-creation probabilities ($\sum_{k=1}^{A} f_k^A = 1$)

and $F_k(x)$ is the structure function of a flucton from 3k valent quarks ($F_k(x) \neq 0$ in the region $0 < x < k$).

Now let us turn to constructing the flucton structure function for the colourless system composed of 3k-valent quarks, the $q\bar{q}$ pair and gluon sea. A concerns the valent quarks, it is easy to show that the wave function of any colourless system of 3k quarks (not being a product of k colourless triplet!) is reduced to an antisymmetrized combination of the products of colourless triplets. On fig.4 an example of such a reduction is shown for the six-quark system. (We call attention to the fact that only a pair of quarks is antisymmetrized, not the triplets!). This implies that the valent-quark distribution over the fractions of the quark-system total momentum can be represented in the form of the Mellin convolution of the colourless-triplet distribution $N_k^{(r)}$ and the quark distribution in a triplet $q_v^{(r)}$ (see fig.5a):

$$q_{vk}(x)=\frac{1}{k}\sum_r \iint_0^1 N_k^{(r)}(\alpha)\cdot q_v^{(r)}(\beta)\cdot\delta\left(\frac{x}{k}-\alpha\cdot\beta\right)d\alpha\, d\beta \equiv \sum_r N_k^{(r)} \circledast q_v^{(r)}, \quad (7)$$

where x, α, β are the corresponding momentum parts, x being defined as the part for one nucleon, and r is the set of all the remaining quantum numbers of the colourless triplet. The baryon number conservation requires that

$$\int_0^k q_{vk}(x)\,dx = 3\cdot k, \quad \text{i.e.} \quad \sum_r \int_0^1 N_k^{(r)}(\alpha)\,d\alpha = k. \quad (8)$$

Using, further, the quark-hadron duality hypothesis, one can decompose every three-quark colourless state over the hadron states N, Δ, N', N'', etc., (fig.5a) and assume the index r to be already a characteristic of the hadron three-quark state and $q^{(r)}$ to be the quark distribution in that state. Such a picture corresponds to the momentum approximation.

Pay attention to the fact that the DIS virtual photon blows up only one of the quarks from some colourless triplet exciting thus colour degrees of freedom and giving rise to a continuous spectrum of hadron states. The colour degrees of freedom of the remaining colourless triplets are then left practically unexcited, due to which they "work" effectively as point objects (like a multiatomic molecule at low temperatures). Thus, in this case we deal with $k-1$ passive point spectators. And owing to the "quark counting" rules [23] (the passive-spectator counting rule), the N_k behaviour at $\alpha\to 1$ should be $N_k(\alpha)\sim(1-\alpha)^{2k-3}$.

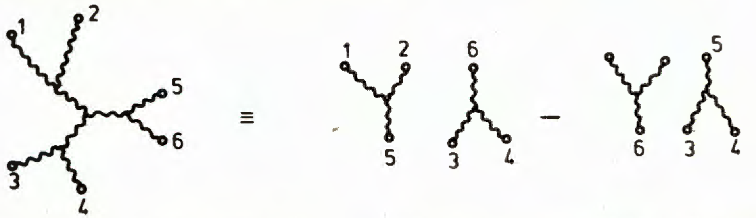


Fig.4. The representation of the six-quark state vector in the form of the product of two colourless triplets antisymmetrized over two quarks.

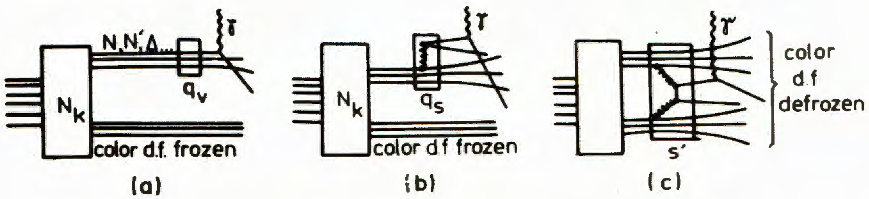


Fig.5. DIS on the six-quark system.

In fact, such a behaviour determines only the upper bound for the decrease power, and as we shall see below, the experiment requires a little faster fall.

Now let us proceed to the sea quark-antiquark pair distribution. Each of such pairs can be produced by gluons connected either with one colourless triplet or with two or more ones (a "collective sea"). In the former case, the colour degrees of freedom of the remaining triplets are left freezed and we again deal with the momentum picture (fig.5b):

$$s_k(x)=\sum_r\frac{1}{k}\iint_0^1 N_k^{(r)}(\alpha)\cdot s^{(r)}(\beta)\cdot\delta\left(\frac{x}{u}-\alpha\cdot\beta\right)d\alpha\, d\beta. \quad (7')$$

However, the collective sea s'_k (fig.5c) is not reduced to the momentum-approximation picture, cannot be represented in the form (7) and should be simply added to s_k. What can only be estimated is the power of decrease owing to the passive-spectator counting rule, e.g., for the six-quark system $s'_2\sim(1-x/2)^{13}$ (there are seven point spectators).

It is now easy to construct the 3k-quark flucton structure function for the nucleus with the atomic number A and the charge Z, the third isospin projection, on an average, being equal to

$-\Delta=\frac{Z-N}{2\cdot A}$, where $N=A-Z$. It is sufficient to understand that

the r three-quark resonance distribution $N^{(r)}$ enters with the weight proportional to $1/2(1-\Delta/|I_3^{(r)}|)$ and the $\bar r$ resonance distribution ($\bar r$ differs from r by the change $u\to d$) has the weight factor $1/2(1+\Delta/|I_3^{(r)}|)$, so that the difference of these weights multiplied by $I_3^{(r)}$ equals the nucleon-isospin third projection. Thus,

$$F_k(\alpha)=\sum_r\left\{(\alpha N_k^{(r)})\circledast F_2^{(r)S}-\frac{\Delta}{|I_3^{(r)}|}\cdot(\alpha N_k^{(r)})\circledast F_2^{(r)NS}\right\}+\frac{4}{3}\cdot\frac{\alpha}{k}\cdot s'_k(\alpha), \quad (9)$$

where F_2^S is a symmetric, with respect to the change $u\to d$, (singlet) combination of the structure functions (see (5)), and

$$F_2^{(r)NS}=\frac{1}{2}\left(F_2^{(r)}-F_2^{(\bar r)}\right)=\frac{1}{6}\left(u_v^{(r)}(x)-d_v^{(r)}(x)\right) \quad (10)$$

is the antisymmetric (nonsinglet) combination.

Further, we might use the well-known circumstance that the resonance fraction in nuclei does not exceed a few percent. However, it would be illegal, since, as commonly assumed, the multiquark-state fraction is not great as well, and probably, the resonance fraction in multiquark states is very considerable.

But we can exploit that the convolutions in eq. (9) for the F_k moments are simply reduced to a product of the $aN_k^{(r)}$ and $F_2^{(r)}$ moments, and therefore the difference of the latter ones from the moments of the nucleon structure functions $F^{(N)} \equiv F$ can always be "pumped" into the difference of the distributions $N_k^{(r)}$ from the nucleon distributions $N_k^{(N)}$ which is, all the same, unknown. Thus, we obtain an effective nucleon distribution N_k. Expression (9) takes then the form:

$$F_k(a) = (aN_k) \circledast F_2^S + \frac{4}{3} \cdot \frac{a}{k} \cdot s_k'(a) + \Delta \cdot (aN_k') \circledast F_2^{NS}, \qquad (11)$$

where the last item represents the correction to a non-isoscalarity of the nucleus, not large as a rule*. The difference of the distribution functions N in the first and last item is caused by the fact that the singlet and non-singlet moment ratios for the nucleon and the r resonance do not generally equal one another. However, the baryon number conservation requires that

$$\int_0^1 N_k(a)\, da = \int_0^1 N_k'(a)\, da = k. \qquad (12)$$

Let us now dwell upon the difference in the interpretation of a flucton as a multiquark object and a few-nucleon correlation (FNC) (see, e.g., the review [6]). The fundamental difference consists in that in the FNC hypothesis the nucleons carry all the momentum of the flucton, i.e.,

$$\langle a \rangle_k = \int_0^1 a \cdot N_k(a)\, da = 1, \qquad (13)$$

while in the quark interpretation a part of the momentum should be carried by the additional gluon g_k' and quark-antiquark s_k' seas, so that the whole momentum part related to nucleons should be less than unity $\langle a \rangle_k < 1$. As has already been said, it is this difference that is responsible for the shift of the crossing point $R = 1$ from the region $x \approx 0.5$ to the right and that allows, as will be seen below, to explain a less magnitude of the nucleus structure function as compared with the nucleon one in the vicinity of $x \approx 0.5$ (i.e., $R(0.5) < 1$).

* The difference of the effective distribution N_k from the nucleon distribution $N_k^{(N)}$ can also be "pumped" into a change of the nucleon structure function in the nucleus. As a matter of fact, just this approach is chosen by the authors of the work [22].

The failures of the FNC picture, pointed out, which are due to the condition (13), seem to be characteristic of any nonrelativistic (let even relativized) nuclear picture based on the Schrödinger equation with a normalized wave function or on a quasipotential type equation (that, as a matter of fact, is as well nonrelativistic if the quasipotential is independent of energy), connected with a selected momentum frame and with a cut-off of the Fock column states there.

For instance, the two-nucleon structure function is defined through an integral over the transverse momentum from a squared module of the wave function depending on the module of the relative momentum of nucleons (see, e.g., [6]). Due to this reason that function is symmetric with respect to the change $a \to 1-a$ and is normalized by the condition (12). This immediately implies that

$$\langle a \rangle_2 = \langle 1-a \rangle_2 = 2 - \langle a \rangle_2, \quad \text{i.e.} \quad \langle a \rangle_2 = 1.$$

The same failures are completely present in the approach of ref. [25] where the flucton structure function is normalized by the equality of the average momenta of the valent quarks in the flucton and in the nucleon, which entails automatically the condition (13). (Although the function N is not introduced explicitly). As well, it concerns the approaches based on the potential interaction of quarks where the valent quarks carry the whole momentum of the multiquark system at all.

Proceed now to determination of the probabilities f_k^A. For this goal, it is now accepted to use the so-called bound channel model (see, e.g., [26,27] and refs. therein). But it is not quite clear to us, how important for computing probabilities is the fact that the multiquark system in that approach are composed of the valent quarks alone, which has just been criticized above. Therefore, we turn to a more simple and clear approximation of a rarefied gas having the origin as for back as in the pioneer work of D.I.Blokhintsev [28]. We shall assume that k nucleons form a multiquark system when their centers approach one another to a distance of the order of the colour-confinement radius $r_c \simeq 1$ fm about the nuclear force core double radius. The probability of such an event for the rarefied gas with the density distribution $\rho(r)$, ($\int d^3r \cdot \rho(r) = 1$) is determined by the well-known binomial formula (see, e.g., [7]):

$$f_k^A = \frac{k}{A} \cdot C_k^A \cdot \int d^3r \cdot \rho(r) \cdot (V_c \cdot \rho(r))^{k-1} \cdot (1 - V_c \cdot \rho(r))^{A-k}. \qquad (14)$$

Here C_k^A is the binomial coefficient, $V_c = 4/3 \cdot \pi \cdot r_c^3$ and, as a density, for intermediate and heavy nuclei, one can use the Woods-Saxon nuclear density (e.g., [7]) or the constant density approximation $\rho(r) = \frac{1}{V_A} \cdot \theta(R_A - r)$. In the latter case the probabilities take a simple form

$$f_k^A = \left(\frac{q_A}{A-1}\right)^{k-1} \cdot C_{k-1}^{A-1} \cdot f_1^A, \quad f_1^A = \left(1 + \frac{q_A}{A-1}\right)^{1-A}, \tag{15}$$

where $q_A = f_2^A / f_1^A = (A-1) \cdot V_C / V_A \cdot (1 - \frac{V_C}{V_A})^{-1}$ is the ratio of the six-quark and nucleon state probabilities in the nucleus A, which is considered as a fitting parameter in what follows. Formulae (15) are evidently true for a deuteron as well.

4. THE CHOICE OF THE FUNCTIONS N_k THE PARAMETERS f_k AND THE SEA

Expressions (6), (11) give the nuclear structure function with no account of the Fermi-motion. To consider it, F^A should be convoluted in the sense of (7), with the Fermi-motion structure function $F^A(x) = N_F^A \bullet F^A$. However, for all functions F_k, but the first one F^N, this implies the convolution N_F with N_k and leads to a change of the form of N_k only. Thus, effectively, the inclusion of the Fermi-motion is reduced to the change

$$F^N \to N_F \bullet F^N = F_1 . \tag{16}$$

In agreement with the supposition made above, that two nucleons form a quark system just as approaching a distance of the order 1 fm, we choose N_F as the Fermi-step function with $k_F \approx 0.19$ GeV. It is known [17] to have the form

$$N_F(x) = \begin{cases} \frac{3}{4\delta^3} \cdot [\delta^2 - (x-1)^2], & |x-1| < \delta^2, \\ 0, & |x-1| \geq \delta^2, \end{cases} \tag{17}$$

where $\delta = k_F/m$. As is seen from fig.8 the Fermi-motion is essential in the vicinity of $x \sim 1$ only.

Let us choose the function $N_k(a)$. As has already been said, the passive-spectator counting rules give for N_k the behaviour $N_k(a) \sim (1-a)^{2k-3}$ in the region $a \sim 1$. The phase volume model where N_k are the phase-volume parts attributed to one nucleon [29], in the k-nucleon flucton, gives

$$N_k(a) = k \cdot (2k-1) \cdot (2k-2) \cdot a \cdot (1-a)^{2k-3}.$$

But in this case $\langle a \rangle_k = 1$ with all that this implies. To make $\langle a \rangle_k < 1$ a more soft distribution is necessary. The numerical game with the functions of form $N_k \sim a^{\gamma}(1-a)^{2k-4+\beta}$ shows that expression (6) has always a point $x = x_0$, where F_2^A is practically independent of the choice of the parameters f_k^A. This is the point where $F_k \approx k \cdot F_1$, i.e., where the nucleus structure function crosses the nucleon one (corrected to the Fermi-motion). This point also corresponds to $R(Fe/D) = 1$. Above this point, F_2^A increases with f_k^A, below it decreases. The position of this point is on the whole determined by the quantities $\langle a \rangle_k$, not by the particular parameters γ and β (Unfortunately, we faild to prove this fact analytically). So, for $\langle a \rangle_k = 1$, $x_0 \approx 0.5$ and shifts to the right with decreasing $\langle a \rangle_k$ (i.e., the decrease in γ and the increase in β). Moreover, for other values of x, $F_2^A(x)$ depends weakly on the choice of γ and β for fixed $\langle a \rangle_k$. Due to this very reason, we have set $\gamma = 0$, i.e., chosen N_k in the form

$$N_k(a) = k \cdot (2k - 3 + \beta) \cdot (1-a)^{2k-4+\beta}. \tag{18}$$

The motion of the x_0 - point for the function of that form is shown in fig.6 where the preliminary experimental results of the NA-4 group [11] are presented. The coincidence with experiment occurs for $\beta \approx 1.5$ (this corresponds to $\langle a \rangle_2 \approx 0.57$) for which $x_0 \approx 0.85$. This is, as well, in a good agreement with the x_0 region where $R(Fe/D) = 1$. Note, that in this region neglecting of the additional sea s_k' proves to be in fact justified.

Now let us choose the parameters $P_A = 2 \cdot q_A$ and $P_D = 2q_D$ and the sea $s_k'(x)$. They should ensure both the experimental R(Fe/D) (fig.1) and the absolute F_2^{Fe} and F_2^D values. As the latter ones we used the EMC group data [28,29] for $Q^2 > 50$ GeV^2. In the region $x < 0.65$ we confined ourselves to $k \leq 3$ and set $s_3'(x) = 3 \cdot s_2'(x) = 3 \cdot s'(x)$ and $s_k'(x) = 0$ $(k > 3)$.

Most limiting were the values of F_2^{Fe} at the point $x = 0.55$ and of F_2^D at the points $x = 0.35$ and $x = 0.25$ and also the maximum R value for $x = 0.65$. The results of that analysis are represented in fig.7. Shaded regions for F_2^{Fe} and F_2^D correspond to a minimum (maximum) value of s', in F_2^{th}, which is allowed by the experimental error in the R(Fe/D) ratio. And the shaded R^{th} region corresponds to $s'(0.65) \geq 0$. It is seen from the figure that the crossing region of all the limitations is absent. However, if we permit the double experimental error in $F_2^D(0.25)$ (dashed line) and in $F_2^D(0.35)$ (dotted-dashed line), then the most probable overlapping region will lie in the vicinity of $P_{Fe} \simeq 0.28$, $P_D \simeq 0.13$. This gives the following multiquark-state contributions: $f_2^{Fe} \approx 32\%$, $f_3^{Fe} \approx 9\%$ (which corresponds to $r_c \approx 0.95$ fm), $f_2^D \approx 20\%$. The corresponding curve for F_2^D is presented in fig.2; for F_2^{Fe}, in fig.8 (where the contributions

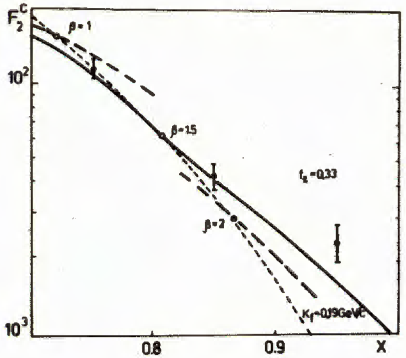
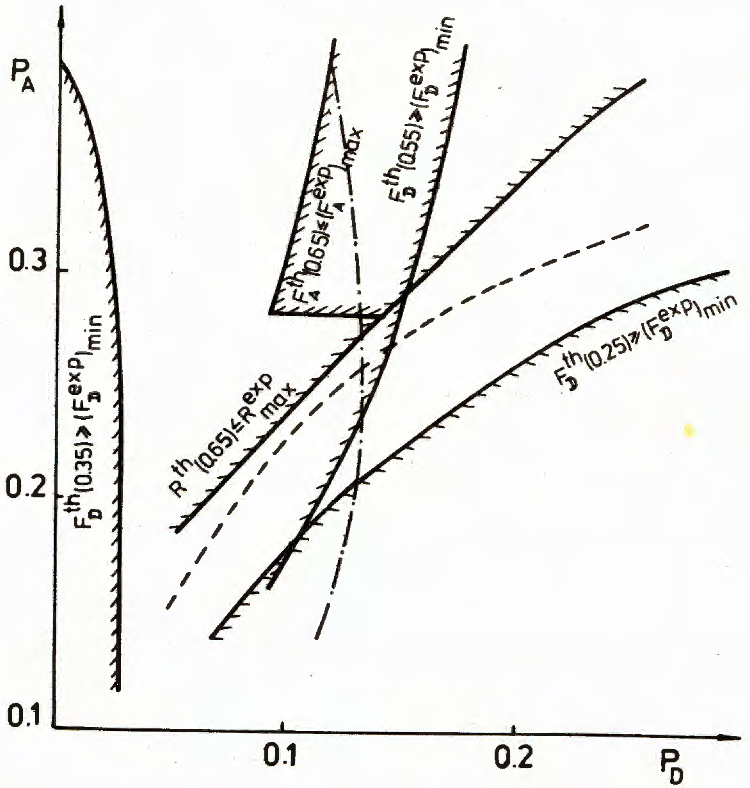


Fig.6. The choice of the β parameter for the colourless triplet distribution $N_2(\alpha)=2(1+\beta)(1-\alpha)^{\beta}$ in the six-quark flucton.

Fig.7. The choice of the multiquark state fractions.



of the six- and nine-quark systems are shown separately); and for R(Fe/D) in fig.1 (in this figure the shaded line shows the R ratio without the additional sea contribution). We should like to stress the sufficiently good agreement of the theoretical curve with the preliminary NA-4 group data (fig.8) in the region $x > 1$ (where $k = 4,5$ have also been taken into account),

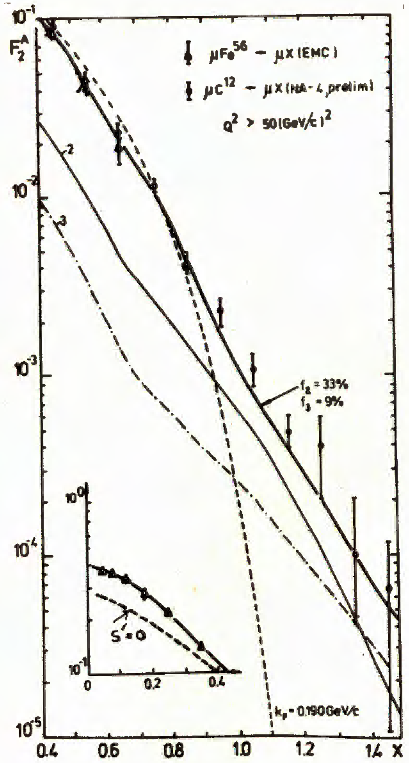
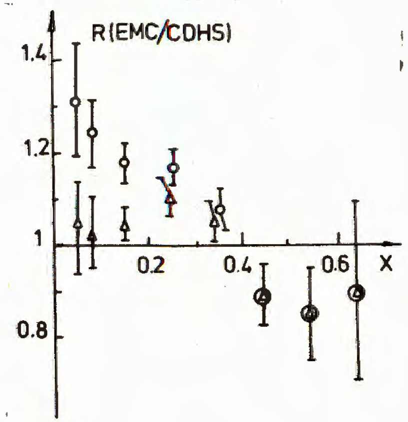


Fig.8. The iron and carbon structure functions (the thick solid line). The thin lines denote the contributions of nucleons taking into account their Fermi-motion in the nucleus (---), of the six-quark (——) and nine-quark (— · —) states. The nucleus structure function with no account of the collective sea (the thick shaded line).

Fig.9. The ratio of the iron structure function of the EMC group to that constructed of the CDHS-group data under assumptions about suppressing the transitions $s \to c$ (a) no suppression (O), (b) full suppression (Δ).



though the parameter $P_C \approx P_{Fe}$ has been fitted in the region $x < 0.65$. This is one of the most convincing evidences of the existence of the multiquark systems in nuclei. The multiquark-flucton percentage, obtained by us, proves to be significantly greater than the usual one. From our point of view, this is caused by two circumstances: a) the necessity of decreasing considerably the momentum fraction of nucleons (more exactly of the valent quarks) in a nucleus; b) the nucleon Fermi-distribution high momentum "tail" cut-off.

The additional sea obtained is shown in fig.2. It is well approximated by the rapidly decreasing function of the form

$$\frac{x}{2} \cdot s'(x) = \frac{3}{8} \cdot \mathrm{EXP}(-12 \cdot x^2). \qquad (19)$$

It is interesting to compare the momentum fractions related to different components in a nucleon and a six-quark system. If in the nucleon with $F_2^N(x)$ being chosen, the valent-quark part is 32% and the sea part is 11%, then in the six-quark system the collective sea obtained (19) amounts to 28% while the "nucleon" quarks (the valent and sea ones) to 25%. For the gluon part in the six-quark system there remains 47%, i.e., 10% less than in the nucleon, that reflects apparently its less bound nature.

The additional sea should most clearly manifest itself in DIS of ν and $\bar{\nu}$ on nuclei in the function $\bar{q}(x) = x(\bar{u} + \bar{d} + ...)$ and from this point of view, it is interesting to compare it with the CDHS-group data [32] for the $\bar{q}(x)$ function of iron. Such a comparison is represented in fig.2. There, the experimental data for each x have been averaged over all $Q^2 > 5$ GeV^2, and the same formulas (6), (11) have been used with the same parameters and suppositions as before but with a natural sudstitution $F_2^N \to \bar{q}^N = 2 \cdot x \cdot s(x)$. Additionally, it has been supposed that the s-quark sea contribution is suppressed by the Cabbibo-angle small value (the $s \to u$ transition) and by the $s \to c$ transition threshold factor. It is seen that the s' value obtained coincides with the former one in the small x region and is approximately two times less for high x. This difference may be related to a systematic error in experiment, to a deviation from the sea SU(3)symmetry supposed and to the $s \to c$ transition threshold suppression. As an illustration, fig.9 shows the ratio of F_2^{Fe} obtained by the EMC-group to the same value constructed from the CDHS-group data, neglecting the $s \to c$ threshold suppression but taking into account the c-quark sea being suppressed [19] $(5/18(xF_3 + 8/5\bar{q})$, is shown by circles), and taking into consideration the threshold suppression $(5/18(xF_3 + 12/5\bar{q})$, shown with triangles). One sees that in both cases the ratio differs appreciably from unity in the region $x > 0.15$. Lately, the preliminary CDHS-group data have become known [33] for the ratio of the sea antiquarks in iron and in proton which display no noticeable additional sea. All this makes difficult the determination of the collective sea s' parameters and establishment of the true reason for the EMC effect in the region of small x's. Thus, an additional experimental and theoretical study is required.

5. THE CUMULATIVE PION PRODUCTION

As has already been said, the knowledge of the nucleus structure function can be gained from the hadron processes. Although

it is not very clear a priori in what particular region the behaviour of the hadron cross section provides a direct information about the structure function and where and to what extent the traditional nuclear effects are important (re-scattering, cascade processes, etc.). For this purpose, it is interesting to compare the nucleus structure function obtained with the secondary hadron distribution over x, particularly, in the cumulative region $x > 1$. Moreover, this region is most sensitive to the multiquark-state contributions and gives a possibility of testing the parameters obtained from DIS.

So, let us study the inclusive processes $p + A \to \pi + X$ of pion production in the fragmentation region for the nucleus A. Though the fragmentation mechanism does not describe all the properties of the cumulative hadron production (see, e.g., [7]), for the pion production by the angle close to 180° in the laboratory system it is the most probable. The pion distribution in the proton-nucleus collision is constructed over the variable

$$x = \frac{(P_B P_C) + 1/2(\delta^2 - \mu^2 + 2\delta m)}{(P_A P_B) - (P_A P_C) - m(m+\delta)},$$

which plays the role of the minimum target mass just as in DIS. Here $P_{A,B,C}$ is the 4-momentum related to one nucleon of the nucleus A, to the initial proton and to the pion; m is the proton mass, δ is the minimum additional mass of the X system: $(M_x^2)_{min} = (m + m \cdot x + \delta)^2$, i.e., $\delta = 0$ for π^+ and $\delta = \mu$ for π^-. In the naive fragmentation model the cross section has the form

$$\frac{\epsilon_C}{A} \cdot \frac{d\sigma}{d^3 P_C}\Big|_{\theta = 180°} \sim \begin{cases} x(u^A(x) + 2s^A(x)) & \text{for } \pi^+, \\ x(d^A(x) + 2s^A(x)) & \text{for } \pi^-. \end{cases}$$

Figs. 10,11 represent the data of the cumulative pion production on deuterium and lead for the initial proton energy 8.9 GeV [34] and on the tantalum nucleus for the energy 400 GeV [35], and also the $F^A = x \cdot (u^A + d^A + 4s^A)\frac{1}{2}$ value calculated with the same parameters as DIS. For the heavy nuclei the states up to $k = 5$ have been taken into account. The normalization factor has been fitted over the region $x \sim 0.8 \div 0.9$ where the F^A value does not depend on the multiquark system percentage. It is seen that for $x > 0.9$ the agreement is sufficiently good, especially for the energy 400 GeV. However, in the region $x < 0.8$ there are differences which seem to indicate a sufficiently high role of the secondary nuclear effects.

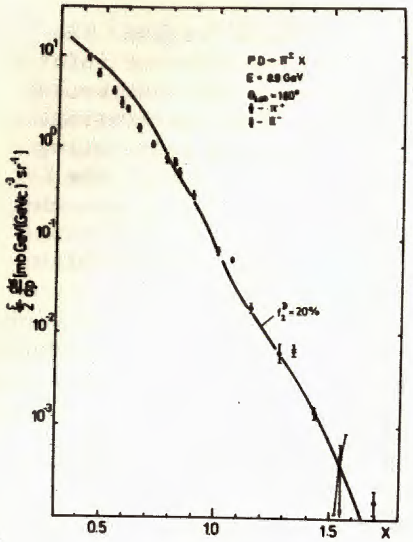


Fig.10. The comparison of the deuterium structure function (solid line) with the cumulative π^+- and π^--meson production

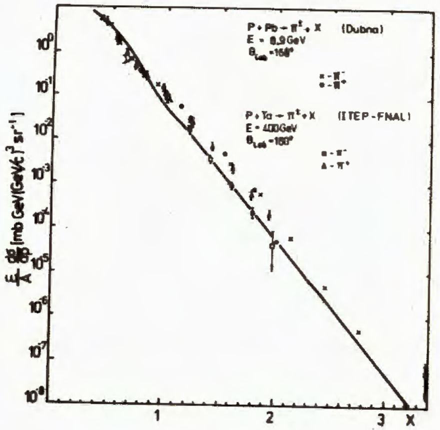


Fig.11. The comparison of the lead and tantalum structure functions with the cumulative π^+- and π^--meson production

6. PREDICTIONS AND DISCUSSIONS

Thus, the idea of the multiquark fluctons seems in principle to allow description of DIS in the whole x region. There is nothing particularly significant in this fact, since there were two more or less arbitrary functions $N_2(x)$ and $s'(x)$ at our disposal. The main question is to what predictions such a description leads? How to test the hypothesis of the multiquark fluctons and the additional sea? First of all, the necessity should be mentioned of testing the preliminary NA-4 results in the region $x>1$. This is the most brilliant and direct confirmation of the multiquark flucton existence. Then, the good data in the neutrino experiments on hydrogen are necessary, which allow one to measure separately the distribution of the valent quarks $F_3 = (u_v + d_v)$ and of the sea $\bar{q}$ for the free nucleon. The comparison of these data with DIS on a nucleus will provide a direct information about the change of the structure function of the valent quarks and the sea. The prediction for the F_3 ratio on iron and deuterium is represented in fig.1. Its characteristic features are a considerable widening of the region

$R<1$ to small x (nearly to $x \approx 0$) and deepening of the hollow as compared with the same ratio for F_2. These measurements will also allow one to distinguish between different models. For example, the "swelled" nucleon model /24/ leads to the R_3 behaviour shown in fig.1 by the wave line. For the sea-quark ratio, on the contrary, we expect a little decrease in the region of the extremely small x (or its absence, depending on the sea s′), which then changes by an increase.

For the muon experiments in the region $x<1$, the most interesting, in our opinion, is the measurement of the A dependence for the $R_2 = F_2^A / F_2^D$ and of the F_2^A difference on the isobar nuclei (i.e., nuclei with the same A, but different charges). The characteristic prediction of our model for R_2 is a weak amplifying of the EMC-picture contrast, i.e., a deepening of the minimum with increasing A, a growth of the raising in the region $x<0.35$ and $x>0.85$, an immobility of the crossing points $R=1$ ($x \approx 0.35$ and $x \approx 0.85$) and a rather quick growth of the ratio in the region $x>1$. This is due to the cancellations of the main part of the A-dependence in the probabilities f_k^A in the region $x<0.85$ (f_1^A decreases and others increase) and with the absence of that in the region $x \geq 1$. The corresponding curve for the dependence of R an A for different x are presented in fig.12. They have been obtained with the use of the probabilities (14) taking into account the inhomogeneity (for the Woods-Saxon potential), normalized by the choice $r_c \approx 0.95$ to the ratio of the iron and deuterium structure functions, and are in fine agreement with the R_2 data for aluminium /2/ and with the dependence of the cumulative pion production cross-sections /34,35/. (The latter are normalized for Ta point).

The cancellation of the sea is characteristic of the difference of the isobar-nuclei structure functions. Therefore, a considerable difference from $(F_2^p - F_2^n)$ in the region of small x is absent, which has been observed for the iron and deuterium structure functions. On the contrary, in the region of the intermediate $x<0.6$, a considerable difference is predicted. The characteristic behaviour of the difference of the isobar-nuclei structure functions is shown in fig.13 in comparison with $(F_2^p - F_2^n)$.

Thus, we have considered the model of the nucleus structure function based on the hypothesis of the multiquark flucton existence in nuclei. A consistent formulation of this model requires the existence in such states of an additional (to the nucleon one) gluon sea, and hence, of an additional sea of the quark-antiquark pairs, and the decrease of the valent quark momentum part. It is these basic properties that distinguish the model both from the few-nucleon correlation model /6/ and from the other models /7,15,24,29,36/. These properties allow

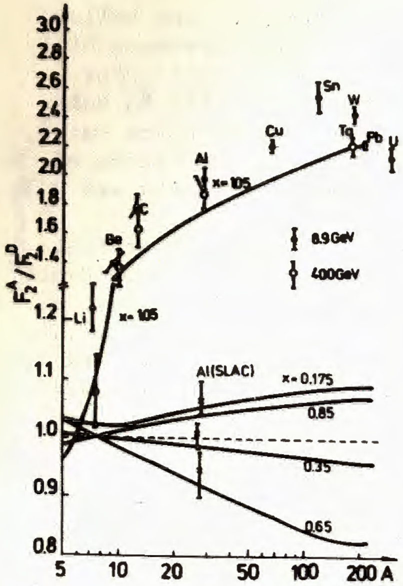


Fig.12. The $R_2(A/O)$ratio A-dependence and the comparison of it with the data of the cumulative pion production[34,35] (O,●) and DIS on aluminium [2] (x).

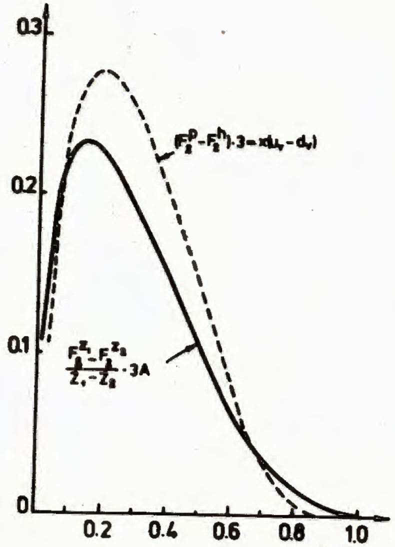


Fig.13. The predictions for the difference of the structure functions of two isobar nuclei (solid line) and for the difference of the proton and neutron structure functions (shaded line).

one to explain in a unique way all the characteristic features of the so-called EMC-effect (the growth of the ratio for small x, the shift of the crossing point $R=1$, as compared to the standard methods of taking nuclear effects into account, to greater x, and the quick R growth in the region $x \approx 1$), a considerable number of DIS events on nuclei in the cumulative region; and also the behaviour of the cumulative pion production cross-section. The model with the so-called "pion condensate"[14,15] is formally similar to ours but differs by a stronger A-dependence. Notice also that one of the consequences of a large collectin sea is the expectation of the increased, as compared to [6], correlations of the DIS leptons with the cumulative protons (flying out to the back semisphere in the laboratory system).

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Ефремов А.В., Бондарченко Е.А. E2-84-124
Многокварковые состояния в ядрах и глубоконеупругое рассеяние

На основе гипотезы о многокварковых состояниях в ядрах рассмотрены структурные функции ядер и проведено сравнение с экспериментом. Показано, что доли многокварковых состояний достаточно велики /до 20% в дейтерии и до 40% в железе/ и они должны обладать большим чем в нуклоне морем кварко-антикварковых пар. Проведено также сравнение с сечениями рождения кумулятивных частиц. Даны предсказания для дальнейшей экспериментальной проверки этой гипотезы.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1984

Efremov A.V., Bondarchenko E.A. E2-84-124
Multiquark States in Nuclei and the Deep Inelastic Scattering

Based on a hypothesis of multiquark states in nuclei, the nucleus structure functions are considered and the results are compared with the experiment. It is shown that the multiquark state contributions are sufficiently high (up to 20% in deuterium and 40% in iron) and must possess a greater, than in a nucleon, sea of quark-antiquark pairs. Also the comparison with the cumulative particle production cross sections is performed. The predictions are given for a further experimental test of that hypothesis.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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