DEEP INELASTIC LEPTON-NUCLEUS SCATTERING AND MULTIQUARK STATES IN NUCLEI

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A deep inelastic scattering of leptons on a nuclear target is considered in the framework of a multiquark cluster model and the nuclear structure functions are calculated. Analysis of the EMC effect is performed and it is shown that the given model can describe experimental data for the nuclear structure functions and their ratios not only in the kinematical region $x < 1$, but also it allows one to predict the behaviour of these quantities in the region $x > 1$ which is not sufficiently well studied experimentally.

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1. *Introduction*

Processes of cumulative particle production in the hadron-nucleus and nucleus-nucleus collisions predicted [1] and discovered experimentally [2] in the early 70-s revealed the necessity of investigation of quark degrees of freedom when studying the high energy nuclear interactions. Experimental data for particle production in the kinematical region forbidden by the nucleon-nucleon kinematics lead to the conclusion of the existence of multiquark states (different from nucleons) inside the nuclei. The same is confirmed by the behaviour of elastic form-factors of light nuclei at a large momentum transfer [3] which corresponds to the quark counting rules [4].

Recent experimental studies of deep inelastic scattering on nuclear targets revealed an essential difference between the structure functions of heavy and light nuclei [5–8] (the so-called EMC-effect) and gave rise to a new interest in a quark structure of nuclei.

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Among different theoretical models (e.g., pion model [9], dynamical rescaling model [10], conventional nuclear models [11]) suggested to explain this effect, the multiquark cluster model [12] should be noted. This model makes it possible to form multiquark configurations (multiquark bags) in nuclei by overlapping several nucleons of nucleus and allows one to explain uniquely all the above-mentioned phenomena.

Most of the experiments on a deep inelastic lepton-nuclear scattering cover the kinematical region $0 < x < 1$, where the results of all the mentioned theoretical models are similar and do not differ qualitatively. One can expect an essential difference between their predictions for the $x > 1$ region, because the multiquark cluster model only predicts non-zero values for nuclear structure functions in this region.

In the present paper we consider the structure functions of nuclei in the framework of a multiquark cluster model and show that EMC effect can be explained by taking into account the scattering on colourless multiquark configurations in nuclei. The fit for the experimental data in the region $x < 1$, as well as the predictions for the behaviour of the nuclear structure functions and their ratios in kinematical region $x > 1$ are given.

2. Structure functions of nuclei in the multiquark cluster model and the EMC effect

Let us consider a deep inelastic scattering of charged leptons on nucleus A. We shall assume that in the nucleus, together with nucleons (three-quark bags), there are formed with definite probabilities, the colourless multiquark configurations with six, nine, etc. quarks (in this connection see [13, 14]), and leptons interact with the nucleus by means of the exchange of virtual photons with quarks from these bags. We shall also assume that the nuclear constituents contribute incoherently and that the final state interaction can be neglected in the deep inelastic region. Then the nucleus structure function can be represented by the sum

$$F_2^A(x) = \sum_{K=1}^{A} N(A, K) F_2^K(x), \tag{1}$$

where x is the usual Bjorken variable $x = Q^2/2m\nu$ (which in the case of scattering on a nucleus varies in the interval $\left(0 < x < \frac{M_A}{m} \approx A\right)$, Q^2 is the 4-momentum transfer squared, ν is a transfered energy, m is a nucleon mass and M_A is a nucleus mass. We neglect the Q^2-dependence of the structure functions, i.e., we shall assume an exact Bjorken scaling. The first term of the sum (1) corresponds to nucleons (three-quark bags), the subsequent terms correspond to the six-quark clusters, nine-quark clusters and so on. F_2^K in (1) denotes the structure function of a configuration which contains a $3K$-quark bag and $(A-K)$ nucleons. The coefficients $N(A, K)$ before these structure functions have the meaning of the effective number of $3K$-quark bags in the nucleus A and satisfy the following condition of baryon number conservation

$$\sum_{K=1}^{A} K N(A, K) = A. \tag{2}$$

Obviously, quantities $P_A^K = KN(A, K)/A$ can be understood as the probabilities of $3K$-quark cluster formation in a nucleus with an atomic number A.

We use the parametrization of $N(A, K)$ in the form of the Bernoulli distribution:

$$N(A, K) = \frac{A!}{K!(A-K)!} p(A)^{K-1}[1-p(A)]^{A-K}. \tag{3}$$

The parameter $p(A)$ deteımining the probability of a three-quark nucleon to get into a $3K$--quark bag, is defined by a ratio of the bag and nucleus cross sections

$$p(A) \sim r_C^2/R_A^2 \sim A^{-2/3}. \tag{4}$$

The coefficient of proportionality in (4) has been obtained by the fit of the A-dependence of EMC effect: $p(A) = 0.07A^{-2/3}$ (see further on). (The values of probabilities P_A^K for different nuclei used in the numerical calculations are shown in Table I). The same A-dependence of $p(A)$ with slightly different coefficient obtained by fitting the data on production of π-mesons with large transverse momenta in proton-nucleus collisions, was used in [15].

TABLE I

Nucleus	P_1^A %	P_2^A %	P_3^A %	p_0, p_F GeV/c
^{4}He	91.89	7.88	0.23	0.151
^{9}Be	87.80	11.55	0.65	0.110
^{12}C	86.29	12.84	0.87	0.127
^{27}Al	81.73	16.64	1.63	0.239
^{40}Ca	79.30	18.59	2.12	0.247
^{56}Fe	77.07	20.30	2.63	0.257
^{107}Ag	72.37	23.75	3.88	0.261
^{197}Au	67.46	27.07	5.47	0.264

The coefficients $N(A, K)$ are the rapidly decreasing functions of K and the main contribution to the structure function is given by the first few terms of sum (1). Therefore, in the sequel, in the numerical calculations we restrict ourselves only to the three-, six- and nine--quark clusters.

Now we proceed to the calculation of the structure functions F_2^K. In the framework of quasipotential formalism in "light front" variables [16], it can be shown that these structure functions can be factorized and expressed [17] via the structure functions of the multiquark clusters $F_2^{3K}(x)$ and the distribution functions of $3K$-quark clusters in nuclei $f_K(z)$, which describe internal motion of clusters inside the nucleus:

$$F_2^K(x) = \int_{x/A}^{1} f_K(z) F_2^{3K}\left(\frac{x}{Az}\right) dz. \tag{5}$$

According to a quark-parton model [18], the structure functions F_2^{3K} can be described by the quark and antiquark densities

$$F_2^{3K}(x) = x \sum_i e_i^2 [q^{3K}(x) + \bar{q}^{3K}(x)].$$

Here e_i denotes the electric charge of a quark of flavour i, q^{3K} and $\bar{q}^{3K}$ are the quark and antiquark densities in $3K$-quark cluster, respectively.

We shall consider only three flavours of quarks (u, d, s) and assume the quark-antiquark sea to be SU(3)-symmetric. Then the structure functions F_2^{3K} can be expressed in terms of the valence and sea quark densities

$$F_2^{3K}(x) = \tfrac{5}{18} x[u_v^{3K}(x) + d_v^{3K}(x)] + \tfrac{4}{3} xS^{3K}(x). \tag{6}$$

Here u_v^{3K}, d_v^{3K}, s^{3K} are valence u and d quark and sea quark densities in $3K$-quark cluster, respectively.

For the quark distributions in proton we shall use the following expressions:

$$xu_v(x) = 2.0723(1+0.5x)x^{1/2}(1-x)^3$$

$$xd_v(x) = 1.1275(1+0.5x)x^{1/2}(1-x)^4$$

$$xs(x) = 0.1517(1-x)^7. \tag{7}$$

The valence quark densities are normalized to the number of corresponding quarks in proton

$$\int_0^1 dxu_v(x) = 2, \quad \int_0^1 dxd_v(x) = 1$$

and the sea quark density is normalized in such a way that the proton's momentum fraction carried by gluons equals 55%.

The quark counting rules [4, 19] were used to determine the valence and sea quark densities in multiquark clusters

$$xu_v^{3K}(x) \sim x^{1/2}(1-x)^{6K-3+\delta}$$

$$xd_v^{3K}(x) \sim x^{1/2}(1-x)^{6K-2+\delta}$$

$$xs^{3K}(x) \sim (1-x)^{6K+1+\delta}. \tag{8}$$

Here δ is connected with the spin of quark and cluster and equals 0 or 1 for clusters with even or odd number of quarks, respectively.

The normalization condition (we assume multiquark cluster to be isoscalar)

$$\int_0^1 u_v^{3K}(x)dx = \int_0^1 d_v^{3K}(x)dx = \frac{3K}{2}$$

allows one to fix the coefficients of proportionality for the valence quark densities in (8). Coefficient for the sea quark density can be determined from the momentum conservation condition. Just as in proton, we shall assume that fraction of multiquark cluster's momentum carried by gluons equals 55%.

Let us now proceed to the definition of functions which describe the distributions of nucleons and multiquark clusters in nucleus. These functions must obey the following condition

$$\int_0^1 f_K(z)dz = 1 \tag{9}$$

and the quantities

$$\int_0^1 zf_K(z)dz = \bar{z}_K \tag{10}$$

can be considered as mean values of nucleus momentum carried by $3K$-quark clusters. The momentum conservation law imposes the following condition on $\bar{z}_K$:

$$\sum_{K=1}^{A} \bar{z}_K N(A, K) = 1. \tag{11}$$

The nucleon distribution function $f_N(z) = f_1(z)$ is connected with the nucleon momentum distribution in nucleus $\varrho_N(\vec{p})$ in the following way

$$f_N(z) = \int d\vec{p}\varrho_N(\vec{p})\delta(z-p_+/m), \tag{12}$$

where $p_+ = p_0+p_z$.

In the case of the deuteron nucleon distribution function f_N^D can be expressed via the deuteron's relativistic wave function [20] in the "light front" variables:

$$f_N^D(z) = \int \frac{d\vec{p}_\perp}{z(1-z)} |\phi_R(1-z, \vec{p}_\perp)|^2. \tag{13}$$

The relativistic wave function ϕ_R, being a function of the "light front" variable $x = 1/2 +(p_0+p_z)/(P_{D0}+P_{Dz})$ and $\vec{p}_\perp$ (where p_μ and $P_{D\mu}$ denote relative 4-momentum of nucleon s internal motion in deuteron and 4-momentum of deuteron as a whole, respectively), is normalized by the condition

$$\int \frac{dxd\vec{p}_\perp}{x(1-x)} |\phi_R(x, \vec{p}_\perp)|^2 = 1,$$

which ensures the fulfilment of (9) for the nucleon distribution in deuteron f_N^D.

For the deuteron relativistic wave function $\phi_R(x, \vec{p}_\perp)$ we choose the relativistic analogue [21] of the well-known non-relativistic wave function $\psi_{NR}(\vec{p})$, noting that in the framework of the "light front" quasipotential formalism the Lorentz-invariant combination $(\vec{p}_\perp^2+m^2)/x(1-x)$ plays a similar role as the three-dimensional relative momentum squared $\vec{p}^2$ (which is invariant in respect to the three-dimensional rotations) in the nonrelativistic theory. For the square of the relativistic wave function we shall use

$$|\phi_R(x, \vec{p}_\perp)|^2 = \frac{m}{2}\, C\left\{\psi_0^2\left(\frac{\vec{p}_\perp^{\,2}+m^2}{4x(1-x)}-m^2\right)+\psi_2^2\left(\frac{\vec{p}_\perp^{\,2}+m^2}{4x(1-x)}-m^2\right)\right\}, \tag{14}$$

where ψ_0 and ψ_2 are the nonrelativistic wave functions corresponding to s- and d-waves, respectively and C can be determined from the normalization condition of these functions

$$4\pi C^2 \int_0^\infty p^2 dp\{\psi_0^2(p^2)+\psi_2^2(p^2)\} = 1.$$

In the numerical calculations we use the Gartenhause-Moravchik wave functions [22].

Note that in the deuteron the contribution of a six-quark state is only a small admixture to that of a two-nucleon state and it does not exceed few per cents (in this connection see [23]).

The deuteron structure function data [24] and the result of calculation with account to the 5% contribution of a six-quark cluster are shown in Fig. 1. (Here and in the sequel, the nuclear structure functions F_2^A are presented per nucleon).

For the nucleon momentum distribution in nuclei with $4 \leqslant A \leqslant 16$ we shall use the Gauss parametrization of [25]:

$$\varrho_N(\vec{p}) = \frac{4}{\pi^{3/2}p_0^2A}\left[1+\frac{A-4}{6}\frac{\vec{p}^{\,2}}{p_0^2}\right]\exp(-\vec{p}^{\,2}/p_0^2)$$

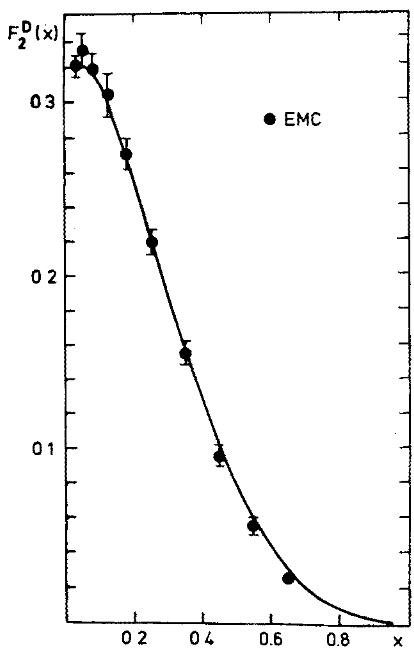

Fig. 1. Deuteron structure function. Data from [24]

which leads to the following distribution function

$$f_N(z) = \frac{4m}{\pi^{1/2} p_0} \left\{ 1 + \frac{A-4}{6} \left[1 + \frac{A^2 m^2 (z-\bar{z}_1)^2}{p_0^2} \right] \right\} \exp\left[- \frac{A^2 m^2 (z-\bar{z}_1)^2}{p_0^2} \right]. \tag{15}$$

For heavier nuclei ($A > 16$) the Fermi-gas approximation is valid and we shall use the distribution function

$$f_N(z) = \frac{3}{4} \left(\frac{mA}{p_F} \right) \left[\left(\frac{p_F}{Am} \right)^2 - (z-\bar{z}_1)^2 \right] \tag{16}$$

obtained from the Fermi-gas distribution

$$\varrho_N(\vec{p}) = \frac{3}{4\pi p_F^3} \theta(p_F - |\vec{p}|),$$

where p_F is the Fermi-momentum. (The values of p_F can be taken from [26] and they are given in Table I together with the values of p_0 from (15).)

The data of the iron structure function [27] and the data for the ratio of iron and deuteron structure functions [5, 7] are given in Figs. 2 and 3 together with the results of calculations made by formulae (1), (5)–(7) and (16) without taking into account the multiquark cluster contributions (dashed curves). One can see that only the nucleon contribution even with the Fermi-motion contradicts the experimental data.

To incorporate the Fermi-motion of multiquark clusters, we shall use the expressions similar to (15) and (16), substituting the nucleon mass m by the cluster mass M_{3K} and $\bar{z}_1$ by $\bar{z}_K$.

It is natural to suppose that each constituent of the nucleus is on the average carrying the momentum proportional to its mass, i.e., $\bar{z}_K = \eta \frac{M_{3K}}{Am}$, where η is a dimensionless coefficient. Then the momentum conservation condition (11) takes the form

$$\eta \sum_{K=1}^{A} N(A, K) \frac{M_{3K}}{Am} = 1. \tag{17}$$

If we suppose that the multiquark clusters masses are equal to those of the corresponding number of nucleons $M_{3K} = Km$, then with account of (2) we can get $\bar{z}_K = \frac{K}{A}$ and $\eta = 1$. The results of calculations exploiting this assumption are presented in Figs. 2 and 3 by dot-dashed curves and show a qualitative agreement with the data. Better agreement can be achieved by supposing that the masses of multiquark clusters M_{3K} are larger than Km. By introducing the parameter Δ:

$$M_{3K} = K(1+\Delta)m$$

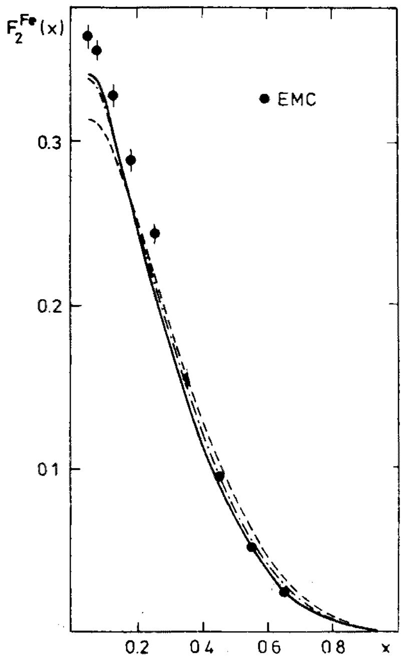

Fig. 2

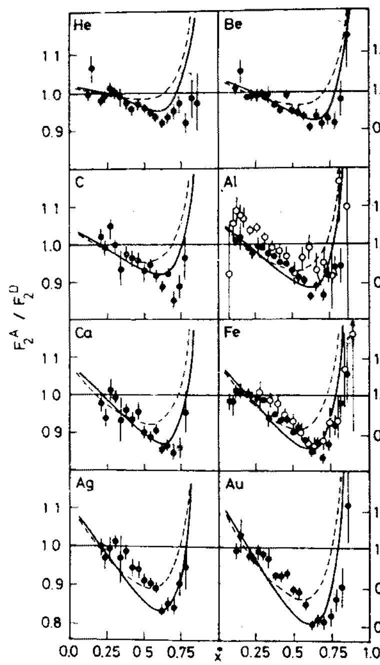

Fig. 3

Fig. 2. Iron structure function. Data from [27]. Dashed curve — calculation with account of only nucleons and their Fermi-motion; dot-dashed curve — with account of multiquark clusters ($\Delta = 0$); solid curve — with account of multiquark clusters ($\Delta = 0.25$)

Fig. 3. Iron and deuteron structure functions ratio. Data from [5] — ● and [7] — ○. Designation of curves is the same as in Fig. 2

from the conservation conditions of baryon number (2) and momentum (17) one can find for η:

$$\eta = \frac{1}{1+\Delta(1-N(A,1)/A)} \leqslant 1.$$

The fractions of the nucleus momentum carried on the average by nucleons and multiquark clusters equal to $\bar{z}_1 = \eta/A$ and $\bar{z}_K = \eta(1+\Delta)K/A$, respectively. Generally, parameter Δ should be K-dependent, but we neglect this dependence. Obviously, putting $\Delta = 0$ leads to the case discussed above ($M_{3K} = Km$). The results of calculations with $\Delta = 0.25$ are given in Figs. 2 and 3 by solid curves.

The experimental data [6, 7] for the cross-section ratios σ_A/σ_D and the theoretical results for the ratios of structure functions F_2^A/F_2^D for the different nuclei with an atomic number varying in a wide range are given in Fig. 4. Here are given both cases: $\Delta = 0$ (dashed curves) and $\Delta = 0.25$ (solid curves). It should be mentioned that more correct comparison of the theoretical results with the experimental data requires the contribution of the structure function F_1 to be taken into account [28].

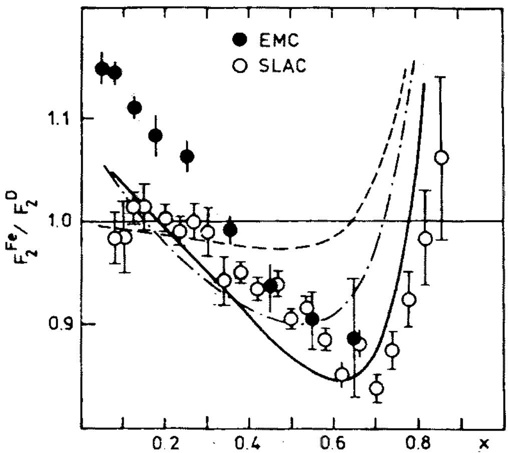

Fig. 4. Ratio of structure functions of different nuclei to that of deuteron. Data from [6] — ○ and [7] — ●. Curves correspond to the calculations in a multiquark cluster model with $\Delta = 0$ (dashed curve) and $\Delta = 0.25$ (solid curve)

3. *Kinematical region $x > 1$*

As has already been mentioned, kinematical region $x > 1$ may turn out to be critical for different models suggested for the explanation of the EMC effect. The preliminary data [29] for the carbon structure function in the range $1 < x < 1.4$ seem to indicate the existence of the multiquark states in nucleus. The region $x > 1$ was investigated earlier in the processes of cumulative particle production. In [30] the possibility of deriving information about the quark parton structure functions of nuclei from the data in a cumulative pion production in the hadron-nucleus collisions was noticed and in [31] the similarity in the x-behaviour of the ratio of pion production cross-sections on different nuclei and the ratio of the deep inelastic structure functions of the same nuclei was pointed out.

We have calculated the behaviour of the nuclear structure functions and their ratios in the region $x > 1$. The results are presented in Fig. 5 together with the iron structure function data [27] and preliminary data [29] on the carbon structure function. One can see that the nuclear structure function calculated by taking into consideration only nucleons and their Fermi-motion (dashed curve), rapidly decreases for $x > 1$ and vanishes for $x = 1 + p_F/m$. Accounting of the multiquark clusters contributions overstates essentially the value of the structure function in this region. The results obtained with $\Delta = 0$ (dot--dashed curve) and $\Delta = 0.25$ (solid curve) values differ considerably in the region and the version of the model with "heavier" clusters fits the data better.

In Fig. 6 the model predictions for the ratios of the iron and deuteron structure functions in the range $0 < x < 2$ is drawn. The versions of the model with $\Delta = 0$ and $\Delta = 0.25$, being in a qualitative agreement in the region $x < 1$, predict quite different behaviour for the structure functions ratio in the $x > 1$ region. Hence, the experimental investigation of a deep inelastic lepton-nuclear scattering in the kinematical region $x > 1$ is of great interest — it can both confirm the multiquark cluster approach, based on the suggestion

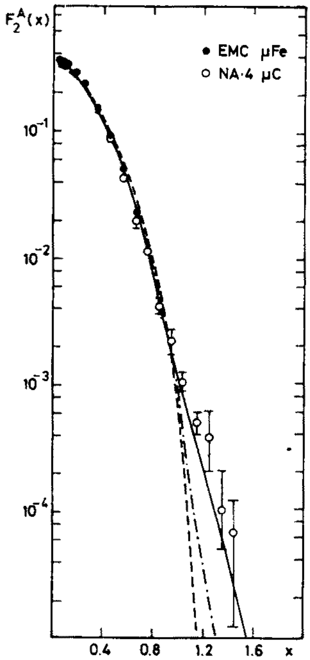

Fig. 5

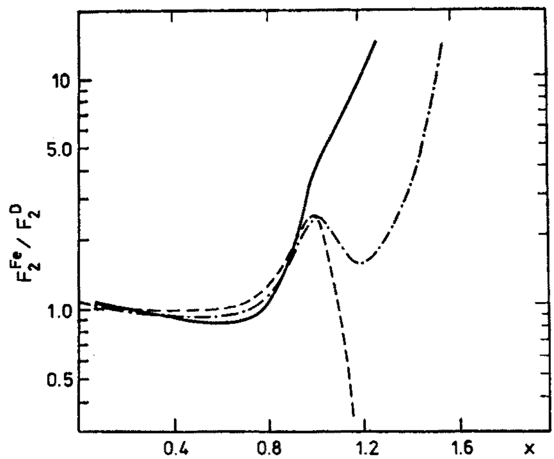

Fig. 6

Fig. 5. Nuclear structure function in the region $0 < x < 2$. Data from [27] — ● and [29] — ○. Designation of curves is the same as in Fig. 2

Fig. 6. Ratio of the iron and deuteron structure functions in the region $0 < x < 2$. Designation of curves is the same as in Fig. 2

of the existence of multiquark states in nuclei, and distinguish between various versions of the model as well.

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