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# NUCLEAR STRUCTURE FUNCTIONS AND QCD

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1. The nontrivial structure of nuclei discovered first in the cumulative particle production and especially in recent deep inelastic experiments (BCDMS and EMC-effects) was by all means the most sudden and remarkable event. It was sudden because the behavior of nuclear structure function appear to be contadicting all our ideas about nucleus which seemed good based and checked. In fact, as we want to demonstrate, the contradiction is much deeper. This effect contradicts any nonrelativistic picture of the nucleus as a system of nucleons coupled by any potential forces. However, this effect seems natural and almost trivial if one considers the nucleus as a relativistic quantum-field bound system.

This is almost evident from a qualitative point of view. Indeed, the main feature of relativistic quantum field picture is the vacuum polarization effect (production and absorption of a particle-antiparticle pair) due to which the nucleus is not only a system of $A$ interacting nucleons or 3A valence quarks but also an additioonal sea of isosinglet $q\bar{q}$ -pairs and gluons (next rows of the Fock column) which carry a fraction of the total momentum of nucleus (in the infinite momentum frame). This has to diminish the fraction of momentum carried by valence quarks with respect to the free nucleon, i.e. the softening of its distribution functions or decrease of the ratio $R = F_2^A / F_2^D$ (the deuterium in first approximation can be considered as a system of free nucleons) in the region of intermediate $x \simeq 0.5$. The increase of the sea momentum results in the increase of $R$ in the region of small $x$. As for the growth of $R$ in the region of $x \simeq 1$, it is natural at least due to the Fermi-motion of nucleus.

These elements of the quantum field picture were present in a more or less distinct form in all first attempts of understanding the

EMC-effect. However, they were not realized, probably, as main reasons of this effect and sank often in detals of models. Some works consider the decrease of $R$ in the region of intermediate $X$ and increase in the region of small ones as a consequence of different mechanisms. In this work we consider the nuclear structure functions from a quantum field theory and quantum chromodynamics (QCD) point of view (Sect.2) and try to compare with different ideas proposed for the explanation of EMC (Sect.3). Our conclusion is that none of pure nucleon models seems satisfactory and a multiquark state seems unavoidable for understanding the EMC-effect.

2. An important feature of renormalizable QFT and QCD is the factorization property of hard-process cross-sections proved for any order of perturbation expansion of the low-twist term /1/. For the moments of structure functions of deep inelastic scattering of a lepton on the target A it has the form

$$M_A(n,Q^2)=\int_0^1 dx_A\, x_A^{n-2} F_A(x,Q^2)=\sum_a \varphi_a(n,Q^2/\mu^2,\alpha(\mu))\, f_{a/A}(n,\mu^2) + O(1/Q^2) \qquad (1)$$

where $\varphi_a$ are the moments of the structure function of parton "a" (of $q$ and $\bar{q}$ of different flavors and gluons), $f_{a/A}$ are the moments of the parton distribution functions over the fraction of the total momentum $X_A$ and $\mu$ is an arbitrary parameter with dimension of the momentum which plays the role of a normalization point and a boundary between small $(P_A^2)$ and large $(Q^2)$ momenta. The independence of $M_A$ of this parameter leads to the evolution (renormalization group) equation

$$\frac{d f_{a/A}(n,\mu^2)}{d \ln \mu^2} = \sum_a \gamma_{ab}(n,\alpha(\mu))\, f_{b/A}(n,\mu^2)$$

where anomalous dimensiones $\gamma_{ab}$ can be calculated in the perturbative QCD if one chooses $\mu$ large enough (e.g. puts $\mu^2 = Q^2$). Another important feature of the factorization we shall explore is the independence of $\varphi_a$ and, consequently, $\gamma_{ab}$ of the sort of target A, wich immediately gives a possibility to connect the parton distributions in an isoscalar nucleus A and a nucleon.

As it is known /2/, this system of equations can be written as one equation for the nonsinglet channel (valence quarks).

$$V_a = q_a - \bar{q}_a; \quad \frac{d V_a(n,Q^2)}{d \ln Q^2} = \gamma_{qq}(n,\alpha(Q^2))\, V_a(n,Q^2) \qquad (2)$$



and the pair of eqations for the singlet quark and gluon distributions function:

$$f_1 = q^S = \sum_a (q_a + \bar{q}_a), \quad f_2 = G$$

$$\frac{d f_\alpha(n,Q^2)}{d \ln Q^2} = \gamma_{\alpha\beta}(n,\alpha(Q^2))\, f_\beta(n,Q^2), \quad \alpha,\beta = 1,2 \qquad (3)$$

From Eq.(2) one can immediately obtain /3/ valence quark distribution functions of a nucleus with a nucleon (all nuclear distribution functions are divided by the atomic number A)

$$\dot{V}_A / V_A = \dot{V}_N / V_N = \gamma_{qq}, \quad \text{i.e.}$$

$$V_A(n,Q^2) = T_A(n)\, V(n,Q^2) \quad \text{or} \qquad (4)$$

$$V_A(x,Q^2) = \int_x^A T_A(\beta)\, V_N\!\left(\frac{x}{\beta},Q^2\right)\frac{d\beta}{\beta} \equiv T_A \otimes V_N$$

where the dot means the derivative with respect to log $Q^2$, $x = Q^2/2m\nu$ is the is Bjorken variable for nucleon and the function $T_A$ does not depend on $Q^2$, $T_A \geqslant 0$ (due to $V_A, V_N \geqslant 0$) and obeys the baryon number sum rule:

$$\int_0^A T_A(\beta)\, d\beta = 1 \qquad (5)$$

So, for nuclear valence quarks one obtains the convolution formula with $T_A$ as a"nucleon distribution" in nucleus.

For the singlet channel one may diagonalize the system (3) and obtains

$$f^\pm = q^S + C^\pm G, \quad \dot{f}^\pm = \gamma^\pm f^\pm \qquad (6)$$

$$\gamma^\pm = \frac{1}{2}\left(Sp\,\gamma \pm \sqrt{(Sp\,\gamma)^2 - 4\det\gamma}\right); \quad C^\pm = \gamma^\pm / \gamma_{Gq} \qquad (7)$$

which gives the connection

$$f_A^\pm = T_A^\pm \otimes f_N^\pm \qquad (8)$$

The values $\gamma^+(2) = 0$ and $C^+(2) = 0$ guarantee the $Q^2$-independence of the energy-momentum sum rule

$$f^+(2) = \int_0^A dx\; x\left(q_A^S(x,Q^2) + G_A(x,Q^2)\right) = 1 \qquad (9)$$

and asks for the condition

$$\int_0^A T_A^+(\beta)\,\beta\,d\beta = 1 \qquad (10)$$

(strictly speaking $1-\mathcal{E}_\ell/m$ where $\mathcal{E}_\ell$ is the nuclear binding energy per nucleon) Using (6), (8) one can easily obtain the connection between see (ocean) quark and gluon distribution functions of the nucleus and nucleon (assuming $SU(3)_f$ symmetry of the sea quarks)

$$O_A(x,Q^2) = \int_x^A T_A(\beta)\,O_N\!\left(\frac{x}{\beta},Q^2\right)\frac{d\beta}{\beta} + O_A'(x,Q^2)$$

$$G_A(x,Q^2) = \int_x^A T_A(\beta)\,G_N\!\left(\frac{x}{\beta},Q^2\right)\frac{d\beta}{\beta} + G_A'(x,Q^2) \qquad (11)$$

where additional collective seas are given by thir moments:

$$O_A' = \left(\frac{C^+T^- - C^-T^-}{C^+ - C^-} - T_A\right) q_N^S + C^+C^-\frac{T^+ - T^-}{C^+ - C^-}\,G_N$$

$$G_A' = \left(\frac{C^+T^+ - C^-T^-}{C^+ - C^-} - T_A\right) G_N + \frac{T^+ - T^-}{C^+ - C^-}\,q_N \qquad (12)$$

So, if $T^+ \neq T^- \neq T_A$, the collective seas are not zero and are $SU(3)_f$-symmetric. Just these sea were used by us/4/ for explaining the EMC and NA-4 effects and cumulative meson production.

3. Now let us turn to the models. In the elastical model nucleons are bound in a nucleus by potential forces, and the distribution function in the nucleon by an expression of type (4) with a unique function $T_A(\beta)$. (The last is expressed mainly through the one nucleon wave function

$$T_A \sim \int d^3p\,dp_0\,|\varphi_A(\vec{p},p_0)|^2\,\delta\!\left(\beta - \frac{pq}{P_A q}\frac{M_A}{m}\right)$$

with a possible addition of some partion of few-nucleon correlations which also have the same form (4).) For this reason for such a model

$$T^+ = T^- = T_A \qquad (13)$$

and the additional quark and gluon seas are absent (see (12)), and the function $T_A$, besides condition (5) (which means the normalization of $\varphi_A$), has to satisfy the condition



$$\bar{\beta} = \int_0^A T_A(\beta)\,\beta\,d\beta = 1 \qquad (14)$$

which means that the total energy of all nucleons is equal (up to the binding energy) to the total energy of nucleus

$$\int d^3p\,dp_0\,\frac{p_0}{m}\,|\varphi(\vec{p},p_0)|^2 = 1$$

Such a classical model immediately leads to the contradiction with EMC data. Really, if one develops $F_N(\frac{x}{\beta})$ in the expression for $F_A(x)$

$$F_A(x) = \int_x^A d\beta\, T_A(\beta)\,F_N\!\left(\frac{x}{\beta}\right)$$

into a series over $\delta = 1-\beta$ (using the fact that $T_A(\beta)$ is peaked at $\beta \simeq 1$ with a width of an order of the average internuclear kinetic energy divided by the mass of the nucleon), then one can obtain for not too large $x$

$$F_A(x) \simeq F_N(x) + \bar{\delta}\,x\,F_N'(x) + \tfrac{1}{2}\overline{\delta^2}\left(x^2 F_N''(x) + 2x F_N'(x)\right) + \cdots \qquad (15)$$

where the bar means the averaging with the function $T_A$. Because of condition (14) $\bar{\delta} = 0$ and the ratio $R = F_A/F_N$ intersects $R = 1$ at points $x = 0$ and $x = x_0$ determined by the condition*

$$x_0 F_N''(x_0) = -2F_N'(x_0)$$

which does not depend on the particular form of $T_A$. If one takes $F_N \sim (1-x)^k$ with $k \simeq 3$ that is close to experiment then one can easily obtain

$$x_0 = 2/(k+1) \simeq 0.5$$

in contradiction with experiment (Fig.1). It is just this contradiction of the experimental data with predictions of different theoretical models that first drew attention of the EMC-collaboration/5/. The discovered phenomenon was confirmed by the SLAC group/6/ and NA-4-collaboration/7/. A similar qualitative phenomenon was observed earlier for the ratio of the cross section of cummulative pion production/8/ in a much wider region of $x$ including $x > 1$. However, it did not draw a proper attention, probably, because of a more complicated relation of the inclusive cross section and the structure function in the region $x < 1$.

*More accurate account of the integral low bound results in decrease of $\bar{\delta}$ and $\overline{\delta^2}$ (due to $T_A \geq 0$) and shifts $x_0$ to the left (see below).

If $\bar\delta \neq 0$, the point $x_0$ is determined (as it is seen from (15)) by the expression

$$x_0 = 2\left(1+\bar\delta/\bar\sigma^2\right)/\left(\kappa+1+\bar\delta/\bar\sigma^2\right) \tag{16}$$

and the increase in $\bar\delta$ shifts $X_0$ to the right as required by experiment. This means a decrease in the fraction of energy carried by nucleons, or more exactly, a decrease in the fraction of momentum of the nuclear valence quarks with respect to the free nucleon (in contradiction with [12])

$$\frac{\langle x_v\rangle_A}{\langle x_v\rangle_N} = \int_0^A T_A(\beta)\,\beta\, d\beta = 1-\bar\delta < 1 \tag{17}$$

In turn, this demands unavoidably nonzero collective seas.

The comparison of experimental data with the simplest model /9/ – "the shifted Fermi step" with $p_F$ = 200 MeV/c:

$$T_A = \frac{3}{4}\left(\frac{m}{p_F}\right)^3 \cdot \begin{cases} (p_F/m)^2 - (1-\bar\delta-\beta)^2 & \text{when } |1-\bar\delta-\beta| < p_F/m \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

gives $\bar\delta$ = (4.5 ± 0.4) $10^{-2}$ the dot-dashed line in fig.1) that is 5-times as large as the effect of binding energy ( $\bar\varepsilon_b \simeq$ 8 MeV).

A natural question arises now: Is it possible to understand this energy effect within the framework of standart nucleon-meson nuclear physics? Such an attempt has recently been undertaken by two groups of physicists /10/ who explore the nucleon levels in nucleus (in this case $\bar\delta = \bar\varepsilon_{lev}/m$ ) and compensate the energy deficiency by the meson (mostly, pion) sea in nucleus. However, the necessary energy levels ( $\bar\varepsilon_{lev} \simeq$ 40 MeV) seem to be too deep to use the standart theory of Fermi-system. Besides, the second-quatized meson fields are unavoidable, which make the theory a nonpotential. But the main objection comes from the character of the collective seas.

Really, the decreas in the fraction of momenta of valence quarks in nucleus

$$\Delta\langle x_v\rangle = \langle x_v\rangle_A - \langle x_v\rangle_N = -\bar\delta\langle x_v\rangle_N \tag{19a}$$

leads to the increase in summary average momentum fraction of the sea quarks and gluons

$$\Delta\langle x_0\rangle = \bar\delta\left(S_0 - \langle x_0\rangle_N\right) \tag{19b}$$



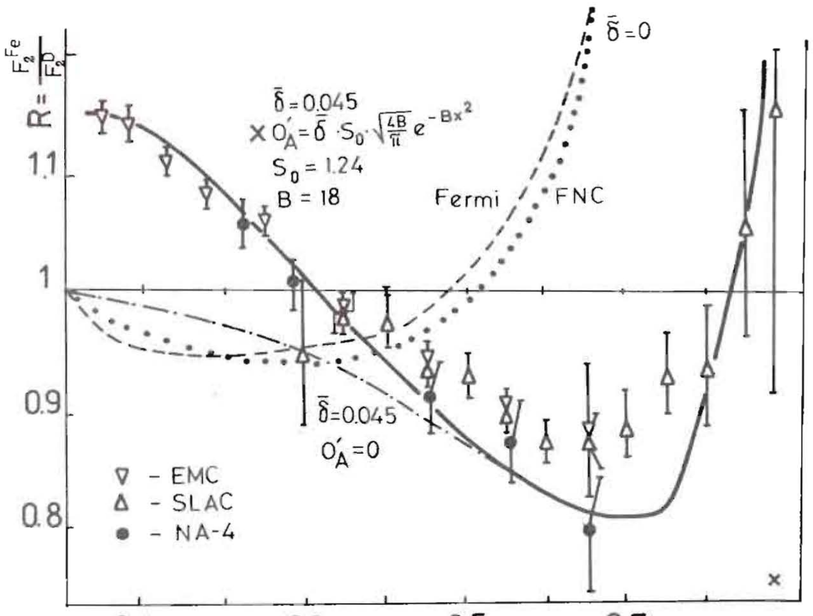


Fig.1

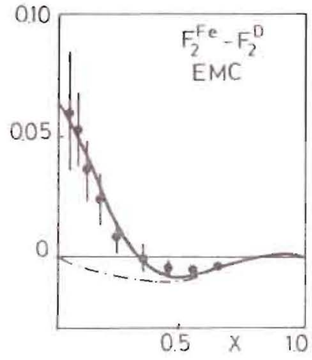


Fig.2

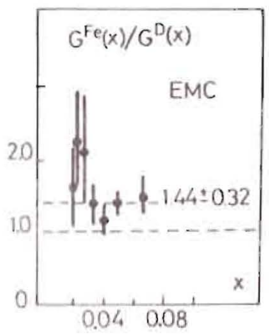


Fig.3

$$\Delta \langle x_G \rangle = \bar{\delta}\,(S_G - \langle x_G \rangle_N) \qquad (19c)$$

where $\bar{\delta} \cdot S_{O,G}$ are the average fraction of momentum carried by the collective oceans $\times O_A'$ and $\times G_A'$ so that $S_O + S_G = 1$. These parameters can be found from the integral

$$I = \int_0^A dx\,\big(F_A(x) - F_D(x)\big) = \frac{2}{9}\,\bar{\delta}\,\Big(S_O - \langle x_O \rangle_N - \frac{5}{4}\langle x_V \rangle_N\Big) \qquad (20)$$

Experimentally[5], this integral is equal to $(0.65 \pm 0.06)\cdot 10^{-2}$ and $\langle x_O \rangle_N + \frac{5}{4}\langle x_V \rangle_N = 0.56$*. If $\bar{\delta} = 0.045$, the integral (20) gives $S_O = 1.24$ and $S_G = -0.24$, i.e. 120% of the momentum of the collective sea is in quarks and -20% is in gluons!
The contribution of sea of that sort is shown in Fig.1,2 by the solide line. Such an ocean seems impossible to pack into any quasi-particles like pions, as it has been proposed in works[9-11] because if the charged quarks in pion carry about 50% of momenta, then $S_O \simeq \frac{5}{4}\langle x_q \rangle_\pi = 0.62$, and $S_O = 0.5$ if the meson sea is $SU(3)_f$ symmetric. So, even the account of the meson quantized fields seems does not give a satisfactory explanation of the effect. Concerning the question of reliability of the EMC data in the region of small $x$ it was discussed in detail in the review report[7] with positive conclusion.

Consider now nonstandart possibilities when the nuclear environment changes the properties of nucleon. In this case the relations (19) can be considered as a change of parton distributions in nuclear nucleons[12], i.e. the softening of spectrum of the valence quarks (the suppression of a pointlike configuration) and gluons and hardening of the sea quarks. Notice, however, that the negative value of $S_G$ leads by all means to a negative value of $G^{Fe}(0)/G^{D}(0) - 1$ which, probably contradicts the preliminary data of the EMC-collaboration[13,7] on the $J/\psi$-production in deep inelastic muon scattering (see Fig.3).

The decrease in the average gluon momenta contradicts also the very popular rescaling hypothesis[14] that assumes the growth of nucleon radii in the nucleus or, more exactly, the dimension of the

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*We use the parametrization $F_N = 5/18\; 2.00\cdot(1 + 1.26x)\sqrt{x}\,(1-x)^{3.29} \times (1 + 0.57(1-x)) + 4/3\; 0.22(1-0.36x)(1-x)^{9.8}$ obtained from the fit of structure functions of proton (EMC-collaboration data at $Q^2 = 30\,(\mathrm{GeV}/c)^2$) and the ratio $d(x)/u(x)$ (data of CDHS). For this parametrization $\langle x_V \rangle_N = 0.35$, $\langle x_O \rangle_N = 0.12$, $\langle x_G \rangle_N = 0.53$.



confinement radius $R_c$ either in the form*

$$q_{N'}(n, QR_c') = q_N(n, Q'R_c) \quad \text{if } QR_c' = Q'R_c \qquad (21)$$

or as the change of initial conditions of evolution equations:

$$q_{N'}(n, Q_0 R_c') = q_N(n, Q_0' R_c) \quad \text{if } Q_0 R_c' = Q_0' R_c, \qquad (21')$$

According to this hypothethis the growth of $R_c$ is equivalent to the growth of $Q^2$. Due to evolution equations this results in a decrease in the average momentum of valuence quarks and in an increase for sea quarks and gluons. However, according to (19), (20) $S_O > 0.56$, $S_G < 0.44$, and due to $\langle x_G \rangle_N = 0.53$ the average momentum of gluons in nucleus has to decrease in contradiction with rescaling.

So, each of the purely nucleon models proposed for the explanation of EMC-SLAC-NA-4 data seems to meet with a difficulty. The main obstacle was a relatively great positive value of the integral (20) and small value of $\bar{\delta}$. To decrease $S_O$ and "normalize" the balance of quarks and gluons (though it is difficult to guess what it has to be except that $S_G$ seems to be positive in the light of abovementioned preliminary EMC data on $J/\psi$ - production), one should increase $\bar{\delta}$ and, consequently, $\bar{\delta^2}$ in order to preserve the position of $x_0$ according to (16). For instance, to reduce $S_O$ to 0.65, one should increase $\bar{\delta}$ and $\bar{\delta^2}$ 6.5 times, which corresponds in the simple model (18) to $p_F \approx 500$ MeV/c. Such a change obviously contradicts the standard models due to extremely deep average nucleon energy level and extremely high average kinetic energy. However, such a change is in good agreement with relatively large value of the carbon structure function in the region $x > 1$ (the preliminary data of NA-4[7]) and inevitably leads to the existence in the nucleus of heavy quasiparticles such as 2"Multiquark Blokhintsev fluctons"[4,15,16]**.

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*Strictly speaking, this form is not valid in QCD because the $Q^2$-dependence of twist = 2 moments has the form

$$q(n, Q^2) = \Big(\exp \int_{Q_0^2}^{Q^2} \gamma(\alpha(\xi))\, d\ln \xi\Big)\, q(n, Q_0^2)$$

and for the validity of (21) the expression in the brackets should have the form $(Q/Q_0)^{b}$, which is possible only when $\gamma(\alpha(\xi))$ is a constant.

**One have to notice however, that an assumption $\langle x_G \rangle_A = \langle x_G \rangle_N$ made in the work [16] leads to $S_O = 0.53$ according to (19c), and to negative value of integral (20).

or few-nucleon short-range correlations [17], proposed earlier for intensive knock-out of nuclear fragments from heavy nuclei [18] and the cumulative effect [19]. Effectively, this leads to a high momentum tail in the one-nucleon" distribution $T_A(\beta)$ i.e. to a growth of $\delta^2$. An additional increase in $\delta$ with respect to the one due to energy levels can be considered either as a change of the internucleon structure in the few-nucleon correlations model or as a change of the parton distribution in a multiquark flucton [4], i.e. $\delta_{corr} = \delta_N$ in the first case and $\delta_{6q} > \delta_N$ in the second one. Just this feature distinguishes these two models.

The naive picture looks as follows. When approaching each other two nucleons have a large relative momentum. Some two quarks scatter each other and change the direction of flight and pull their colour partners. This leads to a stretch of colour bindings and to their breaking with production of additional $q\bar{q}$ -pairs. However, during a short life of such a pair it has no time to grow the gluon cloud and to form a real meson. That is why the additional sea is impoverished by gluons. The nonzero average momentum of the additional sea decreases the average momentum of the valence quarks, i.e. increases the value of $\delta$. We see from this that any short-range two-nulceon correlation looks, by all means, as a six-quark system.

So, we can conclude that not only the region of $X > 1$ but also the region of small $X$ ask for an admixture of the multiquark fluctons. However, the region of small $X$ is not very sensetive to the character of states. To obtain an unambiguous experimental proof of the existence of such states in the nucleus, their fraction and of thieir character, a careful investigation of deep inelastic scattering on nuclei in a wide interval $0.6 \lesssim x \lesssim 2$ is highly desirable. This could be done by the NA-4 installation in CERN after its slight modification. An interesting information can also be obtained from investigation of the cumulative processes and stripping of nuclei. Concerning the region of small $X$, the main problem remains the investigation of quark and gluon seas at high transfer momenta $Q^2$.

So, we see, that nuclear physics of small distances or relativistic nuclear physics, as it is called often, is tightly connected with quark-gluon degrees of freedom of nuclei and with QCD of large distances with its confinement problem and now becomes one of the main directions of elementary particle physics.



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Ефремов А.В. E2-85-542
Структурные функции ядер
и квантовая хромодинамика

Показано, что уравнения эволюции квантовой хромодинамики приводят для структурных функций ядер в области больших $Q^2$ к конволюционной форме с добавочными кварковыми и глюонными морями. Сопоставление с различными классами моделей приводит к выводу, что ни одна из нуклонных моделей ядра не дает удовлетворительного описания ЕМС-эффекта и введение многокварковых конфигураций в ядрах необходимо уже в области $x < 1$.

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Efremov A. E2-85-542
Nuclear Structure Functions and QCD

It is shown that QCD evolution equations lead, for high-$Q^2$ nuclear structure functions, to a convolution form with additional collective quark and gluon seas. Classes of models are confronted with this point of view, and it is shown that none of the nucleon models seems satisfactory and the presence of multiquark states seems unavoidable even in the region of $x < 1$.

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

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