NUCLEAR STRUCTURE FUNCTIONS AND CUMULATIVE PROCESSES[1]

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ABSTRACT

The authors’s point of view, based on QCD, on the nuclear quark structure is presented. Different models for explaining the EMC–effect are considered. It is also shown that cumulative production data are very useful for a better understanding of the EMC–effect and give some evidence in favor of its multiquark nature.

Discovery of the EMC–effect [2] has drawn attention of the world–wide community of physicists to the problem of quark structure of nuclei, and to its irreducibility to the quark structure of constituent nucleons only [3]. Stream of theoretical papers followed the discovery of EMC suggesting a whole spectrum of possibilities for understanding the phenomena [4]. However, many of the suggestions met with difficulties after a change of experimental data on \( F_A/F_D \) in the region of small \( x \) [5, 6]. Nowadays, when all suggestions seem to be made, one can try to analyze them on a general basis and to estimate to what extent the nuclear quark structure is understood and what is still unclear.

1. Connection of nucleon and nuclear quark structure. Probably G.West first noticed [7] that QCD evolution equations result in a simple convolution relation of nonsinglet quark distribution functions (the valence quarks) of nucleus and nucleon [1]

\[
xF_3A \approx V_A(x, Q^2) = \int_x^A d\alpha T_A^{NS}(\alpha)V_N \left( \frac{x}{\alpha}, Q^2 \right)
\]

(1)

where the function \( T_A^{NS}(\alpha) \) satisfies the baryon number sum rule

\[
\int_0^A d\alpha T_A^{NS}(\alpha) = 1
\]

(2)

(all nuclear function here are normalized to A). Due to this, one can consider \( T_A^{NS}(\alpha) \) as an effective ”valence nucleon” distribution function over a fraction of momenta \( \alpha \) in spite of the impossibility of expressing it through a one–nucleon wave function.

[1]
This is an updated version of the talk [1] at 13 International Seminar on Relativistic Nuclear Physics and QCD (Dubna, Sept. 2-7, 1996) which includes new experimental data and some ideas appeared since that time. Partially supported by the RFBR Grant 96-02-17631.

[2] Since the evolution equations do not depend on the kind of object

\[
\dot{V}_A(n, Q^2)/V_A(n, Q^2) = \dot{V}_N(n, Q^2)/V_N(n, Q^2) = \gamma_N(\alpha_S(Q^2))
\]

(the dot means derivative with respect to \( \log Q^2 \) and \( n \) is the number of a moment) the first equality immediately gives \( V_A(n, Q^2) = T_A^{NS}(n)V_N(n, Q^2) \) which is equivalent to [1].
A similar relation can be written for the singlet channel as well \[8, 9\] which mixes the singlet quark, \(\Sigma(x, Q^2) = \sum_q x[q(x, Q^2) + \bar{q}(x, Q^2)] \approx F_2\), and gluon, \(G(x, Q^2)\), distribution functions

\[
\Sigma_A(x, Q^2) = \int_x^A d\alpha T^S_A(\alpha) \Sigma_N \left( \frac{x}{\alpha}, Q^2 \right)
\]

\[
G_A(x, Q^2) = \int_x^A d\alpha T^S_A(\alpha) G_N \left( \frac{x}{\alpha}, Q^2 \right)
\]

where, in general, \(T^S_A \neq T^N_A\) and \(T^S_A\) satisfies the energy–momentum sum rule

\[
\int_0^A d\alpha \alpha T^S_A(\alpha) = \frac{M_A}{AM_N} \approx 1
\]

Really, diagonalizing the system of two linear evolution equations for the moments \(\Sigma_A(n, Q^2)\) and \(G_A(n, Q^2)\), one can obtain the relation for two eigenfunctions \(f^\pm(n, Q^2) = \Sigma(n, Q^2) + C^\pm_n(\alpha_S(Q^2))G(n, Q^2)\) \((C^\pm_n\) are some diagonalizing coefficients depending on anomalous dimension matrix elements):

\[
f^\pm_A(n, Q^2) = T^\pm_A(n) f^\pm_N(n, Q^2)
\]

The quark (and gluon) distribution function is expressed through the limit of quark (or gluon) propagator \(\langle P|\bar{q}(0)q(\xi)|P \rangle\) when \(\xi \to 0\), regularized with the help of an ultraviolet cutoff parameter \(Q^2\). It must satisfy Bethe-Salpeter equations (Fig. 1) with inhomogeneous terms. The second equation for the gluon propagator however become homogeneous, at least in the so–called leading logarithm approximation, i.e. disregarding \(\alpha^n_S(\log Q^2)^{n-1}\) corrections. In this approximation also, it became an algebraic equation for the moments of structure functions with coefficients which are independent of a target. This means that the ratio \(\Sigma(n)/G(n)\) is also independent on the target and as a result of \((3)\) \(T^+_A = T^-_A = T^S_A\) which leads to the relations \((3)(4)\).

Physically this approximation corresponds to a rather widely accepted scheme in which the gluon distribution is totally due to QCD evolution process starting from the valence quark distribution at low \(Q^2\), i.e. when there is no "primordial" gluon distribution (see e.g. the work [10]).

Fig. 1. Bethe-Salpeter equation for singlet quark and gluon structure functions.
An immediate consequence of Eqs. (3,4) is the equality of average momenta fractions of gluons and quarks in the nucleus and nucleon

\[
\frac{<x_G>_A}{<x_G>_N} = \frac{<x_q>^A}{<x_q>^N}
\]  

(7)

This relation is in good agreement with BCDMS [5] data which are the most precise nowadays, e.g. \(<x_q>^N_2 / <x_q>^D_2 - 1 = (0.7 \pm 1.7 \pm 1.0)\%\). The difference of average momenta for other nuclei is also zero within the error bars (see Table 2 in Ref. [10]).

The relation (7) clearly contradicts the very popular rescaling hypothesis [11] in explanation of the EMC–effect. In fact, the passage from nucleon to nucleus in these models is equivalent to the growth of \(Q^2\) for which, according to QCD, \(<x_G>\) increases and \(<x_q>\) decreases.\(^3\)

In conclusion of this section let us stress once more that QCD evolution equations just as relation (6) are results of the leading twist approximation. So, the relations (1) and (3,4) do not include the nuclear screening which is, at least formally, a high–twist effect [12, 13]. Some experimental observation of a significant \(Q^2\)–dependence of \(F_{Sn}/F_C\) in the region \(x < 0.02\) was known recently [14].

2. The EMC–effect. Let us see now what the EMC–effect means in the frame of our approach. Let us assume that the functions \(T_A\) determine, at least approximately, an effective distribution of nucleons in nucleus and therefore they are mostly concentrated in the region of \(\alpha = 1\) (i.e. in the region of zero internal momentum of a nucleon). Expanding \(F_N(\frac{x}{\alpha})\) in (1) and (3) around \(\alpha = 1\), it is easy to obtain for not very large \(x\)

\[
R = \frac{F_A}{F_N} \simeq <T> + <(1-\alpha)T> \frac{x}{F_N} + \frac{1}{2} <(1-\alpha)^2T> x \left( \frac{F''_N}{F_N} + 2 \frac{F'_N}{F_N} \right) + \cdots
\]

(8)

where \(<\cdot\cdot\cdot>\) means integration over interval \(0 < \alpha < A\). If one accept that \(F_N \sim (1-x)^k\) and \(k \simeq 3\), then \(x\)-dependence of the second and the third terms are the factors \(-k[x/(1-x)]\) and \(k[x/(1-x)] \cdot [(k-1)x/(1-x)-2]\) respectively. In the region of \(x \approx 0.5\) the second term is close to zero and to obtain the depletion of \(R\) from unity in this region discovered by EMC one should have

\[
<T_A^S> - 1 = \Delta_A > 0 \quad \text{or} \quad \int_0^A d\alpha \left[ T_A^S(\alpha) - T_A^{NS}(\alpha) \right] = \Delta_A > 0
\]

(9)

for the ratio \(R_2\) of the structure functions \(F_2 \approx \Sigma\) and

\[
1 - <\alpha T_A^{NS}> = \delta_A > 0 \quad \text{or} \quad \int_0^A d\alpha \alpha \left[ T_A^S(\alpha) - T_A^{NS}(\alpha) \right] = \delta_A > 0
\]

(10)

for the ratio \(R_3\) of the structure functions of \(xF_3\).

In addition, in the region \(x \approx 0.5\) the sea quarks are practically absent: therefore one can expect here \(R_3 \simeq R_2\) and

\[
\delta_A \simeq \Delta_A \quad \text{(more exactly } \frac{2}{3}\Delta_A\text{)}
\]

(11)

The relations (3) and (11), mean that the number of "effective nucleons" in a nucleus has to be larger than \(A\), and the valence nucleons have to carry only a part of the total

\(^3\)Another criticism of the hypothesis from QCD point of view can be found in Ref. [8].
nucleus momentum. In other words, the EMC–effect is the result of a repumping of a part of momentum from valence quarks to sea quarks in the nucleus in comparison with free nucleon.

Notice, that the shock produced by the discovery of EMC was due to the prejudice that a nucleus is made of \( A \) nucleons and so the condition \( \Delta_A = 0 \) has to be imposed on the distribution \( T^S \), which unavoidably results in \( R_2(x \approx 0.5) = 1 \), independent of the form of \( T^S \). In this sense, the difference between \( T^S \) and \( T^{NS} \) (necessary to explain the EMC–effect) leads to the irreducibility of the nuclear quark structure to the quark structure of free nucleons.

In spite of generality, this approach allows one to draw a number of interesting conclusions:

i) It immediately follows from (9) that the ratio

\[
R_2(x \simeq 0) = \int_0^A d\alpha T_A^S(\alpha) = 1 + \Delta_A > 1
\]

The most accurate measurement of BCDMS [5] shows a small \( \approx 5\% \) but definite excess of the ratio over 1 in the region of small \( x \), i.e. the same value as the loss of momenta of the valence nucleons \( \delta_A \). This means a small number of particles of the non-nucleon component which have to be heavy enough to supply the 5\% repumping of the momentum (e.g. \( \rho \)-mesons, \( N\bar{N} \)–pairs or pions far off the mass shell).

ii) In addition to the internucleon sea there is a small, \( \approx \Delta_A \), but hard enough ”collective sea” of quark–antiquark pairs in nuclei.

Using (1) and (3) it is easy to obtain for the sea

\[
O_A(x, Q^2) \equiv \Sigma_A - V_A = \int_x^A d\alpha T_A^{NS}(\alpha)O_N \left( \frac{x}{\alpha}, Q^2 \right) + \int_x^A d\alpha \left[ T_A^S(\alpha) - T_A^{NS}(\alpha) \right] \Sigma_N \left( \frac{x}{\alpha}, Q^2 \right)
\]

where the first term comes from the internucleon sea, which rapidly decreases with increasing \( x \), and the second term comes from a ”collective sea”, \( O'_A \), which is hard since its center of gravity is

\[
\bar{\alpha}_O' = \frac{< \alpha(T_A^S - T_A^{NS}) >}{< T_A^S - T_A^{NS} >} = \frac{\Delta_A}{\Delta_A} \approx 1
\]

For pions on the mass shell this number is \( m_\pi/m_N \approx 1/7 \). That is the reason why the repumping of the momentum into the pions [15] gives no satisfactory description of the data in the region of small \( x \) (too many pions are needed to supply the 5\% repumping).

iii) The place of intersection \( R_2(x_0) = 1 \) does not depend on the sort of nucleus and is at \( x_0 \approx 0.3 \). Really, if there are no screening and light particles in nuclei, \( T_A^S(\alpha) \) has to be smooth enough in the region of small \( x \). Using then the first two terms of (8) for \( R_2 \) it is easy to find

\[
\frac{x_0}{1 - x_0} \approx \frac{1}{3} \left( 1 - \frac{\int_0^{x_0} d\alpha \alpha T_A^S(\alpha)}{\int_0^{x_0} d\alpha T_A^S(\alpha)} \right)^{-1}
\]

The ratio of integrals in the r.h.s. is in the interval \([0, x_0]\) and thus \( 0.25 < x_0 < 1/3 \). This feature of the ratio \( R_2 \) has been well confirmed experimentally [16] with \( x_0 = 0.278 \pm 0.010 \).

\[4\text{Recall that the screening phenomena are disregarded here} \]
Now, what about different models proposed? They are, in fact, different suggestions of the repumping mechanisms. Not all of them seem satisfactory from our viewpoint. We have mentioned the rescaling models [11] where part of the repumping comes into gluon component. However, the main drawback of these models is the softness of the gluon and the sea component in nucleon. This leads to an extra big value of $R_2(0)$ after the 5% repumping. (Although the authors deny the applicability of their model to the region of small $x$.) As it was noticed, models with repumping of momenta into the mass shell pions [15] have the same disadvantage.

Other models can be divided into three big categories:

i) Models with repumping of the momentum either into massive meson component [17] ($\rho, \omega$, off the mass–shell pions) or into nucleon–antinucleon pairs [9]. A component like that is probably related to the core of nuclear force at small distances. However, it is hard to believe that the nucleon can conserve at such small distances its individual quark structure without converting it into multiquark states.

ii) Repumping inside each nucleon [18], i.e. change of its quark structure due to the influence of the internuclear field. Transition of part of nucleons into $\Delta$-isobar [19] also belongs to this class. We do not see, however, how it is possible to obtain the hard sea here.

iii) Repumping inside a multiquark fluctuation [20]. By this we mean not only a bound state but also a state of two or more nucleons with interaction of their quarks, as proposed in [12], or with an exchange quark interaction in the final state considered in [21]. That kind of interactions is inevitable in any theory with a composite nucleon. However, the calculation of the quark structure of the states like that seems as difficult as the calculation of the quark structure of nucleus. Recently some progress in this direction has been achieved [22].

It is necessary to stress the important difference between a multiquark state and few-nucleon correlation (FNC) [23]. The loss of momenta of the valence quarks for the latter are the same as averaged over the nucleus, $\Delta_{FNC} = \Delta_A$, due to a change of structure of each nucleon. For the multiquark, however, it has to be much larger

$$\Delta_{\bar{q}q} > \Delta_A$$  \hspace{1cm} (15)

e.g. if there is no repumping inside the nucleons, then $\Delta_A = p_A \Delta_{\bar{q}q}$, where $p_A$ is a probability of multiquark states. In fact, the relation (15) can be considered as a definition of the multiquark state in distinction with FNC. A statistical realization of the hard antiquark sea is also known (see e.g. Kondratyuk paper [20]).

It seems that structure function measurements alone cannot distinguish between these models. So, new sources of information are necessary. One of them is deep inelastic scattering with measurement of hadrons in a final state. Production of $\rho$- and $\Delta$-resonances and also $K^-$-mesons and antiprotons which carry the information about the collective sea is especially interesting for evident reasons.

3. Cumulative particles production. Another source of information is the cumulative particle production. Especially, the production of $K^-$-mesons and antiprotons off nuclei in the region $x \geq 1$, because of the peculiarity of the nuclear quark structure mentioned before.

A question arises however: to what extent is the cumulative production cross section determined by the nuclear structure functions $F_A(x)$? Until now there are no quite reliable
data for nuclear deep inelastic scattering in the region $x \geq 1$, though there are some indications of similarity of the cumulative meson spectra and structure function $F_2(x)$ in this region [25].

There exist two points of view on the physics of cumulative production [3]: (a) "hot models", in which massive clusters in nuclei (which are necessary to produce a cumulative particle) are formed by an incoming hadron either by a sort of compression of the nuclear matter and heavy fireball formation or by multiple rescattering [26]; (b) "cold models", in which formations of that sort already exist in nuclei because of Blokhintsev’s fluctuations of density [27] either in a form of multiquark states or in a form of a few nucleon correlation, resulting in the high momentum tail of Fermi motion. This reflects in the structure functions of the nucleus. A common property of these models is the independence of the nuclear parton fragmentation of the nucleus type. This allows us to write down the cross section of the process in the form

$$
\frac{\epsilon}{A} \frac{d\sigma}{d^3p} = \rho_{A \rightarrow h}(x, y, p_T) = \int_x^A d\alpha F_A(\alpha) f_h \left( \frac{x}{\alpha}, y, p_T \right)
$$

where $x = -u/s, y = -t/s$ and the function $f_h$ does not depend on $A$, i.e. it is the same for a nucleus and for a free nucleon. Combining (16) with (1,3), it is easy to obtain a natural expression

$$
\rho_{A \rightarrow h}(x, y, p_T) = \int_x^A d\alpha N_A(\alpha) \rho_{N \rightarrow h} \left( \frac{x}{\alpha}, y, p_T \right) + \int_x^A d\alpha \tilde{N}_A(\alpha) \rho_{\tilde{N} \rightarrow h} \left( \frac{x}{\alpha}, y, p_T \right)
$$

where we use the notation

$$
N_A = \frac{1}{2} \left( T^S_A + T^{NS}_A \right) \quad \text{and} \quad \tilde{N}_A = \frac{1}{2} \left( T^S_A - T^{NS}_A \right).
$$

The first expression in (18) can be considered approximately, due to smallness of the EMC–effect, as a distribution of nucleons over fractions of the momentum. For cumulative and stripping protons it is necessary to add to (17) a term proportional to $N_A(x)$ which takes into account dissociation of the nucleus. Moreover, just this term gives a major contribution when $p_T \approx 0$ [28]. Parametrizing the form of the spectrum of stripped and cumulative protons with $p_T \approx 0$ (with normalization $< N_A > = 1 + \Delta A/2$, $< \alpha N_A > = 1 - \delta A/2$) and using the experimental cross section for $\rho_{N \rightarrow \pi}$, one obtains the cross section of cumulative pion production without any new parameter. (The second term in (17) naturally gives a small correction.) This program for deuterium (to minimize possible secondary nuclear effects) has been made in work [29] and shows a good agreement with experiment. Also, the ratio $K^+/\pi^+$ agrees with experiment. This agreement confirms the independence of fragmentation of the kind of a nucleus (at least, for light nuclei), which is the base of (17,18) and means also that the valence mesons carry the same information on the nuclear quark structure as the cumulative protons [30]. However, the main peculiarity of the nuclear quark structure is hidden here.

Interpretation of $\tilde{N}_A$ in (17,18) depends on the mechanism of repumping and, due to the second term in (17), dominates for "sea particles" $K^-, \bar{p}$ in the region $x \geq 1$. They are just sensitive to the peculiarity of the nuclear quark structure. For the ratio of $K^+/K^-$ yields in the region we have

$$
r_A = \frac{K^+}{K^-} \approx \frac{\int_x^A d\alpha N_A(\alpha) \rho_{N \rightarrow K^+} \left( \frac{x}{\alpha} \right)}{\int_x^A d\alpha \tilde{N}_A(\alpha) \rho_{\tilde{N} \rightarrow K^+} \left( \frac{x}{\alpha} \right)},
$$

where
where the approximation $\rho_{N\to K^-} \approx \rho_{N\to K^+}$ is used. It is known experimentally \[31, 32, 33\] that the ratio $r_A$ for various nuclei (Be, Al, Cu, Ta, Pb) is constant in $x$, within experimental accuracy, in the region $1 < x < 2.5$ (Figs. 2) \[1\] is in sharp contradiction with its behaviour in region $x < 1$. Therefore, the functions $N_A$ and $\tilde{N}_A$ in this region should only differ by a factor. One can assume that this difference reflects the difference in normalization condition for this functions

$$< \alpha \tilde{N}_A > \approx < \tilde{N}_A > = \Delta A / 2 \quad \text{and} \quad < \alpha N_A > \approx < N_A > \approx 1$$ \hspace{1cm} (20)$$

So for the models of type i) and ii) one would expect from (19) $r_A \approx 2 / \Delta A$. Using the parametrization \[9\] of the SLAC \[34\] and BCDMS \[5\] data for the EMC–effect one finds $r_{Be} = 86$ ($\Delta_{Be} = 0.023$), $r_{Al} = 55$ ($\Delta_{Al} = 0.036$), $r_{Ta} = 36$ ($\Delta_{Ta} = 0.056$) and $r_{Pb} = 35$ ($\Delta_{Pb} = 0.058$), which is significantly higher than the experimental ratio (see Figs. 2), especially for light nuclei.

For the repumping inside multiquark states, which has to determine the cumulative cross sections in this region of $x$, the repumping $\Delta_{6q} \simeq \Delta A / p_A$ has to be larger (due to a small $p_A$) and $r_A \approx 2 / \Delta_{6q}$ has to be lower. E.g. the experimental ratio $r_{Be}^{exp} \approx 9$ corresponds to $\Delta_{6q} \approx 0.22$ and $p_{Be} \approx 0.10$. So, the low ratio of $r_A$ can be considered as an indication of the multiquark mechanism of both cumulative phenomena and the EMC–effect.

Now, let us turn to the cumulative antiprotons. Naturally, they are sensitive to the $N\tilde{N}$-pair repumping mechanism \[9\]. The ratio of $p/\bar{p}$ yields is determined by an expression of the type of (13) and is of the order $2 / \Delta A \approx 10^2$. The experiment \[34\] gives for this ratio $p/\bar{p} \approx 10^8$, which definitely rejects the above mechanism. On the other hand, with no packing of the collective sea into $N\tilde{N}$-pairs, the cumulative $\bar{p}$ can arise in fragmentation of $\tilde{q}$ (just as $K^-$). Then the ratio $\bar{p}/K^-$ has to be $\approx 0.1$ (suppression by an order of

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\[^{5}\text{Notice that the variable } x \text{ here is defined by a minimal mass (in the nucleon mass units) of } M_X^2 = (xp_A + p_B - p_C)^2 \text{ for the process } B + A \to C + X, \text{ where } p_A \text{ is a 4-momentum of a nuclei per a nucleon.}\]
magnitude is due to fragmentation \( q \rightarrow \bar{q} \) and some growth due to a smaller transverse momentum of \( \bar{p} \) at the same value of \( x \)) which is not far from the experimental observation \( \bar{K}^-/\bar{p} \simeq 5 \) for Be (see Fig. 3). More accurate calculations of \( \bar{K}^+/\bar{K}^- \) and \( \bar{p}/\bar{K}^- \) ratios based on the dual string model with the multi-quark fluctuations were done in paper [36]. Notice, however, that the model underestimates the \( \bar{K}^+/\bar{K}^- \)–ratio for the proton target in the region \( x > 0.6 \).

It is necessary to stress also that secondary nuclear effects can be significant for the intermediate and heavy nuclei we have considered. Indications to these effects come, for example, from an enhanced \( A \)-dependence of cumulative proton and \( K^+ \) productions and from an enhanced by 4–5 times depletion from unity of \( \rho_{A \rightarrow \pi} / \rho_{D \rightarrow \pi} \) in the region \( x \approx 0.6 \) compared to the deep inelastic scattering. (Notice also that the ratio of cumulative cross sections \( He/D \) shows even an \( anti \)–EMC effect in this region!) For these reasons it would be very desirable to have accurate data on the kaon and antiproton production off deuterium.

The conclusive headlines are:

i) The cause of the EMC–effect is the repumping of the valence quark momentum to a collective sea of quark–antiquark pairs.

ii) Small excess of the \( A/D \) ratio in the \( x \approx 0 \) region points to a hardness of a collective sea or to a massive non-nucleon component in nuclei.

iii) Many popular models are in trouble due to i) and ii).

iv) The ratio of \( K^+/K^- \) cumulative cross sections supports the multiquark mechanism of the EMC–effect and of the cumulative process.

v) Accurate data on the kaon and antiproton production off deuterium are highly desirable.

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