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ON THE NATURE OF THE EMC EFFECT

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It is shown that none of the popular models suggested to explain the EMC effect seem satisfactory. A new point of view on the effect as a simple relativistic phenomenon is presented and is shown to be favoured by NA4 data.

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From the time of the discovery of the EMC effect¹⁾, a number of explanations were proposed²⁾. However, none of them seems satisfactory. All models incorporate in some form a suppression of the hard part ($x > 0.4$) of the valence quark distribution but differ by the assumed source of compensation of this suppression.

The following compensation mechanisms have been considered:

- (i) by soft part ($x < 0.3$) of valence quark distribution^{3),4)};
- (ii) by pions in nucleus⁵⁾;
- (iii) both by the quark and the gluon sea due to increase of the confinement radius (rescaling models)^{6),7)}.

We shall demonstrate next that none of them seems to give a good description of the experimental data.

1° Since the QCD evolution equations do not depend on the type of the target one can show^{8),9)} that up to higher twist corrections

$$V_A(x, Q^2) = \int_x^A d\beta T_A^{NS}(\beta) V_N\left(\frac{x}{\beta}, Q^2\right) \equiv T_A^{NS} \otimes V_N \quad (1)$$

$$(\Sigma_A + C^\pm \otimes G_A) = T_A^\pm (\Sigma_N + C^\pm \otimes G_N) \quad (2)$$

where V , Σ , G are the valence (non-singlet) quark, singlet quark, and gluon distribution functions, $C^\pm$ are coefficients depending on x and $\alpha_s(Q^2)$ which can be found from the perturbative QCD and T_A^{NS} , $T_A^\pm$ are some functions independent of Q^2 characterizing the nucleus A . Due to the baryon number and energy-momentum sum rule T_A^{NS} and $T_A^\pm$ satisfy the following conditions (the index A will be omitted)

$$\int_0^A T^{NS}(\beta) d\beta = 1, \quad \int_0^A T^\pm(\beta) \beta d\beta = \frac{M}{Am} \approx 1 \quad (3)$$

where M and m are the mass of nucleus and free nucleon.

For large Q^2 and $x > 0.3$ where the sea quark distributions, $0 = \Sigma - V$, in nucleus and free nucleon are negligible, one can write down

$$\Sigma_A(x, Q^2) \approx \int_x^A T^{NS}(\beta) \Sigma_N\left(\frac{x}{\beta}, Q^2\right) d\beta$$

Developing $\Sigma_N(x/p)$ into power series in $\delta = 1-\beta$, it is easy to obtain

$$\Sigma_A(x) = \Sigma_N(x) \cdot \bar{\delta}_x^0 + x \cdot \Sigma_N'(x) \cdot \bar{\delta}_x^1 + \frac{\bar{\delta}_x^2}{2} (x^2 \Sigma_N''(x) + 2x \Sigma_N'(x)) + \dots (4)$$

where $\bar{\delta}_x^k = \int_x^A \delta^k T^{NS}(\beta) d\beta$. (The validity of this approximation assumes, of course, that T^{NS} is a well-behaved function concentrated mostly somewhere around $\beta \approx 1$, i.e., nucleons near the mass shell are "good" quasi-particles in the nucleus.) For $\Sigma_N(x) \sim (1-x)^k$, $k \approx 3$, which is not a bad approximation in the large x region

$$R(x) = \frac{\Sigma_A(x)}{\Sigma_N(x)} \approx \bar{\delta}_x^0 - \bar{\delta}_x^1 \cdot k\xi + \frac{1}{2} \bar{\delta}_x^2 \cdot k\xi((k-1)\xi - 2) + \dots (4')$$

where $\xi = x/(1-x)$ and the third term disappears at $x \approx 0.5$ ($\xi=1$).

Now, it is known from experiment that both $V_N(x)$ and $V_A(x)$ are positive. From (1) then follows that the function T^{NS} is also positive. (It could be negative only in an interval strictly inside the region $[0, A]$ - for that we see no physical reason, however.) Then using the normalization condition (3) and the obvious inequality $\int_0^x \beta T^{NS}(\beta) d\beta < x \int_0^x T^{NS}(\beta) d\beta$ one can prove that the condition

$$\frac{\langle x_V \rangle_A}{\langle x_V \rangle_N} = \int_0^A \beta T^{NS}(\beta) d\beta = 1 - \bar{\delta} < 1 (5)$$

is necessary to have $R(0.5) < 1$ (large x depletion), i.e., it is impossible to compensate the depletion by increase of the soft part of the valence quark distribution assumed in Ref. 3).

This also implies the impossibility of a screening effect for the valence quarks assumed in Ref. 4). Indeed, the function $t(n) = \int_0^A \beta^n T^{NS}(\beta) d\beta$ is convex downward ($d^2 t/dn^2 > 0$), $t(1) = 1 - \bar{\delta} < 1$, $t(0) = 1$ and consequently $V_A/V_N|_{x=0} = t(-\frac{1}{2}) > 1$. A behaviour $V_N(x) \sim \sqrt{x}$ at $x \rightarrow 0$ is assumed. The required depletion for $R(\text{Fe/D})$ is gained when $\bar{\delta} \approx 0.045$.

The above conclusions are valid of course up to higher twist corrections ($\sim 1/Q^2$) which can be important³⁾ in a very small x region $x < m_N/R_0 Q^2$, $r_0 \sim 1$ fm being the average internucleon distance.

2° Let us examine next the possibility of the compensation of the missing momentum $\langle x_V \rangle_A - \langle x_V \rangle_N$ by quark and gluon seas. Consider the ratio

$$R_I = \left(\int_0^A F_{2A}(x) dx \right) / \left(\int_0^A F_{2D}(x) dx \right) \approx \frac{\langle x_q \rangle_A}{\langle x_q \rangle_N} \quad (6)$$

[We assume for simplicity that $\Sigma(x) \approx F_2(x)$ and $F_{2D}(x) \approx F_{2N}(x)$.] It plays the same role as in the integral of the difference of structure functions used in Ref. 9) but is free from many systematic errors.

Estimation of R_I using the EMC data¹⁰⁾ and the natural continuation $F_2(x < 0.05) = F_2(0.05)$ gives

$$R_I^{EMC} - 1 = (7.1 \pm 1.0 \pm 3.0) \cdot 10^{-2} \quad (7)$$

Such a big positive number is difficult to obtain in any pion model. It is easy to show that $R_I - 1 = \bar{\delta}(\langle x_q \rangle_\pi / \langle x_q \rangle_N - 1)$ and with $\bar{\delta} = 0.045$ the number (7) corresponds to $\langle x_q \rangle_\pi / \langle x_q \rangle_N > 1.89$, instead of ≈ 1 .

The number (7) contradicts also any rescaling model because the transition from free nucleon to nucleus is equivalent to increasing of Q^2 . So, $\langle x_G \rangle$ has to increase and $\langle x_q \rangle$ has to decrease, just opposite to (7).

One can possibly argue that the EMC group somehow overestimates the small x region and that the other experiments¹¹⁾ and first of all NA4¹²⁾ do not show such an excess for the ratio N_2/D_2 with a small systematic error. Indeed, a calculation of R_I for the nitrogen nuclei using the NA4 data gives

$$R_I^{NA4} - 1 = (0.7 \pm 1.7 \pm 1.0) \cdot 10^{-2} \quad (8)$$

which is compatible with zero. However, much smaller excess of the data over $R = 1$ in the small x region leads even to a greater difficulty for pion and rescaling models because it implies a much smaller number of pions in nucleus or a much smaller difference in confinement radii of free and bound nucleons which results in a much smaller depletion for $x > 0.3$ in strong disagreement with the data [cf. e.g., Ref. 13)].

So we see that none of these compensation schemes seems satisfactory both for EMC or NA4 data. It should also be added that the multiquark fluctuations¹⁴⁾ in nucleus, the existence of which is supported by many unusual phenomena in

hadron-nucleus scattering, e.g., cumulative particle production¹⁵⁾, can of course be responsible for the EMC effect. However, the structure function of the fluctuations is not constrained enough to consider such an explanation as totally satisfactory.

3° The main reason for such an uneasy situation with the explanation of the EMC effect lies, in our opinion, in the fact that it is usually assumed that the nucleus is a bound state of A nucleons. This is definitely a wrong assumption in a relativistic theory because the number of particles is not conserved in an interacting system like the nucleus. Only the baryon number, i.e., the number of nucleons minus the number of antinucleons is conserved. So, first what we need is a true relativistic description. For this purpose, the Bethe-Salpeter equation (Fig. 1) seems to us to be the most suitable one.

In the impulse approximation it leads to the equation (1) for V_A and to the following equations for the singlet part

$$\Sigma_A(x, Q^2) = \int_x^A T^S(\beta) \Sigma_N\left(\frac{x}{\beta}\right) d\beta \quad (9)$$

$$G_N(x, Q^2) = \int_x^A T^S(\beta) G_N\left(\frac{x}{\beta}\right) d\beta \quad (10)$$

where

$$T^{NS}(\beta) = N(\beta) - \bar{N}(\beta), \quad T^S(\beta) = N(\beta) + \bar{N}(\beta) \quad (11)$$

($\bar{N}$) N being the densities of (anti-) nucleon in the nucleus with a given momentum fraction β . It is equivalent to Eqs. (2) obtained from QCD with an additional ansatz

$$T^+ = T^- \equiv T^S \quad (12)$$

The latter could be a consequence of the absence of free quarks and gluons in the nucleus due to colour confinement and quark-hadron duality. Therefore, we believe that Eqs. (9) to (11) have a more general validity.

Using these equations it is easy to see that $\bar{N}(p) = 0$ immediately results in $\bar{\delta} = \int (1-\beta) T^{NS}(\beta) d\beta = 0$ and the absence of a large x depletion in R as it was shown in Section 1. If, however,

$$\int_0^A \bar{N}(\beta) d\beta = \Delta \neq 0, \quad \int_0^A N(\beta) d\beta = 1 + \Delta > 1 \quad (13)$$

one can obtain from (11) and (3) the excess over $R = 1$ at $x = 0$

$$R(x=0) = \int_0^A T^S(\beta) d\beta = 1 + 2\Delta > 1 \quad (14)$$

Using the development of (9) in power series of $(1-\beta)$ similar to Eq. (4), one obtains

$$R(x) \approx 1 + 2\Delta (1 - \kappa \xi) + \dots \quad (15)$$

which guarantees also a depletion at $\xi > 1/\kappa$ ($x > 1/(\kappa+1)$). So, these two features of the EMC effect are a simple consequence of $\Delta \neq 0$ and are closely linked with each other. For instance, if $\kappa \approx 3$ and $R(0.5) \approx -0.1$, then the excess will be $R(0)-1 \approx 0.05$ independent of the details of $T^S(\beta)$. This is one of the characteristic predictions of our approach.

Notice also that in the approximation (15) the position of the intercept $R = 1$, $x \approx 1/(\kappa+1)$ does not depend on the type of the nucleus, which is also one of the distinctive features of the EMC effects.

We shall try to connect next the number of antinucleons Δ with the average nucleon energy level in the nucleus. For this purpose, let us assume that the inter-nuclear forces are C -independent, i.e., that the average energies per particle for nucleons and antinucleons are equal:

$$\bar{\beta}_N = \left(\int_0^A N(\beta) \beta d\beta \right) / \left(\int_0^A N(\beta) d\beta \right) = \left(\int_0^A \bar{N}(\beta) \beta d\beta \right) / \left(\int_0^A \bar{N}(\beta) d\beta \right) = \bar{\beta}_N$$

From the relations (11) and the normalization condition (3), one can show that the above equality is equivalent to a coincidence of centres of gravity of the functions T_A^S and T_A^{NS}

$$\beta_0 = \int_0^A T^{NS}(\beta) \beta d\beta / \left(\int_0^A T^S(\beta) \beta d\beta \right) / \left(\int_0^A T^S(\beta) d\beta \right) = \frac{1}{1+2\Delta} \quad (16)$$

This guarantees that $V_A(x) \approx \Sigma_A(x)$ for the large x region. Defining now the average nucleon energy level as an energy of evacuation of one nucleon

$$\int \beta N(\beta) d\beta = 1 - \bar{\varepsilon}/m$$

one can obtain

$$\bar{\varepsilon} = \frac{m\Delta}{1+2\Delta} \approx m\Delta \quad (17)$$

i.e., the depletion $R(0.5)-1 \approx 0.1$ for Fe corresponds to $\bar{\varepsilon} \approx 23$ MeV which agrees with standard nuclear physics.

In order to obtain a more detailed behaviour of $R_L(\alpha)$ we have assumed for T^S a simplest form of "shifted" Fermi step function

$$T^S(\beta) = \frac{4}{3\beta_0} \left(\frac{m}{K_F}\right)^3 \cdot \begin{cases} \left(\frac{K_F}{m}\right)^2 - (\beta_0 - \beta)^2 & \text{for } |\beta_0 - \beta| < \frac{K_F}{m} \\ 0 & \text{otherwise} \end{cases} \quad (18)$$

where β_0 [or $\bar{\varepsilon}$ due to (16) and (17)] and K_F/m are considered as parameters to be determined from the data. Figure 2a demonstrates the degree of agreement with the NA4 data¹²⁾ for the ratio $R(N_2/D_2)$ supplemented by the SLAC data¹⁵⁾ for $R(C^{12}/D_2)$ with $x > 0.65$. Figure 2b demonstrates the same for the ratio $R(Fe/D)$. The behaviour in the region $x < 0.2$ can be considered as the prediction. Figure 3 presents the A-dependence of the parameters for the whole set of nuclei measured at SLAC. (Due to a possible correction of SLAC data for small x due to the A dependence of σ_L/σ_T ratio only the points with $x > 0.3$ were included into the fit.) One can see a slight A-dependence of both parameters and an indication on a somewhat higher value of $\bar{\varepsilon}$ for even-even nuclei. Notice also the good coincidence of the parameters for the iron data of SLAC and NA4 and a higher value of $\bar{\varepsilon}$ for nitrogen. The latter could be a consequence of a small, $\approx 1-2\%$ systematic shift of the data. The results of the calculation of Fe/D ratio for the sea quarks and the gluons, and the corresponding data of CDHS¹¹⁾ and of EMC¹⁶⁾ are presented in Fig. 4. A disagreement with EMC data for the gluons does not bother us very much because it seems difficult to agree such a big excess of gluons in nucleus with a decrease of the gluon average momentum resulting from (7).

4° In such a way, we have shown that none of the popular models of the EMC effect gives an acceptable explanation as EMC as NA4 data. From the other side we have demonstrated that the whole EMC phenomenon can be a simple relativistic effect in the bound state: and indefinite number of particle-antiparticle pairs of the order of the ratio of binding energy to the mass. The NA4 experiment with controlled systematic errors at each point supports this point of view. By a χ^2

test, there remains only a little place for other unusual phenomena like multiquarks and colour conductivity. However, it does not exclude them completely because their contributions can be hidden in parameters of T^S and T^{NS} so that the explored region in x is not very sensitive to such contributions. This means that only new accurate measurements in new regions ($x > 1$ or $1/x \gg 1$) could give more definite information about such exotic phenomena.

Notice also that the simplicity of relations between the nuclear and free nucleon structure functions allows us to determine the latter from nuclear data and to use it in a QCD analysis.

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FIGURE CAPTIONS

- Fig. 1 The Bethe-Salpeter equation for nuclear structure function.
- Fig. 2 Fit of NA4 (●) - SLAC (▲) data for (a) the ratio $R(N_2/D_2)$ and (b) $R(Fe/D)$ by expressions (9) and (18).
- Fig. 3 The A-dependence of parameters $\bar{\epsilon}/m$ (●) and K_F/m (▲) obtained from SLAC and NA4 ($A = 14,56$) data.
- Fig. 4 The comparison of the ratio Fe/D for (a) sea quarks and (b) gluons with the data of CDHS and EMC groups.

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b