Does a pion mechanism determine the difference between the structure functions of the nucleus and the nucleon?

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The contribution of the pion mechanism to the EMC effect is subjected to critical analysis. With realistic parameter values this mechanism can explain a large part of the effect over the range $0.1 \leqslant x \leqslant 0.7$.

The discovery of the EMC effect[1]—a difference between the structure functions $F_2(x)$ of a nucleus and a nucleon in the region of Bjorken scaling—was followed immediately by the appearance of many theoretical models attempting to explain the effect (see the review by Strikman and Frankfurt[2]). In most of these models, the difference of the ratio $R(x) = \widetilde{F}_{2N}(x)/F_{2N}(x)(\widetilde{F}_{2N}(x) \equiv F_2^A(x/A)/A)$ from unity is attributed to either a change in a property of a nucleon in a nucleus or the existence of exotic multiquark states.

Llewellyn Smith[3] has hypothesized that $R(x)$ becomes greater than unity at small values of x because of a scattering of a lepton by a virtual pion softened in a nucleus; calculations by Ericson and Thomas[4] and Titov[5] support this hypothesis. According to the calculations of Refs. 4 and 5, the pion mechanism can contribute substantially to $R(x)$ at $x<0.3$. On the other hand, these calculations have definite shortcomings: the particular choice of the structure functions for the pion, $F_{2\pi}(x)$, and of the form factors Γ and the πNN vertex, to which the result is extremely sensitive. This circumstance casts doubt on many of the specific conclusions reached in those studies, in particular, the assertion[4] that the EMC data impose a stringent limit on the value of a constant: $g'_{N\Delta} \geqslant 0.7$.

The pion contribution to the structure function of a nucleon is[3] (see the diagram in Fig. 1a)

$$\delta F_{2N}^{\pi}(x) = \int_x^1 f_\pi(y) F_{2\pi}(x/y)dy, \tag{1}$$

where $f_\pi(y)$ is the probability for finding a pion with a fraction y of the momentum of the nucleon in a system with infinite momentum. In a nucleus, the softening of the pion mode might cause the corresponding probability $\widetilde{f}_\pi$ to exceed f_π. This particular effect was considered in Refs. 3–5. As Berger *et al.*[6] have pointed out, the probability $f_N(z)$ for finding a bare nucleon carrying a fraction z of the momentum of the physical nucleon has been ignored, while these two probabilities are related by a normalization condition:

$$\int_0^1 y f_\pi(y)dy + \int_0^1 z f_N(z)dz = 1. \tag{2}$$

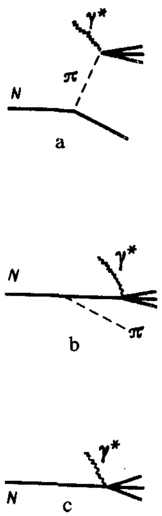

FIG. 1.

It follows from conservation of baryon charge that[6]

$$f_N(z) = (1 - n_\pi)\delta(1 - z) + f_\pi(1 - z), \tag{3}$$

where $n_\pi = \int_0^1 f_\pi(y)dy$ is the "average number of pions per nucleon." We then have

$$F_{2N}(x) = \delta F^\pi_{2N}(x) + \int_x^1 f_\pi(1 - z)F^0_{2N}\left(\frac{x}{z}\right)dz + (1 - n_\pi)F^0_{2N}(x). \tag{4}$$

Here $F^0_{2N}(x)$ is the structure function of the bare nucleon. The three terms in (4) correspond to the three diagrams in Fig. 1, where the solid lines correspond to the bare nucleon. Our use of the word "bare" here is somewhat arbitrary, in that the diagram of Fig. 1a is singled out from F_{2N}. In particular, our bare nucleon contains a virtual Δ isobar and higher-lying resonances, since the corresponding diagrams change only slightly in nuclear matter. For this reason, $f_\pi(y)$ incorporates only those pion-lowering events in which the nucleon remains a nucleon. We start from the assumption that the quark structures of the nucleon and the pion are identical in a nucleus and in a vacuum. Equations (1)–(4) with the replacements $f_\pi \to \tilde{f}_\pi$ and $n_\pi \to \tilde{n}_\pi$ [we call the results $(\tilde{1})$–$(\tilde{4})$][1)] hold for the nuclear structure function. The use of expression (3) in a nucleus requires some explanation. To use this expression actually means to ignore the Fermi motion with correlations that are unrelated to pion exchange. The incorporation of these correlations would result in the replacement of the 1 in the arguments of $\delta(1 - z)$ and $f_\pi(1 - z)$ by some blurred function; the difference would be important only at $x \gtrsim 0.7$. The recipe for incorporating Fermi motion is known[2] and does not bear directly on the mechanism under discussion here. For this reason, we will restrict the discussion to the region $0.1 \leqslant x \leqslant 0.7$ (the basic reason for the lower limit is the screening effect[2]).

Qualitative conclusions can be drawn directly from Eqs. (4) and $(\tilde{4})$. Specifically,[6]

$$R(0) = 1 + (\tilde{n}_\pi - n_\pi)F_{2\pi}(0)/F_{2N}(0). \tag{5}$$

Furthermore, at large values $x \gtrsim 0.6$ the contribution of the first two terms in (4) and $(\tilde{4})$ dies out. Using (5), we then find

$$(R(0) - 1)/(1 - R(x_0)) = (F_{2\pi}(0)/F_{2N}(0))(1 - n_\pi), \quad x_0 \simeq 0,6 - 0,7. \tag{6}$$

Here $F_{2\pi}(0)/F_{2N}(0) \simeq 1.5$, and n_π would be ~ 0.3 under realistic assumptions.[7] Accordingly, the extent to which R exceeds unity at small values of x and the depth of the dip at $x \sim 0.5$–0.7 are approximately equal in magnitude, regardless of the specific features of the nuclear structure; the scale of the effect is determined by the difference $\tilde{n}_\pi - n_\pi$. This quantity, like the particular features of the x dependence of R, is determined by the particular nuclear model that is used.

A numerical calculation of $R(x)$ has been carried out by the following method. Using the known functions $\tilde{f}_\pi(y)$ and $f_\pi(y)$, we solve integral equation $(\tilde{4})$ for F^0_{2N}, taking $\tilde{F}_{2N}(x)$ from Ref. 8. We then find the structure functions $F_{2N}(x)$ and $R(x)$ from (4). The crucial quantity in the calculation of $\tilde{f}_\pi$ is the imaginary part of the reduced pion polarization operator[4] $\Pi(k, \omega)$, in whose calculation there are several uncertainties. In addition to the amplitude of the one-pion exchange, which depends on Γ, we must deal with the local amplitudes g'_{NN}, $g'_{N\Delta}$, and $g'_{\Delta\Delta}$. Two sets of parameters are known to lead to a reasonable description of many pieces of evidence from nuclear

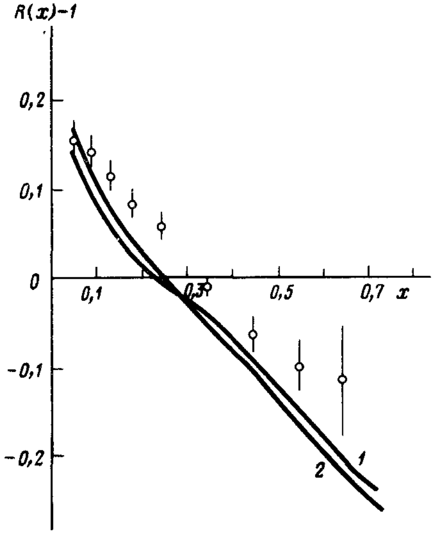

FIG. 2. The difference $R(Fe/D)$-1 calculated for the strengths of Ref. 9. 1—$g'_{NN} = 1.1$; 2—$g'_{NN} = 1.0$. The experimental data are taken from Ref. 1.

experiments (magnetic moments, spectra of anomalous-parity states, etc.): the strengths[9] ($g'_{N\Delta} = g'_{\Delta\Delta} = 0; g'_{NN} = 1$–$1.1$) and the strengths[10] ($g'_{NN} = g'_{N\Delta} = g'_{\Delta\Delta} = 0.78$–$1.04$ in the normalization of Ref. 9). We have accordingly carried out two series of calculations. The structure function of the pion, $F_{2\pi}(x)$, was taken from Ref. 11. The results of the calculations are extremely sensitive to the choice of the form factor Γ. The most systematic approach is to choose Γ in the form proposed in Ref. 7, where a series of experiments described by the exchange of a "reggeized" pion was analyzed. The reggeization leads, in particular, to an important dependence of Γ on the variable y.

Figures 2 and 3 show several versions of the calculations. We see that for both sets of parameters it is possible to explain a large part of the EMC effect over a broad x range by means of the pion mechanism. The pion mechanism is known[2] to intensify the quark sea in nuclei. It is easy to see that at small values of x the sea-intensification coefficient R_S will be equal to $R(x)$. Our calculation of $R(x)$ ignores surface effects and thus applies only to heavy nuclei. The value R_S $(x = 0.075) \simeq 1.10$–1.15 is consistent with data on iron [$R_S^{\text{exp}}(Fe/D) = 1.10 \pm 0.10 \pm 0.07$; Ref. 12]. The value $R_S^{\text{exp}}(Ne/D)$ is slightly lower, but the effect under consideration is weaker in that case. More-accurate measurements of R_S in heavy nuclei would constitute a critical test of the pion mechanism. The absence of sea intensification in heavy nuclei would impose serious limitations on the parameters of the effective nuclear forces.

In summary, although it is difficult at this point to carry out unambiguous calculations on the contribution of the pion mechanism to the EMC effect, this mechanism can explain either the entire effect or a large part of it without running into contradiction with the experimental data available from low-energy physics and without introducing any new parameters or, especially, any new mechanisms. At any rate, if the

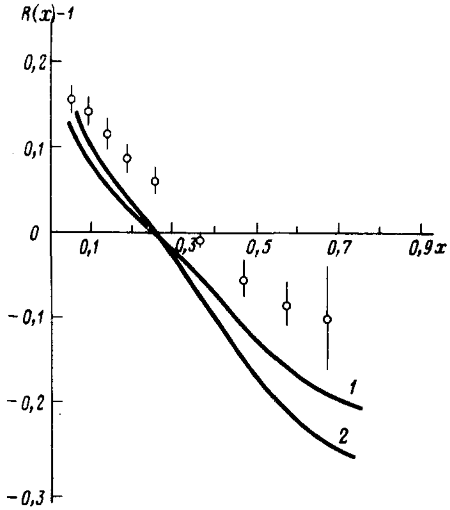

FIG. 3. The same as in Fig. 2, but for the strengths from Ref. 10. 1—$g' = 0.91$; 2—$g' = 0.78$.

pion mechanism does explain the rise at $x < 0.3$, then it also explains the dip at $x \simeq 0.5$–0.7.

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[1)]Berger *et al.*[6] used expression (4) for a nucleon in a nucleus. Here F_{2N}^0 is understood as the structure function of the free nucleon, while $f_\pi(y)$ is understood as the y distribution of the pion "excess" in the nucleus. A variational theory of nuclear matter—ill-suited for describing the softening of a pion mode in a nucleus—was used to calculate this excess.

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