Flucton model with a deviation from scaling: the EMC effect and the production of lepton pairs at nuclei

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The EMC effect is explained in a model of fluctons as a consequence of a breaking of scalar invariance. A nontrivial behavior is predicted for the ratio of structure functions and of the cross sections for the production of lepton pairs for various nuclei at $x > 1$.

Recent studies of the cumulative effect[1] and of deep inelastic scattering of leptons by nuclei[2] have revealed important differences in the structure functions of nuclei and free nucleons. The nuclei turn out to be enriched with soft partons with $x \ll 1$ (the EMC effect)[3] also to contain hard partons with $x > 1$, which cannot be present in free nucleons. Many models have been proposed to explain these results (see Ref. 4, for example), and most of these models[2)] describe the experimental data either at $x \ll 1$ or at $x \simeq 1$. In the present letter we show that the structure functions of nuclei can be described in a common way over a broad range of x on the basis of the flucton model[7,8] with allowance for the quantum-chromodynamics evolution of the quark distributions.

The basic ideas and the formalism of the flucton model can be found in the reviews by Baldin[1] and Efremov,[8] among other places. In this model the structure function of a nucleus can be represented as follows:

$$\frac{1}{A} F_2^A(x) = \sum_{k=1}^{A} \frac{k}{A} P(k,A)\, x \left[\frac{A+3Z}{9A} \tilde{u}_k\left(\frac{x}{k}\right) + \frac{4A-3Z}{9A} \tilde{d}_k\left(\frac{x}{k}\right) + \frac{4}{3} \tilde{s}_k\left(\frac{x}{k}\right) \right] . \quad (1)$$

Here $x = Q^2/2m_N \nu$ is the Bjorken variable; A and k are the numbers of nucleons in the nucleus and in the flucton; Z is the atomic number; $\tilde{u}_k$, $\tilde{d}_k$, and $\tilde{s}_k$ are the distributions of the u, d, and s quarks in the flucton; and $P(k,A)$ is the probability for the formation of a flucton consisting of k nucleons in a nucleus. In the model of a low-density nucleon gas we would have

$$P(k,A) \simeq \frac{A\,!}{k\,!\,(A-k)!} \left(\frac{\rho_0}{A}\right)^{k-1} , \quad (2)$$

where $\rho_0 = (R_c'/r_0)^3 \simeq 0.1$, $r_0 = R_A/A^{1/3}$, and R_c' is the coherence radius.

We consider a deviation from scaling in calculating the structure functions. We parametrize the corresponding Q dependence of the quark distributions in the following form[9]:

$$q(x, Q^2) = q(x, Q_0^2)(Q^2/Q_0^2)^{f(x)}, \quad f(x) = 0{,}25 - x. \tag{3}$$

The scale factor Q_0^2 in (3), which determines the evolution of the parton distributions, depends on the scale dimensions (R_c) of the propagation region of the color degrees of freedom, and this scale factor can be expected to differ for different nuclei.[10] Accordingly, the quark distributions q_N^A for the nucleons making up different nuclei must be compared for different values of Q^2; i.e.,

$$q_N^{A_i}(x, Q_i^2) = q_N^{A_j}(x, Q_j^2) = q_N(x, Q^2), \tag{4}$$

or, in view of (3),

$$q_N^{A_i}(x, Q^2) = q_N(x, Q^2)(Q^2/Q_i^2)^{f(x)}, \tag{5}$$

where the functions q_N are the structure functions of the free nucleon. In numerical calculations we use the following parametrization of q_N:

$$u(x) = \frac{2,25}{\sqrt{x}}(1-x)^3, \; d(x) = \frac{1,23}{\sqrt{x}}(1-x)^4, \; s(x) = \frac{0{,}25}{x}(1-x)^7. \tag{6}$$

It is quite obvious that in the flucton model the radius R_c is determined by the average number of nucleons per flucton in the nucleus, $\langle k \rangle$:

$$\langle k \rangle_A = \sum_{k=1}^{A} kP(k, A) / \sum_{k=1}^{A} P(k, A). \tag{7}$$

We can thus write

$$\frac{Q_i^2}{Q_j^2} \simeq \left(\frac{\langle k \rangle_{A_j}}{\langle k \rangle_{A_i}} \right)^{2\lambda/3}, \tag{8}$$

where we treat the index

$$\lambda \simeq \alpha_s(R_j^{-2}) / \alpha_s(Q_j^2) \tag{9}$$

as the sole adjustable parameter of the model.

For comparison with experimental data,[2,3] we use (1)–(9) to calculate the ratio

$$R(A_2, A_1) = \frac{A_2^{-1} F_2^{A_2}(x)}{A_1^{-1} F_1^{A_1}(x)} \tag{10}$$

for $A_2 = \text{Fe}$ and $A_1 = \text{D}$. As usual, we assume

$$q_N^D(x, Q_D^2) \simeq q_N(x, Q_D^2) = q_N(x).$$

It can be seen from Fig. 1a that the model with $\lambda = 35.36$ and $Q_D^2/Q_{Fe}^2 = 1.8$ gives a good description of the data at $x < 1$ and predicts a nontrivial behavior $R(x)$ at $x > 1$

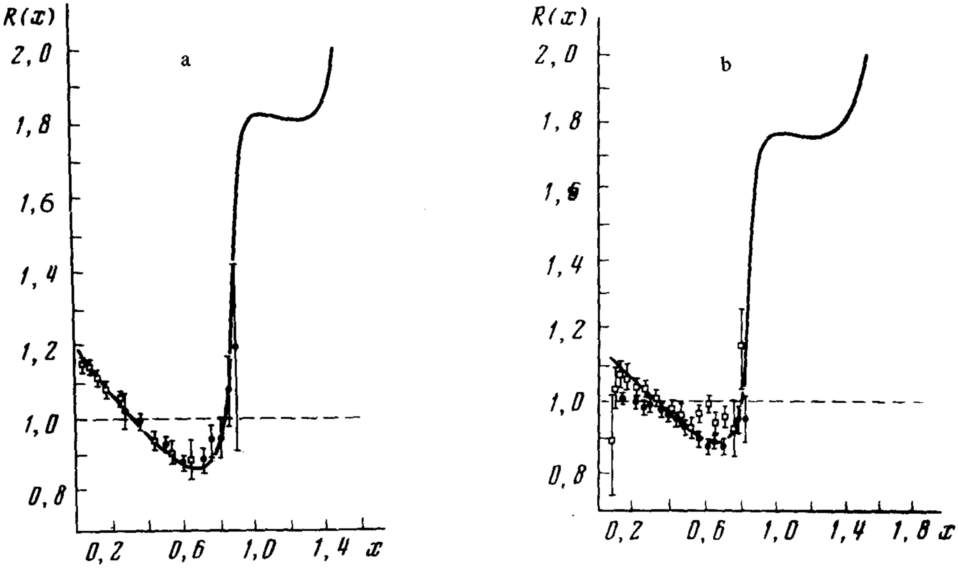

FIG. 1. a—Ratio of the structure functions of Fe and D nuclei calculated for $\rho_0 = 0.1$ ($R_c = 0.56$ fm, $r_0 = 1.2$ fm) and $Q_{\rm D}^2/Q_{\rm Fe}^2 = 1.8$ (the experimental data are from Refs. 2 and 3); b—predicted ratio of the structure functions of Al and D nuclei (experimental data from Refs. 2 and 3).

which is analogous to the EMC effect but which corresponds to the "cumulative region" $1 < x < 2$. Similar "steps" are evidently predicted by this model at higher values of $x(>2)$ for the ratio $R\,(A_2,A_1)$ with $A_2,A_1 > 2$. Here the admixture of many-nucleon states, $\epsilon_k^A = f_k^A / f_1^A (f_k^A = (k/A) P(k,A))$, is $\epsilon_2^{\rm Fe} \simeq 10\%$, $\epsilon_3^{\rm Fe} \simeq 0.5\%$, $\epsilon_4^{\rm Fe} \simeq 0.015\%$, $\epsilon_2^{\rm D} \simeq 5\%$. Using the value found for the parameter λ by fitting (8) and (9) to the experimental data on R (Fe,D), and using the Q^2 dependence of the structure functions in (5), we predict the behavior of R (Al,D) shown in Fig. 1b. This behavior agrees well with experimental data[2] (except at $x \simeq 0$, where screening, which we have ignored—may be having effects). This model thus directly reproduces the softening of the distributions

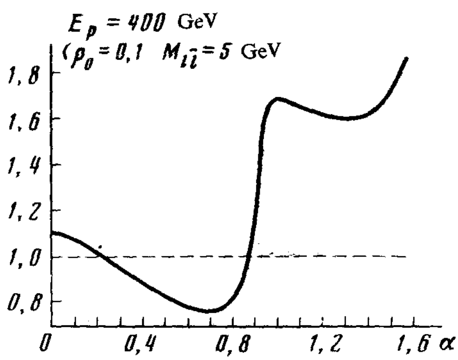

FIG. 2. Predicted ratio of the cross sections for the production of lepton pairs at Fe and D nuclei at $E_p = 400$ GeV and $M_{l\bar{l}} = 5$ GeV.

of partons in quarks from those in free nucleons and reproduces the presence of partons at $x > 1$.

Working in a similar way in this model, we can calculate the cross section for the production of massive lepton pairs at various nuclei. Figure 2 shows results calculated for the ratio $R'(\alpha) = \frac{1}{56}\frac{d\sigma}{d\alpha}(p\,\mathrm{Fe}\to l\bar{l}X)/\frac{1}{2}\frac{d\sigma}{d\alpha}(pD\to l\bar{l}X)$; they show that the behavior of R' is very similar to that of $R(x)$. Measurements of R' over a broad range of α for various sets of nuclei would provide additional information important for studying the quark distributions in nuclei and for deciding among the various theoretical models.

Dias de Deus *et al.*[11] have used a similar approach, based on the quantum-chromodynamics evolution of quark distributions, to describe the EMC effect. However, the concept of an "average" cluster in a nucleus which they use does not make it possible to predict a nontrivial behavior of the ratios $R(x)$ and $R'(\alpha)$ in the cumulative region, and in this regard their treatment is precisely the same as in models with an additional $q\bar{q}$ sea[5] or a $12q$ cluster.[6]

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[2)]References 5 and 6 are exceptional cases, but an additional "collective" sea of $q\bar{q}$ pairs is explicitly introduced in the structure function of the flucton to describe the EMC effect in Ref. 5, while in Ref. 6 an admixture of a $12q$ cluster is introduced; it thus becomes necessary to carry out a further parametrization of the structure functions.

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