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Dependence of the European Muon Collaboration effect on nuclear structure

S. Kumano*
Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996; Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831; and Nuclear Theory Center, Indiana University, Bloomington, Indiana 47408

F. E. Close
Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996 and Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
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We investigate a dependence of the "old" European Muon Collaboration (EMC) effect on nuclear structure, namely the dependence on the location of the struck quark within a nucleus ("local" EMC effect). The EMC effect is examined by the rescaling model and also by the nuclear binding model. We find that they give similar results in the sense that scattering from a central or deeply bound constituent gives a larger EMC effect than scattering from a surface or weakly bound constituent. If accurate experimental data become available, these interesting effects could be investigated in detail.

The "old" European Muon Collaboration (EMC) effect is the experimental finding that the quark momentum distributions in nuclei differ from those in free nucleons.[1] This effect has been an interesting topic for several years because it would be a first quark signature in nuclear physics.[2,3]

Models that attempt to interpret the experimental results can be classified into two categories: The first emphasizes explicit quark effects and the second is a more conservative view based on nuclear physics. The first category, the rescaling model,[4,5] suggested that the effective confinement size for quarks in nuclei is larger than that in the isolated nucleon,[6-8] because two nucleons overlap each other in a nucleus. Then, the EMC effect could be explained by a simple Q^2 rescaling. Although the rescaling idea is probably too simple to confront many details of nuclear physics,[9,10] it is nonetheless a useful effective model to incorporate a nucleon substructure effect into the structure function. Rescaling emphasizes the short distance physics, while the second type of model emphasizes the long distance physics, concentrating explicitly on nuclear physics. These second types of models are pion-excess models[11,12] and nuclear binding models.[13-15] In the binding models, the Compton amplitude for a nucleus is the Compton amplitude for the nucleon folded with the momentum distribution of the nucleons in the nucleus. Then, we find that the nuclear binding mechanism provides the medium-x region depression. If we use a density-dependent Hartree-Fock model, the binding model explains only 20% of the observed EMC effect.[15] However, short-range correlations populate the region above the Fermi sea, and much of the observed EMC effect could be explained by the binding mechanism.[16,17]

At the present time, most discussion has concentrated on the EMC effect averaged over an entire nucleus (we shall refer to this as the "global" EMC effect), as the EMC data do not identify where in the nucleus the struck quark resided. However, it may be possible[18,19] to learn this in more refined experiments and measure interesting "central" and "surface" EMC effects, which we shall call "local" EMC effects.

With this in mind, we apply these models to see how sensitive the local dependence is. It turns out that the models give similar predictions and hence are unlikely to be distinguished by such data. However, this similarity gives confidence that the local dependence is reliably predicted and thus provides a benchmark for planning experiments. Of course, it would be interesting if subsequent data did *not* show these effects.

We now discuss in detail how we extract the "local" dependence from these models. The effective confinement radius in a nucleus is calculated by the two-nucleon overlap probability in the nucleus in the rescaling model. Extending this idea to surface and central constituents, we can expect that the confinement radius for the central quark is larger than that for the surface because the two-nucleon overlap probability is larger in the central region. On the other hand, the explanation by the binding model for this kind of effect is clear:[20] In medium size nuclei ($A\sim20$), the binding energy for a central (or deeply bound) nucleon is about 40 MeV and that for a surface (or weakly bound) nucleon is about 5 MeV; therefore, the EMC effect is much larger for the central nucleon than that for the surface nucleon.

In nuclear physics, we can investigate the momentum distribution (which varies with binding) of a nucleon bound in a nucleus by the $(e,e'p)$ experiment. In the same way, it is possible that the EMC effect varies with the initial conditions of the struck nucleon (or quark), depending on how strongly it is bound or where it is located. The E745 experiment[18,19] has measured dark track events associated with high-energy neutrino interactions. Since the dark tracks are associated with neutrino interactions with the central (or deeply bound) nucleons, it is an experiment of this kind even though it is an inclusive experiment. At the present time, it provides a unique chance to investigate the local EMC effect. In their experiment, the target is the freon liquid which is a mixture of R116,C_2F_6 (27% by weight) and R115, C_2ClF_5 (73%). The ratio of atoms, $^{12}C:^{19}F:^{35}Cl$, is 0.16:0.67:0.17 (in the event rate) and the average A is 20.7, so that the target nucleus approximates ^{19}F. Throughout the theoretical investigation presented here, we simply assume that the target nucleus is ^{19}F.

We analyze the local EMC effects by two different models, the rescaling model and the nuclear binding model. We do not pass judgement on these models but take them as defined in the literature and then study their local dependences. According to the rescaling model, an effective confinement scale of quark changes when it is located inside a nucleus. Then, in the framework of perturbative QCD this scale change is manifested by a Q^2 rescaling of the nucleon structure function which relates it to the nuclear structure function at intermediate x as follows:

$$F_2^A(x,Q^2)=F_2^N(x,\xi_A(Q^2)Q^2) , \tag{1}$$

where $\xi_A(Q^2)$ is the rescaling parameter given by the confinement size (λ_A) and the running coupling constant $[\alpha_s(Q^2)]$:

$$\xi_A(Q^2)=\left[\frac{\lambda_A^2}{\lambda_N^2}\right]^{\alpha_s(\mu_A^2)/\alpha_s(Q^2)} , \tag{2}$$

where the running coupling constant ratio is

$$\frac{\alpha_s(\mu_A^2)}{\alpha_s(Q^2)}=\frac{\ln(Q^2/\Lambda_{\rm QCD}^2)}{\ln(\mu_A^2/\Lambda_{\rm QCD}^2)} . \tag{3}$$

In this work, $\Lambda_{\rm QCD}=0.25$ GeV and $\mu_A^2=0.66$ GeV^2 are used.[21] The effective confinement size is estimated by the overlapping volume (V_A) as $\lambda_A/\lambda_N=1+V_A(2^{1/3}-1)$. The overlapping volume for the ith nucleon with the rest of the nucleons is

$$V_A^i=(A-1)\int d^3r_1d^3r_2\rho_i(\mathbf{r}_1)\rho_{A-i}(\mathbf{r}_2)F_c(|\mathbf{r}_1-\mathbf{r}_2|)V_0(|\mathbf{r}_1-\mathbf{r}_2|) , \tag{4}$$

where both ρ_i and ρ_{A-i} are normalized to 1, and the two-nucleon correlation function, $F_c(r_{12})$, is simply taken as that by the Fermi gas model with $k_F=250$ MeV. (It has been shown that other models for this correlation function change the results very little.[5]) The two-nucleon overlapping volume (V_0) measured in the unit of the nucleon volume is

$$V_0(r)=\begin{cases}\left[1-\frac{3}{4}\left[\frac{r}{r_0}\right]+\frac{1}{16}\left[\frac{r}{r_0}\right]^3\right], & r\le 2r_0;\\ 0, & r>2r_0,\end{cases} \tag{5}$$

where r_0 is given by the rms radius of the nucleon ($r_{\rm rms}=0.9$ fm) as $r_0=\sqrt{\frac{5}{3}}r_{\rm rms}$.

We also investigate the local EMC effect in the nuclear binding model. According to this model,[13-15] the EMC effect in the medium–large-x region could be explained solely by the nuclear binding mechanism. If we apply the idea of nuclear binding to a single nucleon (nucleon in orbital i), then the nuclear Compton amplitude is the nucleon Compton amplitude folded with the momentum distribution of the nucleon inside the nucleus:

$$W_{\mu\nu}^{A(i)}(p_A,q)=\int d^4p\, S_i(p)W_{\mu\nu}^N(p,q) . \tag{6}$$

The spectral function in a simple shell model is given by

$$S_i(p)=|\phi_i(\mathbf{p})|^2\delta[p_0-m_N-\varepsilon_i+\mathbf{p}^2/(2M_{A-i})] . \tag{7}$$

Projecting out the structure function $F_2^{A(i)}(x,Q^2)$ from Eq. (6), we obtain[3,15,22]

$$F_2^{A(i)}(x,Q^2)=\int d^3p|\phi_i(\mathbf{p})|^2zF_2^N\left[\frac{x}{z},Q^2\right] , \tag{8}$$

where z is defined by $z=(p\cdot q)/(m_Nq^0)\rightarrow(p_0+p_z)/m_N$, and $\phi(\mathbf{p})$ is normalized by the baryon number sum rule, $\int d^3p\, z|\phi_i(\mathbf{p})|^2=1$. In order to evaluate the above structure function, we need a reasonable nuclear model for the ^{19}F nucleus. As a reasonable model to reproduce gross properties of nuclei, we choose the density-dependent Hartree-Fock (HF) method developed by Bonche, Koonin, and Negele (BKN).[23] By this model, we obtain the binding energy and the rms radius for ^{19}F as $B=147$ MeV and $r_{\rm rms}=2.76$ fm, which agree with the experimental values,[24,25] $B=147.801$ MeV and $r_{\rm rms}=2.86$ fm. The single-particle energies for neutrons in the BKN model are $\varepsilon_n(1s)=-31.6$ MeV, $\varepsilon_n(1p)=-18.9$, and $\varepsilon_n(1d)=-5.4$ (we neglect the small occupation probability of the 2s level). The removal energies are slightly different from the HF single-particle energies because of the rearrangement term in the density-dependent theory. However, the differences are of the order of 3% in the BKN model, so that we simply use the HF single-particle energies in Eq. (7). This corresponds to the situation that wave functions of the other nucleons do not change[26] when a nucleon is removed from the nucleus. We notice that the above HF single-particle energies are slightly different to the energy levels indicated by the $(e,e'p)$ experiment. [For example, the $(e,e'p)$ experiment[27,28] indicates that the removal energy for the 1s level in ^{16}O is around 40 MeV.] However, the energy spread of the spectral function is too wide to determine exactly what the single-particle energy is for the 1s nucleon. Consequently, there are some theoretical ambiguities especially about the 1s nucleon single-particle energy. For example, the 1s level calculated in the relativistic Hartree by Horowitz and Serot[29] (HS) is smaller and it is -41.7 MeV even though other level energies [$\varepsilon_n(1p_{3/2})=-20.8$

MeV, $\varepsilon_n(1p_{1/2})=-12.5, \varepsilon_n(1d_{5/2})=-3.4$] roughly agree with the BKN results on the average. In order to show the ambiguities for the 1s level, results are shown by both BKN and HS models.

In Fig. 1, the EMC effects for each nucleon are shown by assuming that the struck nucleon is the neutron and the nuclear structure function is divided by the neutron structure function, which is taken from Ref. 30. In Eqs. (4) and (8), ρ_i is averaged over m_l (BKN case) or m_j (HS).

In both rescaling and binding models, the results show that the EMC effect is larger for the scattering from a central constituent (localized mainly in the interior) than that from a surface constituent. The EMC effect for the 1s in the HS model is larger than that in the BKN model. In the rescaling model, the local EMC effect could be explained as follows. The 1s nucleon overlap probability with other nucleons is larger than the 1d nucleon overlap and thus gives rise to a larger confinement radius for the 1s nucleon than that for the 1d nucleon. The resulting effective confinement radii in the BKN model are $\lambda_A(1s)/\lambda_N=1.14$, $\lambda_A(1p)/\lambda_N=1.11$, and $\lambda_A(1d)/\lambda_N=1.08$; hence, the confinement radius for a central quark is larger than that for a surface quark by approximately 6%. In the binding model, it is obvious that the medium-x region depression is larger for the 1s nucleon because the binding energy is larger. Another interesting piece of physics is that the nucleon Fermi motion is larger for a surface nucleon, for example, the rms momenta are $(\langle p^2\rangle)^{1/2}=210$ MeV (for 1d nucleon), 179 MeV (1p), and 135 MeV (1s). The effect of the Fermi motion is clearly shown in Fig. 1(b). Furthermore, calcu-

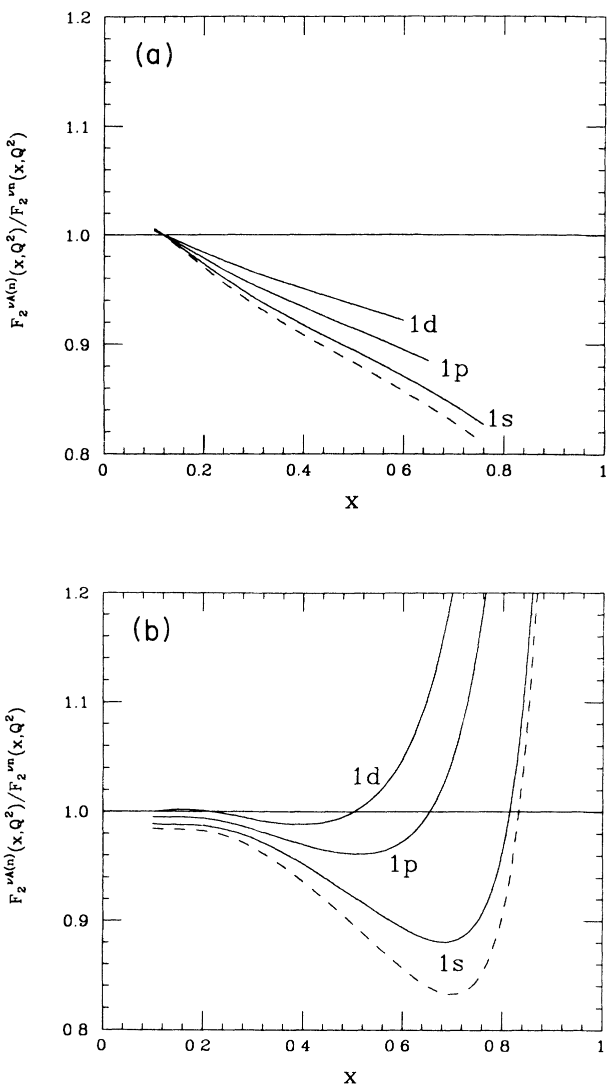

FIG. 1. Different EMC effects for each nucleon ("local" EMC effects) (a) by the rescaling model, and (b) by the binding model. Q^2 is taken as $Q^2=27$ GeV^2 Solid (dashed) curves are the results in the BKN (HS) model. Both results indicate that the EMC effect is larger for a central constituent than that for a surface constituent.

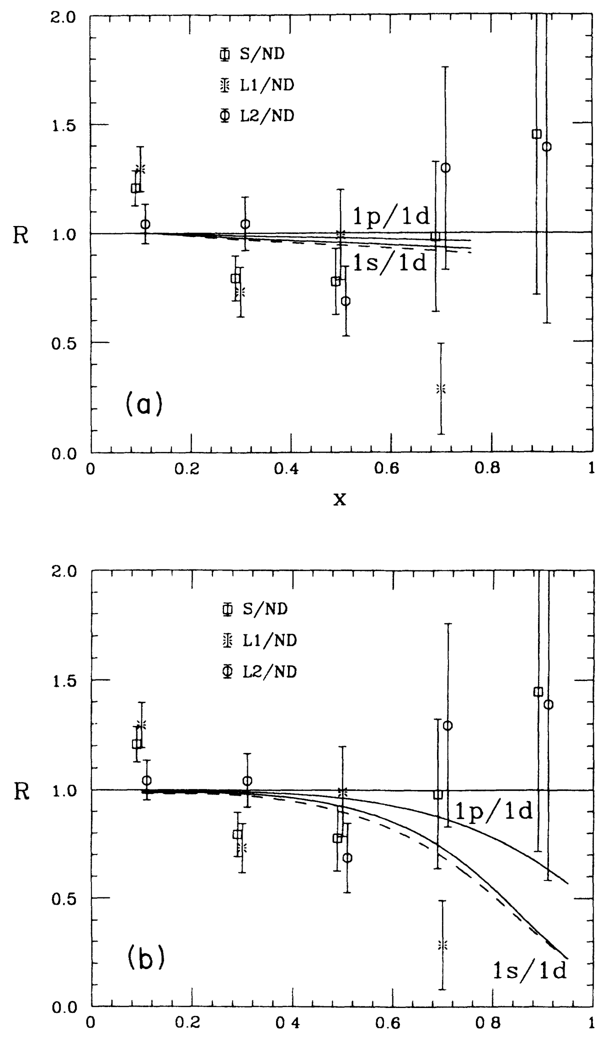

FIG. 2. E745 experimental data are compared with structure function ratios (a) by the rescaling model, and (b) by the binding model. Solid (dashed) curves are the results in the BKN (HS) model. See text for explanations of ND, S, $L1$, and $L2$ events.

lating $\langle p_z^2 \rangle$, we find that the Fermi motion in the z direction is larger for $m_l=0$ and becomes smaller as $|m_l|$ becomes larger. In Fig. 1(b), only the averages over m_l are shown.

In a recent report,[19] the E745 collaboration have classified their experimental results into four categories depending on the dark tracks they observe. The events without a dark track (ND) come from a neutrino interaction with quasifree nucleons. They observe short dark tracks (S) which are nuclear debris arising from the thermalization of the nucleus. A single long dark track ($L1$) should be a direct slow proton from the primary neutrino interaction with a central constituent. Events with multiple dark tracks with at least one long dark track ($L2$) are interpreted as a direct proton and protons due to hadron rescattering. The experimental results are shown by cross sections divided by that of no dark track event. Examining the density distributions of $1s, 1p, 1d$ levels, we can reasonably expect that the ND events correspond to the neutrino interaction mainly with the $1d$ nucleon and possibly also with the $1p$ nucleon. In order to present our results, we simply assume that the ND events correspond to the neutrino interaction with the $1d$ nucleon and show our results by $F_2(1s)/F_2(1d)$ and $F_2(1p)/F_2(1d)$ in Fig. 2. The rescaling model results shown in Fig. 2(a) indicate that the "EMC effect" is rather small compared with experimental results. On the other hand, the effect calculated by the binding model is larger and shows the same kind of feature as the $L1$ events. Even though the experiment is crude, it implies that the EMC effect for a central constituent is larger and our theoretical analyses in the rescaling and binding models support their experimental results. In the pion-excess model, similar results are expected if the pion excess in the central region is larger. In the future, if an exclusive experiment becomes available at SLAC, it will be possible to investigate more about the local EMC effects, and it may help to discriminate among different models.

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*Present address: Nuclear Theory Center, Indiana University, Bloomington, IN 47408

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