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# From constituent quark to current quark: Origin of the European Muon Collaboration effect

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We have shown the predictions of the constituent quark model for nuclei are consistent with the New Muon Collaboration data in the $x$, $Q^2$, and $A$ dependences of the European Muon Collaboration effect.

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Recently, the New Muon Collaboration (NMC) measured deep inelastic scattering (DIS) off nuclei and presented some interesting features in nuclear parton distributions [1]. We report here that the predictions of the constituent quark model for nuclei (CQMN) [2–4] are quantatively consistent with the NMC data.

The reason that we employ the constituent quark picture to analyze the distortions of quark distributions in nuclei [i.e., the European Muon Collaboration (EMC) effect] is based on the following consideration [2]: Although the EMC effect reveals itself with distortions of current quark distributions in nuclei, which are observed by the probe with high $Q^2$, it is mainly caused by the nuclear effect at the scale of low momentum on the wave functions involving the three constituent quarks. It is therefore convenient to study the EMC effect with a model relating to the nuclear quark structure on both large and small scales. The relation between current and constituent quarks can be established phenomenologically in a convolution form [5,6]

$$F_2^{N(A)}(x,Q^2)=\sum_c \int_x^{1(A)} dy\, G_c^{N(A)}(y) F_c^{N(A)}(x/y,Q^2)\ , \tag{1}$$

where $F_2^{N(A)}(x,Q^2)$ is the structure function of a free (bound) nucleon, and $G_c^{N(A)}(y)$ and $F_c^{N(A)}(z,Q^2)$ are the distribution of a constituent quark in a free (bound) nucleon and the structure function of a constituent quark, respectively. In Ref. [2] we extended its application to the case of a bound nucleon and retained the baryon-charge conservation

$$\int_0^1 G_c^N(y)dy=\int_0^A G_c^A(y)dy=1$$

and the momentum sum rule

$$\int_0^1 G_c^N(y)y\,dy=\int_0^A G_c^A(y)y\,dy=\tfrac{1}{3}\ .$$

In a nuclear surrounding there are two different modifications of parton distributions, which lead to $G_c^N(y)\neq G_c^A(y)$ and $F_c^N(z,Q^2)\neq F_c^A(z,Q^2)$, respectively: (1) The overlapping of a nucleon with the others around it reduces the confinement force between constituent quarks and gives rise to nucleon swelling. Therefore, the distribution $G_c^N(y)=105/16y^{1/2}(1-y)^2$ changes generally into

$$G_c^A=B^{-1}(\delta_A+\tfrac{3}{2})y^{\delta_A+1/2}(1-y)^{2(\delta_A+1)}\ ,$$

where $B$ is the Bessel function and $\delta_A$ is the distortion factor [2]. The relation between $\delta_A$ and nuclear mass number $A$ can be established in the following simple way. We define the dispersion of the distribution $G_c^{N(A)}$ as

$$D_{N(A)}\equiv(\langle G_c^{N(A)}\rangle_3-\langle G_c^{N(A)}\rangle_2^2)^{1/2}\ ,$$

where $\langle G\rangle_n$ is the $n$th moment of $G$. The dispersion will decrease ($D_A<D_n$) with the increase of the confinement scale of the constituent quark ($R_N\to R_N+\delta R_A$, $\delta R_A>0$) in a way consistent with the uncertainty principle. For $\delta R_A \ll R_N$ the value of $\delta_A$ can be estimated by

$$D_A/D_N=R_N/(R_N+\delta R_A)\ , \tag{2}$$

assuming that the swelling of a bound nucleon relates to the number of nucleons around it, i.e.,

$$\delta R_A/R_N=f(AV_N/V_A)=f(n_A V_N)\ ,$$

where $V_{N(A)}$ is the volume of a nucleon (nucleus) and $n_A$ is the nuclear density. If swelling is small, the right-hand part of the above equation can be linearized as $\delta R_A/R_N=\kappa n_A V_N$, in which $\kappa$ is a constant relating to the confinement force between constituent quarks. We take $\delta_A=0.27$ and $n_A=0.17\ \mathrm{fm}^{-3}$ for an inner nucleon in a middle-heavy nucleus as input and find $\kappa R_N^3=0.106$. The values of $\delta_A$ for different nuclei can be evaluated in Eq. (2) by using the nuclear surface effect [2], from which we get $\delta_A=0.005$, 0.070, 0.17, and 0.19 for $^2$D, $^6$Li, $^{12}$C, and $^{40}$Ca, respectively. We call the above-mentioned modifications combined with Fermi smearing the "nuclear global effect." (2) Another factor to distort the structure function of a bound nucleon is the recombination of wee partons in different nucleons under DIS condition, which violates the universality of the constituent quark, i.e., $F_c^N(z,Q^2)\neq F_c^A(z,Q^2)$. This effect corresponds to the shadowing and antishadowing in the left-hand side of Eq. (1) and is called the "nuclear local effect." In Refs. [3] and [4] we have developed the partonic shadowing theory, in which shadowing and antishadowing would merge in a natural phenomenological way. We would like to point out here the differences of the CQMN from other shadowing models [7]. In the CQMN shadowing is caused by the correlation among wee partons, while antishadowing coexists with shadowing in all small-$x$ regions [3]. On the other hand, both the $Q^2$- dependence of the shadowing strength and the momentum loss due to the annihilation of the shadowed sea quarks will reduce shadowing and antishadowing. As a consequence, the distribution of sea quarks in a bound nucleon will become

$$F_s^A(0,Q^2)=F_{s_0}^A(0,Q^2)[1-n_s K_s(Q^2)] ,$$

when $x$ approaches zero, where $F_{s_0}^A(z,Q^2)$ is the distribution of sea quarks neglecting shadowing, $k_s(Q^2)$ is the shadowing strength, and $n_s$ is the average number of shadowed nucleons. For a middle-heavy nucleus, $n_s \approx A^{1/3}-1$, and for a light nucleus, one can use geometric consideration; thus we obtain $n_s=0.02$, 0.75, 1.29, and 2.42 for $^2$D, $^6$Li, $^{12}$C, and $^{40}$Ca, respectively [3]. In the deuteron only the nucleon inside the cubic angle $\Delta\Omega=\pi R_N^2/R_D^2$ is possible to shadow the other nucleon, $R_D$ being the deuteron radius. It is natural to expect that the EMC effect in deuterons can be neglected.

Now let us discuss the results from the CQMN and compare them with the NMC data of Ref. [1]. In the first step of our analysis, we neglect the shadowing effect. In such case the constituent quark will keep its universality: $F_c^N(z,Q^2)=F_c^A(z,Q^2)$. One can see that the ratio of structure functions $R=F_2^A(x,Q^2)/F_2^D(x,Q^2)$ will be restricted to the neighborhood of unity as $x$ approaches zero as long as baryon-charge conservation is considered. This conclusion is independent of the concrete forms of $G_c^{N(A)}$ and $F_c^{N(A)}$. Furthermore, from the momentum sum rule we have $\langle F_v^A(Q^2)\rangle_2=\langle F_v^N(Q^2)\rangle_2$, where $v$ indicates the valence quark distribution in the structure function. It means that the slight enhancement of $R$ ($\sim 1.02$) around $x \sim 0.15$ is caused by momentum compensation of the valence quark for its momentum loss in the region $x>0.3$. Calculation shows that the sea quark in the small-$x$ region does not increase [2]. The flat behavior of the ratio $R$ in the small-$x$ region ($x<0.3$), which is caused by the nuclear global effect, provides an ideal background for describing nuclear shadowing.

As shown in Ref. [3], the point $x_c$, on which the ratio $R$ cross unity, will move with $A$. This is caused by the coexistence of shadowing and antishadowing. Antishadowing makes the ratio $R$ increase more rapidly with the increase of $x$. As a consequence, the weaker the shadowing is, the smaller the values of $n_s$ and $x_c$.

In Ref. [4] we have pointed out that shadowing and antishadowing will be somewhat suppressed with the increase of $Q^2$. Moreover, when $Q^2>40$ GeV$^2$ antishadowing would disappear in the region $0.1<x<0.3$ and only the nuclear global effect relating to the nuclear density $n_A$ would remain. On the contrary, when $Q^2$ is low ($Q^2 \ll 10$ GeV$^2$), a large part of the contribution to the ratio $R$ in the region $0.1<x<0.3$ comes from antishadowing which relates to $n_s$. In the NMC data [1] the values of $Q^2$ (1–40 GeV$^2$) are significantly higher than that of the EMC data ($\sim 1$ GeV$^2$) [8]. The results of C/D and Ca/D in the CQMN are displayed in Fig. 1 in which the dashed curve (for $Q^2=1$ GeV$^2$) fits the EMC data [8] (cf. Ref. [4], Fig. 4) and the solid curve (for $Q^2=40$ GeV$^2$) is close to the NMC data. It is shown that the prediction of the CQMN about scaling violations in the shadowing-antishadowing region is in agreement with the data. The NMC also measured the ratios of the structure functions at high $Q^2$ precisely for $^{12}$C/$^6$Li (different nuclear densi-

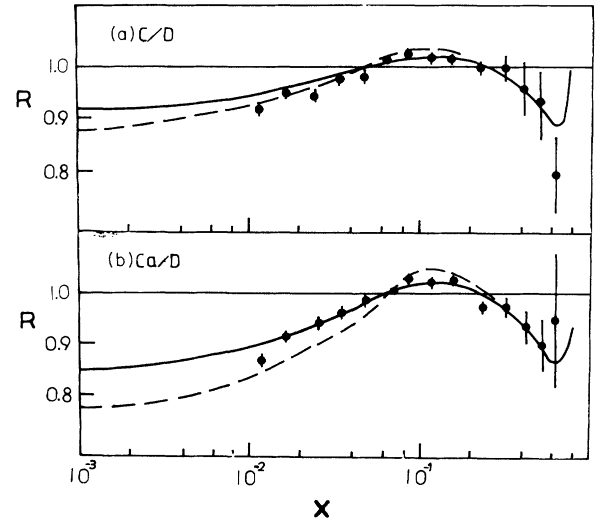


FIG. 1. (a) Structure function ratio $R=^{12}$C/D from the CQMN is compared with the NMC data of Ref. [1]: solid curve, $Q^2=40$ GeV$^2$; dashed curve, $Q^2=1$ GeV$^2$. (b) Analog of (a), but for the ratio $R=^{40}$Ca/D.

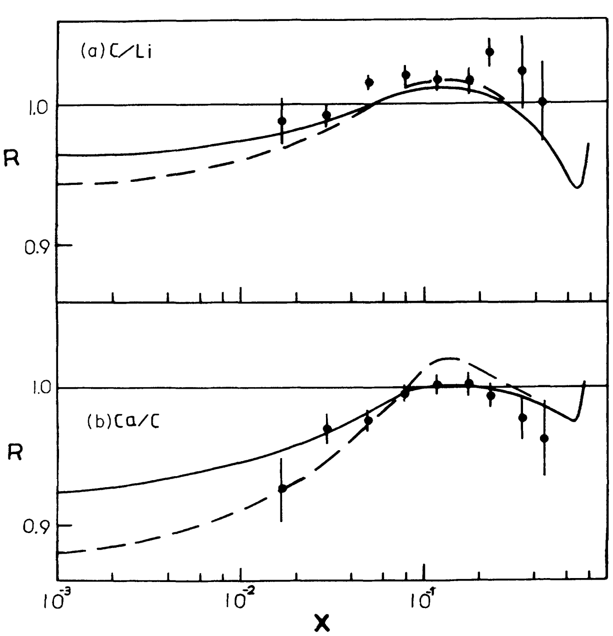


FIG. 2. Analog of Fig. 1, but (a) for the ratio $^{12}$C/ $^6$Li and (b) for the ratio $^{40}$Ca/$^{12}$C.

ties) and $^{40}Ca/^{12}C$ (similar nuclear densities). The results from the CQMN are displayed in Fig. 2 with the solid curve for $Q^2=40$ GeV$^2$ and the dashed one for $Q^2=1$ GeV$^2$. We can see that in the ratio C/Li with high $Q^2$ an extended enhancement exists in the intermediate-$x$ domain, while no enhancement appears in the ratio Ca/C. These results could be taken as verification that there is a correlation between the nuclear global effect and nuclear density as predicted by the CQMN.

To summarize, we have shown the consistency of the CQMN with the new NMC data. The influence of nuclear medium on the nucleon structure function can be considered as the distortion of constituent quark distribution and the violation of the universality of the structure function. The former one has nothing to do with $Q^2$, but relates to the nuclear density $n_A$. The latter relates to the $n_s$ of shadowed nucleon number and $Q^2$.

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