Evidence for Enhancement of Gluon and Valence-Quark Distributions in Nuclei from Hard Lepton-Nucleus Processes

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Current data on deep-inelastic processes off nuclei are analyzed by using exact QCD sum rules for the total momentum and baryon charge of nuclei. Evidence for an overall enhancement of the gluon field in heavy nuclei ($\geq 4\%$) is found which, combined with the calculation of nuclear shadowing, yields a substantial enhancement of valence-quark and gluon distributions at $x \approx 0.1$, as well as a suppression of the sea for $x \leq 0.1$. It is also shown that scaling violations lead to a strong decrease of shadowing for the sea at $x \approx 0.05$. Implications for disentangling the origin of internuclear forces are further discussed.

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The main aim of this Letter is to analyze the implications for the nuclear structure of current experimental results on parton distributions in nuclei at small values of x obtained both in deep-inelastic muon-nucleus scattering[1,2] and in the Drell-Yan process.[3] We show that valence-quark and gluon distributions in nuclei are enhanced at $x \approx 0.1$, namely, for the kinematics where essential longitudinal distances in deep-inelastic processes, l ($l \approx 1/2M_N x$ in the nucleus rest frame), are comparable with mean internucleon distances r_{NN}:

$$r_{NN} = 1.7\ \text{fm} > 1/2M_N x > r_N = 0.6\ \text{fm}\,, \tag{1}$$

r_N being the nucleon radius (the nontrivial relationship between the nucleus-rest-frame and the infinite-momentum-frame descriptions at small x is discussed at length in Ref. 4).

In the first step of our analysis we use only exact QCD sum rules for parton distributions in nuclei, while in the second step we add information from calculations of nuclear shadowing at small x.[4,5] The sum rules for the baryon-charge and total-momentum conservation in nucleus A may be written as

$$\int_0^A \frac{1}{A} V_A(x_A,Q^2)\,dx_A - \int_0^1 V_N(x,Q^2)\,dx = 0 \tag{2}$$

and

$$\int_0^A \frac{1}{A}[G_A(x_A,Q^2)+V_A(x_A,Q^2)+S_A(x_A,Q^2)]x_A\,dx_A - \int_0^1 [G_N(x,Q^2)+V_N(x,Q^2)+S_N(x,Q^2)]x\,dx = 0\,, \tag{3}$$

where V_A, G_A, S_A and V_N, G_N, S_N represent the valence, gluon, and sea parton distributions in nucleus A and in the free nucleon, respectively. Moreover, x is the usual Bjorken variable, whereas $x_A = AQ^2/2M_A q_0 = AM_N/M_A x$. Equations (2) and (3) are valid for $Q^2 \geq Q_0^2 \approx 1\text{-}2\ \text{GeV}^2$, where the parton model seems to be applicable.

Since, for an isoscalar target,

$$\frac{F_2^{A(N)}(x,Q^2)}{x} = \frac{5}{18}[V_{A(N)}(x,Q^2)+S_{A(N)}(x,Q^2)] - \frac{s_{A(N)}(x,Q^2)+\bar{s}_{A(N)}(x,Q^2)}{6} \tag{4}$$

[$s_{A(N)}$ ($\bar{s}_{A(N)}$) being the strange-quark (-antiquark) distribution] and, experimentally, $\int_0^1 G_N(x,Q^2)x\,dx \approx 0.5$, one can define (neglecting contributions from the charm sea which are very small for the values of Q^2 of interest)

$$\gamma_G^A = \frac{\int_0^A (1/A) G_A(x_A,Q^2) x_A\,dx_A}{\int_0^1 G_N(x,Q^2)x\,dx} - 1 \tag{5a}$$

or, equivalently,

$$\gamma_G^A \approx \frac{\int_0^1 F_2^N(x,Q^2)dx - \int_0^A (1/A) F_2^A(x_A,Q^2)dx_A}{\int_0^1 F_2^N(x,Q^2)dx} - \frac{6}{5}\,\frac{\int_0^A (1/A)\bar{s}_A(x_A,Q^2)x_A\,dx_A - \int_0^1 \bar{s}_N(x,Q^2)x\,dx}{\int_0^1 G_N(x,Q^2)x\,dx}\,. \tag{5b}$$

Equation (5b) can be calculated by using the New Muon Collaboration data[1] on the ratio between the second moments for F_2^A in ^{40}Ca and in the deuteron. By disregarding both the change of gluon momentum in the deuteron with respect to the free nucleon (i.e., by assuming $\gamma_G^A=0$ for $A=2\equiv\mathrm{D}$) and the possible change in the strange sea, we find for ^{40}Ca,

$$\gamma_G^A=(2.18\pm0.28\pm0.50)\% , \tag{6a}$$

$$\gamma_G^A=(2.31\pm0.35\pm0.39)\% , \tag{6b}$$

corresponding to Ref. 1(a) [Eq. (6a)] and Ref. 1(b) [Eq. (6b)], respectively.

Nevertheless, it is natural to expect that $\gamma_G^{\mathrm{D}}>0$, though much smaller than γ_G^A ($\gamma_G^{\mathrm{D}}/\gamma_G^A\approx\frac{1}{10}-\frac{1}{5}$ for $A=40$; cf. Ref. 4); moreover, accounting for the strange-quark term in Eq. (4) would somewhat increase the value of γ_G^A, provided the strange-sea distribution in nuclei has a dependence upon A similar to the one found for the nonstrange distribution (for the nonstrange sea, both deep-inelastic muon data[1,2] and Drell-Yan data[3] show a decrease with A of the momentum fraction). If the above corrections are taken into account, the value of γ_G^A [Eqs. (6)] is enhanced by 0.2%–0.7%.

γ_G^A should increase with A due to the increase of the mean nuclear density $\langle\rho_A\rangle$ with A. In fact, an enhancement of the gluon field in nuclei is likely to arise in the range $x>0.05$, where the gluon component of the virtual photon interacts mostly with two nucleons (see Ref. 5 and discussion below); thus for small nuclear densities, $\gamma_G^A\propto\langle\rho_A\rangle$, whereas in the case of nuclear matter (NM),

$$\gamma_G^{A\to\infty}\approx\gamma_G^A\rho_{\mathrm{NM}}/\langle\rho_A\rangle\approx4\% , \tag{7}$$

where ρ_{NM}, the nuclear-matter density, is taken equal to 0.17 fm^{-3}. Note that, due to scaling violations, γ_G^A decreases with increasing Q^2, mostly because of the anomalous dimension of the difference between the second moments of G_A and G_N which is equal to $\frac{50}{81}$. γ_G^A was evaluated in Eqs. (5)–(7) by using the experimental determination of the ratio between the second moments for F_2^A and F_2^N, corresponding to $Q^2\geq3$ GeV^2;[1] accounting for scaling violations thus leads to a 20% increase of γ_G^A at $Q_0^2\approx1$ GeV^2 (for $\Lambda=200$ MeV), with respect to the values given in Eqs. (6) and (7).

Therefore, we conclude that in the nonperturbative parton wave function for nuclear matter, the gluon field is enhanced by about 5%, whereas the momentum carried by charged partons is depleted by the same amount.

The second question we want to address concerns the value of x at which the enhancement of the gluon field is concentrated. In Ref. 5 it was demonstrated that shadowing of the soft component of the nuclear wave function is responsible for the nuclear shadowing of F_2^A which was observed in Refs. 1 and 2. Similarly, we expect shadowing of the gluon field $G_A(x,Q_0^2)$ to be of the same magnitude as for $F_2^A(x,Q_0^2)$, since the essential longitudinal distances for small x are practically equivalent in both the gluon and quark channels (cf. discussion in Ref. 4). Thus, one may write

$$\frac{G_A(x,Q_0^2)}{AG_N(x,Q_0^2)}\approx\frac{F_2^A(x,Q_0^2)}{AF_2^N(x,Q_0^2)}\Bigg|_{x<x_{\mathrm{sh}}=0.01-0.02} . \tag{8}$$

At the same time, the positive contribution to γ_G^A should arise from the region of relatively small x where both Eq. (1) and the requirement that the virtual-photon components can interact with two nucleons are satisfied ($x\leq0.15$). Thus, it is natural to expect the positive contribution to γ_G^A to be localized in the region $x_0<x<x_1$, where $x_0\approx0.05$ ($x>x_{\mathrm{sh}}$) and $x_1\leq0.15$. The mean value of the enhancement factor in this x range is given by

$$c_G(A)=\frac{\int_{x_0}^{x_1}[(1/A)G_A(x,Q_0^2)-G_N(x,Q_0^2)]x\,dx}{\int_{x_0}^{x_1}G_N(x,Q_0^2)x\,dx} . \tag{9}$$

For ^{40}Ca we find, based on the above value of γ_G^A, $c_G(A)=0.06$ when the negative contribution in Eq. (3) in the $x<x_0$ region is neglected, whereas $c_G(A)=0.10$ when such contribution is taken into account by using Eq. (8). The corresponding estimates for nuclear matter are $c_G(\mathrm{NM})=0.10$ and 0.20, respectively. Therefore, quite a significant gluon enhancement is expected for heavy nuclei at $x=0.1$ and $Q^2\approx Q_0^2$. As Q^2 increases, such an enhancement shifts to smaller values of x, due to scaling violations (see Fig. 1). In our calculations we neglect higher-twist corrections to the QCD evolution equations, since it was demonstrated in Ref. 6 that they lead to negligible corrections for the x and Q^2 range of interest in this Letter.

The enhancement of G_A in the range $x_0<x<x_1$ leads to a significant scaling violation for the sea distribution S_A at $x\simeq0.05$, for which shadowing was recently observed in the Drell-Yan process at $Q^2>16$ GeV^2 (note that the data of Ref. 3 refer to the $\bar u$ and $\bar d$ distributions only; therefore, in the following, S_A will represent the $\bar u$ and $\bar d$ contributions to the sea-quark distribution). By using QCD evolution equations and the above estimates of the gluon enhancement [Eqs. (7) and (8)],

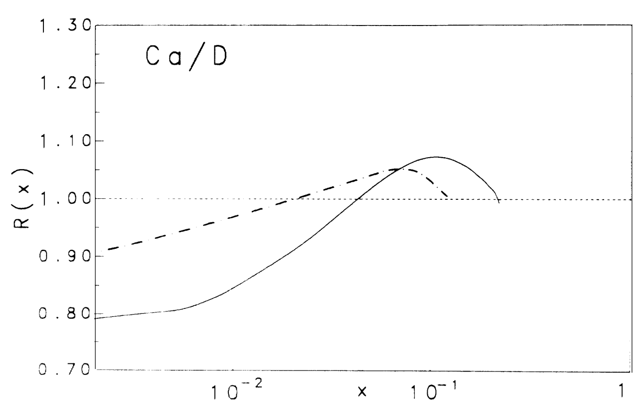

FIG. 1. Ratio $R\equiv R_G(x,Q^2)=(2/A)G_A(x,Q^2)/G_{\mathrm{D}}(x,Q^2)$ plotted vs x, for different values of Q^2: solid line, $Q^2=2$ GeV^2; dot-dashed line, $Q^2=15$ GeV^2.

we find that the difference $R_S(x,Q^2)-1 \equiv S_A(x,Q^2)/AS_N(x,Q^2)-1$, evaluated at $x=0.05$, increases by a factor of 2 as Q^2 varies between $Q^2=3$ and 25 GeV^2. In particular, if we use the QCD aligned-jet model (QAJM) of Refs. 4 and 5 (which is a QCD extension of the well-known parton logic of Bjorken) to calculate $R_S(x,Q^2)$, we find, in the case of ^{40}Ca, $R_S(x=0.04, Q^2=3\ \mathrm{GeV}^2)=0.9$ and $R_S(x=0.04, Q^2=25\ \mathrm{GeV}^2)=0.97$. The last number is in good agreement with Drell-Yan data[3] (see Fig. 2). Thus, we conclude that the small shadowing for S_A observed in Ref. 3 for $x \simeq 0.04$ and $Q^2>16\ \mathrm{GeV}^2$ corresponds to a much larger shadowing for $Q^2 \simeq Q_0^2$.

Shadowing in the sea-quark distribution at $x=0.04$ [$R_S(x=0.04, Q^2=3\ \mathrm{GeV}^2)=0.9$], combined with the experimental data for $F_2^A(x,Q^2)/AF_2^N(x,Q^2)$ at the same value of x [$F_2^A(x,Q^2)/AF_2^N(x,Q^2)>1$], unambiguously implies an enhancement of the valence quarks, i.e., $R_V(x,Q^2) \equiv V_A(x,Q^2)/AV_N(x,Q^2)>1$. For ^{40}Ca, $R_V(x=0.04\text{–}0.1,\ Q^2=3\ \mathrm{GeV}^2) \approx 1.1$, whereas for infinite nuclear matter, we find $R_V(x=0.04\text{–}0.1, Q^2=3\ \mathrm{GeV}^2) \geq 1.2$. By applying the baryon-charge sum rule [Eq. (2)], we conclude that experimental data require the presence of shadowing for valence quarks at small values of x [i.e., $R_V(x,Q^2)<1$ for $x_{\mathrm{sh}}<0.01\text{–}0.03$]. Moreover, the amount of shadowing for $R_V(x,Q^2)$ is about the same (somewhat larger) as the shadowing for the sea-quark channel (see Fig. 3). The overall change of the momentum carried by valence and sea quarks at $Q^2=1\ \mathrm{GeV}^2$ is

$$\gamma_V^A(Q_0^2)=1.3\%\,,\quad \gamma_S^A(Q_0^2)=-4.6\%\,.$$

To summarize, the present data are consistent with the parton-fusion scenario first suggested in Ref. 7: All parton distributions are shadowed at small x, while at larger x, only valence-quark and gluon distributions are enhanced. At the same time, other scenarios inspired by the now popular (see, e.g., Ref. 8) idea of parton fusion, which assume that the momentum fraction carried by sea quarks in a nucleus remains the same as in a free nucleon,[9] are hardly consistent with deep-inelastic and Drell-Yan data.

Let us briefly consider dynamical ideas that may be consistent with the emerging picture of the small-x ($x \leq 0.1$) parton structure of nuclei. In the nucleus rest frame the $x \approx 0.1$ region corresponds to a possibility for the virtual photon to interact with two nucleons which are at distances of about 1 fm [cf. Eq. (1)]. But at these distances quark and gluon distributions of different nucleons may overlap. So, in analogy with the pion model of the European Muon Collaboration effect, the natural interpretation of the observed enhancement of gluon and valence-quark distributions is that intermediate-range internucleon forces are a result of interchange of quarks and gluons. Within such a model, screening of the color charge of quarks and gluons would prevent any significant enhancement of the meson field in nuclei. Such a picture of internucleon forces does not necessarily contradict the experience of nuclear physics. Really, in the low-energy processes where quark and gluon degrees of freedom cannot be excited, the exchange of quarks (gluons) between nucleons is equivalent, within the dispersion representation over the momentum transfer, to the exchange of a group of a few mesons. Another

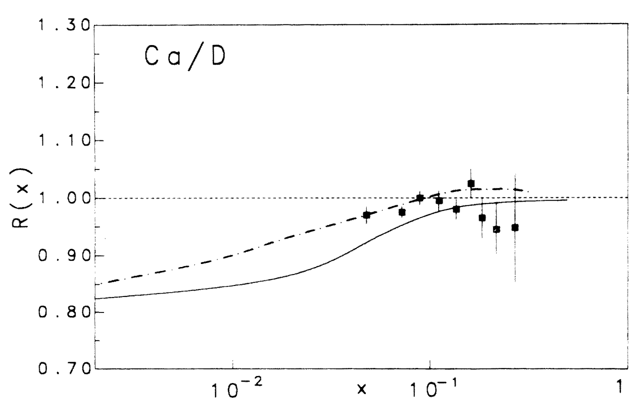

FIG. 2. Ratio $R=(2/A)\bar{u}_A(x,Q^2)/\bar{u}_D(x,Q^2)$ plotted vs x, for different values of Q^2. Notations as in Fig. 1. Experimental data from Ref. 3.

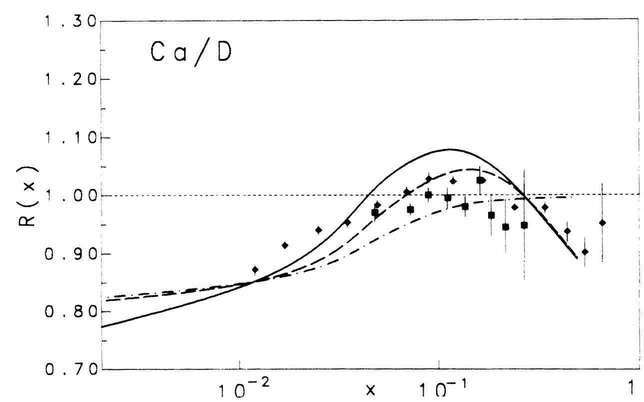

FIG. 3. Ratios $R(x,Q_0^2)=(2/A)F_2^A(x,Q_0^2)/F_2^D(x,Q_0^2)$ (dashed line), $R \equiv R_V(x,Q_0^2)=(2/A)V_A(x,Q_0^2)/V_D(x,Q_0^2)$ (solid line), and $R \equiv R_S(x,Q_0^2)=(2/A)S_A(x,Q_0^2)/S_D(x,Q_0^2)$ (dot-dashed line) in ^{40}Ca. All curves have been obtained at $Q_0^2=2\ \mathrm{GeV}^2$. The low-x behavior ($x \leq x_{\mathrm{sh}}$) corresponds to the predictions of the QAJM of Refs. 4 and 5; the antishadowing pattern (i.e., a 10% enhancement in the valence channel whereas no enhancement in the sea, leading to a less than 5% increase of F_2^A at $x \approx 0.1\text{–}0.2$) has been evaluated within the present approach by requiring that sum rules (2) and (3) are satisfied. Experimental data are from Ref. 1 (diamonds) and Ref. 3 (squares), the latter representing the sea-quark ratio R_S (cf. Fig. 2). The theoretical curves are located below the data at small x, due to the high experimental values of Q^2: $\langle Q^2\rangle = 14.5\ \mathrm{GeV}^2$ in Ref. 1 and $\langle Q^2\rangle = 16\ \mathrm{GeV}^2$ in Ref. 3, respectively.

(the same?) option is that the discussed change of parton distributions is a consequence of the difference between structure functions of bound and free nucleons. Both options suggest "melting" of nucleon degrees of freedom with the increase of the nucleon density, i.e., the tendency to a phase transition in superdense nuclear matter. It is also worth emphasizing that the comparatively large ($\geq 20\%$) enhancement deduced above of valence quarks and gluons in infinite nuclear matter for $x \approx 0.1$ should lead to a comparable change of some bound-nucleon properties, for example, to a change of bound-nucleon elastic form factors at intermediate Q^2 (though not to a noticeable change of the radii or to large-Q^2 asymptotic behavior). Obviously, even larger effects of the same kind may be expected in the cores of neutron stars.

It seems necessary, therefore, to perform further experimental studies of parton distributions in nuclei aimed at a direct determination of the A dependence of the valence-quark and gluon distributions at small values of x, which could be obtained from μ-$\bar{\mu}$ pair production in πA scattering, by carefully analyzing final states in μA scattering, the A dependence of σ_L/σ_T, etc. (see the list of suggestions given in Ref. 4). Another interesting opportunity would be the comparison of hard processes in peripheral and central high-energy heavy-ion collisions at BNL Relativistic Heavy Ion Collider energies, which would allow a direct measurement of the parton structure of nuclear matter.

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