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Gluon EMC Effects in Nuclear Matter

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We investigate the gluonic structure of nuclei within a mean-field model of nuclear structure based upon the self-consistent modification of the structure of a bound nucleon, with the nucleon described by the Nambu–Jona-Lasinio model. This approach has been shown to reproduce the European Muon Collaboration (EMC) effect, involving the ratio of the spin-independent structure functions of a heavier nucleus to that of the deuteron. It also predicts a significant nuclear modification for the spin structure functions, known as the polarized EMC effect. Here we report sizeable nuclear modifications of the gluon distributions (a "gluon EMC effect") for the ratios of both the unpolarized and polarized gluon distributions in nuclear matter to those of a free nucleon.

I. INTRODUCTION

The European Muon Collaboration (EMC) effect [1–4]—which refers to the observation that the ratios of the spin-independent structure functions of heavier nuclei to that of the deuteron $[F_{2A}(x)/F_{2D}(x)]$ differ substantially from unity in the valence region—is still one of the most challenging topics in modern nuclear physics. It has triggered numerous experimental and theoretical investigations into dynamical mechanisms that might potentially generate the EMC effect. However, it has now become clear that a quantitative description of the EMC effect requires a change in the internal structure of the nucleons [5–8] bound within nuclei.

Here we shall be concerned with one particular approach to nuclear structure, based upon the self-consistent modification of the structure of the bound nucleons by the scalar and vector mean-fields in nuclei. The first model within which this idea was applied to nuclear structure was the quark meson coupling (QMC) model [9–12], which was used to calculate the EMC effect soon after its discovery [13]. While that initial work was based upon the MIT bag model [14], more recently, using an analogous approach, a theory of nuclear structure based upon the Nambu-Jona-Lasinio (NJL) model [15, 16] has been developed [17, 18]. This model exhibits similar properties to the QMC model, with the advantage that it is completely covariant. Having demonstrated that it yields an excellent description of both the spin-independent and spin-dependent parton distributions of the nucleon [19], the model was then applied to investigate nuclear medium modifications to structure functions, successfully reproducing the unpolarized EMC data across the periodic table [20–22]. This framework was also extended to the spin-dependent case, predicting a significant effect in the ratio of polarized structure functions, $g_{1A}(x)/g_{1p}(x)$, for nuclei where the spin is largely carried by the protons and in nuclear matter [20, 23].

While the EMC effects associated with the quark content of nuclei have been investigated extensively, there have been very few experimental and theoretical studies of the nuclear modification of the gluon distribution or "gluon EMC effect". Indeed, the only experimental indication of the behaviour of nuclear gluons available was reported recently by the CMS Collaboration. They reported that the gluon parton distribution function (PDF) at large Bjorken-x in lead ions is strongly suppressed with respect to the gluon PDF in a free nucleon [24]. On the other hand, studies of J/Ψ production on Sn and C by the New Muon Collaboration [25] suggested that there might be an enhancement of the gluon distribution in these nuclei. Exploring such changes with unprecedented precision is one of the primary scientific goals of the planned Electron-Ion Collider (EIC) [26–28]. Lastly, lattice QCD simulations of the gluonic structure of light nuclei were reported in Refs. [29, 30] for large quark masses, $m_\pi \sim 450$ and 806 MeV, finding a hint of a small EMC-like effect in the gluon momentum fractions in the spin-averaged nuclei.

In this work we focus on the gluon EMC effects within the framework provided by the NJL model and the QCD evolution of the nucleon and nuclear PDFs. We make predictions for two new EMC ratios, that is, the (per-nucleon) ratios of the unpolarized and polarized gluon distributions of nuclear matter to those of the free proton, $g_A(x)/g_p(x)$ and $\Delta g_A(x)/\Delta g_p(x)$. For the spin-dependent case we take one proton in symmetric nuclear matter to be polarized, as the proton and neutron gluon PDFs are equal.

II. CALCULATION AND PDF RESULTS

The NJL model is an effective model based upon the chiral symmetry of QCD that is characterized by a 4-Fermi contact interaction of the form, $\mathcal{L}_I = \sum_i G_i \left(\overline{\psi}\,\Gamma_i\,\psi\right)^2$, where the Γ_i are matrices in Dirac, colour and flavour space, and the G_i are dimensionful coupling constants [15, 16]. Applying Fierz transformations, the interaction Lagrangian can be decomposed into various interacting $q\bar{q}$ and qq channels. For the present purposes we need

$$\mathcal{L} = \overline{\psi}\,(i\partial\!\!\!/ - m)\,\psi + \mathcal{L}_{I,\pi} + \mathcal{L}_{I,s} + \mathcal{L}_{I,a}, \tag{1}$$

with m the current quark mass and the interaction terms read

$$\mathcal{L}_{I,\pi} = \frac{1}{2}\,G_\pi \left(\left(\overline{\psi}\psi\right)^2 - \left(\overline{\psi}\,\gamma_5\vec{\tau}\,\psi\right)^2\right), \tag{2}$$

$$\mathcal{L}_{I,s} = G_s\left(\overline{\psi}\,\gamma_5 C\tau_2\beta^A\,\overline{\psi}^T\right)\left(\psi^T\,C^{-1}\gamma_5\tau_2\beta^A\,\psi\right), \tag{3}$$

$$\mathcal{L}_{I,a} = G_a\Big(\overline{\psi}\,\gamma_\mu C\tau_i\tau_2\beta^A\,\overline{\psi}^T\Big)\Big(\psi^T\,C^{-1}\gamma^\mu\tau_2\tau_i\beta^A\,\psi\Big), \qquad (4)$$

where $\beta^A = \sqrt{\frac{3}{2}}\,\lambda^A$ ($A = 2, 5, 7$) are the colour $\overline{3}$ matrices and $C = i\gamma_2\gamma_0$. $\mathcal{L}_{I,\pi}$ generates the constituent quark mass, M, via the gap equation and the pion emerges as a $q\bar{q}$ bound state. The terms $\mathcal{L}_{I,s}$ and $\mathcal{L}_{I,a}$ generate the interactions in the scalar ($J^P = 0^+, T = 0$, colour $\overline{3}$) and axial-vector ($J^P = 1^+, T = 1$, colour $\overline{3}$) diquark channels. These yield diquark states from which the nucleon is constructed as a quark-diquark bound state. While the couplings G_π, G_s and G_a are related to the original couplings, G_i, via the Fierz transformation, we take them to be free parameters which will be fixed by the properties of the pion and the nucleon. To regularize the NJL model we use the proper-time scheme, which simulates important aspects of confinement [17, 31, 32]. A detailed discussion of the specific values of the model parameters is given in Refs. [20, 23].

We solve the appropriate Bethe-Salpeter equations to obtain the standard NJL results for the diquark t-matrices [33, 34]. Following Refs. [17, 35] these are approximated by the forms

$$\tau_s(q) = 4i\,G_s\,-\frac{ig_s}{q^2 - M_s^2}, \qquad (5)$$

$$\tau_a^{\mu\nu}(q) = 4i\,G_a\,g^{\mu\nu} - \frac{ig_a}{q^2 - M_a^2}\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{M_a^2}\right). \qquad (6)$$

The masses of the diquarks M_s, M_a and their couplings to the quarks g_s, g_a are defined as the poles and residues of the full diquark t-matrices [35].

The nucleon (quark-diquark) scattering amplitude satisfies the Faddeev equation

$$T = Z + Z\,\Pi_N\,T = Z + T\,\Pi_N\,Z, \qquad (7)$$

where Z is the quark exchange kernel and Π_N the product of a quark propagator and a diquark t-matrix. The quark-diquark vertex function, Γ_N, is defined by the behaviour of T near the pole

$$T \overset{p_+\to\varepsilon_p}{\longrightarrow} \frac{\Gamma_N\,\overline{\Gamma}_N}{p_+ - \varepsilon_p}\,. \qquad (8)$$

Here, $\varepsilon_p = \frac{M_N^2}{2p^+}$ is the light-cone energy of the nucleon with M_N the nucleon mass. Substituting Eq. (8) into Eq. (7) gives the homogeneous Faddeev equations for the vertex functions

$$\Gamma_N = Z\,\Pi_N\,\Gamma_N, \quad \text{and} \quad \overline{\Gamma}_N = \overline{\Gamma}_N\,\Pi_N\,Z. \qquad (9)$$

We employ the static approximation, where the momentum dependence of the quark exchange kernel, Z, is neglected. Including both scalar and axial-vector diquark channels, in the colour singlet and isospin-$\frac{1}{2}$ channel Z becomes:

$$Z = \frac{3}{M}\begin{pmatrix} 1 & \sqrt{3}\gamma_{\mu'}\gamma_5 \\ \sqrt{3}\gamma_5\gamma^\mu & -\gamma_{\mu'}\gamma^\mu \end{pmatrix}. \qquad (10)$$

The quantity Π_N describes the quark-diquark bubble graph:

$$\Pi_N(p) = \int \frac{d^4k}{(2\pi)^4}\,\tau(p-k)\,S(k), \qquad (11)$$

where

$$\tau(q) = \begin{pmatrix} \tau_s(q) & 0 \\ 0 & \tau_a^{\mu\nu}(q) \end{pmatrix}, \qquad (12)$$

and $S(k)$ is the propagator for the dressed quark. The eigenfunction of the kernel $K \equiv Z\,\Pi_N$, in Eq. (9), has the following form, up to an overall normalization:

$$\Gamma(p,s) = \begin{bmatrix} \alpha_1 \\ \alpha_2\,\frac{p^\mu}{M_N}\,\gamma_5 + \alpha_3\,\gamma^\mu\gamma_5 \end{bmatrix} u_N(p,s)\,. \qquad (13)$$

Here the upper and lower components refer to the scalar and axial-vector diquark channels, respectively, and u_N is a free nucleon Dirac spinor with mass M_N. The normalization is given by the residue at the t-matrix pole defined by Eq. (8) and we dropped the isospin structure for clarity. Inserting this form into Eq. (9) gives three homogeneous equations for the α's, while the nucleon mass, M_N, is determined by the requirement that the eigenvalue of K, in Eq. (9), should be unity.

In nuclear matter the quark mass is modified by the mean scalar field. This, in turn, leads to changes in the diquark masses as well as the quark spinors and this finally modifies the structure of the bound nucleon. Because the coupling of the composite nucleon to the scalar field depends on the structure of the nucleon, one must solve all of these equations self-consistently. In addition, the mean vector field shifts the energy of the quarks in medium, which results in a scale transformation of the nuclear PDFs [18]. Full details of this procedure may be found in Refs. [18, 20].

The spin-independent quark light-cone momentum distribution in a free nucleon is defined by [36, 37]

$$q(x) = -i\int \frac{d^4k}{(2\pi)^4}\delta\left(x - \frac{k^+}{p^+}\right)\mathrm{Tr}\left(\gamma^+\,M(p,k)\right), \qquad (14)$$

where x is the Bjorken scaling variable and $M(p,k)$ is the quark (momentum k) two-point function in the nucleon (momentum p). The spin-dependent distribution, $\Delta q(x)$, is defined by the replacement $\gamma^+ \to \gamma^+\gamma_5$ in Eq. (14). An analogous expression holds for the nucleon PDFs in nuclear matter, where the dressed quark propagators include effects from the mean scalar and vector fields, and Fermi motion is included following the standard convolution formalism [23, 36].

The spin-independent and spin-dependent valence u and d quark distributions for a free nucleon are shown in Fig. 1, both at the model scale of $Q_0^2 = 0.16$ GeV^2 and evolved to a scale of $Q^2 = 5\,\mathrm{GeV}^2$.[1] The model scale was chosen so that the valence up quark distribution best reproduces the empirical parametrization after Q^2 evolution at NLO [19]. Fig. 2 presents our results for the per-nucleon spin-independent PDF in isospin symmetric nuclear matter (top panel) and results for the spin-dependent PDFs for a polarized proton embedded in isospin symmetric unpolarized nuclear matter

[1] We evolve our PDF results at next-to-leading order (NLO) from the model scale to $Q^2 = 5\,\mathrm{GeV}^2$ using the APFEL program [38].

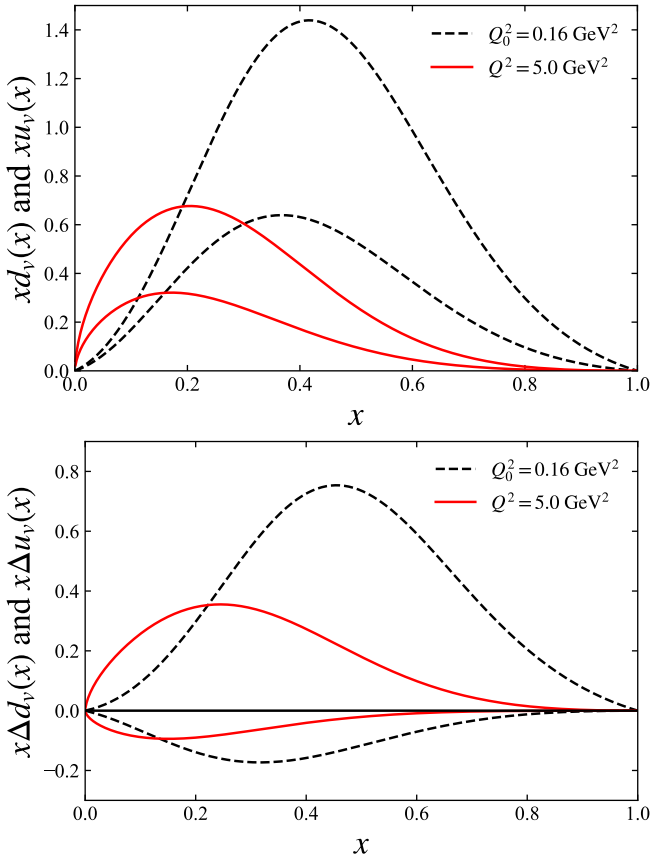

Figure 1. (Colour online) Results for the spin-independent (*top*) and spin-dependent (*bottom*) valence quark distributions of a free nucleon, with the lower curve of each type respresenting the d distribution. The dashed lines are the results at the model scale and the solid lines are obtained by NLO QCD evolution to the scale $Q^2 = 5\,\mathrm{GeV}^2$.

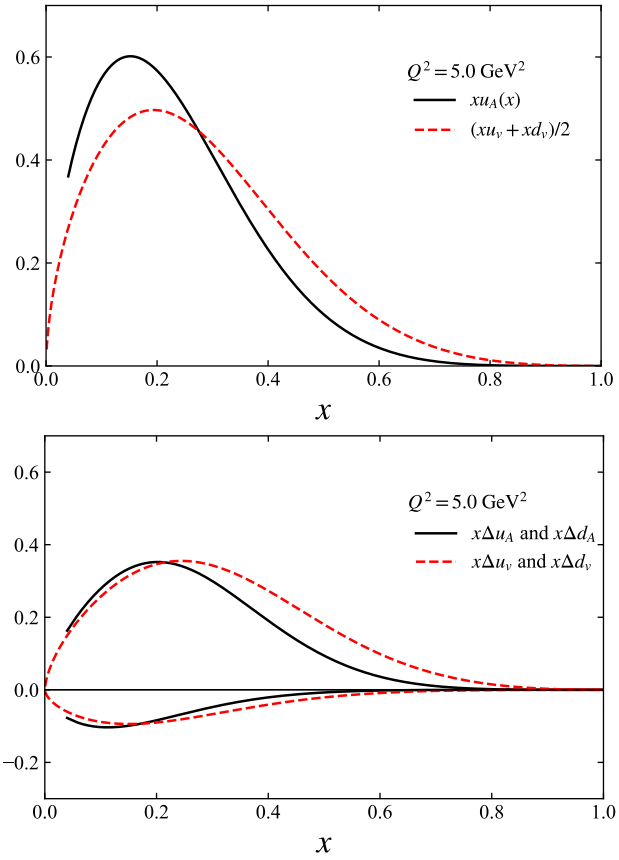

Figure 2. The solid lines represent the (per-nucleon) spin-independent valence quark PDF in isospin symmetric nuclear matter (*top*) and the spin-dependent valence u and d PDF of a single polarized proton embedded in isospin symmetric nuclear matter (*bottom*). These results are at the scale $Q^2 = 5\,\mathrm{GeV}^2$ and are compared with the free nucleon PDFs (dashed lines) at the same scale.

(bottom panel) at $Q^2 = 5\,\mathrm{GeV}^2$. Note, since the NJL model has no dynamical gluons, the gluon PDFs are zero at the model scale. In addition, at the level of approximation used herein, the sea-quark PDFs also vanish at the model scale. A more sophisticated treatment including the pion would generate a non-perturbative sea distribution with $\bar{d} > \bar{u}$ [39, 40]. However, in the present approach both the gluon and sea-quark PDFs are generated by the QCD evolution from the model scale to the scales associated with deep inelastic scattering.

III. GLUON EMC EFFECT RESULTS

The unpolarized and polarized EMC effects for gluons can be defined in analogy to the more familiar EMC effects, that is:

$$R_G = \frac{g_A(x)}{Z/A\, g_p(x) + N/A\, g_n(x)} \to \frac{g_A(x)}{g_p(x)}, \qquad (15)$$

$$\Delta R_G = \frac{\Delta g_A(x)}{P_p\, \Delta g_p(x) + P_n\, \Delta g_n(x)} \to \frac{\Delta g_A(x)}{\Delta g_p(x)}, \qquad (16)$$

where g_p, g_n are the unpolarized gluon PDFs for the nucleon and $\Delta g_p, \Delta g_n$ the polarized nucleon gluon PDFs. The analogous nuclear quantities are g_A and Δg_A, respectively, Z is the proton number and N the neutron number of the target, and P_p the effective proton polarization and P_n the effective neutron polarization for the nuclear target. In Eqs. (15)–(16) the denominators are further simplified by noting that, to a very good approximation, the proton and neutron gluon PDFs are equal and $P_p + P_n \simeq 1$.

For this initial study we consider gluon distributions in isospin symmetric ($N = Z$) nuclear matter. Because we use the NJL model, the gluon distributions vanish at the model scale, both for the free nucleon and in nuclear matter. However, compared to the free nucleon PDFs, the quark distributions in nuclear matter are modified by the scalar and vector mean fields in the nuclear medium. This medium modification changes the initial quark distributions in medium, and therefore the gluon distributions generated by QCD evolution will inherit this medium modification, and a gluon EMC effect will be generated. In a more complete calculation the gluons may be modified directly by the nuclear medium, so this initial study provides a baseline from which to study the gluon EMC effect in unpolarized and polarized PDFs.

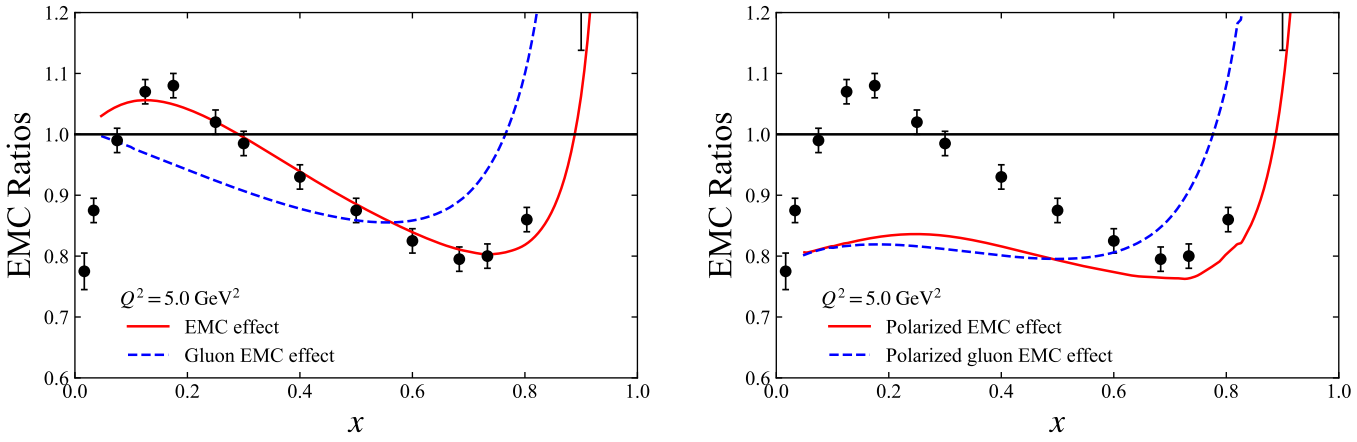

Figure 3. (Colour online) (*Left panel*) Unpolarized EMC ratios for the structure functions $F_{2A}(x)/F_{2N}(x)$ (red solid) and the unpolarized gluon distributions $g_A(x)/g_p(x)$ (blue dashed). (*Right panel*) Polarized EMC ratios for the structure functions $g_{1A}(x)/g_{1p}(x)$ (red solid) and polarized gluon distributions $\Delta g_A(x)/\Delta g_p(x)$ (blue dashed). The empirical data points are the unpolarized nuclear matter results for the EMC ratio from Ref. [41].

In Fig. 3 we show our results for the EMC ratios of the unpolarized and polarized structure functions [20, 23], as well as for the gluon distributions as defined in Eqs. (15)–(16). These results are obtained from the PDF results presented in Sec. II. Because of the neglect of shadowing effects in the present calculation, the description of nuclear structure functions in the low x region is incomplete, which is why this region is not shown in Fig. 3.

The left panel in Fig. 3 shows the spin-independent EMC ratios. In the valence quark region, the model is able to reproduce the empirical nuclear matter results [41] for $F_{2A}(x)/F_{2N}(x)$ at nuclear matter density extremely well [23], where $F_{2N}(x)$ is the free isoscalar nucleon structure function and $F_{2A}(x)$ represents the in-medium per-nucleon result. Also shown in this figure is the predicted ratio of the nuclear gluon distribution (per nucleon) to that of the free nucleon as defined in Eq. (15). Clearly our analysis predicts for the first time a sizeable gluon EMC effect.

The EMC effects in the spin-dependent case are given in the right panel of Fig. 3. The size of the structure function ratio $g_{1A}(x)/g_{1p}(x)$ is at least as large as that of the spin-independent case, consistent with the previous results in Refs. [20, 23, 42, 43]. It is also clear from this figure that we find a large EMC effect for the polarized gluon distribution ratio $\Delta g_A(x)/\Delta g_p(x)$, which is again larger than the gluon EMC effect seen in the unpolarized case.

IV. CONCLUSION

Starting with the NJL model to describe the structure of free nucleons, we used our previous results [20, 23] to self-consistently obtain the change in the structure of nucleons bound in nuclear matter, taking into account the Lorentz scalar and vector mean-fields. These results give the spin-independent and spin-dependent quark distributions for both free nucleons and nucleons in nuclear matter. Gluon distributions at any scale $Q^2 > Q_0^2$ were generated dynamically through NLO QCD evolution. We found significant EMC effects for both the unpolarized and polarized gluon distributions. Sizeable gluon EMC effects therefore follow naturally from the observed unpolarized EMC effect and predictions for the polarized EMC effect [20, 23, 42, 43].

An experiment at Jefferson Lab is planned to measure the polarized EMC effect in ^{7}Li [44]. The gluonic aspects of the structure of nucleons and nuclei will be accessible at the future Electron-Ion Collider (EIC) [26–28]. Experimental confirmation of our predictions for the gluon EMC effects would provide further insight into QCD effects in nuclei.

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