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Parity-Violating Deep Inelastic Scattering and the Flavor Dependence of the EMC Effect

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Isospin-dependent nuclear forces play a fundamental role in nuclear structure. In relativistic models of nuclear structure constructed at the quark level these isovector nuclear forces affect the u and d quarks differently, leading to nontrivial flavor-dependent modifications of the nuclear parton distributions. We explore the effect of isospin dependent forces for parity-violating deep inelastic scattering on nuclear targets and demonstrate that the cross sections for nuclei with $N \neq Z$ are sensitive to the flavor dependence of the EMC effect. Indeed, for nuclei like lead and gold we find that these flavor-dependent effects are large.

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Understanding the mechanisms responsible for the change in the per-nucleon deep inelastic scattering (DIS) cross section between the deuteron and heavier nuclei remains one of the most important challenges confronting the nuclear physics community. In the valence quark region this effect is characterized by a quenching of the nuclear structure functions relative to those of the free nucleon, known as the EMC effect [1]. This discovery has led to a tremendous amount of experimental and theoretical investigation [2–4]. However, after the passage of almost 30 years there remains no broad consensus regarding the underlying mechanism responsible for the EMC effect.

Early attempts to explain the EMC effect focused on detailed nuclear structure investigations [5] and the possibility of an enhancement in the pionic component of the nucleon in-medium [6,7]. The former studies were unable to describe the data and the latter explanation appears to be ruled out by Drell-Yan measurements of the antiquark distributions in nuclei [8]. Other ideas included the possibility of exotic six-quark bags in the nucleus [9] or traditional short-range correlations [10]. It has also been argued that the EMC effect is a result of changes in the internal structure of the bound nucleons brought about by the strong nuclear fields inside the nucleus [11]. Many of these approaches can explain the qualitative features of the EMC effect but the underlying physics mechanisms differ substantially.

To make further progress in our understanding of the mechanism responsible for the EMC effect, it has become clear that we require new experiments that reveal genuinely novel features of this effect. In this Letter we propose an important step in this direction, namely the exploitation of parity-violating DIS (PVDIS), to identify the difference between the EMC-type ratios for u and d quarks separately, particularly for nuclei with $N > Z$. The PVDIS structure functions result from the interference between photon and Z^0 exchange and in conjunction with traditional DIS data, one can obtain explicit information about the quark flavor dependence of the nuclear parton distribution functions (PDFs), in the valence quark region.

The parity-violating effect of the interference between photon and Z^0 exchange, in the DIS of longitudinally polarized electrons on an unpolarized target, leads to the nonzero asymmetry

$$A_{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}, \qquad (1)$$

where σ_L and σ_R denote the double differential cross sections for DIS of right- and left-handed polarized electrons, respectively. In the Bjorken limit $A_{\rm PV}$ can be expressed as [12]

$$A_{\rm PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{\rm em}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}\,a_3(x_A)\right], \qquad (2)$$

where x_A is the Bjorken scaling variable of the nucleus multiplied by A, G_F is the Fermi coupling constant and $y = \nu/E$ is the energy transfer divided by the incident electron energy. The $a_2(x_A)$ term in Eq. (2) originates from the product of the electron weak axial current and the quark weak vector current and has the form

$$a_2(x_A) = -2g_A^e\,\frac{F_{2A}^{\gamma Z}(x_A)}{F_{2A}^{\gamma}(x_A)} = \frac{2\sum_q e_q g_V^q q_A^+(x_A)}{\sum_q e_q^2 q_A^+(x_A)}. \qquad (3)$$

The plus-type quark distributions are defined by $q_A^+(x_A) = q_A(x_A) + \bar{q}_A(x_A)$, e_q is the quark charge, $g_A^e = -\frac{1}{2}$ [13] and the quark weak vector couplings are [13]

$$g_V^u = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W, \qquad g_V^d = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W, \qquad (4)$$

where θ_W is the weak mixing angle. The target structure function arising from γZ interference is labelled by $F_{2A}^{\gamma Z}$, while F_{2A}^{γ} is the familiar structure function of traditional DIS. The parton model expressions for these structure functions are [13]: $F_{2A}^{\gamma Z} = 2x_A \sum_q e_q g_V^q q_A^+$ and $F_{2A}^{\gamma} = x_A \sum_q e_q^2 q_A^+$. The a_3 term in Eq. (2) is given by

$$a_3(x_A) = -2g_V^e \frac{F_{3A}^{\gamma Z}(x_A)}{F_{2A}^{\gamma}(x_A)} = -4g_V^e \frac{\sum_q e_q g_A^q q_A^-(x_A)}{\sum_q e_q^2 q_A^+(x_A)}, \qquad (5)$$

where $g_V^e = -\frac{1}{2} + 2\sin^2\theta_W$, $g_A^u = -g_A^d = \frac{1}{2}$ [13], and $q_A^-(x_A) = q_A(x_A) - \bar{q}_A(x_A)$. This term is suppressed in the parity-violating asymmetry, $A_{\rm PV}$, because of its y-dependent prefactor and the fact that $g_V^e \ll g_A^e$. Therefore, we will not consider the $a_3(x_A)$ term further in this Letter.

The $F_{2A}^{\gamma Z}$ structure function has a different flavor structure to that of F_{2A}^{γ} and, as a consequence, $a_2(x_A)$ is sensitive to flavor-dependent effects. Expanding $a_2(x_A)$ about $u_A^+ \simeq d_A^+$ and assuming $s_A^+ \ll u_A^+ + d_A^+$ gives

$$a_2(x_A) \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+(x_A) - d_A^+(x_A) - s_A^+(x_A)}{u_A^+(x_A) + d_A^+(x_A)}, \qquad (6)$$

where we have ignored heavier quark flavors. The correction from strange quarks given in Eq. (6) may be of importance in the low-x region [14], however, recent HERMES data [15] has confirmed that $s^+(x)$ is negligible compared with $u^+(x) + d^+(x)$ in the region $x > 0.1$. Therefore, a measurement of $a_2(x_A)$ will provide information about the flavor dependence of the nuclear quark distributions and when coupled with existing measurements of F_{2A}^{γ}, a reliable extraction of the u and d quark distributions of a nuclear target becomes possible in the valence quark region.

As an alternative, if the correction term in Eq. (6) is known, then the parity-violating asymmetry provides an independent method with which to determine the weak mixing angle. For example, if we ignore strange quark effects, quark mass differences [16–18] and electroweak corrections, the u- and d-quark distributions of an isoscalar target will be identical, and in this limit Eq. (6) becomes

$$a_2(x_A) \overset{N=Z}{\longrightarrow} \frac{9}{5} - 4\sin^2\theta_W. \qquad (7)$$

This result is analogous to the Paschos-Wolfenstein ratio [19,20] in neutrino DIS, which motivated the NuTeV collaboration measurement of $\sin^2\theta_W$ [21,22]. An important advantage of $a_2(x_A)$ as a measure of the weak mixing angle is that in the valence quark region s-quark effects are almost absent, which eliminates the largest uncertainty in the NuTeV measurement of $\sin^2\theta_W$ [22]. Also, the isovector correction term in Eq. (6) does not depend on $\sin^2\theta_W$ and thus a measurement of $a_2(x_A)$ at each value of x_A constitutes a separate determination of the weak mixing angle. More importantly, however, in the context of this work, is that $a_2(x_A)$ is sensitive to flavor-dependent nuclear effects that influence the quark distributions of nuclei. Indeed, because of this sensitivity, a measurement of $a_2(x_A)$ on a target with $N > Z$ would provide an excellent opportunity to test the importance of the isovector EMC effect [20,22] for the interpretation of the NuTeV $\sin^2\theta_W$ result.

To investigate the effect of isospin dependent nuclear forces on $a_2(x_A)$, we use nuclear matter quark distribution functions determined using the Nambu-Jona-Lasinio (NJL) model [23–26], which explicitly depend on the Z/N ratio. The nucleon wave function is obtained as the solution of a relativistic Faddeev equation [27], where the nucleon is approximated as a quark-diquark bound state [28–31] and the static approximation is used to truncate the quark exchange kernel [29]. To regularize the NJL model we choose the proper-time scheme, which eliminates unphysical thresholds for nucleon decay into quarks, and hence simulates quark confinement [32–34]. In the nuclear medium, effects from the isoscalar-scalar (σ_0), isoscalar-vector (ω_0), and isovector-vector (ρ_0) mean fields are included and these fields self-consistently couple to the quarks inside the bound nucleons. To determine the strength of these mean scalar and vector fields, an equation of state for nuclear matter is derived from the NJL Lagrangian using hadronization techniques [32]. For the vector fields we find $\omega_0 = 6G_\omega(\rho_p + \rho_n)$ and $\rho_0 = 2G_\rho(\rho_p - \rho_n)$, where ρ_p and ρ_n are the proton and neutron densities, respectively, and G_ω, G_ρ are the NJL four-fermion couplings [20].

The model parameters are determined by reproducing standard hadronic properties, such as masses and decay constants, as well as the empirical saturation energy and density of symmetric nuclear matter and the nuclear matter symmetry energy. A discussion of the model parameters can be found in Refs. [20,31].

NJL model results for free nucleon and nuclear matter PDFs were obtained in Refs. [20,28,30]. The PVDIS structure function ratio, $a_2(x_A)$, can then be determined using Eq. (3), where for the weak mixing angle we take the on-shell renormalization scheme value of $\sin^2\theta_W = 0.2227 \pm 0.004$ [21]. Figure 1 presents our results for nuclear matter with a proton-neutron ratio equal to that of iron (top) and lead (bottom). The full result, which includes the effects from Fermi motion and the scalar and vector mean fields, is represented by the solid line. The dot-dashed line is the naive expectation where the nuclear quark distributions are obtained from the free proton and neutron PDFs without modification. The dotted line is the result for isoscalar nuclear matter, which, at our level of approximation is given by Eq. (7). In each case the total baryon density, $\rho_B = \rho_p + \rho_n$, is kept fixed, with only the Z/N ratio being varied, which then determines the strength of the ρ_0 mean field.

The leading correction to $a_2(x_A)$ is isovector, as illustrated in Eq. (6). As a consequence, the difference between the naive and full results of Fig. 1 is primarily caused by the nonzero ρ_0 mean field. This is precisely the same effect

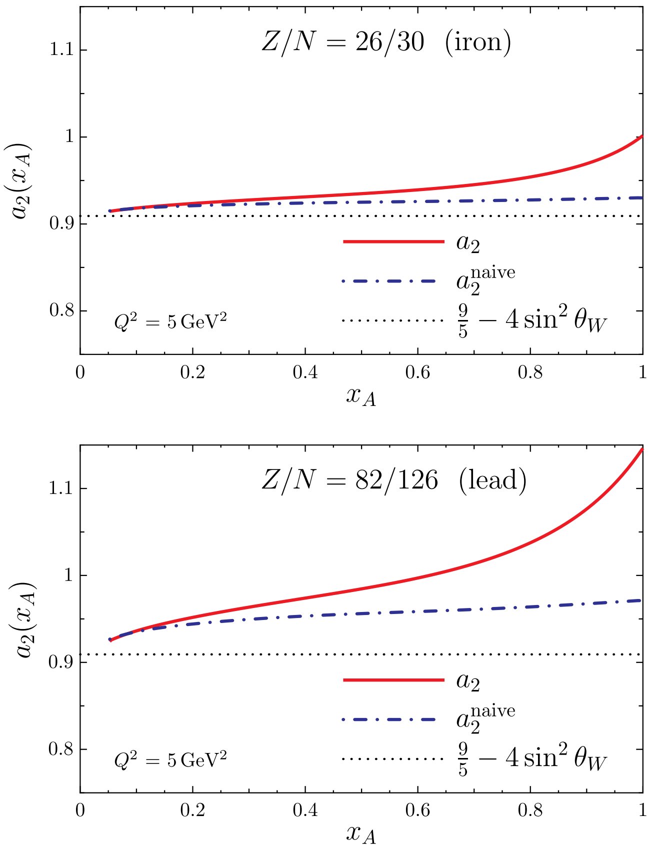

FIG. 1 (color online). Asymmetric nuclear matter results for $a_2(x_A)$ obtained by using the Z/N ratio of iron (top) and lead (bottom). In each figure the dotted line is the isoscalar result, the dot-dashed line the naive expectation where no medium effects are included, and the solid line is the full result.

which eliminates 1 to 1.5σ [20,22] of the NuTeV discrepancy with respect to the standard model in their measurement of $\sin^2\theta_W$. Thus, quite apart from the intrinsic importance of understanding the dynamics of quarks within nuclei, the observation of these large flavor-dependent nuclear effects illustrated in Fig. 1 would be direct evidence that the isovector EMC effect plays an important role in interpreting the NuTeV data. It would also indicate the importance of flavor-dependent effects in our understanding of the EMC effect in nuclei like lead and gold.

The a_2 function is potentially sensitive to charge symmetry violation effects as well, which are a consequence of the light quark mass differences and electroweak corrections [16–18]. In this case Eq. (6) reduces to

$$a_2(x) \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{6}{25}\frac{\delta u^+(x) - \delta d^+(x)}{u_p^+(x) + d_p^+(x)}, \quad (8)$$

where $\delta u^+ \equiv u_p^+ - d_n^+$ and $\delta d^+ \equiv d_p^+ - u_n^+$. These effects are largely independent of the medium effects already discussed [22] and by using the central value of the parametrizations of Ref. [35] we find this correction to be negligible on the scale of Fig. 1. Therefore, nuclear effects should dominate the discrepancy between the naive expectation and an empirical result for $a_2(x_A)$. However, if charge symmetry violation effects turn out to be larger than expected, together with any residual uncertainty associated with strange quarks at low x, these effects can be constrained via measurements on isospin symmetric nuclei.

The EMC effect can be defined for both the traditional DIS and γZ interference structure functions, via the ratio

$$R^i = \frac{F_{2A}^i}{F_{2A}^{i,\text{naive}}} = \frac{F_{2A}^i}{ZF_{2p}^i + NF_{2n}^i}, \quad (9)$$

where $i \in \gamma, \gamma Z$. The target structure function is labelled by F_{2A}^i, while $F_{2A}^{i,\text{naive}}$ is the naive expectation with no medium effects whatsoever, and can be expressed as a sum over the free proton and neutron structure functions. Therefore, if there were no medium effects R^i would be unity. Expressing the EMC effect in terms of the PDFs we find the parton model expressions

$$R^\gamma \simeq \frac{4u_A^+ + d_A^+}{4u_f^+ + d_f^+}, \qquad R^{\gamma Z} \simeq \frac{1.16u_A^+ + d_A^+}{1.16u_f^+ + d_f^+}, \quad (10)$$

where q_f are the quark distributions of the target if it were composed of free nucleons. For an isoscalar target we have $R^\gamma = R^{\gamma Z}$ (modulo electroweak, quark mass and heavy quark flavor effects). However, for nuclei with $N \neq Z$ these two EMC effects need not be equal. The solid line in Fig. 2 illustrates our EMC effect results for F_{2A}^γ in nuclear matter, with Z/N ratios equal to that of iron (top) and lead (bottom), while the corresponding EMC effect in $F_{2A}^{\gamma Z}$ is represented by the dot-dashed line. The dotted and dashed lines illustrate the EMC effect in the u and d quark sectors, respectively. We find that as the proton-neutron ratio is decreased, the EMC effect in F_{2A}^γ increases, whereas the EMC effect in $F_{2A}^{\gamma Z}$ is reduced. Consequently, for $N > Z$ nuclei we find that $R^\gamma < R^{\gamma Z}$ on the domain $x_A \gtrsim 0.3$, which is the domain over which our valence quark model can be considered reliable.

The fact that $u_A/u_f < d_A/d_f$ and as a consequence $R^\gamma < R^{\gamma Z}$ in nuclei with a neutron excess is a direct consequence of the isovector mean field and is a largely model independent result. In Ref. [20] it was demonstrated that the isovector mean field leads to a small shift in quark momentum from the u to the d quarks, and hence, the in-medium depletion of u_A is stronger than that of d_A in the valence quark region. Because u_A is multiplied by a factor four in the ratio R^γ, the depletion is more pronounced for this ratio than for $R^{\gamma Z}$, where the d quark quickly dominates as Z/N becomes less than one.

We find that the flavor-dependent effects in nuclei like lead and gold are approximately at the 5% level or greater, in the valence quark region. Effects of this size are large enough to be observed in planned PVDIS experiments [36] at Jefferson Lab after the 12 GeV upgrade. Because of the

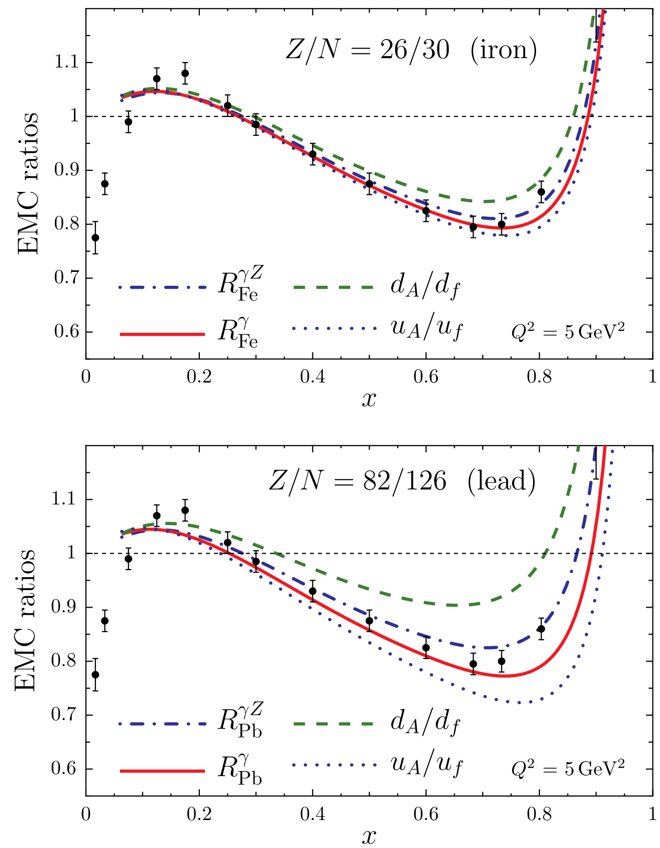

FIG. 2 (color online). The solid line in each figure is our full result for the EMC effect in DIS on nuclear matter, with the Z/N ratio chosen to be that of iron (top) and lead (bottom). The dash-dotted line illustrates the EMC ratio for PVDIS on the same target. The dotted and dashed lines show the EMC effect in the u and d quark sectors, respectively. The data in each figure are for isoscalar nuclear matter and are taken from Ref. [40].

relatively small difference between R^{γ} and $R^{\gamma Z}$ in nuclei like iron and lead, an accurate extraction of u_A and d_A would require that R^{γ} and $R^{\gamma Z}$ be measured with the same detector to reduce systematic uncertainties. This is exactly what is planned [36] and therefore an important step in our understanding of the EMC effect can be expected in the not too distant future.

We have demonstrated that an accurate comparison of the electromagnetic and γZ interference structure functions of a target have the potential to pin down the flavor dependence of the EMC effect in the valence quark region. The most direct determination of this flavor dependence (cf. Fig. 2) would involve charged current reactions on heavy nuclei at an electron-ion collider [37] or with certain Drell-Yan reactions [38,39]. However, such experiments will not be possible for at least 10–20 years. On the other hand, accurate measurements of PVDIS on heavy nuclei should be possible at Jefferson Lab after the 12 GeV upgrade [36] and would therefore provide a timely, critical test of an important class of models which aim to describe the modification of the nuclear structure functions. These experiments would complement alternative methods to access the quark substructure of nuclei, for example, the measurement of the EMC effect for spin structure functions [28,31], and, as a corollary, would also offer a unique insight into the description of nuclear structure at the quark level. Finally, they would constitute a direct test of the isovector EMC effect correction to the NuTeV measurement of $\sin^2\theta_W$.

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