Isovector EMC Effect and the NuTeV Anomaly

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A neutron or proton excess in nuclei leads to an isovector-vector mean field which, through its coupling to the quarks in a bound nucleon, implies a shift in the quark distributions with respect to the Bjorken scaling variable. We show that this result leads to an additional correction to the NuTeV measurement of $\sin^2\theta_W$. The sign of this correction is largely model independent and acts to reduce their result. Explicit calculation in nuclear matter within a covariant and confining Nambu–Jona-Lasinio model predicts that this vector field correction may account for a substantial fraction of the NuTeV anomaly. We are therefore led to offer a new interpretation of the NuTeV measurement, namely, that it provides further evidence for the medium modification of the bound nucleon wave function.

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Within relativistic, quark-level models of nuclear structure, the mean scalar and vector fields in the medium generate fundamental changes in the internal structure of bound hadrons. These modifications lead to a good description of the EMC effect in finite nuclei and predict a more dramatic modification of the bound nucleon spin structure function [1–3]. We show that in nuclei with $N \neq Z$ this approach leads to interesting and hitherto unexplored effects connected with the isovector-vector mean field, which is usually represented by the ρ^0, and is in part responsible for the symmetry energy. In a nucleus such as ^{56}Fe or ^{208}Pb where $N > Z$, the ρ^0 field will cause the u quark to feel a small additional vector attraction and the d quark to feel additional repulsion.

In this Letter we explore the way in which this additional vector field modifies the traditional EMC effect. However, there is an even more important issue which is our main focus. Even though the ρ^0 mean field is completely consistent with charge symmetry, the familiar assumption that $u_p(x) = d_n(x)$ and $d_p(x) = u_n(x)$ will clearly fail for a nucleon bound in a nucleus with $N \neq Z$. Therefore correcting for the ρ^0 field is absolutely critical in a situation where symmetry arguments are essential, such as the use of $N \neq Z$ nuclear data from ν and $\bar{\nu}$ deep inelastic scattering (DIS) to extract $\sin^2\theta_W$ via the Paschos-Wolfenstein (PW) relation [4]. Indeed, we show that the deviation from the naive application of charge symmetry to the ν and $\bar{\nu}$ data on ^{56}Fe may naturally explain the famous NuTeV anomaly.

The PW ratio is defined by [5]

$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}}, \tag{1}$$

where A represents the target, NC indicates weak neutral current, and CC weak charged current interaction. Expressing the cross sections in terms of quark distributions and ignoring heavy flavor contributions, the PW ratio becomes

$$R_{PW} = \frac{(\frac{1}{6} - \frac{4}{9}\sin^2\theta_W)\langle x_A u_A^- \rangle + (\frac{1}{6} - \frac{2}{9}\sin^2\theta_W)\langle x_A d_A^- \rangle}{\langle x_A d_A^- \rangle - \frac{1}{3}\langle x_A u_A^- \rangle}, \tag{2}$$

where x_A is the Bjorken scaling variable of the nucleus multiplied by A, $\langle \ldots \rangle$ implies integration over x_A, and $q_A^- \equiv q_A - \bar{q}_A$ are the nonsinglet quark distributions of the target.

Ignoring quark mass differences and possible electroweak corrections the u- and d-quark distributions of an isoscalar target will be identical, and in this limit Eq. (2) becomes

$$R_{PW} \overset{N=Z}{\longrightarrow} \frac{1}{2} - \sin^2\theta_W. \tag{3}$$

If corrections to Eq. (3) are small the PW ratio provides a unique way to measure the Weinberg angle.

Motivated by Eq. (3) the NuTeV Collaboration extracted a value of $\sin^2\theta_W$ from neutrino and antineutrino DIS on an iron target [6], finding $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$. The three-sigma discrepancy between this result and the world average [7], namely $\sin^2\theta_W = 0.2227 \pm 0.0004$, is the NuTeV anomaly. Some authors have speculated that the NuTeV anomaly supports the existence of physics beyond the standard model [8]. Standard model corrections to the NuTeV result have largely been focused on nucleon charge symmetry violating effects [9] and a nonperturbative strange quark sea [8]. Charge symmetry violation, arising from the u- and d-quark mass differences, is probably the best understood and constrained correction and can explain approximately one-third of the NuTeV anomaly [10]. Standard nuclear corrections such as Fermi motion, binding, and off-shell effects are found to be small [11]. However, effects from the medium modification of the bound nucleon, in particular, the impact of the ρ^0 field, have hitherto not been explored in relation to the NuTeV anomaly. These effects are potentially important because they are now widely accepted as an essential ingredient in explaining the EMC effect [12].

In our approach, presented in Refs. [2,3,13], the scalar and vector mean fields inside a nucleus couple to the quarks in the bound nucleons and self-consistently modify their internal structure. The influence of the vector fields on the quark distributions arises from the nonlocal nature of the quark bilinear in their definition [13]. This leads to a largely model independent result for the modification of the in-medium parton distributions of a bound nucleon by the vector mean fields [13–15], namely

$$q(x) = \frac{p^+}{p^+ - V^+} q_0\left(\frac{p^+}{p^+ - V^+}x - \frac{V_q^+}{p^+ - V^+}\right). \quad (4)$$

The subscript 0 indicates the absence of vector fields and p^+ is the nucleon light cone plus component of momentum. The quantities V^+ and V_q^+ are the light cone plus component of the net vector field felt by the nucleon and a quark of flavor q, respectively.

Before embarking on explicit calculations, we first explore the model independent consequences of Eq. (4) for the PW ratio and the subsequent NuTeV measurement of $\sin^2\theta_W$. The NuTeV experiment was performed on a predominately ^{56}Fe target, and therefore isoscalarity corrections need to be applied to the PW ratio before extracting $\sin^2\theta_W$. Isoscalarity corrections to Eq. (3) for small isospin asymmetry have the general form

$$\Delta R_{PW} \simeq \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{\langle x_A u_A^- - x_A d_A^-\rangle}{\langle x_A u_A^- + x_A d_A^-\rangle}, \quad (5)$$

where the Q^2 dependence of this correction resides completely with $\sin^2\theta_W$. NuTeV perform what we term naive isoscalarity corrections, where the neutron excess correction is determined by assuming that the target is composed of free nucleons [16]. However, there are also isoscalarity corrections from medium effects, in particular, from the medium modification of the structure functions of every nucleon in the nucleus, arising from the isovector ρ^0 field. For nuclei with $N > Z$ the ρ^0 field develops a nonzero expectation value that results in $V_u < V_d$, so the u quarks feel less vector repulsion than the d quarks. A direct consequence of this and the transformation given in Eq. (4) is that there must be a small shift in quark momentum from the u to the d quarks. Therefore the momentum fraction $\langle x_A u_A^- - x_A d_A^-\rangle$ in Eq. (5) will be negative, even after naive isoscalarity corrections are applied. Correcting for the ρ^0 field will therefore have the model independent effect of reducing the NuTeV result for $\sin^2\theta_W$. As we shall see, this correction may largely explain the NuTeV anomaly.

To determine the nuclear quark distributions we use the Nambu–Jona-Lasinio (NJL) model [17], which is viewed as a low energy chiral effective theory of QCD and is characterized by a 4-fermion contact interaction between the quarks. The NJL model has a long history of success in describing mesons as $\bar{q}q$ bound states [18] and more recently as a self-consistent model for free and in-medium baryons [2,3,13,19]. The original 4-fermion interaction term in the NJL Lagrangian can be decomposed into various $\bar{q}q$ and qq interaction channels via Fierz transformations [20], where the relevant terms to this discussion are given in Ref. [2].

The scalar $\bar{q}q$ interaction term generates the scalar field, which dynamically generates a constituent quark mass via the gap equation. The vector $\bar{q}q$ interaction terms are used to generate the isoscalar-vector, ω_0, and isovector-vector, ρ_0, mean fields in-medium. The qq interaction terms give the diquark t matrices whose poles correspond to the scalar and axial-vector diquark masses. The nucleon vertex function and mass are obtained by solving the homogeneous Faddeev equation for a quark and a diquark, where the static approximation is used to truncate the quark exchange kernel [19]. To regularize the NJL model we choose the proper-time scheme, which enables the removal of unphysical thresholds for nucleon decay into quarks, and hence simulates an important aspect of confinement [21,22].

To self-consistently determine the strength of the mean scalar and vector fields, an equation of state for nuclear matter is derived from the NJL Lagrangian, using hadronization techniques [22]. In a mean field approximation the result for the energy density is [22] $\mathcal{E} = \mathcal{E}_V - \frac{\omega_0^2}{4G_\omega} - \frac{\rho_0^2}{4G_\rho} + \mathcal{E}_p + \mathcal{E}_n$, where G_ω and G_ρ are the $\bar{q}q$ couplings in the isoscalar-vector and isovector-vector channels, respectively. The vacuum energy $\mathcal{E}_V$ has the familiar Mexican hat shape and the energies of the protons and neutrons moving through the mean scalar and vector fields are labeled by $\mathcal{E}_p$ and $\mathcal{E}_n$, respectively. The corresponding proton and neutron Fermi energies are $\varepsilon_{F\alpha} = E_{F\alpha} + V_\alpha = \sqrt{M_N^{*2} + p_{F\alpha}^2} + 3\omega_0 \pm \rho_0$, where $\alpha = p$ or n, the plus sign refers to the proton, M_N^* is the in-medium nucleon mass, and $p_{F\alpha}$ the nucleon Fermi momentum. Minimizing the effective potential with respect to each vector field gives the following useful relations: $\omega_0 = 6G_\omega(\rho_p + \rho_n)$ and $\rho_0 = 2G_\rho(\rho_p - \rho_n)$, where ρ_p is the proton and ρ_n the neutron density. The vector field experienced by each quark flavor is given by $V_u = \omega_0 + \rho_0$ and $V_d = \omega_0 - \rho_0$.

As explained in Ref. [2], the parameters of the model are determined by standard hadronic properties, and the empirical saturation energy and density of symmetric nuclear matter. The new feature of this work is the ρ^0 field, where G_ρ is determined by the empirical symmetry energy of nuclear matter, namely $a_4 = 32$ MeV, giving $G_\rho = 14.2$ GeV^{-2}.

Details of our results for the free and $N \simeq Z$ in-medium parton distributions are given in Refs. [2,3,19]. For in-medium isospin dependent parton distributions our procedure is as follows: Effects from the scalar mean field are included by replacing the free masses with the effective

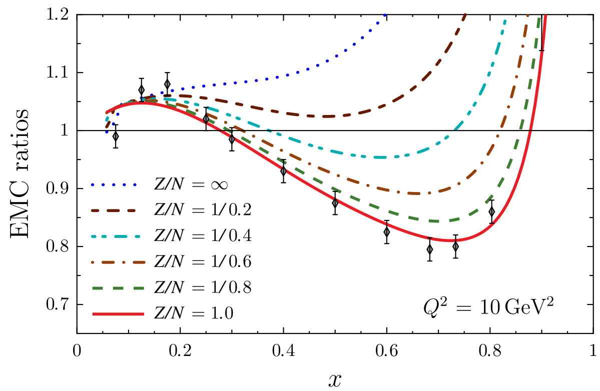

FIG. 1 (color online). Isospin dependence of the EMC effect for proton-neutron ratios greater than one. The data are from Ref. [31] and correspond to $N = Z$ nuclear matter.

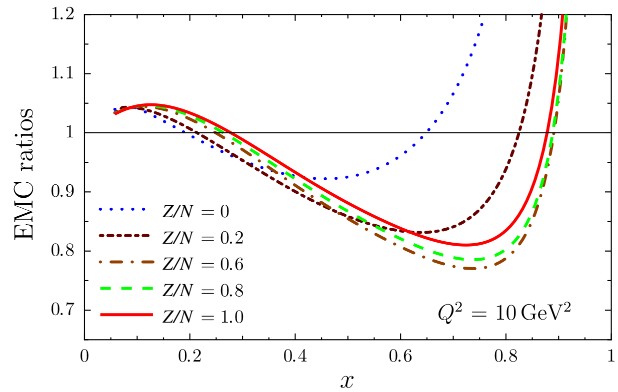

FIG. 2 (color online). Isospin dependence of the EMC effect for proton-neutron ratios less than one.

masses in the expressions for the free parton distributions discussed in Ref. [19]. To include the nucleon Fermi motion, the quark distributions modified by the scalar field are convoluted with the appropriate Fermi smearing function, namely

$$f_{\alpha 0}(y_A) = \frac{\mathcal{N}\alpha}{A}\frac{3}{4}\left(\frac{\hat{M}_N}{p_{F\alpha}}\right)^3\left[\left(\frac{p_{F\alpha}}{\hat{M}_N}\right)^2 - \left(\frac{E_{F\alpha}}{\hat{M}_N} - y_A\right)^2\right], \quad (6)$$

where $\mathcal{N}_p = Z$, $\mathcal{N}_n = N$, and $\hat{M}_N = \frac{Z}{A}E_{Fp} + \frac{N}{A}E_{Fn}$. Vector field effects can be included in Eq. (6) by the substitutions $E_{F\alpha} \to \varepsilon_{F\alpha}$ and $\hat{M}_N \to \bar{M}_N = \frac{Z}{A}\varepsilon_{Fp} + \frac{N}{A}\varepsilon_{Fn}$. Our final result for the infinite asymmetric nuclear matter quark distributions, which includes vector field effects on both the quark distributions in the bound nucleon and on the nucleon smearing functions, is given by

$$q_A(x_A) = \frac{\bar{M}_N}{\hat{M}_N} q_{A0}\left(\frac{\bar{M}_N}{\hat{M}_N}x_A - \frac{V_q}{\hat{M}_N}\right). \quad (7)$$

The subscript $A0$ indicates a distribution which includes effects from Fermi motion and the scalar mean field. The distributions calculated in this way are then evolved [23] from the model scale, $Q_0^2 = 0.16\ \mathrm{GeV}^2$, to an appropriate Q^2 for comparison with experimental data.

The EMC effect is defined by the ratio

$$R = \frac{F_{2A}}{F_{2A}^{\mathrm{naive}}} = \frac{F_{2A}}{ZF_{2p} + NF_{2n}} \simeq \frac{4u_A + d_A}{4u_f + d_f}, \quad (8)$$

where q_A are the quark distributions of the target and q_f are the distributions of the target if it was composed of free nucleons. Results for the isospin dependence of the EMC effect are given in Figs. 1 and 2.

Figure 1 illustrates the EMC effect for proton rich matter, where we find a decreasing effect as Z/N increases. An intuitive understanding of this result may be obtained by realizing that it is a consequence of binding effects at the quark level. For $Z/N > 1$ the ρ_0 field is positive, which means $V_u > V_d$ and hence the u quarks are less bound than the d quarks. Therefore the u-quark distribution becomes less modified while medium modification of the d-quark distribution is enhanced. Since the EMC effect is dominated by the u quarks it decreases. The isospin dependence of the EMC effect for nuclear matter with $Z/N < 1$ is given in Fig. 2. Here the medium modification of the u-quark distribution is enhanced, while the d-quark distribution is modified less by the medium. Since the EMC ratio is initially dominated by the u quarks the EMC effect first increases as Z/N decreases from one. However, eventually the d-quark distribution dominates the ratio and at this stage the EMC effect begins to decrease in the valence quark region. We find a maximal EMC effect for $Z/N \simeq 0.6$, which is slightly less than the proton-neutron ratio in Pb. This isospin dependence is clearly an important factor in understanding the A dependence of the EMC effect, even after standard neutron excess corrections are applied.

Now we turn to the consequences of the isospin dependence of the EMC effect for the NuTeV measurement of $\sin^2\theta_W$. The NuTeV experiment was performed on an iron target, which, because of impurities had a neutron excess of 5.74% [6]. Choosing our Z/N ratio to give the same neutron excess, we use our medium modified quark distributions and Eq. (5) to determine the full isoscalarity correction to the isoscalar PW ratio, given by Eq. (3). Using the standard model value for the Weinberg angle we obtain $\Delta R_{PW} = -0.0139$. If we break this result into the three separate isoscalarity corrections, by using Eq. (5) and the various stages of modification of the in-medium quark distributions, we find

$$\Delta R_{PW} = \Delta R_{PW}^{\mathrm{naive}} + \Delta R_{PW}^{\mathrm{Fermi}} + \Delta R_{\mathrm{PW}}^{\rho^0}$$
$$= -(0.0107 + 0.0004 + 0.0028). \quad (9)$$

Higher order corrections to Eq. (5) do not change this result. The NuTeV analysis includes the naive isoscalarity correction [16] but is missing the medium corrections. The new correction of $\Delta R_{\mathrm{PW}}^{\rho^0} = -0.0028$ would account for almost two-thirds of the NuTeV anomaly.

To estimate the effect on the NuTeV experiment, we use the standard classical nuclear matter approximation for an iron nucleus, based on the quasielastic electron scattering results of Ref. [24]. In practice this means that we rescale the nuclear matter density by 0.89. The ρ^0 field depends linearly on the density, and therefore a first order estimate of the isovector correction for an ironlike nucleus, that is, a finite nucleus with the same neutron excess as the NuTeV experiment, would be $\Delta R_{\rm PW}^{\rho^0} \to -0.89 \times 0.0028 = -0.0025$. Another approach is to take our medium modified nucleon distributions and use the NuTeV CSV functional given in Ref. [25], this gives $\Delta R_{\rm PW}^{\rho^0} \to -0.0021$. Therefore we conclude that medium effects, in particular, a nonzero ρ^0 field, can explain approximately 1.5σ of the NuTeV anomaly.

If we also include the well constrained charge symmetry violation (CSV) correction, $\Delta R_{PW}^{\rm CSV} = -0.0017$ [10], which originates from the quark mass differences, we have a total correction of $\Delta R_{PW}^{\rm medium} + \Delta R_{\rm PW}^{\rm CSV} \simeq -0.0045$. The combined correction largely accounts for the NuTeV anomaly [26]. Corrections to the NuTeV result from s quarks may also be important; however, current experimental uncertainties are too large to draw any firm conclusions [8,27].

Since our nuclear matter calculation suggests that CSV and medium modification corrections largely explain the discrepancy between the NuTeV result and the standard model, we propose that this NuTeV measurement provides strong evidence that the nucleon is modified by the nuclear medium, and should not be interpreted as an indication of physics beyond the standard model. In our opinion this conclusion is equally profound since it may have fundamental consequences for our understanding of traditional nuclear physics. We stress that the physics presented in this Letter, in particular, the effects of the ρ^0 mean field, are consistent with existing data [28–30], but can strongly influence other observables. For example, the ρ^0 field gives rise to a strong flavor dependence of the EMC effect, and there is an excellent chance this effect will be measured in future experiments at, for example, Jefferson Lab.

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