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# The structure of a bound nucleon

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**Abstract.** We highlight some of the progress made in understanding the EMC effect and the NuTeV anomaly using a chiral effective theory of QCD, that is, the Nambu–Jona-Lasinio model. A natural consequence of this approach is that for nuclear systems the mean scalar and vector fields couple to the quarks inside the bound nucleons and therefore nucleon properties are modified in the medium. In particular, we demonstrate that the medium modification of nucleon quark distributions provides a natural explanation of the EMC effect. We also illustrate how a proton-neutron asymmetry in nuclei leads to an isovector-vector mean-field which couples to the quarks in the bound nucleons and that this mechanism leads to an additional correction to the NuTeV measurement of $\sin^2\theta_W$.

**Keywords:** EMC effect, medium modification, NuTeV Anomaly
**PACS:** 24.85.+p, 13.60.Hb, 11.80.Jy, 21.65.Cd

Since the discovery of QCD in the early seventies a central goal of nuclear physics has been to understand how the fundamental degrees of freedom – the quarks and gluons – give rise to nucleons and to the inter-nucleon forces that bind nuclei. A key milestone on the path to achieving this goal is to understand how the structure of a nucleon bound in a nucleus differs from that of a free nucleon. It was not until the EMC experiment [1] in 1983 that the idea of a difference in structure between a bound and free nucleon was widely entertained. This landmark experiment observed, in the valence quark region, a depletion of the $F_2$ structure function of iron relative to that of the deuteron [1, 2, 3] . This discovery, now known as the EMC effect, rattled the nuclear physics community at the time and fomented a large experimental and theoretical effort in order to understand its origin. Despite many attempts to understand this effect in terms of binding corrections it has now become clear that one cannot understand it without a change in the structure of the nucleon-like quark clusters in matter [4, 5, 6].

Although the EMC effect has received the most attention, there are a number of other phenomena which may require a resolution at the quark level, such as the quenching of spin matrix elements in nuclei [7] and the quenching of the Coulomb sum-rule [8, 9]. Important hints for medium modification also come from recent electromagnetic form factor measurements on $^4$He [10, 11], which suggest a reduction of the proton's electric to magnetic form factor ratio in-medium. Sophisticated nuclear structure calculations fail to fully account for the observed effect [12] and agreement with the data is only achieved by also including a small change in the internal structure of the nucleon [11], predicted a number of years before the experiment [13].

The focus of this work is on nuclear quark distribution functions with a view to understanding the EMC effect, as a consequence of the medium modification of the

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structure of the bound nucleons. We will also investigate an interesting correction to the NuTeV analysis arising from the isovector-vector mean field in the iron nucleus.

## THE NJL MODEL, NUCLEAR MATTER AND THE EMC EFFECT

To determine the nuclear quark distributions we use the Nambu–Jona-Lasinio (NJL) model [14, 15], 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 [16, 17] and more recently as a self-consistent model for free and in-medium baryons [18, 19, 20, 21, 22]. 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 [23], where the relevant terms to this discussion are given in Ref. [20].

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, $\omega_0$, and isovector-vector, $\rho_0$, 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 [18].

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 [24]. In a mean-field approximation the result for the energy density is [24], $\mathscr{E} = \mathscr{E}_V - \frac{\omega_0^2}{4G_\omega} - \frac{\rho_0^2}{4G_\rho} + \mathscr{E}_p + \mathscr{E}_n$, where $G_\omega$ and $G_\rho$ are the $\bar{q}q$ couplings in the isoscalar-vector and isovector-vector channels respectively. The vacuum energy $\mathscr{E}_V$ has the familiar Mexican hat shape and the energies of the protons and neutrons moving through the mean scalar and vector fields are labelled by $\mathscr{E}_p$ and $\mathscr{E}_n$, 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: $\omega_0 = 6\,G_\omega\,(\rho_p + \rho_n)$ and $\rho_0 = 2\,G_\rho\,(\rho_p - \rho_n)$, where $\rho_p$ is the proton and $\rho_n$ the neutron density. The vector field experienced by each quark flavour is given by $V_u = \omega_0 + \rho_0$ and $V_d = \omega_0 - \rho_0$.

Details of our results for the free and $N \simeq Z$ in-medium parton distributions are given in Refs. [18, 20, 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 masses in the expressions for the free parton distributions discussed in Ref. [18]. To include the nucleon Fermi motion, the quark distributions modified by the scalar field are convoluted with the appropriate Fermi smearing function. 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



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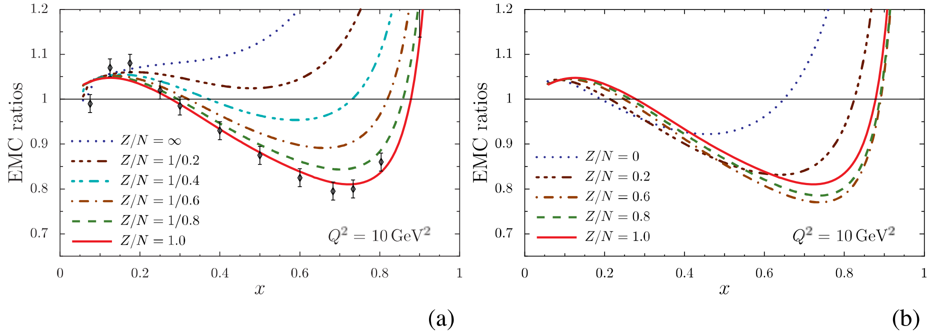


**FIGURE 1.** On the left we illustrate the isospin dependence of the EMC effect for proton-neutron ratios greater than one and on the right we have $Z/N < 1$. The data is from Ref. [25] and corresponds to $N = Z$ nuclear matter.

the nucleon smearing functions, is given by

$$q_A(x_A) = \frac{\overline{M}_N}{\hat{M}_N}\, q_{A0}\left(\frac{\overline{M}_N}{\hat{M}_N} x_A - \frac{V_q}{\hat{M}_N}\right). \tag{1}$$

The subscript $A0$ indicates a distribution which includes effects from Fermi motion and the scalar mean-field.

The EMC effect is defined by the ratio

$$R = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z F_{2p} + N F_{2n}} \simeq \frac{4u_A + d_A}{4u_f + d_f}, \tag{2}$$

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. Fig. 1a 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 $\rho_0$ 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. 1b. 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.



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# THE NUTEV ANOMALY

In 2001 the NuTeV collaboration announced the result of their measurement of the weak mixing angle, finding $\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.})$ [26], which has a $3\sigma$ discrepancy with the Standard Model (SM) value, namely $\sin^2\theta_W = 0.2227 \pm 0.0004$ [27]. This disagreement became known as the NuTeV anomaly and was immediately interpreted as possible evidence for physics below the SM. However, such explanations have the unenviable task of attempting to explain the NuTeV result, while leaving other electroweak observables unchanged. Such beyond the SM explanations have thus far proven unsuccessful [28].

At the same time a number of SM corrections to the NuTeV analysis have been proposed [29, 30, 31, 32, 33, 21]. These corrections are likely to reduce the discrepancy between the NuTeV result and the SM. However until recently a complete explanation of the NuTeV anomaly within the SM appeared elusive [21]. This work focuses on an important nuclear correction to the NuTeV analysis, that can explain a large fraction of the discrepancy with the SM. Our discussion will be framed around the Paschos-Wolfenstein (PW) relation, which motivated the NuTeV experiment, and serves as a useful focal point for such studies.

The Paschos-Wolfenstein (PW) ratio is defined by [34]

$$R_{PW} = \frac{\sigma_{NC}^{\nu A} - \sigma_{NC}^{\bar{\nu} A}}{\sigma_{CC}^{\nu A} - \sigma_{CC}^{\bar{\nu} A}} \simeq \frac{\left(\frac{1}{6}-\frac{4}{9}\sin^2\theta_W\right)\langle x_A\, u_A^-\rangle + \left(\frac{1}{6}-\frac{2}{9}\sin^2\theta_W\right)\langle x_A\, d_A^-\rangle}{\langle x_A\, d_A^-\rangle - \frac{1}{3}\langle x_A\, u_A^-\rangle}, \tag{3}$$

where $A$ represents the target, NC indicates weak neutral current and CC weak charged current interaction. In expressing the PW ratio in terms of quark distributions we have ignored heavy flavour contributions, 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 non-singlet 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. (3) becomes $R_{PW} \overset{N=Z}{\longrightarrow} \frac{1}{2} - \sin^2\theta_W$. SM corrections have largely focused on nucleon charge symmetry violating effects [35, 36] and a non-perturbative strange quark sea [28]. However, effects from the medium modification of the bound nucleon, in particular, the impact of the $\rho^0$ field have only recently been explored in relation to the NuTeV anomaly [21]. As we have seen these effects are potentially important because they are an essential ingredient in explaining the EMC effect [4, 5].

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 $\sin^2\theta_W$. For small isospin asymmetry these corrections have the general form

$$\Delta R_{PW} \simeq \left(1 - \frac{7}{3}\sin^2\theta_W\right) \frac{\langle x_A\, u_A^- - x_A\, d_A^-\rangle}{\langle x_A\, u_A^- + x_A\, d_A^-\rangle}. \tag{4}$$

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 [37].



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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 $\rho^0$ field. For nuclei with $N > Z$ the $\rho^0$ field develops a non-zero 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. (1) 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. (4) will be negative, even after naive isoscalarity corrections are applied. Correcting for the $\rho^0$ field will therefore have the *model independent effect of reducing the NuTeV result for* $\sin^2\theta_W$.

The NuTeV experiment was performed on a steel target with a neutron excess of 5.74% [26]. Choosing our $Z/N$ ratio to give the same neutron excess, we use our medium modified quark distributions [21] and the SM value of $\sin^2\theta_W$ in to determine the full isoscalarity correction to PW ratio, expressed via Eq. (4). Breaking this result into the three separate isoscalarity corrections, representing the various stages of modification of the in-medium quark distributions, we find [21]

$$\Delta R_{PW} = \Delta R_{PW}^{\text{naive}} + \Delta R_{PW}^{\text{Fermi}} + \Delta R_{PW}^{\rho^0} = -\left(0.0107 + 0.0004 + 0.0028\right). \tag{5}$$

The NuTeV analysis includes the naive isoscalarity correction but is missing the medium corrections.

The results expressed in Eq. (5) are for asymmetric nuclear matter. To estimate the effect for an iron nucleus and therefore the NuTeV experiment, we use a standard classical approximation based on the quasi-elastic electron scattering results of Ref. [38]. This means in practice to rescale the nuclear matter density by 0.89, and since the $\rho^0$ field varies linearly with the density we simply multiply our nuclear matter result by the same factor, giving $\Delta R_{PW}^{\rho^0} \to -0.89 \times 0.0028 = -0.0025$. As an alternative we can also use the NuTeV functionals [39] to estimate the correction to the NuTeV result, which gives $\Delta R_{PW}^{\rho^0} \to -0.0021$. Therefore we conclude that medium effects, in particular a non-zero $\rho^0$ field, can explain approximately $1.5\,\sigma$ of the NuTeV anomaly.

## CONCLUSION

Using a NJL model, where the quarks in the bound nucleons respond to the nuclear environment, we calculated the quark distributions for asymmetric nuclear matter. We were readily able to describe the EMC effect in symmetric nuclear matter and also found a large isospin dependence in the EMC effect. Further, by including the effect of this isovector EMC effect in the NuTeV analysis we where able to explain approximately $1.5\,\sigma$ of the NuTeV anomaly. When coupled with the charge symmetry violation correction [29] the discrepancy between the NuTeV measurement and the Standard Model completely disappears. Therefore, we propose that the 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.



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