Neutron Properties in the Medium

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We demonstrate that for small values of momentum transfer Q^2 the in-medium change of the G_E/G_M form factor ratio for a bound neutron is dominated by the change in the electric charge radius and predict within stated assumptions that the in-medium ratio will *increase* relative to the free result. This effect will act to increase the predicted cross section for the neutron recoil polarization transfer process $^4\mathrm{He}(\vec{e}, e'\vec{n})^3\mathrm{He}$. This is in contrast with medium modification effects on the proton G_E/G_M form factor ratio, which act to *decrease* the predicted cross section for the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction. Experiments to measure the in-medium neutron form factors are currently feasible in the range $0.1 < Q^2 < 1$ GeV^2.

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The discovery by the European Muon Collaboration (EMC) that the deep inelastic structure function of a nucleus, in the valence quark region, is reduced relative to the free nucleon occurred more than 20 years ago [1]. The immediate parton model interpretation is that the valence quarks in a nucleon bound in a nucleus carry less momentum than when the nucleon is in free space. The uncertainty principle then implies that the nucleon's size may also increase [2]. A modification in which the nucleon's basic properties are changed by the medium could have vast implications for the structure of nuclei, neutron stars, and how QCD effects lead to quark confinement. However, unambiguous evidence for such modifications, independent of deep inelastic scattering, is yet to be obtained.

Searches for medium modifications have been performed using the (e, e') reaction [3]. The polarization transfer reaction $(\vec{e}, e'\vec{p})$ on a proton target measures quantities proportional to the ratio of the proton's electric and magnetic form factors [4]. When such measurements are performed on a nuclear target, e.g., the reaction $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$, the polarization transfer observables are sensitive to the G_E/G_M form factor ratio of a proton embedded in the nuclear environment. Several such ^{4}He experiments have been performed [5]. The data can be described well by including the effects of medium-modified form factors [6–10] (where the ratio is reduced by the influence of the medium) or by including effects from strong charge-exchange final state interactions (FSI) [11]. However, the effects of the strong FSI may not be consistent with measurements of the induced polarization [4]. It is therefore important to find an alternative method to distinguish between the influence of medium modifications and FSI. The purpose of this Letter is to suggest that important progress can be achieved by measuring neutron recoil polarization in the $^4\mathrm{He}(\vec{e}, e'\vec{n})^3\mathrm{He}$ reaction. Recent advances in experimental techniques make such considerations very timely.

Before proceeding, it is worthwhile to consider the validity of the general proposition that the structure of a single nucleon is modified by its presence in the nuclear medium. The root cause of any such modification is the interaction between nucleons, so one needs to consider whether the entire concept of single nucleon modification makes sense. Our assertion is that, if the kinematics of a given experiment select single nucleon properties, such as in quasielastic scattering, it does make sense to consider how a single nucleon is modified. Therefore, the influence of long-range effects, such as pion exchange, occur as multinucleon operators and are not considered medium modification effects of a single nucleon that we wish to isolate using quasielastic scattering. Within the quasielastic region, it may be possible to characterize these medium modifications by the virtuality of the bound nucleon [12].

More than 50 years of experience in nuclear physics has taught us that to a good approximation the nucleus can be regarded as a collection of nucleonlike objects whose properties resemble those of free nucleons. Therefore, in relativistic treatments of nuclear matter it is usual to make the assumption [7–10] that the bound nucleons satisfy an in-medium Dirac equation of the form $(\not{p}^* - M^*)u^*(p^*) = 0$, where an asterisk denotes an in-medium quantity, so that M^* is the in-medium nucleon mass and p^* the in-medium nucleon four-momentum. The in-medium quantities p^* and M^* are related to free quantities p and M, via $p^* = p - V_v$ and $M^* = M - V_s$, where V_v and V_s are the scalar and vector nuclear potentials, respectively. The twin constraints of gauge invariance and the in-medium Dirac equation imply that the electromagnetic current of a bound nucleon has the same form as a free nucleon, except the free form factors and nucleon mass are replaced by the effective in-medium quantities, namely, F_{1N}^*, F_{2N}^*, and M^*. Therefore the familiar relations for the radii, Sachs form factors, etc., for a free nucleon remain unchanged for an in-medium nucleon, except the free quantities are replaced by the effective in-medium analogs.

We begin the analysis by considering the situation for small values of Q^2, where Q^2 is the negative of the square of the virtual photon's four-momentum. In this region the Sachs electric and magnetic form factors [13] for the free proton can be expressed in the form

$$G_{Ep}(Q^2) \simeq 1 - \tfrac{1}{6}Q^2\hat{R}^2_{Ep}, \tag{1}$$

$$\frac{1}{\mu_p}G_{Mp}(Q^2) \simeq 1 - \frac{1}{6}Q^2\hat{R}^2_{Mp}, \tag{2}$$

where μ_p is the proton magnetic moment and the effective electric and magnetic radii [14]—defined via the Sachs form factors—are labeled by $\hat{R}_{Ep}$ and $\hat{R}_{Mp}$, respectively. Keeping only the leading Q^2 dependence, the proton electric to magnetic form factor ratio can be expressed as

$$\mathcal{R}_p \equiv \frac{G_{Ep}(Q^2)}{G_{Mp}(Q^2)} \simeq \frac{1}{\mu_p}\left[1 - \frac{1}{6}Q^2(\hat{R}^2_{Ep} - \hat{R}^2_{Mp})\right]. \tag{3}$$

For a bound proton we may define an analogous ratio which we label by $\mathcal{R}^*_p$. The influence of the medium may change any of the three quantities μ_p, $\hat{R}_{Ep}$, and $\hat{R}_{Mp}$. Extensive studies of the EMC effect seem to imply that the nucleon expands in-medium. Therefore, since $\hat{R}^2_{Ep} \simeq \hat{R}^2_{Mp}$ in free space, and if we assume that the in-medium changes are similar for the electric and magnetic radii, the influence of the term proportional to Q^2 in Eq. (3) would be negligible. However, one may expect that in-medium μ_p will increase, along with the increasing magnetic radius. In this scenario the superratio $\mathcal{R}^*_p/\mathcal{R}_p$ would be less than 1 and largely independent of Q^2.

This expectation is borne out by specific model calculations [7,9,10] and, more importantly, by the experimental data [5]. The basic idea behind the models is that confined quarks in a nucleon—which is treated as a Massachusetts Institute of Technology bag in Ref. [7] or as a solution of a relativistic Faddeev equation in Refs. [9,10]—are influenced by the quarks of neighboring nucleons through the exchange of scalar mesons. The results of Ref. [10] for the proton superratio in nuclear matter are given in Fig. 1. These results were obtained in a covariant and confining Nambu–Jona-Lasinio (NJL) model, where the formalism described in Ref. [9] was extended to include axial-vector diquarks, in the same manner outlined in Ref. [15]. A contrasting model is that of Smith and Miller [8], where the quarks are confined in a chiral soliton which is identified as the nucleon. In-medium, the confined quarks are also influenced by the exchange of scalar objects between quarks of neighboring nucleons. In this model the magnetic properties are dominated by the sea, which is resistant to the influence of the medium. Thus μ_p and $\hat{R}_{Mp}$ remain largely unchanged, whereas $\hat{R}_{Ep}$ increases. Once again the superratio $\mathcal{R}^*_p/\mathcal{R}_p$ is less than unity; however, in this model it varies linearly with Q^2.

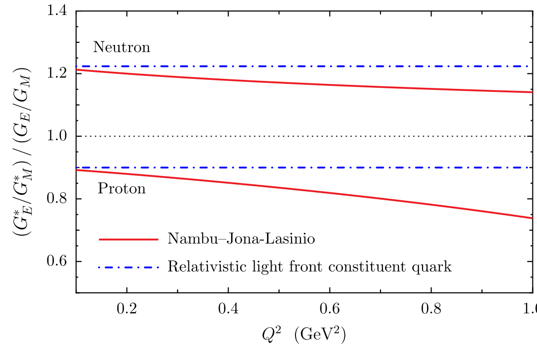

FIG. 1 (color online). Superratios for the proton and neutron form factors in nuclear matter, obtained from the NJL model of Ref. [10] and the relativistic light front constituent quark model of Ref. [16].

There are two lessons from this. First, very different models predict the superratio to be less than 1 for the proton, but for different reasons. Therefore we need another experimental way to determine which, if any, of the relevant parameters are changed in the medium. Second, we need more precise data and an increase in the Q^2 range of the $(\vec{e}, e'\vec{p})$ experiments.

One way to help resolve the different mechanisms responsible for the medium modification of nucleons and to also determine the influence of FSI is to consider the neutron in the medium. The analogous expression to Eq. (3) for the neutron, valid at small Q^2, is

$$\mathcal{R}_n \equiv \frac{G_{En}(Q^2)}{G_{Mn}(Q^2)} \simeq -\frac{1}{\mu_n}\frac{1}{6}Q^2\hat{R}^2_{En}, \tag{4}$$

where the effective magnetic radius does not appear, since it is the coefficient of a Q^4 term. We immediately see that, in contrast with the proton, the medium modifications are generally expected to depend on possible changes in both the electric radius and the magnetic moment. This implies that the behavior of the superratio $\mathcal{R}^*_n/\mathcal{R}_n$ at small Q^2 is determined by a competition between the expected increases in both of these quantities. The electric radius is potentially more important in Eq. (4) because it enters quadratically. Therefore one may expect, in contrast with the proton, that the neutron superratio will be larger than 1.

It is worthwhile to consider specific models as examples of the previous general statements. In the NJL model of Refs. [9,10,15], both $\hat{R}_{En}$ and $\hat{R}_{Mn}$ increase in-medium; however, there is only a small in-medium change in the neutron magnetic moment. Therefore at low Q^2 one finds that the superratio is dominated by the change in $\hat{R}_{En}$ and therefore increases. This is shown in Fig. 1, where the results of Ref. [10] are illustrated. In the model of Smith and Miller [8], the values of μ_n and $\hat{R}_{Mn}$ are largely unchanged in the medium; however, $\hat{R}_{En}$ increases.

Therefore both models predict that the superratio goes up for the neutron and down for the proton.

We can also consider placing the relativistic light front constituent quark model of Ref. [16] in the medium. This model for the nucleon is characterized in free space by a confinement scale $1/\alpha$ and a quark mass m_q. The medium may change each of these quantities, and in this analysis we assume that these effects are limited to $\sim$30%. With this assumption we find that the in-medium change of the nucleon anomalous magnetic moments behaves as $\delta\kappa_p/\kappa_p \approx \delta\kappa_n/\kappa_n \approx -\delta m_q/m_q$. Therefore the percentage change in the neutron and proton anomalous magnetic moments is expected to be very similar in this model. If the nucleon mass changes in the medium, then the change in the proton magnetic moment does not simply equal $\delta\kappa_p$, because the contribution from the Dirac form factor is also modified, which in nuclear magnetons becomes M/M^* [17]. The proton radii are proportional to $1/\alpha$; therefore, the proton superratio $\mathcal{R}_p^*/\mathcal{R}_p$ will be dominated by the in-medium change of the proton magnetic moment. The neutron electric charge radius is given by $\frac{3}{2M^2}\kappa_n$; therefore, using Eq. (4) we see that the neutron superratio behaves like $(M/M^*)^2$. Since masses are expected to decrease in the medium, this model predicts that the proton superratio is less than unity and the neutron superratio is greater than unity. Assuming a 10% reduction of the masses in-medium, we obtain the results in Fig. 1.

It is intriguing that for each model considered earlier we find that $\mathcal{R}^*/\mathcal{R}$ is greater than unity for neutrons and less than unity for protons. Can this be understood from a more formal perspective? Consider the expression for the anomalous magnetic moment derived in Ref. [14], namely,

$$\kappa = \langle X|\sum_q e_q \int d^2b\, b_y q_+^\dagger(0,\mathbf{b})q_+(0,\mathbf{b})|X\rangle, \tag{5}$$

where $q_+(x^-,\mathbf{b})$ is a quark-field operator of flavor q and impact parameter $\mathbf{b}$. The subscript $+$ indicates a light-cone good component of the quark field, defined by $q_+ = \gamma^0\gamma^+ q$, and therefore the operator $q_+^\dagger(0,\mathbf{b})q_+(0,\mathbf{b})$ is a number operator for valence quarks with impact parameter $\mathbf{b}$. Explicitly, the state $|X\rangle$ has the form

$$\begin{aligned}|X\rangle &\equiv \frac{1}{\sqrt{2}}[|X,+\rangle + |X,-\rangle]\\ &\equiv \frac{1}{\sqrt{2}}[|p^+,\mathbf{R}=\mathbf{0},+\rangle + |p^+,\mathbf{R}=\mathbf{0},-\rangle],\end{aligned} \tag{6}$$

where the first term represents a transversely localized state of definite p^+ momentum and positive light-cone helicity whereas the second state has negative light-cone helicity. The state $|X\rangle$ may be interpreted as a transversely polarized target [18,19], up to relativistic corrections caused by the transverse localization of the wave packet [18].

Define the quark sector contribution to the proton anomalous magnetic moment matrix element as

$$q = \langle X|\int d^2b\, b_y q_+^\dagger(0,\mathbf{b})q_+(0,\mathbf{b})|X\rangle, \tag{7}$$

where $q \in u, d$. With this definition, and by neglecting the contribution from heavy quark flavors, the proton and neutron anomalous magnetic moments can be expressed as

$$\kappa_p = \tfrac{2}{3}u - \tfrac{1}{3}d, \qquad \kappa_n = -\tfrac{1}{3}u + \tfrac{2}{3}d. \tag{8}$$

For the neutron we have assumed charge symmetry [20]. In the medium the nucleon matrix elements u and d may be shifted from their free values by δu and δd, respectively. We see no general, model-independent way to relate these two quantities, even in the case of symmetric nuclear matter (with $N = Z$) where the external forces on the confined quarks are flavor independent. This is because of the necessary interplay between the quark orbital angular momentum and spin. Therefore the changes in the anomalous magnetic moments are simply

$$\delta\kappa_p = \tfrac{2}{3}\delta u - \tfrac{1}{3}\delta d, \qquad \delta\kappa_n = -\tfrac{1}{3}\delta u + \tfrac{2}{3}\delta d. \tag{9}$$

To determine each of these quantities requires a measurement of both the proton and the neutron magnetic moment in the medium.

Using the relation that the transverse charge density is the two-dimensional Fourier transform of F_1 [18,21], one may analyze the nucleon radii in a similar manner to the anomalous magnetic moments. The quark sector contribution to the F_1 electric charge radius squared is

$$R_{1q}^2 = \langle X,+|\int d^2b \frac{3}{2} b^2 q_+^\dagger(0,\mathbf{b})q_+(0,\mathbf{b})|X,+\rangle, \tag{10}$$

where $q \in u, d$. The factor $3/2$ accounts for the two-dimensional integration. By recalling that $G_E = F_1 - \frac{Q^2}{4M^2}F_2$, the effective charge radii related to G_E are given by

$$\hat{R}_{Ep}^2 = \frac{2}{3}R_{1u}^2 - \frac{1}{3}R_{1d}^2 + \frac{3}{2M^2}\kappa_p, \tag{11}$$

$$\hat{R}_{En}^2 = -\frac{1}{3}R_{1u}^2 + \frac{2}{3}R_{1d}^2 + \frac{3}{2M^2}\kappa_n. \tag{12}$$

From the above analysis we see no model-independent way to determine the behavior of the proton G_E/G_M form factor ratio in the medium. However, for the neutron the Foldy term [22] $\frac{3}{2M^2}\kappa_n = -0.126\ \text{fm}^2$ is by far the dominant contribution to the neutron effective charge radius, which equals $\hat{R}_{En}^2 = -0.113 \pm 0.005\ \text{fm}^2$ [23]. In model calculations, medium modification effects generally appear at the 10%–20% level; therefore, it is natural to assume that the Foldy term will remain the dominant contribution to the effective charge radius of an in-medium neutron. Under this assumption, and using Eq. (4), we find that for small values of Q^2 the leading term of the neutron superratio is

$$\frac{\mathcal{R}_n^*}{\mathcal{R}_n} \simeq \left(\frac{M}{M^*}\right)^2, \tag{13}$$

because the anomalous magnetic moments in the Foldy terms cancel the neutron magnetic moments. In deriving Eq. (13) we have made three assumptions, namely, that the concept of a single nucleon makes sense in the medium, that a bound nucleon satisfies an in-medium Dirac equation, and that the Foldy term remains the dominant contribution to the in-medium neutron effective charge radius. Binding effects imply that $M^* < M$, and therefore we have obtained on rather general grounds that at small Q^2 the neutron superratio should be greater than 1.

This general prediction is worthy of an experimental test, and recent technical developments make this an ideal time to plan such an experiment. By using recoil polarization, high precision, low Q^2 measurements of the free proton [24] and neutron [25] form factors have already been performed. With a straightforward extension of these experiments, at, e.g., the Thomas Jefferson National Accelerator Facility (JLab), it would be possible to perform low Q^2 measurements of the reactions $p(\vec{e}, e'\vec{p})$, $d(\vec{e}, e'\vec{p})n$, $d(\vec{e}, e'\vec{n})p$, ${}^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$, and ${}^4\mathrm{He}(\vec{e}, e'\vec{n})^3\mathrm{He}$. This would allow a direct test of the predictions made in this Letter. Because of the large cross section for these reactions at low Q^2 and the availability of a high current polarization and duty factor electron beam at JLab, these experiments would achieve excellent statistical precision within a relatively short time period. Such experiments could also probe the Q^2 dependence of the form factor superratios. An experimental proposal to this effect is being developed by the authors for the JLab facility. This includes extending the current considerations to finite nuclei.

Understanding how a nucleon is modified when in the nuclear environment remains a central challenge for the nuclear physics community. In this Letter, we present a unique result pertaining to the structure of a bound neutron, which is expressed in Eq. (13) and states that, in contrast to the proton, the neutron superratio is greater than 1 at small Q^2. We therefore conclude that the measurement of $(\vec{e}, e'\vec{n})$ processes on nuclear targets can provide important additional and complementary information to that already obtained using the $(\vec{e}, e'\vec{p})$ reaction. These measurements would provide an independent test of any model seeking to explain the EMC effect and offer the hope of providing its long-sought universally accepted explanation.

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