Medium Modifications of Neutron Electromagnetic Form Factors

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Abstract

We propose to investigate possible medium modifications of neutron electromagnetic form factors by measuring recoil polarizations for the semi-inclusive quasifree $^{4}\mathrm{He}(\vec{e}, e'\vec{n})$ reaction at $Q^2 = 1.0$ (GeV/c)^2.

Requirements

Beam energy	:	1.645 GeV
Beam polarization	:	$\sim 80\%$
Beam current	:	$\leq 20\ \mu$A
Target	:	15 cm cryogenic helium
Luminosity	:	4×10^{37} cm^{-2} s^{-1}
Detectors	:	Hall C HMS + neutron polarimeter
Beam time	:	336 hours

I. INTRODUCTION

It has long been speculated that the internal structure of nucleons is sensitive to the local baryon density. Although the most dramatic structural change may be observed at rather high density and temperature as a transition to a quark-gluon plasma phase, density dependence of the nucleon electromagnetic form factors may be significant at normal nuclear density also. For example, Thomas *et al.* [1–4] predict substantial density dependence of the ratio G_E/G_M for nucleons in nuclear matter using the quark-meson coupling (QMC) model. Alternatively, if meson masses and meson-nucleon couplings are density dependent, as suggested by Brown and Rho [5], the vector-meson dominance model would also yield density-dependent nucleon form factors. Regardless of the model applied to these quantities, it is fundamentally important to determine the degree to which nucleon form factors depend upon density.

Although it is difficult to obtain unambiguous tests of this hypothesis using cross section measurements, recoil polarization in nucleon knockout by electron scattering offers a relatively clean probe of the ratio G_E/G_M in the nuclear medium. For a free nucleon at rest, this form factor ratio

$$\frac{G_E}{G_M} = -\frac{P'_S}{P'_L}\frac{\varepsilon_i+\varepsilon_f}{2m_N}\tan\frac{\theta_e}{2} \tag{1}$$

can be obtained directly from the ratio between transverse and longitudinal components of recoil polarization [6,7]; the proportionality factor depends upon the electron scattering angle, θ_e, and the initial and final electron energies, ε_i and ε_f. In the absence of final-state interactions, there would also be a relatively simple relationship between $\frac{G_E}{G_M}$ and $\frac{P'_S}{P'_L}$ for a bound nucleon that accounts for its initial nucleon momentum and binding energy. Many theoretical analyses have shown that, for modest missing momenta and reasonably large Q^2, recoil polarization for quasifree nucleon knockout from light targets is rather insensitive to two-body currents (MEC+IC) and to ambiguities in final-state interactions (FSI). For example, the Laget calculation cited by JLab proposal 93-049 [8] to support a closely related experiment on the $^4\mathrm{He}(\vec{e},e'\vec{p})$ reaction shows that FSI+MEC+IC effects upon polarization transfer are negligible. Furthermore, Kelly [9] has shown the effects of gauge ambiguities in the single-nucleon current operator are much smaller for polarization transfer than for cross sections or separated response functions. Therefore, recoil polarization appears to provide the best available technique for investigating possible density-dependent variations of nucleon electromagnetic form factors.

Milbrath *et al.* [10] found that the recoil polarization for quasifree proton knockout from deuterium for $Q^2 = 0.38$ and 0.50 (GeV/c)^2 is consistent with that for a free proton. Furthermore, Barkhuff *et al.* [11] have shown that the helicity-dependent recoil polarization in $d(\vec{e},e'\vec{p})$ for $Q^2 = 0.38$ (GeV/c)^2 and missing momenta up to 100 MeV/c, comparable to the deuteron Fermi momentum, are consistent with theoretical calculations that include small corrections for final-state interactions and two-body currents [12]. Therefore, recoil polarization measurements for quasifree neutron knockout from deuterium are also expected to accurately represent the electromagnetic form factors for a free neutron. JLab experiment 93-038 [13] will use the quasifree $d(\vec{e},e'\vec{n})p$ reaction to measure the ratio G_{En}/G_{Mn} at $Q^2 = 0.5$, 1.0, 1.4, and 1.7 $(\mathrm{GeV/c})^2$ with estimated statistical relative uncertainties ranging from 3 to 10%. In addition, cross section measurements will be used to measure G_{Mn} with anticipated uncertainties of approximately 3%. The management has indicated its intention to schedule experiment 93-038 during the second half of year 2000.

JLab experiment 89-033 [14] proposed to use the recoil polarization technique to search for medium modification of proton form factors using the $^{16}\mathrm{O}(\vec{e},e'\vec{p})$ reaction at $Q^2 = 0.8$ $(\mathrm{GeV/c})^2$. Although this experiment received some beam during the summer of 1997, it was the first experiment to use polarized beam and the Hall A focal-plane polarimeter; unfortunately, the limited statistical precision achieved by that commissioning experiment cannot exclude medium modifications at the 10–15% level. Similarly, JLab experiment 93-049 is designed to investigate with high precision possible medium modifications of G_{Ep}/G_{Mp} using the $^4\mathrm{He}(\vec{e},e'\vec{p})$ reaction at several values of Q^2 between about 0.8 and 3.0 $(\mathrm{GeV/c})^2$ and is expected to run in 1999. It is important to investigate these effects for both neutrons and protons in nuclei. Therefore, we propose to make complementary measurements for the quasifree $^4\mathrm{He}(\vec{e},e'\vec{n})$ reaction at $Q^2 = 1.0$ $(\mathrm{GeV/c})^2$ using the same neutron polarimeter as JLab experiment 93-038. Measurements of the ratio $\frac{G_E}{G_M}$ with a relative statistical precision of about 5% will provide a stringent test of models of the density dependence of neutron electromagnetic form factors.

II. RECOIL POLARIZATION METHOD

The differential cross section for coincident scattering of polarized electrons, can be expressed as

$$\frac{d^5\sigma_{hs}}{d\epsilon_f d\Omega_e d\Omega_x} = \sigma_0 \left[1 + \boldsymbol{P}\cdot\boldsymbol{\sigma} + h(A + \boldsymbol{P}'\cdot\boldsymbol{\sigma})\right] \tag{2}$$

where σ_0 is the unpolarized differential cross section, A is the beam analyzing power, P is the induced or helicity-independent recoil polarization, P' is the polarization transfer or helicity-dependent recoil polarization, s indicates the nucleon spin projection upon $\boldsymbol{\sigma}$, and h is the beam helicity. Thus, the net polarization of the recoil nucleon, $\mathbf{\Pi}$ has two contributions of the form

$$\mathbf{\Pi} = \boldsymbol{P} + h\boldsymbol{P}' \,. \tag{3}$$

For parallel kinematics, both A and P vanish while P' has only two independent components, P'_z and P'_x, which may be referred to a basis defined by

$$\hat{z} = \hat{q} \tag{4a}$$

$$\hat{y} = \frac{\boldsymbol{k}_i \otimes \boldsymbol{k}_f}{|\boldsymbol{k}_i \otimes \boldsymbol{k}_f|} \tag{4b}$$

$$\hat{x} = \hat{y} \otimes \hat{z} \; . \tag{4c}$$

For a free nucleon at rest, the recoil polarization components are then given by

$$P'_x = -\frac{2g\tan(\frac{\theta_e}{2})\sqrt{\tau(1+\tau)}}{g^2 + \tau(1 + 2(1+\tau)\tan^2(\frac{\theta_e}{2}))} \tag{5a}$$

$$P'_z = \frac{\tan^2(\frac{\theta_e}{2})\sqrt{\tau(1+\tau)}}{g^2 + \tau(1 + 2(1+\tau)\tan^2(\frac{\theta_e}{2}))} \frac{\varepsilon_i + \varepsilon_f}{m_N} \tag{5b}$$

where $g = G_E/G_M$ and $\tau = Q^2/4m_N^2$. Thus, for a nucleon target the electromagnetic form factor ratio

$$g = \frac{G_E}{G_M} = -r_{xz}\frac{\varepsilon_i + \varepsilon_f}{2m_N}\tan\frac{\theta_e}{2} \tag{6}$$

can be deduced directly from the ratio

$$r_{xz} = \frac{P'_x}{P'_z} \tag{7}$$

between components of the helicity-dependent recoil polarization.

The initial momentum of a bound nucleon introduces modest dependences upon missing momentum which can be evaluated easily in PWIA. In addition, the binding energy requires an off-shell extrapolation of the current operator that changes r_{xz} by only a few percent. Fortunately, all common off-shell extrapolations (cc1, cc2, cc3) give very nearly identical estimates for this effect; nor is r_{xz} for modest p_m dependent upon gauge. Finally, final-state interactions also have little effect upon r_{xz} for modest p_m [15,9,16].

III. EXPERIMENTAL PROCEDURE

A detailed discussion of the equipment and experimental procedures can be found in proposal 93-038, which has been approved with A priority. We intend to employ the same configuration and to integrate the two experiments for maximum efficiency. Therefore, for the present purposes it should be sufficient to summarize only the most important features of the configuration and procedures.

The HMS spectrometer will be operated in reversed-quad mode and the forward position. This configuration gives a solid angle, $\Omega_e = 11$ msr, that is well-matched to the neutron detector.

The neutron polarimeter is based upon neutron scattering by hydrogen and carbon in the scintillators that determine the time of flight and has been calibrated using measurements at IUCF [17] and Saturne [18]. In the present design a 10 cm lead entrance window shields the front detectors from photons and charged particles while transmitting 57% of the neutrons, but a thinner window may be used if background rates permit. To measure the longitudinal component of the neutron polarization, the neutron spin will be precessed through 90° by a magnet preceding the polarimeter; both clockwise and counterclockwise precession will be used to eliminate the sideways component. These techniques will be commissioned by experiment 93-038 before performing the helium measurements.

A Monte Carlo code [19] was used to estimate counting rates and to correct the polarizations for finite angular and energy acceptances. The missing-momentum distribution was based upon Urbana VII wave functions and the $\bar{\Gamma}_{cc1}$ current operator was employed in plane-wave approximation using Galster electric and dipole magnetic form factors. Figure 1 shows missing-momentum distributions of recoil polarization using a $\pm 10\%$ acceptance in electron energy, a 15 cm target cell, and the nominal angular acceptances of HMS and the neutron polarimeter. The normalized yield shows the weighting of the missing momentum distributions. Calculations for helium and deuterium targets are compared using the same experimental conditions and acceptances. The small differences between the recoil polarization distributions for deuterium versus helium targets arise primarily from the population of the phase space by different initial momentum distributions. In addition, there are small kinematic effects upon the current operator. Thus, we estimate that acceptance averaging increases the net r_{xz} by about 9.1% for ^{4}He. Although this effect is similar in magnitude to the $\sim 15\%$ reduction in g for ^{4}He predicted by the QMC model, we can make the acceptance averaging corrections with enough accuracy to measure a compensating medium modification of g, if present, with minimal uncertainties due to acceptance averaging.

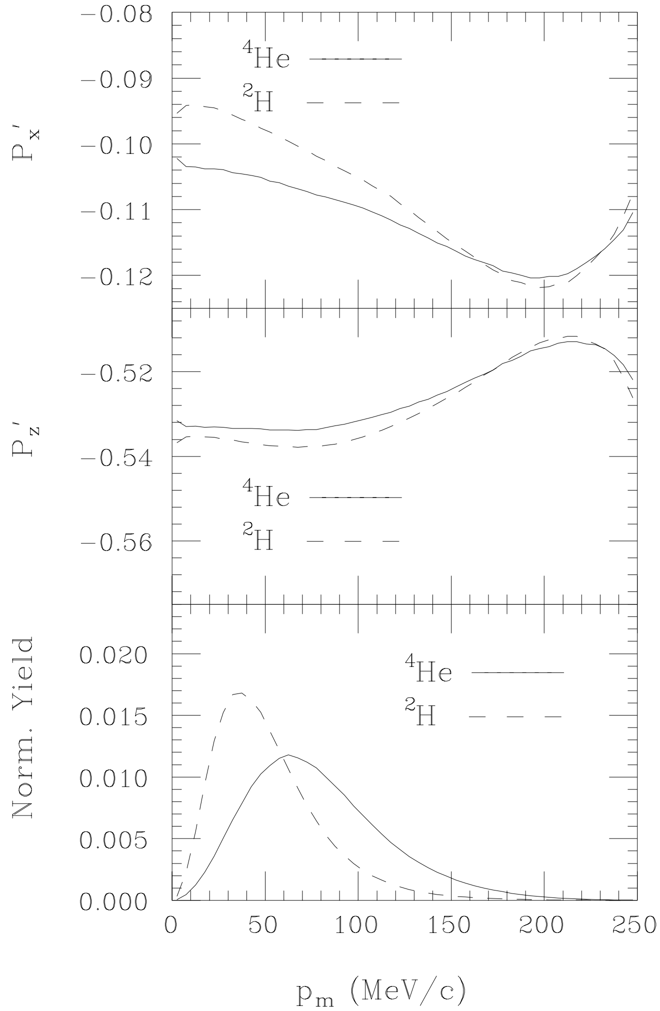

FIG. 1. Simulated missing-momentum distributions for neutron recoil polarization are compared for ^{4}He and ^{2}H targets using $\pm 10\%$ acceptance in electron energy, a 15 cm target cell, and nominal angular acceptances of HMS and the neutron polarimeter. Normalized yields are shown in the bottom panel for both targets.

IV. BEAM TIME REQUEST

A. Count Rate Estimates

Count rate estimates were made based upon the parameters summarized in Table I. A DWIA calculation using the van Oers optical potential [20] suggests that an attenuation factor of 0.82 should be applied to PWIA calculations. The MCEEP simulation gives an acceptance averaging factor of 0.36, defined in terms of the ratio between the accepted yield and the quasifree DWIA cross section for parallel kinematics at $p_m = 0$. Thus, using a spectroscopic factor of 0.75 we estimate that the average cross section will be about 0.19 μb/GeV/sr^2 for the proposed kinematics and acceptances.

To obtain an acceptable counting rate, we require a cryogenic helium target and luminosities up to about 4×10^{37} cm^{-2}s^{-1}, which corresponds to about 20 μA on a 15 cm cell operating at standard conditions, namely about 5 K and 10 atm. Hall A has already successfully operated 700 Watt LH2 and LD2 targets and will soon commission a helium target similar to that proposed here. Although it may be necessary to upgrade the cooling capacity of the Hall C cryotarget, the experience in Hall A with similar targets will be very helpful.

TABLE I. Count Rate Assumptions

target	cryogenic He
luminosity	$L \approx 4 \times 10^7$ (μb s)$^{-1}$
HMS solid angle	$\Delta\Omega_e \approx 11.1$ msr
HMS momentum acceptance	$\Delta k_f/k_f \approx \pm 10\%$
chamber efficiency	0.95
computer livetime	0.95
radiative correction	0.83
NPOL solid angle	$\Delta\Omega_n \approx 14.3$ msr
beam polarization	$h \sim 0.8$
NPOL efficiency	$f \approx 0.021$
neutron transmission	0.57
NPOL analyzing power	$\overline{A_y} \approx 0.15$
acceptance-averaging factor	0.36
spectroscopic factor	0.75
acceptance-averaged cross section	$\tilde{\sigma}_0 \approx 0.19$ μb/GeV/sr^2

B. Statistical Uncertainties

The statistical uncertainty in r_{xz} is obtained by adding in quadrature the statistical uncertainties in the sideways and longitudinal components. For a small counting asymmetry and large signal/noise ratio, these statistical uncertainties can be approximated by

$$\delta P_i' \approx \frac{1}{h\overline{A_y}}\sqrt{\frac{1}{N_i}} \tag{8}$$

where h is the beam polarization, $\overline{A_y}$ is the mean analyzing power of the polarimeter, and N_i is the total number of counts for component i. The minimum uncertainty in r_{xz} is obtained by dividing the beam time such that

$$\frac{N_x}{N_z} = |r_{xz}|^{-1} \Longrightarrow \frac{\delta r_{xz}}{r_{xz}} = \left[h\overline{A_y}\sqrt{N}\right]^{-1} \left|\frac{1}{P_x'} + \frac{1}{P_z'}\right| . \tag{9}$$

Therefore, to achieve a statistical precision goal of $\delta g/g \sim 0.05$ given $h = 0.8$ and $\overline{A_y} \approx 0.15$, requires a total of about 2.4×10^6 counts divided optimally between sideways and longitudinal polarization measurements. Using Galster electric and dipole magnetic form factors with a counting rate of 2.4 Hz estimated according to Table I, we need approximately 12 days of beam time to reach this goal.

C. Beam Time Request

Table II presents a summary of our beam time request. We estimate that approximately 12 days of beam time are needed to achieve the desired statistical accuracy. We assume that the polarimeter, precession magnet, and HMS configuration will be commissioned as part of experiment 93-038 and do not include any additional time here for testing of equipment. Nor do we include the time that might be needed to upgrade the cryotarget to handle the high-power helium cell. We do include 24 hours to make several Moller measurements of the beam polarization to accompany transitions between sideways and longitudinal polarization modes and an additional 24 hours for configuration changes. We do not include time for maintainance of the polarized source (spot motion, recesiation, etc.). Therefore, our request totals 14 days.

TABLE II. Beam Time Request

production runs	288 hr
configuration changes	24 hr
Moller measurements	24 hr
total	336 hr

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