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Measurement of the neutron magnetic form factor from inclusive quasielastic scattering of polarized electrons from polarized ^{3}He

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We report a measurement of the asymmetry in spin-dependent quasielastic scattering of longitudinally polarized electrons from a polarized ^{3}He target. The neutron magnetic form factor G_M^n has been extracted from the measured asymmetry based on recent PWIA calculations using spin-dependent spectral functions. Our determination of G_M^n at $Q^2=0.19$ (GeV/c)^2 agrees with the dipole parametrization. This experiment represents the first measurement of the neutron magnetic form factor using spin-dependent electron scattering.

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Electromagnetic form factors are of fundamental importance for an understanding of the underlying structure of nucleons. Knowledge of the distribution of charge and magnetization within the nucleons provides a sensitive test of models based on QCD, as well as a basis for calculations of processes involving the electromagnetic interaction with complex nuclei. Due to the lack of a free neutron target, the neutron electromagnetic form factors are known with less precision than the proton electric and magnetic form factors. They have been deduced in the past from elastic or quasielastic electron-deuteron scattering. This procedure involves considerable model dependence. The development of polarized targets and beams has allowed more complete studies of electromagnetic structure than has been possible with unpolarized reactions. In quasielastic scattering, the spin degrees of freedom introduce new response functions into the inclusive cross section, thus providing additional information on nuclear structure [1].

^{3}He is an interesting nucleus for polarization studies because its ground state wave function is predominantly a spatially symmetric S state in which the spin of the nucleus is carried mainly by the unpaired neutron. Therefore, inelastic scattering of polarized electrons from polarized ^{3}He in the vicinity of the quasielastic peak should be useful for studying the neutron electromagnetic form factors. This idea was first investigated by Blankleider and Woloshyn in closure approximation [2]. Friar *et al.* [3] have studied the model dependence in the spin structure of the ^{3}He wave function and its effect on the quasielastic asymmetry. Recently the plane wave impulse approximation (PWIA) calculations performed independently by two groups [4,5] using a spin-dependent spectral function show that the spin-dependent asymmetry is very sensitive to the neutron electric or magnetic form factors at certain kinematics near the top of the quasielastic peak. Two previous experiments [6,7] measured the spin-dependent asymmetry in quasielastic scattering of polarized electrons from polarized ^{3}He, and demonstrated that this new experimental technique is feasible for studying the neutron electromagnetic structure. As a result, new experimental programs utilizing polarized electrons and polarized ^{3}He targets to study the neutron electromagnetic structure and the nucleon spin structure are under way at several electron accelerator laboratories (SLAC, MIT-Bates, CEBAF, MAMI, DESY HERA).

The spin-dependent asymmetry for longitudinally polarized electrons scattered from a polarized spin-$\frac{1}{2}$ nuclear target can be written [1] as

$$A=-\frac{\cos\theta^* v_{T'}R_{T'}+2\sin\theta^*\cos\phi^* v_{TL'}R_{TL'}}{v_L R_L+v_T R_T}, \tag{1}$$

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where the ν_K are kinematic factors, and θ^* and ϕ^* are the polar and azimuthal angles of the target spin with respect to the 3-momentum transfer vector **q**. $R_L(Q^2,\omega)$ and $R_T(Q^2,\omega)$ are the longitudinal and transverse nuclear response functions associated with the unpolarized cross section and are functions of the square of the 4-momentum transfer Q^2 and the electron energy loss ω. $R_{T'}(Q^2,\omega)$ and $R_{TL'}(Q^2,\omega)$ are the two response functions arising from the polarization degrees of freedom. $R_{T'}$ is a transverse response function and $R_{TL'}$ represents the interference between the transverse and the longitudinal multipoles. By orienting the target spin at $\theta^* = 0°$ or $\theta^* = 90°$, corresponding to the spin direction either along the 3-momentum transfer vector **q** or normal to it, one can select the transverse asymmetry $A_{T'}$ (proportional to $R_{T'}$) or the transverse-longitudinal asymmetry $A_{TL'}$ (proportional to $R_{TL'}$). PWIA calculations [2–5] neglecting final state interactions (FSI) and meson exchange currents (MEC) indicate that the transverse asymmetry $A_{T'}$ is very sensitive to the square of the neutron magnetic form factor, ${G_M^n}^2$. The asymmetry calculation of Laget [8] shows that the effect of MEC and FSI on the transverse asymmetry for the exclusive process $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)pp$ at the Q^2 of the present work is negligible. Thus one can experimentally extract the neutron magnetic form factor from a measurement of the transverse asymmetry $A_{T'}$.

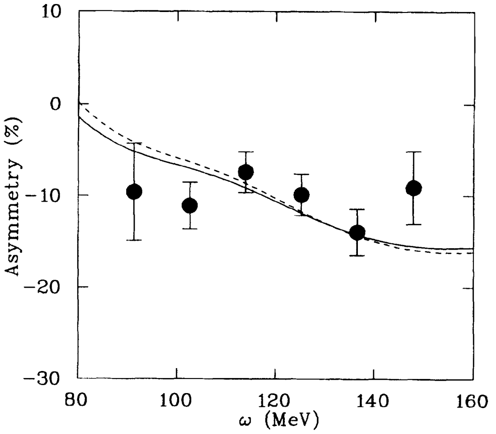

FIG. 1. The transverse asymmetry $A_{T'}$ as a function of electron energy loss ω. The solid circles are the data points from the present work with statistical uncertainties only. The dashed line is the calculation by Salmè *et al.*, and the solid line is the calculation by Schulze *et al.* [16].

We report in this Rapid Communication a measurement of the transverse asymmetry $A_{T'}$ at quasielastic kinematics and the extracted neutron magnetic form factor. The experiment was performed at the MIT-Bates Linear Accelerator Center using a 370 MeV longitudinally polarized electron beam. The source of the polarized electrons was a crystal of GaAs optically pumped by a Ti:sapphire laser driven with an Ar-ion laser. A Wien spin rotator was employed to produce longitudinally polarized electrons at the target. The average beam current during the experiment was 25 μA and the average beam polarization was determined using a Møller apparatus [9] to be 36.5%. The polarized ^{3}He target used in this experiment was a double-cell system consisting of a glass pumping cell and a copper target cell. The target was polarized by the metastability-exchange optical pumping technique [10]. A weak electric discharge was maintained in the pumping cell to excite ^{3}He atoms into the metastable state. The optical pumping light was supplied by a Nd-doped lanthanum magnesium hexaluminate crystal (LNA) pumped by a krypton arc lamp in a Laser Application 9560 cavity. The target was operated at 13 K during the experiment with a ^{3}He gas pressure of 2.2 torr. The target wall was coated with a thin layer of nitrogen to maintain a sufficiently long relaxation time at low temperature. A holding field of 36 G provided by a pair of Helmholtz coils defined the target spin quantization axis. The target spin direction was aligned at an angle of 42.5° to the electron beam. High voltage on a Pockels cell was varied to change the helicity of the circularly polarized laser light, thus reversing the target spin direction. The target spin was flipped several times a day to minimize systematic uncertainties. The pumping cell polarization was measured continuously by monitoring the circular polarization of the 668-nm line excited by the ^{3}He discharge. The target polarization was inferred from the polarization of the pumping cell and the time constants of the coupled system. This optical measurement of the ^{3}He nuclear polarization was calibrated by an NMR measurement [11] with an accuracy of ±2%. With 25μA of beam, the target polarization was 38% or greater. With no depolarization from the beam, the target polarization was typically higher by a factor of 1.15.

The scattered electrons were detected in the Medium Energy Pion Spectrometer (MEPS) configured at an electron scattering angle $\theta = 91.4°$ to the left of the beam. The spectrometer central momentum was 250 MeV/c corresponding to $Q^2 = 0.19$ (GeV/c)^2 and $\theta^* = 8.9°$ or 171.1° for positive or negative target polarization, respectively. The MEPS spectrometer had a momentum acceptance of ±10% and an extended target acceptance of 2 cm resulting in a target thickness of 3.3×10^{18} cm^{-2}. Tungsten collimators were installed to minimize the background from the target window seen by the spectrometer. The detector package consisted of two vertical drift chambers, three planes of trigger hodoscopes, and an Aerogel Čerenkov detector. The trigger was formed by events for which all three hodoscopes fired. The Čerenkov detector was used for pion rejection. The dominant spectrometer background came from the target wall. The empty target background yield was measured periodically during the experiment to be 12% of the full target yield at the quasielastic kinematics for the asymmetry measurement. Beam position monitors were employed to monitor the location of the beam near the target for each electron helicity. The contribution of the helicity-correlated beam motion to the measured asymmetry was negligible. The spin-averaged ^{3}He quasielastic yield has been extracted from the data and it agrees well with a y-scaling calculation [12] which describes the quasielastic cross section as the product of a kinematic factor, a single-nucleon cross section, and a universal scaling function of the scaling variable y. The yield also agrees within ±5% with measured cross sections [13] scaled to the kinematics of this experiment. The ^{3}He elastic asymmetry was measured in another spectrometer during the experiment as a check of the experimental procedure. The measured elastic asymmetry is 29.9±3.9%, as compared to the ex-

TABLE I. Results of asymmetry measurements.

Charge (μA-h)	θ^* (deg)	ϕ^* (deg)	A (%)
3956	8.9	180	-10.66 ± 1.40
2573	171.1	0	9.51 ± 1.81
6529 (combined)			$-10.23 \pm 1.11 \pm 0.56$
Theory [15]	8.9	180	-9.85
Theory [16]	8.9	180	-10.09

pected 29.2% using form factors measured by Rosenbluth separation [14].

The transverse asymmetry $A_{T'}$ has been extracted from the spin-dependent quasielastic inclusive cross section as a function of the electron energy loss ω for a total beam charge of 6529 μA-h. Corrections have been made for the empty target background, the elastic radiative tail, and the quasielastic radiative effect. The measured quasielastic transverse asymmetry $A_{T'}(\omega)$ is shown in Fig. 1 along with calculations at the kinematics of the present work by Salmè *et al.* (Gari-Krüpelmann form factor parametrization) [15] and Schulze *et al.* (Galster parametrization) [16]. The difference between the two calculations arises from the different wave functions and form factor parametrizations used in the calculations. The data are in good agreement with both calculations. The measured asymmetry averaged over the experimental ω acceptance, together with the calculated asymmetry averaged over the spectrometer acceptance from Refs. [15,16], are listed in Table I. The sign change in the measured asymmetry corresponds to a flip in the target spin direction. The uncertainties listed for the combined measured asymmetry are the statistical and systematic uncertainty, respectively.

To determine ${G_M^n}^2$ from the experimental measurement, the calculations of Salmè *et al.* [15] and Schulze *et al.* [16] have been used to generate $A_{T'}({G_M^n}^2)$ independently. The extracted ${G_M^n}^2$ values at $Q^2=0.19$ (GeV/c)^2 agree within 3% for the two calculations. The standard dipole form factor parametrization [17] gives

$$\frac{G_M^n}{\mu_n}=\frac{G_M^p}{\mu_p}=G_E^p=G_D=\left[1+\frac{Q^2}{0.71}\right]^{-2}, \tag{2}$$

where Q^2 is in (GeV/c)^2. In units of $(\mu_n G_D)^2$, the average of the two extracted ${G_M^n}^2$ values discussed above gives $(G_M^n/\mu_n G_D)^2$ = 0.998 ± 0.117 ± 0.059 ± 0.030, with the uncertainties corresponding to the statistics, systematics, and model dependence, respectively. The systematic uncertainty is dominated by the uncertainties in the determination of the beam polarization (±4%) and the target polarization (±3%). The uncertainty from the model dependence of the extracted ${G_M^n}^2$ arises from both the uncertainty of the ^{3}He wave function and the uncertainty of the proton electromagnetic form factors involved in the calculations. The wave function uncertainty was estimated from calculations by Salmè *et al.* [15] using the Reid soft-core interaction and by Schulze *et al.* [16] using the Paris potential. The uncertainty due to proton form factors was estimated using Höhler [18], Gari-Krümpelmann [19], Galster [17], and Iachello-Jackson-Lande [20] parametrizations, and was found to dominate the uncertainty due to model dependence. The extracted ${G_M^n}^2$ value from this experiment at $Q^2=0.19$ (GeV/c)^2 is shown in Fig. 2 with its total uncertainty determined by adding all three uncertainties in quadrature. Plotted also are the previous data on ${G_M^n}^2$ from the electron-deuteron experiments in the low Q^2 region. The uncertainties in the inclusive data from Hughes *et al.* [21] include a global 5% theoretical uncertainty. The uncertainties in the data from Refs. [22–27] do not include a theoretical uncertainty. The recent data of Markowitz *et al.* [28] include a theoretical uncertainty of 3%. The Gari-Krümpelmann [19] and Höhler [18] form factor parametrizations are also shown in Fig. 2.

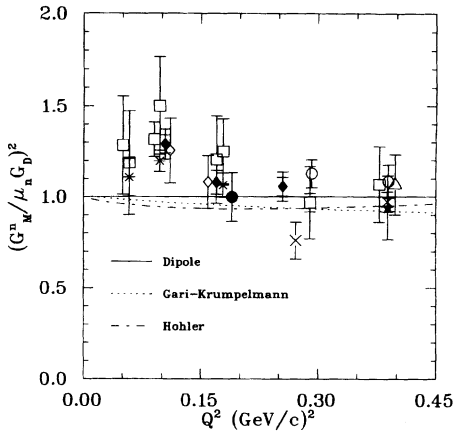

FIG. 2. The square of the neutron magnetic form factor ${G_M^n}^2$, in units of the standard dipole parametrization, $(\mu_n G_D)^2$, in the low Q^2 region. The solid circle is from the present work shown with the total uncertainty dominated by the statistical error. The hollow squares are from Hughes *et al.* [21], the hollow diamonds are from the analysis by Kramer *et al.* [22] of the data from Grossetête *et al.* [23], the asterisks are from Braess *et al.* [22], the crosses are from Hanson *et al.* [24], the hollow circles are from Budnitz *et al.* [25], the star is from Bartel *et al.* [26], the triangle is from Stein *et al.* [27], and the solid diamonds are from Markowitz *et al.* [28] with the inner (outer) error bars being the statistical (total) uncertainties. The data of Markowitz *et al.*, Hughes *et al.*, and Stein *et al.* have been displaced slightly to improve readability.

In conclusion, the neutron magnetic form factor at low Q^2 has been extracted for the first time from spin-dependent electron scattering using a polarized ^{3}He target. The uncertainty of the extracted neutron magnetic form factor is dominated by the statistical error; the uncertainty from model dependence is comparatively small. This experiment further demonstrates that polarized ^{3}He is very useful for studying the electromagnetic structure of the neutron, and provides strong motivation to proceed with further experiments using polarized ^{3}He targets.

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