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Determination of the neutron electric form factor in 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 gas target. The asymmetry is measured at kinematics sensitive to the transverse-longitudinal response function $R_{TL'}(Q^2,\omega)$. The value of the neutron electric form factor $G_E^n(Q^2=0.16\ (\text{GeV}/c)^2)=+0.070\pm0.100\pm0.035$ is extracted from the asymmetry using a Faddeev calculation of the ^{3}He wave function.

The development of both polarized targets and beams has allowed more complete studies of electromagnetic structure than is possible with unpolarized reactions alone. In quasielastic scattering, the spin degrees of freedom introduce new response functions into the inclusive cross section which provide additional information on the nuclear structure [1]. In particular, ^{3}He is an interesting nucleus for polarization studies because in the quasielastic scattering region the spin-dependent properties are dominated by the neutron within the nucleus. This occurs because the ^{3}He wave function is predominantly a spatially symmetric S state and antisymmetrization of the wave function requires that the protons be in a spin singlet state. If the ^{3}He wave function were entirely a symmetric S state, the spin of the nucleus would be carried solely by the unpaired neutron, and measurements of spin-dependent quantities in inclusive quasielastic scattering of polarized electrons from polarized ^{3}He would measure the neutron electromagnetic form factors directly. There are small admixtures of other states in the ^{3}He wave function which introduce a dependence upon the proton electromagnetic form factors, but realistic calculations for the three-body system give a reliable estimate of these contributions. Calculations using a Faddeev wave function indicate that in the vicinity of the quasielastic peak the neutron properties dominate [2]. This is supported by recent experimental results measuring the spin-dependent asymmetry in quasielastic scattering of polarized electrons from polarized ^{3}He [3].

Our current knowledge of the neutron electric form factor is rather limited. Only the slope of G_E^n at zero squared four-momentum transfer ($Q^2=0$) is well determined, from measurements of neutron scattering from atomic electrons [4]. The bulk of our knowledge about the Q^2 dependence of G_E^n comes from measurements of the deuteron electric structure function $A(Q^2)$ in elastic electron-deuteron scattering [5,6]. There is uncertainty in the values obtained from these studies because of the sensitivity to the deuteron wave function. A recent measurement [6] of $A(Q^2)$ has reduced the statistical and systematic errors for Q^2 between 0.16 and 0.70 $(\text{GeV}/c)^2$; the authors quote a systematic error due to the choice of the NN

potential on the extracted $G_E^n(Q^2)$ of ±40% at $Q^2=0.58$ $(\mathrm{GeV}/c)^2$ and an overall systematic error of approximately ±45% when errors due to meson-exchange currents, relativistic corrections and the proton form factor are included. The systematic errors for this technique of extracting G_E^n become even larger at $Q^2 \geq 1$ $(\mathrm{GeV}/c)^2$. Clearly a new experimental approach is needed. The use of polarization observables can reduce the model dependence of the extracted information. Several new techniques taking advantage of this are currently being pursued. One approach involves the detection of the polarization of the recoil neutron in quasielastic polarized electron-deuteron scattering. Theoretical calculations show that the neutron polarization component perpendicular to the momentum transfer and in the scattering plane is directly proportional to G_E^n and is insensitive to the deuteron model [7]. Another technique is the use of a polarized electron beam and a polarized ^{3}He target discussed in this paper. The model dependence of the G_E^n values obtained using this technique is much less than that from elastic electron-deuteron scattering. Although it has been suggested that the neutron form factors will be modified by medium effects within nuclei [8], the effect at the Q^2 value of this experiment is small.

The spin-dependent asymmetry can be written as

$$A=\left[\left(\frac{d^2\sigma}{d\Omega dE}\right)_+ - \left(\frac{d^2\sigma}{d\Omega dE}\right)_-\right] \Bigg/ \left[\left(\frac{d^2\sigma}{d\Omega dE}\right)_+ + \left(\frac{d^2\sigma}{d\Omega dE}\right)_-\right], \tag{1}$$

where the + (−) indicates scattering by a positive (negative) helicity electron. Assuming single photon exchange and the extreme relativistic limit, the asymmetry for scattering longitudinally polarized electrons from a spin-$\frac{1}{2}$ target is given by [1]

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

where the v_K are kinematic factors (see Ref. [1]) and the direction of the target polarization is specified by the angles θ^* and ϕ^*, as defined in Fig. 1. The asymmetry measured experimentally is

$$A_{\mathrm{exp}}=p_e p_T A, \tag{3}$$

where p_e and p_T are the electron and target polarizations, respectively. In general, the response functions R are a function of Q^2 and the electron energy loss ω. $R_L(Q^2,\omega)$ and $R_T(Q^2,\omega)$ are the spin-dependent longitudinal and transverse response functions and $R_{T'}(Q^2,\omega)$ and $R_{TL'}(Q^2,\omega)$ are two additional response functions which contribute when both the target and beam are spin polarized. $R_{TL'}$ arises from interference of transverse and longitudinal multipoles. By orienting the target spin along **q** ($\theta^*=0°$) or normal to **q** ($\theta^*=90°$), one selects the measured asymmetry to be proportional to $R_{T'}$ or $R_{TL'}$, respectively. The calculations of Blankleider and Woloshyn [2] indicate that for ^{3}He, $R_{T'}$ is primarily sensitive to the square of the neutron magnetic form factor, G_M^{n2}, and $R_{TL'}$ is sensitive to the product $G_E^n G_M^n$. The measured asymmetry for $\theta^* \approx 0°$ agrees with this calculation [3].

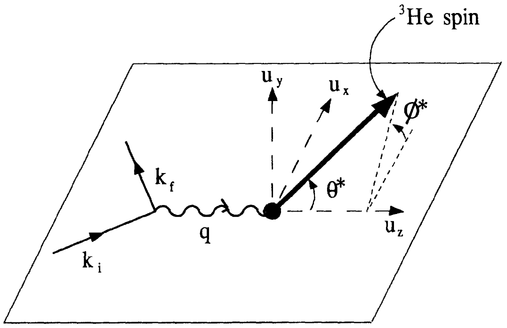

FIG. 1. Kinematics for electron scattering from polarized targets. Here $\mathbf{u}_z$ is along the direction of momentum transfer **q**. The vector $\mathbf{u}_y$ is normal to the electron scattering plane and $\mathbf{u}_x=\mathbf{u}_y\times\mathbf{u}_z$ lies in the scattering plane. The target polarization direction is specified by the angles (θ^*,ϕ^*) in this coordinate system.

The measurement reported in this paper was performed at quasielastic kinematics near $\theta^*=105°$ where the term involving the response function $R_{TL'}$ contributes approximately two-thirds of the spin-dependent cross section. The experiment was carried out at the MIT-Bates Linear Accelerator Center using a longitudinally polarized electron beam at 574-MeV incident energy. A polarized ^{3}He-gas target, polarized by metastability exchange optical pumping [9], was developed for the experiment. A general description of the target is given in Ref. [3]; a detailed description will be reported elsewhere [10]. The target contained 2 torr of ^{3}He at 17 K. Collimators were used to limit the target length viewed by the spectrometer to 10 cm. This corresponds to an effective target thickness of 1.1×10^{19} nuclei/cm^2. The ^{3}He polarization was monitored continuously during the experiment. The target polarization typically ranged between 20% and 30% over the duration of the experiment. The presence of the electron-beam current reduced the target polarization to approximately 85% of the value when the beam was off.

Electrons scattered at a central angle of $\theta=44.0°$ from the polarized ^{3}He target were detected in the BIGBITE magnetic spectrometer. The average four-momentum transfer in the quasielastic region was $Q^2=0.16$ $(\mathrm{GeV}/c)^2$. The spectrometer was set at a central momentum of 517 MeV/c and had a momentum acceptance of $\sim\pm130$ MeV/c, sufficient to cover the entire quasielastic peak. Events analyzed by the BIGBITE spectrometer are bent in the horizontal plane, so there is a correlation between the position along the target at which an event originates and the reconstructed momentum. This limited the momentum resolution for the experiment to 19 MeV/c. The scattering events analyzed to obtain the quasielastic spin-dependent asymmetry were limited to the region 57 MeV $\leq \omega \leq$ 160 MeV to restrict the analyzed events to kinematics near the quasielastic peak where contributions from the D-state components are minimized.

Because the target was polarized through direct optical pumping of the ^{3}He atoms, the only gaseous atomic species present was ^{3}He. The major background was from the target cell walls, which contributed 15 ± 4% of the total yield in the quasielastic region used for the asymmetry calculation. Other sources of background were pions (1.4 ± 1.4%) and events in the elastic radiative tail (4.4 ± 0.4%). The measured unpolarized cross section, corrected for the empty-target events, was compared with a Monte Carlo calculation which folded previous ^{3}He cross-section data [11] (scaled to the present kinematics using y scaling [12]) with the spectrometer acceptance. The calculated yield in the quasielastic region was radiated using the procedure of Mo and Tsai [13] for the comparison and includes the pion and elastic radiative backgrounds. A plot of the experimental and calculated yield is shown in Fig. 2. The yield on the low ω side of the peak is the elastic and threshold continuum strength which is not calculated by the model. The integrated yield within the energy region used for the asymmetry calculation agrees with the Monte Carlo calculation to within 12%.

To reduce the systematic errors, the data were acquired in individual runs, each containing approximately 10 μA h of charge. The target polarization of each run was corrected for temperature and pressure fluctuations. The electron polarization was measured by Møller scattering from a removable magnetized foil upstream of the target [14]. Systematic errors of ± 10% are assigned to both the target and beam polarizations.

Radiative corrections to the asymmetry were calculated for both the continuum scattering and the elastic tail background. Integrated across the energy range used for the asymmetry calculation, the quasielastic radiative correction is (2.2 ± 1.2)% of A. The calculation assumes a constant quasielastic asymmetry over the quasielastic peak. The correction for the elastic tail is much larger because at the kinematics of this experiment the elastic asymmetry is calculated to be 18%. Therefore, even though the cross section from the tail is only ~4% of the experimental cross section, the correction to the quasielastic asymmetry for the elastic background is (−25.2 ± 4.4)% of A. In addition, a systematic error of ± 10% is included to account for a possible background asymmetry in the pion yield.

TABLE I. Results of asymmetry measurements.

Charge μA h	θ^* degrees	ϕ^* degrees	A (%)
228	108.4	0	+3.2 ± 2.7
336	101.4	0	+2.8 ± 2.6
808	78.6	180	−1.9 ± 1.7
1372 (combined)			+2.38 ± 1.27 ± 0.44

Variations of the beam properties with the electron helicity can result in a false asymmetry and are a potential source of error for asymmetry measurements. The beam position was monitored and analyzed for helicity correlated shifts which could give rise to different count rates for the background scattering because of the geometry of the target system. Runs with beam position shifts in either direction more than two standard deviations from the average were eliminated from the data set. This requirement eliminated ~5% of the data, most of which were acquired at the beginning of the experiment when the beam stability was the poorest. An estimate of the false asymmetry, made from empty target spectra acquired at different beam positions, is ± 1% of A.

The experimental data were obtained at spin angles which differed from the value maximally sensitive to G_E^n by 18.4° (228 μA h) and 11.4° (1144 μA h). The theoretical asymmetries for the two orientations differ by ≈ 15% and are both dominated by $R_{TL'}$. The asymmetry was measured for three different configurations of target spin direction and the results are given in Table I. Combining

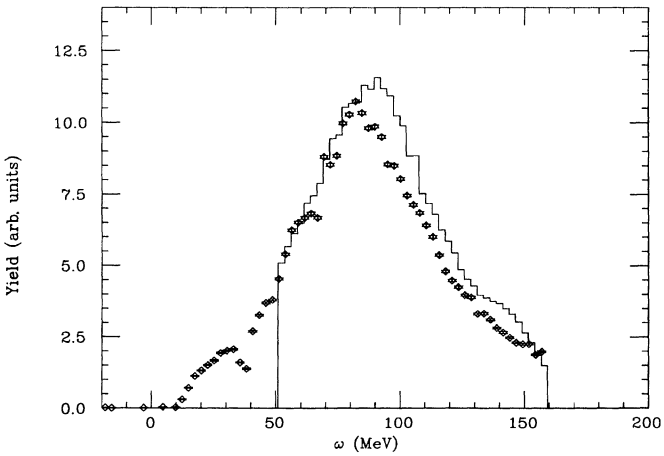

FIG. 2. Experimental yield. The histogram is a Monte Carlo calculation of the yield in the quasielastic region folded with the spectrometer acceptance.

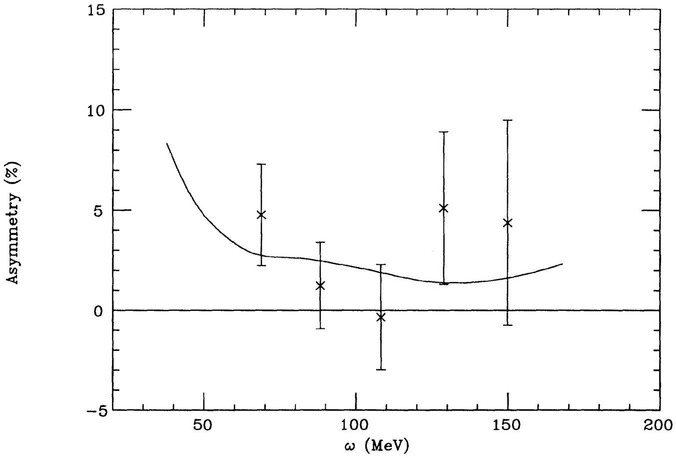

FIG. 3. Experimental $A(\omega)$ and calculation using a Faddeev wave function for ^{3}He. The solid line is the best fit, $G_E^n = +0.070$. The error bars on the data are statistical only.

all the data (reversing the sign of the $\theta^* = 78.6°$ result) yields the asymmetry $A = +2.38 \pm 1.27 \pm 0.44\%$, where the first uncertainty is statistical and the second is the systematic uncertainty. Calculations based on two different models of the neutron contribution to the quasielastic asymmetry predict $A = 2.0\%$ [2] and $A = 2.2\%$ [15] using the best fit neutron form factor parametrization of Ref. [5].

To extract an estimate of G_E^n from this experiment, the computer code of Blankleider and Woloshyn [2] was used to generate values of $A(G_E^n)$. The form factor corresponding to our experimental asymmetry along with statistical and systematic uncertainties were extracted from a linear fit to the calculated asymmetry. The resulting value of the neutron electric form factor is $G_E^n(Q^2) = +0.070 \pm 0.100 \pm 0.035$. Based upon the quoted uncertainties in the neutron and proton polarizations within a polarized ^{3}He target in Ref. [15], there is an additional systematic error of approximately ±13% in the extraction of G_E^n arising from model dependence. Figure 3 shows the experimental asymmetry and the calculation of $A(\omega)$ which corresponds to the best fit. For comparison, the measurement by Platchkov *et al.* [6] gives $G_E^n = 0.040$ at $Q^2 = 0.16$ (GeV/c)^2 with a systematic error due to the choice of the deuteron wave function of approximately ±40%.

In summary, this experiment demonstrates the new experimental technique of inclusive quasielastic polarized electron scattering from polarized ^{3}He as a means of determining the neutron electric form factor. The measurement reported here was limited by the statistical uncertainty, a problem which can be overcome in future experiments with more beam time. Recent advancements [16] in the laser technology have significantly improved laser stability and increased the achievable polarizations and pumping rates for optical pumping through ^{3}He metastability exchange. These improvements will greatly increase the sensitivity of future experiments measuring the quasielastic asymmetry of polarized electrons scattering from polarized ^{3}He.

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