Quasielastic Scattering of Polarized Electrons from Polarized ^{3}He and Measurement of the Neutron's Form Factors

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We report measurements of asymmetries in quasielastic scattering of polarized electrons from polarized ^{3}He at $Q^2=-0.2$ (GeV/c)^2. We measure $A_{T'}=(-2.6\pm0.9\pm0.46)\%$ and $A_{TL'}=(+1.75\pm1.2\pm0.31)\%$. The asymmetry $A_{T'}$ depends predominantly on the previously measured neutron magnetic form factor and provides a test of theories of spin-dependent quasielastic scattering. Our result for $A_{T'}$ is consistent with a previously reported measurement and suggests that the current theoretical picture is incomplete and final-state-interaction and meson-exchange corrections are necessary if the electric form factor of the neutron is to be reliably extracted from the asymmetry $A_{TL'}$.

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The electric form factor of the neutron (G_E^n) is an important fundamental quantity sensitive to the charge distribution of the neutron [1]. It plays a role in extracting nuclear structure information in electron scattering experiments, and more fundamentally, it reveals the elementary particle structure of the neutron. Data on G_E^n are limited: We know $G_E^n(Q^2=0)=0$ (the neutron charge) [2], and the slope near $Q^2=0$ has been measured [3] revealing that the charge radius of the neutron is negative, i.e., there is a concentration of negative charge on the outside. At the quark level, an explanation of the negative charge radius is provided by including the tensor interaction of the quark's color-magnetic moments [4]. At $|Q^2|>0$, large uncertainties limit our knowledge of G_E^n. Precise measurements, particularly in the range $0.2<|Q^2|<1.0$ (GeV/c)^2, are crucial in distinguishing among parametrizations, predictions, and models of nucleon structure [5-8].

Inelastic scattering of polarized electrons from polarized ^{3}He at the quasielastic peak may be useful for extracting G_E^n. This idea was initially investigated by Blankleider and Woloshyn [9], who point out that a polarized ^{3}He target nucleus contains one neutron with its spin nearly parallel to the ^{3}He spin and two protons with their spins nearly canceling. Friar *et al.* have calculated the polarizations of the neutron (P_n) and proton (P_p) as $P_n=0.87\pm0.02$ and $P_p=-0.027\pm0.004$ [10]. Thus, in the impulse-approximation picture of quasielastic scattering, spin dependence can be described as elastic scattering from the polarized nucleons which is dominated by the neutron. The spin dependence leads to an asymmetry for inclusive polarized-electron–polarized-^{3}He scattering. For fixed E, θ, and $Q^2=\nu^2-|\mathbf{q}|^2$, where $\nu=E-E'$, it is [11]

$$A=\Delta(\theta^*,\phi^*)/\Sigma\,, \tag{1}$$

where the total differential cross section for longitudinally polarized electrons of helicity $h=\pm1$ is

$$\frac{d^2\sigma}{d\Omega\,dE}=\Sigma(E,\theta,\nu)+h\Delta(E,\theta,\nu,\theta^*,\phi^*)\,, \tag{2}$$

with $\sigma_M(E,\theta)$ the Mott cross section and θ^* and ϕ^* the polar angles of the target polarization in the coordinate system illustrated in Fig. 1. The helicity-dependent and helicity-independent contributions are given by

$$\Delta=-\sigma_M(E,\theta)[v_{T'}R_{T'}(Q^2,\nu)\cos\theta^* + v_{TL'}R_{TL'}(Q^2,\nu)\sin\theta^*\cos\phi^*]$$

and

$$\Sigma=\sigma_M(E,\theta)[v_LR_L(Q^2,\nu)+v_TR_T(Q^2,\nu)]\,. \tag{3}$$

The quantities v_T, etc., are defined in Table I.

In the impulse approximation, the spin-dependent

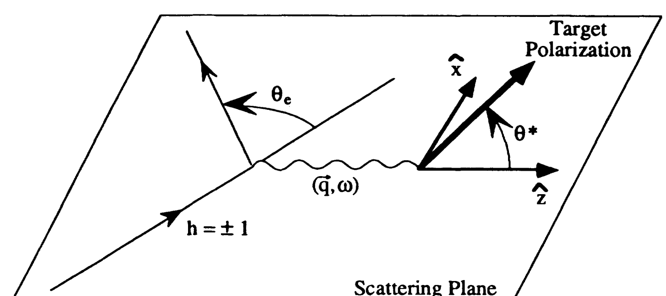

FIG. 1. Kinematics for inclusive scattering of longitudinally polarized electrons from polarized ^{3}He with target polarization in the scattering plane. A right-handed coordinate system is used.

response functions at the quasielastic peak (labeled by ν_0) are given in terms of the elastic form factors for the nucleons as

$$R_{T'}(Q^2,\nu_0) = -2\left(1+\frac{|\mathbf{q}|^2}{Q^2}\right)\{P_n(G_M^n)^2+2P_p(G_M^p)^2\}F(\nu_0)\,, \tag{4}$$

$$R_{TL'}(Q^2,\nu_0) = -2\left[2\left(1+\frac{|\mathbf{q}|^2}{Q^2}\right)\frac{|\mathbf{q}|^2}{Q^2}\right]^{1/2}\{P_nG_E^nG_M^n+2P_pG_E^pG_M^p\}F(\nu_0)\,. \tag{5}$$

The spin-independent response functions are

$$R_T(Q^2,\nu_0) = -2\left(1+\frac{|\mathbf{q}|^2}{Q^2}\right)\{(G_M^n)^2+2(G_M^p)^2\}F(\nu_0)\,, \tag{6}$$

$$R_L(Q^2,\nu_0) = -\frac{|\mathbf{q}|^2}{Q^2}\{(G_E^n)^2+2(G_E^p)^2\}F(\nu_0)\,, \tag{7}$$

where $G_E^{n,p}(Q^2)$ and $G_M^{n,p}(Q^2)$ are the electric and magnetic form factors of the nucleons and $F(\nu)$ is the scaling function for quasielastic scattering. The nucleon polarization P_n or P_p is the average over all initial momenta of the nucleon of the difference between the probability that the nucleon is spin up and the probability that it is spin down. At the quasielastic peak, all nucleon momenta are included and the average polarizations are indicated. The connection to elastic scattering from nucleons is made by replacing the factor $-(1+|\mathbf{q}|^2/Q^2)$ with $\tau=-Q^2/4M_p^2$. The asymmetry sensitive to $R_{T'}$ is labeled $A_{T'}$ (for $\theta^*=0,\pi$). $A_{TL'}$ is sensitive to $R_{TL'}$ (for $\theta^*=\pi/2,3\pi/2$). $A_{TL'}$ is particularly interesting since it depends linearly on G_E^n. The calculation of Blankleider and Woloshyn is more general and can be used for values of ν in the wings of the peak where different portions of the nucleon momentum and angular momentum distributions contribute.

The experiment was performed at the MIT Bates Linear Accelerator Center. A longitudinally polarized electron beam was produced by photoemission from a GaAs crystal using circularly polarized laser light. The electron gun used is similar to a SLAC design [12], although the injector is matched to the higher Bates injection energy. The beam was accelerated in two passes through the linac to an energy of 578 MeV. This energy was chosen so that the electrons' spins precess relative to their momentum by 2π in the acceleration, recirculation, and steering process. The longitudinal polarization of the high-energy electron beam was confirmed by Møller scattering after the final steering magnet to be 0.4 ± 0.05 [13]. A high-density polarized ^{3}He target based on spin exchange with laser optically pumped Rb [14] has been developed for this work. The important target properties are ^{3}He density of about 10^{20} cm^{-3} and total length of 7.5 cm. The target polarization, which depended most strongly on laser power, varied during the run with polarization magnitude 10% to 27%. A novel two cell target [15] was employed and high ^{3}He polarizations were achieved with 2–3 W of laser power at 795 nm, the Rb $D1$ resonance line. For the measurement of $A_{T'}$, (θ^*,ϕ^*) was $(3.2°,0)$ and $(176.8°,180°)$ and for $A_{TL'}$, (θ^*,ϕ^*) was $(90.2°,0)$.

TABLE I. Definition of quantities used in polarized-electron–polarized-^{3}He scattering.

Quantity	Definition
v_L	$(Q^2/\lvert\mathbf{q}\rvert^2)^2$
v_T	$-\frac{1}{2}(Q^2/\lvert\mathbf{q}\rvert^2)+\tan^2\theta/2$
$v_{T'}$	$\tan(\theta/2)[-(Q^2/\lvert\mathbf{q}\rvert^2)+\tan^2\theta/2]^{1/2}$
$v_{TL'}$	$(1/\sqrt{2})(Q^2/\lvert\mathbf{q}\rvert^2)\tan\theta/2$

Electrons scattered from the target were detected by the One Hundred Inch Proton Spectrometer (OHIPS), a vertical bend quadrupole-quadrupole-dipole spectrometer oriented at 51.1°. The central momentum was 0.462 GeV/c [$Q^2=-0.2$ (GeV/c)^2], and the total momentum bite was $\pm5\%$. In order to shield the spectrometer aperture from electrons scattered from the target end windows (0.015 cm of glass), the target length viewed by the spectrometer was collimated with slits to a total length of 4 cm along the beam. The beam current of polarized electrons on target was 5–7 μA, limited by the polarized electron source and accelerator performance.

The asymmetry for quasielastic scattering is defined as

$$A=\frac{1}{P_e}\frac{1}{P_3}\frac{1}{D}\frac{\eta_R-\eta_L}{\eta_R+\eta_L}\,, \tag{8}$$

where η_R and η_L are the number of scattered electrons per incident electron for positive (R) and negative (L) electron helicities, respectively, (i.e., corrected for any charge asymmetry), P_e is the electron polarization, and P_3 is the ^{3}He polarization. f is the dilution factor, the ratio of total counts from ^{3}He to that from all other sources. f and P_3 are not independently determined quantities since both depend on knowledge of the ^{3}He number density. The ^{3}He magnetization is determined by adiabatic fast passage NMR signals from the polarized ^{3}He. These are calibrated relative to proton (^{1}H) signals from an H_2O sample in a cell identical to the target cell. The ^{3}He polarization derived from the NMR measurement is

$$P_3=\frac{S_3}{S_1}\frac{[^1\mathrm{H}]}{[^3\mathrm{He}]}\frac{\mu_1}{\mu_3}P_1\,, \tag{9}$$

where $S_{1,3}$ are the NMR signal sizes, [^{1}H] and [^{3}He] are the number densities, $\mu_{1,3}$ are the magnetic moments, and the subscripts 1 and 3 refer to ^{1}H and ^{3}He, respectively. The dilution factor is given by

$$f=\frac{[^3\mathrm{He}]}{\eta_{\mathrm{total}}}\int\frac{d^2\sigma_3}{dE\,d\Omega}dE\,d\Omega\,dz\,. \quad (10)$$

η_{total} is the total number of scattered electrons per incident electron from all target materials and the integral is taken over the target length (along z) and the spectrometer solid angle and energy bite. With the target slits in position, we measured proton elastic scattering from an extended H_2 gas target with precisely known density to determine $\int(d\sigma_1/d\Omega)d\Omega\,dz$. We used previous data and y scaling to determine $\int(d^2\sigma_3/dE\,d\Omega)dE$ [16]. Thus the product of $P_3 f$ does not depend on knowledge of [^{3}He]. Both the target polarization and the dilution factor varied with time and $P_3 f$ was extracted for each run. f varied from 0.59 to 0.73 since the beam halo in particular changed the fraction of electrons scattered from the target cell walls. In Table II, we list the contributions to the total systematic error of the measured asymmetries as percentages of the asymmetry. The total systematic error assigned is 17% of the asymmetry derived when all sources are combined in quadrature. Measurements with the same setup of asymmetries for elastic scattering from ^{3}He are consistent with the values of P_e and P_3 used in our analysis. The precision of the elastic scattering measurement corresponds to a relative uncertainty of 30% and cannot be used to reduce the systematic error for the quasielastic scattering measurements. The elastic scattering results are reported in Ref. [15].

The measured asymmetries for each run of about 1-h duration are extracted with $P_3 f$ determined from η_{total} for the run and NMR scans at the beginning and end of the run. The time between NMR scans, 1 h, is short compared to the time constant for build up or decay of ^{3}He polarization in the target and therefore provides a valid measure of the average of S_3 for each run. The combined asymmetries for each target polarization configuration are given in Table III. The first uncertainty is statistical and the second is the systematic uncertainty. For the measurement of the asymmetry $A_{T'}$, the target spin was reversed to provide an additional consistency check.

The prediction for $A_{T'}$ given in Table III is derived from total cross sections for each helicity including contributions from quasielastic and elastic scattering. These are combined, corrected for radiative effects, energy loss, and finite momentum resolution, and averaged over the spectrometer momentum bite. For the quasielastic contribution, we have used measured values of G_M^n and G_M^p [17] as input data to the calculation of Blankleider and Woloshyn [9]. The work of Friar *et al.* shows that the average polarization of the neutron and proton in ^{3}He combined with the impulse-approximation model is consistent to within 5% with the calculation of Blankleider and Woloshyn. For the elastic scattering contributions, elastic form factors for ^{3}He appear in the "Super-Rosenbluth" formalism [11,18]. The uncertainties assigned to the prediction are due to uncertainties of the polarizations of the neutron and proton in polarized ^{3}He [10], and the uncertainties of the nucleon form factors. The dominant uncertainty is in G_M^n, the neutron magnetic form factor [17]. The prediction's error does not include any estimate of the model's reliability or shortcomings. The previously published result [19] for kinematics identical to one of our measured target polarization angles is also given in Table III. Since $A_{TL'}$ depends linearly on G_E^n, an arguably unknown quantity, we provide no prediction.

The asymmetry $A_{T'}$ can be used to assess the reliability of models that might be utilized to extract G_E^n. The result for $A_{T'}$ presented here is consistent with the previous measurement of Woodward *et al.* [19]. Figure 2 shows the results of the two experiments, the combined result, and the prediction. Our results for $A_{T'}$, when combined with those of Ref. [19], suggest that the impulse approxi-

TABLE II. Contributions to systematic error.

Source	% of A
Proton NMR	5
$\int(d^2\sigma_3/dE\,d\Omega)dE$	10
$\int(d\sigma_1/d\Omega)d\Omega\,dz$	6
Møller measurement of P_e [a]	12
Total	17

[a] Reference [13].

TABLE III. Inelastic asymmetries.

	$A_{T'}$ (%)
Measured asymmetry	$-2.6\pm0.9\pm0.46$
Reference [19]	$-3.49\pm1.23\pm0.54$
Combined measured asymmetry	-2.9 ± 0.8
Predicted asymmetry	-4.5 ± 0.9
	$A_{TL'}$ (%)
Measured asymmetry	$+1.75\pm1.2\pm0.31$

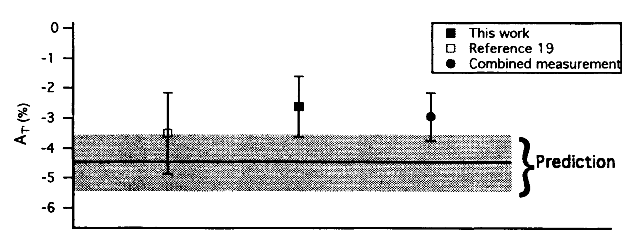

FIG. 2. Comparison of measurements and prediction for $A_{T'}$. The shaded area indicates the uncertainty of the prediction around the central value (bold line) due to the uncertainty in G_M^n.

mation is not reliable for calculating spin dependence in quasielastic scattering. In particular, the roles of meson-exchange currents, final-state interactions, and polarization are not taken into account. Earlier studies of spin-independent quasielastic scattering for $A=3$ demonstrate the crucial role of final-state interactions in order to establish consistency between experiment [16] and continuum Fadeev calculations [20]. More recently, Laget [21] has shown that significant corrections are necessary for spin-dependent quasielastic scattering at $Q^2=0.2$ $(\mathrm{GeV}/c)^2$ and experiments at TRIUMF with quasielastic proton scattering from polarized ^{3}He are also inconsistent with the impulse-approximation picture [22]. It is most likely that the calculation of proton and neutron polarization in ^{3}He is reliable and that a complete calculation including final-state and meson-exchange corrections will be consistent with the measurements.

For $A_{TL'}$ the prediction of the impulse approximation for the contribution of the polarized protons given by the term proportional to P_p in Eq. (5) is $(0.98 \pm 0.13)\%$. Therefore in the analysis provided by Blankleider and Woloshyn [9], we find $G_E^n = 0.044 \pm 0.074$, providing no useful information on G_E^n, even if we assume the impulse-approximation result. However, at higher $|Q^2|$, the relative contribution of the polarized protons becomes significantly less and a precise measurement of G_E^n is possible with sufficient statistical precision of the experiment and confirmation of a complete theoretical treatment by measurement of $A_{T'}$ [23].

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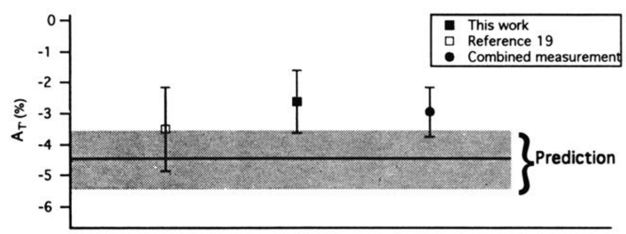

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