Transverse Asymmetry $A_{T'}$ from the Quasielastic $^3\vec{\mathrm{He}}(\vec{e},e')$ Process and the Neutron Magnetic Form Factor

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We have measured the transverse asymmetry $A_{T'}$ in $^3\vec{\mathrm{He}}(\vec{e},e')$ quasielastic scattering in Hall A at Jefferson Laboratory with high precision for Q^2 values from 0.1 to 0.6 $(\mathrm{GeV}/c)^2$. The neutron magnetic form factor G_M^n was extracted based on Faddeev calculations for $Q^2 = 0.1$ and 0.2 $(\mathrm{GeV}/c)^2$ with an experimental uncertainty of less than 2%.

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The electromagnetic form factors of the nucleon have been a long-standing subject of interest in nuclear and particle physics. They describe the distribution of charge and magnetization within nucleons and allow sensitive tests of nucleon models based on quantum chromodynamics. This advances our knowledge of nucleon structure and provides a basis for the understanding of more complex strongly interacting matter in terms of quark and gluon degrees of freedom.

The neutron form factors are known with much poorer precision than proton form factors because of the lack of free neutron targets. Over the past decade, with the advent of polarized beams and targets, the precise determination of both the neutron electric form factor, G_E^n, and the magnetic form factor, G_M^n, has become a focus of experimental activity. Considerable attention has been devoted to the precise measurement of G_M^n. While knowledge of G_M^n is interesting in itself, it is also required for the determination

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of G_E^n, which is usually measured via the ratio G_E^n/G_M^n. Further, precise data for the nucleon electromagnetic form factors are essential for the analysis of parity violation experiments [1,2] designed to probe the strangeness content of the nucleon.

Until recently, most data on G_M^n had been deduced from elastic and quasielastic electron-deuteron scattering. For inclusive measurements, this procedure requires the separation of the longitudinal and transverse cross sections and the subsequent subtraction of a large proton contribution. Thus, it suffers from large theoretical uncertainties due in part to the deuteron model employed and in part to corrections for final-state interactions (FSI) and meson-exchange currents (MEC). The proton subtraction can be avoided by measuring the neutron in coincidence [$d(e, e'n)$] [3], and the sensitivity to nuclear structure can be greatly reduced by taking the cross-section ratio of $d(e, e'n)$ to $d(e, e'p)$ at quasielastic kinematics. Several recent experiments [4–6] have employed the latter technique to extract G_M^n with uncertainties of $<2\%$ [6] in the low Q^2 region. While this precision is very good, there is considerable disagreement among the results [3–6] with respect to the absolute value of G_M^n.

An alternative approach to a precision measurement of G_M^n is through the inclusive quasielastic reaction $^3\vec{\mathrm{He}}(\vec{e}, e')$. In comparison to deuterium experiments, this technique employs a different target and relies on polarization degrees of freedom. It is thus subject to completely different systematics. A pilot experiment using this technique was carried out at MIT-Bates and a result for G_M^n was extracted [7]. In this Letter, we report the first precision measurement of G_M^n using a polarized ^{3}He target.

Polarized ^{3}He is useful for studying the neutron structure because its ground state is dominated by a spatially symmetric S wave in which the proton spins cancel and the spin of the ^{3}He nucleus is carried by the unpaired neutron [8,9]. The spin-dependent contribution to the $^3\vec{\mathrm{He}}(\vec{e}, e')$ cross section is contained in two nuclear response functions, a transverse response $R_{T'}$ and a longitudinal-transverse response $R_{TL'}$, in addition to the spin-independent longitudinal and transverse responses R_L and R_T. $R_{T'}$ and $R_{TL'}$ can be isolated experimentally by forming the spin-dependent asymmetry A defined as $A = (\sigma^{h+} - \sigma^{h-})/(\sigma^{h+} + \sigma^{h-})$, where $\sigma^{h^\pm}$ denotes the cross section for the two different helicities of the polarized electrons. In terms of the nuclear response functions, A can be written [10]

$$A = \frac{-(\cos\theta^* \nu_{T'} R_{T'} + 2\sin\theta^* \cos\phi^* \nu_{TL'} R_{TL'})}{\nu_L R_L + \nu_T R_T}, \qquad (1)$$

where the ν_k are kinematic factors and θ^* and ϕ^* are the polar and azimuthal angles of target spin with respect to the 3-momentum transfer vector $\mathbf{q}$. The response functions R_k depend on Q^2 and the electron energy transfer ω. By choosing $\theta^* = 0$, i.e., by orienting the target spin parallel to the momentum transfer $\mathbf{q}$, one selects the transverse asymmetry $A_{T'}$ (proportional to $R_{T'}$).

$R_{T'}$ at quasielastic kinematics contains a dominant neutron contribution and is essentially proportional to $(G_M^n)^2$, similar to elastic scattering from a free neutron. Unlike the free neutron case, however, the unpolarized part of the cross section [the denominator in Eq. (1)] contains contributions from both the protons and the neutrons in the nucleus. Therefore, $A_{T'}$ is expected to first order to have the form $(G_M^n)^2/[a + b(G_M^n)^2]$ in the plane-wave impulse approximation (PWIA), where a is much larger than $b(G_M^n)^2$ at low Q^2. Thus, the sensitivity to the neutron form factor is enhanced in inclusive scattering from polarized ^{3}He because of the cancellation of the proton spins in the ground state. This picture has been confirmed by several PWIA calculations [11,12], as well as a more recent and more advanced calculation which fully includes FSI [13]. Therefore, the inclusive asymmetry $A_{T'}$ in the vicinity of the ^{3}He quasielastic peak is most sensitive to the neutron magnetic form factor.

The experiment was carried out in Hall A at the Thomas Jefferson National Accelerator Facility (JLab), using a longitudinally polarized continuous wave electron beam of 10 μA current incident on a high-pressure polarized ^{3}He gas target [14]. The target was polarized by spin-exchange optical pumping at a density of 2.5×10^{20} nuclei/cm^3. The beam and target polarizations were approximately 70% and 30%, respectively, and the beam helicity was flipped at a rate of 1 Hz (30 Hz for part of the experiment). To improve the optical pumping efficiency, the target contained a small admixture of nitrogen ($\sim 10^{18}$ cm^{-3}). Backgrounds from the target cell walls and the nitrogen admixture were determined to be a few percent of the full target yield in calibration measurements using a reference cell with the same dimensions as those of the ^{3}He target cell.

Six kinematic points were measured corresponding to $Q^2 = 0.1$ to 0.6 (GeV$/c)^2$ in steps of 0.1 (GeV$/c)^2$. An incident electron beam energy, E_i of 0.778 GeV was employed for the two lowest Q^2 values of the experiment and the remaining points were completed at $E_i = 1.727$ GeV. To maximize the sensitivity to $A_{T'}$, the target spin was oriented at 62.5° to the right of the incident electron momentum direction. This corresponds to θ^* from $-8.5°$ to 6°, resulting in a contribution to the asymmetry due to $R_{TL'}$ of less than 2% at all kinematic settings, as determined from PWIA.

Electrons scattered from the target were observed in the two Hall A high resolution spectrometers, HRSe and HRSh. Both spectrometers were configured to detect electrons in single-arm mode using nearly identical detector packages consisting of two dual-plane vertical drift chambers for tracking, two planes of segmented plastic scintillators for trigger formation, and a CO_2 gas Cherenkov detector and Pb-glass total-absorption shower counter for pion rejection. The HRSe was set for quasielastic kinematics while the HRSh detected elastically scattered electrons. Since the elastic asymmetry can be calculated very well at low Q^2 using the well-known elastic form factors of ^{3}He [15], the elastic measurement allows precise monitoring of the product of the beam and target polarizations, $P_t P_b$. For $E_i = 0.778$ GeV, the HRSh was set to $Q^2 = 0.1$ for the elastic scattering kinematics and $P_t P_b$ can be determined to better than 2%. For $E_i = 1.727$ GeV, $P_t P_b$ can be determined to better than 3% at $Q^2 = 0.2$ $(\mathrm{GeV}/c)^2$ for the elastic scattering. Standard Möller and NMR polarimetry were performed as a cross-check of the elastic polarimetry. The average $P_t P_b$ of this experiment determined from the elastic polarimetry was $0.208 \pm 0.001 \pm 0.005$ [16], where the errors are statistical and systematic, respectively. Combining the Möller and the NMR measurements, the average $P_t P_b$ was 0.215 ± 0.013 [16] with the error being the total systematic error.

The yield for each electron helicity state was corrected by its corresponding charge and computer dead time, and the raw experimental asymmetry was extracted as a function of ω. The raw asymmetry was then corrected for dilutions due to scattering from the empty target walls, the nitrogen content, and $P_t P_b$. The physics asymmetry $A_{T'}$ was obtained after corrections for radiative effects. Continuum radiative corrections were calculated using the covariant formalism of Akushevich *et al.* [17], which was generalized to quasielastic kinematics. This procedure requires knowledge of ^{3}He nuclear response functions at various kinematic points. These response functions were obtained from the full Faddeev calculation for $Q^2 = 0.1$ and 0.2 $(\mathrm{GeV}/c)^2$ and the PWIA calculation [11] for $Q^2 = 0.3$ to 0.6 $(\mathrm{GeV}/c)^2$.

Results for $A_{T'}$ as a function of ω are shown in Fig. 1 for all six kinematic settings of the experiment. The error bars on the data are statistical only, and the total experimental systematic error is indicated as an error band. PWIA calculations [11] using the AV18 for the *NN* interaction potential and the Höhler nucleon form factor parametrization [18] are shown as dashed lines. The Faddeev calculations with FSI only and with both FSI and MEC using the Bonn-B potential and the Höhler parametrization are shown as dash-dotted lines and solid lines, respectively, for $Q^2 = 0.1$ and 0.2 $(\mathrm{GeV}/c)^2$. All theory results were averaged over the spectrometer acceptances using a Monte Carlo simulation. The systematic uncertainty in $A_{T'}$ includes contributions from $P_t P_b$, background subtraction, radiative corrections, helicity-correlated false asymmetries, and pion contamination. A Monte Carlo simulation code was employed to determine $P_t P_b$ from the measured elastic asymmetry, taking into account the spectrometer acceptance, energy loss, detector resolutions, and radiative effects. The overall systematic uncertainty of $A_{T'}$ is 2% for Q^2 values of 0.1 and 0.2 $(\mathrm{GeV}/c)^2$ dominated by the uncertainty in determining $P_t P_b$, and 5% for Q^2 values of 0.3 to 0.6 $(\mathrm{GeV}/c)^2$ dominated by the uncertainty in the radiative correction, which

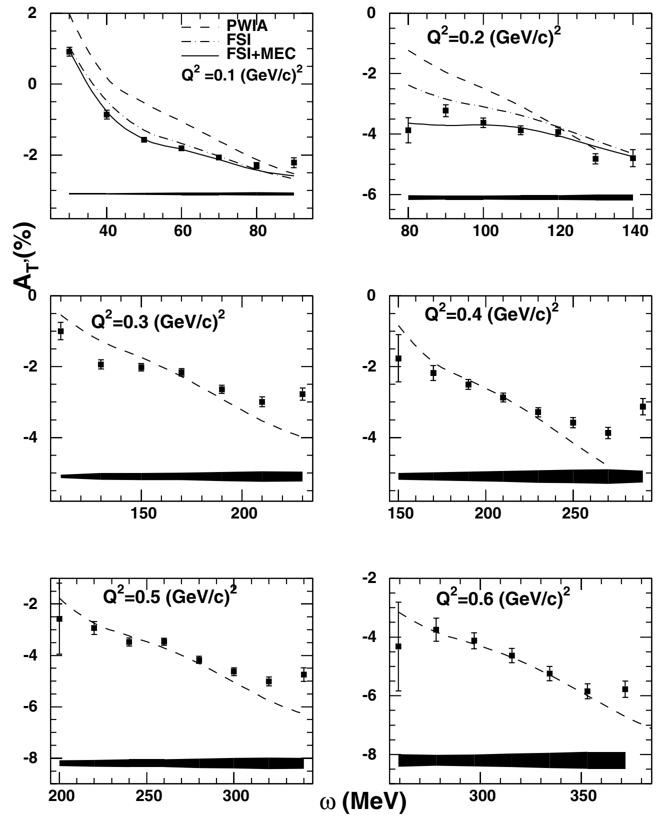

FIG. 1. The transverse asymmetry $A_{T'}$ at $Q^2 = 0.1$–0.6 $(\mathrm{GeV}/c)^2$.

can be reduced with improved theoretical calculations for these values of Q^2.

The state-of-the-art three-body calculation treats the ^{3}He target state and the 3*N* scattering states in the nuclear matrix element in a consistent way by solving the corresponding 3*N* Faddeev equations [19]. The MEC effects were calculated using the prescription of Riska [20], which includes π- and ρ-like exchange terms. While the agreement between the data and full calculations is very good at $Q^2 = 0.1$ and 0.2 $(\mathrm{GeV}/c)^2$, the full calculation is not expected to be applicable at higher Q^2 because of its fully nonrelativistic framework. A full calculation within the framework of relativity is highly desirable.

To extract G_M^n for the two lowest Q^2 kinematics, the transverse asymmetry data were averaged over a 30 MeV bin around the quasielastic peak. The full Faddeev calculation including MEC [21] was employed to generate $A_{T'}$ as a function of G_M^n in the same ω region. By comparing the measured asymmetries with the predictions, the G_M^n values at $Q^2 = 0.1$ and 0.2 $(\mathrm{GeV}/c)^2$ were extracted. The extracted values of G_M^n are shown in Fig. 2 along with results from previous measurements and several theoretical calculations. The uncertainties shown are the quadrature sum of the statistical and experimental systematic uncertainties. These results are tabulated in Table I.

Since the full calculation described above is at present the only theoretical calculation available which treats FSI

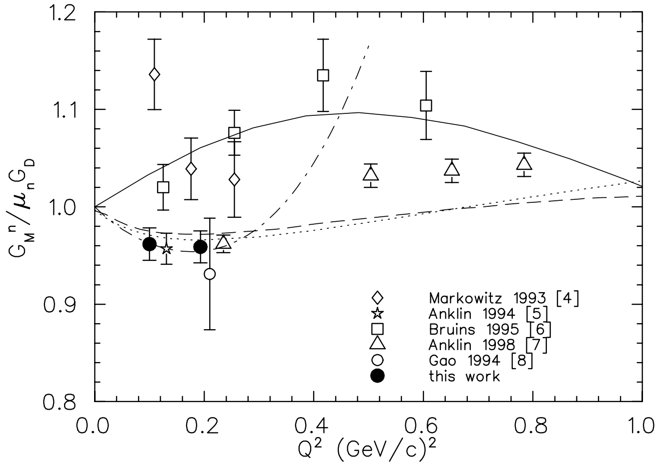

FIG. 2. The neutron magnetic form factor G_M^n in units of the standard dipole form factor $(1 + Q^2/0.71)^{-2}$, as a function of Q^2, along with previous measurements and theoretical models. The Q^2 points of Anklin 94 [4] and Gao 94 [7] have been shifted slightly for clarity. The solid curve is a recent cloudy bag model calculation [22], the long dashed curve is a recent calculation based on a fit of the proton data using dispersion theoretical arguments [23], and the dotted curve is from the Höhler [18] parametrization. The dash-dotted curve is an analysis based on the relativistic baryon chiral perturbation theory [24].

and MEC under the present experimental conditions, it is important to mention one highly nontrivial internal test. The nuclear response functions for the inclusive scattering on ^{3}He were calculated in two independent ways by either integrating explicitly over the *pd* and *ppn* breakup channels (with full inclusion of FSI) or using a completeness relation [25]. The agreement between these two approaches is within 1% [26]. The Faddeev based formalism has been applied to other reaction channels and good agreements have been found with experimental results [26], in particular, the most recent data on A_y^0 at $Q^2 = 0.16$ (GeV$/c)^2$ from the quasielastic $^3\vec{\mathrm{He}}(\vec{e}, e'n)$ process [27].

To investigate the theoretical uncertainty in extracting G_M^n at $Q^2 = 0.1$ and 0.2 (GeV$/c)^2$, the full calculations were carried through with two different *NN* potentials, Bonn-B and AV18. The difference in the calculated asymmetries is less than 1% around the quasielastic peak. The uncertainty due to G_E^p, G_M^p, and G_E^n was studied by varying these quantities over their experimental errors, and the range of variation in the calculated asymmetry was 1%. The uncertainty due to MEC was estimated by comparing results with and without the inclusion of the Δ isobar current. At $Q^2 = 0.1$ and 0.2 (GeV$/c)^2$ relativistic corrections to $A_{T'}$ were estimated to be 2% and 4% [28]

TABLE I. G_M^n as a function of Q^2, the uncertainties are statistical and experimental systematic, respectively.

Q^2 (GeV$/c)^2$	G_M^n/G_M^n (Dipole)	Uncertainties
0.1	0.962	$\pm 0.014 \pm 0.010$
0.2	0.959	$\pm 0.013 \pm 0.010$

around the quasielastic peak, respectively. Based on these studies, the overall theoretical uncertainty in calculating $A_{T'}$ was estimated to be 3.8% and 5.1% for $Q^2 = 0.1$ and 0.2 (GeV$/c)^2$, respectively. This results in an estimated theoretical uncertainty of 1.9% and 2.6% in extracting G_M^n for these two Q^2 points correspondingly, which can be reduced once relativistic full calculations become available. The errors on G_M^n from the present work shown in Fig. 2 and Table I are experimental errors only, which do not include the theoretical uncertainties discussed above.

In conclusion $A_{T'}$ from the quasielastic $^3\vec{\mathrm{He}}(\vec{e}, e')$ process has been measured with high precision at Q^2 values from 0.1 to 0.6 (GeV$/c)^2$. Using a full Faddeev calculation we have extracted G_M^n at Q^2 values of 0.1 and 0.2 (GeV$/c)^2$. The extracted values of G_M^n agree with the previous measurements of Anklin *et al.* [4,6]. The present experiment provides the first precision data on G_M^n using a fundamentally different experimental approach than previous experiments. Thus it is a significant step towards resolving the discrepancy among the existing data sets in the low Q^2 region. Although we have presented precise data on $A_{T'}$ at higher Q^2 [0.3–0.6 (GeV$/c)^2$], full calculations are at present not available for these values of Q^2 to allow the extraction of G_M^n with high precision. Theoretical efforts are currently underway to extend the full calculation to higher Q^2 [29].

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