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Plane-wave impulse approximation extraction of the neutron magnetic form factor from quasielastic $^3\overrightarrow{\mathrm{He}}(\vec{e},e')$ at $Q^2=0.3$ to 0.6 $(\mathrm{GeV}/c)^2$

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A high precision measurement of the transverse spin-dependent asymmetry $A_{T'}$ in $^3\overrightarrow{\mathrm{He}}(\vec{e},e')$ quasielastic scattering was performed in Hall A at Jefferson Lab at values of the squared four-momentum transfer, Q^2, between 0.1 and 0.6 $(\mathrm{GeV}/c)^2$. $A_{T'}$ is sensitive to the neutron magnetic form factor, G_M^n. Values of G_M^n at $Q^2=0.1$ and 0.2 $(\mathrm{GeV}/c)^2$, extracted using Faddeev calculations, were reported previously. Here, we report the extraction of G_M^n for the remaining Q^2 values in the range from 0.3 to 0.6 $(\mathrm{GeV}/c)^2$ using a plane-wave impulse approximation calculation. The results are in good agreement with recent precision data from experiments using a deuterium target.

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The electromagnetic form factors of the nucleon have been a longstanding 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. Precise knowledge of the form factors advances our understanding of nucleon structure.

The proton electromagnetic form factors have been determined with good precision at low values of the squared four-momentum transfer, Q^2, while the neutron form factors are known with much poorer precision because of the lack of free neutron targets. Over the past decade, with the advent of high-quality 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. While knowledge of G_M^n is interesting in itself, it is also required for the determination of G_E^n, which is often measured via the ratio G_E^n/G_M^n. Furthermore, 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). These complications can largely be avoided if one measures the cross-section ratio of $d(e,e'n)$ to $d(e,e'p)$ at quasielastic kinematics. Several recent experiments [3–6] have employed this technique to extract G_M^n with uncertainties of $<2\%$ [5,6] at Q^2 below 1 $(\mathrm{GeV}/c)^2$. Despite the high precision reported, however, there is considerable disagreement among some of the experiments [7,3–6] with respect to the absolute value of G_M^n. The most recent deuterium data [6] further emphasize this discrepancy.

While the discrepancies among the deuterium experiments described above may be understood [8], additional data on G_M^n, preferably obtained using a complementary method, are highly desirable. Inclusive quasielastic $^3\overrightarrow{\mathrm{He}}(\vec{e},e')$ scattering provides just such an alternative approach [9]. 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. As demonstrated recently by this collaboration [10], a precision comparable to that of deuterium ratio experiments can be achieved with the ^{3}He technique if the ^{3}He structure and the reaction mechanism are properly treated, which has become possible, at least in the nonrelativistic kinematic regime, with recent advances in Faddeev calculations [11,12].

The sensitivity of spin-dependent $^3\overrightarrow{\mathrm{He}}(\vec{e},e')$ scattering to neutron structure originates from the cancellation of the proton spins in the dominant spatially symmetric S wave of the ^{3}He ground state. As a result of this cancellation, the spin of the ^{3}He nucleus is predominantly carried by the unpaired neutron alone [13,14]. Hence, the spin-dependent contributions to the $^3\overrightarrow{\mathrm{He}}(\vec{e},e')$ cross section are expected to be sensitive to neutron properties. Formally, the spin-dependent part of the inclusive cross section is contained in two nuclear response functions, a transverse response $R_{T'}$ and a longitudinal-transverse response $R_{TL'}$, which occur in addition to the spin-independent longitudinal and transverse responses R_L and R_T [15]. $R_{T'}$ 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 [15]

TABLE I. The spectrometer settings for the six quasielastic kinematics of the experiment, where E is the incident electron, E' and θ are the spectrometer central momentum and scattering angle settings, respectively.

Q^2 $(\mathrm{GeV}/c)^2$	E (GeV)	E' (GeV)	θ (degrees)
0.10	0.778	0.717	24.44
0.193	0.778	0.667	35.50
0.30	1.727	1.559	19.21
0.40	1.727	1.506	22.62
0.50	1.727	1.453	25.80
0.60	1.727	1.399	28.85

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

where the ν_k are kinematic factors and θ^* and ϕ^* are the polar and azimuthal angles of target spin with respect to the three-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 $R_{T'}$). Various detailed calculations [16–19,11] have confirmed that $R_{T'}$, and thus $A_{T'}$, is strongly sensitive to $(G_M^n)^2$.

The experiment was carried out in Hall A at the Thomas Jefferson National Accelerator Facility (JLab), using a longitudinally polarized continuous-wave electron beam incident on a high-pressure polarized ^{3}He gas target [20]. Six kinematic points were measured corresponding to $Q^2=0.1$ to 0.6 $(\mathrm{GeV}/c)^2$ in steps of 0.1 $(\mathrm{GeV}/c)^2$. An incident electron beam energy, E, of 0.778 GeV was employed for the two lowest Q^2 values, while the remaining points were obtained at $E=1.727$ GeV. The spectrometer settings of the six quasielastic kinematics are listed in Table I. 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 kinematical settings, as determined from plane-wave impulse approximation (PWIA) calculations. Further experimental details can be found in Refs. [10,20,21].

Results for $A_{T'}$ (Fig. 1) as a function of ω for all six kinematical settings of this experiment together with the extracted G_M^n values at the two lowest Q^2 kinematics of the experiment were reported previously [10]. A state-of-the-art nonrelativistic Faddeev calculation [12] had been employed in the extraction of G_M^n at those two Q^2 kinematics. High precision asymmetry data in the ^{3}He breakup region from the same experiment [22] at Q^2 values of 0.1 and 0.2 $(\mathrm{GeV}/c)^2$ provide a stringent test of this Faddeev calculation and further support the approach used in Ref. [10] for extracting G_M^n at Q^2 values of 0.1 and 0.2 $(\mathrm{GeV}/c)^2$. However, as discussed in [10], this Faddeev calculation, while very accurate at low Q^2, is not believed to be sufficiently precise for a reliable extraction of G_M^n from the ^{3}He asymmetry data at higher Q^2 because of its nonrelativistic nature.

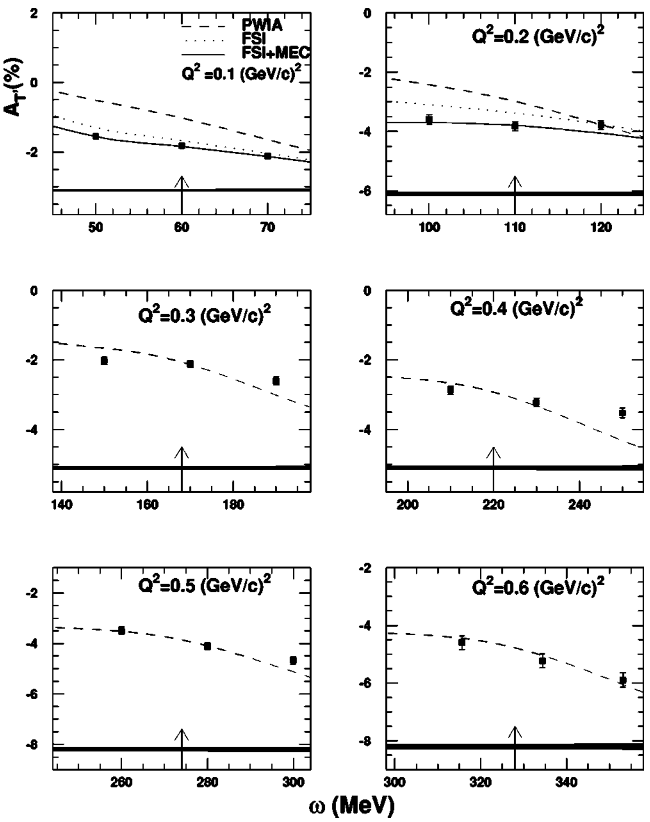

FIG. 1. The transverse asymmetry $A_{T'}$ in the vicinity of the quasielastic peak at the six kinematics of the experiment. The data points are shown with statistical uncertainties only; the experimental systematic uncertainties are shown as dark bands. Arrows indicate the position of the quasielastic peak in each panel. The solid and the dotted curves represent the Faddeev calculation [11]; the solid curve includes the FSI and MEC effects, while the dotted curve includes FSI effects only. The dashed curve is the PWIA calculation [17] used in this paper.

Thus, even though the Faddeev calculation has been extended numerically up to a Q^2 value of 0.4 $(\mathrm{GeV}/c)^2$, it was not used to extract G_M^n from the $Q^2 \geqslant 0.3$ $(\mathrm{GeV}/c)^2$ data discussed in this Rapid Communication. An extraction of G_M^n from our ^{3}He asymmetry data at higher values of Q^2 with the same quality as that achieved at low Q^2 requires a fully relativistic three-body calculation. Unfortunately, such a calculation is not available and difficult to carry out at the present time.

On the other hand, the size of FSI and MEC corrections to inclusive scattering data near the top of the quasielastic peak has been predicted to diminish with increasing momentum transfer in the region of Q^2 from 0.1 to 0.6 $(\mathrm{GeV}/c)^2$ that is relevant for this experiment [23–25], and so PWIA may describe our data well at higher Q^2. Indeed, as shown in Fig. 1, a PWIA calculation [17] (described in detail below) is in excellent agreement with the data at Q^2 values of 0.5 and 0.6 $(\mathrm{GeV}/c)^2$; in particular, the ω dependence of the data is well reproduced. In light of this, we felt it was reasonable to extract G_M^n from our asymmetry data using PWIA. In order to estimate the model uncertainty of this procedure, we used results from the full Faddeev calculation up to a Q^2 value of 0.4 $(\mathrm{GeV}/c)^2$ to study quantitatively the size and Q^2 dependence of FSI and MEC corrections.

A recent PWIA calculation [17] was used for the extraction of G_M^n at $Q^2 \geqslant 0.3$ $(\mathrm{GeV}/c)^2$. This PWIA calculation takes into account the relativistic kinematics and current, and employs the Argonne V18 NN interaction potential and the Höhler nucleon form factor parametrization [26] (for the proton form factors and G_E^n). The struck nucleon is described by a plane wave, and the interaction between the nucleons in the spectator pair is treated exactly by including the NN and the Coulomb interaction between the pp pair. The de Forest CC1 off-shell prescription [27] was adopted for the electron-nucleon cross section. Furthermore, the Urbana IX three-body forces [28] are included in the ^{3}He bound state.

To extract G_M^n, measured transverse asymmetry data from a 30 MeV region around the quasielastic peak were used in order to improve the statistical uncertainties of the extracted G_M^n values. The variation of the Q^2 value in this 30 MeV region is small, as such the corresponding change in the G_M^n value is negligible. The PWIA calculation [17] was employed to generate $A_{T'}$ as a function of G_M^n in the same 30 MeV-wide ω region. In doing so, spectrometer acceptance effects were taken into account. By comparing the measured asymmetries with the PWIA predictions, G_M^n values could be extracted. Results for G_M^n were obtained in two ways: (a) by taking the weighted average of $A_{T'}$ from three neighboring 10 MeV bins around the quasielastic peak (30 MeV total for ω) and then extracting G_M^n from this average asymmetry, and (b) by first extracting G_M^n from each of these 10 MeV bins separately and then taking the weighted average of the resulting G_M^n values. Both methods yield essentially the same results (within 0.1%).

The experimental systematic uncertainty in G_M^n is dominated by the systematic error from the determination of the beam and target polarizations. This error is 1.7% in $A_{T'}$ (or 0.85% in $\delta G_M^n/G_M^n$). Such a high precision can be achieved by using elastic polarimetry [10]. An additional systematic error occurs in the extraction of G_M^n due to the experimental uncertainty in the determination of the energy transfer ω. The uncertainty from this source is 1.4% at $Q^2 = 0.3$ and becomes negligible ($< 0.5\%$) at the higher Q^2 points.

The model uncertainty inherent in the extraction procedure depends on the various ingredients of the calculation, such as the NN potential, the other nucleon form factors, relativity, and the reaction mechanism, including FSI and MEC. The main processes neglected in PWIA are FSI and MEC; therefore, these two contributions are expected to dominate the overall model uncertainty. As mentioned, we used results from the non-relativistic Faddeev calculation carried out up to a Q^2 value of 0.4 $(\mathrm{GeV}/c)^2$ to estimate the uncertainties resulting from the omission of FSI and MEC. [Faddeev results for $Q^2 > 0.4$ $(\mathrm{GeV}/c)^2$ were not generated because the calculation manifestly breaks down in that kinematical regime.]

To estimate the effect of FSI, the nonrelativistic Faddeev calculation with FSI, corrected for relativistic effects, was compared [21] with the relativistic PWIA calculation [17].

TABLE II. The ratio of G_M^n to the dipole parametrization as a function of Q^2, the uncertainties are statistical, systematic, and theoretical uncertainties, respectively.

Q^2 (GeV/c)^2	G_M^n/G_D	Uncertainties $\left(\frac{\delta G_M^n}{G_M^n}\right)$
0.30	0.972	$\pm 0.014 \pm 0.016^{+0.026}_{-0.054}$
0.40	0.984	$\pm 0.011 \pm 0.028^{+0.028}_{-0.025}$
0.50	0.984	$\pm 0.009 \pm 0.024^{+0.028}_{-0.013}$
0.60	1.010	$\pm 0.013 \pm 0.027^{+0.031}_{-0.014}$

Relativistic corrections to the Faddeev calculation were derived from a comparison between the standard, relativistic PWIA calculation [17] and a modified, nonrelativistic PWIA calculation [21]. One can thus study the size and the Q^2 dependence of the FSI effect up to a Q^2 value of 0.4 (GeV/c)^2. As expected, FSI corrections to $A_{T'}$ decrease with increasing Q^2. The estimated errors in $A_{T'}$ due to the neglect of the FSI effect in PWIA are 9.0%, 3.6% for Q^2 of 0.3, 0.4, and on the order of 1–2 % for Q^2 values of 0.5 and 0.6 (GeV/c)^2 based on an extrapolation beyond a Q^2 value of 0.4 (GeV/c)^2.

The MEC effect can be addressed in a similar manner. Based on the Faddeev calculation [11], we find that MEC corrections to $A_{T'}$ near the top of the quasielastic peak decrease exponentially as Q^2 increases. Similar conclusions have been drawn from studies of the quasielastic $\vec{d}(\vec{e},e')$ process [25]. We estimate the uncertainty due to the neglect of the MEC effect in PWIA for $A_{T'}$ on top of the quasielastic peak to be 3.6%, 2.4%, 1.0%, and 1.0% for Q^2 of 0.3, 0.4, 0.5, and 0.6 (GeV/c)^2, respectively.

The effect of various different off-shell prescriptions [29] was studied in the framework of the PWIA calculation, and the contribution to the uncertainty of extracting G_M^n from $A_{T'}$ was found to be negligible. Differences in G_M^n arising from different choices of NN potential and other nucleon form factor parametrizations were found to be about 1%.

Results for G_M^n extracted at $Q^2=0.3$ to 0.6 (GeV/c)^2 using the PWIA calculation are presented in Table II along with statistical, systematic, and model uncertainties. The model uncertainties of between 1% and 5% were obtained based on the studies described previously. The results are plotted in Fig. 2 along with the previously reported G_M^n results [10] at $Q^2=0.1$ and 0.2 (GeV/c)^2, which were extracted using the Faddeev calculation. All other results published since 1990 are also shown. The error bars shown on our data are the quadratic sum of the statistical and experimental systematic uncertainties reported in Table II, which do not include the estimated model uncertainty.

While limitations exist in our analysis approach due to theoretical uncertainties, we note that our results are in very good agreement with the recent deuterium ratio measurements from Mainz [5,6], and in disagreement with results by Bruins *et al.* [4].

In conclusion, we have measured the spin-dependent

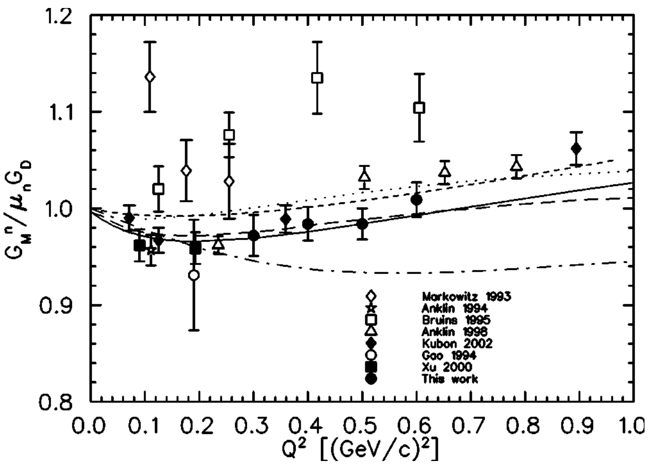

FIG. 2. The neutron magnetic form factor G_M^n in units of the standard dipole form factor $(1+Q^2/0.71)^{-2}$, at Q^2 values of 0.3 to 0.6 (GeV/c)^2 extracted using PWIA calculations. The error bars shown do not include the model dependent uncertainties, which are typically 3–4 %. Also shown are measurements published since 1990 and a few selected theoretical models. The Q^2 data points of Anklin 94 [3] and Gao 94 [9] have been shifted slightly for clarity. The solid curve is the Höhler nucleon form factor parametrization [26], the long-dashed curve is a recent calculation based on a fit of the proton data using dispersion theory arguments [30], and the dotted curve is a recent analysis based on the vector meson dominance model [31]. The dashed curve is a Skyrme/soliton model calculation [32], and the dash-dotted curve is a relativistic quark model calculation [33].

asymmetry $A_{T'}$ in the quasielastic $^3\vec{\mathrm{He}}(\vec{e},e')$ process with high precision at Q^2 values from 0.1 to 0.6 (GeV/c)^2. In this Rapid Communication, we report the extraction of G_M^n at Q^2 values of 0.3 to 0.6 (GeV/c)^2 based on PWIA calculations, which are expected to be reasonably reliable in our range of Q^2. We estimate the total uncertainty of our results to be about 4–6 %, which includes model errors of typically 1–5 %. A more precise extraction of G_M^n at these Q^2 values requires a fully relativistic three-body calculation, which is unavailable at present. Efforts are underway to extend the theory into this regime [34].

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