A Measurement of the Electric Form Factor of the Neutron through $d(\vec{e}, e'n)p$ at $Q^2 = 0.5$ (GeV/c)$^2$

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We report the first measurement of the neutron electric form factor $G^e_n$ via $d(\vec{e}, e'n)p$ using a solid polarized target. $G^e_n$ was determined from the beam–target asymmetry in the scattering of longitudinally polarized electrons from polarized deuterated ammonia ($^{15}$ND$_3$). The measurement was performed in Hall C at Thomas Jefferson National Accelerator Facility (TJNAF) in quasi free kinematics with the target polarization perpendicular to the momentum transfer. The electrons were detected in a magnetic spectrometer in coincidence with neutrons in a large solid angle segmented detector. We find $G^e_n = 0.04632 \pm 0.00616$ (stat.) $\pm 0.00341$ (syst.) at $Q^2 = 0.495$ (GeV/c)$^2$.

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Precise data on the neutron (and proton) form factors are important for understanding the non-perturbative mechanism responsible for confinement and are necessary in the interpretation of the electromagnetic properties of nuclei. The magnetic form factor of the neutron has recently been measured with high precision. The neutron charge form factor $G^p_n$, in contrast, is only now yielding to intense efforts focused on its determination.

The major difficulty faced in a measurement of the neutron form factor is the lack of a free neutron target. The determination of $G^p_E$ is further impeded by its small size. Advances in polarized electron sources, CW accelerators, polarimeters and polarized targets, now allow $G^p_E$ to be extracted from experiments which exploit spin degrees of freedom. In particular the interference of the magnetic and electric scattering amplitudes is responsible for an asymmetry that can be measured in both polarized electron/polarized target experiments ($d(\vec{e}, e'n)p$ $\parallel$ $\parallel$) and in polarized electron recoil polarization measurements ($d(\vec{e}, e'n)p$ $\parallel$ $\perp$ $\parallel$).

For a vector polarized target of free neutrons, with the polarization $P_n$, in the scattering plane and perpendicular to the momentum transfer $\vec{q}$, $G^p_E$ is related to the helicity asymmetry $A^{ve}_{en}$ $\parallel$ by

$$A^{ve}_{en} = \frac{-2\sqrt{(\tau + 1)\tan(\theta_e/2)G^p_E G^e_n}}{(G^p_E)^2 + \tau[1 + 2(1 + \tau)\tan^2(\theta_e/2)](G^e_n)^2}$$

where $Q^2$ is the four momentum transfer, $\tau = Q^2/4M_n^2$, and $\theta_e$ is the electron scattering angle. $A^{ve}_{en}$ is related to the experimental counts asymmetry $\epsilon = (L - R)/(L + R)$, where $L$ and $R$ are charge normalized counts for opposite beam polarizations $P_e$, by $A^{ve}_{en} = \epsilon/(P_eP_nf)$, where $f$ is the dilution factor due to scattering from materials other
The average beam polarization for the data taking was measured in a pair–wise pseudo-random sequence once the accelerator injector had been turned on. The helicity of the beam was illuminated by circularly polarized laser light \cite{12} at the entrance of the target. The scattered electrons were detected in coincidence with the knockout neutrons.

The experiment took place in Hall C with an incident electron energy of 2.725 GeV and a beam current of 100 nA. Photomultiplier tubes (PMTs) were used to view the phototube at each end to allow good measurement of the scattered electron energy allowed us to eliminate events associated with pion production. The neutron vertical position was determined from the time of flight peak of photons (from the \( ^{12}C \) decay) in the meantime spectrum. With the detector positioned 4 m from the target for neutrons with kinetic energy of 267 MeV it provided an energy resolution of 16.5 MeV. The neutron energy combined with the scattered electron energy allowed us to eliminate events associated with pion production. The neutron vertical position was determined by the segmentation of the detector (10 cm) while the horizontal position was determined from the time difference of the phototubes on the first bar hit along the \( n \) track. The measured horizontal resolution was \( \approx 5 \) cm.

The electron–nucleon trigger was formed by a coincidence between the HMS electron and a hit in any one of the 5 bar planes. Neutrons were identified as events with no hits in the paddles along the track to the target, within a narrow time interval, and in a narrow range of invariant mass \( W \) around the quasi elastic peak (\( |W - 938\text{MeV}| < 50\text{MeV} \)). In addition, cuts on the horizontal position (\( |y_{pos}| < 40 \) cm) in the neutron detector and on the angle between \( \vec{q} \) and the neutron momentum...
(θ_{pq} < 110 mrad) were applied to optimize the dilution factor. The θ_{pq} cut served also to limit the recoil momentum $p_r$ to values where the model dependence of $A_V^{ed}$ has been shown to be small ($p_{max} \approx 85$ MeV/c) \[1]. The protons were bent vertically in the target field by nearly 18° almost eliminating their overlap with the neutrons which further improved their rejection.

The experimental asymmetry was diluted by scattering from materials other than polarized deuterium nuclei. These include the nitrogen in $^{15}$ND$_3$, the liquid helium, the NMR coils, and target windows. A Monte Carlo (MC) simulation program was developed \[17\] to determine the dilution factor and to perform the detector averaging of the theoretical asymmetries. It was based on MCEEP \[18\] and included an HMS model, the neutron detector geometry and approximate efficiencies, the target magnetic field, the beam raster and radiative effects. Quasi elastic scattering from all the target materials was simulated in the MC. The normalization was fixed by data from carbon (which approximates nitrogen) and liquid helium. A comparison of the simulated distributions to experimental data is shown in Fig. [1] for four kinematic variables. The good agreement of the distributions indicates that quasi elastic scattering is the dominant process for events passing our selection criteria.

The accidental background under the meantime distribution was 4% and had no statistically significant asymmetry. The measured asymmetry was corrected for this dilution. A correction of 0.2% was made for the proton contamination. Charge exchange in deuterium was taken into account in the theoretical calculations of final state interactions (FSI). No correction was applied for charge exchange reactions with other target materials or the shielding (estimated to be 0.24%). The role of radiative effects on $A_V^{ed}$ was estimated and found to be small. Corrections to the asymmetry for internal radiative effects of 2% and 0.5% for external effects were applied.

In order to extract $G_E^{n}$, the corrected experimental asymmetry was compared to the MC simulation which weights theoretical calculations of the asymmetry by the event distribution. The theoretical asymmetries have been calculated on a grid reflecting our experimental arrangement under different assumptions for the size of $G_E^{n}$. Asymmetry values between grid points were obtained by interpolation.

The theoretical $A_V^{ed}$ values were calculated following \[14, 11\]. The calculations are based on a non-relativistic description of the n–p system in the deuteron, using the Bonn R-Space NN potential \[19\] for both the bound state and the description of FSI. The full calculations include meson exchange currents and isobar configurations as well as relativistic corrections. The dipole parameterization for $G_M^{n}$ was assumed. It was verified that the acceptance averaged value of $A_V^{ed}$ is linear in the size of $G_M^{n}$. Thus any (experimental) value could be incorporated easily if desired. The grid of asymmetries was calculated for 3 values of $G_E^{n}$. In each case the $Q^2$ variation of $G_E^{n}$ was assumed to be given by the Galster parameterization \[24\] (with $p = 5.6$) with the magnitude set by an overall scale parameter of 0.5, 1 or 1.5. The narrow acceptance in $Q^2$, $0.4 < Q^2 < 0.6$ (GeV/c)$^2$, makes the extracted value of $G_E^{n}$ insensitive to the assumed $Q^2$ dependence.

\[ \text{FIG. 1: A comparison between the data and the MC simulation for (e,e'n) from } ^{15}\text{ND}_3 \text{ for four kinematic variables: } E' \text{ (scattered electron energy), } y_{pos} \text{ (horizontal position in the neutron detector), } \theta_{pq} \text{ (the angle between } q \text{ and the neutron in the lab), and } \theta_{np}^{cm} \text{ (the calculated angle between the proton and } q' \text{ in the n-p center of mass).} \]

\[ \text{FIG. 2: Comparison between the measured asymmetries and calculated values of } A_V^{ed} \text{ for three scaled parameterizations of Galster shown against four kinematic variables (See Fig. 1).} \]
The MC simulation averaged the asymmetry over all kinematic variables except the one under investigation. The comparisons are shown in Fig. 2. To determine the best value of the scale parameter, it was fit as a free parameter to the data. The resulting value for \( G_E^0 \) at \( Q^2 = 0.495 \) (GeV/c)^2 is \( G_E^0 = 0.04632 \pm 0.00616 \text{(stat.)} \pm 0.00341 \text{(syst.)} \).

The major sources of systematic errors are: \( \delta P_1^d/\delta P_1^d = 5.8\% \), and the uncertainty in determining the average dilution factor is 3.9\%. Cut dependencies give a 2.4\% systematic error. Errors associated with the determination of various kinematic quantities contribute another 2.2\%. The determination of \( P_e \) contributes 1\%. Finally, the error in the value of \( G_M^0 \) was taken to be 1.7\% as derived from a recent fit to world data [21]. The quadratic sum of all the contributions gives a total systematic error \( \delta G_E^0/G_E^0 = 7.4\% \).

Our measurement is compared to \( G_E^0 \) measurements from other polarized experiments in Fig. 3. For reference the standard parameterization of Galster is shown [20]. The figure shows also the results of recent lattice QCD calculations [22]. In these calculations \( G_E^0 \) is quite sensitive to the disconnected insertions which account for the sea-quarks. The magnitude of these sea contributions to the various nucleon form factors is almost constant so they are relatively much more important for \( G_E^0 \). Thus \( G_E^0 \) may provide a valuable testing ground for lattice calculations of other sea sensitive quantities such as the strangeness electric and magnetic form factors.

The size of reaction dynamic effects beyond the plane wave Born approximation (PWBA) was determined by repeating the same extraction procedure using PWBA calculations. The result for \( G_E^0 \) was found to be 13\% smaller than when it was extracted from \( A_{th}^{PV} \) using the full calculation. The bulk of the difference is due to FSI.

In conclusion we present the results of a new measurement of the neutron electric form factor at \( Q^2 = 0.495 \) (GeV/c)^2, the highest momentum transfer to date in polarized scattering using a deuteron target. This measurement sets a new constraint on the parameterizations of \( G_E^0 \) and, more importantly, on theoretical models which describe it. In addition it will contribute to the extraction of strange quark form factors from parity violating (PV) elastic scattering from protons [24, 25] where errors on previous measurements of \( G_E^0 \) are the largest contributor to the theoretical PV asymmetry, \( A_{th}^{PV} \). The ongoing effort to measure \( G_E^0 \) will considerably extend our understanding of nucleon structure.

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REFERENCES

[1] H. Anklin et al., Phys. Lett. B 336, 313 (1994).
[2] H. Anklin et al., Phys. Lett. B 428, 248 (1998).
[3] I. Passchier et al., Phys. Rev. Lett. 82, 4988 (1999).
[4] M. Meyerhoff et al., Nucl. Phys. A551, 247 (1993).
[5] D. Rohe et al., Phys. Rev. Lett. 83, 4257 (1999).
[6] J. Becker et al., Eur. Phys. J A6, 329 (1999).
[7] M. Eden et al., Eur. Phys. J C 50, R1749 (1999).
[8] C. Herberg et al., Eur. Phys. J A5, 131 (1999).
[9] T. W. Donnelly and A. S. Raskin, Ann. Phys. (New York) 169, 247 (1986); 191, 81 (1989).
[10] H. Arenhövel, W. Leidemann and E. L. Tomusiak, Z. Phys. A331, 123 (1988); A334, 363 (E) (1989).
[11] H. Arenhövel, W. Leidemann and E. L. Tomusiak, Phys. Rev. C 46, 455 (1992).
[12] C. Sinclair, TJNAF Technical Note, TJNAF-TN-97-021.
[13] M. Hauger et al., "A High Precision Polarimeter", nucl-exp/9910013. To be published in Nucl. Instrum. Meth.
[14] M. Steinacher and I. Sick, Nucl. Instrum. Meth. A455/3, 759 (2000).
[15] D. Crabb and D. Day, Nucl. Instrum. Meth. A356,
9 (1995), T.D. Averett et al. Nucl. Instrum. Meth. A427, 440 (1999).
[16] G. Court, Nucl. Instrum. Meth. A324, 443 (1993).
[17] H. Zhu, Ph.D. Thesis, University of Virginia, August 2000. Details of the analysis can be found therein.
[18] P. Ulmer, “Monte Carlo for Electro-Nuclear Coincidence Experiments”, MCEEP, Version 3.3, March 2000.
[19] R. Machleidt, K. Holinde and Ch. Elster, Phys. Rep. 149, 1 (1987).
[20] S. Galster et al., Nucl. Phys. B32, 221 (1971).
[21] J. Jourdan, Proceedings of the XVIth European Conference on Few-Body Problems in Physics, Évora 2000.
[22] S.J. Dong, K.F. Liu and A.G. Williams, Phys. Rev. D 58, 074504 (1998) and K.F. Liu, private communication.
[23] J. Golak et al., nucl-th/0008008.
[24] K.A. Aniol et al., Phys. Rev. Lett. 82, 1096 (1999).
[25] K.A. Aniol et al., nucl-ex/0006002.