Measurement of the Electric Form Factor of the Neutron at $Q^2 = 0.5$ and 1.0 GeV$^2$/c$^2$

G. Warren,$^{1,2}$ F. Wesselmann,$^3$ H. Zhu,$^4$ P. McKee,$^3$ N. Savinov,$^4$ M. Zeier,$^3$ A. Aghalaryan,$^5$ A. Ahmidouch,$^6$ H. Arenhövel,$^7$ R. Asatryan,$^5$ I. Ben-Dayan,$^8$ F. Bloch,$^1$ W. Boeglin,$^9$ B. Boillat,$^1$ H. Breuer,$^4$ J. Brower,$^{10}$ C. Carasco,$^1$ M. Carl,$^9$ R. Carlini,$^2$ J. Cha,$^{11}$ N. Chant,$^3$ E. Christy,$^4$ L. Cole,$^{12}$ L. Coman,$^9$ M. Coman,$^9$ D. Crabb,$^3$ S. Danagoulian,$^6$ D. Day,$^3$ K. Duek,$^8$ J. Dunne,$^{11}$ M. Elaasar,$^{13}$ R. Ent,$^2$ J. Farrell,$^3$ R. Fatemi,$^3$ D. Fawcett,$^3$ H. Fenker,$^2$ T. Forest,$^{14}$ K. Garrow,$^2$ A. Gasparian,$^{12}$ I. Goussev,$^1$ P. Gueye,$^{12}$ M. Harvey,$^{12}$ M. Hauger,$^3$ J. Hage,$^4$ J. Jourdan,$^1$ C. Keith,$^2$ J. Kelly,$^4$ C. Keppel,$^{12}$ M. Khandaker,$^{15}$ A. Klein,$^{16}$ A. Klimenko,$^{16}$ L. Kramer,$^9$ B. Krusche,$^1$ S. Kuhn,$^{16}$ Y. Liang,$^{12}$ J. Lichtenstadt,$^8$ R. Lindgren,$^3$ J. Liu,$^4$ A. Lung,$^2$ D. Mack,$^2$ G. Maclachlan,$^{10}$ P. Markowitz,$^9$ D. McNulty,$^9$ D. Meekins,$^2$ J. Mitchell,$^2$ H. Mkrtchyan,$^5$ R. Nasseripour,$^9$ I. Niculescu,$^2$ K. Normand,$^1$ B. Norum,$^3$ A. Opper,$^6$ E. Piasetzky,$^8$ J. Pierce,$^3$ M. Pitt,$^{17}$ Y. Prok,$^3$ B. Raue,$^9$ J. Reinhold,$^9$ J. Roche,$^2$ D. Rohe,$^1$ O. Rondon,$^3$ D. Sacker,$^1$ B. Sawatzky,$^3$ M. Seely,$^2$ I. Sick,$^1$ N. Simicevic,$^{14}$ C. Smith,$^3$ G. Smith,$^2$ M. Steinacher,$^1$ S. Stepanyan,$^5$ J. Stout,$^6$ V. Tadevosyan,$^5$ S. Tajima,$^{18}$ L. Tang,$^{12}$ G. Testa,$^1$ R. Trojer,$^1$ B. Vlahovic,$^{19}$ B. Vulcan,$^2$ K. Wang,$^3$ S. Wells,$^{14}$ H. Woehrle,$^1$ S. Wood,$^2$ C. Yan,$^2$ Y. Yanay,$^9$ L. Yuan,$^{12}$ J. Yun,$^{17}$ and B. Zihlmann$^{20}$

(The Jefferson Lab E93-026 Collaboration)

$^1$Universität Basel, CH-4056 Basel, Switzerland
$^2$Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606
$^3$University of Virginia, Charlottesville 22903
$^4$University of Maryland, College Park, Maryland 20742
$^5$Yerevan Physics Institute, Yerevan, Armenia
$^6$North Carolina A&T State University, Greensboro, North Carolina 27411
$^7$Johannes Gutenberg-Universität, D-55099 Mainz, Germany
$^8$Tel Aviv University, Tel Aviv, 69978 Israel
$^9$Florida International University, Miami, Florida 33199
$^{10}$Ohio University, Athens, Ohio 45011
$^{11}$Mississippi State University, Mississippi State, Mississippi 37962
$^{12}$Hampton University, Hampton, Virginia 23668
$^{13}$Southern University at New Orleans, New Orleans, Louisiana 70126
$^{14}$Louisiana Tech University, Ruston, Louisiana 71272
$^{15}$Norfolk State University, Norfolk, Virginia 23504
$^{16}$Old Dominion University, Norfolk, Virginia 23529
$^{17}$Virginia Polytechnic Institute & State University, Blacksburg, Virginia 24061
$^{18}$Duke University and TUNL, Durham, North Carolina 27708
$^{19}$North Carolina Central University, Durham, North Carolina 27707
$^{20}$Vrije Universiteit, 1081 HV Amsterdam, The Netherlands

(Dated: January 30, 2004)

The electric form factor of the neutron was determined from measurements of the $d(\vec{c}, e' n) p$ reaction for quasielastic kinematics. Polarized electrons were scattered off a polarized deuterated ammonia ($^{15}$ND$_3$) target in which the deuteron polarization was perpendicular to the momentum transfer. The scattered electrons were detected in a magnetic spectrometer in coincidence with neutrons in a large solid angle detector. We find $G_E^n = 0.0526 \pm 0.0033(stat) \pm 0.0026(sys)$ and 0.0454 $\pm$ 0.0054 $\pm$ 0.0037 at $Q^2 = 0.5$ and 1.0 (GeV/c)$^2$, respectively.

PACS numbers: 14.20.Dh, 13.40.Gp, 24.70.+s, 25.40.Ve

The electric form factor of the neutron $G_E^n$ is a fundamental quantity in nuclear physics. Knowledge of $G_E^n$ over a large range of momentum transfer leads to insights to physics beyond the simple SU(6) symmetric models, for which it must vanish. Beyond nucleon structure, our understanding of $G_E^n$ has an impact on a broad range of topics, which vary from the charge radii of nuclei$^1$ to extracting the strangeness content of the nucleon$^2$. Historically, measurements of $G_E^n$ have suffered from large uncertainties due to experimental technique and nuclear model dependence. Early attempts to measure $G_E^n$ from cross sections sometimes failed to determine even the sign. Until recently, the best determination of $G_E^n$ came from elastic electron-deuteron measurements, but the errors were large, $\sim$30%, due to their dependence on the nucleon-nucleon potential model$^3$. The first polarization measurements of $G_E^n$, conducted with $^2$H and $^3$He targets, differed significantly because final state interactions were not addressed$^4$. These experiences highlight the importance of measuring $G_E^n$ using different reactions.

In the last few years the experimental understanding...
of $G^n_E$ has improved considerably. The results from polarization experiments described in Ref. 8-11 are consistent and provide good accuracy in the kinematic region of the four-momentum transferred squared $Q^2 \leq 0.7$ (GeV/c)^2 (henceforth units of $Q^2$ are assumed to be (GeV/c)^2). Until now, values of $G^n_E$ determined from the deuteron quadrupole form factor 12 provide the only information in the kinematic region above $Q^2$ > 0.7 and leave the $Q^2 > 1.6$ region undetermined.

This letter describes a first measurement of $G^n_E$ at $Q^2 = 1.0$ using a polarized target. In addition, the result for $Q^2 = 0.5$ has half the uncertainty as the previous measurement 10 and is the most precise result near the peak of $G^n_E$. These results are largely insensitive to the model of the nucleon-nucleon (NN) potential so that, compared to those of Ref. 12, they are more reliable.

To determine $G^n_E$, the helicity dependent rate asymmetry in electron scattering was measured. In the ideal case of a polarized electron scattering elastically off a free polarized neutron, with the neutron polarization vector in the scattering plane and perpendicular to the momentum transfer $\vec{q}$, $G^n_E$ is related to the beam-target asymmetry term $A_{en}$ 13 by

$$A_{en}^V = \frac{-2\sqrt{\tau} \tan(\theta_e/2) G^n_E G^2_M}{(G^n_E)^2 + \tau(1 + 2(1 + \tau) \tan^2(\theta_e/2)) |G^2_M|^2},$$

where $\tau = Q^2/4M^2_n$, $M_n$ is the mass of the neutron, $G^2_M$ is the magnetic form factor of the neutron, and $\theta_e$ is the electron scattering angle.

For lack of a free neutron target, the actual measurements were performed on a polarized deuteron target. The measured experimental asymmetries were due to a combination of several physics asymmetries scaled by the electron and target vector and tensor polarizations (that are described in detail in our previous work 10, not repeated here for brevity’s sake). The proper averaging of the asymmetry (symmetrically around $\vec{q}$) and the negligible contributions from the target tensor asymmetry simplify the relationship of the measured asymmetry $\epsilon$ to the deuteron vector asymmetry $A_{ed}$ so that $\epsilon = fP_eP_{1d}A_{ed}$, where $P_e$ is the beam polarization, $P_{1d}$ is the deuteron vector polarization and $f$ is the dilution factor due to scattering from nucleons other than polarized deuterons in the target. Calculations show that $A_{en}^V$ depends linearly on $G^n_E$ for the kinematics of the experiment 14.

The measurements were conducted in Hall C of the Thomas Jefferson National Accelerator Facility in a setup similar to that of the previous measurement 10. The longitudinally polarized electron beam 15 was scattered off a polarized frozen deuterated ammonia (^13ND3) target. The scattered electrons were detected by the High Momentum Spectrometer (HMS), and the neutrons were detected by a dedicated neutron detector. The central kinematics for the two measurements as well as the average beam and target polarizations are listed in Table I.

| $Q^2$ (GeV/c)^2 | E (GeV) | $E'$ (GeV) | $\theta_e$ (deg) | $\theta_n$ (deg) | $\theta_B$ (deg) | $(P_e)$ (%) | $(P\nu)$ (%) |
|-----------------|--------|-----------|-----------------|-----------------|----------------|--------|--------|
| 0.5             | 2.331  | 1.963     | -18.5           | 60.5            | 150.4          | 78.2   | 24.1   |
| 1.0             | 3.481  | 2.810     | -18.0           | 53.3            | 143.3          | 71.8   | 23.8   |

The measurements were performed in Hall C of the Thomas Jefferson National Accelerator Facility in a setup similar to that of the previous measurement 10. The longitudinally polarized electron beam 15 was scattered off a polarized frozen deuterated ammonia (^13ND3) target. The scattered electrons were detected by the High Momentum Spectrometer (HMS), and the neutrons were detected by a dedicated neutron detector. The central kinematics for the two measurements as well as the average beam and target polarizations are listed in Table I

| $Q^2$ (GeV/c)^2 | E (GeV) | $E'$ (GeV) | $\theta_e$ (deg) | $\theta_n$ (deg) | $\theta_B$ (deg) | $(P_e)$ (%) | $(P\nu)$ (%) |
|-----------------|--------|-----------|-----------------|-----------------|----------------|--------|--------|
| 0.5             | 2.331  | 1.963     | -18.5           | 60.5            | 150.4          | 78.2   | 24.1   |
| 1.0             | 3.481  | 2.810     | -18.0           | 53.3            | 143.3          | 71.8   | 23.8   |

The polarized target 14 consisted of ammonia granules submerged in liquid He and maintained at 1 K by a ^4He evaporation refrigerator. The target spins were aligned by a 5 T magnetic field generated by a pair of superconducting coils. The polarization was enhanced via dynamic nuclear polarization 16, and measured with a continuous-wave NMR system 17. To minimize localized heating and depolarization of the target material, the electron beam was rastered uniformly in a circular pattern with a 1 cm radius.

A two-magnet chicane compensated for the deflection of the electron beam by the target field. After traversing the target, the beam passed through a helium bag to a special dump in the experimental hall. The polarization of the beam was measured at regular intervals throughout the experiment with a Møller polarimeter 19. The beam helicity was changed in a pseudorandom sequence 30 times per second to minimize charge fluctuations correlated with helicity.

The HMS was operated in its standard mode for the detection of electrons. The established reconstruction algorithms were augmented to account for the large beam rastering and the effects of the target magnetic field on the scattered electrons.

The neutron detector consisted of multiple vertical planes of segmented plastic scintillators. Two planes of thin scintillators served to distinguish charged particles. Behind these were six planes of thick scintillators to detect the neutrons. All scintillators were equipped with photomultipliers on both ends to provide spatial and time information for the detected particle. The 88 thick scintillators provided a neutron detection volume that was roughly 160 cm wide, 160 cm tall and 90 cm deep. The front of the detection volume was approximately 4.2 m and 6.2 m from the target during the $Q^2 = 0.5$ and 1.0 measurements, respectively. The detector was shielded from direct gamma rays from the target by a 2.5 cm lead curtain, and the entire assembly was housed in a thick-walled concrete hut, which was open to the target.

The trigger was set up so that the neutron detector was read out for every electron trigger in the HMS. Coincidences between the electrons and the knock-out nucleon were determined offline.

The experiment was simulated using Monte Carlo
Several corrections to the measured asymmetry were applied. The leading correction was for charge exchange of protons in the lead shielding: \(-3.8 \pm 1.1\% (-3.3 \pm 3.0\%)\) for \(Q^2 = 0.5\) \((Q^2 = 1.0)\). The charge exchange in the target material itself was small: \(-0.3 \pm 0.3\% (-0.3 \pm 0.3\%)\). The accidental background rate was \(1.9 \pm 0.1\% (0.5 \pm 0.2\%)\) with no statistically significant asymmetry. Internal radiation effects on the asymmetry were also corrected: \(0.9 \pm 0.5\% (0.6 \pm 0.5\%)\). The effect of external radiation was insignificant compared to the 0.5\% MC statistical uncertainty. The contamination from neutral pions generated by protons in the lead shielding of the neutron detector was also found to be insignificant.

The physics model of \(A_{em}^n\) used in the MC was based on the calculations of Arenhövel, Leidemann and Tomusiak. It included a non-relativistic description of the \(n-p\) system in the deuteron using the Bonn \(R\)-space \(NN\) potential for both the bound state and the final state interactions. The full calculation included meson exchange, isobar configuration currents and relativistic corrections.

The model assumed a scaled Galster parameterization \((22)\) for \(G_E^n\) and the dipole parameterization for \(G_M^n\). The Galster parameterization is \(G_E^n(Q^2) = -\mu_n \tau/(1 + 5.6\tau)\), whereas \(G_D = 1/(1 + Q^2/0.71)^2\) is the dipole form factor. Various scale factors of this parameterization, ranging from 0.5 to 1.5, were examined. The potential impact of the \(Q^2\) dependence of the \(G_E^n\) parameterization was found to be negligible because the \(Q^2\) acceptance was not large and the \(Q^2\) dependence of \(G_E^n\) over the acceptance was mostly linear. The acceptance-averaged value of \(A_{em}^n\) has a linear dependence on \(G_M^n\), so one can trivially correct for more accurate \(G_M^n\) values.

The value of \(G_E^n\) was determined by comparing the acceptance averaged \(A_{em}^n\) of the data to that of the MC. The theoretical asymmetries were determined for a range of scaling factors of the Galster parameterization to determine the corresponding \(G_E^n\): \(G_E^n/Galster = 1.003 \pm 0.064\) and \(1.172 \pm 0.140\) for \(Q^2 = 0.5\) and 1.0, respectively. The uncertainties are statistical only. To account for the slight deviations of \(G_M^n\) from the dipole form factor, the recent fit to the \(G_M^n\) data was used: \(G_M^n/\mu_n G_D = 1.007 \pm 0.005\) and \(1.072 \pm 0.014\) for \(Q^2 = 0.5\) and 1.0, respectively. Then the values for \(G_E^n\) are:

\[
G_E^n(Q^2 = 0.5) = 0.0526 \pm 0.0033 \pm 0.0026, \quad G_E^n(Q^2 = 1.0) = 0.0454 \pm 0.0054 \pm 0.0037,
\]

where the first uncertainty is statistical and the second is systematic. The \(Q^2 = 0.5\) result agrees well with the previous result reported in Ref. \(\text{[17]}\).

Other systematic uncertainties for \(Q^2 = 0.5\) \((Q^2 = 1.0)\) were: dilution factor, 3.4\% \((3.0\%)\); target polarization, 2.9\% \((4.6\%)\); central kinematic values, 1.2\% \((3.4\%)\); beam polarization, 1.1\% \((3.3\%)\).

The results as compared to recent measurements are shown in Fig. 4. The new data at \(Q^2 = 1.0\) provides the
rigorous challenge for models of the nucleon structure because this electromagnetic form factor is the most sensitive to physics beyond the simplistic SU(6) symmetric picture.

In conclusion, the electric form factor of the neutron at $Q^2 = 0.5$ and $1.0$ has been determined from measurements of the beam-target asymmetry. This experiment provides the highest $Q^2$ measurement to date using a polarized target and the most precise measurement near the maximum of $G_E^n$.

We wish to thank the Hall C technical and engineering staff at TJNAF as well as the injector, target and survey groups for their outstanding support. This work was supported by the Commonwealth of Virginia, the Schweizerische Nationalfonds, the U.S. Department of Energy, the U.S. National Science Foundation, the U.S.-Israel Binational Science Foundation and the Deutsche Forschungsgemeinschaft. The Southeastern University Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the U.S. Department of Energy under contract DE-AC05-84ER40150.

[1] J.L. Friar and J.W. Negele, Advances in Nuclear Physics, Vol. 8, 219, 1975.
[2] K.S. Kumar and P.A. Souder, Prog. Part. Nucl. Phys. 45, S333 (2000).
[3] S. Platchkov et al., Nucl. Phys. A510, 749 (1999).
[4] J. Becker et al., Eur. Phys. J. A 6, 329 (1999).
[5] M. Ostrick et al., Phys. Rev. Lett. 83, 276 (1999).
[6] H. Zhu et al., Phys. Rev. Lett. 87, 081801 (2001).
[7] I. Passchier et al., Phys. Rev. Lett. 82, 4988 (1999).
[8] J. Golak et al., Phys. Rev. C 63, 034006 (2001).
[9] T. Eden et al., Phys. Rev. C 50, R1749 (1994).
[10] C. Herberg et al., Eur. Phys. J. A 5, 131 (1999).
[11] J. Bernmuth et al., Phys Lett B. 564, 199 (2003). D. Rohe et al., Phys. Rev. Lett. 83, 4257 (1999).
[12] R. Schiavilla and I. Sick, Phys. Rev. C 64, 041002(R) (2002).
[13] T.W. Donnelly and A.S. Raskin, Ann. Phys. (N.Y.) 169, 247 (1986). A.S. Raskin and T.W. Donnelly, Ann. Phys. (N.Y.) 191, 78 (1989).
[14] H. Arenhövel, W. Leidemann, E.L. Tomusiak, Z. Phys A 331, 123 (1988); 334, 363(E) (1989). H. Arenhövel, W. Leidemann, E.L. Tomusiak, Phys. Rev. C 46, 455 (1992). H. Arenhövel, private communication.
[15] C. Sinclair, TJNAF Report No. TJNAF-TN-97-021.
[16] D. Crabb and D. Day, Nucl. Inst. Meth. A 356, 9 (1995). T. D. Averett et al. Nucl. Inst. Meth. A 427, 440 (1999).
[17] D.G. Crabb and W. Meyer, Ann. Rev. Nucl. Part. Sci. 47, 67 (1997).
[18] G. Court, Nucl. Inst. Meth A 324, 433 (1993).
[19] M. Hauger et al., Nucl. Inst. Meth. A 462, 382 (2001).
[20] P. Ulmer, MCEEP: Monte Carlo for Electro-Nuclear Coincidence Experiments, Version 3.5.
[21] J. Arrington, SIMC.
[22] S. Janssen, J. Ryckebusch, W. Van Nespen and D. Debruyn, Nucl. Phys. A 672, 285 (2000).
[23] R. Machleidt, K. Holinde and Ch. Elster, Phys. Rep. 149, 1 (1987).
[24] S. Galster et al., Nucl. Phys. B32, 221 (1971).
[25] G. Kubon et al., Phys. Lett. B 524, 26 (2002).
[26] S. Kopecky et al., Phys. Rev. Lett. 74, 2427 (1995).
[27] E.L. Lomon, Phys. Rev. C 66, 045501 (2002).
[28] F. Cardarelli and S. Simula, Phys. Rev. C 62, 065201 (2000). Phys. Lett. B 467, 1 (1999).

[29] G. Holzwarth hep-ph/020138; Z. Phys. A 356, 339 (1996) [Fit B2 is shown in Fig. 2].
[30] S. Boffi, L. Ya. Glozman, W. Klink, W. Plessas, M. Radici, and R.F. Wagenbrunn, Eur. Phys. J. A 14, 17 (2002).
[31] G.A. Miller, Phys. Rev. C 66, 032201(R) (2002).