Measurement of the Neutron Electric Form Factor G_{en} at 0.67 $(\mathrm{GeV}/c)2$ via $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$

D. Rohe,[1] P. Bartsch,[2] D. Baumann,[2] J. Becker,[2] J. Bermuth,[1] K. Bohinc,[3] R. Böhm,[2] S. Buttazzoni,[4] T. Caprano,[2] N. Clawiter,[2] A. Deninger,[1] S. Derber,[2] M. Ding,[2] M. Distler,[2] A. Ebbes,[2] M. Ebert,[1] I. Ewald,[2] J. Friedrich,[2] J. M. Friedrich,[2] R. Geiges,[2] T. Großmann,[1] M. Hauger,[4] W. Heil,[1] A. Honegger,[4] P. Jennewein,[2] J. Jourdan,[4] M. Kahrau,[2] A. Klein,[5] M. Kohl,[6] K. W. Krygier,[2] G. Kubon,[4] A. Liesenfeld,[2] H. Merkel,[2] K. Merle,[2] P. Merle,[2] M. Mühlbauer,[4] U. Müller,[2] R. Neuhausen,[2] E. W. Otten,[1] Th. Petitjean,[4] Th. Pospischil,[2] M. Potokar,[3] G. Rosner,[2] H. Schmieden,[2] I. Sick,[4] S. Širca,[3] R. Surkau,[1] A. Wagner,[2] Th. Walcher,[2] G. Warren,[4] M. Weis,[2] H. Wöhrle,[4] and M. Zeier[4]

[1]*Institut für Physik, Universität Mainz, D-55099 Mainz, Germany*
[2]*Institut für Kernphysik, Universität Mainz, D-55099 Mainz, Germany*
[3]*Institute "Jožef Stefan," University of Ljubljana, SI-1001 Ljubljana, Slovenia*
[4]*Department für Physik und Astronomie, Universität Basel, CH-4056 Basel, Switzerland*
[5]*Department of Physics, Old Dominion University, Norfolk, Virginia 23507*
[6]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
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We have measured the neutron electric form factor G_{en} via $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$ at $Q^2 = 0.67$ $(\mathrm{GeV}/c)^2$ using the 3-spectrometer facility of the A1 Collaboration at the Mainz Microtron and a dedicated neutron detector. High pressure polarized $^3\overrightarrow{\mathrm{He}}$ gas was used as a target of polarized neutrons. G_{en} is determined from the ratio of the asymmetries $A_\perp/A_\parallel$ measured in quasifree kinematics with the target spin perpendicular and parallel to the momentum transfer. We find $G_{en} = 0.052 \pm 0.011 \pm 0.005$.

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Introduction.—Form factors probed by the scattering of electrons are important observables for our understanding of the many-body structure of the nucleon. While the electric and magnetic form factors of the proton, G_{ep} and G_{mp}, and the magnetic form factor of the neutron G_{mn} are known over a wide range of momentum transfer $\vec{q}$, the electric form factor of the neutron G_{en} is only poorly known. The reason for this is twofold. First, measurements on the neutron are hampered by the fact that there are no free neutron targets. Second, G_{en} is difficult to measure since it is small due to the zero total charge. Only at very low momentum transfer is the slope of G_{en} known from the coherent scattering of slow neutrons by atomic electrons [1,2]. At low momentum transfer G_{en} is dominated by the contribution from the anomalous magnetic moment of the neutron. Since this contribution is of purely kinematic origin, the dominant term does not contain new information about the nucleon's structure (see, e.g., [3,4]). In order to get information on the intrinsic charge structure of the neutron, precise measurements of G_{en} are needed over a large range of momentum transfer.

In the determination of G_{en} from elastic scattering on the deuteron the extraction of G_{en} is severely hampered by the model dependence of the necessary unfolding of the deuteron structure and the removal of the proton contribution [5]. Sufficient sensitivity to G_{en} can be obtained only through observables which depend on interference terms in which the small contribution of G_{en} is amplified by another, dominating amplitude. This is the case in quasifree $(e, e'n)$ double polarization coincidence experiments, where the electron and the target nucleus (or the recoiling neutron) are polarized [6–8]. Such double polarization experiments, using ^{3}He and/or deuterium as neutron targets, were recently performed at the Mainz Microtron (MAMI) [9–13] and at Bates [14]. The detection of the neutron in such experiments suppresses the contribution of quasielastic scattering from protons.

The polarization dependent part of the cross section contains an interference term between the electric and magnetic scattering. Since the magnetic scattering amplitude, but not the electric one, changes sign when flipping the electron helicity, this interference term can be measured in the cross section asymmetry $A = (\sigma_- - \sigma_+)/(\sigma_- + \sigma_+)$ with regard to the helicity of the incident electron. In the plane wave impulse approximation (PWIA) the asymmetry can be written as [6,15]

$$A = P_e P_n V \frac{a \sin\theta \cos\phi G_{en} G_{mn} + b \cos\theta G_{mn}^2}{c G_{en}^2 + d G_{mn}^2}, \quad (1)$$

where θ and ϕ describe the direction of the neutron's spin relative to the momentum transfer and the scattering plane, respectively. The quantities a, b, c, d are determined by the electron kinematics (see [6,10]). P_e denotes the longitudinal polarization of the electron beam, and P_n, the polarization of the neutron. The factor V accounts for a possible dilution due to contributions with vanishing asymmetry [10,11].

When the target spin is oriented perpendicular to $\vec{q}$ $(\theta = 90°)$, the asymmetry $A_\perp$ contains the interference term $G_{en}G_{mn}$ we are interested in. The asymmetry $A_\parallel$ $(\theta = 0°)$ does, to first order, not depend on the form factors, because $G_{en}^2 \ll G_{mn}^2$. Therefore, it can serve as

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normalization and G_{en} can be determined via

$$G_{en} \simeq \frac{b}{a} G_{mn} \frac{(P_e P_n V)_\parallel}{(P_e P_n V)_\perp} \frac{A_\perp}{A_\parallel}. \quad (2)$$

Thus, there is no need for knowing P_e, P_n, and V. Since P_e and V do not depend on the orientation of the target spin, they drop out in the ratio of the parallel and perpendicular measurement, just as a number of systematic errors do.

Setup.—In the experiment reported in this paper, G_{en} is determined at $Q^2 = 0.67\ (\mathrm{GeV}/c)^2$ via the reaction $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)pp$. Longitudinally polarized electrons were produced using a strained layer GaAs crystal [16,17]. Currents up to 10 μA were available. The polarization was measured as $P_e = 0.70 \pm 0.04$ with a Mott polarimeter before injection into MAMI [18], where the electrons were accelerated to 854 MeV. The longitudinal orientation of the spin at the target position was adjusted by fine-tuning of the electron energy, exploiting the energy dependence of the spin precession in MAMI [19]. The spin alignment was controlled in a separate experiment in which the polarization of the recoil protons from the reaction $p(\vec{e}, e'\vec{p})$ was measured with a polarimeter [20] in the focal plane of spectrometer A [21].

The quasielastically scattered electrons were momentum analyzed in the magnetic spectrometer A (Fig. 1). Over the target-length acceptance of 5 cm, it allows reconstruction of the scattered electron's direction, θ_e and ϕ_e [21]. Neutrons (and also protons) were detected in coincidence in a dedicated neutron detector. Each of its four layers consisted of five plastic scintillator bars equipped with photomultipliers on both ends, thus allowing reconstruction of the neutron angles, θ_n and ϕ_n. At a distance of 1.6 m from the target, the detector covered 75% of the events in the Fermi cone. Two additional layers of ΔE counters enabled distinction between protons and neutrons. The small contribution of protons to the neutron yield due to the inefficiency of the veto counters has been eliminated in the off-line analysis using the energy deposition in the first E counter. In order to suppress electromagnetic background the detector was shielded with 2 cm of lead towards the target direction and 10 cm elsewhere. In addition, collimators were placed near the entrance and exit windows of the target to suppress background from the target walls.

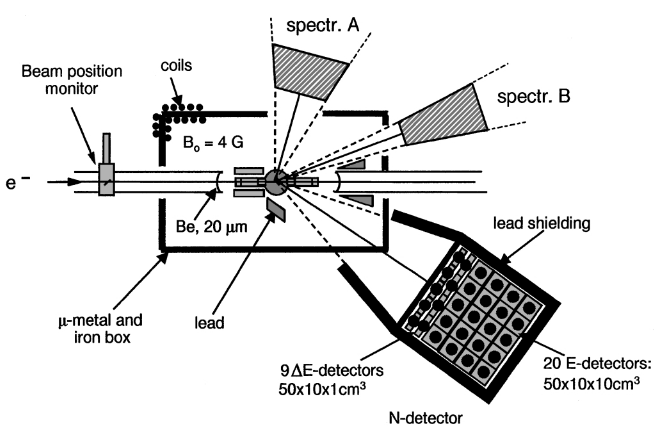

FIG. 1. Detector and target setup. The spectrometers B and A and the neutron detector were placed at 25°, 78.6°, and −32.2°, respectively. They covered solid angles of 5.6, 28, 100 msr.

Polarized $^3\overrightarrow{\mathrm{He}}$ serves as an effective polarized neutron target. Averaged over all momenta, with 90% probability the two protons are in the S state with the spins coupled to zero. Thus, it is predominantly the neutron that carries the ^{3}He spin [22].

With the known target and electron polarization P_t and P_e, we find from a measurement of the asymmetry $A_\parallel$ the value $P_n = 1.03 \pm 0.06$, which is to first order independent of G_{mn} and G_{en}. This value agrees within the error with the prediction [23]. We emphasize again that the extraction of G_{en} from the ratio of asymmetries does not depend on the absolute value of P_n.

The ^{3}He gas was polarized by metastable optical pumping at pressures around 1 mbar and subsequently compressed by a two-stage titanium piston compressor [24] to 6 bar. The target polarization achieved was approximately 0.5. To achieve relaxation times of tens of hours, the target container consisted mainly of glass prepared by heat treatment (350 °C), sputtering and subsequent coating with Cs [25]. The target featured three cells containing ^{3}He, $^3\overrightarrow{\mathrm{He}}$, ^{3}He with identical pressure. This allowed for very thin (25 μm) glass windows for the inner cell and thin Havar windows (which are much stronger but depolarize) for the outer ones. This construction resulted in an empty-target thickness of 27 mg cm^{-2}, which compares favorably to the 24 mg cm^{-2} of ^{3}He.

For the ^{3}He target we used a novel setup. The target cells were filled with polarized ^{3}He in the laboratory and transported to the experimental hall in a small magnetic holding field. Relaxation of the polarization and the measurement of the polarization require magnetic guiding fields with relative gradients of less than 10^{-3} cm^{-1}. The stray field of the magnetic spectrometers of $\approx$2 G, with a relative gradient of 1.5×10^{-2} cm^{-1}, was reduced by a rectangular box of 2 mm thick μ-metal and iron which enclosed the target cell. With additional correction coils a relative field gradient of less than 5×10^{-4} cm^{-1} was achieved. The holding field ($\approx$4 G) was produced by three independent pairs of coils. This allowed us to rotate the target spin in any desired direction to measure $A_\parallel$ and $A_\perp$. The time dependence of the polarization of the target cell was continuously measured during the experiment by nuclear magnetic resonance (NMR), while the absolute polarization P_t was measured by the method of adiabatic fast passage (AFP) based on the measurement of the static magnetic field which is produced by the aligned spins in the polarized gas [26]. Because of the nearly spherical shape of the target cell the correction of the polarization calculated from a pure magnetic dipole field amounted to only -1.8%. A single AFP measurement yields the absolute polarization with a relative error of 3.5% and leads to a polarization loss of less than 0.2%.

Data taking and analysis.—During the experiment, the influence of the beam and impurities in the cell reduced the relaxation time to 20–30 h. Therefore, target cells were changed among five available cells twice a day; changing the target cell took 1 h. The time-averaged polarization was 32%. To avoid systematic errors, the beam helicity was flipped in a random sequence every second and the asymmetries $A_\perp$ and $A_\parallel$ were measured alternately each for $\approx$1 h. The total charge accumulated with beam currents between 2 and 10 μA amounted to 1.4 C.

Parallel to the $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)$ measurement, electrons scattered elastically from $^3\overrightarrow{\mathrm{He}}$ were detected in spectrometer B. The asymmetry in the $^3\overrightarrow{\mathrm{He}}(\vec{e},e')$ reaction is given by Eq. (1), but where the form factors are those for elastic scattering off ^{3}He, both of which are known to $\approx$2% [27]. Therefore, the measurement of this asymmetry allowed one to continuously measure P_eP_t. Knowing P_t from the AFP measurements, P_e could be deduced; it agreed within error with that measured at the source.

In order to determine the various corrections to the raw asymmetries, the quasielastic scattering process was simulated by the Monte Carlo method based on PWIA. The momentum distribution was taken from Ref. [28] under the assumption that proton and neutron momentum distributions are equal. The simulation accounts for energy loss via bremsstrahlung and for the angle and momentum acceptances of the spectrometer and the hadron detector. Figure 2 shows a comparison between the simulated and the measured energy distributions in spectrometer A. The good agreement of simulation and measurement is also due to the low background contribution, which amounts to 1.3% of $^3\mathrm{He}(e,e'n)$ only.

G_{en} is extracted from the ratio of $A_\perp/A_\parallel$ weighted by $P_n^\parallel/P_n^\perp$ [see Eq. (2)]. Within 2%, the latter ratio was unity. The measured asymmetry ratio was corrected for the asymmetrically restricted momentum acceptance of the spectrometer. This leads to a shift of the average $\vec{q}$ vector relative to $\vec{q}$ at the top of the quasielastic peak. This angular shift results in a correction of -3.4%. Further corrections of -2.5% and -0.9% are due to the influence of bremsstrahlung and missing energy.

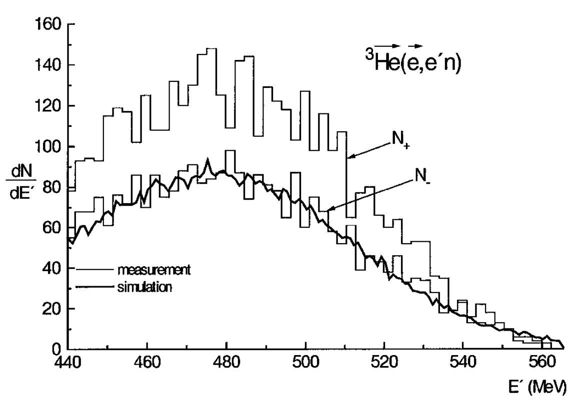

FIG. 2. Energy distribution of the scattered electrons in the reaction $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)$ for the two helicity states of the electron within the momentum acceptance of spectrometer A. Histogram: data; line: Monte Carlo simulation (normalized to the data with negative helicity).

The neutrons from (p,n) charge exchange in the Pb shielding contribute in first order to the dilution factor V but not to the ratio $A_\perp/A_\parallel$ since the asymmetry of protons from $^3\overrightarrow{\mathrm{He}}(\vec{e},e'p)$, averaged over the acceptance of the experiment, was found to be $<$1%, in agreement with theoretical predictions [22]. There is then no need for a correction due to these events.

Even in double-polarization observables, nuclear corrections to the asymmetry of G_{en} are not negligible. Particularly at low q meson exchange currents, final state interaction (FSI) and isobar components lead to correction terms to Eq. (2). As indicated by calculations [29] for $\mathrm{D}(\vec{e},e'\vec{n})$, it is expected that the main correction to the extraction of G_{en} from $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)$ is due to $(\vec{e},e'p)$ followed by (p,n) charge exchange in the 3-body system (FSI) [13]. The FSI correction for the analysis of the $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)$ reaction at four momentum transfer $Q^2 = 0.35\ (\mathrm{GeV}/c)^2$ is being calculated [30] using Faddeev techniques for both the initial state and the final state. Scaling the relevant cross sections and asymmetries to $Q^2 \approx 0.7\ (\mathrm{GeV}/c)^2$ leads to an estimate of this correction of $\Delta G_{en} = +0.005$. Since this number is a preliminary estimate, it will be considered here as a systematic uncertainty and not as a correction.

Finally, using $G_{mn}[Q^2 = 0.652\ (\mathrm{GeV}^2/c)^2] = (1.037 \pm 0.012)\mu_n\, G_D$ [31] with the magnetic moment μ_n and the dipole form factor G_D, we obtain G_{en} via Eq. (2). The statistical error amounts to $\pm 21.7\%$. The experimental systematic error of 4.3% results from the uncertainty of $\pm 0.2°$ in the alignment of the magnetic field (systematic error $\epsilon_{\mathrm{syst}} = 1.9\%$), the error in the polarization ratio $P_n^\parallel/P_n^\perp$ ($\epsilon_{\mathrm{syst}} = 2.0\%$) and an estimate for the uncertainty in the Monte Carlo simulation ($\epsilon_{\mathrm{syst}} = 3.0\%$). Taking the theoretical uncertainty of 9.5% into account results in a total systematic error of 10.4%. Our final result is $G_{en} = 0.052 \pm 0.011 \pm 0.005$. The overall error is similar to the one at lower q despite the 10 times smaller e-n cross section.

G_{en} is shown in Fig. 3 together with the results from other recent double-polarized coincidence measurements at MAMI. While the new value is normalized to the recently remeasured G_{mn} [31], the other data are normalized to the dipole fit. (Normalizing them to the new measurement has negligible influence compared to the experimental uncertainties.) Overall, the values from the $\mathrm{D}(\vec{e},e'\vec{n})$ reaction [12,13] and the present result are significantly larger than the result from elastic scattering on the deuteron, analyzed using the Paris potential [5]. For the results extracted from the $^3\overrightarrow{\mathrm{He}}(\vec{e},e'n)$ reaction

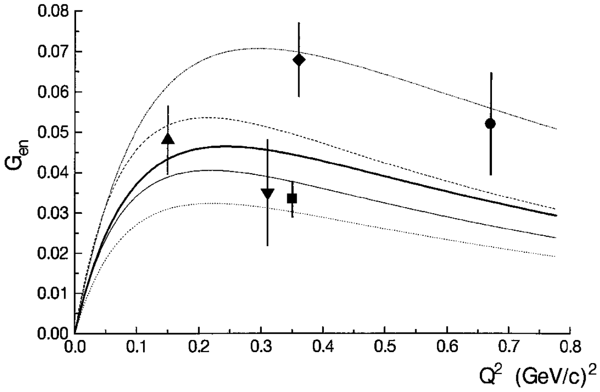

FIG. 3. Neutron electric form factor G_{en} versus momentum transfer squared measured in exclusive double polarization experiments. ●: result of the present experiment; ▼ [9] and ■ [10]: from $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$; ♦ [12] and ▲ [13]: from $D(\vec{e}, e'\vec{n})$. Corrections for nuclear binding effects are applied to the data from the $D(\vec{e}, e'\vec{n})$ reaction but not to that from $^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$. The curves represent the results from elastic e-d scattering analyzed with four different NN potentials for the calculation of the deuteron wave function (RSC, Paris, Argonne V14, Nijmegen from bottom to top) [5]. Also shown as a thick line is a new analysis [32] of these data using the Paris potential but including $\Delta\Delta$ excitation in the deuteron.

around 0.3 $(\mathrm{GeV}/c)^2$, the influence of nuclear effects must still be clarified.

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[1] V. E. Krohn and G. R. Ringo, Phys. Rev. D **8**, 1305 (1973).
[2] S. Kopecky *et al.*, Phys. Rev. C **56**, 2229 (1997).
[3] D. R. Yennie *et al.*, Rev. Mod. Phys. **29**, 144 (1957).
[4] F. Klein, in *Proceedings of the XIVth International Conference on Particles and Nuclei*, edited by C. Carlson and J. Domingo (World Scientific, Singapore, 1997), Sec. 121.
[5] S. Platchkov *et al.*, Nucl. Phys. **A510**, 740 (1990).
[6] B. Blankleider and R. M. Woloshyn, Phys. Rev. C **29**, 538 (1984).
[7] H. Arenhövel, Z. Phys. A **331**, 123 (1988); **334**, 363(E) (1989).
[8] R. G. Arnold *et al.*, Phys. Rev. C **23**, 363 (1981).
[9] M. Meyerhoff *et al.*, Phys. Lett. B **327**, 201 (1994).
[10] J. Becker *et al.* (to be published).
[11] D. Rohe, Ph.D. thesis, Mainz University, 1998.
[12] M. Ostrick *et al.*, Phys. Rev. Lett. **83**, 276 (1999).
[13] C. Herberg *et al.*, Eur. Phys. J. A **5**, 131 (1999).
[14] T. Eden *et al.*, Phys. Rev. C **50**, R1749 (1994).
[15] T. W. Donnelly and A. S. Raskin, Ann. Phys. (N.Y.) **169**, 247 (1986).
[16] P. Drescher *et al.*, Appl. Phys. A **63**, 203 (1996).
[17] K. Aulenbacher *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **391**, 498 (1997).
[18] J. Ahrens *et al.*, Nucl. Phys. News **2**, 5 (1994).
[19] M. Steigerwald, Ph.D. thesis, Mainz University, 1998.
[20] Th. Pospischil, Ph.D. thesis, Mainz University, 1999.
[21] K. I. Blomqvist *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **403**, 263 (1998).
[22] J. L. Friar *et al.*, Phys. Rev. C **42**, 2310 (1990).
[23] R. W. Schulze and P. U. Sauer, Phys. Rev. C **48**, 38 (1993).
[24] R. Surkau *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **384**, 444 (1997).
[25] W. Heil *et al.*, Phys. Lett. A **201**, 337 (1995).
[26] E. Wilms *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **401**, 491 (1997).
[27] A. Amroun *et al.*, Nucl. Phys. **A579**, 596 (1994).
[28] E. Jans *et al.*, Nucl. Phys. **A475**, 687 (1987).
[29] H. Arenhövel (private communication).
[30] G. Ziemer, Ph.D. thesis, Ruhr-University Bochum, 1999.
[31] H. Anklin *et al.*, Phys. Lett. B **428**, 248 (1998).
[32] A. Amghar, N. Aissat, and B. Desplanques, Eur. Phys. J. A **1**, 85 (1998).