The Charge Form Factor of the Neutron at Low Momentum Transfer from the $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e'n})\mathrm{p}$ Reaction

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We report new measurements of the neutron charge form factor at low momentum transfer using quasielastic electrodisintegration of the deuteron. Longitudinally polarized electrons at an energy of 850 MeV were scattered from an isotopically pure, highly polarized deuterium gas target. The scattered electrons and coincident neutrons were measured by the Bates Large Acceptance Spectrometer Toroid (BLAST) detector. The neutron form factor ratio G_E^n/G_M^n was extracted from the beam-target vector asymmetry A_{ed}^V at four-momentum transfers $Q^2 = 0.14$, 0.20, 0.29 and 0.42 (GeV/c)^2.

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The neutron is composed of charged constituents, whose net distribution is described by the charge (or electric) form factor G_E^n. Differences in the up and down quark distributions produce a nonuniform distribution of the net charge [1]. The neutron electric form factor G_E^n exhibits a maximum in the region of $Q^2 \approx 0.1 - 0.5$ (GeV/c)^2; when Fourier-transformed this corresponds to a positively charged core and a concentration of negative charge at intermediate to large distances of ≈ 1 fm, commonly associated with a meson cloud surrounding the nucleon. Models which emphasize the role of the meson cloud have been successful in explaining important aspects of nucleon structure [2, 3, 4, 5, 6]. Precise knowledge of G_E^n is essential for the description of electromagnetic structure of nuclei, and for the interpretation of parity violating electron scattering experiments to determine the strangeness content of the nucleon. Further, it is anticipated that exact *ab initio* QCD calculations of G_E^n using lattice techniques will eventually be possible [7].

In the absence of a free neutron target, determinations of G_E^n at finite Q^2 are typically carried out using quasielastic electron scattering from deuterium or ^{3}He targets. Despite the small value of G_E^n compared to the neutron magnetic form factor G_M^n, it can be obtained with high precision from double-polarization observables based on the interference of G_E^n with G_M^n. With the availability of high-duty-factor polarized electron beams over the last decade, experiments have employed recoil polarimeters [8], and targets of polarized ^{2}H [9] and ^{3}He [10] to perform precision measurements of G_E^n using polarization techniques with inherently small systematic uncertainties. The slope of $G_E^n(Q^2)$ at $Q^2 = 0$, which defines the square of the neutron charge radius, is determined precisely by the scattering of thermal neutrons from atomic electrons [11].

This paper reports on new measurements of G_E^n/G_M^n at low Q^2 in the vicinity of the maximum of G_E^n, using a longitudinally polarized electron beam incident on a vector-polarized ^{2}H target internal to the South Hall Ring at the MIT-Bates Linear Accelerator Center. The BLAST detector was used to detect quasielastically scattered electrons in coincidence with recoil neutrons over a range of Q^2 between 0.10 and 0.55 (GeV/c)^2.

The differential cross section for the $^2\mathrm{H}(\mathrm{e},\mathrm{e'n})$ reaction with polarized beam and target can be written [12, 13, 14]

$$\begin{aligned}
\frac{d^3\sigma}{d\Omega_e d\Omega_{pq} d\omega} &= \sigma_{unp}(1 + \Sigma + P_e\Delta), \quad \text{with} \\
\Sigma &= \sqrt{\frac{3}{2}} P_z A_d^V + \sqrt{\frac{1}{2}} P_{zz} A_d^T \qquad\qquad (1) \\
\Delta &= A_e + \sqrt{\frac{3}{2}} P_z A_{ed}^V + \sqrt{\frac{1}{2}} P_{zz} A_{ed}^T,
\end{aligned}$$

where σ_{unp} is the unpolarized differential cross section, $P_z = n_+ - n_-$ and $P_{zz} = n_+ + n_- - 2n_0$ are the vector and tensor polarizations of the deuteron target defined by the relative populations n_m of the three deuteron magnetic substates with respect to the deuteron orientation axis, $m = +1, 0, -1$, respectively, and P_e is the longitudinal polarization of the electron beam.

With BLAST, all of the polarization observables A_i in Eq. (1) have been measured for the first time with precision in a single experiment. The beam-target vector polarization observable A_{ed}^V is particularly sensitive to the neutron form factor ratio G_E^n/G_M^n [14]. In the Plane Wave Born Approximation (PWBA) and with the deuteron in a pure S-state, the asymmetry A_{ed}^V can be written analogously to elastic scattering from the free neutron as

$$\begin{aligned} A_{ed}^V &= \frac{a\, {G_M^n}^2 \cos\theta^* + b\, G_E^n G_M^n \sin\theta^* \cos\phi^*}{c\, {G_E^n}^2 + {G_M^n}^2} \\ &\approx \qquad a\cos\theta^* + b\,\frac{G_E^n}{G_M^n}\sin\theta^*\cos\phi^*, \end{aligned} \tag{2}$$

where θ^* and ϕ^* are the target spin orientation angles with respect to the momentum transfer vector and a, b, and c are known kinematic factors. This asymmetry has the largest sensitivity to G_E^n when the momentum transfer vector is perpendicular to the target polarization, *i.e.* $\theta^* = 90°$.

However, there are sizable corrections to the asymmetry in Eq. (2), mainly at low Q^2 where they are dominated by final state interactions (FSI). The relative contributions of meson exchange currents (MEC), isobar configurations (IC) and relativistic corrections (RC) become more significant as the momentum transfer increases (see Fig. 1). Extracting G_E^n must be done by comparison with theoretical asymmetries that include these effects.

The effects of FSI can be monitored with the other polarization observables in Eq. (1). The asymmetries A_e, A_d^V, and A_{ed}^T all vanish in the Born approximation due to parity and time reversal conservation and remain very small (below 1%) even in the presence of FSI. This permits these observables to be used to identify any false asymmetries in the experiment. FSI gives a sizable contribution to the target tensor asymmetry A_d^T, which is insensitive to G_E^n and otherwise close to zero in the quasifree limit. Figure 1 displays a Monte Carlo simulation of the reaction mechanism effects on the asymmetries A_{ed}^V (upper panel) and A_d^T (lower panel) as a function of Q^2 along with the measured values. The calculations use the standard dipole form factor $G_D = (1+Q^2/0.71)^{-2}$ for G_E^p, G_M^p/μ_p, and G_M^n/μ_n, and $1.91\tau/(1+5.6\tau)\,G_D$ for G_E^n [15], where $\mu_p = 2.79$, $\mu_n = -1.91$, and $\tau = Q^2/(4m_n^2)$. The good agreement of the measured tensor asymmetry A_d^T with the full model supports the calculations of FSI for a reliable extraction of G_E^n from the beam-target vector asymmetry A_{ed}^V at the percent level.

On the other hand, the corrections at low Q^2 to A_{ed}^V measured in the $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e'p})\mathrm{n}$ reaction in quasifree kinematics are negligible [14], which allows for a precise determination of the product of beam and target polarizations P_eP_z along with the proton form factor ratio G_E^p/G_M^p in this reaction channel [16].

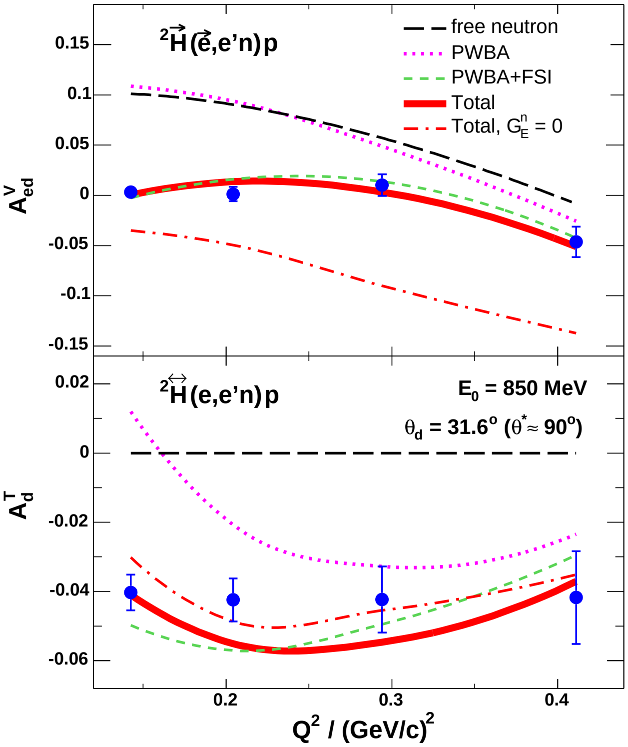

Abbildung 1: Measured (solid blue points) and calculated beam-target vector polarization observable A_{ed}^V (upper panel) and tensor asymmetry A_d^T (lower panel) for the $^2\mathrm{H}(\mathrm{e},\mathrm{e'n})\mathrm{p}$ reaction at 850 MeV, a target orientation of $\theta_d = 31.6°$ into the left sector of BLAST, and with neutrons detected in the right sector. The colored curves are Monte Carlo simulations based on the deuteron electrodisintegration model of Ref. [13] (dotted magenta = PWBA, short-dashed green = PWBA+FSI, solid red = PWBA+FSI+MEC+IC+RC) using standard parameterizations for the nucleon form factors (see text). In addition, the corresponding curves for $G_E^n \equiv 0$ (dash-dotted red) and for elastic scattering from the free neutron (dashed black line) are shown.

The BLAST experiment was designed to carry out spin-dependent electron scattering from hydrogen [17] and light nuclei. Details on the experimental setup can be found in [18]. The internal target consisted of an atomic beam source (ABS) combined with an open-ended storage cell through which the stored electron beam passed continuously [19]. The ABS produced polarized monoatomic deuterium gas in the storage cell with nuclear vector ($V+$: m=1; $V-$: m=-1) and tensor ($T-$: m=0) polarization states. In addition, the helicity h of the electron beam was flipped every injection cycle. Linear combinations of the six charge-normalized yields Y_{hm} define all five polarization observables in Eq. (1). The experimental value of the beam-vector polarization observable A_{ed}^V can be written as

$$A_{ed}^V = \sqrt{\frac{3}{2}}\,\frac{1}{P_eP_z}\,\frac{Y_{++} + Y_{--} - Y_{+-} - Y_{-+}}{Y_{tot}}, \tag{3}$$

where Y_{tot} is the total yield obtained by summing up all six combinations hm. A modest magnetic holding field was applied to define the polarization angle θ_d within the horizontal plane and to minimize the depolarization of target atoms. The variation of θ_d was carefully mapped over the extent of the target cell. The average value of θ_d was determined along with the tensor polarization P_{zz} by comparing the simultaneously measured tensor asymmetries in elastic scattering from tensor-polarized deuterium [20] with those expected at low Q^2 based on a parameterization of previous data [21].

The BLAST detector is a toroidal spectrometer (8 sectors) with the horizontal sectors instrumented with wire chambers, aerogel Čerenkov counters, thin plastic timing scintillators, and thick plastic scintillator walls for neutron detection. With the target polarization vector pointing into the left sector, the neutron detection efficiency was augmented in the right sector covering the kinematic region most sensitive to the neutron form factor ratio, as indicated by the $\sin\theta^*$ term in Eq. (2). The detection of neutrons in the left sector was primarily used to independently verify the determination of P_eP_z from the $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})\mathrm{n}$ reaction.

Figure 2 shows the $(\mathrm{e},\mathrm{e}'\mathrm{n})$ yield normalized to the collected beam charge for the measurements with deuterium, hydrogen and empty target. The selection of $(\mathrm{e},\mathrm{e}'\mathrm{n})$ events is very clean; the number of proton tracks misidentified as neutrons is negligible, due to the highly efficient charged particle veto provided by the thin scintillator bars and the large-volume drift chambers in front of the neutron detectors. A set of cuts applied on the time correlation between the charged and the neutral track, and on kinematic constraints for the electrodisintegration process, was employed to identify the quasielastic $(\mathrm{e},\mathrm{e}'\mathrm{n})$ events. The background from scattering off the aluminum target cell walls, measured with a hydrogen (empty) target, is less than 4% (3%) of the normalized yield obtained with deuterium.

The corrected asymmetries were compared to Monte Carlo simulations based on the deuteron electrodisintegration model [13], for which events were generated according to the unpolarized cross section and weighted event-by-event with the spin-dependent terms in Eq. (1). The acceptance-averaged asymmetry A_{ed}^V was simulated for different values of G_E^n/G_M^n and compared to the experimental values. In order to extract the best value of the form factor ratio for each Q^2 bin, a χ^2 minimization was performed independently with respect to the missing momentum of the reaction and the angle of the neutron in the hadronic center-of-mass system. Both extractions produced consistent results.

The data reported here were acquired in two separate runs in 2004 and 2005, corresponding to a target polarization angle of $31.64° \pm 0.43°$ and $46.32° \pm 0.45°$, respectively. With a total accumulated beam charge of 451 kC (503 kC) in the first (second) data set, final samples of 268,914 (205,252) coincident electron-neutron events were collected. The average product of beam and target polarization determined from the $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$ reaction was $P_eP_z = 0.5796 \pm 0.0034(\mathrm{stat}) \pm 0.0034(\mathrm{sys})$ in the first and $0.5149 \pm 0.0043(\mathrm{stat}) \pm 0.0054(\mathrm{sys})$ in the second data set [16]. In comparison, the polarization product determined from $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})\mathrm{p}$ with neutrons detected in the left sector of BLAST corresponding to $\theta^* \approx 0°$, was found to be $0.587 \pm 0.019(\mathrm{stat})$ and $0.481 \pm 0.026(\mathrm{stat})$ consistent with the above $(\mathrm{e},\mathrm{e}'\mathrm{p})$ results. The two data sets were treated as separate experiments producing two consistent results for the form factor ratio, which were combined for a final result. The data were divided into four Q^2 bins to determine G_E^n/G_M^n with a comparable statistical significance (see Table I).

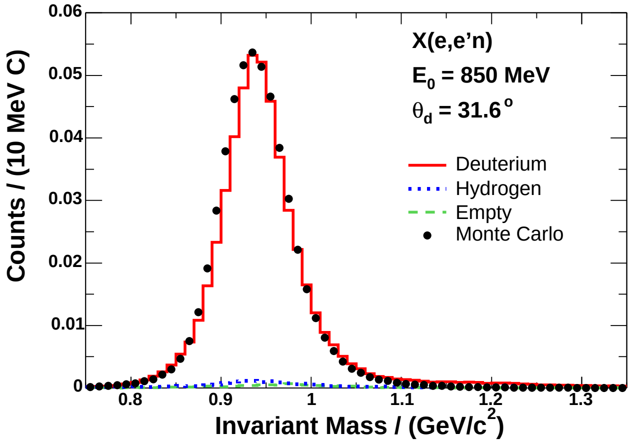

Abbildung 2: Measured yields of $(\mathrm{e},\mathrm{e}'\mathrm{n})$ events normalized to the accumulated beam charge for deuterium (solid red line), hydrogen (dotted blue line) and empty target (dashed green line), as a function of the invariant mass, shown for the data set at $\theta_d = 31.6°$. The Monte Carlo data (black circles) have been normalized to the measured yield from deuterium. The peak corresponds to quasielastic scattering. The background measured with hydrogen (empty) target is less than 4% (3%) of the yield obtained with deuterium target.

The systematic error of G_E^n/G_M^n is dominated by the uncertainty of the target spin angle θ_d. Other systematic uncertainties include that of the beam-target polarization product P_eP_z, the accuracy of kinematic reconstruction, as well as the dependency on software cuts. The systematic uncertainties were evaluated individually for each Q^2 bin and data set by combining the errors from each source, taking covariances into account; the correlated and uncorrelated error categories of the two measurements were then combined for a resulting systematic error of each bin. False asymmetries were studied with the observables A_d^V and A_{ed}^T and found to be consistent with zero. Radiative corrections to the asymmetries calculated in a

$Q^2/(\mathrm{GeV/c})^2$	$\langle Q^2\rangle/(\mathrm{GeV/c})^2$	$\mu_n G_E^n/G_M^n$
0.10−0.17	0.142	$0.0505 \pm 0.0072 \pm 0.0031$
0.17−0.25	0.203	$0.0695 \pm 0.0084 \pm 0.0039$
0.25−0.35	0.291	$0.1022 \pm 0.0127 \pm 0.0046$
0.35−0.55	0.415	$0.1171 \pm 0.0182 \pm 0.0052$

Tabelle I: Results for the extracted neutron form factor ratio $\mu_n G_E^n/G_M^n$ ($\mu_n = G_M^n(0) = -1.91$) with statistical and systematic errors, respectively.

PWBA formalism using the code MASCARAD [22] are <1% and therefore also neglected. The uncertainties of the reaction mechanism and FSI corrections, which are small compared to the experimental errors, are not included in the systematic error.

The world's data on G_E^n from double-polarization experiments [8, 9, 10] are displayed in Fig. 3 along with the results of this work. All of the polarization data were experimentally determined as electric to magnetic form factor ratios. We used parameterization [23] for G_M^n, which is in good agreement with recent measurements [24], to determine G_E^n from BLAST and to adjust the previously published values. The data from a variety of experiments are consistent and remove the large model uncertainty of previous G_E^n extractions from elastic electron-deuteron scattering [25]. The new distribution is also in agreement with G_E^n extracted from the deuteron quadrupole form factor [26].

The measured distribution of G_E^n can be parameterized as a function of Q^2 based on the sum of two dipoles, $\sum_i a_i/(1+Q^2/b_i)^2$ $(i{=}1,2)$, shown as the BLAST fit in Fig. 3 (blue line) with a one-sigma error band. With $G_E^n(0) = 0$ and the slope at $Q^2 = 0$ constrained by $\langle r_n^2 \rangle = (-0.1148 \pm 0.0035)$ fm^2 [11], one parameter is fixed, resulting in $a_1 = -a_2 = 0.095 \pm 0.018$, $b_1 = 2.77 \pm 0.83$, $b_2 = 0.339 \pm 0.046$ and $\mathrm{cov}(a_1, b_1) = -0.014$, $\mathrm{cov}(a_1, b_2) = 0.0008$, $\mathrm{cov}(b_1, b_2) = -0.036$ with Q^2 in units of $(\mathrm{GeV/c})^2$. The parameterization [27] (magenta dash-dotted line) is based on the form introduced in [23] with an additional bump structure around $0.2-0.4$ $(\mathrm{GeV/c})^2$. Also shown are recent results based on vector meson dominance (VMD) and dispersion relations (red short-dashed [4] and green long-dashed lines [5]), and the prediction of a light-front cloudy bag model with relativistic constituent quarks [6] (cyan dotted line).

The new data from BLAST do not show a bump structure at low Q^2 as previously suggested [23, 27]. The BLAST data are in excellent agreement with VMD based models [4, 5] and also agree with the meson-cloud calculation [6]. The improved precision of the data at low Q^2 provides strong constraints on the theoretical understanding of the nucleon's meson cloud.

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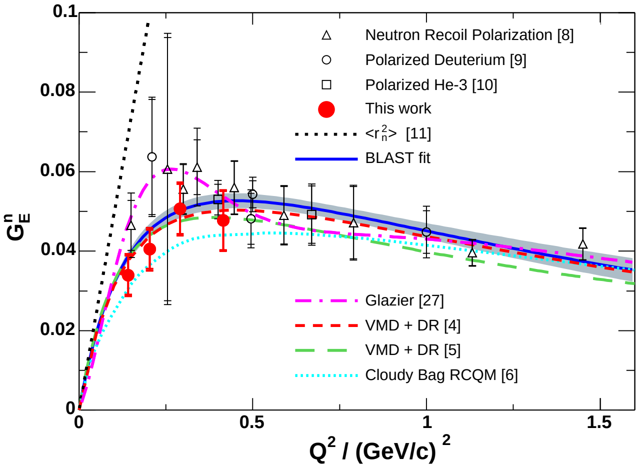

Abbildung 3: World data on G_E^n from double-polarization experiments. The data correspond to neutron recoil polarization experiments with unpolarized ^{2}H target [8] (open triangles) and experiments with polarized ^{2}H (open circles = Ref. [9], solid red dots = this work) and ^{3}He targets [10] (open squares). The data are shown with statistical (small error bars) and with statistical and systematic errors added quadratically (large error bars). The "BLAST fit" (blue solid line) is a parameterization of the data based on the sum of two dipoles shown with a one-sigma error band. The recent parameterization [27] (magenta dash-dotted line) is based on the form introduced in [23]. Also shown are recent results based on vector meson dominance and dispersion relations (red short-dashed [4] and green long-dashed lines [5]), and of a light-front cloudy bag model with relativistic constituent quarks [6] (cyan dotted line).

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