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

5 Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
5 University of New Hampshire, Durham, NH 03824
5 Triangle Universities Nuclear Laboratory and Duke University, Durham, NC 27708-0305
5 United States Naval Academy, Annapolis, MD 21402
5 Ohio University, Athens, OH 45701
5 Dartmouth College, Hanover, NH 03755
(Dated: 26. März 2008)

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 $A^{\theta}_{BT}$ at four-momentum transfers $Q^2 = 0.14, 0.20, 0.29$ and 0.42 (GeV/c)$^2$.

Keywords: Neutron, form factor, polarization, internal target, elastic, deuteron

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 electric charge [1]. The neutron electric form factor at intermediate to large distances of $Q^2 ≈ 1$ 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 deuteron or $^3\text{He}$ 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 $^2\text{H}$ [9] and $^3\text{He}$ [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 $^2\text{H}$ 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 $^2\text{H}(e, e'\text{n})p$ reaction with polarized beam and target can be written [12, 13, 14]:

$$\frac{d^3\sigma}{d\Omega_{\text{ee}}d\Omega_{p\text{n}}dq} = \sigma_{unp}(1 + \Sigma + \Delta),$$

$$\Sigma = \sqrt{\frac{3}{2}} P_z A^V_d + \frac{1}{2} P_z A^T_d$$

$$\Delta = A_z + \sqrt{\frac{3}{2}} P_z A^V_d + \frac{1}{2} P_z A^T_d,$$

where $\sigma_{unp}$ 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 \( G_E^n/G_M^n \) [13]. 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

\[
A_{ed}^{V} = \frac{a G_E^n 2 \cos \theta^* + b G_E^n G_M^n \sin \theta^* \cos \phi^*}{c G_E^n 2 + G_M^n 2} \approx a \cos \theta^* + b \frac{G_E^n}{G_M^n} \sin \theta^* \cos \phi^*,
\]  

(2)

where \( \theta^* \) and \( \phi^* \) 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. \( \theta^* = 90^\circ \).

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 \( A_e, A^n_{V}, \) and \( A^n_{d} \) 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 \( A^n_{d} \), 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 \( A_{V}^{e} \) (upper panel) and \( A_{V}^{d} \) (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 \( G^n_E, G^n_M, \) and \( G^n_M/\mu_n \), and 1.91 \( \tau/(1 + 5.6 \tau) \) for \( G^n_M \) [15], where \( \mu_n = 2.79, \) \( \mu_n = -1.91 \), and \( \tau = Q^2/(4m_n^2) \). The good agreement of the measured tensor asymmetry \( A_{V}^{d} \) 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 \( ^{2}\text{H}(e,e'p) \) reaction in quasi-free kinematics are negligible [15], which allows for a precise determination of the product of beam and target polarizations \( P_e P_z \) along with the proton form factor ratio \( G_E^n/G_M^n \) in this reaction channel [16].

The BLAST experiment was designed to carry out spin-dependent electron scattering from hydrogen and light nuclei. Details on the experimental setup can be found in [17]. 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 [18]. The ABS produced polarized monoatomic deuterium gas in the storage cell with nuclear vector \( (V+: |\mathbf{v}| = 1; V-: |\mathbf{v}| = -1) \) 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

\[
A_{ed}^{V} = \sqrt{\frac{3}{2} \frac{1}{P_e P_z} \frac{Y_{++} - Y_{+-} - Y_{-+} - Y_{--}}{Y_{tot}}},
\]

(3)

where \( Y_{tot} \) is the total yield obtained by summing up all six combinations \( hm \). A modest magnetic holding field

![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 \(^{2}\text{H}(e,e'p) \) reaction at 850 MeV, a target orientation of \( \theta_t = 31.6^\circ (\theta = 90^\circ) \).](image-url)
was applied to define the polarization angle \( \theta_d \) within
the horizontal plane and to minimize the depolarization of target atoms. The variation of \( \theta_d \) was carefully mapped
over the extent of the target cell. The average value of \( \theta_d \) was determined along with the tensor polarization
\( P_{z^*} \) 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 sec-
tors) with the horizontal sectors instrumented with wire
chambers, aerogel Čerenkov counters, thin plastic timing
scintillators, and thick plastic scintillator walls for neu-
tron detection. With the target polarization vector point-
ing 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 in-
dependently verify the determination of \( P_z \) from the
\( ^2\text{H}(e,e'n) \) reaction.

Figure 2 shows the \( (e,e'n) \) yield normalized to the col-
lected beam charge for the measurements with deuteri-
um, hydrogen and empty target. The selection of \( (e,e'n) \)
events is very clean; the number of proton tracks mi-
sidentified as neutrons is negligible, due to the highly
efficient charged particle veto provided by the thin scin-
tillator 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 electrodissintegration
process, was employed to identify the quasielastic \( (e,e'n) \)
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 electrodissinte-
gration model \[13\], for which events were generated ac-
cording to the unpolarized cross section and weighted
by the spin-dependent terms in Eq. (1). The acceptance-averaged asymmetry \( A_{el}^{V_d} \) was simulated for different values of
\( G_E^d / G_M^d \) and compared to the experimental values. In order to extract the best value of the
form factor ratio for each \( Q^2 \) bin, a \( \chi^2 \) 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 polar-
ization angle of \( 31.6^\circ \pm 0.43^\circ \) and \( 46.32^\circ \pm 0.45^\circ \),
respectively. With a total accumulated beam charge of 451
kC (503 kC) in the first (second) data set, final samples
of 269,914 (205,252) coincident electron-neutron events
were collected. The average product of beam and tar-
get polarization determined from the \( ^2\text{H}(e,e'p) \) reaction
was \( P_z P_z = 0.5796 \pm 0.0034 \text{(stat)} \pm 0.0034 \text{(sys)} \) in the
first and \( 0.5149 \pm 0.0043 \text{(stat)} \pm 0.0054 \text{(sys)} \) in the se-
cond data set \[16\]. In comparison, the polarization pro-
duct determined from \( ^2\text{H}(e,e'n)p \) with neutrons detected in
the left sector of BLAST corresponding to \( \theta^* \approx 0^\circ \), was
found to be \( 0.587 \pm 0.019 \text{(stat)} \) and \( 0.481 \pm 0.020 \text{(stat)} \) consistent with the above \( (e,e'p) \) 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 \( G_E^d / G_M^d \) with a comparable
statistical significance (see Table I).

The systematic error of \( G_E^d / G_M^d \) is dominated by the
uncertainty of the target spin angle \( \theta_d \) Other systematic
uncertainties include that of the beam-target polarization
product \( P_z P_z \), the accuracy of kinematic reconstruction,
as well as the dependency on software cuts. The systema-
tic uncertainties were evaluated individually for each \( Q^2 \)
bin and data set by combining the errors from each sour-
ce, 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 observ-
ables \( A_{el}^{V_d} \) and \( A_{el}^{V_d} \) and found to be consistent with zero.
Radiative corrections to the asymmetries calculated in a

<table>
<thead>
<tr>
<th>( Q^2 )/(GeV/c)^2</th>
<th>( (Q^2) )/(GeV/c)^2</th>
<th>( \mu_n G_E^d / G_M^d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10–0.17</td>
<td>0.142</td>
<td>0.0505 \pm 0.0072 \pm 0.0031</td>
</tr>
<tr>
<td>0.17–0.25</td>
<td>0.203</td>
<td>0.0695 \pm 0.0084 \pm 0.0039</td>
</tr>
<tr>
<td>0.25–0.35</td>
<td>0.291</td>
<td>0.1022 \pm 0.0127 \pm 0.0046</td>
</tr>
<tr>
<td>0.35–0.55</td>
<td>0.415</td>
<td>0.1171 \pm 0.0182 \pm 0.0052</td>
</tr>
</tbody>
</table>

Tabelle I: Results for the extracted neutron form factor ra-
tio \( \mu_n G_E^d / G_M^d \) (\( \mu_n = G_M^d(0) = -1.91 \)) with statistical and
systematic errors, respectively.
PWBA formalism using the code MASCARAD 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, 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, $\sum a_i/(1 + Q^2/b_i)^2$ ($i = 1, 2$), 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 $\langle r^2_n \rangle = (-0.1148 \pm 0.0035)$ 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 $\text{cov}(a_1, b_1) = -0.014$, $\text{cov}(a_1, b_2) = 0.0008$, $\text{cov}(b_1, b_2) = -0.036$ with $Q^2$ in units of (GeV/c)$^2$. The parameterization [27] (magenta dash-dotted line) is based on the form introduced in [25] with an additional bump structure around 0.2 – 0.4 (GeV/c)$^2$. 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).

The new data from BLAST do not show a bump structure at low $Q^2$ as previously suggested [24, 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.

We thank the staff of the MIT-Bates Linear Accelerator Center for delivering high quality electron beam and for their technical support, and A. Bernstein for suggesting the form of the BLAST fit. This work has been supported in part by the US Department of Energy and National Science Foundation.

---

Abbildung 3: World data on $G_E^n$ from double-polarization experiments. The data correspond to neutron recoil polarization experiments with unpolarized $^2\text{H}$ target [3] (open triangles) and experiments with polarized $^3\text{He}$ (open circles = Ref. [9], solid red dots = this work) and $^3\text{He}$ 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 [25]. 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).

---

C 66, 045501 (2002); arXiv:nucl-th/0609020v2; to be published and private communication.


[18] D. Hasell et al., The BLAST Experiment (to be published).


