Developments in the measurement of $G^n_E$, the neutron electric form factor

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Outline

★ Introduction: Formalism, Interpretation, Motivation
★ Models
★ Experimental Techniques
  Traditional (unpolarized beams)
  Modern (polarized beams, targets, polarimeters)
★ Experiments using polarized electrons at Jefferson Lab
  – Recoil polarization
  – Beam-target asymmetry
★ Outlook
Formalism

\[ \frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \frac{E'}{E_0} \left\{ (F_1)^2 + \tau \left[ 2 (F_1 + F_2)^2 \tan^2(\theta_e) + (F_2)^2 \right] \right\} \]

\[
\begin{align*}
F_1^p &= 1 & F_1^n &= 0 \\
F_2^p &= 1.79 & F_2^n &= -1.91
\end{align*}
\]

In Breit frame $F_1$ and $F_2$ related to charge and spatial current densities:

\[
\begin{align*}
\rho &= J_0 = 2eM[F_1 - \tau F_2] \\
J_i &= e\bar{u}\gamma_i u[F_1 + F_2]_{i=1,2,3}
\end{align*}
\]

\[
\begin{align*}
G_E (Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\
G_M (Q^2) &= F_1(Q^2) + F_2(Q^2)
\end{align*}
\]

* For a point like probe $G_E$ and $G_M$ are the FT of the charge and magnetizations distributions in the nucleon, with the following normalizations

\[
Q^2 = 0 \text{ limit: } \quad \begin{align*}
G_E^p &= 1 & G_E^n &= 0 \\
G_M^p &= 2.79 & G_M^n &= -1.91
\end{align*}
\]
\( G^n_E \) Interpretation

In the NR limit (Breit Frame), \( G_E \) is FT of the charge distribution \( \rho(r) \):

\[
G^n_E (q^2) = \frac{1}{(2\pi)^3} \int d^3r \rho(r) e^{i\mathbf{q} \cdot \mathbf{r}} = 0 - \frac{q^2}{6} \langle r^2_{ne} \rangle + ...
\]

Experimental: Mean square charge radius \( \langle r^2_{ne} \rangle \) is negative.

Theory has intuitive explanation:

pion-nucleon theory:
\[ n = p + \pi^- \text{ cloud} \]

valence quark model:
\[ n = ddu \text{ & spin-spin force } \Rightarrow d \rightarrow \text{ periphery} \]
Charge radius, Foldy term

\[ \langle r_{ne}^2 \rangle = -6 \frac{dG^n_{E}(0)}{dQ^2} = -6 \frac{dF^n_{1}(0)}{dQ^2} + \frac{3}{2M^2} F^n_{2}(0) \]

\[ = \langle r_{in}^2 \rangle + \langle r_{Foldy}^2 \rangle \]

Foldy term, \( \frac{3\mu_n}{2m_n} = (-0.126)\text{fm}^2 \), has nothing to do with the rest frame charge distribution.

\[ \langle r_{ne}^2 \rangle \] is measured through neutron-electron scattering

\[ \langle r_{ne}^2 \rangle = \frac{3m_e a_0}{m_n} b_{ne} = -0.113 \pm 0.003 \pm 0.004 \text{fm}^2. \]

\[ \langle r_{in}^2 \rangle = -0.113 + 0.126 \approx 0 \] suggesting that the spatial charge extension seen in \( F_1 \) is about 0 or very small. Recent Work:


Pionic loop fluctuations make minute contribution to \( \langle r_{in}^2 \rangle \).

\( G^n_{E} \) arises from the neutron’s rest frame charge distribution.
Why measure $G_E^m$?

- FF are fundamental quantities
- Test of QCD description of the nucleon
  Symmetric quark model, with all valence quarks with same wf: $G_E^m \equiv 0$
  $G_E^m \neq 0 \rightarrow$ details of the wavefunctions

- Sensitive to sea quark contributions
- Soliton model: $\rho(r)$ at large $r$ due to sea quarks

Necessary for study of nuclear structure.

- Few body structure functions
Proton Form Factor Data

Rosenbluth separation

\[
\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{(1 + \tau)} \frac{E'}{E_0} \left[ G_E^2 + \tau(1 + (1 + \tau)\tan^2(\theta/2))G_M^2 \right]
\]

\* \(G_M^P\) well measured via Rosenbluth, but not \(G_E^P\) hence Recoil Polarization

\* Dipole Parametrization: Good description of early \(G_{E,M}^P\) data

\[
G_E^P = \frac{G_M^P}{\mu_p} = G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}
\]

\[
G_D = \left(1 + \frac{Q^2}{k^2}\right)^{-2}
\]

implies an exponential charge distribution: \(\rho(r) \propto e^{-kr}\)
Neutron Form Factors without Polarization

No neutron target, $G_M^n$ dominates $G_E^n$

**Traditional techniques** used to measure $G_M^n$ and $G_E^n$ have been:

- Elastic scattering $^2\text{H}(e, e')^2\text{H}$
- Inclusive quasielastic scattering: $^2\text{H}(e, e')X$
- Neutron in coincidence with electron: $^2\text{H}(e, e'n)p$
- Neutron in anti-coincidence with electron: $^2\text{H}(e, e'\bar{p})p$
- Ratio techniques $\frac{d(e,e'n)p}{d(e,e'p)n}$ minimizes roles of g.s. wavefunction and FSI.
# Measurements of the Neutron Form Factors

<table>
<thead>
<tr>
<th>Target</th>
<th>Type</th>
<th>$Q^2$(GeV/c)$^2$</th>
<th>Deduced quantities</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>$^2$H</td>
<td>elastic</td>
<td>0.004-0.032</td>
<td>$G_{En}$</td>
<td>F.A. Bumiller et al., PRL 25, 1774 (1970)</td>
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<td>$^2$H</td>
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<td>0.012-0.085</td>
<td>$G_{En}$</td>
<td>Drickey &amp; Hand, PRL 9, 1774 (1962)</td>
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<tr>
<td>$^2$H</td>
<td>ratio</td>
<td>0.11</td>
<td>$G_{Mn}$</td>
<td>H.A. Anklin et al., PL B336, 313 (1994)</td>
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<td>$^2$H</td>
<td>quasieelastic</td>
<td>0.11-0.16</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>B. Grossette et al., PR 141, 1435 (1966)</td>
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<tr>
<td>$^2$H</td>
<td>elastic</td>
<td>0.116-0.195</td>
<td>$G_{En}$</td>
<td>P. Benaksas et al., PRL 13, 1774 (1964)</td>
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<td>$^2$H</td>
<td>coincidence</td>
<td>0.109-0.255</td>
<td>$G_{Mn}$</td>
<td>P. Markowitz et al. PR C48, R5 (1993)</td>
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<td>$^2$H</td>
<td>quasielastic</td>
<td>0.06-0.3</td>
<td>$G_{En}$</td>
<td>E.B. Hughes et al. PR 146, 973 (1966)</td>
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<td>$^2$H</td>
<td>elastic</td>
<td>0.116-0.195</td>
<td>$G_{Mn}$</td>
<td>J.I. Friedman et al. PR 120, 992 (1960)</td>
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<td>$^2$H</td>
<td>elastic</td>
<td>0.2-0.56</td>
<td>$G_{En}$</td>
<td>S. Galster et al. NP B32, 221 (1971)</td>
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<td>0.22-0.58</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>P. Stein et al. PRI 16, 592 (1966)</td>
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<td>$^2$H</td>
<td>ratio</td>
<td>0.25-0.605</td>
<td>$G_{Mn}$</td>
<td>E.E. Bruins et al. PRL 75, 21 (1995)</td>
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<td>$^2$H</td>
<td>ratio</td>
<td>0.2-0.9</td>
<td>$G_{Mn}$</td>
<td>H.A. Anklin et al., PL B428, 248 (1998)</td>
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<td>$^2$H</td>
<td>quasielastic</td>
<td>0.48-0.83</td>
<td>$G_{Mn}$</td>
<td>E.S. Esaulov et al. Sov. J. NP 45, 258 (1987)</td>
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<td>$^2$H</td>
<td>quasielastic</td>
<td>0.04-0.72</td>
<td>$G_{En}$</td>
<td>S. Platchov et al. NP A510, 740 (1990)</td>
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<td>$^2$H</td>
<td>ratio</td>
<td>0.39-0.78</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>W. Bartel et al. PL 30B, 285 (1969)</td>
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<td>$^2$H</td>
<td>quasielastic</td>
<td>0.04-1.2</td>
<td>$G_{Mn}$</td>
<td>A. Hughes et al. PR 139, B458 (1965)</td>
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<td>$^2$H</td>
<td>quasielastic</td>
<td>0.04-0.2</td>
<td>$G_{Mn}$</td>
<td>D. Braess et al. Zeit Phys. 198, 527 (1967)</td>
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<td>quasielastic</td>
<td>0.39-1.5</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>W. Bartel et al. NP B58, 429 (1973)</td>
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<td>$^2$H</td>
<td>ratio</td>
<td>1.0-1.53</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>W. Bartel et al. PL 39B, 407 (1972)</td>
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<tr>
<td>$^2$H</td>
<td>anticoinsidence</td>
<td>0.28-1.8</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>K.M. Hanson et al. PR D8, 753 (1973)</td>
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<td>$^2$H</td>
<td>quasieelastic</td>
<td>0.75-2.57</td>
<td>$G_{Mn}$</td>
<td>R.G. Arnold et al. PRL 61, 806 (1988)</td>
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<td>$^2$H</td>
<td>quasielastic</td>
<td>1.75-4.0</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>A. Lung et al. PRL 70, 718 (1993)</td>
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<td>$^2$H</td>
<td>anticoinsidence</td>
<td>0.27-4.47</td>
<td>$G_{En}$, $G_{Mn}$</td>
<td>R.J. Budnitz et al. PR 173, 1357 (1968)</td>
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<td>$^2$H</td>
<td>quasielastic</td>
<td>2.5-10.0</td>
<td>$G_{Mn}$</td>
<td>S. Rock et al. PRL 49, 1139 (1982)</td>
</tr>
</tbody>
</table>
$G^m_M$ unpolarized

Kubon ratio
Anklin ratio
Bruins ratio
Lung $D(e, e')X$
Markowitz $D(e, e'n)p$

ratio $\equiv \frac{D(e, e'n)p}{D(e, e'p)n}$
$G_M^n$ unpolarized and polarized

![Graph showing $G_M^n$ unpolarized and polarized](image)

- **Kubon** ratio
- **Anklin** ratio
- **Bruins** ratio
- **Lung** $D(e, e')X$
- **Markowitz** $D(e, e'n)p$
- **Xu** $\leftarrow^3\text{He}(\vec{e}, e')X$

Ratio $\equiv \frac{D(e, e'n)p}{D(e, e'p)n}$
$G^m_E$ Before Polarization

No free neutron – extract from $e - D$ elastic scattering:

$$\frac{d\sigma}{d\Omega} = \sigma_{NS} \left[ A (Q^2) + B (Q^2) \tan^2 \left( \frac{\theta_e}{2} \right) \right]$$

small $\theta_e$ approximation

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega} \left( (G^p_E + G^n_E)^2 \left[ u(r)^2 + w(r)^2 \right] j_0 \left( \frac{qr}{2} \right) dr \right)$$

Galster Parametrization: $G^m_E = -\frac{\tau \mu_n}{1 + 5.6\tau} G_D$
$G_E^m$ from Elastic Scattering – $D(e, e'd)$

Components of the tensor polarization give useful combinations of the form factors,

$$t_{20} = \frac{1}{\sqrt{2S}} \left\{ \frac{8}{3} \tau_d G_C G_Q + \frac{8}{9} \tau_d^2 G_Q^2 + \frac{1}{3} \tau_d \left[ 1 + 2(1 + \tau_d) \tan^2(\theta/2) \right] G_M^2 \right\}$$

allowing $G_Q(Q^2)$ to be extracted. Exploiting the fact that $G_Q(Q^2) = (G_E^p + G_E^n) C_Q(q)$ suffers less from theoretical uncertainties than $A(Q^2)$, $G_E^m$ can be extracted to larger momentum transfers.

E94-018!!
\( G_E^n \) at large \( Q^2 \) through \(^2\text{H}(e, e')\)X

PWIA model \( \sigma \) is incoherent sum of p and n cross section folded with deuteron structure.

\[
\sigma = (\sigma_p + \sigma_n) I(u, w) = \varepsilon R_L + R_T
\]

* Extraction of \( G_E^n \):
  Rosenbluth Separation \( \Rightarrow R_L \)
  Subtraction of proton contribution

* Problems:
  Unfavorable error propagation
  Sensitivity to deuteron structure

SLAC: A. Lung et al, PRL. 70, 718 (1993)
  →No indication of non-zero \( G_E^n \)

If \( G_E^n \) is small at large \( Q^2 \) then \( F_1^n \) must cancel \( \tau F_2^n \), begging the question, how does \( F_1^n \) evolve from 0 at
\( Q^2 = 0 \) to cancel \( \tau F_2^n \) at large \( Q^2 \)?
Models of Nucleon Form Factors

VMD
\[ F(Q^2) = \sum_i \frac{C_{\gamma Vi}}{Q^2 + M^2_{Vi}} F_{ViN}(Q^2) \]
breaks down at large \( Q^2 \)

pQCD
\[ F_2 \propto F_1 \left( \frac{M}{Q^2} \right) \] helicity conservation
Counting rules: \( F_1 \propto \frac{\alpha_s^2(Q^2)}{Q^4} \)
\( Q^2 F_2 / F_1 \rightarrow \text{constant} \)

JLAB proton data: \( Q F_2 / F_1 \rightarrow \text{constant} \)

Hybrid VMD-pQCD
GK, Lomon

Lattice
Dong .. (1998)

RCQM
point form (Wagenbrunn..)
light front (Cardarelli ..)

di-quark
Kroll ...

CBM
Lu, Thomas, Williams (1998)

LFCBM
Miller

Helicity non-conservation
pQCD (Ralston..) LF (Miller..)
Theoretical Models

Vector Meson Dominance

Interaction in terms of coupling strengths of virtual photon and vector mesons and vector mesons and nucleon. Success at low and moderate $Q^2$ offset by failure to accommodate pQCD.

pQCD
High $Q^2$ helicity conservation requires that $Q^2 F_1 / F_2 \rightarrow$ constant as $F_2$ helicity flip arises from second order corrections and are suppressed by an additional factor of $1/Q^2$. Furthermore for $Q^2 > \Lambda_{QCD}$ counting rules find $F_1 \propto \alpha_s (Q^2)^2 / Q^4$. Thus $F_1 \propto \frac{1}{Q^4}$ and $F_2 \propto \frac{1}{Q^6} \Rightarrow Q^2 \frac{F_2}{F_1} \rightarrow$ constant.

Hybrid Models
Failure to follow the high $Q^2$ behavior suggested by pQCD led GK to incorporate pQCD at high $Q^2$ with the low VMD behavior. Inclusion of $\phi$ by GK had significant effect on $G_{E}^n$. Lomon has updated with new fits to selected data.

Lattice calculations of form form factors
Fundamental but limited in stat. accuracy
Dong et al PRD58, 074504 (1998)

QCD based Models
Try to capture aspects of QCD
RCQM, Di-quark model, CBM

Helicity non-conservation shows up in the light front dynamics analysis of Miller which predicted $Q \frac{F_2}{F_1} \rightarrow$ constant and the violation of helicity conservation. Ralston’s pQCD model also predicts that $Q \frac{F_2}{F_1} \rightarrow$ constant. Both models include quark orbital angular momentum.
Spin Correlations in elastic scattering

- Dombey, Rev. Mod. Phys. 41 236 (1968): \( \vec{p}(\vec{e}, e') \)
- Akheizer and Rekalo, Sov. Phys. Doklady 13 572 (1968): \( p(\vec{e}, e', \vec{p}) \)

Essential statement

Exploit spin degrees of freedom

- \( \mathcal{O} \propto G_E \times G_M \) instead of \( \mathcal{O} \propto G_E^2 + G_M^2 \)

Early work at Bates, Mainz

- \( ^2\text{H}(\vec{e}, e'\vec{n})p \), Eden et al. (1994)
- \( ^1\text{H}(\vec{e}, e'\vec{p}) \), Milbrath et al. (1998)
- \( ^3\text{He}(e, e') \), Woodward, Jones, Thompson, Gao (1990 - 1994)
- \( ^3\text{He}(e, e'\vec{n}) \), Meyerhoff, (1994)
Neutron Form Factors

Polarized Beam

Spin Correlations

Recoil Polarimetry

Beam-Target Asymmetry

Unpolarized Beam

Cross Section Measurements

Ratio Method

Quasielastic eD

Elastic eD

\[ D(\vec{e}, e'n)p \]

\[ \frac{D(e, e'n)p}{D(e, e'p)n} \]

\[ D(e, e')X \]

\[ D(e, e' \rightarrow d) \]

\[ G_E^m \]

\[ G_E^m \]

\[ G_M^m \]

\[ G_E^m \]

\[ G_E^m \]

\[ G_E^m \]

\[ G_E^m \]
$G_E^m$ from spin observables

No free neutron targets – scattering from $^2$H or $^3$He – can not avoid engaging the details of the nuclear physics.

**Minimize** sensitivity to the how the reaction is treated and **maximize** the sensitivity to the neutron form factors by working in quasifree kinematics. **Detect neutron.**

- **Indirect measurements:** The experimental asymmetries ($\xi_{s'}, A_{V}^{ed}, A_{exp}^{qe}$) are compared to theoretical calculations.

- Theoretical calculations are generated for scaled values of the form factor.

- Form factor is extracted by comparison of the experimental asymmetry to acceptance averaged theory. **Monte Carlo**

- **Polarized targets**
  
  The deuteron and $^3$He only **approximate** a polarized neutron
  
  Scattering from other unpolarized materials, $f$ dilution factor
Recoil Polarization

Electron scattering plane
Secondary scattering plane

$I_0 P_t = -2 \sqrt{\tau(1 + \tau)} G_E G_M \tan(\theta_e/2)$

$I_0 P_I = \frac{1}{M_N} (E_e + E_{e'}) \sqrt{\tau(1 + \tau)} G_M^2 \tan^2(\theta_e/2)$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_I} \frac{E_e + E_{e'}}{2M_N} \tan\left(\frac{\theta_e}{2}\right)$$

Direct measurement of form factor ratio by measuring the ratio of the transferred polarization $P_t$ and $P_I$
Recoil Polarization – Principle and Practice

★ Interested in transferred polarization, $P_l$ and $P_t$, at the target

★ Polarimeters are sensitive to the perpendicular components only, $P_{n}^{\text{pol}}$ and $P_{t}^{\text{pol}}$

Measuring the ratio $P_t/P_l$ requires the precession of $P_l$ by angle $\chi$ before the polarimeter.

★ If polarization precesses $\chi$ (e.g. in a dipole with $\vec{B}$ normal to scattering plane):

$$P_{t}^{\text{pol}} = \sin \chi \cdot P_l + \cos \chi \cdot P_t$$

For $\chi = 90^\circ$, $P_{t}^{\text{pol}} = P_l$ and is related to $G_M^2$

For $\chi = 0^\circ$, $P_{t}^{\text{pol}} = P_t$ and is related to $G_E G_M$

★ $G_{E}^{n}/G_{M}^{n}$ via $^2H(\vec{e}, e'\vec{n})p$ in JLAB’s Hall C - Charybdis and N-Pol
Quality of polarimeter data optimized by taking advantage of proper flips (helicity reversals).

\[
L_1 = N_o[1 + pA_y(\theta + \alpha)]
\]

\[
R_2 = N_o[1 - pA_y(\theta + \beta)]
\]

\[
R_1 = N_o[1 - pA_y(\theta + \alpha)]
\]

\[
L_2 = N_o[1 + pA_y(\theta + \beta)]
\]

Using the geometric means, \( L \equiv \sqrt{L_1 L_2} \) and \( R \equiv \sqrt{R_1 R_2} \), the false (instrumental) asymmetries, \( \alpha \) and \( \beta \), cancel.

\[
\xi = pA_y = \frac{L - R}{L + R}
\]
Recoil polarization, $^2\text{H}(\vec{e}, e' \vec{n})p$

- In quasifree kinematics, $P_{s'}$ is sensitive to $G_{E}^m$ and insensitive to nuclear physics
- Up–down asymmetry $\xi \Rightarrow$ transverse (sideways) polarization $P_{s'} = \frac{\xi_{s'}}{P_{e} A_{\text{pol}}}$. Requires knowledge of $P_{e}$ and $A_{\text{pol}}$
- Rotate the polarization vector in the scattering plane (with Charybdis) and measure the longitudinal polarization, $P_{l'} = \frac{\xi_{l'}}{P_{e} A_{\text{pol}}}$
- Take ratio, $\frac{P_{s'}}{P_{l'}}$. $P_{e}$ and $A_{\text{pol}}$ cancel
- Three momentum transfers, $Q^2 = 0.45, 1.13,$ and $1.45 (\text{GeV/c})^2$.
$G_E^n$ in Hall C via $^2\text{H}(\vec{e}, e'\vec{n})p$

$E_e = 0.884 \text{ GeV}; E_{e'} = 0.643 \text{ GeV}; \Theta_{e'} = 52.65^\circ; \ Q^2 = 0.45 \text{ (GeV/c)}^2; \text{ Galster Parameterization}$

- $P_{x'}$
- $P_{y'}$
- $P_{z'}$

\[ \phi_{\text{np}} = 180^\circ \]

\[ \Theta_{\text{np}} \text{ [deg]} \]

- $\phi_{\text{np}} = 0^\circ$
- $\Theta_{\text{np}} = 0^\circ$

- PWBA (RC)
- FULL (RC): FSI+MEC+IC

Quasifree Emission

Graphs showing the distribution of $P_{x'}$, $P_{y'}$, and $P_{z'}$ for different angles $\Theta_{\text{np}}$ and $\phi_{\text{np}}$. The graphs illustrate the impact of the Galster Parameterization on the quasifree emission for the reaction $^2\text{H}(\vec{e}, e'\vec{n})p$. The $Q^2$ value of 0.45 (GeV/c)$^2$ and the energy transfer to the system are evident from the graphs.
\[ G_E^n \text{ in Hall C via } ^2\text{H}(\vec{e}, e'\vec{n})p \]

Taking the ratio eliminates the dependence on the analyzing power and the beam polarization \( \rightarrow \) greatly reduced systematics

\[
\frac{G_E^n}{G_M^n} = K \tan \delta \quad \text{where} \quad \tan \delta = \frac{P_{s'}}{P_{l'}} = \frac{\xi_{s'}}{\xi_{l'}}
\]
Left: Coincidence TOF for neutrons. Difference between measured TOF and calculated TOF assuming quasi-elastic neutron. Right: $\Delta TOF$ for neutron in front array and neutron in rear array.

$\Delta TOF$ is kept as the four combinations of (-,+), helicity, and (Upper,Lower) detector and cross ratios formed. False asymmetries cancel.

$$r = \left( \frac{N_U^+ N_D^-}{N_U^- N_D^+} \right)^{1/2} \quad \xi = (r - 1)/(r + 1)$$
$G_E^n$ in Hall C via $^2H(\bar{e}, e'\bar{n})p$

\[ Q^2 = 1.14 \text{ (GeV/c)}^2 \quad \text{(n,n) In Front} \quad \Delta p/p = -3/+5\% \]

**\(\chi^2/\text{ndf} = 0.90\)**

\(\xi_S^- = -1.29 \pm 0.13\%\)  \(\chi = 0^\circ\)

\(\chi = -90^\circ\) \(\chi^2/\text{ndf} = 0.79\)

\(\xi_L^- = 6.21 \pm 0.33\%\)

\(\chi = +90^\circ\) \(\chi^2/\text{ndf} = 0.59\)

\(\xi_L^- = -6.36 \pm 0.36\%\)
$G_E^n$ in Hall C via $^2H(\bar{e}, e'\bar{n})p$
$G_E^n$ in Hall C via $^2\text{H}(\vec{e}, e'\vec{n})p$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Graph showing the distribution of $G_E^n$ for different data points.}
\end{figure}

\begin{itemize}
\item Herberg (99)
\item Ostrik (99)
\item Passchier (99)
\item Golak (01)
\item Bermuth (03)
\item Sick (01)
\item Zhu (01)
\item Madey - Preliminary
\end{itemize}

\begin{align*}
Q^2 (\text{GeV}/c)^2
\end{align*}
Beam–Target Asymmetry - Principle

Polarized Cross Section:
\[ \sigma = \Sigma + h\Delta \]

Beam Helicity \( h \pm 1 \)

\[ A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma} \]

\[
A = \sqrt[\scriptscriptstyle AT]{\frac{a \cos \Theta^* (G_M)^2 + b \sin \Theta^* \cos \Phi^* G_E G_M}{c (G_M)^2 + d (G_E)^2}} + \sqrt[\scriptscriptstyle ATL]{\frac{A_{TL}}{}}; \quad \varepsilon = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = P_B \cdot P_T \cdot A
\]

\[ \Theta^* = 90^\circ \quad \Phi^* = 0^\circ \]

\[ \implies A = \frac{b G_E G_M}{c (G_M)^2 + d (G_E)^2} \]

\[ \Theta^* = 0^\circ \quad \Phi^* = 0^\circ \]

\[ \implies A = \frac{a G^{\scriptscriptstyle 2}_M}{c (G_M)^2 + d (G_E)^2} \]
Beam–Target Asymmetry in E93-026

$$^{2}\text{H}(e', e'n)p$$

$$\sigma(h, P) \approx \sigma_0 (1 + hP A^V_{ed})$$

$h$: Beam Helicity  
$P$: Vector Target Polarization  
$T$: Tensor Target Polarization  
$$T = 2 - \sqrt{4 - 3P^2}$$

$A^T_d$ is suppressed by $T \approx 3\%$

Theoretical Calculations of electrodisintegration of the deuteron by H. Arenhövel and co-workers
\[ \vec{D}(\vec{e}, e'n)p \]

\[ \sigma(h, P) = \sigma_0 \left( 1 + hP A_{ed}^V \right) \]

\( A_{ed}^V \) is sensitive to \( G_{E}^n \)

has low sensitivity to potential models

has low sensitivity to subnuclear degrees of freedom (MEC, IC)

in quasielastic kinematics

Sensitivity to \( G_{E}^n \) – Insensitivity to Reaction
$G^m_E$ in Hall C
* Polarized Target
* Chicane to compensate for beam deflection of \( \approx 4 \) degrees
* Scattering Plane Tilted
* Protons deflected \( \approx 17 \) deg at \( Q^2 = 0.5 \)
* Raster to distribute beam over 3 cm\(^2\) face of target
* Electrons detected in HMS (right)
* Neutrons and Protons detected in scintillator array (left)
* Beam Polarization measured in coincidence Möller polarimeter
Solid Polarized Targets

- frozen(doped) $^{15}$ND$_3$
- $^4$He evaporation refrigerator
- 5T polarizing field
- remotely movable insert
- dynamic nuclear polarization

![Graph: Deuteron Polarization (%)]

- Deuteron Polarization (%)
- Time (min)

Gen Target Performance, 10Sep01
Neutron Detector

- Highly segmented scintillator
- Rates: 50 - 200 kHz per detector
- Pb shielding in front to reduce background
- 2 thin planes for particle ID (VETO)
- 6 thick conversion planes
- 142 elements total, >280 channels

- Extended front section for symmetric proton coverage
- PMTs on both ends of scintillator
- Spatial resolution $\sim 10$ cm
- Time resolution $\sim 400$ ps
- Provides 3 space coordinates, time and energy
Experimental Technique for $\overrightarrow{D}(\overrightarrow{e}, e'n)p$

For different orientations of $h$ and $P$: $N^{hP} \propto \sigma (h, P)$

Beam-target Asymmetry:

$$
\epsilon = \frac{N^{\uparrow\uparrow} - N^{\downarrow\uparrow} + N^{\downarrow\downarrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\downarrow\uparrow} + N^{\downarrow\downarrow} + N^{\uparrow\downarrow}} = hPfA^V_{ed}
$$
Data and MC Comparison

- $y_{\text{pos}}$ (cm)
- $E'$ (MeV)
- $W$ (MeV)
- $Q^2$, (GeV/c)$^2$
- $\theta_{\text{np}}$ (radian)
- $\theta_{\text{np}}^\text{cm}$ (degree)
Extracting $G^n_E$

[Graphs and data plots showing various parameters and data points, including $A_{ed}$ vs. $E^'$, $y_{pos}$, $\theta_{nq}$, $\theta_{np}$, and $\chi^2$ vs. scale factor.]
Preliminary results

Systematic Errors (included):

- $P_{target}$: 3-5%
- $f$: 3%
- cuts: 2%
- kinematics: 2%
- $G^m_M$: 1.7%
- $P_{beam}$: 1-3%
- other: 1%
- total: 6-8%
Preliminary results

\[ Q^2 (\text{GeV}/c)^2 \]

- Herberg (99)
- Ostrik (99)
- Passchier (99)
- Golak (01)
- Bermuth (03)
- Sick (01)
- Zhu (01)
- E93026 - Preliminary
- E93038 - Preliminary
<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Collaboration</th>
<th>$Q^2 (\text{GeV/c})^2$</th>
<th>Reaction</th>
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<td>MIT-Bates</td>
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<td>0.255</td>
<td>$^2\text{H}(\bar{e}, e'\bar{n})$</td>
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<td>Jefferson Lab</td>
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<td>1.3, 2.4, 3.4</td>
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Conclusions

✴ $G_E^m$ remains the poorest known of the four nucleon form factors.

✴ $G_E^m$ is a fundamental quantity of continued interest.

✴ Significant progress has been made at several laboratories by exploiting spin correlations

✴ $G_E^m$ can be described by the Galster parametrization (surprisingly) and data under analysis is of sufficient quality to test QCD inspired models.

✴ Future progress likely with new experiments and better theory.