Measurement of the Electric Form Factor of the Neutron at High Momentum Transfer

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Overview

• Neutron Form Factors
• High $Q^2$ Experiment
• $G_E^n$ Results
• Interpretation
  – Quark Orbital Angular Momentum
  – Flavor Form Factors – $F_d/F_u$
• Conclusions
The Electric Form Factor of the Neutron

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \frac{E_f}{E_i} \left[ \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta_e}{2} \right],
\]

\[
\tau = \frac{Q^2}{4M^2}
\]

Above is the Rosenbluth formula for the differential cross section for a free nucleon. It is difficult to find \( G_E^n \) from the cross section because \( G_E \) is small compared to \( G_M \) for the neutron. The Mott cross section is the cross section for a structureless spin \( \frac{1}{2} \) particle.

Sachs form factors are related to the Dirac and Pauli form factors and the magnetic moment.

\[
G_E^n(0) = 0 \quad G_E = F_1 - \kappa \tau F_2
\]
\[
G_M^n(0) = \mu_n \quad G_M = F_1 + \kappa F_2
\]

In these expressions \( \kappa \) is anomalous contribution to the nucleon's magnetic moment.
In the experiment, polarized electrons scatter from polarized helium-3 and the final electron and hadron are detected.

The polarized cross section has helicity dependent term. The asymmetry determined from this is dependent on the form factor ratio and kinematic coefficients.

\[ A = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\downarrow\uparrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow}} \]

\[
= -\frac{G_E}{G_M} \left[ 2\sqrt{\tau(1+\tau)} \tan\left(\frac{\theta_e}{2}\right) \sin\theta^* \cos\phi^* - 2\tau \sqrt{1+\tau+(1+\tau)^2} \tan^2\left(\frac{\theta_e}{2}\right) \tan\left(\frac{\theta_e}{2}\right) \cos\theta^* \right]
\]

\[
= \left( \frac{G_E}{G_M} \right)^2 + \left( \tau + 2\tau(1+\tau) \tan^2\left(\frac{\theta_e}{2}\right) \right) \]

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CEBAF provides a polarized (83%) electron beam.
The polarized $^3$He (45-50% polarization) acts as a free polarized neutron target.
Big Bite is a large acceptance spectrometer for scattered electrons.
The Neutron Arm, with an 11m$^2$ active area, detects and identifies protons and neutrons.
Selection of Quasi-elastic Events at $Q^2=2.5 \text{ GeV}^2$

Events are selected so that they are in time and so that they are parallel to the $q$. Below is the invariant mass spectrum for all events and neutrals, with the shaded region being the selected quasi-elastic events.

Additionally, cuts on perpendicular missing momentum to suppress the effects of Final State Interactions (FSI).

$$\vec{p}_m, \perp = \hat{q} \times \vec{p}_m$$
Electric Form Factor of the Neutron

The electric form factor of the neutron pre E02013 data.

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Electric Form Factor of the Neutron

New experimental data significantly lower than favored predictions.
Generalized Parton Distributions

GPDs provide the quark contribution at a given $x$ to the form factors:

$$F_1^q(t) = \int_{-1}^{1} dx H^q(x, \xi, t)$$
$$F_2^q(t) = \int_{-1}^{1} dx E^q(x, \xi, t)$$

GPDs parameterize the non-forward elements of the light cone operators. There is a GPD for every quark flavor. GPDs are functions of $x$ which is the longitudinal momentum fraction, $\xi$ which is the skewness or longitudinal momentum asymmetry, and $t$ which is the transferred momentum squared.

For Form Factors and orbital angular momentum, we can choose $\xi = 0$

Classes of processes:
- DIS
- Elastic Scattering
- DVCS
GPD Model

\[ E^q(x, 0, t) = \frac{\kappa_q}{N_q} (1 - x)^{\eta_q} q_v(x)x^{-\alpha(1-x)t} \]
\[ H^q(x, 0, t) = q_v(x)x^{-\alpha(1-x)t} \]

Guidal, Polyakov, Radyushkin, and Vanderhaeghen
Phys Rev D 72, 054013 (2005)

- Model depends on 3 parameters and the form of the \( q(x) \).
- \( \alpha \) is the Regge parameter defined by the Dirac mean squared radius of the proton.
- The exponents \( \eta \) are determined from the neutron and proton FF data, in the original parameters only the proton was used.
- The model contains an extra \((1-x)\) dependence for \( E \) compared to \( H \) because \( E \) scales faster with \( t \) at \( x \approx 1 \).
- \( N \) is a normalization constant resulting from this \((1-x)\) dependence.
- \( H \) and \( E \) are the nonforward parton densities.

\[ H^q(x, \xi, t) = H^q(x, 0, t) + H^q(-x, 0, t) \]
\[ E^q(x, \xi, t) = E^q(x, 0, t) + E^q(-x, 0, t) \]
The new fit is in agreement with both the proton and neutron data, while the previous was not in agreement with the neutron data.
Quark Orbital Angular Momentum

In the framework of this GPD model, Ji’s sum rule can be evaluated.

\[ 2J^q = (\Delta q) + 2L^q = \int_{-1}^{1} dx x [H^q(x, 0, 0) + E^q(x, 0, 0)] \]

<table>
<thead>
<tr>
<th>Quark</th>
<th>(\Delta q)</th>
<th>(\int H)</th>
<th>(\int E)</th>
<th>2J Guidal</th>
<th>2J Our Fit</th>
<th>2L Guidal</th>
<th>2L Our Fit</th>
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</thead>
<tbody>
<tr>
<td>u</td>
<td>0.6</td>
<td>0.37</td>
<td>0.238</td>
<td>0.595</td>
<td>0.600</td>
<td>-0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>d</td>
<td>-0.25</td>
<td>0.20</td>
<td>-0.207</td>
<td>-0.031</td>
<td>-0.016</td>
<td>0.219</td>
<td>0.234</td>
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<tr>
<td>s</td>
<td>0.04</td>
<td>0</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>Total</td>
<td>0.61</td>
<td>0.568</td>
<td></td>
<td>0.624</td>
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</table>

The values of the integral of H are calculated according to the NNLO fit. Here the antiquark contributions are ignored.

Ji X. D., Phys Rev Lett. 78, 610 (1997)
Here are the Pauli and Dirac form factors. For the neutron magnetic form factor the dipole parameterization was used:

\[ G^m_n = \mu_n G_D \]
Using measurements of the $G_E^n$ including our data and traditional parameterizations for the form factors: $G_M^n = \mu_n G_D$, $G_E^p = (1.06 + 0.14 t) G_D$, and $G_M^p = \mu_p G_D$, we calculated the up and down quark form factors.
Conclusions

• The E02013 collaboration has measured $G_E^n$ at $Q^2$ up to 3.5 GeV$^2$, more than doubling the range covered.

• Our measurement provides new input for models to describe the physics of nucleon structure.

• Including our data in a GPD model, we extracted the orbital angular momentum of the down quark and up quark, found to be 0.23 and 0.00 respectively.
Experiment Overview

Measurements were undertaken at four different energies, included to the right was the expected statistical precision. Below the components to systematic uncertainty are tabulated as a fraction of $G_E^n$.

<table>
<thead>
<tr>
<th>Beam Energy (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>Statistical Expected</th>
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<tbody>
<tr>
<td>1.519</td>
<td>1.2</td>
<td>0.0025</td>
</tr>
<tr>
<td>2.079</td>
<td>1.7</td>
<td>0.0011</td>
</tr>
<tr>
<td>2.638</td>
<td>2.5</td>
<td>0.0015</td>
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<tr>
<td>3.290</td>
<td>3.5</td>
<td>0.0012</td>
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<table>
<thead>
<tr>
<th>Analysis Element</th>
<th>1.7 (GeV$^2$)</th>
<th>2.5 (GeV$^2$)</th>
<th>3.5 (GeV$^2$)</th>
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<tbody>
<tr>
<td>Proton Contamination</td>
<td>0.035</td>
<td></td>
<td>0.057</td>
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<tr>
<td>Target Polarization</td>
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<td>0.035</td>
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<tr>
<td>Beam Polarization</td>
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<td>0.011</td>
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<tr>
<td>Acc. Back. Contamination</td>
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<td>0.017</td>
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<tr>
<td>Neutron Polarization</td>
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<td>0.019</td>
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<tr>
<td>Nitrogen Contamination</td>
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<tr>
<td>FSI Corrections</td>
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<td>0.043</td>
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