Experimental Studies on the Electric Form Factor of the Neutron

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Outline

• Introduction
• History: Neutron Electric Form Factor from Cross Sections
• Double Polarization Experiments
  - Polarized Deuterium: e.g. JLab Hall C - E93-026
  - Recoil Polarization: e.g. JLab Hall C - E93-038
  - Polarized Helium-3: e.g. JLab Hall A - E02-013
• Summary/Outlook
**EMFFs: Fundamental Property of the Nucleon**

- **EMFFs**: functions of the hadron current operator

- **Fundamental part of a “classical” nucleon theory**
  - A testing ground for models constructing nucleons from quarks and gluons (e.g. Lattice QCD or GPDs)
  - Provides insight in spatial distribution of charge and magnetization
  - Wavelength of probe can be tuned by changing the momentum transfer $Q$:
    - $< 0.1 \ (GeV/c)^2$ integral quantities (charge radius, ... )
    - $0.1 - 10 \ (GeV/c)^2$ internal structure of the nucleon
      hadronic structure of the photon (VMD) and nucleon structure (pion cloud constituent quarks / valence quarks
    - $> 20 \ (GeV/c)^2$ pQCD scaling
  - Connection to DIS and Compton scattering via framework of GPDs

- **Caution:**
  - at large $Q$ (several times the nucleon mass, Compton wavelength) dynamical effects due to relativistic boosts are introduced, making the physical interpretation of EMFF more difficult (no simple Fourier transformation any more)

- **Not to forget:**
  - EMFF are also essential for understanding form factors of few-body systems, or for extraction of the strange form factors of the nucleons
Form Factors in Elastic Electron - Nucleon Scattering

Nucleon vertex:

\[ \Gamma_{EM}^{\mu}(p_N, p_{N'}) = F_1(Q^2) \gamma^{\mu} + \frac{i\kappa}{2m} F_2(Q^2) \sigma^{\mu\nu} q_\nu \]

Sachs form factors:

\[ G_E(Q^2) = F_1(Q^2) - \kappa \frac{Q^2}{4m^2} F_2(Q^2) \]
\[ G_M(Q^2) = F_1(Q^2) - \kappa F_2(Q^2) \]

Cross Section:

\[ \frac{d\sigma}{d\Omega} = \sigma_{NS} \left[ \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta}{2} \right] \]

with \( \tau = Q^2/4M^2 \), \( \kappa \) the anomalous magnetic moment and \( \theta \) the scattering angle.
Rosenbluth Separation

\[ \frac{\epsilon(1 + \tau)}{\sigma_{NS}} \frac{d\sigma}{d\Omega} = \tau (G_M)^2 + \epsilon (G_E)^2 \]

\[ Q^2 = 4E_E' \sin^2(\theta/2) \]

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

\[ \epsilon = \left[ 1 + 2(1 + \tau) \tan^2(\theta/2) \right]^{-1} \]

- Measures $d\sigma/d\Omega$ at constant $Q^2$; intercept gives $G_M$, slope gives $G_E$
- $G_E$ inversely weighted with $Q^2$, increasing the systematic error above $Q^2 \sim 1 \text{ (GeV/c)}^2$
- Very sensitive to kinematics, acceptances, and radiative corrections
Electric Form Factor of the Neutron

Platchkov et al.: elastic scattering off deuterons

- No target with free neutrons
  - elastic scattering of D or $^3$He
- Challenges:
  - Contribution from the proton
  - Elastic cross section gets small (limiting method to low $Q^2$)
  - Nuclear effects, model dependencies, FSI, MEC
- Net charge of neutron is 0,
  - $G^n_E$ is small at low $Q^2$
- Cross section dominated by $G^n_M$

\[
\frac{d\sigma}{d\Omega} = \left. \frac{d\sigma}{d\Omega} \right|_M \frac{E'}{E} \left( \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \frac{\theta}{2} \right)
\]
Electric Form Factor of the Neutron at Higher $Q^2$

- No target with free neutrons
- Quasi-elastic scattering of D
- Nuclear effects, model dependencies, FSI, MEC
- Contributions from the proton
- Contributions from magnetic form factors dominate
Constraints on $G_E^n$ from the Inverse Reaction

See e.g.: S. Kopecky et al., Phys. Rev. C56 (1997) 2229

- Scattering of thermal neutrons on atomic electrons
- Kinematically limited to very low momentum transfers
- Gives charge radius of the neutron
  \[ \langle r^2_{ch,n} \rangle = -0.1148(23) \text{ fm}^2 \]
- Charge radius is related to the slope of $G_E^n$ at $Q^2=0$
Modern Era

- Akhiezer et al., Sov. Phys. JETP 6, 588 (1958) and Arnold, Carlson and Gross, PR C 23, 363 (1981) showed that:
  - accuracy of form-factor measurements can be significantly improved by measuring an interference term $G_E G_M$ through the beam helicity asymmetry with a polarized target or with recoil polarimetry

- It took a while (over 30 years) to develop:
  - Polarized electron beams with high intensity (~100uA) and high polarization (>70%, strained GaAs, high-power diode/TiSa lasers)
  - Beam polarimetry with 1-3% accuracy
  - Polarized targets with high polarization
  - Ejectile polarimeters with large analyzing powers
Double Polarization Approaches to Measure $G_E^n$

- $^2\overline{D}(\overline{e}, e'n)$ with polarized beam and polarized $ND_3$ target
  (NIKHEF, JLab Hall C)
  limitations: low current (~80 nA)
  deuteron polarization (25%)

- $^2\overline{D}(\overline{e}, e'n)$ from $LD_2$ target and utilizing recoil polarimeter
  (Bates, Mainz, JLab Hall C)
  limitations: Figure of Merit of polarimeter

- $^3\overline{He}(\overline{e}, e'n)$ with polarized beam and polarized $^3He$ target
  (Bates, NIKHEF, Mainz, JLab E02-013)
  limitations: current on target (12 $\mu$A), target polarization (40%),
  nuclear medium corrections

For all three types:

- Asymmetry measurement, interference enhances the small amplitude contribution
- Avoids Rosenbluth separation
- Avoids subtraction of large proton contribution
Spin Transfer Reaction

Polarized electrons transfer longitudinal polarization due to $G_E$, but transverse polarization due to $G_M$

$$\frac{G_E}{G_M} = -\frac{P_t E_e + E_{e'}}{P_t 2M} \tan(\theta_e/2)$$

Polarimeter only sensitive to transverse polarization components, therefore magnet is needed to precess longitudinal component to normal

By measuring the ratio, no error contributions from analyzing power or beam polarimetry
E93-038: $G_E^n$ in Hall C via $^2$H($\tilde{e}',e'\tilde{n}$)

- quasi-elastic kinematics: insensitive to nuclear potential and MEC/IC
- ratio $P_t/P_l$ neither depends on absolute value of analyzing power nor beam polarization
- Charybdis magnet for spin-precession
- Experiment run in 2000/2001
- $Q^2=0.45, 1.13$ and $1.45$ (GeV/c)$^2$
- Similar experiments at MIT Bates and at MAMI A1 and A3 covering $Q^2=0.15-0.8$ (GeV/c)$^2$
Beam / Target Asymmetry

Asymmetry:

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

\[
= A_\perp \sin \theta^* \cos \phi^* + A_\parallel \cos \theta^*
\]

(assuming \( P_e = P_n = 1 \))

\[
A_\perp = -\frac{2\sqrt{\tau(\tau + 1)} \tan(\theta/2) \frac{G_{nM}}{G_{nM}}}{(\frac{G_{nM}}{G_{nM}})^2 + (\tau + 2\tau(1 + \tau) \tan^2(\theta/2))}
\]

\[
A_\parallel = -\frac{2\tau \sqrt{1 + \tau + (1 + \tau)^2 \tan^2(\theta/2)} \tan(\theta/2)}{(\frac{G_{nM}}{G_{nM}})^2 + (\tau + 2\tau(1 + \tau) \tan^2(\theta/2))}
\]

(with \( \tau = Q^2/4m_N^2 \))

Experiments either:

- measure both components (by rotating target spin)

or

- rely on polarimetry
E93-026: $G_E^n$ in Hall C via $^2H(e,e'\text{n})$

- Polarized Deuterium Target
  - frozen $^{15}$ND$_3$
  - 5T magnetic field
  - dynamic polarization
- HMS spectrometer + neutron array
- $Q^2 = 0.5$ and 1.0 (GeV/c)$^2$
\[ G_E^n \text{ from } \vec{D}(\vec{e}, e'n)p \]

- measuring \( A_{ed}^V \): \( \sigma(h,P) = \sigma_0 (1 + hP A_{ed}^V) \)
- quasielastic kinematics
  - low sensitivity to potential, and to MEC and IC
  - sensitive to \( G_E^n \)
Results on $G_E^n$ from $A(Q^2)$ and T20


method is also limited to $Q^2$ below 2 (GeV/c)^2
Data on $G_E^n$ from Double Polarization Experiments

- **Galster:**
  parametrization fitted to old (<1971) data set

- **For $Q^2 > 1 \text{(GeV/c)}^2$:**
  similar $Q^2$ behaviour as $G_E^p$

- **Most recent results** (from Mainz and JLab) using all three approaches are in excellent agreement

- **no accurate data available for**
  $Q^2 > 1.5 \text{(GeV/c)}^2$
\[ ^3\text{He as an Effective Neutron Target} \]

\[ \begin{align*}
^3\text{He} & \quad \text{n} \quad \text{p} \quad \text{p} \\
= & \quad \text{Spin}=0 \\
= & \quad \text{Spin}=0 \\
\end{align*} \]

- **Naïve picture:**
  - neutron carries the spin of \(^3\text{He}\), protons are unpolarized

- **Actual calculations:**
  - neutron polarization \( \sim 86\% \);
  - proton polarization \( \sim -2.8\% \)
  - further medium effects: reduction of cross section
    (reproduced by Glauber approximation type calculations e.g.)
Generalized Eikonal Approximation (GEA)

Calculations in the framework of GEA

- Fully relativistic
- Includes FSI
- Good agreement with JLab $A(e,e'p)$ data for $Q^2 > 1 \text{ (GeV/c)}^2$
  (Garrow et al.)
- FSI accurate for $p_{miss} < 250 \text{ MeV/c}$

Calculations by M. Sargsian
The Hall A Polarized Helium-3 Target

So far: \( G_m^n, A1n, g2n, GDH, SAGDH \)
- Spin exchange between optically pumped alkali-metal vapor and \(^3\)He
- High pressure cell, 10 atm, 40cm long
- Target polarization ~40%
- Beam currents up to 15\( \mu \)A
- Luminosity \( 1.0 \times 10^{36} \) e-neutron/s/cm\(^2\)

For \( G_E^n \) in Hall A
- Improved cell geometry
- Laser-Combiner with fiber optics
- K/Rb mixture instead of pure Rb
- Metal-box: magnet plus shielding
Two New Detector Systems
(Large Acceptance, Open Geometry)

BigBite (electrons)
- large drift chamber, 15 planes, 2500 wires
- lead glass calorimeter (pion separation)
- scintillators

BigHAND (neutrons)
- 240 neutron bars
- 180 veto detectors
- 4.7m x 1.6m active area
- good timing resolution (300 ps)
- good efficiencies for neutrons, high thresholds to minimize background
E02-013: $G_E^n$ for large $Q^2$ in Hall A

- medium luminosity of the Hall A pol. $^3$He target allows use of two large acceptance devices with open geometry
- better FOM than with deuterium and recoil polarimetry
Boosting the Recoil Polarization Method to Measure $G_E^n$ at Higher $Q^2$

- so far: highest $Q^2 = 1.5 \text{ (GeV/c)}^2$ with this method (E93-038, Hall C)
- approved Hall C experiment (E04-110) will
  - utilize successful approach of E93-038
  - increase acceptance of polarimeter (larger neutron array, tapering the poles of Charybdis magnet)
  - increase efficiency of the neutron polarimeter (more neutron detectors, steel converters)
  - with JLab at 6 GeV: $Q^2 = 4.3 \text{ (GeV/c)}^2$ and $\partial G_E^n = 0.002$ in 25 days
  - with JLab at 12 GeV: $Q^2$ values up to 8.1 $\text{(GeV/c)}^2$ are possible (using HMS in Hall C)
Spectrometers and Beams for Measurements at Higher Momentum Transfers

present: BigBite or HRS(HMS)

- maximum beam energy 6 GeV
- BigBite has large solid angle (76 msr) but electron momentum limited to 1.5 GeV/c, therefore it needs to stay at backward angles (smaller cross section)
- HRS/HMS would allow larger electron momenta, but solid angle is significantly smaller (6 msr / 8 msr)
- below ~4 (GeV/c)^2 BigBite wins

after 12 GeV upgrade:

- using 8.8 and 11 GeV beam and existing HMS and neutron detector:
  Q^2 values of ~6.4 (GeV/c)^2 feasible
- using a larger acceptance spectrometer (SuperBigBite, MAD) for electron detection:
  Q^2 values of up to 8.0 (GeV/c)^2 seem feasible
## Summary / Outlook

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Collaboration</th>
<th>$Q^2$ (GeV/c$^2$)</th>
<th>Reaction</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>MIT-Bates</td>
<td>E85-05</td>
<td>0.26</td>
<td>$D(\bar{e},e'n)$</td>
<td>1994</td>
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<td>Blast</td>
<td>&lt; 0.8</td>
<td>$\bar{D}(\bar{e},e'n)$</td>
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<tr>
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<td>Blast</td>
<td>&lt; 0.8</td>
<td>$^3He(\bar{e},e'n)$</td>
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<tr>
<td>Mainz MAMI</td>
<td>A3</td>
<td>0.31</td>
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<td>0.15, 0.34</td>
<td>$D(\bar{e},e'n)$</td>
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<tr>
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<td>A1</td>
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<td>A1</td>
<td>0.3, 0.6, 0.8</td>
<td>$D(\bar{e},e'n)$</td>
<td>2004</td>
</tr>
<tr>
<td>NIKHEF</td>
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<td>0.21</td>
<td>$\bar{D}(\bar{e},e'n)$</td>
<td>1999</td>
</tr>
<tr>
<td>JLab</td>
<td>E93-026</td>
<td>0.5, 1.0</td>
<td>$\bar{D}(\bar{e},e'n)$</td>
<td>2001/2004</td>
</tr>
<tr>
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<td>E93-038</td>
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<td>$D(\bar{e},e'n)$</td>
<td>2003</td>
</tr>
<tr>
<td></td>
<td>E02-013</td>
<td>1.3, 2.4, 3.4</td>
<td>$^3He(\bar{e},e'n)$</td>
<td>Approved</td>
</tr>
<tr>
<td></td>
<td>E04-110</td>
<td>4.3</td>
<td>$D(\bar{e},e'n)$</td>
<td>Approved</td>
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<tr>
<td>JLab @ 12 GeV</td>
<td>Hall A</td>
<td>&gt; 6.0</td>
<td>$^3He(\bar{e},e'n)$</td>
<td>Feasible</td>
</tr>
<tr>
<td>JLab @ 12 GeV</td>
<td>Hall C</td>
<td>6.0 – 8.0</td>
<td>$D(\bar{e},e'n)$</td>
<td>Feasible</td>
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</tbody>
</table>
Summary/Outlook

- Very active experimental program on electro-magnetic form factors of the nucleon at JLab and elsewhere
- Possible because of the availability of polarized electron beam (>100uA, >75% polarized), polarized targets and polarimeters with high analyzing power
- Exciting new data on $G_E^n$ from JLab (and MAMI), but also on $G_E^p$ and $G_M^n$
- JLab Experiment E02-013 will significantly increase our knowledge about the electric form factor of the neutron at higher momentum transfers
- Future plans to extend EMFF measurements at JLab
Possible Boosts for $G^n_E$ Experiments:

Polarized $^3\text{He}$-Target Improvements

- Increase in usable beam current and polarization very desirable
- New laser technology is becoming available, allowing to combine light of several Lasers in a compact setup (E02-013 will use a 5-1 combiner)
- Modifications of the cell design with larger pumping cells (long term: cylindrical instead of spherical pumping cells) and improved gas flow
- Coating of glass, modifications of the end-caps to decrease depolarization and increase durability
- Use of Rb/K mixture instead of pure Rb
Hall A
February 10, 2006

GEN Electronics

Pol He Target

BigBite

BigHand

HRS-L

HRS-R
Asymmetry does not vary strongly within our bins in missing momentum.
- Phenomenological ansatz, using
  - experimental data on $q(x)$ from DIS (here CTEQ)
  - ansatz consistent with phenom. and theo. constraints
    (large $-t$ and $x$: gaussian L.C. w.f., small $-t$ and $x$ Regge behavior)
  - simple ansatz, with only a few fit parameters,
    determined by fitting against $F_1$, $F_2$ and $F_A$
- Data on Electric Form Factor of Neutron is currently weakest point of the fit
High-$Q^2$ Behaviour
Or: Neutron Data Wanted!

\[ \ln^2 \left( \frac{Q^2}{\Lambda^2} \right) \frac{Q^2 F^p_2}{F^p_1} \]

\[ \frac{-1}{15} \ln^2 \left( \frac{Q^2}{\Lambda^2} \right) \frac{Q^2 F^n_2}{F^n_1} \]

\[ \Lambda = 300 \text{ MeV} \]
Jefferson Lab Experiment E02-013

Cross Section Asymmetry in $^{3}\text{He}(\vec{e}, e'\text{n})$

To obtain $G_E^n$ at three different $Q^2$

<table>
<thead>
<tr>
<th>$Q^2$ $(\text{GeV}/c)^2$</th>
<th>$E_i$ (GeV)</th>
<th>$\theta_e$ (deg)</th>
<th>$p_e$ (GeV/c)</th>
<th>$\theta_n$ (deg)</th>
<th>$p_n$ (GeV/c)</th>
<th>$T_n$ (GeV)</th>
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<td>1.31</td>
<td>1.644</td>
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<td>2.40</td>
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<td>1.43</td>
<td>25.4</td>
<td>2.58</td>
<td>1.81</td>
</tr>
</tbody>
</table>

Approved beam time: 32 days
Expected (statistical) uncertainty: less than 15%
Scheduled for early 2006
E02-013: Layout for $^3\text{He}(e,e'n)$