Nucleon Form Factors and the Nuclear Medium

Vincent Sulkosky
University of Virginia

HUGS 2014, Lecture 2
June 11th, 2014
1) What can we learn from form factors at low $Q^2$?
2) What is the proton radius puzzle?
3) What about neutron form factors?
4) What can we learn from combining proton and neutron information?
What do we know about their internal structure?

**Mass:** ~ 940 MeV, but u- and d-quark mass only a few MeV each!

\[ 1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J} \]

**Charge:** proton, +1; neutron, 0

**Magnetic moment:** large part is anomalous, > 150%!

**Spin-1/2:** but total quark spin contributes only ~ 30%!

*Sum of the parts is not equal to the whole!
CLAS (Hall B) Two Photon Exchange Experiment

Measure the positron-proton to electron-proton cross section ratio to determine the TPE correction.

- $e^+ p$ and $e^- p$ scattering measured simultaneously using a mixed electron-positron beam

Lepton-proton elastic scattering cross-section,

$$
\sigma(e^\pm p) \propto |A_{ep\rightarrow ep}|^2 = |A_{\text{Born}} + \ldots + A_{2\gamma}|^2
$$

$$
\sigma(e^\pm p) \propto |A_{\text{Born}}|^2 \pm 2A_{\text{Born}} \text{Re}(A_{2\gamma})
$$

$$
R = \frac{\sigma(e^+ p)}{\sigma(e^- p)} = 1 + \frac{4\text{Re}(A_{2\gamma})}{A_{\text{Born}}}
$$

$R$ provides a model-independent measurement of the TPE contribution.
Results and World Data at $Q^2 \sim 1.5 \text{ GeV}^2$

Plots from D. Adikaram
What can we learn from form factors?

- At small $Q^2 \rightarrow$ larger length scale, closely related to the proton size.
- In the non-relativistic limit:

$$\langle r_{E,M}^2 \rangle = \frac{-6}{G_{E,M}(0)} \left[ \frac{d}{dQ^2} G_{E,M}(Q^2) \right]_{Q^2=0}$$

- The slope of the form factors versus $Q^2$ is related to the charge and magnetic radius of the proton.
2003 – Friedrich & Walcher fit:
- Smooth dipole form + “bump & dip”
- All four FFs exhibit similar structure at small momentum transfer ($Q^2 \sim 0.25 \text{ GeV}^2$).
- Was interpreted as evidence for meson cloud effects.
Recent Experimental Efforts at low $Q^2$

- **BLAST** - program for low $Q^2$ nucleon and deuteron structure with polarized beam - internal polarized target
- **Mainz A1** - unpolarized cross sections, 0.01 - 1 GeV$^2$
- **E05-103**
  Calibrations for low energy deuteron photodisintegration used to determine proton ratio of $G_E/G_M$
- **E08-007** run 2008
  Dedicated experiment to cover the 0.3 - 0.7 GeV$^2$ range with higher statistics
- **E08-007 part II** run 2012 (along with E08-027 “g2p”)
  Dedicated polarized beam - polarized NH$_3$ target measurements to cover the range about 0.015 - 0.16 GeV$^2$ with high precision
E08-007: Proton FFs at Low $Q^2$

- Substantial deviation from unity is observed in **LEDEX** (Ron et al.) and **E08-007**, Part 1 (Zhan et al.).
- Both data are inconsistent with F&W fit.
- Complementary to the high precision cross-section measurement at **Mainz** ($Q^2 \sim 0.1 – 2 \text{ GeV}^2$).

- Improved EMFFs:
  - strange form factors through PV $A^{PV} + G_{E,M}^{p,ny} + G_A^{pZ}$ (calculated) $\rightarrow G_{E,M}^s$
  - proton Zemach radius and hydrogen hyperfine splitting

$$\Delta Z = -2\alpha Z \frac{m_e m_p}{m_e + m_p} \frac{r_Z}{r_Z} = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[ \frac{\mu_N}{\mu_p} G_E(Q^2) G_M(Q^2) - 1 \right]$$
E08-007 Impact

Fit of world data except Mainz A1 data.

- $G_E$ reduced up to $\approx 2\%$ from 0.3 - 1 GeV$^2$
- $G_M$ increased $\approx 0.5\%$ from 0.1 - 0.8 GeV$^2$
- FF ratio smaller by up to $\approx 2.5\%$ from 0.3 - 0.8 GeV$^2$
- Slopes changed at $Q^2 = 0$ changing "radii".
Muonic Hydorgen Measurements

- 2S $\rightarrow$ 2P Lamb Shift + 2S-HFS
The Proton Charge Radius Puzzle

- 7σ discrepancy between *muonic* hydrogen Lamb shift and combined *electronic* Lamb shift and electron scattering
- High-profile articles in Nature, NYTimes, etc.
- Puzzle unresolved, possibly new physics

<table>
<thead>
<tr>
<th>#</th>
<th>Extraction</th>
<th>$&lt;r_E&gt;^2$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sick</td>
<td>0.895 ± 0.018</td>
</tr>
<tr>
<td>2</td>
<td>Bernauer Mainz</td>
<td>0.879 ± 0.008</td>
</tr>
<tr>
<td>3</td>
<td>Zhan JLab</td>
<td>0.875 ± 0.010</td>
</tr>
<tr>
<td>4</td>
<td>CODATA’06</td>
<td>0.877 ± 0.007</td>
</tr>
<tr>
<td>5</td>
<td>Combined 2-4</td>
<td>0.877 ± 0.005</td>
</tr>
<tr>
<td>6</td>
<td>Muonic Hydrogen</td>
<td>0.842 ± 0.001</td>
</tr>
</tbody>
</table>
Electron vs Muon Radius Techniques

\[
\left\langle r_E^2 \right\rangle^{1/2}_{ep} = 0.8418 \pm 0.0007
\]

\[
\left\langle r_E^2 \right\rangle^{1/2}_{ep} = 0.875 \pm 0.009
\]

\[
\left\langle r_E^2 \right\rangle^{1/2}_{\mu p} = ?
\]
Resolutions to the Puzzle?

- **Extraction from muonic-hydrogen is incorrect.** No doubts about the experiment, but some discussion about the theory and proton structure for extracting the proton radius.

- **Extraction from ep (scattering) is incorrect.** The fit procedures are not good enough. $Q^2$ not low enough, and there could be structures in the form factors.

- **Proton structure issues in theory.** Theory critique of theory - off-shell proton in two-photon exchange leads to enhanced effects differing between $\mu$ and e, or leads to theoretically unjustified sticking-in-form-factor models.

- **Novel missing physics.** Physics differentiates between $\mu$ and e. Constraints on novel physics exist, and there seems to be no generally accepted solution at present.
e-μ Universality in Lepton Scattering

1960s-1970s: several experiments tested e-μ universality in scattering

- Elastic μp scattering:
  Ellsworth et al., Phys. Rev. 165 (1968)


  \[ \sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04 \text{ (±8.6% systematics)} \]

- e-C, and μ-C are in agreement

Constraints are not as good as one would like

\[ 1/\Lambda^2 = 0.006 \pm 0.016 \text{ GeV}^2 \]
High precision (≈1%) survey of FF ratio at $Q^2 = 0.01 - 0.05 \text{ GeV}^2$

- Beam-target asymmetry measurement by electron scattering from polarized NH$_3$ target
- Electrons detected in two matched spectrometers
- Ratio of asymmetries cancels systematic errors.

Completed data taking in May 2012 and currently being analyzed.
High precision (≈1%) survey of FF ratio at $Q^2 = 0.01 – 0.05 \text{GeV}^2$

Beam-target asymmetry measurement by electron scattering from polarized NH$_3$ target

Electrons detected in two matched spectrometers

Ratio of asymmetries cancels systematic errors.

Completed data taking in May 2012 and currently being analyzed
Approved Experiment: $\mu$-p Scattering at PSI

- Directly test the most interesting possibility, that **muon** and **electron** scattering are different at Paul Scherrer Institut (PSI) in Switzerland:
  - to higher precision, in the low $Q^2$ region for sensitivity to the radius
  - Measuring both $\mu^-p$ and $e^-p$ to have direct comparisons and a robust, convincing result.

- Depending on the results, a 2\textsuperscript{nd} generation experiment might be desirable.
Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing electron-proton extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons

Relative comparison reduces errors by a factor of 2

Should measure \( r_{ep} - r_{\mu p} = 0.0 \) vs. 0.034 to \( \approx \pm 0.0045 \)
# MUSE Time Line

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 2012</td>
<td>Physics Approval, proposal Deferral</td>
</tr>
<tr>
<td>July 2012</td>
<td>PAC/PSI technical review</td>
</tr>
<tr>
<td>Fall 2012</td>
<td>Test run in πM1 beam-line</td>
</tr>
<tr>
<td>January 2013</td>
<td>Experiment approved</td>
</tr>
<tr>
<td>Summer 2013</td>
<td>Second test run in πM1 beam-line</td>
</tr>
<tr>
<td>Fall 2013</td>
<td>Third test run in πM1 beam-line</td>
</tr>
</tbody>
</table>

2012 Test run verified the basic properties of the muon beam at PSI.
## MUSE Time Line

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-2014</td>
<td>Seek funding via grant proposals</td>
</tr>
<tr>
<td>June 2014</td>
<td>Beam tests in πM1 beam-line</td>
</tr>
<tr>
<td>mid 2014</td>
<td>Start development activities (TBD)</td>
</tr>
<tr>
<td>December 2014</td>
<td>Beam tests in πM1 beam-line</td>
</tr>
<tr>
<td>February 2015</td>
<td>PSI review</td>
</tr>
<tr>
<td>Mid 2015</td>
<td>Mini-dress rehearsal</td>
</tr>
<tr>
<td>Late 2016</td>
<td>Dress rehearsal</td>
</tr>
<tr>
<td>2017-2018</td>
<td>2 year experiment run</td>
</tr>
</tbody>
</table>
PRad Proton Radius Experiment (JLab)

- Low intensity beam in Hall B @ JLab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0°
- Lower $Q^2$ than Mainz. Very forward angle, insensitive to $2\gamma$, $G_M$
- Approved June 2012, A-rated experiment
Expected $Q^2$ Range & Precision of PRad
Notice there are no nuclei that only contain neutrons.

Protons, neutrons, and electrons seem like our fundamental particles.
Why is the structure of the neutron interesting?

1) At first glance the proton and neutron are very similar:
   a) Approximately the same mass (1.3 MeV difference)
   b) Both spin-1/2
2) But clearly they are different:
   a) Charge: +1 versus 0 (Electrostatics)
   b) Magnetic moment: +2.79 versus -1.91 (Magnetism)
   c) Stability: proton seems to be stable, neutron decays (Weak force)

To fully check our understanding of the strong force, it would be negligent to ignore the neutron and solely focus on the proton, especially since we rely on effective theories and models to approximate QCD

However, there are no nuclei that only contain neutrons and free neutrons decay in 15 minutes.
Light Nuclei as Effective Neutron Targets

- **Proton** is well known and its properties are reasonably measured.
- **Neutron** not understood to a desirable accuracy, especially charge, magnetization and spin distributions.

**Problem:** no neutron target, direct measurements not possible.

**Solution:** indirect measurements using appropriate targets:

1) Deuteron

2) $^3$He

Proton + Neutron

Two Protons + Neutron

Detailed knowledge on the structure of light nuclei is crucial for extracting precise information on neutron structure.
Neutron Form Factors Before JLab

J. Arrington et al., JoP 299, 012002 (2011)
Measuring $G_M^n$ by the Ratio Method

QE scattering: simultaneous $d(e,e'p)$ and $d(e,e'n)$

$$\frac{d(e,e'n)}{d(e,e'p)} \sim \frac{n(e,e')}{p(e,e')} \sim \kappa \left( G_E^2 + \frac{\tau}{\epsilon} G_M^2 \right) / \sigma_p(e,e')$$

- Bound-nucleon effects should be very small in ratio
- Expect $G_E << G_M$ so correction is very small
- Many experimental systematic effects cancel in ratio
- Neutron/proton acceptance and detection efficiency
Results on $G_M^n$ from Hall A and CLAS

J. Lachniet et al., PRL 102, 192001 (2009)
B. Anderson et al., PRC 75, 034003 (2007)
Measuring $G^n_E/G^n_M$ Using Recoil Polarimetry

Recoil polarization

\[ P_x = -P_e K_t G_{En} G_{Mn} \]
\[ P_z = P_e K_\ell G^2_{Mn} \]

Analyzed by second scattering in polarimeter with analyzing power $A_y$

Ratio Technique:
Measure $P_x$ and $P_z$

\[ \frac{P_x}{P_z} = -\frac{K_t}{K_\ell} \frac{G_{En}}{G_{Mn}} \]
small systematics

$A_y(\theta)$ and $P_e$ cancel

- Electrons detected in spectrometer
- Neutron spin precessed in dipole magnet
- Neutron detected, polarization analyzed in neutron polarimeter
- Detect two linear combinations of $P_x$ and $P_z$ (two spin precession angles)
Polarized Target Measurements

Longitudinal polarized beam/target transverse to $\hat{q}$ in scattering plane

Helicity-dependent asymmetry roughly proportional to $G_E/G_M$

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx A_\perp = -\frac{2\sqrt{\tau(\tau + 1)}\tan(\theta/2)G_E/G_M}{(G_E/G_M)^2 + (\tau + 2\tau(1 + \tau)\tan^2(\theta/2))}$$
Caveats of Measuring Asymmetries

Asymmetry:

\[ A_{meas} = \frac{N^+ - N^-}{N^+ + N^-} \]

Asymmetry Uncertainty: \(1/\sqrt{N_{total}}\), where \(N_{total} = N^+ + N^-\)

- The physics asymmetry is diluted by the unpolarized target material, which also increases the uncertainty on the asymmetry

\[ A_{phys} = \frac{A_{meas}}{f \cdot P_B \cdot P_T} \]

- \(f\) is a dilution factor, \(P_B\) is the beam polarization, \(P_T\) is the target polarization

Typically these factors are much less than 1 and dependent on the target material
Deuterium Spin Structure

Spin-1 Particle, 2 spin-$\frac{1}{2}$ Nucleons (Proton and Neutron)

Angular Momentum

S

L=0
~90%

D

L=2
~10%
Requirements for DNP

- Target material doped with paramagnetic centers
- Cryogenic system to reach temperatures of < 1K
- Magnetic field > ~ 2 Tesla
- Microwave system – 140 GHz at 5 T
- NMR to measure polarization
Asymmetry Measurements at NIKHEF

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

- A sign flip of asymmetry is a clear sign that **D-state component manifests itself in the nucleus at high** \( p_{\text{miss}} \)
- Sign flip happened at around Fermi momentum of deuterium nucleus
- **Asymmetries** are the ratio of cross-section differences over the unpolarized cross-section for different orientations of electron and target spins

3^He spin structure

- Spin-1/2 Particle, 3 spin-1/2 Nucleons (Proton and Neutron)
- Protons are in spin-singlet state. \(^3\)He spin is dominated by n spin. Therefore \(^3\)He can be used as an effective n target
- \(S'\) mixed symmetry, higher energy level compared to \(S\)-state

Effective Polarized Neutron Target

\[
\frac{\mu_{^3\text{He}}}{\mu_n} = \frac{-2.131}{-1.913} \approx 1
\]

Angular Momentum:

- \(S\): \(L=0\) ~90%
- \(S'\): \(L=0\) ~1-2%
- \(D\): \(L=2\) ~8%
Polarized $^3$He Target
Polarized $^3$He Target
Neutron FFs Including JLab Data

\[ G_{En} \text{ and } G_{Mn}/\mu \sim G_D \]

Requires the use of light nuclei such as the deuteron and $^3\text{He}$.
Quark Flavor Decomposition

- General Parton Distribution (GPD) models are constrained by nucleon form factors:

\[ F_{1,2}^p = \frac{2}{3} F_{1,2}^u - \frac{1}{3} F_{1,2}^d \]

\[ F_{1,2}^n = -\frac{1}{3} F_{1,2}^u + \frac{2}{3} F_{1,2}^d \]

- High Q^2 for \( G_E^n \) data allows for quark decomposition

- Lattice QCD is better suited for isovector FF

Lattice: Bratt et al., arXiv: 1001.3620, \( m_\pi = 140 \) MeV
JLab 12 GeV Upgrade

- JLab’s 12 GeV upgrade is currently in the construction phase
- Hall D will be added
- The three current experimental halls are being upgraded
- Several new experiments are already approved to run after the 12-GeV upgrade with 6 approved form factor experiments
Approved FF Experiments: 12 GeV

Proton

- E12-07-108: elastic cross section experiment H(e,e’)p
- E12-07-109: FF ratio experiment using Super BigBite Spectrometer (SBS)
Approved FF Experiments: 12 GeV

Proton
- E12-07-108: elastic cross section experiment $H(e,e')p$
- E12-07-109: FF ratio experiment using Super BigBite Spectrometer (SBS)

Neutron
- E12-07-108: cross section ratio: $^2H(e,e'n)/^2H(e,e'p)$ to measure $G_{Mn}$ with CLAS12
- E12-09-019: also cross section ratio to measure $G_{Mn}$ using SBS
Approved FF Experiments: 12 GeV

Proton

- E12-07-108: elastic cross section experiment $H(e,e')p$
- E12-07-109: FF ratio experiment using Super BigBite Spectrometer (SBS)

Neutron

- E12-07-108: cross section ratio: $^2H(e,e'n)/^2H(e,e'p)$ to measure $G_{Mn}$ with CLAS12
- E12-09-019: also cross section ratio to measure $G_{Mn}$ using SBS
- E12-09-016 ($GEn$ II): polarized $^3He(e,e'n)$ using SBS, ratio $G_{En}/G_{Mn}$
- E12-11-009: $D(e,e'n)$ using recoil polarimetry in Hall C to measure ratio $G_{En}/G_{Mn}$
Motivations to Study FFs

- Form factors are a fundamental property of the nucleon
- Provide excellent testing ground for QCD and QCD-inspired models
- Gives constraints on models of nucleon structure
- Are not yet calculable from first principles
- Electromagnetic form factors of the proton were thought to be well understood prior to Jefferson Lab data:
  - At high $Q^2$, discovery of significant difference between techniques
  - Proton radius puzzle at low $Q^2$; experiments at JLab and PSI (MUSE) continue the investigation