Nucleon Form Factor Experiments:
Present and Future

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Nucleon Elastic Form Factors

• The Form Factors (FF) are fundamental quantities which describe internal structure of the nucleons
• Related to charge and magnetization distributions of the nucleon
• Investigation of FFs provide a powerful tool toward understanding of non-perturbative QCD and confinement
• Much experimental progress in past two decades: unexpected results that is inspiring theoretical progress.

Standard Model is not complete till we figure out non-perturbative QCD and confinement.

• How does the nucleon acquire its mass: only 2% of the nucleon mass comes from Higgs.
• How does the confinement come about?
Elastic scattering: ground state properties of the nucleon

\[ \sigma(\theta_e) = \sigma_{\text{Mott}} \left| \int_{\text{volume}} \rho(\vec{r}) e^{i\vec{q} \cdot \vec{r}} d^3\vec{r} \right|^2 = \sigma_{\text{Mott}} |F(\vec{q})|^2 \]
Elastic Electro-Magnetic Form Factors

The hadronic current in one photon exchange

\[ J^\mu = e \bar{u}(p') \left[ F_1(q^2) \gamma^\nu + i \frac{\kappa}{2M} q_{\nu} \sigma^{\nu\lambda} F_2(q^2) \right] u(p) \]

\( F_1 \), Dirac form factor; helicity conserving
\( F_2 \), Pauli form factor; helicity non-conserving

Or in terms of Sachs form factors

\[ G_E = F_1 - \kappa \tau F_2 \]
\[ G_M = F_1 + \kappa F_2, \tau = \frac{Q^2}{4M} \]

So the elastic cross section

\[ \frac{d\sigma}{d\Omega} = \left. \frac{d\sigma}{d\Omega} \right|_{Mott} \frac{E'}{E} \left[ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \theta \right] \]
In the Breit Frame, \( G_E \) and \( G_M \) are the Fourier transforms of charge and magnetization distributions of the nucleon.

\[
\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \left\{ G_E^2 + \frac{\tau}{\epsilon} G_M^2 \right\} / (1 + \tau)
\]

Rosenbluth Formula

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

\[
\epsilon = \frac{1}{1 + 2(1 + \tau) \tan^2(\theta^* / 2)}
\]

\[
\sigma_R = \frac{\epsilon(1+\tau)}{\tau} \left[ \sigma_{\text{exp}} / \sigma_{\text{Mott}} \right] = G_{E_p}^2 + \epsilon G_{E_p}^2 / \tau
\]
Better way to measure $G_E$ at high $Q^2$

Double polarization methods

Polarization transfer in

$$
e N \rightarrow e \bar{N}
$$

Spin asymmetry in

$$
e \bar{N} \rightarrow e N
$$

$$
\frac{G_E}{G_M} = - \frac{P_x (E_{beam} + E_e)}{P_z} \frac{\tan(\theta_e/2)}{2M}
$$

$$
A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \sim \frac{-2 \sqrt{\tau(1+\tau)} \tan(\theta_e/2)}{2M (\frac{G_E}{G_M})^2 + \frac{\tau}{\epsilon}}
$$

Most systematic effects cancel in the ratio
The Jlab data from polarization transfer method

The difference between two methods is now understood to be mostly due to two photon exchange and other radiative corrections. When these corrections are properly done Rosenbluth results move towards polarization results.

$\mu G_{Ep}/G_{Mp}$ is not constant as previously believed; It drops with $Q^2$ and may cross zero soon.

(mostly) previous data from Rosenbluth method
Nucleon form factors scaling

\[
F_1 = \frac{G_E + \tau G_M}{1 + \tau} \quad F_2 = \frac{-G_E - G_M}{1 + \tau}
\]

\[
F_2 / F_1 = \frac{1 + G_E / G_M}{\tau + G_E / G_M}
\]

Analysis was motivated by pQCD: \( Q^2 F_2 / F_1 = \text{const} \)

Discovery: It is rising and it looks like a higher \( F_2 \) can explain the data.

Jerry Miller suggested accounting for Orbital Angular Momentum!

For constant \( G_E / G_M \) at large \( Q^2 \)
Several calculations able to reproduce the new data.

- Descriptions differ in details, but nearly all are directly or indirectly related to quark angular momentum

Dyson-Schwinger equations, as continuum approach to QCD (Roberts et al.)

Modified pQCD scaling prediction by Ji, Belitsky et al: includes quark angular momentum component

\[
\mu_{P_{E_p}} G_{E_p}/G_{M_p} \text{ data at high } Q^2
\]

\[
\frac{G_{E_p}}{G_{M_p}} \text{ data at high } Q^2
\]

VMD fits

\[
pQCD \text{ prediction for large } Q^2: \quad S \rightarrow Q^2 F_2/F_1
\]

\[
pQCD \text{ updated prediction: } \quad S \rightarrow [Q^2/\ln^2(Q^2/\Lambda^2)] \ F_2/F_1
\]
The pQCD scaling with logarithmic corrections (Ji, Belitsky) is too high.

Relativistic constituent quark models also too high.

Dyson Schwinger Equation approach is in good agreement with our high Q2 data.

We clearly need higher Q2 data to distinguish between these models.
Four contributions to the nucleon FFs

\[ F_{1p}^u = 2F_{1p} + F_{1n} \]

\[ F_{1p}^d = 2F_{1n} + F_{1p} \]

G. D Cates et al.  

M. Diehl and P. Kroll (GPDs)  

Using the D&K table of \( F^u, F^d \)

The down quark contribution to the \( F_1 \) proton form factor is strongly suppressed at high \( Q^2 \)
• Well suited to Relativistic Quantum Field Theory. Non Perturbative, continuum approach to QCD
• Hadrons as composites of current Quarks and Gluons
• Incorporates di-quark degrees of freedom.
• Confinement and DCSB are readily expressed
• Prediction: owing to DCSB in QCD, strong diquark correlations exist within baryons

Dynamic generation of mass

![Dynamic generation of mass diagram](image)
Nucleon and Roper electromagnetic elastic and transition form factors

Wilson, Cloet, Chang, Roberts, PRC 85, 025205 (2012)

Interplay between the [qq] and {qq} diquarks creates a zero crossings

Jefferson lab Super Bigbite Spectrometer (SBS)

- Double Polarimeter
- Hadron Calorimeter
- SBS Dipole
- Front GEM tracker
- Target

**Detectors behind a large dipole magnet:**

- **Major advantages which pave way to large FOM:**
  - Relatively large solid angle
  - Large momentum bite
  - Straight line track analysis.
  - Detectors shielded from charged particle background.

- **Consequences:**
  - High rates at detectors.
  - Need good coordinate resolution.

~ 2 x 10^{38} Luminosity and ~ 70 msr solid angle.
Gas Electron Multiplier (GEM) trackers make SBS possible

- Largest GEM tracker system in the world at present
  - Front tracker: Six 150×40 cm² GEM layers; built by INFN
  - Polarimeter trackers: Ten 200×60 cm² GEM layers; built by U. of Virginia

GEM provide very good tracking resolutions (~ 70 μm) in very high rate environments ~100s of MHz/cm².
SBS experimental setup

**Proton magnetic form factor: E12-07-108**

**Proton form factors ratio, GEp(5): E12-07-109**

**Neutron/proton form factors ratio: E12-09-019**

**Neutron form factors ratio, GEN(2): E12-09-016**
12 GeV GEp experiment

\[ \frac{\mu_p G_E^p}{G_M^p} \]

- **VMD - E. Lomon (2002)**
- **VMD - Bijker and Iachello (2004)**
- **RCQM - G. Miller (2002)**
- **DSE - I. Cloet (2009)**

\[ \frac{F_2}{F_1} \propto \ln^2 \left( \frac{Q^2}{\Lambda^2} \right)/Q^2, \Lambda = 300 \text{ MeV} \]

**Data Points:**
- GEp(1)
- GEp(2)
- GEp(3)
- GEp(5), SBS

**Q^2 [GeV^2]**
Asymmetry in the polarized electron scattering from the polarized $^3\text{He}$
12 GeV GMn experiment

Ratio of the cross sections $D(e, e' n)$ and $D(e, e' p)$

![Graph showing the ratio $G_M^n / \mu_n G_D$ vs. $Q^2$ for different experiments and models.](image)
Low Q2 form factor measurements: Measuring the Proton Radius

Different methods to measure the Proton Radius.

- Hydrogen spectroscopy (lepton-proton bound state, Atomic Physics):
  - regular hydrogen;
  - muonic hydrogen.

- Lepton-proton elastic scattering (Nuclear Physics):
  - ep- scattering;
  - µp- scattering.

- Over 60 years of experimentation!
  - started from $0.78 \times 10^{-13}$ cm (fm) (R. Hofstadter);
  - ended to 0.895 fm by 2010.

Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).
Proton Radius Puzzle (recent status)

- Regular hydrogen and electron scattering: $0.8751 \pm 0.0061$ fm (CODATA 2014)
- Muonic hydrogen spectroscopy: $0.8409 \pm 0.0004$ fm (CREMA 2010, 2013)
- New regular hydrogen spectroscopy: $0.8335 \pm 0.0095$ fm (Science 358 (6359). 2017)

- Confirmation needed from other regular hydrogen spectroscopy experiments.
- Discrepancy between ep-scattering and muonic hydrogen experiments is still there.
Experimental goals:
- reach to very low $Q^2$ range ($\sim 10^{-4}$ GeV/C$^2$)
- reach to sub-percent precision in cross section
- large $Q^2$ range in one experimental setting

Suggested solutions:
- use high resolution high acceptance calorimeter:
  - reach smaller scattering angles: ($\Theta = 0.7^0 - 7.0^0$)
  - ($Q^2 = 1 \times 10^{-4} \div 6 \times 10^{-2}$) GeV/c$^2$
  - large $Q^2$ range in one experimental setting!
  - essentially, model independent $r_p$ extraction
- Simultaneous detection of $ee \rightarrow ee$ Moller scattering
  - (best known control of systematics)
- Use high density windowless $H_2$ gas flow target:
  - beam background fully under control
  - minimize experimental background

- Two beam energies: $E_0 = 1.1$ GeV and 2.2 GeV to increase $Q^2$ range
- Will reach sub-percent precision in $r_p$ extraction
- Approved by JLab PAC39 (June, 2012) with high “A” scientific rating
<table>
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<tr>
<th>Main detector elements:</th>
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<tbody>
<tr>
<td>windowless H₂ gas flow target</td>
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<tr>
<td>PrimEx HyCal calorimeter</td>
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<tr>
<td>vacuum box with one thin window at HyCal end</td>
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<tr>
<td>X,Y – GEM detectors on front of HyCal</td>
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<table>
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<tr>
<th>Beam line equipment:</th>
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<tr>
<td>standard beam line elements (0.1 – 50 nA)</td>
</tr>
<tr>
<td>photon tagger for HyCal calibration</td>
</tr>
<tr>
<td>collimator box (6.4 mm collimator for photon beam, 12.7 mm for e⁻ beam halo “cleanup”)</td>
</tr>
<tr>
<td>Harp 2H00</td>
</tr>
<tr>
<td>pipe connecting Vacuum Window through HyCal</td>
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PRad Experimental Apparatus

PRad Setup (Side View)

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 µm)
- Improve position resolution of the setup by > 20 times
- Large improvement for Q² determination
Data Analysis – Event Selection

Event selection method

- Hit matching between GEMs and HyCal required
- Apply angle dependent energy cut based on kinematics:
  - cut size depend on local detector resolution $(4\sigma)$.
- For ee, if requiring double-arm events, apply additional cuts:
  - elasticity;
  - co-planarity;
  - vertex z.
Proton Electric Form Factor: \(G_E\) (Preliminary)

- \(G_E\) vs. \(Q^2\), from 2.2 (1.1) GeV data, \(G_M\) used from J.J Kelly, PRC 70 (2004) 068202

- \(Q^2\) range from \(6\times10^{-4}\) to \(1.5\times10^{-2}\) GeV\(^2\) shown only

- Plan to finalize cross section s for both energy runs and preliminary radius by ~ April 2018.

- Final extraction of the proton charge radius summer 2018
Conclusion

• The ground state structure studies of the nucleon provides an excellent test bed to understand non-perturbative QCD.

• Jlab 12 GeV beam combined with Super Bigbite spectrometer allows for high Q2 elastic form factor measurements with high precision.

• May pave way to answer some of the most profound questions in particle physics:
  • How does the nucleon acquire its mass: only 2% of the nucleon mass comes from Higgs.
  • How does the confinement come about?

• The novel, very low Q2 proton form factor measurement in pRad experiment will help solve the proton radius puzzle.