Hadron Form Factors
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• Introduction
• Pion Form Factor
• $G_E^p/G_M^p$ ratio
• $G_E^n$
• $G_M^n$
• Strangeness Form Factors
• Outlook
How are the Nucleons Made from Quarks and Gluons?

Why are nucleons interacting via $V_{NN}$ such a good approximation to nature?
How do we understand QCD in the confinement regime?

A) The distribution of u, d, and s quarks in the hadrons
   (spatial structure of charge and magnetization in the nucleons is an essential ingredient for conventional nuclear physics; the flavor decomposition of these form factors will provide new insights and a stringent testing ground for QCD-based theories of the nucleon)

B) The excited state structure of the hadrons

C) The spin structure of the hadrons

D) Other hadron properties
   (polarizability, quark correlations, ….)
Nucleon and Pion Form Factors

• Fundamental ingredients in “Classical” nuclear theory
• A testing ground for theories constructing nucleons from quarks and gluons.
  - spatial distribution of charge, magnetization
• Experimental insights into nucleon structure from the flavor decomposition of the nucleon form factors

\[
\begin{align*}
&G_E^p, G_E^n, G_E^{p,Z} \\
&G_M^p, G_M^n, G_M^{p,Z}
\end{align*}
\]

\[\Rightarrow\]

\[
\begin{align*}
&G_E^u, G_E^d, G_E^s \\
&G_M^u, G_M^d, G_M^s
\end{align*}
\]

• Additional insights from the measurement of the form factors of nucleons embedded in the nuclear medium
  - implications for binding, equation of state, EMC…
  - precursor to QGP
Historical Overview

Stern (1932) measured the proton magnetic moment $\mu_p = 2.79 \mu_{\text{Dirac}}$ indicating that the proton was not a point-like particle.

Hofstadter (1950's) provided the first measurement of the proton's radius through elastic electron scattering.

Subsequent data ($\leq$ 1993) were based on:
- Rosenbluth separation for proton, severely limiting the accuracy for $G_{E}^{p}$ at $Q^2 > 1 \text{ GeV}^2$

As yet, no “ab initio” calculations available, waiting for Lattice QCD.

Main interpretation based on Vector-Meson Dominance:
- In simplest form resulting in dipole form factor:

$$G_D = \left( \frac{\Lambda^2}{\Lambda^2 + Q^2} \right)^2 \quad \text{with} \quad \Lambda = 0.84 \text{ GeV}$$

Adylov et al. (1970's) provided the first measurement of the pion's radius through pion-atomic electron scattering.

Subsequent measurements at Fermilab and CERN (1980's)

“Ab initio” calculations of the pion far simpler
- In asymptotic region, $F_\pi \rightarrow 8\pi\alpha_s f_\pi^2 Q^{-2}$
Charged Pion Electromagnetic Form Factor

Potential to approach region where perturbative QCD applies

Hall C E93-021 results
Projected E01-004 and 12 GeV results
World Data in 1993
Measurement of $G_E^p/G_M^p$ to $Q^2 = 5.6 \text{ GeV}^2$ (E99-007)

Earlier nucleon form factor data used Rosenbluth separation
Leading to large systematic errors in $G_E^p$ since $G_E^p < G_M^p$ for $Q^2 > 1 \text{ (GeV/c)}^2$
Measurement of $G_E^p/G_M^p$ to $Q^2 = 5.6 \text{ GeV}^2$ (E99-007)

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Polarization observables resolve this shortcoming
f.i. by measuring recoil polarization:

$$^1\text{H}(\bar{e}, e'\bar{p})$$

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

Key is high beam current
high polarization
focal plane polarimeter
Measurement of $G_E^p/G_M^p$ to $Q^2 = 5.6$ GeV$^2$ (E99-007)

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E93-027 observed linear decrease of $G_E^p/G_M^p$
E99-007 extended the data set to 5.6 (GeV/c)$^2$ using a Pb-glass calorimeter

Linear trend is observed to continue

The data do not approach basic pQCD scaling
$F_2/F_1 \propto 1/Q^2$ (Bjørken)

Ralston et al. include quark orbital angular momentum $L_q$
$F_2/F_1 \propto 1/Q$
Measurement of $G_E^p/G_M^p$ to $Q^2 = 5.6 \text{ GeV}^2$

Hall A E93-027 and E99-007 results

$Q^2 \text{ [GeV}^2\text{]}$

$\mu_p G_E^p/G_M^p$

- E93-027
- E99-007
- SU(6) breaking + CQ FF
- SU(6) breaking
- CQM
- Soliton
- VMD
- CQM + Goldstone
Radial Charge Distribution

In Breit frame

\[ G_E^p(k^2) = \int p(r) j_0(kr)r^2 dr \quad \text{with} \quad k^2 = \frac{Q^2}{1 + \tau} \]

k first-order correction for Breit-frame transformation

• Fourier-Bessel analysis

\[ \rho(r) = \sum_{n=1}^{n_{\text{max}}} a_n j_0(k_n r) \Theta(R - r) \quad \text{with} \quad k_n = \frac{n\pi}{R} \]

Jim Kelly

Proton densities

[Jefferson Lab]

Thomas Jefferson National Accelerator Facility
Extensions

J. Arrington and R. Segel
E01-001 (Hall A)
Super Rosenbluth separation

\[ R_1 = \frac{\sigma(E_A, Q_1^2)}{\sigma(E_B, Q_1^2)} = K_1 \frac{\rho_1^2 + \varepsilon_{A1}^{-1} K Q_1^2}{\rho_1^2 + \varepsilon_{B1}^{-1} K Q_1^2} \]

with \( \rho_1 = \frac{G_E^P}{G_M^P} \)

at \( Q_1^2 = 1.9, 2.8 \) and 4.2 GeV\(^2\)
and \( Q_2^2 = 0.5 \) GeV\(^2\)

C.F. Perdrisat et al.
E01-109 (Hall C)
Use HMS (with new Focal Plane Polarimeter)
and larger Pb-glass calorimeter
$^{2\text{H}}(\vec{e},e'^{\prime}\vec{n})$
$G_n^E$ Experiment with DNP ND$_3$ Target $^2\bar{\text{H}}(\bar{e}, e'n)$
Neutron Electric Form Factor $G_E^n$

• $G_E^n$(Madey,Kowalski) – high current polarized beam, unpolarized LD$_2$ target, neutron polarimeter & neutron precession magnet.
• $G_E^n$(Day) – low intensity polarized beam ND$_3$ polarized target and neutron detector.
Neutron Electric Form Factor $G_E^n$

Hall C Experiment E93-038 (Madey, Kowalski)

- $G_E^n$ (Hall A) – polarized beam, polarized $^3$He target, and neutron detector

Pion cloud not sufficient

Relativistic effects important ingredient
Measurement of $G^n_M$ at low $Q^2$ from $^3\text{He}(\bar{e},e')$

Hall A E95-001

$Q^2=0.1,0.2 \ (\text{GeV/c})^2$
extracted from full calculation (W.Xu et al.
PRL 85, 2900 (2000))

$Q^2=0.3-0.6$ extracted from PWIA, more reliable extraction requires improved theory (in progress)
Measurement of $G^m_n$ at low $Q^2$ from $^3\text{He}(\bar{e},e')$

Hall A E95-001

$Q^2=0.1,0.2$ (GeV/c)$^2$ extracted from full calculation (W.Xu et al. PRL 85, 2900 (2000))

$Q^2=0.3-0.6$ extracted from PWIA, more reliable extraction requires improved theory (in progress)
Measurement of $G^n_M$ from CLAS

\[ \frac{^2H(e,e'n)}{^2H(e,e'p)} \Rightarrow G^n_M \]

- 6 GeV Projections
- 12 GeV Projections
Strange Quark Currents in the Nucleon $G^s_E$, $G^s_M$

Polarized Electron
Unpolarized Target

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

For a Nucleon:

$$A = \left[ \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \varepsilon G^\gamma_E G^Z_E + \tau G^\gamma_M G^Z_M (1 - 4\sin^2\theta_W) \varepsilon' G^\gamma_M G^e_A$$

\[
\varepsilon = \frac{1}{1 + 2(1 + \tau) \tan^2\theta/2} \quad \varepsilon' = [\tau (1 + \tau)(1 - \varepsilon^2)]^{-1/2}
\]

$$\tau = Q^2/4m^2$$
$Q^2$ is the four momentum transfer
$\theta$ is the laboratory electron scattering angle

forward angles
HAPPEX, Mainz, $G^s$: sensitive to $G^s_E$ and $G^s_M$

backward angles
SAMPLE, $G^s$: sensitive to $G^s_M$ and $G^e_A$

weak charge of the proton $Q^p_{\text{weak}}$
Strange Form Factors $G_E^s$ and $G_M^s$

What we have on the books now
Strange Form Factors $G_E^s$ and $G_M^s$

Expected Forward Angle Results by late 2003
Strange Form Factors $G_E^s$ and $G_M^s$

Rosenbluth separation of $G_E^s$ and $G_M^s$

Projected data indicated by open symbols are not approved yet
# High Precision Nucleon Form Factors at JLab

## $Q^2$ range

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>Planned (12 GeV)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_E^p$</td>
<td>5.6</td>
<td>9.0 (14.0)</td>
<td>Precision Measurements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Does $G_E^p/G_M^p$ keep dropping linearly?</td>
</tr>
<tr>
<td>$G_M^p$</td>
<td></td>
<td>(20.0)</td>
<td>Q$^2 &gt; 14$ makes assumptions about $G_E^p$</td>
</tr>
<tr>
<td>$G_E^n$</td>
<td>1.5</td>
<td>3.4 (5.5)</td>
<td>Precision Measurements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^3\text{He}(\bar{e}, e' n)$ for $Q^2 &gt; 1.5$</td>
</tr>
<tr>
<td>$G_M^n$</td>
<td>5.0</td>
<td>(14.0)</td>
<td>Precision Measurements</td>
</tr>
<tr>
<td>$G_E^s + \alpha G_M^s$</td>
<td>0.5</td>
<td>1.0</td>
<td>$\alpha$ small (non-0), now only at $Q^2=0.5$</td>
</tr>
<tr>
<td>$G_M^s$</td>
<td></td>
<td>0.8</td>
<td>Presently only approved at $Q^2=0.1$ and 0.8</td>
</tr>
</tbody>
</table>
Summary

- **$F^\pi$** First measurement away from $Q^2 \approx 0$
  no Q\(^{-2}\) behavior yet
- **$G_{E}^{p}$** Precise data set up to $Q^2 = 5.6$ (GeV/c\(^2\))
  charge differs from current distribution
  $Q^2 = 9$ (GeV/c\(^2\)) planned
- **$G_{E}^{n}$** 2 successful experiments, precise data anticipated
  higher $Q^2$ possible and approved
- **$G_{M}^{n}$** $Q^2 < 1$ data from $^3$He(e,e’)
  high $Q^2$ data from $^2$H(e,e’n)/$^2$H(e,e’p) anticipated
- **$G_{E}^{s}$, $G_{M}^{s}$** Happex-2, Happex-He, G0 coming up
  + Sample, Happex, Mainz
  $\Rightarrow$ Stringent constraints on strangeness contributions
  $\Rightarrow$ Enables Q-Weak Standard Model test