New Measurements of $G_{Ep}/G_{Mp}$ to High $Q^2$ at Jefferson Lab

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XIII WORKSHOP ON HIGH ENERGY SPIN PHYSICS
Dubna, Russia September 1 - 5, 2009
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Outline

Introduction

Electron-proton elastic scattering and form factors

Rosenbluth separation of $G_E^2$ and $G_M^2$

Recoil polarization in elastic $ep$

Polarization transfer measurements at Jlab, $GEp(I)$ and $GEp(II)$ experiments

$GEp(III)$ experiment, analysis and new preliminary results

Comparison of $G_{Ep}/G_{Mp}$ and $F_{2p}/F_{1p}$ to theoretical model predictions

Conclusions

(see also review in “Nucleon electromagnetic form factors”, C.F.Perdrisat, V. Punjabi and M. Vanderhaeghen, Prog. Part. Nucl. Phys. 59, 694-764, 2007)
Quantum Chromo Dynamics (QCD) is the theory of strong interaction, responsible for binding the components of nucleus and nucleons.

Key ingredient of QCD are quarks and gluons.

One of the most important objective of nuclear and particle physics is to understand the structure of the nucleon in terms of quarks and gluons and how they are confined in the nucleon.

Important step toward this goal is the characterization of the internal structure of the nucleon.

High energy electron scattering provides one of the most powerful tool to investigate the structure of the nucleon.
The static properties of the proton are well known: $M$, $S$, $\mu_p$

A spin $\frac{1}{2}$ point-like Dirac particle would have $\mu_p = \frac{e\hbar}{2mp}$

$\mu_p$ was first measured by Otto Stern in 1933. He concluded from result $\mu_p = 2.7928$ that Proton - not a point particle - Nobel prize 1943

1950–1960: Does the proton have finite size?

Earliest elastic electron scattering experiments at Stanford, under leadership of Bob Hofstadter, determined proton charge radius $\sim 0.8$ fm, close to modern value 0.895 fm

Nobel prize 1961 - R. Hofstadter

1960–1990: What is the internal structure of the proton?

Deep inelastic scattering, discover proton/quarks in 'scaling' of structure function and measure their momentum and spin distributions

Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Today: How are the nucleon’s charge & current distributions related to the quark momentum & spin distributions?
Electron - Proton Elastic Scattering

\[ j_\mu = \langle e' | \gamma_\mu | e \rangle \]

\[ p_\mu = (E_p, \mathbf{p}) \]

\[ q_\mu = (\omega, \mathbf{q}) \]

\[ k_\mu = (E_e, \mathbf{k}) \]

\[ p' \mu = (E'_p, \mathbf{p'}) \]

Nucleon vertex:

\[ \Gamma_\mu (p', p) = F_1(Q^2) \gamma_\mu + \frac{i \kappa_p}{2 M_p} F_2(Q^2) \sigma_{\mu \nu} q^\nu \]

\( F_1 \) is the helicity conserving form factor

\( F_2 \) is the helicity non-conserving form factor

Relationship to Electric, \( G_E \), and Magnetic, \( G_M \), form factors:

\[ G_E(Q^2) = F_1(Q^2) - \kappa_p \frac{Q^2}{4 M_p^2} F_2(Q^2) \]

\[ G_M(Q^2) = F_1(Q^2) + \kappa_p F_2(Q^2) \]

In Breit frame, \( G_E(Q^2) \) and \( G_M(Q^2) \) are the Fourier transforms of the charge and current distributions.
Rosenbluth separation of $G_E^2$ and $G_M^2$

Rosenbluth cross section in terms of $F_1$, $F_2$ and $G_E$, $G_M$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} \times \left\{ F_1^2(Q^2) + \kappa^2 F_2^2(Q^2) + 2\tau \left( F_1(Q^2) + \kappa F_2(Q^2) \right)^2 \tan^2 \frac{\theta_e}{2} \right\},$$

$$\frac{d\sigma}{d\Omega_{exp}} = \frac{d\sigma}{d\Omega_{mott}} \left\{ G_{Ep}^2 + \tau \left[ 1 + 2(1+\tau) \tan^2 \frac{\theta_e}{2} \right] G_{Mp}^2 \right\} \frac{1}{1+\tau}$$

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

• this form leads to the Rosenbluth separation method:

$$\sigma_R \equiv \left\{ \left( \frac{d\sigma}{d\Omega} \right)_{exp} / \left( \frac{d\sigma}{d\Omega} \right)_{mott} \right\} \frac{\varepsilon(1+\tau)}{\tau} = \frac{\varepsilon}{\tau} G_{Ep}^2 + G_{Mp}^2$$

• where $\varepsilon$ is the virtual photon polarization.
all Rosenbluth separation data

Divided by the dipole form factor $G_D = (1 - Q^2/0.71)^{-2}$
General wisdom before JLab experiments:

\[ G_{E_p} \sim \frac{1}{(1+Q^2/0.71)^2} = G_D \sim G_{M_p}/\mu_p \]
Recoil Polarization Technique (I)

Transferred polarization in Born approximation is: (Akhiezer and Rekalo)

\[ P_n = 0 \]
\[ \pm h P_t = \mp h 2 \sqrt{\tau(1 + \tau)} G_E^p G_M^p \tan \left( \frac{\theta_e}{2} \right) / I_0 \]
\[ \pm h P_l = \pm h (E_e + E_{e'}) (G_M^p)^2 \sqrt{\tau(1 + \tau)} \tan^2 \left( \frac{\theta_e}{2} \right) / M / I_0 \]

Where, \( h = |h| \) is the beam helicity

\[ I_0 = (G_E^p(Q^2))^2 + \frac{\tau}{\epsilon} (G_M^p(Q^2))^2 \]

• Measures an interference term which is absent in unpolarized ep cross section
Recoil Polarization Technique (II)

The ratio of $G_{Ep}/G_{Mp}$ is directly proportional to measured $P_t/P_l$

\[
\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l} \frac{(E_e + E_{e'})}{2M} \tan \left( \frac{\theta_e}{2} \right)
\]

- The beauty of the method is that the form factor ratio is independent of the electron polarization and of the polarimeter analyzing power

- Better sensitivity to the electric F.F. at large $Q^2$

- This technique measures the relative sign of $G_E$ and $G_M$, which is not possible for Rosenbluth separation
Focal Plane Polarimeter

$P_{t}^{fpp}$ and $P_{n}^{fpp}$ are the polarization components at the FPP

$$f^\pm(\theta, \varphi) = \frac{\varepsilon(\theta, \varphi)}{2\pi} \left( 1 \pm A_y(\theta) P_t^{fpp} \sin \varphi - A_y(\theta) P_n^{fpp} \cos \varphi \right)$$

Front Trackers  CH₂ Analyzer  Rear Trackers
φ Distribution and Physical Asymmetries

At the $Q^2$ of 5.6 GeV$^2$, Proton Momentum 3.8 GeV/c

Physical Asymmetries are obtained from the difference distributions

$$D_i = \left( f_i^+ - f_i^- \right) / 2$$

$$D_i = \frac{1}{2\pi} \left[ A_y P_t^{fpp} \sin \phi - A_y P_n^{fpp} \cos \phi \right]$$

Sum distribution give instrumental asymmetries

$$E_i = \left( f_i^+ + f_i^- \right) / 2$$

$$E_i = \frac{\varepsilon_i}{2}$$
Spin Precession

Precession angle, $\chi = \gamma \kappa_p \theta_{\text{bending}}$

$$
\begin{pmatrix}
  P_N \\
  P_T \\
  P_L
\end{pmatrix}_{\text{fp}} =
\begin{pmatrix}
  S_{n'n} & S_{n't} & S_{n'l} \\
  S_{t'n} & S_{t't} & S_{t'l} \\
  S_{\nu'n} & S_{\nu't} & S_{\nu'l}
\end{pmatrix}
\begin{pmatrix}
  P_N \\
  P_T \\
  P_L
\end{pmatrix}_{\text{tgt}}
$$

If only dipole field: $S_{t't} = 1$ and $S_{n'l} = -\sin \chi$

$S_{\nu'l} = S_{n't} = 0$

$P_{T}^{fp} = P_T$ and $P_{N}^{fp} = -P_L \sin(\chi)$
Data From GEp(I) and GEp(II) Experiments

New wisdom after JLab experiments:

\[ G_{Ep} \sim \frac{1}{(1+Q^2/0.71)^2} = G_D \sim G_{Mp}/\mu_p \]
The ratio $G_{Ep}/G_{Mp}$ was measured with the recoil polarization technique at $Q^2$ of 5.2, 6.8 and 8.54 GeV$^2$ in Hall C at JLab, between October 2007 and June 2008.

The experiment used the high momentum spectrometer (HMS) to detect proton; a new double focal plane polarimeter (FPP) in the focal plane of the HMS measured the polarization of the recoil proton.

A large area electromagnetic calorimeter (BigCal) assembled for this experiment was used to detect the elastically scattered electrons in coincidence with the protons.
GEp(III) Setup

1.87- 5.71 GeV beam
80-100 μA beam current
80-85% polarization
20cm LH₂ target
Changes in standard HMS detector package:

- Focal Plane Polarimeter with Double Analyzer: 
  \[ \rightarrow 70\% \text{ increased efficiency (30\% for FOM)} \]

- Scintillator plane S0 in front of drift chambers needed for triggering

1744 channel E.M. Calorimeter (BigCal):

- from \( \frac{6.8\%}{\sqrt{E}} \) to \( \frac{23\%}{\sqrt{E}} \) (due to radiation damage) needed for triggering

- position resolution \( \sim 5 \text{ mm} \) - most important parameter for elastic separation
$\text{CH}_2$ Analyzing Power Data

$Q^2 = 5.6 \text{ GeV}^2$

$Q^2 = 8.4 \text{ GeV}^2$

GEP-2γ

GEP-III

Proton Momentum Spectrum

\[ p(\theta_p) = \frac{2M_pE_{\text{beam}}(M_p + E_{\text{beam}}) \cos \theta_p}{M_p^2 + 2M_pE_{\text{beam}} + E_{\text{beam}}^2 \sin^2 \theta_p} \]

- Looking only at the proton, we know:
- Elastic peak is located at \( p-p(\theta_p)=0 \)
- Clearly visible at 5.2 and 6.8 GeV\(^2\)
- Barely visible at 8.5 GeV\(^2\)
- Need to look for the electron!
With significant background, kinematic correlation with electron becomes crucial.

Can achieve drastic background reduction by calculate electron impact point $(x,y)$ in BigCal from proton momentum, angle and beam energy assuming elastic $ep$, and compare with observed impact point.

Elastic Event Selection (I)

8.5 GeV$^2$
Elastic Event Selection (II)

Showing the various components of proton momentum: In black all events, in blue elastic, in red Residual background, and in green rejected events.
Physical Asymmetry at $Q^2$ of 8.5 GeV$^2$

Inelastic asymmetry has a different amplitude, and phase shift compared to elastic.

At $Q^2$ of 8.5 GeV$^2$ the “F.F. ratio” of background is large and negative.

Difficult to suppress background fraction to less than 7-8% without a significant reduction of inelastic events.

Non-negligible correction to the elastic “F.F. ratio” due to the background polarization.

Should be able to achieve small uncertainty on the correction.

Comparison of Elastic and Inelastic Asymmetries at 8.5 GeV$^2$
Preliminary results of GEp(III)

Rosenbluth separation

\[ \frac{\mu_p G_{Ep}}{G_{Mp}} \]

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

POLYNOMIAL FIT

JLab Hall A GEp(I)
JLab Hall A GEp(II)
JLab Hall C GEp(III)
VMD (dispersion relation) earliest model for nucleon e.m. Form Factors

Virtual photon couples to nucleon through exchange of a vector meson

Iachello's in 1973, first to predict zero crossing of GEp: VMD+small structure.

Early work of Höhler (DR) (76): \(\rho(770), \omega(782), \Phi(1020)\) and effective \(\rho'(1250)\)

Gary and Krumpelman (85) asympt. pQCD

Mergell, Meissner and Drechsel (96) (DR)

Lomon (01,02) used two more VMs, 11 parameters. Lomon (06) revised fit better for GEn.

Bijker and Iachello (02); now fits \(G_{En}\) data
Constituent Quark Models

Initially proposed by Isgur and Karl (78) Non-relativistic CQM. Very successful in predicting baryon spectrum.

Variety of q-q potentials (harmonic oscillator, hypercentral, linear).

RCQM: Many different approaches: light-front formalism, point form, instant form; ad hoc quark momentum wave function, or quark potential models wave function; relativistic treatment necessary:

Parameters: $m_q$, confinement scale, $\kappa_u$, $\kappa_d$. 
Proton: $F_2 / F_1$ and pQCD

Brodsky and Farrar (75):

$Q^2 F_2 / F_1$ constant

Belitsky, Ji and Yuan (03):

$Q^2 F_2 / F_1 \ln^2(Q^2/\Lambda^2)$
GPD predictions of Electromagnetic FF

The first moments of GPDs are related to the elastic FF (Ji, 97)

\[ \int_{-1}^{+1} dx \, H^q(x, \xi, Q^2) = F_1^q(Q^2), \quad \int_{-1}^{+1} dx \, E^q(x, \xi, Q^2) = F_2^q(Q^2), \]

Modified Regge Parametrization for H and E (Guidal et al., (2005))

\[ H^q(x, 0, Q^2) = q_V(x)x^{\alpha'(1-x)}Q^2, \quad E^q(x, 0, Q^2) = \frac{\kappa^q}{N^q} (1-x)^{\eta q} q_V(x)x^{\alpha'(1-x)}Q^2 \]
Transverse Charge Densities for Proton and Neutron

Charge density $\rho(b)$ of partons in the transverse plane is a two-dimensional Fourier transform of the $F_1$ form factor.

It is calculated in the infinite momentum frame, from the measured FF.

Miller, PRL 99, 112001 (2007)

$$q(x, b) = \int \frac{d^2 q}{(2\pi)^2} e^{iq\cdot b} H_q(x, t = -q^2)$$

$$\rho(b) = \sum_q e_q \int dq q(x, b) = \int \frac{d^2 q}{(2\pi)^2} F_1(Q^2 = q^2) e^{iq\cdot b}.$$
Kelly has performed simultaneous fit to all four EMFF in coordinate space using Laguerre-Gaussian expansion and first-order approximation for Lorentz contraction of local Breit frame.

Friedrich and Walcher have performed a similar analysis using a sum of dipole FF for valence quarks but neglecting the Lorentz contraction.

Both observe a structure in the proton and neutron densities at ~0.9 fm which they assign to the pion cloud.
Electric FF of the neutron

All polarization results, including new JLab Hall A, Abrahamyan et al. (2009, unpublished).

CQM from Miller, F2/F1 for modified scaling, Belitsky
VMD from Lomon
q(2q) from Cloët and Roberts (2008) (Dyson-Schwinger equation)
Magnetic FF of the neutron

BLAST preliminary results from Bates d(e,e') Kohl et al (2008)

The 12 GeV upgrade has officially started; beams of 11 GeV in Halls A, B and C; beam of 12 GeV into new Hall D, dedicated to search for exotic hadronic states. Complete shut down expected in 2011. First experiment in 2014!

Hall B upgrades to CLAS12, Hall C gets new 12 GeV/c high resolution spectrometer (SHMS).

After the 12 GeV upgrade

Approved experiment E12-09-001 in Hall C $G_{Ep}/G_{Mp}$ to 13 GeV$^2$, with SHMS, double polarimeter and calorimeter BigCal.

Approved experiment E12-07-109 in Hall A, $G_{Ep}/G_{Mp}$ to 15 GeV$^2$ with new large acceptance Super Bigbite Spectrometer (SBS), to be built with single dipole and GEM trackers.

Approved experiment E12-09 in Hall A, $G_{En}$ to 8 GeV$^2$, with SBS
$G_{Ep}/G_{Mp}$ with 12 GeV at JLab
Conclusions

Discrepancy between Rosenbluth and polarization transfer well established, not an experimental problem, caused by TPE effects or incomplete radiative corrections (next talk by Prof. Perdrisat).

**GEp(III)** experiment very successfully took data at $Q^2$ of 5.2, 6.8 and 8.45 GeV$^2$. The new data shows good agreement with the Hall A polarization data.

Many new model calculations inspired by our experimental results: VMD models give good parametrization of FF at low to intermediate $Q^2$. All constituent quark models predict decreasing ratio with increasing $Q^2$ but relativistic treatment necessary.

GPDs describe hadrons in terms of quarks and gluons: combine features of FFs and parton densities and distribution amplitudes; elastic FF provide powerful constraint on parameterizations of GPDS.

Older pQCD prediction that asymptotically $Q^2 F_2 / F_1$ becomes constant not seen. New pQCD, include logarithmic corrections in pQCD limit; Brodsky argues that $F_2$ must contain logarithmic term from higher twist contribution.

$G_{Ep}/G_{Mp}$ measurements to $Q^2 = 15$ GeV$^2$ with JLab at 12 GeV.