Strange elastic form factors from the $G^0$ experiment at Jefferson Lab and combined fits with other elastic scattering results

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Outline

- Existing evidence for strange quark matrix elements
- Electric and magnetic nucleon form factors in parity-violating, elastic electron-nucleon scattering
- The $G^0$ experiment at Jefferson Lab
- Final results from forward-scattering run
- Future plans: backward-scattering-angle running
- A global look at elastic-scattering data: how much do we know about the nucleon strange form factors?
Strange Quarks in the Nucleon

- From $\pi$–N $\sigma$ term: perhaps $>5\%$ of nucleon mass due to strange quarks
- From $\nu$–N DIS: Strange sea accounts for $\sim 10\%$ of nucleon momentum in infinite-momentum frame
  - Also some indication that strange quark/antiquark distributions may be different
- From violation of Ellis-Jaffe sum rule in spin-dependent DIS: strange quarks contribute $\sim 10\%$ to proton spin with opposite sign

Not yet explored: Charge and magnetism of nucleon due to strange quarks
- Can be studied with elastic lepton-nucleon scattering
- Strange form factors probe differences in quark-antiquark distributions
  - Electric form factor: different quark-antiquark charge distributions
  - Magnetic form factor: different momentum distributions
Form Factors in Elastic e-N Scattering

Hadronic matrix element of electromagnetic current between nucleon states with momenta $p, p'$ expressed in terms of two form factors, $F_1$ and $F_2$

$$J_{\mu}^{EM} = \bar{u}(p') \left[ \gamma_\mu F_1^{\gamma,N}(q^2) + i \frac{\sigma_{\mu\nu}q^\nu}{2M} F_2^{\gamma,N}(q^2) \right] u(p)$$

Weak neutral current similar, with additional axial form factor $G_A$

$$J_{\mu}^{NC} = \bar{u}(p') \left[ \gamma_\mu F_1^{\gamma,N}(q^2) + i \frac{\sigma_{\mu\nu}q^\nu}{2M} F_2^{\gamma,N}(q^2) + \gamma_\mu \gamma_5 G_A^{Z,N}(q^2) \right] u(p)$$

(Ignoring pseudoscalar form factor $G_p$ which does not contribute in processes discussed here)

We usually use the Sachs electric and magnetic form factors instead:

$$G_{E}^{p,n} = F_1^{p,n} - \tau F_2^{p,n}, \quad G_{M}^{p,n} = F_1^{p,n} + F_2^{p,n}, \quad \tau = \frac{Q^2}{4M^2}$$
Flavor Decomposition of Form Factors

They can be written in terms of quark form factors with relevant coupling constants

\[ G^{\gamma,p}_{E(M)} = \frac{2}{3} G^u_{E(M)} - \frac{1}{3} G^d_{E(M)} - \frac{1}{3} G^s_{E(M)} \]

\[ G^{Z,p}_{E(M)} = \left(1 - \frac{8}{3} \sin^2 \theta_W\right) G^u_{E(M)} + \left(-1 + \frac{4}{3} \sin^2 \theta_W\right) \left[G^d_{E(M)} + G^s_{E(M)}\right] \]

Similarly for the axial form factor \( G_A \) (weak current only)

Usual charge symmetry is assumed:

\[ G^{u,p}_{E(M)} = G^{d,n}_{E(M)} \equiv G^u_{E(M)}, \quad G^{d,p}_{E(M)} = G^{u,n}_{E(M)} \equiv G^d_{E(M)} \]

If \( G^s \) can be ignored, scattering from proton and neutron (e.g. deuteron) enough to determine form factors for up and down quarks

\( Z^0 \) exchange provides a third equation for determining \( G^s \)
Strange Form Factors

Eliminate $G^u$, $G^d$ in favor of measured EM form factors $G^{\gamma p}$, $G^{\gamma n}$

$$G^u_{E(M)} = 2G^{\gamma p}_{E(M)} + G^{\gamma n}_{E(M)} + G^s_{E(M)}$$

and

$$G^d_{E(M)} = G^{\gamma p}_{E(M)} + 2G^{\gamma n}_{E(M)} + G^s_{E(M)}$$

Then a measurement of neutral-current form factors allows to extract $G^s$

Electroweak processes are parity-violating

- Allows measurements of quantities other than cross sections
**P-Violating Elastic e-N Scattering**

Polarized electron beam, unpolarized hydrogen target

Parity-violating asymmetries $\sim 10^{-6}$ due to electroweak interference:

Difference in cross sections for left- and right-handed electrons

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

$$A_{LR} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\varepsilon G^\gamma, N_E G^Z, N_E + \tau G^\gamma, N_M G^Z, N_M}{\varepsilon (G^\gamma, N_E)^2 + \tau (G^\gamma, N_M)^2} - (1 - 4 \sin^2 \theta_W) \varepsilon' G^\gamma, N_M G^e_A$$

- Axial form factor $G^s_A$ is suppressed by factor $(1 - \sin^2 \theta_W) \sim 0.08$
- Separation of $G^s_E$, $G^s_M$ requires measurements at different angles
- Determination of $G^e_A$ requires measurements with deuterium
The $G^0$ Collaboration


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**Experiment Overview**

- **Measure** $G^Z_E$, $G^Z_M$
  - Different linear combinations of $u$, $d$ and $s$ contributions than E.M. form factors
  -> Strange quark contributions to sea
- **Measure forward and backward asymmetries**
  - Recoil protons for forward measurement
  - Electrons for backward measurements
    - Elastic/inelastic for $^1$H, elastic for $^2$H
- **Forward measurements** complete (101 Coulombs)

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**Beam Parameters**

- $E_{\text{beam}} = 3.03$ GeV, 0.33 - 0.93 GeV
- $I_{\text{beam}} = 40$ µA, 80 µA
- $P_{\text{beam}} = 75\%, 80\%$
- $\theta = 52^\circ - 76^\circ$, $104^\circ - 116^\circ$
- $\Delta \Omega = 0.9$ sr, 0.5 sr
- $l_{\text{target}} = 20$ cm
- $L = 2.1$, $4.2 \times 10^{38}$ cm$^{-2}$ s$^{-1}$
- $A \sim -1$ to $-50$ ppm, $-12$ to $-70$ ppm
Spectrometer Optics

- Zero magnification along beam axis
- Elastic protons dispersed in $Q^2$ along focal surface

- Acceptance $0.12 < Q^2 < 1.0 \text{ GeV}^2$ for 3 GeV incident beam

- Detector 15 acceptance: $0.44 - 0.88 \text{ GeV}^2$
  - 3 $Q^2$ bins at 0.51, 0.63 and 0.78 GeV$^2$
- Detector 14: $Q^2 = 0.41, 1.0 \text{ GeV}^2$
- Detector 16: no elastic acceptance
  - important for measuring backgrounds
Detectors

- 16 detectors per octant
- Arc shape (const. $Q^2$), protons at normal incidence
- Each detector: scintillator pair
  - BC408: 0.5, 1.0 cm thick
  - 1/8 in. shielding in-between
- PMT at each end of each scintillator
  - XP2262B (NA), XP2282B (Fr)
- Signal: mean-time-front .AND. mean-time-back
- Assembled with ~ 2 mm accuracy
- Octants in light-tight enclosures
- 20 cm LH$_2$, aluminum target cell
- Longitudinal flow, v $\sim$ 8 m/s, P $>$ 1000 W!
- Negligible density change < 1.5%
- Measured small boiling contribution
  - 260 ppm/1200 ppm statistical width
Beam Polarization

- Beam polarization measured with interleaved Møller measurements
  - std Hall C polarimeter
    - (M. Hauger, et al. NIM A462 (2001) 382.)
  - apply for groups of runs as shown
  - average: \( P = 73.7\% \)

<table>
<thead>
<tr>
<th>Source</th>
<th>Rel. uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>0.42</td>
</tr>
<tr>
<td>Leakage</td>
<td>0.2</td>
</tr>
<tr>
<td>Current extrap’n</td>
<td>1</td>
</tr>
<tr>
<td>Beam</td>
<td>0.52</td>
</tr>
<tr>
<td>Levchuk</td>
<td>0.3</td>
</tr>
<tr>
<td>Detection</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.32</strong></td>
</tr>
</tbody>
</table>
Timing

Special beam structure (32 ns rep rate) allows use of time-of-flight

32 ns

Accelerator pulse structure

Beam Helicity

+1

-1

Measurement timing

“Typical” ToF spectrum

“Quartet”
Helicity + − − + or − + + − (random)

“Macropulse”

1/30 s

~500 µs

“Typetie”

ON

OFF

DAQ

“Typetie” ToF spectrum

Measurement timing
Analysis Overview

- Blinding Factor
- Raw Asymmetries, $A_{\text{meas}}$
  
  "Beam" corrections:
  - Leakage beam asymmetry
  - Helicity-correlated beam properties
  - Deadtime
  - Beam polarization
  
  Background correction

  Unblinding $A_{\text{phys}}$

  $Q^2$

  Elastic form factors

  $G_E^s + \eta G_M^s$
Background Corrections

- Fit yields and asymmetries for ToF spectrum
- Correct asymmetry: \( A_{\text{meas}} = (1-f)A_{\text{el}} + fA_{\text{back}} \)
- Vary shapes to estimate uncertainties
- Detector 16 only background, no elastic peak
- For detector 15 use interpolation (1-14,16)

Background asymmetries understood from GEANT simulation: protons from weak decays of \( \Lambda, \Sigma \)

- Measured asymmetry used in correction, not from simulation
- Corrections can be large (for \( Q^2 > 0.3 \ \text{GeV}^2 \))
Forward Run Data Summary

• 101 Coulombs of parity-quality beam
  - cuts on helicity-correlated beam parameter are
    4 x std. dev. for given run:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartet charge asymmetry</td>
<td>600 ppm</td>
</tr>
<tr>
<td>$x, y$ position differences</td>
<td>8, 10 µm</td>
</tr>
<tr>
<td>$x, y$ angle difference</td>
<td>0.6, 1.1 µrad</td>
</tr>
<tr>
<td>energy difference</td>
<td>7.5 keV</td>
</tr>
</tbody>
</table>

• Includes running with both Hall A and Hall B (leakage beam asymmetry measured satisfactorily)

• Corresponds to: 701 h at 40 µA
  19 x $10^6$ quartets
  76 x $10^6$ MPS
Asymmetry with EW Radiative Corrections

- Full form of asymmetry used to extract $G_E^\xi + \eta G_M^s$

$$A = -\frac{G_F Q^2}{4 \pi\alpha \sqrt{2}} \frac{1}{\epsilon G_E^p + \tau G_M^p} \left[ (1 - 4 \sin^2 \theta_W) \left( \epsilon G_E^p + \tau G_M^p \right) (1 + R_V^p) - (\epsilon G_E^n G_M^n) (1 + R_V^n) \right.$$

$$\left. \left( \epsilon G_E^p G_M^n + \tau G_M^p G_M^n \right) (1 + R_V^n) - \left( \epsilon G_E^p G_E^s + \tau G_M^p G_M^s \right) (1 + R_V^0) - \epsilon' \left( 1 - 4 \sin^2 \theta_W \right) G_M^p G_A^e \right]$$

where

$$G_A^e = -G_A^p \left( 1 + R_A^{T=1} \right) + \left[ \frac{1}{2} (3F - D) R_A^{T=0} + \Delta s \left( 1 + R_A^{(0)} \right) \right] G_A^{dip}$$

and

$$G_A^p = g_A G_A^{dip} = (F + D) G_A^{dip} = \frac{g_A}{\left( 1 + Q^2 / \Lambda_A^2 \right)^2}$$
Strange Quark Contribution to Asymmetry

“No Vector Strange” Asymmetry: Set $G_E^s = G_M^s = 0$

$$G_E^s + \eta G_M^s = \frac{4 \pi \alpha \sqrt{2}}{G_F Q^2} \frac{\varepsilon G_E^p + \tau G_M^p}{\varepsilon G_E^p \left(1 + R_V(0)\right)} \left(A_{phys} - A_{NVS}\right)$$

$$\eta(Q^2, E_i) = \frac{\tau G_M^p}{\varepsilon G_E^p}$$
**Experimental Asymmetries**

- “No vector strange” asymmetry, $A_{\text{NVS}}$, is $A(G_E^s, G_M^s = 0)$
- Inside error bars: stat, outside: stat & pt-pt
Strange Quark Contribution

From difference between measured $A_{\text{phys}}$ and calculated $A_{\text{NVS}}$

$G_E^s + \eta G_M^s$

$Q^2 (\text{GeV}^2)$

$G_E^s = G_M^s = 0$ excluded to 89% CL
Speculation on Individual Form Factors

Separation of electric and magnetic form factors requires measurements at backward angles for same $Q^2$ values (“Rosenbluth separation”)

- Backward runs coming this spring and fall
- Meanwhile, attempt global fit to world hydrogen data with simple forms

\[
G_E^s(Q^2) = \frac{c_2 Q^4}{1 + d_1 Q^2 + d_2 Q^4 + d_3 Q^6}
\]

\[
G_M^s(Q^2) = \frac{G_M^s(Q^2 = 0)}{\left(1 + Q^2/\Lambda_M^s\right)^2}
\]

\[
\chi^2 = \frac{31}{20}
\]
Fit to World Hydrogen Data

c_2 = -0.51 \pm 0.25

d_1 = -8.5 \pm 0.9

d_2 = 24 \pm 6

d_3 = 1

\Lambda_M^2 = \Lambda^2 / 1.3

Remember the factor of -1/3
Separation of $G^S_E$ and $G^S_M$

World Data @ $Q^2 = 0.1 \ (\text{GeV/c})^2$

$G^S_E(0.1) = -0.013 \pm 0.028$

$G^S_M(0.1) = +0.62 \pm 0.31$

$\mu_S$ contributes at the level of 10% in $\mu_p$

(factor 1/3 for s quarks)
$G^0$ Forward Run Summary

- First measurement of parity-violating asymmetries over broad $Q^2$ range: D.S. Armstrong et al., PRL 95, 092001 (2005)
- Excellent performance of accelerator, experimental equipment
- Conservative estimates of uncertainties
  - careful assessment of backgrounds

- Results consistent with previous measurements
- Emerging picture

- $G^s_M > 0$ at low $Q^2$
- $G^s_E < 0$ at medium $Q^2$ a possibility
- $G^s_E + \eta G^s_M$ positive at higher $Q^2$
Current and Future $G^0$ Runs

- Spectrometer turned around to measure backward-angle scattering
  - Two different beam energies for two $Q^2$ points
    - $0.8 \text{ GeV}^2/c^2$ and either 0.23 or 0.48 GeV$^2/c^2$
  - Electrons detected rather than protons
  - Added Cerenkov detector for pion background suppression
  - Data taking now and in late 2006
- Hope to run with deuterium target to measure $G^e_A$
  - Contains $G^s_A$, related to net strange-quark helicity $\Delta s$ in DIS
- Ultimate goal: complete separation of $G^s_E$, $G^s_M$, $G^e_A$ at four $Q^2$ values
  - 0.1, 0.23, 0.48, and 0.8 GeV$^2/c^2$
**Combined Fit with Neutrino Data**

- Idea: Combine elastic $ep$ and $\nu p$ data to extract axial form factors
  - *Method described in S. Pate, PRL 93, 082002 (2004)*
- Elastic $ep$ data from $G^0$, HAPPEX, SAMPLE, and PVA4
- Elastic $\nu p$ data from BNL experiment E734
  - Results presented at *JPARK Workshop on Hadron Structure, KEK, Tsukuba, December 2005* (S. Pate)
- Extract strange axial form factor, related to strange-quark contribution to proton spin $\Delta s$
  
  \[
  \Delta s = G_A^s (Q^2 = 0) = \int_0^1 \Delta s(x, Q^2 = \infty) dx
  \]

  - Polarized DIS data hint at non-zero, negative $\Delta s$
  - To explain violation of Ellis-Jaffe sum rule
Elastic $\nu p$ Cross Section

Elastic $\nu p$ scattering dominated by axial form factors at low $Q^2$

$$
\frac{d\sigma}{dQ^2}(\nu p \rightarrow \nu p) \propto \frac{G_F^2 M_p^2}{128\pi E_\nu^2} \left[ \left( -G_A^u + G_A^d + G_A^s \right)^2 + \left( 1 - 4\sin^2\theta_W \right)^2 \right]
$$

In terms of measured form factors

$$
\frac{d\sigma}{dQ^2}(\nu p \rightarrow \nu p) = \frac{G_F^2 Q^2}{2\pi E_\nu^2} \left( A \pm BW + CW^2 \right)
$$

with

$$
W = 4 \left( E_\nu / M_p - \tau \right) \quad \tau = Q^2 / 4M_p^2
$$

$$
A = \frac{1}{4} \left[ \left( G_A^Z \right)^2 (1 + \tau) - \left( F_1^Z \right)^2 - \tau \left( F_2^Z \right)^2 \right] \left( 1 - \tau \right) + 4\tau F_1^Z F_2^Z
$$

$$
B = -\frac{1}{4} G_A^Z \left( F_1^Z + F_2^Z \right)
$$

$$
C = \frac{1}{64\tau} \left[ \left( G_A^Z \right)^2 + \left( F_1^Z \right)^2 + \tau \left( F_2^Z \right)^2 \right]
$$

Dependence on strange form factors is buried in the weak ($Z$) form factors.
Extraction of Axial Form Factors

Consistent with negative $\Delta s$

- **G0 & E734**
  [to be published]

- **HAPPEx & E734**
  [Pate, PRL 92 (2004) 082002]

- **G0 Projected**

- **HAPPEx, SAMPLE & PVA4 combined**
  (nucl-ex/0506011)

First determination of the strange axial form factor.
Conclusions

● The proton is stranger than you may think

● Strange matrix elements show contributions beyond what one might expect from perturbative generation of strange sea (not expected to affect quantum numbers other than mass, or momentum)

  – Electric and magnetic properties indicate different strange quark-antiquark distributions

  ● Also hints by neutrino DIS data

  – Strange quarks may contribute net spin to nucleon