Strangeness in the Proportion:
Strangeness in the Nucleon probed via Parity-Violating Electron Scattering

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GO and HAPPEx Collaborations

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Outline

• Parity violation in electron scattering
• Vector Strange Form Factors: $G_E^s$ and $G_M^s$
• World Experimental Effort

• Recent Results from PV-A4, G0 at backward angles:
  - Separated form factors at $Q^2 = 0.23, 0.63 \text{(GeV/c)}^2$

• Implications & Conclusions

“There is no excellent beauty that hath not some strangeness in the proportion”
Francis Bacon  1561-1626
Strangeness in the nucleon

Goal: Determine the contributions of the strange quark sea \((s\bar{s})\) to the charge and magnetization distributions in the nucleon.

Vector “strange form factors”: \(G^s_E\) and \(G^s_M\)

\[
P = uuud + u\bar{u} + d\bar{d} + s\bar{s} + g + \ldots\
\]

• \(s\) quark: clean candidate to study the sea

• How much do virtual \(s\bar{s}\) pairs contribute to the structure of the nucleon?
  - Momentum: 4\% (DIS)
  - Spin: 0 to -10\% (polarized DIS)
  - Mass: 0 to 30\% (\(\pi N\)-sigma term)*

(update: see Tony Thomas’ talk...)

*also: OZI violations in \(p\bar{p} \rightarrow \frac{\phi\gamma}{\omega\gamma}\)
Parity Violating Electron Scattering
Weak NC Amplitudes

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible

Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2\text{Re}(M^{EM*}M^{NC})$

$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M^{NC}_{PV}|}{|M^{EM}|} \sim \frac{Q^2}{(M_Z)^2}$

Small (~$10^{-6}$) cross section asymmetry isolates weak interaction
Nucleon Form Factors

Adopt Sachs FF:

\[ G_E^\gamma = F_1^\gamma + \tau F_2^\gamma \quad G_M^\gamma = F_1^\gamma + F_2^\gamma \]

(Roughly: Fourier transforms of charge and magnetization)

NC and EM probe same hadronic flavor structure, with different couplings:

\[ G_{E/M}^\gamma = \frac{2}{3} G_{E/M}^u - \frac{1}{3} G_{E/M}^d - \frac{1}{3} G_{E/M}^s \]

\[ G_{E/M}^Z = \left(1 - \frac{8}{3} \sin^2 \theta_W\right) G_{E/M}^u - \left(1 - \frac{4}{3} \sin^2 \theta_W\right) G_{E/M}^d - \left(1 - \frac{4}{3} \sin^2 \theta_W\right) G_{E/M}^s \]

\[ G_{E/M}^Z \] provide an important benchmark for testing non-perturbative QCD structure of the nucleon
Charge Symmetry

One expects the neutron is \(\approx\) an isospin rotation of the proton\(^*\):

\[
G_{E/M}^{p,u} = G_{E/M}^{n,d}, \quad G_{E/M}^{p,d} = G_{E/M}^{n,u}, \quad G_{E/M}^{p,s} = G_{E/M}^{n,s}
\]

\[
G_{E/M}^{\gamma,p} = \frac{2}{3} G_{E/M}^{u} - \frac{1}{3} G_{E/M}^{d} - \frac{1}{3} G_{E/M}^{s} \quad \rightarrow \quad G_{E/M}^{\gamma,n} = \frac{2}{3} G_{E/M}^{d} - \frac{1}{3} G_{E/M}^{u} - \frac{1}{3} G_{E/M}^{s}
\]

\[
\begin{vmatrix}
G_{E,M}^{\gamma,p} \\
G_{E,M}^{\gamma,n} \\
G_{E,M}^{Z,p}
\end{vmatrix}
\begin{align*}
\text{Charge} \\
\text{symmetry}
\end{align*}

\begin{vmatrix}
G_{E,M}^{u} \\
G_{E,M}^{d} \\
G_{E,M}^{s}
\end{vmatrix}
\begin{align*}
\text{Shuffle}
\end{align*}

\begin{vmatrix}
G_{E,M}^{p} \\
G_{E,M}^{n} \\
G_{E,M}^{s}
\end{vmatrix}

\[\langle N | s_{\gamma}^{\mu} s | N \rangle\]

\[
A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_{\gamma}}{\left| M_{\gamma} \right|^2} = -\frac{G_F Q^2}{\sqrt{2\pi \alpha}} F\left(G_{E/M}^{p}, G_{E/M}^{n}, G_{E/M}^{s}, G_A\right)
\]

Isolating individual form factors:

**vary kinematics or target**

For a proton:

\[
A = \left[ -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \frac{A_E + A_M + A_A}{\sigma_p} \quad \sim \text{few parts per million}
\]

\[
A_E = \varepsilon G_E^p G_E^Z, \quad A_M = \tau G_M^p G_M^Z, \quad A_A = -(1 - 4\sin^2 \theta_W) \varepsilon G_M^p G_A^e
\]

Forward angle: \( G_{E,M}^Z = (1 - 4\sin^2 \theta_W)(1 + R_V^p)G_{E,M}^p - (1 + R_V^n)G_{E,M}^n - G_{E,M}^s \)

Backward angle: \( G_A^e = -\tau_3 (1 + R_{A}^{T=1})G_A + \sqrt{3} R_{A}^{T=0} G_A + \Delta s \)

For \(^4\text{He}: G_E^s \text{ alone}\)

\[
A_{PV} = \frac{G_F Q^2}{\pi\alpha\sqrt{2}} \left[ \sin^2 \theta_W + \frac{G_E^s}{2(G_E^p + G_E^n)} \right]
\]

For deuteron:

For enhanced \( G_A^e \) sensitivity

\[
A_d = \frac{\sigma_p A_p + \sigma_n A_n}{\sigma_d}
\]
Theoretical Approaches to Strange Form Factors

Models - a non-exhaustive list:

kaon loops, vector dominance, Skyrme model, chiral quark model, dispersion relations, NJL model, quark-meson coupling model, chiral bag model, HBChPT, chiral hyperbag, QCD equalities, ...

- no consensus on magnitudes or even signs of $G_E^s$ and $G_M^s$!

Only model-independent statement: $G_E^s(Q^2=0)=0$

A challenging problem in non-perturbative QCD

What about QCD on the lattice?

- Dong, Liu, Williams PRD 58(1998)074504
- Doi, et al. (2009) arXiv:0903.3232 - and see talk CF-3...

Disconnected insertions - technically challenging
Strangeness Models

(as/of circa 2005)

note: caveats...
What would non-zero $G^s_E$ and $G^s_M$ imply?

$G^s_E \neq 0 \quad \Rightarrow \quad s$ and $\bar{s}$ have different spatial distributions in proton

$G^s_M \neq 0 \quad \Rightarrow \quad s$ and $\bar{s}$ have different magnetization distributions in proton

$\rightarrow \text{contribute to magnetic moment, etc.}$

Kaon = us

proton

Hyperon = uds

(probe model for illustration)
The Axial Current Contribution

- Recall:

\[ A^{PV} \propto \frac{A_E + A_M + A_A}{2\sigma_{unp}} \]

\[ A_E = \varepsilon(\theta) G_E^Z G_E^Z, \quad A_M = \tau G_M^Z G_M^Z \]

\[ A_A = -(1 - 4 \sin^2 \theta_W) \varepsilon'(\theta) G_M^\gamma G_M^\gamma \]

\[ G_A^e = -\tau_3 (1 + R_A^{T=1}) G_A + \sqrt{3} R_A^{T=0} G_A^8 + \Delta s \]

- Effective axial form factor: \( G_A^e(Q^2) \)
- related to form factor measured in \( \nu \) scattering
- also contains “anapole” form factor
- determine isovector piece by combining proton and neutron (deuteron) measurements
Measurement of P-V Asymmetries

\[ A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-6} \]

- e.g. 5% Statistical Precision on 1 ppm
- \( \rightarrow \) requires \( 4 \times 10^{14} \) counts

**Rapid Helicity Flip:** Measure the asymmetry at \( 10^{-4} \) level, 10 million times

\[ A_{LR} = \frac{N_R - N_L}{N_R + N_L} \]

- High luminosity: thick targets, high beam current
- Control noise (target, electronics)
- High beam polarization and rapid flip

**Statistics:** high rate, low noise

**Systematics:** beam asymmetries, backgrounds, helicity-correlated pickup

**Normalization:** Polarization, linearity, dilution
### Parity-Violating Electron Scattering Program

<table>
<thead>
<tr>
<th>Expt/Lab</th>
<th>Target/ Angle</th>
<th>Q$^2$ (GeV$^2$)</th>
<th>$A_{phys}$ (ppm)</th>
<th>Sensitivity</th>
<th>Status</th>
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<tbody>
<tr>
<td>SAMPLE/Bates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAMPLE I</td>
<td>LH$_2$/145</td>
<td>0.1</td>
<td>-6</td>
<td>$G_M + 0.4G_A$</td>
<td>2000</td>
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<tr>
<td>SAMPLE II</td>
<td>LD$_2$/145</td>
<td>0.1</td>
<td>-8</td>
<td>$G_M + 2G_A$</td>
<td>2004</td>
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<tr>
<td>SAMPLE III</td>
<td>LD$_2$/145</td>
<td>0.04</td>
<td>-4</td>
<td>$G_M + 3G_A$</td>
<td>2004</td>
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<tr>
<td>HAPPEx/JLab</td>
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<tr>
<td>HAPPEx</td>
<td>LH$_2$/12.5</td>
<td>0.47</td>
<td>-15</td>
<td>$G_E + 0.39G_M$</td>
<td>1999</td>
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<tr>
<td>HAPPEx II</td>
<td>LH$_2$/6</td>
<td>0.11</td>
<td>-1.6</td>
<td>$G_E + 0.1G_M$</td>
<td>2006, 2007</td>
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<tr>
<td>HAPPEx He</td>
<td>$^4$He/6</td>
<td>0.11</td>
<td>+6</td>
<td>$G_E$</td>
<td>2006, 2007</td>
</tr>
<tr>
<td>HAPPEx III</td>
<td>LH$_2$/14</td>
<td>0.63</td>
<td>-24</td>
<td>$G_E + 0.5G_M$</td>
<td>(2009)</td>
</tr>
<tr>
<td>PV-A4/Mainz</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>LH$_2$/35</td>
<td>0.23</td>
<td>-5</td>
<td>$G_E + 0.2G_M$</td>
<td>2004</td>
</tr>
<tr>
<td></td>
<td>LH$_2$/35</td>
<td>0.11</td>
<td>-1.4</td>
<td>$G_E + 0.1G_M$</td>
<td>2005</td>
</tr>
<tr>
<td></td>
<td>LH$_2$/145</td>
<td>0.23</td>
<td>-17</td>
<td>$G_E + \eta G_M + \eta'G_A$</td>
<td>2009</td>
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<td></td>
<td>LH$_2$/35</td>
<td>0.63</td>
<td>-28</td>
<td>$G_E + 0.64G_M$</td>
<td>(2009)</td>
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<tr>
<td>G0/JLab</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Forward</td>
<td>LH$_2$/35</td>
<td>0.1 to 1</td>
<td>-1 to -40</td>
<td>$G_E + \eta G_M$</td>
<td>2005</td>
</tr>
<tr>
<td>Backward</td>
<td>LH$_2$/LD$_2$/110</td>
<td>0.23, 0.63</td>
<td>-12 to -45</td>
<td>$G_E + \eta G_M + \eta'G_A$</td>
<td>2009</td>
</tr>
</tbody>
</table>
HAPPEX-I  Jlab/Hall-A

Hydrogen Target:  $E=3.3\ \text{GeV} \ \theta=12.5^\circ \ \mathcal{Q}^2=0.48\ (\text{GeV}/c)^2$

$A^{PV} = -14.92\ \text{ppm} \pm 0.98\ (\text{stat})\ \text{ppm} \pm 0.56\ (\text{syst})\ \text{ppm}$

$G^{s}_{E} + 0.39G^{s}_{M} = 0.014 \pm 0.020\ (\text{exp}) \pm 0.010\ (\text{FF})$

*Phys. Rev. Lett. 82, 1096 (1999)*;
*Phys. Rev. C 69, 065501 (2004)*
Backward angle ($\theta=150^\circ$), integrating

<table>
<thead>
<tr>
<th>$Q^2$ (GeV$^2$)</th>
<th>$A_{PV}$ (ppm)</th>
<th>$A_0 + \alpha G^s_M + \beta G^e_A (T=1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1, $LH_2$</td>
<td>$-5.61 \pm 0.67 \pm 0.88$</td>
<td>$-5.56 + 3.37 G^s_M + 1.54 G^e_A$</td>
</tr>
<tr>
<td>0.1, $LD_2$</td>
<td>$-7.06 \pm 0.73 \pm 0.72$</td>
<td>$-7.06 + 0.72 G^s_M + 1.66 G^e_A$</td>
</tr>
<tr>
<td>0.03, $LD_2$</td>
<td>$-3.51 \pm 0.57 \pm 0.58$</td>
<td>$-2.14 + 0.27 G^s_M + 0.76 G^e_A$</td>
</tr>
</tbody>
</table>

Results of Zhu et al. commonly used to constrain $G^s_M$ result:

\[ G^s_M = 0.37 \pm 0.20^{\text{Stat}} \pm 0.36^{\text{Syst}} \pm 0.07^{\text{FF}} \]
HAPPEX-II

$E=3 \text{ GeV} \quad \theta=6^\circ \quad Q^2=0.1 \ (\text{GeV}/c)^2$

- Hydrogen: $G_E^s + \eta G_M^s$
- $^4$He: Pure $G_E^s$

\[ A^{PV} = -\frac{A_0}{2} \left( 2 \sin^2 \theta_W + \frac{G_E^s}{G_E^{p\gamma} + G_E^{n\gamma}} \right) \]

2 runs: 2004 & 2005

World Data near $Q^2 \sim 0.1 \text{ GeV}^2$

\[ G_M^s = 0.28 \pm 0.20 \]

21\% of $\mu_T^{N}$

\[ \langle r^2 \rangle_P^E = 0.766 \pm 0.012 f \, \hat{m} \]

\[ \langle r^2 \rangle_S^E = 0.002 \pm 0.015 f \, \hat{m} \]
Summary of data at $Q^2 = 0.1$ GeV$^2$

Solid ellipse:
K. Paschke, priv. comm.
[$\approx$ J. Liu et al.
PRC 76, 025202 (2007)]
uses theoretical constraints
on the axial form factor

Dashed ellipse:
R.D. Young et al.
PRL 97 (2006) 102002,
does not constrain $G_A$
with theory

% contrib = $\frac{G_{E,M}^s}{G_{E,M}^p} \times \left( -\frac{1}{3} \right) \times 100$

Note: Placement of SAMPLE band
on depends on choice for $G_A$

(figure: thanks to K. Paschke, R. Young)
Theoretical Refinements

   \( \gamma Z \) box dominates the two boson effects at HAPPex, PVA4 kinematics
   \rightarrow \text{reduces extracted } G^s_E + \beta G^s_M
   (not yet put into global fits)

2. Charge-symmetry breaking effects:

   \(^4\text{He: Viviani, Schiavilla, Kubis, Lewis, et al.}\)

   still only a (modest) fraction of smallest experimental statistical errors.
   (not yet put into global fits)
**PV-A4 (MAMI/Mainz)**

<table>
<thead>
<tr>
<th>$Q^2$ (GeV$^2$)</th>
<th>$A \pm \text{stat} \pm \text{syst}$ (ppm)</th>
<th>$G_E^s + \eta G_M^s$</th>
</tr>
</thead>
</table>
| 0.230           | $-5.44 \pm 0.54 \pm 0.26$       | $G_E^s + 0.225 G_M^s$  
|                 |                                 | $= 0.039 \pm 0.034$ |
| 0.110           | $-1.36 \pm 0.29 \pm 0.13$       | $G_E^s + 0.106 G_M^s$  
|                 |                                 | $= 0.071 \pm 0.036$ |

"Evidence for Strange Quark Contributions to the Nucleon's Form Factors at $Q^2 = 0.1$ GeV$^2$"  
New results from PV-A4  
(MAMI/Mainz)

$\Theta = 145^\circ$

$Q^2 = 0.22 \text{ (GeV/c)}^2$

$A_{\text{meas}} = -17.23 \pm 0.82 \pm 0.89 \text{ ppm}$

$G^{s_E} = 0.050 \pm 0.038 \pm 0.019$

$G^{s_M} = -0.14 \pm 0.11 \pm 0.11$

(Use theoretical constraint of Zhu et al., for the axial FF)

% contribution to proton:

electrical: $3.0 \pm 2.5 \%$

magnetic: $2.9 \pm 3.2 \%$

S. Baunack et al., PRL 102 (2009) 151803

Deuterium results at same $Q^2$ - still being analyzed....
\( G^0 \) (JLab - Hall C)

- Superconducting toroidal magnetic spectrometer

Forward angle mode
- LH\(_2\): \( E_e = 3.0 \text{ GeV} \)
  - Recoil proton detection
  \( \Rightarrow \) \( 0.12 \leq Q^2 \leq 1.0 \) (GeV/c\(^2\))
- Counting experiment – separate backgrounds via time-of-flight

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    height=5cm,
    width=8cm,
    xtick={0, 8, 16, 24, 32},
    xticklabels={0, 8, 16, 24, 32},
    ytick={0, 2, 4, 6, 8, 10},
    yticklabels={0, 2, 4, 6, 8},
    xlabel={Time-of-flight (ns)},
    ylabel={Yield (kHz/μA/ns)}
]
\addplot [fill=yellow!50] table [y index=0] {data.csv};
\addlegendentry{Pions}
\addlegendentry{Inelastic protons}
\addlegendentry{Elastic cut}
\end{axis}
\end{tikzpicture}
\end{center}
Hypothesis excluded at 89% C.L.

\[ G_E^S = G_M^S = 0 \]

Hypothesis excluded at 89% C.L.

D.S. Armstrong et al., PRL 95, 092001 (2005)
Polarized electron beam at 362, 687 MeV
Target: 20 cm LH$_2$, LD$_2$
(q)elastic, inelastic scattering at ~108°
Electron/pion separation using aerogel Cerenkov
**GO Asymmetries**  
(*backward angle measurements*)

<table>
<thead>
<tr>
<th>Set</th>
<th>Asymmetries (ppm)</th>
<th>Stat (ppm)</th>
<th>Sys pt (ppm)</th>
<th>Sys Global (ppm)</th>
<th>Total (ppm)</th>
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<tbody>
<tr>
<td>H 362</td>
<td>-11.416</td>
<td>0.872</td>
<td>0.268</td>
<td>0.385</td>
<td>0.990</td>
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<tr>
<td>D 362</td>
<td>-17.018</td>
<td>0.813</td>
<td>0.411</td>
<td>0.197</td>
<td>0.932</td>
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<td>H 687</td>
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<td>2.43</td>
<td>0.84</td>
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<tr>
<td>D 687</td>
<td>-55.87</td>
<td>3.34</td>
<td>1.98</td>
<td>0.64</td>
<td>3.92</td>
</tr>
</tbody>
</table>

See Fatiha Benmokhtar's talk: CF-4
Forward Angle Results - reminder
GO Backward Angle Results

Combined with interpolation of GO forward measurements

assumes:

\[ G_{A,NS}^{T=0}(Q^2) = R_A^{T=0} \frac{3F - D}{2} G_A^{dipole}(Q^2) \]

\[ G_{A,NS}^{T=0}(Q^2 = 0) = 0.070 \]

Also assumes: no CSV

\[ \text{Global systematic} \]

D. Androic et al. arXiv:0909.5107
Contributions to Overall Form Factors
Advertisement: other physics from G0

- First measurement of neutral current $N\Delta$ transition around $Q^2 = 0.3 \, \text{GeV}^2$
  (See Carissa Capuano’s talk BD-9, Wed. evening)

- First measurement of PV asymmetry in inclusive $\pi^-$ production at low $Q^2$
  (related to anomalous $\Delta S = 1$ hyperon decays)

- Two-photon exchange seen via beam-normal single spin asymmetries
  (See Juliette Mammei’s talk BF-6, Wed. evening)
A higher precision repeat of HAPPEX-I, at slightly higher $Q^2$
(0.63 GeV$^2$ - matches G0 backward data point)
- 100 $\mu$A beam current, 89% polarization (c.f. 35 $\mu$A at 70% polarization for HAPPEX-I)
- If central value from G0 holds, could see $\approx 5\sigma$ non-zero strange quark signal.

PV-A4 also now taking data at $\approx$ same $Q^2$
Summary

• Comparison of electromagnetic and weak neutral elastic form factors allows determination of strange quark contribution
  - large distance scale dynamics of the sea
• Separated form factors at three $Q^2$
• Small positive $G^s_E$ at highest $Q^2$, $G^s_M$ consistent with zero, small quenching of $G^e_A$, consistent with theory

• Next steps:
  - newer data very soon at $Q^2 = 0.63$ (HAPPEX-III, PV-A4)
  - global fits to all 36 asymmetries, including 2-boson & CSV effects, consistent electromagnetic form factors
  - no plans on pushing experimental effort further… lattice?

“Do not infest your mind with beating on the strangeness of this business” - W. Shakespeare (The Tempest)