Strangeness in the Nucleon

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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:
  \[ \text{HAPPEX-III (forward angle):} \]
  - Separated form factors at $Q^2 = 0.23, 0.63 \ (\text{GeV/c)}^2$
• Implications for Standard Model Tests
• Conclusions

“There is no excellent beauty that hath not some strangeness in the proportion”

Francis Bacon 1561-1626
Nucleon in QCD

- \( P = uud + u\bar{u} + d\bar{d} + s\bar{s} + g + \ldots \) « sea »
- \( s \) 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)
  (the latter two are far from settled)

also: OZI violations in \( p\bar{p} \rightarrow \phi\gamma \) / \( \omega\gamma \)

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 \( G^s_M \)
The “Lamb Shift” of QCD

Strangeness contribution is a (QCD) vacuum polarization effect*

*Analogy borrowed from A.W. Thomas
Genesis of a Strange Idea

Puzzle: Initial DIS measurements of spin-structure of nucleon (EMC): valence quarks contribute unexpectedly low fraction to total spin - “Spin Crisis”


Theoretical realization: not only did available nucleon model calculations allow this, but they also allowed (and in some cases favored) large strange quark contributions to other properties of nucleon

Consternation and excitement: at the time, data gave no constraint on strange contributions to charge distribution and magnetic moment!

Challenge: how to isolate strange vector form factors?

Answer: exploit the weak neutral current as a probe
Parity-Violating Electron Scattering

Weak NC Amplitudes

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

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:

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

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

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

\[
G_{E,M}^u \quad G_{E,M}^d \quad G_{E,M}^s
\]

\[
G_{E,M}^{g,p} \quad G_{E,M}^{g,n} \quad G_{E,M}^{Z,p}
\]

\[
G_{E,M}^{u} \quad G_{E,M}^{d} \quad G_{E,M}^{s}
\]

\[
< N | s \gamma^\mu | s | N >
\]

\[
A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_\gamma}{|M_\gamma|^2} = - \frac{G_F Q^2}{\sqrt{2}\pi\alpha} F(G_{E/M}^p, G_{E/M}^n, G_{E/M}^s, G_A)
\]
Isolating individual form factors: vary *kinematics* or target

For a proton:

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

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

Forward angle  Backward angle

For $^4\text{He}$: $G_E^s$ 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: 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 meson 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

QCD on the lattice?

- Dong, Liu, Williams PRD 58(1998)074504
- Doi, et al. PRD 80 (2009) 094503

Disconnected insertions - technically challenging
Strangeness Models

(as/of circa 2005)

note: caveats...
What would non-zero strange form factors 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

$\rightarrow$ contribute to magnetic moment, etc.

\(\text{Kaon} = u\bar{s}\)

\(\text{Hyperon} = uds\)

(\text{naive model for illustration})
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
  -> requires \(4 \times 10^{14}\) counts

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

- High luminosity: thick targets, high beam current
- Control noise (target, electronics)
- High beam polarization and rapid flip
### Parity-Violating Electron Scattering Program

<table>
<thead>
<tr>
<th>Expt/Lab</th>
<th>Target/Angle</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$A_{pv}$ (ppm)</th>
<th>Sensitivity</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SAMPLE/Bates</strong></td>
<td></td>
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<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>
</tr>
<tr>
<td><strong>HAPPEEx/JLab</strong></td>
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<td></td>
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</tr>
<tr>
<td>HAPPEEx</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>HAPPEEx 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>
</tr>
<tr>
<td>HAPPEEx 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>HAPPEEx III</td>
<td>LH$_2$/14</td>
<td>0.63</td>
<td>-24</td>
<td>$G_E + 0.5G_M$</td>
<td>2011</td>
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<tr>
<td><strong>PV-A4/Mainz</strong></td>
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<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>
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<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>
</tr>
<tr>
<td></td>
<td>LH$_2$/35</td>
<td>0.63</td>
<td>-28</td>
<td>$G_E + 0.64G_M$</td>
<td>(2009)</td>
</tr>
<tr>
<td><strong>G0/JLab</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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: $E=3.3\text{ GeV}$, $\theta=12.5^\circ$, $Q^2=0.48\text{ (GeV/c)}^2$

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

$G^s_E + 0.39G^s_M = 0.014 \pm 0.020\text{ (exp)} \pm 0.010\text{ (FF)}$

*Phys. Rev. Lett. 82, 1096 (1999);
Phys. Lett. B509, 211 (2001);
If theory [Zhu et al. Phys. Rev. D 62, 033008 (2000)] for $G^e_A (T=1)$ used to constrain $G^S_M$:

$$G^S_M = 0.37 \pm 0.20^{\text{Stat}} \pm 0.36^{\text{Syst}} \pm 0.07^{\text{FF}}$$
HAPPEx-II

E=3 GeV  θ=6°  Q^2= 0.1 (GeV/c)^2

- Hydrogen: \( G_E^s + \eta G_M^s \)
- \(^4\text{He}: \) 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

HAPPEX data at $Q^2 \sim 0.1$ GeV$^2$

Including all data at $Q^2 \approx 0.1$

$G_M^s = 0.28 \pm 0.20$

$21\%$ of $\mu_{T=0}^N$

$\langle r^2 \rangle_E^p = 0.766 \pm 0.012 \text{ fm}^2$

$\langle r^2 \rangle_E^s = 0.002 \pm 0.015 \text{ fm}^2$
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

---

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

$$\% \text{ contrib} = \frac{G_{E,M}^S}{G_{E,M}^P} \times \left( -\frac{1}{3} \right) \times 100$$
Theoretical Refinements

1. Two Boson exchange:  
   eg. H.Q. Zhou, C.W. Kao and S.N. Yang  
   $\gamma Z$ box dominates the two boson effects at HAPPEX, PVA4 kinematics  
   $\rightarrow$ reduces extracted $G_s^E + \eta G_M^s$  
   (not yet put into global fits)

2. Charge-symmetry breaking effects:

   Hydrogen: B. Kubis & R. Lewis  
   $^4$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: Forward angle (MAMI)**

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

"Evidence for Strange Quark Contributions to the Nucleon's Form Factors at $Q^2 = 0.1$ GeV$^2$”
PV-A4: Backward angle

\[ \theta = 145^\circ \quad Q^2 = 0.22 \text{ (GeV/c)}^2 \]

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

\[ G^s_E = 0.050 \pm 0.038 \pm 0.019 \]
\[ G^s_M = -0.14 \pm 0.11 \pm 0.11 \]

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

% contribution to proton:
- electric: \(3.0 \pm 2.5\%\)
- magnetic: \(2.9 \pm 3.2\%\)

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

Deuterium results at same \(Q^2\) - results expected soon....
G° (JLab – Hall C)

- Superconducting toroidal magnetic spectrometer

**Forward angle mode:**

- \( \text{LH}_2: \ E_e = 3.0 \text{ GeV} \)
- Recoil proton detection
- \( 0.12 \leq Q^2 \leq 1.0 \ (\text{GeV}/c)^2 \)

**Backward angle mode:**

- \( E_e = 362, 687 \text{ MeV} \)
- \( \text{LH}_2, \text{LD}_2 \) electron detection
- (quasi)elastic at \( \sim 108^\circ \)
- \( Q^2 = 0.22 \text{ GeV}^2, 0.63 \text{ GeV}^2 \)
Major Canadian Content:
U. Manitoba, U, Winnipeg,
TRIUMF, UNBC

also several Canadians at
U.S. institutions eg.
D. Beck (spokesperson), B. Quinn,
D. Armstrong
G0: Forward-angle results

\[ G_E^s + \eta G_M^s = 0 \]  Hypothesis excluded at 89% C.L.

D.S. Armstrong et al., PRL 95, 092001 (2005)
Forward Angle Results

$G_E^S + \eta G_M^S$

$Q^2$

- $G0$ Backward angle kinematics

- HAPPEX-H (2005)

- HAPPEX-I


- MAMI A4 (different $\eta$)
Strange form factors contribute at most a few % to overall vector form factors... except maybe near $Q^2 = 0.6$...
A higher precision repeat of HAPPEX-I, at somewhat higher $Q^2$
(0.624 GeV$^2$ - heart of the $G_0$ “signal”)
- 100 $\mu$A beam current, 89.6% polarization, 25 cm lH2 target
  (c.f. 35 $\mu$A at 70% polarization, 15 cm target for HAPPEX-I)
- Precision (0.8%) beam polarimetry with Moller and Compton polarimeters
HAPPEX-III Results

\[ A_{PV} = -23.742 \pm 0.776 \text{ (stat)} \pm 0.353 \text{ (syst)} \text{ ppm} \]

\[ A(G^s=0) = -24.158 \text{ ppm} \pm 0.663 \text{ ppm} \]

\[ G^s_E + 0.52 G^s_M = 0.005 \pm 0.010 \text{ (stat)} \pm 0.004 \text{ (syst)} \pm 0.008 \text{ (FF)} \]

Separated Form Factors at $Q^2=0.63$

Z. Ahmed et al., PRL 108(2012)102001
Interpretation…

Suggestions from PDF fits of strange asymmetry

Small $G_E^s$ indicates no corresponding spatial asymmetry - the $s$ and $\bar{s}$ are produced with very similar spatial distributions

Small $G_M^s$ indicates either that $s$ $\bar{s}$ are produced spin-aligned, and/or that their magnetizations are not random with respect to nucleon spin orientation

ATLAS has new results that further constrain strange asymmetry
Beyond Strangeness: Parity-Violating Electron Scattering as a Standard Model Test

revisit History: SLAC E122 (Prescott, et al). first PV electron scattering experiment - seminal test of electroweak Standard Model

at low $Q^2$ & forward angles: $A_{PV} \propto Q_w^P = (1 - 4 \sin^2\theta_W)$

$Q_w^P$: Weak charge of the proton - precise Standard Model prediction, poorly tested experimentally

Experiment at JLab: just completed data-taking (May 2012)

Strange form factors crucial input (extrapolation to $Q^2=0$)
Beyond Strangeness:
Parity-Violating Electron Scattering as a Standard Model Test

\textit{revisit History:} SLAC E122 (Prescott, et al). first PV electron scattering experiment - seminal test of electroweak Standard Model

\[ A_{PV} \propto Q^2_w = (1 - 4 \sin^2 \theta_w) \]

\(Q^p_w\): Weak charge of the proton - precise Standard Model prediction, poorly tested experimentally

\textbf{Major Canadian Content:}
U. Manitoba, U. Winnipeg, TRIUMF, UNBC

\textbf{Talks yesterday:}
P. Wang, J. Pan, V. Tvaskis
**Summary**

- Comparison of electromagnetic and weak neutral elastic form factors allows determination of strange quark contribution
  - large distance dynamics of the sea
- Separated form factors at three different $Q^2$
  - $G_E^s$, $G_M^s$ small, consistent with zero
- Important input for Standard Model test (QWeak)

**Next steps:**
- Mainz PVA4 results at $Q^2 = 0.63$ expected soon
  (similar kinematics to HAPPEX-III)
- 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*)
At a resolution of $10^{-24}$ metres, isolated clumps of Strange Matter pop briefly out of the quantum foam to debate the possible existence of Particle Physicists.