HAPPEX: Measuring Strange Quark Contributions to the Charge and Magnetic Distributions of the Proton

Kent Paschke

University of Virginia

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The Sea in the Nucleon

The nucleon contains three quarks... embedded in a teeming sea of gluons and additional quarks and anti-quarks.

The sea is dominated by the three light quark flavors: up, down, strange.

Quark sea contributions to nucleon static properties are unsettled.

strangeness contribution must be from the sea

Spin polarized DIS
\[ \Delta S = 0.0-0.10 \]

Strange mass
\[ \pi N \text{ scattering: 0-30\%} \]

Strange charge radius and magnetic moment

Goal: Determine the contributions of the strange quark sea \((\bar{s}s)\) to the charge and magnetization distributions in the nucleon: “strange form factors” \(G_{S_E}^s\) and \(G_{S_M}^s\)
Expectations for Nucleon Strangeness

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, ...

What about QCD on the lattice?
- Dong, Liu, Williams PRD 58(1998)074504
- Wang et al, PRC 79(2009)065202
- Doi et al., hep-lat 0903.3232
these suggest very small effects

might the strange quark behave in the same way?

![Image of neutron and proton distributions](image-url)
Flavor-separating the Vector Form Factors

\[
G_E^p = \frac{2}{3} G_E^{u,p} - \frac{1}{3} G_E^{d,p} - \frac{1}{3} G_E^s \\
G_E^n = \frac{2}{3} G_E^{u,n} - \frac{1}{3} G_E^{d,n} - \frac{1}{3} G_E^s
\]
Flavor-separating the Vector Form Factors

\[ G^p_E = \frac{2}{3} G_{E}^{u,p} - \frac{1}{3} G_{E}^{d,p} - \frac{1}{3} G_{E}^s \]

\[ G^n_E = \frac{2}{3} G_{E}^{u,n} - \frac{1}{3} G_{E}^{d,n} - \frac{1}{3} G_{E}^s \]
Flavor-separating the Vector Form Factors

\[ G^p_E = \frac{2}{3} G^u_E - \frac{1}{3} G^d_E - \frac{1}{3} G^s_E \]

\[ G^n_E = \frac{2}{3} G^d_E - \frac{1}{3} G^u_E - \frac{1}{3} G^s_E \]

Two equations and three unknowns
Flavor-separating the Vector Form Factors

\[ G^p_E = \frac{2}{3} G^u_E - \frac{1}{3} G^d_E - \frac{1}{3} G^s_E \]

Two equations and three unknowns

\[ G^m_E = \frac{2}{3} G^d_E - \frac{1}{3} G^u_E - \frac{1}{3} G^s_E \]

Three equations and three unknowns

Measure neutral weak
proton form-factor

Measuring all three enables separation of up, down and strange contributions

\[ G^{p,Z}_E = \left( 1 - \frac{8}{3} \sin^2 \theta_W \right) G^u_E - \left( 1 - \frac{4}{3} \sin^2 \theta_W \right) G^u_E - \left( 1 - \frac{4}{3} \sin^2 \theta_W \right) G^u_E \]
Measuring Strange Vector Form Factors

\[ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left( \frac{A_E + A_M + A_A}{\sigma_p} \right) \sim 10^{-4} Q^2 / \text{GeV}^2 \]

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

For a proton:

\[ A_E = \epsilon G_E^p G_Z^E \quad A_M = \tau G_M^p G_M^Z \quad A_A = (1 - 4 \sin^2 \theta_W) \epsilon G_M^p \tilde{G}_A \]

Forward angle

Backward angle

Difficult radiative corrections accompany the axial form-factor

For spin=0, T=0 (\(^4\)He):

\( G_s^E \) only!

nuclear corrections:
forward angle, low \( Q^2 \) only

For deuterium:

Enhanced \( G_A \)

Back-angle quasi-elastic.
The Axial Term and the Anapole Moment

Axial form-factors $G_A^p, G_A^n$:

$$\tilde{G}_A^{p,n} = -\tau_3 \left( 1 + R_A^{T=1} \right) G_A^{(3)} + \sqrt{3} R_A^{T=0} G_A^{(8)} + \Delta s$$

- Biggest uncertainty comes from radiative corrections

Anapole Moment Correction:
Multiquark weak interaction modifies axial form-factor


- Large uncertainty estimated to account for specific uncalculated terms
- Uncertainty dominates axial term
- Difficult to achieve tight experimental constraint

This adds a new degree of freedom to the strange quark extraction (really, two, for both isoscaler and isovector anapole terms)
### Experimental Overview

**HAPPEX**

- Precision spectrometer, integrating
- Open geometry, integrating

**SAMPLE**

- $G_M^s, (G_A)$ at $Q^2 = 0.1 \text{ GeV}^2$

**A4**

- Open geometry
- Fast counting calorimeter for background rejection

**G0**

- Open geometry
- Fast counting with magnetic spectrometer + timing for background rejection

**Results**

- $G_E^s + 0.39 G_M^s$ at $Q^2 = 0.48 \text{ GeV}^2$
- $G_E^s + 0.08 G_M^s$ at $Q^2 = 0.1 \text{ GeV}^2$
- $G_E^s$ at $Q^2 = 0.1 \text{ GeV}^2$ ($^4\text{He}$)
- $G_E^s + 0.48 G_M^s$ at $Q^2 = 0.62 \text{ GeV}^2$
- $G_E^s + \eta G_M^s$ over $Q^2 = [0.12, 1.0] \text{ GeV}^2$
- $G_M^s, G_A^e$ at $Q^2 = 0.23, 0.62 \text{ GeV}^2$
Goal: Small Asymmetry Measured to a Few Percent
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Psuedo-random, rapid helicity flip

Flux ~ 1-100 MHz
Goal: Small Asymmetry Measured to a Few Percent

Pockels Cell

Psuedo-random, rapid helicity flip

Flux ~ 1-100 MHz

Measure the asymmetry to high precision, millions of times

HAPPEX-II

# Pairs = 25.3 M
RMS = 538

25 million trials

0.05% precision
Goal: Small Asymmetry Measured to a Few Percent

Psuedo-random, rapid helicity flip

Flux ~ 1-100 MHz

Calorimeter

electron flux

# Pairs = 25.3 M
RMS = 538

25 million trials
50 MHz @ 15 Hz
\( \sigma_A \sim 540 \text{ ppm} \)

\[ \delta(A_{PV}) = \frac{540 \text{ ppm}}{\sqrt{25 \times 10^6}} \sim 110 \text{ ppb} \]
Experimental Techniques for PVeS

Statistical Precision
- High beam current, high polarization
- High power cryotargets with small density fluctuations
- Large acceptance
- Precision beam monitoring
- Large acceptance, or very forward angle, spectrometer
- Integrating Detection: low noise, linear

Systematic Accuracy - False Asymmetries
- Large acceptance or very forward angle
- Spectrometers: separate background channels, minimize re-scattered backgrounds (especially magnetized material)
- Helicity-correlated beam asymmetries small: $\frac{\Delta I}{I} < 1 \text{ ppm}, \Delta x \sim 1 \text{ nm}, \Delta E/E \sim 1 \text{ ppb}$
- Measurements of sensitivity to beam position changes
- sign flips (g-2, laser optics)

Systematic Accuracy - Normalization
- beam polarimetry
- absolute energy scale and angle measurement ($Q^2$)
- detector linearity
- background dilutions
**HAPPEX at JLab**

**HRS:** twin high-resolution spectrometers
- Limited acceptance (~5-8 msr) but very clean.
- Statistical FOM suitable for forward-angle studies
- 6-14° angles, 2.8-3.5 GeV
- 500 kHz - 50 MHz signal rates: analog integration

- **H$_2$ at** $Q^2$ ~ 0.1, 0.5, 0.62 GeV$^2$
- **Helium-4** at $Q^2$ ~ 0.1 GeV$^2$

- Highest statistical precision at specific kinematics
- Very clean isolation of $^4$He elastic
- Very low backgrounds ($f$ ~ 1.5%)

**clean measurement of $G_M^s$, $G_E^s$**
Precision Data at $Q^2 \sim 0.1 \text{ GeV}^2$ shows small $G^s$

- $\sim 3\% \pm 2.3\%$ of $G^p_M$
- $\sim 0.2 \% \pm 0.5\%$ of $G^p_E$

Excellent consistency between data sets

Caution: the combined fit is approximate. Correlations due to common assumptions or sources of error are not taken into account.

For a more rigorous treatment, see published fits by:
World Data vs. $Q^2$

Simple fit to “leading order” in $Q^2$

\[ G_E^s = \rho_s \tau \]
\[ G_M^s = \mu_s \]

Includes only data $Q^2 < 0.3 \text{ GeV}^2$

Sizeable contributions at higher $Q^2$ are not still not definitively ruled out.

G0 Global error allowed to float with unit constraint
Zhu et al axial constraints are used
Includes backangle results as constraint on $G_M^s$
only (neglects correlations with $G_E^s$ from extraction)
Sources of correlated error, such as electromagnetic form factor assumptions are neglected

Again, a more careful fit with somewhat different assumptions is available::
Expected data at higher $Q^2$

\[ \eta \sim Q^2 \]

\[ G_E^s \pm \eta G_M^s \]

\[ Q^2 \sim 0.62 \text{ GeV}^2 \]

Data taking completed in 2009

\[ \delta(G_E^s + 0.48 G_M^s) \sim 0.015 \]

Statistics-limited error bar, with leading systematic error from polarimetry

Analysis proceeding similarly to HAPPEX-I:

Beam Polarization for HAPPEX-III

- Energy-weighted integration minimizes calibration uncertainties
- Non-statistical jitter dominated by background instabilities
- Analysis still in progress

Compton: $<P> \sim 90\%$
Moller: $<P> \sim 89\%$

Expected systematic error
1-2% on each
HAPPEX-III analysis underway

(Blinded) asymmetry analysis nearly complete

Background, $Q^2$, polarimetry, PMT linearity analyses underway

Results expected Fall 2010
Outlook for improved precision

Anapole correction and other $\Upsilon \Upsilon$ and $\Upsilon Z$ box

- The uncertainties in the axial form-factor continue to complicate interpretation in terms of $G_{E/M}^s$
- Anapole uncertainty contribution to H-III: 1.5%

Charge Symmetry Breaking

**Old Story:** theoretical CSB estimates indicate <1% violations

**New Story:** effects could be large as statistical error on HAPPEx-II data

New improvements on precision (in the forward angle) may test charge symmetry

Electromagnetic Form Factors

- Limited to few percent precision (including 2-$\gamma$ uncertainties)

Further improvements in precision would require additional theoretical and empirical input for interpretation
Summary

- Significant and accessible contributions are still allowed... but the range has been narrowed.

- No more than a few percent of the neutron charge or proton magnetic moment can be due to strange quarks.

- Precision data at middle $Q^2$ can finish the question of large contributions to the vector form-factors.

Further improvements in precision would require additional theoretical and empirical input for interpretation.