Strangeness Contributions to the Nucleon Vector Form-Factors: Results from HAPPEX–III

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for the HAPPEX Collaboration

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Strange Quarks in the Nucleon

Strange quarks exist in the nucleon at short distance scales.

How do they influence the interactions of the nucleon?

Momentum ~ 4%

\[ \int_0^1 x (s + \bar{s}) dx \]

Mass 0-30%

\[ \langle N | s \bar{s} | N \rangle, \sum_{\pi} N \]

Spin 0 - -10%

\[ \Delta s \]

Magnetic moment, charge radius

\[ \rho_s, \mu_s \]

\[ G^s_E, G^s_M \]
Extracting the Strange Form Factor with the Neutral Weak Interaction

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

\[ G_{E}^{n} = \frac{2}{3} G_{E}^{u,n} - \frac{1}{3} G_{E}^{d,n} - \frac{1}{3} G_{E}^{s} \]
Extracting the Strange Form Factor with the Neutral Weak Interaction

Two equations and three unknowns

$$G^p_E = \frac{2}{3} G^{u,p}_E - \frac{1}{2} G^{d,p}_E - \frac{1}{3} G^s_E$$

$$G^n_E = \frac{2}{3} G^{u,n}_E - \frac{1}{2} G^{d,n}_E - \frac{1}{3} G^s_E$$
Extracting the Strange Form Factor with the Neutral Weak Interaction

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

Two equations and three unknowns
Extracting the Strange Form Factor with the Neutral Weak Interaction

\[ G_P^E = \frac{2}{3} G_u^E - \frac{1}{3} G_d^E - \frac{1}{3} G_s^E \]

Two equations and three unknowns

\[ G_n^E = \frac{2}{3} G_d^E - \frac{1}{3} G_u^E - \frac{1}{3} G_s^E \]

Three equations and three unknowns

Measure neutral weak proton form-factor

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

The weak form factor is accessible via parity violation
Measuring Strange Vector Form Factors

\[ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\gamma}{2} \sim \frac{10^{-4} Q^2}{\text{GeV}^2} \]

Proton:

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

\[ A_E = \epsilon G^p_E G^Z_E \]
\[ A_M = \tau G^p_M G^Z_M \]
\[ A_A = (1 - 4\sin^2\theta_W)\epsilon' G^p_M \tilde{G}_A \]

Forward angle

Backward angle

Neutral weak proton form factor

\[ G^Z_{E,M} = (1 - 4\sin^2\theta_W)G^p_{E,M} - G^n_{E,M} - G^s_{E,M} \]

Spin=0, T=0 $^4\text{He}$: $G^s_E$ only!

Deuterium: Enhanced $G_A$
**Experimental Overview**

**SAMPLE**
open geometry, integrating, back-angle only

**HAPPEX**
Precision spectrometer, integrating
Forward angle, also $^4$He at low $Q^2$

**HAPPEX–3:** $G_E^s + 0.52 \ G_M^s$ at $Q^2 = 0.62 \ GeV^2$

**A4**
Open geometry
Fast counting calorimeter for background rejection
Forward and Backward angles

**G0**
Open geometry
Fast counting with magnetic spectrometer + TOF for background rejection
Forward and Backward angles over a range of $Q^2$
World data on $G^s$

- "Form Factor" error: precision of EMFF (including $2\gamma$) and Anapole correction
- Significant systematic uncertainty in higher $Q^2$ points

\[ \eta = \frac{\tau G_M^p}{\epsilon G_E^p} \sim Q^2 \]
World data on $G^s$

- "Form Factor" error: precision of EMFF (including $2\gamma$) and Anapole correction
- Significant systematic uncertainty in higher $Q^2$ points

At $Q^2 \sim 0.1 \text{ GeV}^2$, $G^s < \text{few percent of } G^p$
World data on $G^s$

- "Form Factor" error: precision of EMFF (including $2\gamma$) and Anapole correction
- Significant systematic uncertainty in higher $Q^2$ points

At $Q^2 \sim 0.1$ GeV$^2$, $G^s < \text{few percent of } G^p$

\[ \eta = \frac{\tau G^p_M}{\epsilon G^p_E} \sim Q^2 \]
Global fit of all world data

- Data set appears to show consistent preference for positive effect
- Significant contributions at higher $Q^2$ are not ruled out.
Integrating in the High Resolution Spectrometers

Very clean separation of elastic events by HRS optics

no PID needed; detector sees only elastic events

Entries 2.694749e+07
RMS 3733

Psuedo-random, rapid helicity flip

Lead – Lucite Cerenkov Shower Calorimeter
phototube current integrated over fixed time periods
HAPPEX–III Error Budget

<table>
<thead>
<tr>
<th></th>
<th>δA_{PV} (ppm)</th>
<th>δA_{PV} / A_{PV}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>0.20</td>
<td>0.8%</td>
</tr>
<tr>
<td>Q^2</td>
<td>0.18</td>
<td>0.8%</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.19</td>
<td>0.8%</td>
</tr>
<tr>
<td>Linearity</td>
<td>0.12</td>
<td>0.5%</td>
</tr>
<tr>
<td>Finite</td>
<td>0.05</td>
<td>0.2%</td>
</tr>
<tr>
<td>False</td>
<td>0.04</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.369</strong></td>
<td><strong>1.51%</strong></td>
</tr>
<tr>
<td>Statistics</td>
<td>0.778</td>
<td>3.27%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.857</strong></td>
<td><strong>3.60%</strong></td>
</tr>
</tbody>
</table>

Compton + Moller polarimeters

Spectrometer Calibration

HRS Backgrounds

Systematic uncertainties are well controlled - experiment is statistics dominated
Determining $Q^2$

$Q^2$ measured using standard HRS tracking package, with reduced beam current  

**Goal:** $\delta Q^2 < 0.5\%$

Water cell optics target for central angle

$\delta p$ between elastic and inelastic peaks reduces systematic error from spectrometer calibration  

$\delta \theta \sim 0.55$ mrad (0.23%)

$Q^2 = 0.6241 \pm 0.0032$ (0.52%)

**Table:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Angle</td>
<td>0.45%</td>
</tr>
<tr>
<td>Beam Energy, HRS momenta</td>
<td>0.11%</td>
</tr>
<tr>
<td>Drifts</td>
<td>0.2%</td>
</tr>
<tr>
<td>ADC weighting</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.52%</td>
</tr>
</tbody>
</table>
Backgrounds

• Aluminum from target windows
• Signal from inelastic electrons scattering inside spectrometer

<table>
<thead>
<tr>
<th>background</th>
<th>fraction</th>
<th>Asymmetry</th>
<th>Net Correction</th>
<th>Net Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (target window)</td>
<td>1.15% (30%)</td>
<td>-34.5 ppm (30%)</td>
<td>125 ppb</td>
<td>126 ppb</td>
</tr>
<tr>
<td>Rescattering</td>
<td>0.3% (25%)</td>
<td>-63 ppm (25%)</td>
<td>114 ppb</td>
<td>55 ppb</td>
</tr>
</tbody>
</table>
Compton: $89.41 \pm 0.96\%$
Moller: $89.22 \pm 1.7\%$
Average: $89.36 \pm 0.84\%$

**Moller systematic errors**

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Polarization</td>
<td>1.5%</td>
</tr>
<tr>
<td>Analyzing Power</td>
<td>0.3%</td>
</tr>
<tr>
<td>Levchuk</td>
<td>0.2%</td>
</tr>
<tr>
<td>Background</td>
<td>0.3%</td>
</tr>
<tr>
<td>Deadtime</td>
<td>0.3%</td>
</tr>
<tr>
<td>other</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1.7%</strong></td>
</tr>
</tbody>
</table>

**Compton systematic errors**

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser polarization</td>
<td>0.80%</td>
</tr>
<tr>
<td>Analyzing Power</td>
<td>0.33%</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>0.43%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.96%</strong></td>
</tr>
</tbody>
</table>
Beam Asymmetries

Charge asymmetry (with feedback) averages to 200 parts per billion

Implies energy asymmetry at 3 ppb

Individual detector response measured to be at the level of 5 ppb/nm

Total Correction: $-0.016$ ppm (0.07%)

Trajectory at target averages to $<3\text{nm}, <0.5\text{nrad}$
HAPPEX-III Measurement of $A_{PV}$

$A_{RAW} = -21.591 \pm 0.688 \text{ (stat) ppm}$

This includes
- beam asymmetry correction (-0.01 ppm)
- charge normalization (0.20 ppm)

OUT / IN from “slow” spin reversals to cancel systematics

Trajectory at target averaged to <3nm, <0.5nrad

Corrections are then applied:
- backgrounds (1.0%)
- acceptance averaging (0.5%)
- beam polarization (11%)

3.27% (stat)± 1.5% (syst)  
total correction ~2.5% + polarization

Analysis Blinded ± 2.5 ppm
HAPPEX–III Result

\[ A_{PV} = -23.803 \pm 0.778 \text{ (stat)} \pm 0.359 \text{ (syst)} \text{ ppm} \]

\[ Q^2 = 0.6241 \pm 0.0032 \text{ (GeV/c)}^2 \]
HAPPEX–III Result

\[ A_{PV} = -23.803 \pm 0.778 \text{ (stat)} \pm 0.359 \text{ (syst) ppm} \]

\[ Q^2 = 0.6241 \pm 0.0032 \text{ (GeV/c)^2} \]

\[ A(G^s=0) = -24.062 \text{ ppm} \pm 0.734 \text{ ppm} \]

\[ G^s_E + 0.52 \, G^s_M = 0.003 \pm 0.010_{\text{(stat)}} \pm 0.004_{\text{(syst)}} \pm 0.009_{\text{(FF)}} \]

arXiv: 1107.0913v1
$Q^2 = 0.62 \text{ GeV}^2$ in combination

Combined fit includes form-factor uncertainties, experimental bands do not.

Zhu constraint is used for axial form-factor.
Considering only the 4 HAPPEX measurements

- High precision
- Small systematic error
- Clean theoretical interpretation
Strange Vector Form Factors Are Small

- HAPPEX–III provides a clean, precise measure of $A_{PV}$ at $Q^2=0.62$ GeV$^2$, and finds that it is consistent with no strangeness contribution to the long-range electromagnetic interaction of the nucleon.

- Recent lattice results indicate values smaller than these FF uncertainties.

- Further improvements in precision would require additional theoretical and empirical input for interpretation.
Backup
Detector Linearity

Studied *in situ* and on bench with LED system optimized to linearity for *differential rates of similar pulses*.

Measurements taken in short deviations from high rate, to maintain consistent thermal properties.

Phototube and readout non-linearity bounded at the 0.5% level.
Hall A Compton Polarimeter

Resonant cavity “photon target”, up to 2kW intensity

\[ A_{\text{exp}} = \frac{n^+ - n^-}{n^+ + n^-} = P_\gamma \times P_e \times < A_{th} > \]

Calibration of the analyzing power is usually the leading uncertainty

measure asymmetry independently in:
- momentum analyzed electrons
- photons in calorimeter

Electron detector achieved 1% accuracy for HAPPEX-2, but system was broken for HAPPEX-3
Compton Polarimetry

Electron detector achieved 1% accuracy for HAPPEX-2, but e-det system was not functioning for HAPPEX-3

Photon self-triggered analysis has been limited in accuracy, and required electron coincidence measurements for calibration

**Integrating photon detection:**
immune to calibration, pile-up, deadtime, response function

New DAQ, with SIS 2230 Flash ADC read out in two modes:

**Triggered mode:** triggered “snap shot” of fixed time interval (for calibration)

**Accumulator readout:** all FADC samples are summed on board for entire helicity window
Compton Integrating Analysis, online

Online plots from run 20457
Compton Polarimetry

Non-linearity mapped out in with pulsed LED system.

Compton spectrum very well simulated
  • linearity
  • collimator/detector alignment
  • synchrotron light shielding

Analyzing power calculation is not extremely sensitive to these corrections
Parameterizations

$G_E^s = \rho_s \tau$

$G_M^s = \mu_s$

Fit includes all world data $Q^2 < 0.65$ GeV$^2$
G0 Global error allowed to float with unit constraint

$G_E^s = \rho_s \text{galster}$

$G_M^s = \mu_s \text{dipole}$

$G_E^s = \rho_s \tau + a_2 \tau^2$

$G_M^s = \mu_s + m_2 \tau$