**Strangeness in the nucleon**

**Goal:** Determine the contributions of the strange quark sea ($S\bar{S}$) to the charge and current/spin distributions in the nucleon:

“strange form factors” $G^s_E$ and $G^s_M$

- $P = uud + u\bar{u} + d\bar{d} + s\bar{s} + g + \ldots$
  
  “sea”

- $s$ quark: cleanest 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)

(large uncertainties on these contributions)
Strange Quarks in the Nucleon

momentum:
- 2 muons from charm quark production: $\nu_\mu + s \rightarrow c + X + \mu^-$

mass:
- $\pi$-N scattering

spin:
- Polarized deep-inelastic scattering

$\nu$-p elastic scattering

\[ \frac{1}{2} = \frac{1}{2} (\Delta u + \Delta d + \Delta s) + L_q + J_g \]

NuTeV, e.g.

\[
\begin{align*}
2\int_0^1 [s + \bar{s}] dx &= 0.42 \pm 0.07 \pm 0.06 \\
\int_0^1 [u + \bar{u} + d + \bar{d}] dx &= 0.4 \\
2\langle N | m_s \bar{s}s | N \rangle &\approx 0.4 \\
\langle N | \hat{m}(u\bar{u} + d\bar{d}) | N \rangle &\approx 0.4
\end{align*}
\]

$\Delta u + \Delta d + \Delta s = 0.20 \pm 0.10$

$\Delta s = -0.1 \pm 0.1$

$\Delta s = -0.15 \pm 0.09$
Parity violating electron scattering

\[ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]

McKeown, 1989; Beck, 1989

\[ G_M^Z \text{ (Neutral weak magnetic form factor)} \]

With \( G_M^p, G_M^n \), isospin symmetry

Kaplan and Manohar, 1988

\[ G_M^S \text{ (Strange magnetic form factor)} \]
**Parity Violating Electron Scattering**

→ Weak NC Amplitudes

\[
M^{EM} = \frac{4\pi\alpha}{Q^2} Q_1 \ell^\mu J^EM_{\mu} \\
M^{NC} = \frac{G_F}{2\sqrt{2}} \left[ g_A \ell^\mu s^5 J^{NC}_{\mu} + g_V \ell^\mu J^{NC}_{\mu} \right]
\]

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

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

\[
A_{PV} = \sigma_R - \sigma_L \approx \left| \frac{M^{NC}_{PV}}{M^{EM}_{PV}} \right| \sim \frac{Q^2}{(M_Z)^2}
\]

Tiny (~10^{-6}) cross section asymmetry isolates weak interaction.
Form Factors

\[ J_{\mu}^{EM} = \sum_q Q_q \left\langle \bar{N} \left\vert \bar{u}_q \gamma_{\mu} u_q \right\rangle \right. \]

\[ = \bar{N} \left[ \gamma_{\mu} F_{1}^{\gamma} + \frac{i \sigma_{\mu \nu} q^{\nu}}{2M_N} F_{2}^{\gamma} \right] N \]

Adopt the 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 probes 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 new benchmark for testing non-perturbative QCD structure of the nucleon
Charge Symmetry

One expects the neutron to be an isospin rotation of the proton:

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

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

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

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

For a proton:

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

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

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

\[
G_A^e = -G_A + \Delta s + \eta F_A + R^e
\]

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

For deuterium: enhanced $G_A^e$ sensitivity

\[
A_{pv} = \frac{G_F Q^2}{\pi\alpha\sqrt{2}} \left[ \sin^2 \theta_W + \frac{G_E^s}{2(G_E^p + G_E^n)} \right]
\]
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 $G^s_E$ and $G^s_M$!

a challenging problem in non-perturbative QCD

QCD on the lattice

- Dong, Liu, Williams PRD 58(1998)074504
- Leinweber, et al. PRL 94(2005) 212001 and hep-lat/0601025
Strangeness Models (as/of 2000)

Leading moments of form factors:

\[ \mu_s = G^s_M (Q^2=0) \]

\[ \rho_s = \frac{\partial G^s_E}{\partial \tau} (Q^2=0) \]
SAMPLE Experiments

California Institute of Technology
University of Illinois
MIT-Bates Linear Accelerator Center
University of Maryland
Virginia Polytechnic Institute
Louisiana Tech
University of Kentucky
College of William and Mary
Argonne National Laboratory
2001: add MIT, ISN Grenoble

SAMPLE 1998: H$_2$ target, 200 MeV beam energy
(Spokespersons: McKeown, Beck)

SAMPLE 1999: D$_2$ target, 200 MeV beam energy
(Spokespersons: Beise, Pitt)

SAMPLE 2001: D$_2$ target, 125 MeV beam energy
(Spokesperson: Ito)
**SAMPLE Experiment Schematic**

- **Polarized Injector**
- **Wien Filter**
- **Accelerator**
  - $E = 200\ (125)\ MeV$
  - 600 pulses/s
  - $I_{pk} = 3\ mA$
  - $I_{ave} = 44\ \mu A$
  - $P_B = 36\%$
- **Fast phase shift (energy) feedback**
- **Beam current feedback**
- **Beam position feedback**
- **K11**
- **SAMPLE Detector**
  - Position, Angle, Charge
  - Halo
  - Moller Polarimeter
- **Lumi**
MIT-Bates Polarized Electron Source

- GaAs Crystal
- Gun Anode
- Halfwave plate (Manual helicity Reversal: 2-3 days)
- Pockels Cell (Fast helicity Reversal: 600Hz)
- Piezoelectric laser beam shifter
- Ti:Sapphire Laser
- Argon Ion Drive Laser
SAMPLE Target/Detector
**Experimental procedures**

\[ A_{Measured} = \frac{Y^{Positive}}{Y^{Positive}} - \frac{Y^{Negative}}{Y^{Negative}} \]

- Asymmetry between pulses separated by 1/60 s → remove effects due to 60 Hz
- Rapid helicity reversal → reduce effects of long-term drifts
- Slow helicity reversal → remove helicity-correlated electronics effects
World Data (early 2005) at $Q^2 \sim 0.1 \text{ GeV}^2$

Note: SAMPLE result adopts Zhu et al. calculation of $G_A^e$

PRD 62(2000)033008

$G_E^s = -0.12 \pm 0.29$

$G_M^s = 0.62 \pm 0.32$

Would imply that 5-10% of nucleon magnetic moment is Strange

Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account
Measurement of P-V Asymmetries

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

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

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

• 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 DAQ
Normalization: Polarization, Linearity, Dilution
HAPPEX  (second generation)

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

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

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

New 2005 results:

PRL98 (2007) 032301
Hall A at Jefferson Lab
Hall A at Jefferson Lab

**Polarimeters**
- Compton: 1.5-2% syst, Continuous
- Møller: 2-3% syst

**Target**
- 400 W transverse flow
- 20 cm, LH2
- 20 cm, 200 psi $^4$He

**High Resolution Spectrometer**
- + septum
- 5 mstr over $4^\circ-8^\circ$
### Summary of Data Runs: HAPPEX-II

<table>
<thead>
<tr>
<th>Date</th>
<th>Experiment</th>
<th>Description</th>
<th>$\delta A_{stat}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2004</td>
<td>HAPPEX-He</td>
<td>• about 3M pairs at 1300 ppm</td>
<td>~ 0.74 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=&gt; $\delta A_{stat}$ ~ 0.74 ppm</td>
<td></td>
</tr>
<tr>
<td>June – July 2004</td>
<td>HAPPEX-H</td>
<td>• about 9M pairs at 620 ppm</td>
<td>~ 0.2 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=&gt; $\delta A_{stat}$ ~ 0.2 ppm</td>
<td></td>
</tr>
<tr>
<td>July-Sept 2005</td>
<td>HAPPEX-He</td>
<td>• about 35M pairs at 1130 ppm</td>
<td>~ 0.19 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=&gt; $\delta A_{stat}$ ~ 0.19 ppm</td>
<td></td>
</tr>
<tr>
<td>Oct – Nov 2005</td>
<td>HAPPEX-H</td>
<td>• about 25M pairs at 540 ppm</td>
<td>~ 0.105 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=&gt; $\delta A_{stat}$ ~ 0.105 ppm</td>
<td></td>
</tr>
</tbody>
</table>
High Resolution Spectrometers

Clean separation of elastic events by HRS optics → Locate detector over elastic line and integrate the flux

Elastic Rate:

$^1$H: 120 MHz

$^4$He: 12 MHz

Large dispersion & heavy shielding reduce backgrounds at focal plane
Backgrounds

Shown is the single-particle momentum spectra.

- Aluminum target windows
- Inelastics and re-scattering
- Poletip (negligible)
Correcting Beam Asymmetries

\[ A_{\text{raw}} = A_{\text{det}} - A_Q + \sum_{i=1,5} \beta_i \Delta x_i \]

**Slopes from**
- natural beam jitter (regression)
- beam modulation (dithering)

Independent methods provide a cross-check. Each is subject to different systematic errors.

**Regression:**
- Natural beam motion, measure \( dA/d\Delta x_i \)
- Simultaneous fit establishes independent sensitivities
- By definition, removes correlation of asymmetry to beam monitors
- Sensitive to highly correlated beam motion and electronics noise

**“Dithering”:**
- Induce non-HC beam motion with coils, measure \( dS/dC_i, dx_i/dC_i \)
- Relate slopes to \( dS/dx_i \)
- Not compromised by correlated beam motion
- Robust, clear signals for failures
- Sensitive to non-linearities
Beam Position Differences, Helium

Position difference goal: 3 nanometers!

Problem: Helicity signal deflecting the beam through electronics “pickup”

Large beam deflections even when Pockels cell is off

All’s well that ends well

- Problem clearly identified as beam steering from electronic cross-talk
- No helicity-correlated electronics noise in Hall DAQ at < ppb level
- Large position differences \(\approx\) cancel in average over both detectors

Raw ALL Asymmetry

X Angle BPM

Helicity signal to driver reversed

Helicity signal to driver removed
Beam Position Corrections, Helium

Beam Asymmetries
- Energy: -3 ppb
- X Target: -5 nm
- X Angle: -28 nm
- Y Target: -21 nm
- Y Angle: 1 nm

Total Corrections:
- Left: -370 ppb
- Right: 80 ppb
- All: 120 ppb
Beam Position Corrections, Hydrogen

Surpassed Beam Asymmetry Goals for Hydrogen Run

- Energy: -0.25 ppb
- X Target: 1 nm
- X Angle: 2 nm
- Y Target: 1 nm
- Y Angle: <1 nm

Corrected and Raw, Left arm alone, Superimposed!

Total correction for beam position asymmetry on Left, Right, or ALL detector: **10 ppb**
$^{4}$He Results

Raw Parity Violating Asymmetry

$A_{\text{raw}}$ correction $\sim 0.3$ ppm

$Q^2 = 0.07725 \pm 0.0007 \text{ GeV}^2$

$A_{\text{raw}} = 6.40 \text{ ppm} \pm 0.23 \text{ (stat)}$

$\pm 0.12 \text{ (syst)}$
$^1$H Results

Raw Parity Violating Asymmetry

$A_{raw}$ correction $\sim 3$ ppb

$Q^2 = 0.1089 \pm 0.0011 \text{GeV}^2$

$A_{raw} = -1.58 \text{ ppm} \pm 0.12 \text{ (stat)} \pm 0.04 \text{ (syst)}$
Compton Polarimetry

Hydrogen: $87.1 \pm 0.9 \%$

Helium: $84.4 \pm 0.8 \%$

Continuous, non-invasive

Here: Electron Detector analysis

Cross-checked with Møller, Mott polarimeters

also: independent electron analysis

Helium ran with lower beam energy, making the analysis significantly more challenging.

Breakthroughs in both photon and electron analyses obtained 1% systematic uncertainty
HAPPEX-II 2005 Results

HAPPEX-\(^4\)He:

\[ Q^2 = 0.0772 \pm 0.0007 \text{ (GeV/c)}^2 \]
\[ A_{PV} = +6.40 \pm 0.23 \text{ (stat)} \pm 0.12 \text{ (syst) ppm} \]

\[ A(G^s=0) = +6.37 \text{ ppm} \]
\[ G^s_E = 0.002 \pm 0.014_{\text{(stat)}} \pm 0.007_{\text{(syst)}} \]

HAPPEX-H:

\[ Q^2 = 0.1089 \pm 0.0011 \text{ (GeV/c)}^2 \]
\[ A_{PV} = -1.58 \pm 0.12 \text{ (stat)} \pm 0.04 \text{ (syst) ppm} \]

\[ A(G^s=0) = -1.640 \text{ ppm} \pm 0.041 \text{ ppm} \]
\[ G^s_E + 0.09 \ G^s_M = 0.007 \pm 0.011_{\text{(stat)}} \pm 0.004_{\text{(syst)}} \pm 0.005_{\text{(FF)}} \]
HAPPEX-II 2005 Results

Three bands:
1. Inner: Project to axis for 1-D error bar
2. Middle: 68% probability contour
3. Outer: 95% probability contour

Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account
World Data near $Q^2 \sim 0.1$ GeV$^2$

$G_M^s = 0.28 +/- 0.20$
$G_E^s = -0.006 +/- 0.016$

~3% +/- 2.3% of proton magnetic moment

~0.2 +/- 0.5% of electric distribution

HAPPEX-only fit suggests something even smaller:
$G_M^s = 0.12 +/- 0.24$
$G_E^s = -0.002 +/- 0.017$

Caution: the combined fit is approximate. Correlated errors and assumptions not taken into account
World data consistent with state of the art theoretical predictions


Acknowledgement

• R. Michaels, Chiral Dynamics Workshop CD2006, Chapel Hill/Durham, NC 2006
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