Results from HAPPEX

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College of William & Mary

For the HAPPEX Collaboration

August 16 2005 - JLAB/INT Precision Electroweak Interactions Workshop - W&M
What role do strange quarks play in nucleon properties?

**Momentum:**
\[ \int x(s + \bar{s})dx \sim 4\% \quad \text{(DIS)} \]

**Spin:**
\[ \langle N | \bar{s} \gamma^5 s | N \rangle \sim -10\% \quad \text{(polarized DIS)} \]

**Mass:**
\[ \langle N | \bar{s}s | N \rangle \sim 30\% \quad \text{(πN σ-term)} \]

**Charge and current:**
\[ \langle N | \bar{s} \gamma^\mu s | N \rangle = ?? \rightarrow G_E^s \ G_M^s \]

**Goal:** Determine the contributions of the strange quark sea \((s \bar{s})\) to the electromagnetic properties of the nucleon ("strange form factors").
“There is no excellent beauty that hath not some strangeness in the proportion.”

Francis Bacon  1561-1626
Parity Violating Electron Scattering

\[ M_{\text{EM}} = \frac{4\pi\alpha}{Q^2} Q_1 \ell^\mu J_{\mu}^{\text{EM}} \]

\[ M_{\text{PV}}^{\text{NC}} = \frac{G_F}{2\sqrt{2}} \left[ g_A \ell^\mu J_{\mu}^{\text{NC}} + g_V \ell^\mu J_{\mu5}^{\text{NC}} \right] \]

Interference with EM amplitude makes NC amplitude accessible

\[ A_{\text{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|M_{\text{PV}}^{\text{NC}}|}{|M_{\text{EM}}|} \sim \frac{Q^2}{(M_Z)^2} \]
Connections to TPE physics

1. Beyond single boson exchange in electroweak interference:
   - $\gamma\gamma$ and $\gamma Z$ box and crossing diagrams.
   - Effects appear small at large $\varepsilon$ and small $Q^2$ → P. Blunden’s talk
   - Not a concern at present experimental precision.

2. Electromagnetic Form Factors used to extract strange form factors:
   - Which form factors to use? → J. Arrington’s talk

3. Transverse Asymmetry/Beam normal asymmetry/Vector analyzing power:
   - 😞 “background” to PV measurements, if electron beam not 100% longitudinal and detectors not perfectly symmetric.
   - 😊 Interesting in its own right – imaginary parts of TPE.
   → S. Wells’ talk, and rest of Wed. AM session
Form Factors

\[ J_{\mu}^{EM} = \sum_q Q_q \langle \bar{N} | \bar{u}_q \gamma_\mu u_q | N \rangle = N \left[ \gamma_\mu F_1^\gamma + \frac{i \sigma_{\mu\nu} q^\nu}{2M_N} F_2^\gamma \right] N \]

Adopt the Sachs FF: \[ G_E^\gamma = F_1^\gamma + \pi F_2^\gamma \quad G_M^\gamma = F_1^\gamma + F_2^\gamma \]

NC vector current probes same hadronic flavor structure, with different couplings:

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

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

\( G_{EM}^{Z} \) provide an important new benchmark for testing non-perturbative QCD structure of the nucleon.
Neutrino to be an isospin rotation of the proton.

Neglecting trivial breaking due to Coulomb force, one expects the charge symmetry.
Theoretical Approaches to Strange Form Factors

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

What about the lattice?

- Dong, Liu, Williams  PRD 58(1998)074504
- Leinweber, et al.  PRL 94(2005) 212001

→ A. Thomas’ talk
HAPPEX (first generation)

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

\[
A^{PV} = \left[ \frac{-G_FM_p^2 \tau}{\pi \alpha \sqrt{2}} \right] \left\{ (1 - 4 \sin^2 \theta_W) - \frac{\epsilon G_{E}^{p\gamma} (G_{E}^{m\gamma} + G_{E}^{s}) + \tau G_{M}^{p\gamma} (G_{M}^{m\gamma} + G_{M}^{s})}{\epsilon (G_{E}^{p\gamma})^2 + \tau (G_{M}^{p\gamma})^2} \right\} - A_A
\]

$A^{PV} = -14.92 \text{ ppm} \pm 0.98 \text{ (stat) ppm} + 1.00 \text{ (syst) ppm}$

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

"Parity Quantity" Beam @ JLab


$A_A$ suppressed by $\epsilon'(1 - 4 \sin^2 \theta_W)$ where $\epsilon' = \left[ \tau(1 + \tau)(1 - \epsilon^2) \right]^{1/2} \approx (0.08)(0.08)$ here.
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.

Hadronic
**Other Measurements**

**SAMPLE (MIT/Bates):**
measured $G_M^s + \beta G_A$

at $Q^2 = 0.1 \text{ GeV}^2$

**PAVI-A4 (Mainz):**
measured $G_E^s + \alpha G_M^s$

at $Q^2 = 0.23, 0.1 \text{ GeV}^2$

→ S. Taylor’s talk

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**Graphical Data**

- **Data Sets:**
  - Zhu et al.
  - MAMI A4, published
  - MAMI A4, 2004
  - HAPPEX-I, published

**Axes:**
- $G_M^s$
- $G_A^{(T=1)}$
- $Q^2 (\text{GeV}^2)$

**Regions:**
- $D_2$
- $H_2$
Other Measurements cont’d

$G_0$ at JLab/Hall C measured $G_E^s + \alpha G_M^s$ at $Q^2 = 0.12 \rightarrow 1.0 \text{ GeV}^2$

→ S. Pate’s talk
HAPPEX (second generation)

$E = 3$ GeV \hspace{1em} $\theta = 6^\circ$ \hspace{1em} $Q^2 = 0.1$ (GeV/c)$^2$

- Hydrogen: $G^s_E + \alpha G^s_M$
- $^4$He: Pure $G^s_E$:
  \[ A^{PV} = -\frac{A_0}{2} \left( 2 \sin^2 \theta_W + \frac{G^s_E}{G^{p\gamma}_E + G^{n\gamma}_E} \right) \]

<table>
<thead>
<tr>
<th>target</th>
<th>$A_{PV}$</th>
<th>Stat. Error (ppm)</th>
<th>Syst. Error (ppm)</th>
<th>sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1H$</td>
<td>-1.4</td>
<td>0.08 (5.7%)</td>
<td>0.04 (2.9%)</td>
<td>$\delta (G^s_E + 0.08G^s_M) = 0.010$</td>
</tr>
<tr>
<td>$^4He$</td>
<td>+7.8</td>
<td>0.18 (2.2%)</td>
<td>0.18 (2.1%)</td>
<td>$\delta (G^s_E) = 0.015$</td>
</tr>
</tbody>
</table>
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
\rightarrow requires 4 \times 10^{14} counts

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

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

- Analog integration of rates \sim 100 \text{ MHz}
- High luminosity: thick targets, high beam current
- Control noise (target, electronics)
- Polarized source uses optical pumping of strained photocathode: high polarization and rapid flip

Statistics: high rate, low noise
Systematics: beam asymmetries, backgrounds, Helicity correlated DAQ
Normalization: Polarization, Linearity, Background
Apparatus Upgrade

HAPPEX-I precision: 
~ 1 ppm, 15%

HAPPEX-H precision ~ 50 ppb
HAPPEX-He precision ~ 2%

- High Luminosity => High I and $P_e$ (superlattice), thick new targets, rad-hard integrating det., improved DAQ.
- Small forward angle => new Septum magnets
- Accurate Normalization => improved polarimetry, new focal plane profile scanner
- High systematic accuracy => improved polarized source, close attention to beam optics, luminosity monitor.
# First Run, 2004

<table>
<thead>
<tr>
<th>Date Range</th>
<th>Experiment</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 8 - June 22</td>
<td>HAPPEX-He</td>
<td>· about 3M pairs at 1300 ppm &lt;br&gt;=&gt; $\delta A_{stat} \sim 0.7$ ppm</td>
</tr>
<tr>
<td>June 24 - July 26</td>
<td>HAPPEX-H</td>
<td>· about 8M pairs at 600 ppm &lt;br&gt;=&gt; $\delta A_{stat} \sim 0.2$ ppm</td>
</tr>
</tbody>
</table>

**Second run started July 15 ’05**  
*(underway right now...)*
High Resolution Spectrometers

Very clean separation of elastic events by HRS optics

Overlap the elastic line above the focal plane and integrate the flux

Elastic Rate:

$^1\text{H}$: 120 MHz

$^4\text{He}$: 30 MHz

12 m dispersion sweeps away inelastic events

Large dispersion and heavy shielding reduce backgrounds at the focal plane
Focal Plane Detectors

Brass-Quartz Integrating Cerenkov Shower Calorimeter
-Insensitive to background
-Directional sensitivity
-High-resolution
-Rad hard

Two segment “L”-shape covers hydrogen elastic peak

Smaller 4He elastic peak requires only $\frac{1}{2}$ single-segment detector
Electrons scattered at 6 deg sent to the HRS at 12.5 deg.

- Superconducting magnets, sensitive to scattered flux from the target.

- Sweep Magnet, to sit inside the scattering chamber, is being built to protect bore tube from Moller flux in 2005
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 \( \frac{dA}{d\Delta x_{i}} \)
- Simultaneous fit establishes independent sensitivities
- By definition, removes correlation of asymmetry to beam
- Sensitive to highly-correlated beam motion

**“Dithering”:**
- Induce non-HC beam motion with coils, measure \( \frac{dS}{dC_{i}}, \frac{dx_{i}}{dC_{i}} \)
- Relate slopes to \( \frac{dS}{dx_{i}} \)
- Not compromised by correlated beam motion
- Robust, clear signals for failures
- Sensitive to non-linearities
# Raw Asymmetry Corrections

## Hydrogen, '04 run

<table>
<thead>
<tr>
<th></th>
<th>Magnitude</th>
<th>Approximate Correction</th>
<th>Uncertainty Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Asymmetry</td>
<td>-2.6 ppm</td>
<td>-2.6 ppm</td>
<td>5 ppb</td>
</tr>
<tr>
<td>Energy Asymmetry</td>
<td>22 ppb</td>
<td>-120 ppb</td>
<td>12 ppb</td>
</tr>
<tr>
<td>Position Difference</td>
<td>-4 nm</td>
<td>&lt;5 ppb</td>
<td>Negligible</td>
</tr>
<tr>
<td>Angle Difference</td>
<td>-7 nrad</td>
<td>60 ppb</td>
<td>30 ppb</td>
</tr>
</tbody>
</table>
$^4$He Results

Raw Parity-Violating Asymmetry

3.3 M pairs, total width $\sim 1300$ ppm

$A_{\text{raw}}$ correction $< 0.2$ ppm

Helicity Window Pair Asymmetry

$Q^2 = 0.091 \ (GeV/c)^2$

$A_{\text{raw}} = 5.63 \ \text{ppm} \pm 0.71 \ \text{ppm (stat)}$
$^1H$ Results

Raw Parity-Violating Asymmetry

9.5 M pairs, total width ~620 ppm

$A_{\text{raw}}$ correction ~ 0.06 ppm

Helicity Window Pair Asymmetry

$Q^2 = 0.099 \text{ (GeV}/c\text{)}^2$

$A_{\text{raw}} = -0.95 \text{ ppm} \pm 0.20 \text{ ppm (stat)}$
Compton Polarimetry

- photon
- electron

Superlattice: \( P_e = 85-89\% \)
Background

Dedicated runs at very low current using track reconstruction of the HRS

Dipole field scan to measure the probability of rescattering inside the spectrometer

Helium QE in detector: 1.6 +/- 0.8%
Helium QE rescatter: 0.6 +/- 0.6%

Hydrogen Tail + Delta rescatter: <0.2%

Dedicated run with Al Dummy for Al window QE background: <1%
Determining $Q^2$

Asymmetry explicitly depends on $Q^2$:

$$A_{PV} = \frac{-G_F Q^2}{4\pi \alpha \sqrt{2}} \left\{ \left( 1 - 4 \sin^2 \theta_W \right) - \frac{\epsilon G_E^p (G_E^n + G_E^s) + \tau G_M^p (G_M^n + G_M^s)}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \right\}$$

$$Q^2 = 2EE'(1 - \cos \theta)$$

Goal: $\delta Q^2 < 1\%$

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

- Central scattering angle must be measured to $\delta \Theta < 0.5\%$
- Asymmetry distribution must be averaged over finite acceptance
Effective Kinematics

\[ \langle Q^2 \rangle \sim 0.09 \ (\text{GeV/c})^2 \]
measured at low current with Drift Chambers

EMFF dependence of Hydrogen requires a correction factor to relate measured asymmetry to central kinematics.

External radiative corrections are nearly irrelevant: finite detector acceptance is important.

\[ A_v = C A_{\text{meas}} \]

\[ C_{\text{hydro}} = 0.976 \pm 0.006 \]

\[ C_{\text{helium}} = 1.000 \pm 0.001 \]
EM Form Factors


<table>
<thead>
<tr>
<th>FF</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_E^p$</td>
<td>2.5%</td>
</tr>
<tr>
<td>$G_M^p$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$G_E^n$</td>
<td>30%</td>
</tr>
<tr>
<td>$G_M^n$</td>
<td>1.5%</td>
</tr>
<tr>
<td>$G_A^{(3)}$</td>
<td>–</td>
</tr>
<tr>
<td>$G_A^{(8)}$</td>
<td>–</td>
</tr>
</tbody>
</table>
2004 HAPPEX-II Results

**HAPPEX-$^4$He:**

\[ Q^2 = 0.091 \, (\text{GeV/c})^2 \]
\[ A_{PV} = +6.72 \pm 0.84 \, \text{(stat)} \pm 0.21 \, \text{(syst)} \, \text{ppm} \]

\[ A(G_s=0) = +7.507 \, \text{ppm} \pm 0.075 \, \text{ppm} \]

\[ G_E^s = -0.039 \pm 0.041_{\text{(stat)}} \pm 0.010_{\text{(syst)}} \pm 0.004_{\text{(FF)}} \]

**HAPPEX-H:**

\[ Q^2 = 0.099 \, (\text{GeV/c})^2 \]
\[ A_{PV} = -1.14 \pm 0.24 \, \text{(stat)} \pm 0.06 \, \text{(syst)} \, \text{ppm} \]

\[ A(G_s=0) = -1.440 \, \text{ppm} \pm 0.105 \, \text{ppm} \]

\[ G_E^s + 0.08 \, G_M^s = 0.032 \pm 0.026_{\text{(stat)}} \pm 0.007_{\text{(syst)}} \pm 0.011_{\text{(FF)}} \]
2004 HAPPEX-II Results

\[ G^s_E = -0.039 \pm 0.041_{(\text{stat})} \pm 0.010_{(\text{syst})} \pm 0.004_{(\text{FF})} \]

\[ G^s_E + 0.08 \ G^s_M = 0.032 \pm 0.026_{(\text{stat})} \pm 0.007_{(\text{syst})} \pm 0.011_{(\text{FF})} \]

\[ Q^2 = 0.1 \text{ GeV}^2 \]
The near future

• '04 run has demonstrated control over systematic errors
• Expected to achieve full proposed precision in 2005 (underway)
• Suggestions of positive $G_M$ from 2004 data set will be well tested by final HAPPEX-II result
The world data at $Q^2 = 0.1$
2005 HAPPEX-Helium Online Results

- Asymmetry is “blinded”.
- Each $\lambda/2$ setting is $\sim 10$ hrs of data.
New Proposal: HAPPEX at higher $Q^2$

Paschke & Souder, submitted to PAC28
Conclusions

- Marvelous consistency of present data, esp. at $Q^2=0.1 \text{ GeV}^2$.
- $Q^2 = 0.1 \text{ GeV}^2$ data suggest that $G^s_M$ is non-zero and positive.
- 2005 HAPPEX-hydrogen & helium results should clarify situation: pushing the precision frontier...
- Future run at $Q^2 = 0.6 \text{ GeV}^2$ (if approved) of compelling interest given forward-angle GO results.

Many slides shamelessly stolen from various colleagues: K. Kumar, M. Pitt, E. Beise, D. Beck, and especially K. Paschke...
### Error Budget - Helium

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>False Asymmetries</td>
<td>103 ppb</td>
</tr>
<tr>
<td>Polarization</td>
<td>115 ppb</td>
</tr>
<tr>
<td>Linearity</td>
<td>78 ppb</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td>7 ppb</td>
</tr>
<tr>
<td>$Q^2$ Uncertainty</td>
<td>66 ppb</td>
</tr>
<tr>
<td>Al background</td>
<td>14 ppb</td>
</tr>
<tr>
<td>Helium quasi-elastic background</td>
<td>86 ppb</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>205 ppb</td>
</tr>
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</table>
## Error Budget - Hydrogen

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>False Asymmetries</td>
<td>43 ppb</td>
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<tr>
<td>Polarization</td>
<td>23 ppb</td>
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<tr>
<td>Linearity</td>
<td>15 ppb</td>
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<tr>
<td>Radiative Corrections</td>
<td>7 ppb</td>
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<tr>
<td>$Q^2$ Uncertainty</td>
<td>12 ppb</td>
</tr>
<tr>
<td>AI background</td>
<td>16 ppb</td>
</tr>
<tr>
<td>Rescattering Background</td>
<td>32 ppb</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>63 ppb</strong></td>
</tr>
</tbody>
</table>
Present results, and looking ahead

\[ G_E^s + \alpha(Q^2) G_M^s \]

HAPPEX-H 2004 result joins the trend at low \( Q^2 \)

The situation is suggestive, but still ambiguous!

Final anticipated HAPPEX precision has the potential to provide a clear answer.
Controlling Position Differences

Identify and control sources of position differences

- Intrinsic birefringence gradient in the Pockels cell
- Steering from distortions due to piezo-electric deformation of the Pockels cell
- Analyzing power gradients
- Plus: vacuum window, QE hole, transmission, upstream gradients, beam loading, current limit...

Close Collaboration with the Electron Gun Group in analyzing causes and developing solutions

Laser Test Stand studies and Electron Beam studies have been crucial for developing an understanding of these effects.

G.D. Cates, Proceedings from PAVI '04
New "race track" design - 20 cm (transverse cryogen flow)

20 cm LH$_2$
20 cm $^4$He gas cell
Cold (6.6K), dense (230 psi)
Al walls 3-7 mils thick
COMPTON POLARIMETRY

- Non-invasive, continuous polarimetry
- 2% systematic error at 3 GeV
- Independent photon and electron analyses
- Cross-checked with Hall A Moller, 5 MeV Mott
- Requires $\sim 10^{-10}$ halo, 5mm from primary beam
Measuring Central Angle

Novel Water Cell optics target developed
δp between elastic and excited state peaks
reduced systematic error from spectrometer calibration

δθ ~ 0.3% → δQ² ~ 0.7%

$$E' = E_0 - \frac{1}{2} \left( m'^2 - m^2 \right)$$
$$\frac{E_0}{1 + \frac{E_0}{m(1 - \cos \theta)}}$$