Parity-Violating Electron Scattering: Hadron Structure and New Physics

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- Electron scattering
- Parity-violation
- Structure
- New Physics
"Regular" Electron Scattering

The EM interaction does not violate parity
Parity-violation in electron scattering?

Interference term in cross-section violates parity.
Structure

- Decomposition of the proton's electromagnetic form factors into contributions from up, down, and strange quarks.

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

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

\[
G_{E,M}^{Z,p} = \left(1 - \frac{8}{3} \sin^2 θ_W\right) G_{E,M}^{u,p} + \left(-1 + \frac{4}{3} \sin^2 θ_W\right) G_{E,M}^{d,p} + \left(-1 + \frac{4}{3} \sin^2 θ_W\right) G_{E,M}^{s,p}
\]

- And axial structure!
At tree level in the standard model:

\[ Q^p_{weak} = 1 - 4 \sin^2 \theta_W \]

A sensitive, low-energy extraction of the weak mixing angle.
Structure

- Strange quark form factors
- Inelastic scattering, axial transition form factors
- Pb neutron skin
- (Transversely polarized beams)
Parity-violating Asymmetry

\[ A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[ -\frac{G_F Q^2}{4 \pi^2 \sqrt{2}} \right] \frac{A_E + A_M + A_A}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2} \]

- \( A_E = \varepsilon(\theta) \, G_E^Z(Q^2) G_E^\gamma(Q^2) \)
- \( A_M = \tau(Q^2) \, G_M^Z(Q^2) G_M^\gamma(Q^2) \)
- \( A_A = -(1 - 4 \sin^2 \theta_W) \varepsilon' \, G_A^e(Q^2) G_M^\gamma(Q^2) \)

Program of the last two decades:
- Measure at forward and backward angles, on a variety of targets.
Strange-quark Experiments

- SAMPLE (MIT-Bates)
- HAPPEx I, II, and III (JLab)
- G0 (JLab)
- A4 (MAMI)

- A variety of techniques used to measure with (sub)ppm precision in a scattering experiment.
- Feedback to the injector on helicity-correlated beam properties measured in the experimental hall.
Basic Experiment

- High rates $\sim$ MHz.
Helicity-Correlated Systematics

must have excellent control of all “helicity-correlated” beam properties (in this case at 1 nm level)
Results as of last year

(HAPPEX on the next slide)

Note: \( G_E^s \) and \( G_A \)
New: HAPPEX III Results

See: M. Dalton, Session 1A, and global fit
New: A4 Experiment
Preliminary LD2 results

Thank you to S. Baunack.
Strange-quark Summary

- No large or obvious contributions of strange vector form factor in this range of $Q^2$. Contributions limited to the few percent level.

- Some enticing results on the axial form factor.
  - Is it being suppressed by electroweak radiative corrections?

- Results being analyzed by A4 at $Q^2 = 0.6 \text{ GeV}^2$. Future running at $Q^2 = 0.1 \text{ GeV}^2$ by A4.
Inelastic Scattering in the Resonance Region

- Determination of N->Delta axial transition form factors using PV electron scattering
- An interesting suggestion by Zhu et al (based partly on hyperon radiative decay) that the electroweak radiative corrections for this process might also be large.
- Zhu et al suggested the PV asymmetry could be as large as $\pm 5$ ppm at $Q^2 = 0$ (that's very large, by my standards).
G0 Inclusive Pions Results

- Pion photoproduction asymmetry extracted:

\[ A_\gamma^- = -0.36 \pm 1.06 \pm 0.37 \pm 0.03 \text{ ppm} \]

A. Coppens, PhD thesis (U. Manitoba, 2010).
G0 Collaboration – in preparation.

- The possibility of an unexpectedly large PV asymmetry in pion photoproduction has been limited to the ppm level.

- More results, in inclusive electron scattering, expected from G0 (higher $Q^2$) and Qweak (lower $Q^2$) soon.
Weak Charge Distribution of Heavy Nuclei

Nuclear theory predicts a neutron "skin" on heavy nuclei

Neutron distribution is challenging to interpret from strongly interacting probes (protons, pions, etc.), and is not accessible to the charge-sensitive photon.

But the weak interaction sees the neutrons clearly:

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric charge</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Weak charge</td>
<td>~0.08</td>
<td>1</td>
</tr>
</tbody>
</table>

PREX (Pb-Radius EXperiment)

$Q^2 \sim 0.01 \text{ GeV}^2$

$5^\circ$ scattering angle $\rightarrow A_{PV} \sim 0.6 \text{ ppm}$

Rate $\sim 1.5 \text{ GHz}$

$M_{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$

$M_{PV}^{NC} = \frac{G_F}{\sqrt{2}} \left[ (1 - 4\sin^2 \theta_W) F_p(Q^2) - F_n(Q^2) \right]$ $A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha \sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$
PREX Interpretation

First electroweak observation of the neutron skin of a heavy nucleus (CL = 95%)

Projected error bar for proposed follow up

Neutron Skin = $R_N - R_P = 0.34 + 0.15 - 0.17$ fm

Preliminary estimate from C.J. Horowitz

Thank you, K. Paschke
Parity-Violating Electron Scattering
and New Physics
New Physics

As $Q^2 \to 0$

- **Measure** $\sin^2 \theta_w$ **using:**
  - Moller (ee)
  - Elastic (ep)
  - Deep-inelastic (eq)

PV electron scattering to probe the weak charges of electrons, protons, and quarks

<table>
<thead>
<tr>
<th>Species</th>
<th>Charge</th>
<th>Weak Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>$+\frac{2}{3}$</td>
<td>$1-\frac{8}{3}\sin^2 \theta_w$</td>
</tr>
<tr>
<td>d</td>
<td>$-\frac{1}{3}$</td>
<td>$-1+\frac{4}{3}\sin^2 \theta_w$</td>
</tr>
<tr>
<td>s</td>
<td>$-\frac{1}{3}$</td>
<td>$-1+\frac{4}{3}\sin^2 \theta_w$</td>
</tr>
<tr>
<td>p</td>
<td>1</td>
<td>$1-4\sin^2 \theta_w$</td>
</tr>
<tr>
<td>e</td>
<td>-1</td>
<td>$-1+4\sin^2 \theta_w$</td>
</tr>
</tbody>
</table>
What New Physics?

- Z-exchange could compete with:

\[ \text{leptoquark} \]  
\[ e \rightarrow p \]

\[ \text{Z'} \]  
\[ e \rightarrow p \]

\[ \text{SUSY} \]

which would affect the running of \( \sin^2 \theta_w \) with energy.
Running of $\sin^2 \theta_w$
Experiments

- **Past:**
  - SLAC E122 – PV deep-inelastic scattering of D2
  - SLAC E158 – PV Moller scattering

- **Present:**
  - Qweak (PV Elastic ep at JLab)
  - PV DIS at 6 GeV (JLab)

- **Future:**
  - Moller (JLab 11 GeV)
  - SOLID (PV DIS at JLab 11 GeV)
  - P2 (PV elastic ep at MAMI)
Complementary Diagnostics for New Physics

- Elastic, deep-inelastic (semi-leptonic) and Moller (pure leptonic) scattering experiments together make a powerful program to search for and identify new physics. Erler, Kurylov, Ramsey-Musolf, PRD 68, 016006 (2003)
Qweak Experiment

- Elastic scattering at forward angle
- Longitudinally polarized electrons
- Rapid helicity-flip: 960 Hz
- Low momentum transfer: \( Q^2 = 0.027 \text{ (GeV/c)}^2 \)

Expect: \( A_{PV} \approx -230 \text{ ppb} \)

\( \approx 5 \text{ ppb} \) statistical error in \( \sim 2200 \text{ hours} \)

Use eight detectors, 800 MHz each, in "current integrating mode"

2.5% on \( A_{PV} \)  
4% on \( Q_{\text{weak}} \)  
0.3% on \( \sin^2 \theta_W \)

See: R. Carlini, Session 3G
- Scanner detector for current mode tracking results
- New Compton polarimeter has produced %/hr relative measurements.
Main Detectors

Eight fused silica bars with dimensions 200 x 18 x 1.25 cm
Cerenkov radiator
low noise electronics; high precision ADCs
radiation hard
background insensitive
preradiated to boost signal and kill backgrounds

QTOR focuses the elastically scattered electrons onto each bar
Polarimetry

Motivation:
1% measurement of polarization

Moller (invasive)
Compton Photon (noninvasive)
Compton Electron (noninvasive)
Qweak Status

- First commissioning beam  July 2010
- Commissioning    Fall 2010
- “Run I”       Jan - May 2011
- “Run II”       Nov 2011 - May 2012

Beam: routine data-taking at 165 $\mu$A, tests up to 180 $\mu$A (scheduled for 150 $\mu$A)
    - $\approx 86-89\%$ polarization
    - helicity-correlated properties acceptable

Some teething pains:  Target pump, Toroid power supply, beam dump vacuum,…

At present: have “in hand” $\approx 1/4$ of proposed statistics

Initial Auxiliary measurements done:
    - APV for Aluminum  (target windows)
    - APV for
    - Parity-conserving transverse asymmetry
        (each valuable and competitive measurements on their own)

See:  R. Carlini, Session 3G
### Electroweak Radiative Corrections

#### Estimates of Zy box diagram on $Q^p_{\text{weak}}$

<table>
<thead>
<tr>
<th>Source</th>
<th>$Q^p_{\text{weak}}$ Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sin \theta_W (M_Z)$</td>
<td>±0.0006</td>
</tr>
<tr>
<td>$Z\gamma$ box</td>
<td>±0.0003</td>
</tr>
<tr>
<td>$\Delta \sin \theta_W (Q)_{\text{hadronic}}$</td>
<td>±0.0001</td>
</tr>
<tr>
<td>$WW, ZZ$ box - pQCD</td>
<td>0</td>
</tr>
<tr>
<td>Charge symmetry</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>±0.0008</td>
</tr>
</tbody>
</table>

(c.f. $Q^p_{\text{weak}} \approx 0.07$)

Erler, Kurylov, Ramsey-Musolf

Phys. Rev. Lett. 102, 091806 (2009)

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Gorchechin & Horowitz

Phys. Rev. Lett. 102, 091806 (2009)

- 7%

Sibirtsev, Blunden, Melnitchouk, Thomas


- 6.6

+1.5%

- 0.6%

Rislow and Carlson

arXiv:1011.2397

8.0 ± 1.3%

See: C. Carlson, Session 1A

Gorchechin, Horowitz, Ramsey-Musolf

arXiv:1102:3910

7.6 ± 2.8%
E08-011 Measurement of PV Asymmetry in e-D Deep Inelastic Scattering (PVDIS) Using a 6 GeV Beam at JLab

- e-D PVDIS asymmetry:

\[ A_d = (540 \text{ ppm}) Q^2 \frac{2 C_{1u} [1 + R_C(x)] - C_{1d} [1 + R_S(x)] + Y (2 C_{2u} - C_{2d}) R_V(x)}{5 + R_S(x) + 4 R_C(x)} \]

Standard Model Neutral Weak Couplings:

- \( C_{1q} = g_A^e g_V^q \)
- \( C_{2q} = g_V^e g_A^q \)

\[ R_S(x) = \frac{2 [s(x) + \bar{s}(x)]}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)} \quad R_C(x) = \frac{2 [c(x) + \bar{c}(x)]}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)} \quad R_V(x) = \frac{u_V(x) + d_V(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)} \]

- E08-011: measured \( A_d \) at \( Q^2 = 1.1 \) and 1.9 GeV\(^2\), to statistical precision of 3% and 4%, respectively.
- 100 microA, 90% polarized beam
- 20-cm LD2 target, two standard spectrometers collecting electrons independently.
- Custom-built scaler-counting DAQ with hardware-based PID to accommodate ~500kHz rate
- Ran in October-December 2009, expect to unblind the asymmetries by end of 2011.

See: Kai Pan, Session 1A

Thank you, X. Zheng
Expected Results on $C_{2q}$ from E08-011 all are $1\sigma$ limit

Best world data: $\Delta(2C_{2u} - C_{2d}) = 0.24$

Expected: JLab 6 GeV PV-DIS E08-011
(assuming small hadronic effects and a 4% stat error on Ad)
**MOLLER Apparatus**

- **Polarized Beam**
  - Unprecedented polarized luminosity
  - Unprecedented beam stability

- **Liquid Hydrogen Target**
  - 5 kW dissipated power (2 x Qweak)
  - Computational fluid dynamics

- **Toroidal Spectrometer**
  - Novel 7 “hybrid coil” design
  - Warm magnets, aggressive cooling

- **Integrating Detectors**
  - Build on Qweak and PREX
  - Intricate support & shielding
  - Radiation hardness and low noise
  - Compact structure: plan to make apparatus and shielding easily removable

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K. Kumar

The MOLLER Project at Jefferson Laboratory
SoLID Spectrometer

Babar Solenoid

Gas Cerenkov

Shashlyk Calorimeter

Baffles

GEM’s

International Collaborators:
China (Gem’s)
Italy (Gem’s)
Germany (Moller pol.)

JLab/UVA prototype

See: P. Souder, Session 1A
New project: P2

- Measurement of the weak charge of the proton at low $Q^2 \sim 0.0022$ GeV$^2$
- New detector
- Enhanced polarimetry (*Brute force Moller, Double Mott => Mainz 0.5*)
- Beam energy 137 MeV (*low theoretical uncertainties due to two-boson-exchange*)
- Precision goal: $\Delta \sin^2 \Theta_W = 0.0003$ (1%)
- Time scale: 2015 - 2020

Being considered for MAMI accelerator at Mainz

Thank you, S. Baunack.
In different TeV-scale new physics scenarios, the future points could be scattered about, ...even appearing on different sides of the curve!
Summary

- Parity-violating electron scattering is a useful tool to study hadron structure and to probe new physics beyond the standard model.

- The field is in an exciting period where past investments in the use of this technique for structure studies are transitioning to precision measurements of standard model parameters.

- Complementary to other neutral-current techniques (please come to session 3G, this afternoon)

- There are many opportunities and a long-term future in this exciting field.
Acknowledgments

- Thank you to: