Testing Fundamental Symmetries with Parity-Violating Electron Scattering

David S. Armstrong
College of William & Mary

(Qweak, HAPPEX, GO Collaborations)

APS April Meeting Denver May 3 2009
Outline

• Precision tests of Standard Model
• Parity-violation in electron scattering
  Early work: SLAC E122 etc.
  Recent work: Strange form factors
• Weak Charges
• Physics Reach of Weak charge of proton
• Qweak experiment at JLab
• After Qweak

• Conclusions
Precision Tests of the Standard Model

• Received Wisdom: *Standard Model is the effective low-energy theory of underlying more fundamental physics*

• Finding new physics: Two complementary approaches:
  - **Energy Frontier** (direct): *eg. Tevatron, LHC*
  - **Precision Frontier** (indirect): (aka *Intensity Frontier*)
    *eg.*
    - $\mu(g-2)$, EDM, $\beta\beta$ decay, $\mu \rightarrow e \gamma$, $\mu A \rightarrow e A$, $K^+ \rightarrow \pi^+ \nu \nu$, etc.
    - $\nu$-oscillations
    - Atomic Parity violation
    - Parity-violating electron scattering

*Hallmark of Precision Frontier:*
choose observables that are *zero or suppressed* in Standard Model

*Often at modest or low energy...*

When new physics found in direct measurements, precision measurements useful to determine e.g. couplings...
Parity Violating Electron Scattering:
Weak Neutral Current Amplitudes

\[ M^{EM} = \frac{4\pi\alpha}{Q^2} Q \ell^\mu J_{\mu}^{EM} \]
\[ M^{NC}_{PV} = \frac{G_F}{2\sqrt{2}} \left[ g_A \ell^\mu J_{\mu}^{NC} + g_V \ell^\mu J_{\mu5}^{NC} \right] \]

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

scatter electrons of opposite helicities from unpolarized target

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

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

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

First discussed: Ya. B Zel'dovich JETP 36 (1959)
We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6 \text{ (GeV/c)}^2$ the asymmetry is $(\sim 9.5 \times 10^{-3})Q^2$ with statistical and systematic uncertainties each about 10%.

Pivotal to establishing Weinberg-Salam-Glashow SU(2)×U(1) gauge theory

Techniques
Optically pumped electron source: rapid helicity reversal,
integrate scattered flux
monitor & feedback to control electron beam fluctuations

Followed by:
1989: Mainz $^9$Be
  W. Heil et al.
1990: MIT/Bates $^{12}$C
  P.A. Souder et al.
# Weak Charges

**Govern strength of neutral current interaction with fermion**

<table>
<thead>
<tr>
<th>Charge Particle</th>
<th>Electric</th>
<th>Weak (vector)</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>+2/3</td>
<td>-2C_{1u} = 1 - 8/3 \sin^2\theta_W</td>
</tr>
<tr>
<td>d</td>
<td>-1/3</td>
<td>-2C_{1d} = -1 + 4/3 \sin^2\theta_W</td>
</tr>
<tr>
<td><strong>Proton</strong></td>
<td>+1</td>
<td>( Q_W^p = 1 - 4 \sin^2\theta_W \approx 0.07 )</td>
</tr>
<tr>
<td><strong>Neutron</strong></td>
<td>0</td>
<td>( Q_W^n = -1 )</td>
</tr>
</tbody>
</table>

Note "accidental" suppression of \( Q_W^p \)

→ *sensitivity to new physics*

For axial couplings: \( C_{2u} \) and \( C_{2d} \)
All Data & Fits
Plotted at 1 \( \sigma \)

\[
Q_{\mu}^w = -2(2C_{1u} + C_{1d})
\]
Running of $\sin^2 \theta_W$

PDG 2008 Review: "Electroweak and constraints on New Physics Model"
J. Erler & P. Langacker
Running of $\sin^2\theta_W$ : recent developments

1) Atomic Parity Violation ($^{133}\text{Cs}$): W.G. Porsev, K. Beloy, A. Derevianko

   New calculation of many-body atomic theory (up to triple excitations)
   in $6S_{1/2} \rightarrow 7S_{1/2}$ transition (100 Gb basis set)

   $Q_W(^{133}\text{Cs})^{\exp} : -73.25 \pm 0.29 \pm 0.20$
   $Q_W(^{133}\text{Cs})^{SM} : -73.16 \pm 0.03$

2) NuTeV anomaly: originally quoted 3σ violation of Standard Model

   • Erler & Langacker include corrections due to asymmetry in strange quark PDFs (from NuTeV and CTEQ)
   • Charge Symmetry violations (eg Londergan & Thomas PL B 558(2003)132 )
     (u/d quark mass difference) account for 1σ

   → vector mean fields in nucleus modifies in-medium PDFs
   claims entire anomaly accounted for
Weak Charges from Existing PVES experiments

A “strange” digression..
- recent program of elastic (quasi-elastic) parity-violation experiments measuring strange quark contributions to nucleon vector form factors...

Parity-violating asymmetry sensitive to both weak charges and to hadron structure

recall Kent Paschke’s plenary talk  Saturday AM
Hadron Structure effects

\[ A_{PV}^{\sigma} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[ \frac{-G_F Q^2}{\pi \alpha \sqrt{2}} \right] \frac{\epsilon G_E^{P\tau} G_{E}^{PZ}}{\epsilon (G_{E}^{P})^2 + \tau (G_{M}^{P})^2} \]  

Neutral-weak form factors

\[ 4G_{E,M}^{PZ} = (1 - 4\sin^2 \theta_W) G_{E,M}^{P\tau} - G_{E,M}^{n\tau} - G_{E,M}^{s} \]

Proton weak charge (tree level)

Strangeness

Assume charge symmetry:

Axial form factor
Strange form factor program

- **SAMPLE** (MIT/Bates) \( Q^2 = 0.1 \)
- **HAPPEX-I** (JLab/Hall A) \( Q^2 = 0.48 \)
- **PV-A4** (MAMI) \( Q^2 = 0.23, 0.11 \)
- **GO** (JLab/Hall C) \( Q^2 = 0.12 \rightarrow 1.0 \)
- **HAPPEX-II/helium** (JLab/Hall A) \( Q^2 \approx 0.1 \)
- **PV-A4** (backward) \( Q^2 = 0.22 \) (PRL 102, 151803 (2009))

- **GO** (backward) \( Q^2 = 0.23, 0.63 \) (completed)*
- **HAPPEX-III** (forward) \( Q^2 = 0.63 \) (Aug-Oct 2009)

*analysis recently unblinded; results to be released May 20
Proton Strange form factors: a snapshot

Marvelous consistency of difficult experiments!

What about weak charge?

Figure appeared in NSAC 2007 Long Range plan
Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$

(R.D. Young et al. PRL 99, 122003 (2007))

\[ A_{LR}^p = A_z / \left( -G_F Q^2 / 4\pi \alpha \sqrt{2} \right) = Q_{\text{weak}}^p + Q^2 B(Q^2) \]

1σ bound from global fit to all PVES data (as of 2007)
All Data & Fits Plotted at 1 \( \sigma \)

\[ Q^p_{IV} = -2(2C_{1u} + C_{1d}) \]

Standard Model Prediction

HAPPEx: H, He
G\(^0\): H,
PVA4: H
SAMPLE: H, D

Isovector weak charge

Isoscalar weak charge
All Data & Fits Plotted at 1 σ

\[ Q_{\text{wr}}^T = -2(2C_{1u} + C_{1d}) \]

Young, Carlini, Thomas & Roche, PRL
Energy Scale of an Indirect Search

- Estimate sensitivity to new physics Mass/Coupling ratio
  → add new contact term to the electron-quark Lagrangian:

  \[ \mathcal{L}_{PV}^{e-q} = \mathcal{L}_{SM}^{PV} + \mathcal{L}_{New}^{PV} \]

  \[ = \frac{G_F}{\sqrt{2}} \bar{e} \gamma_{\mu} \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_{\mu} \gamma_5 e \sum_q h^q_v \bar{q} \gamma^\mu q \]

  \[ \Lambda = \text{mass} \quad g = \text{coupling} \]

  \[ \frac{\Lambda}{g} = \frac{1}{\sqrt{\sqrt{2}G_F}} \cdot \frac{1}{\sqrt{\Delta Q_W(p)}} \]

  TeV scale can be reached with a 4% Qweak experiment.
  If Qweak didn’t happen to be suppressed, would have to do a 0.4% measurement to reach the TeV-scale.
New Physics Reach

Erler et al., PRD68(2003)

$$L^\text{PV}_{\text{SM}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma^\mu \gamma_5 e \sum_q C_{1q}^\text{SM} \bar{q} \gamma^\mu q$$

$$L^\text{PV}_{\text{NP}} = -\frac{g^2}{4\Lambda^2} \bar{e} \gamma^\mu \gamma_5 e \sum_q h^q_V \bar{q} \gamma^\mu q$$

Arbitrary quark flavour dependence of new physics:

$$h^u_V = \cos \theta_h \quad h^d_V = \sin \theta_h$$

Data sets limits on: $$\frac{g^2}{\Lambda^2}$$
Lower Bound for "Parity Violating" New Physics

\[ \Lambda_{PV} \] (TeV)

\begin{align*}
\frac{\pi}{2} & \quad \pi & \quad \frac{3\pi}{2} & \quad 2\pi \\
\theta_h & \quad \frac{\pi}{2} & \quad \frac{3\pi}{2} & \quad 2\pi \\
0.1 & \quad 0 & \quad \pi & \quad 2\pi
\end{align*}

95% CL

Atomic PV only
Lower Bound for "Parity Violating" New Physics

New PV physics scale $> 0.9$ TeV! (from 0.4 TeV)
Lower Bound for “Parity Violating” New Physics

Qweak constrains new PV physics to beyond 2 TeV

95% CL

Qweak (4%) with PVES
Atomic only

Analysis by R.D. Young et al.
New Physics: Examples

• Extra neutral gauge bosons: \( Z' \) e.g. \( E6 \to SO(10) \times U(1)_\psi \) GUT, SUSY, left/right symmetric models, technicolor, string theories...

• Composite fermions

• Leptoquarks (scalar LQs can arise in R-parity violating SUSY)


Direct search at Tevatron: \( M_{Z'\psi} > 0.82 \) TeV
CDF  PRL 99 (2007)171802
Complementarity of proton & electron weak charge

**JLab Qweak**

- \( Q_W^p = 0.0716 \pm 0.0029 \)
  - Experiment
  - SUSY Loops
  - \( E_6 Z' \)
  - RPV SUSY
  - Leptoquarks
  - SM

**SLAC E158**

- \( -Q_W^e = 0.0449 \)

- **Qweak** measurement will provide a stringent stand alone constraint on Leptoquark based extensions to the SM.

- \( Q_{p\text{weak}} \) (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.
Electroweak Global Fit

1σ contours:
- $A_{LR}^{(had.)}$ [SLC]
- $A_{FB}(b)$ [LEP]
- $M_W$
- low-energy
- $m_t$

Figure courtesy of Jens Erler
The QWeak Collaboration


¹Spokespersons
²Project Manager

College of William and Mary, University of Connecticut, Instituto de Fisica, Universidad Nacional Autonoma de Mexico, University of Wisconsin, Hendrix College, Louisiana Tech University, University of Manitoba, Massachusetts Institute of Technology, Thomas Jefferson National Accelerator Facility, Virginia Polytechnic Institute & State University, TRIUMF, University of New Hampshire, Yerevan Physics Institute, Mississippi State University, University of Northern British Columbia, Ohio University, Hampton University, University of Winnipeg, University of Virginia, George Washington University, Syracuse University, Idaho State University, University of Connecticut, Christopher Newport University
QWeak Experiment Overview

• Forward-angle elastic scattering 1.16 GeV e’s from proton at 8°
  \[ Q^2 = 0.026 \text{ (GeV/c)}^2 \]
  Hall C at Jefferson Lab
• Expected Asymmetry: 234 parts per billion
• Capitalize on success/techniques of PV program
• Installation begins November 2009
• Runs June 2010 to May 2012
  - Final expt. in Hall C before 12 GeV upgrade

Some Challenges:
• 6.5 GHz rate – rad-hard detectors  (see D. Mack’s talk - J10 5)
• 2.5 kW cryogenic lH\textsubscript{2} target  (see S. Covrig’s talk - J10 6)
• Helicity-correlated beam properties:
  intensity <0.1 ppm  position <2 nm  angle < 30 nrad
  diameter <0.7 \textmu m  energy \( \Delta E/E < 10^{-9} \)
• 1% precision on electron beam polarization
# Error Budget

2% on $A_{PV} \approx 4\%$ on $Q_w \approx 0.3\%$ on $\sin^2\theta_W$

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\Delta A_{PV}/A_{PV}$</th>
<th>$\Delta Q_w/Q_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical (2,544 hours at 180 $\mu$A)</td>
<td>2.1%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Systematic:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hadronic structure uncertainties</td>
<td>---</td>
<td>1.5%</td>
</tr>
<tr>
<td>Beam polarimetry</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Absolute $Q^2$ determination</td>
<td>0.5%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Helicity correlated beam properties</td>
<td>0.5%</td>
<td>0.7%</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>2.5%</strong></td>
<td><strong>4.1%</strong></td>
</tr>
</tbody>
</table>

$$\overline{A_{LR}^p} = A_z/(-G_F Q^2/4\pi \alpha \sqrt{2}) = Q_{weak}^p + Q^2 B(Q^2)$$

Final error on $\Delta \sin^2\theta_W / \sin^2\theta_W$ includes QCD uncertainties (1-loop) in calculation of the running $0.2\% \rightarrow 0.3\%$. 
Schematic of the QWeak Experiment

Elastically Scattered Electron

Region III Drift Chambers

Toroidal Magnet

Region II Drift Chambers

Region I GEM Detectors

Primary Collimator with 8 openings

35 cm Liquid Hydrogen Target

Polarized Electron Beam, 1.165 GeV, 150 µA, P ~ 85%

Eight Fused Silica (quartz) Čerenkov Detectors - Integrating Mode

Luminosity Monitors

Region I, II and III detectors are for $Q^2$ measurements at low beam current

~3.2 m
QWeak experiment
Qweak Magnet

Experiment on track for first beam  May 2010
What’s after Qweak?

• PVDIS: Parity-violating Deep Inelastic Scattering at 11 GeV JLab
  → go after $C_{2u}$ and $C_{2d}$ and higher-twist in nucleon
    Exploratory 6 GeV version to run this Fall in Hall A

• Parity-violating Moller (e-e) scattering at 11 GeV/JLab
  → improve on E158 precision
    experiment approved this January
Parity-violating Moller at 11 GeV

**Goal:** measure 36 ppb asymmetry with 0.7 ppb error
Would determine $Q_{\text{weak}}^e$ to 2.3%  
$\sin^2 \theta_W$ to ±0.00026(stat) ±0.00013(syst)

competitive with most precise collider data at Z-pole

Novel two-toroid spectrometer exploits identical particles topology to capture full azimuthal acceptance

Physics reach to 7.5 TeV
Moller experiment with JLab upgrade
Conclusion

• Parity-violating electron scattering useful tool in arsenal of precision tests of Standard Model

• Already providing constraints on new physics

• Qweak experiment at JLab will extend reach in TeV scale for certain classes of new physics

• Program developing for major PV experiments for 12 GeV upgraded JLab

- finis -
Electroweak Radiative Corrections

<table>
<thead>
<tr>
<th>Source</th>
<th>$Q^p_{Weak}$</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sin \theta_W (M_Z)$</td>
<td>±0.0006</td>
<td></td>
</tr>
<tr>
<td>$Z\gamma$ box</td>
<td>±0.0005</td>
<td></td>
</tr>
<tr>
<td>$\Delta \sin \theta_W (Q)_{hadronic}$</td>
<td>±0.0003</td>
<td></td>
</tr>
<tr>
<td>WW, ZZ box - pQCD</td>
<td>±0.0001</td>
<td></td>
</tr>
<tr>
<td>Charge symmetry</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>±0.0008</td>
<td></td>
</tr>
</tbody>
</table>


Estimates of 2 Boson Exchange effects on $A_{PV}$ at $Q_{weak}$ Kinematics

TPE (Blunden et.al.) -0.05%
TBE (Tjon, Blunden, Melnitchouk) 0.13% (N and $\Delta$)
TBE (Gorchtein & Horowitz) ~ 6% (dispersion relations)

$Q^p_{Weak}$ Standard Model ($Q^2 = 0$) 0.0713 ± 0.0008
$Q^p_{Weak}$ experiment precision goal ± 0.003