First Results from Qweak

P.M. King
Ohio University
for the Qweak Collaboration

Sixth Asia-Pacific Conference on Few-Body Problems in Physics
6 April 2014, Hahndorf, SA
Overview

- Qweak measures the parity violating elastic asymmetry in e-p scattering at $Q^2 = 0.025 \text{ GeV}^2$ in order to extract $Q_w(p)$ and $\sin^2 \theta_w$
  - Deviation from SM expectations would be a sign of new physics with a TeV mass-scale

- Qweak had three running periods in Hall C at Jefferson Lab
  - Run 0: (Jan-Feb 2011); about 1/25 of the total data set.
  - Run 1 (Feb-May 2011)
  - Run 2 (Nov 2011-May 2012) Ongoing analysis; results likely within a year or so

- Several ancillary measurements were taken to determine or constrain background processes or corrections
Parity-Violating Electron Scattering

Parity violated in the weak interaction: form a parity-violating asymmetry

\[
\mathcal{M}^{EM} \propto \frac{1}{Q^2} \quad \mathcal{M}^{NC}_{PV} \propto \frac{1}{M_Z^2 + Q^2}
\]

\[
\sigma \propto |\mathcal{M}^{EM}|^2 + 2\mathcal{M}^{EM}\mathcal{M}^{NC}_{PV} + |\mathcal{M}^{NC}_{PV}|^2
\]

Parity violated in the weak interaction: form a parity-violating asymmetry

\[
A_{PV}(p) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \quad \text{when } Q^2 \ll M_Z^2
\]
Parity violating electron scattering

\[ A_{LR} = \frac{-G_\mu}{4\pi\alpha\sqrt{2}} \left[ \varepsilon G_E^y G_E^Z + \tau G_M^y G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^y G_A^e \right] \frac{\varepsilon(G_E^y)^2 + \tau(G_M^y)^2}{\varepsilon G_E^2} \]

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

\[ A_{LR}^p \equiv \frac{A_{LR}^p}{-(G_\mu/4\pi\alpha\sqrt{2}) Q^2} \]

\[ A_{LR}^p = Q_{\text{weak}}^p + Q^2 B(Q^2) \]
Weak Charges

Electron-quark scattering, four-fermion contact interaction

\[ \mathcal{L}_{eq}^{PV} = -\frac{G_F}{\sqrt{2}} \sum_i \left[ C_{1i} \bar{e} \gamma_\mu \gamma_5 e \overline{q} \gamma^\mu q + C_{2q} \bar{e} \gamma_\mu \overline{q} \gamma^\mu \gamma^5 q \right] + \mathcal{L}_{new}^{PV} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>Electric charge</th>
<th>Weak vector charge ((\sin^2 \theta_W \approx \frac{1}{4}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>-1</td>
<td>(Q_e^w = -1 + 4 \sin^2 \theta_W \approx 0)</td>
</tr>
<tr>
<td>u</td>
<td>+(\frac{2}{3})</td>
<td>(-2C_{1u} = +1 - \frac{8}{3} \sin^2 \theta_W \approx +\frac{1}{3})</td>
</tr>
<tr>
<td>d</td>
<td>-(\frac{1}{3})</td>
<td>(-2C_{1d} = -1 + \frac{4}{3} \sin^2 \theta_W \approx -\frac{1}{3})</td>
</tr>
<tr>
<td>p(uud)</td>
<td>+1</td>
<td>(Q_p^W = 1 - 4 \sin^2 \theta_W \approx 0.07)</td>
</tr>
<tr>
<td>n(udd)</td>
<td>0</td>
<td>(Q_n^W = -1)</td>
</tr>
</tbody>
</table>

Note “accidental” suppression of \(Q^{weak}_p\); this leads to sensitivity to New Physics
Sensitivity to new physics

- Suppose some new physics adds a contact term to the PV electron-quark Lagrangian, with coupling constant, $g$, and mass, $\Lambda$:


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

$$= -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_1 q \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_V^q \bar{q} \gamma^\mu q$$

$$\frac{\Lambda}{g} \sim (\sqrt{2} G_F \Delta Q_W^p)^{-\frac{1}{2}} \sim O(\text{TeV})$$
Qweak Overview

Jefferson Lab (6 GeV Era)

Qweak Installation: May 2010-May 2012

~1 year of beam in 3 running periods:
- Run 0
  Jan – Feb 2011
- Run 1
  Feb – May 2011
- Run 2
  Nov 2011 – May 2012

Asymmetry ~250 ppb
Error goal ~5 ppb
Qweak Apparatus

Production Mode:
180 μA, Integrating

- e-beam
- E = 1.16 GeV
- I = 180 μA
- P = 88%

- 35 cm LH$_2$ target
- Acceptance-defining Pb collimator
- Toroidal Spectrometer
- High-density concrete shielding wall
- Quartz Bar Detectors 8-fold symmetry
**Production Mode:**
180 μA, Integrating

**Tracking Mode:**
50 pA, Counting
($Q^2$ Systematics)

- **$E = 1.16$ GeV**
- **$I = 180$ μA**
- **$P = 88\%$**

- 35 cm LH$_2$ target
- e- beam
- **Toroidal Spectrometer**
- **Vertical Drift Chambers**
- **Horizontal Drift Chambers**
- **8-fold symmetry**
- **Quartz Bar Detectors**
- **Trigger Scintillators**
- **Acceptance-defining Pb collimator**
- **High-density concrete shielding wall**
Qweak During Installation

- Toroidal Spectrometer
- Acceptance-defining Pb collimator
- e-beam
- Quartz Bar Detectors
- High-density concrete shielding wall

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Target Design and Performance

- 35 cm LH$_2$ (4% X$_0$)
  - 20K, 30-35 psia
  - ~3 kW power
- Designed using CFD

Target “Boiling” Noise:
- target density fluctuations

Beam Raster Size Scan @ 182 μA

47 ppm/quartet; small contribution to ~230 ppm width from statistics
Main Detectors

- Eight 2m long radiation-hard fused silica Čerenkov detectors

Azimuthal Symmetry

Electrons focused on detectors by QTOR
Photons show collimator aperture shape

Installed 2cm lead pre-radiators

Measured profile in 6 o'clock octant
Kinematics Determination

- Drift chambers before and after magnetic field
- Low current, reconstruct individual events
- Systematic studies

Measure light-weighted acceptance ($Q^2$ varies by factor of 2 over acceptance)

Projection of Hits at Detector

$Q^2$ Distribution in Octant 1 (Sim & Data)

Simulation
Data

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Precision Polarimetry

- Two independent devices for <1% polarization

**Møller**
- low current only, invasive

**Compton: Photon and Electron**
- continuous measurement, high current
Measurement process

- “Helicity windows” occur at about 960 Hz
- Groups of four windows have helicity pattern +--+- or -++- chosen pseudorandomly
- Helicity reporting is delayed
- Detector and beam monitor signals are integrated over the window
- Asymmetries are constructed for each pattern
  \[ A = \frac{Y_+ - Y_-}{Y_+ + Y_-} \]
Beam Parameter Corrections

- Helicity correlated beam parameter variations can produce an asymmetry in the detectors
  - Symmetric detectors give partial cancellation
  - Large HC beam variations can be reduced by retuning
  - Measured detector-beam correlations can provide a correction

\[
A_{\text{corr}} = \sum_{i=1}^{5} \left( \frac{\partial A}{\partial x_i} \right) \Delta x_i
\]

\((x,x',y,y',E)\)

Example: Detector Sensitivity to X position variation

Regression Correction from Qweak "Wien0"

(PRL 111, 141803): \(A_{\text{corr}} = -35 \pm 11\) ppb
Beam Parameter Corrections

- Two ways to determine sensitivity of the detector asymmetries to beam parameter variations
  - Regression: Natural jitter of beam parameters
  - Dithering: Occasional “large” driven variation of each beam parameter
- Corrections based on the two methods are in excellent agreement for this subset of our data where both are available
- About 77% of the run2 data-set
- Asymmetries have no corrections other than beam parameter correction
Some Backgrounds

- Target cell backgrounds
  - Recall that $Q_{\text{weak}}^n \sim 1$
    Scattering from the aluminum cell walls will contribute a large asymmetry
  - Need dilution and Al asymmetry
- Inelastic scattering from LH2
  - Measure the asymmetry with reduced magnetic field

- Two-boson exchange
  - Longitudinal e- spin
    $\gamma$-Z box contributions lead to $\sim 6\%$ shift in $Q_{\text{weak}}^p$ with error estimates of about $1\%$
  - Transverse e- spin
    2-$\gamma$ exchange with transverse electron spin leads to an azimuthal asymmetry variation
Backgrounds: Aluminum

- Largest background correction from aluminum alloy target windows (0.25% $X_0$): $-64 \pm 10$ ppb

Dilution measured with empty target and cold gas tracking runs

$$f_{A1} = 3.23 \pm 0.24 \%$$

Asymmetry measured with thick dummy target (4%)

$$A_{PV} = \frac{-G_FQ^2}{4\pi\alpha\sqrt{2}} \left[ Q_W^p + \left( \frac{N}{Z} \right) Q_W^n \right]$$

$$A_{A1} = 1.76 \pm 0.26 \text{ ppm}$$

Need correction for hydrogen presence
Transverse Asymmetry

- Dedicated measurement with fully transverse beam
  - Constrains false asymmetry for \( A_{ep} \) result

- Transverse result: nucleon structure and \( 2\gamma \) exchange

The data provide an integral test of all allowed virtual excitations of the proton up to \( E_{cm} = 1.7 \) GeV.
Ancillary Measurements

Many additional measurements under analysis:

- PV asymmetry:
  - elastic $^{27}$Al
  - $N \rightarrow \Delta$
    \[(E = 1.16 \text{ GeV}, 0.877 \text{ GeV})\]
  - Near $W = 2.5 \text{ GeV}$
    (related to $\gamma Z$ box)
  - Pion photoproduction
    \[(E = 3.3 \text{ GeV})\]

- PC Transverse asymmetry:
  - elastic $ep$
  - elastic $^{27}$Al, Carbon
  - $N \rightarrow \Delta$
  - Møller
  - Near $W = 2.5 \text{ GeV}$
  - Pion photoproduction
    \[(E = 3.3 \text{ GeV})\]
First Results: Asymmetry

- Run 0 Results (1/25th of total dataset)

Kinematics:

\[
\langle Q^2 \rangle = 0.0250 \pm 0.0006 \text{ GeV}^2
\]

\[
\langle E_{beam} \rangle = 1.155 \pm 0.003 \text{ GeV}
\]

\[
A_{ep} = -279 \pm 35 \text{ (stat)} \pm 31 \text{ (syst)} \text{ ppb}
\]
Extracting the Weak Charge

Global fit in $Q^2$ and $\theta$ to the reduced asymmetry

$$A_{LR}/A_0 = Q_{\text{weak}}^P + Q^2 B(Q^2)$$

$$A_0 = -\left(\frac{G_\mu}{4\pi\alpha}\sqrt{2}\right)Q^2$$

- Using 5 free parameters: $C_{lu}^1$, $C_{1d}^1$, $\rho_s$, $\mu_s$, & the isovector part of $G_A^Z$
  - $G_E^S$, $G_M^S$, and $G_A^Z$ use a dipole, $(1+Q^2/\lambda^2)^{-2}$, with $\lambda = 1$ GeV/c
- Employs all PVES data up to $Q^2 = 0.63$ (GeV/c)$^2$
  - On $p$, $d$, & $^4$He targets, forward and back-angle data
    - SAMPLE, HAPPEX, G0, PVA4
- Uses constraints on isoscalar part of $G_A^Z$
- All ep data corrected for E & $Q^2$ dependence of $\gamma Z$-box
Electroweak Corrections

\[ Q_W^P = [1 + \Delta \rho + \Delta e] \left[ (1 - 4 \sin^2 \theta_W(0)) + \Delta e' \right] + \Box WW + \Box ZZ + \Box \gamma Z \]

- Most of these well known and precisely calculated – except for $\gamma Z$-box
- $\gamma Z$-box: significant energy-dependent correction first identified by Gorchtein & Horowitz
- Hall et al model dependence constrained by JLab PVDIS data

Table 1: $\Box_{\gamma Z}^V$ contribution to $Q_W^P$ (Qweak kinematics)

<table>
<thead>
<tr>
<th>Author</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gorchtein &amp; Horowitz</td>
<td>0.0026 ± 0.0026</td>
</tr>
<tr>
<td>Sibirtsev, Blunden, Melnitchouk, &amp; Thomas</td>
<td>0.0047 +0.0011 −0.0004</td>
</tr>
<tr>
<td>Rislow &amp; Carlson</td>
<td>0.0057 ± 0.0009</td>
</tr>
<tr>
<td>Gorchtein, Horowitz &amp; Ramsey-Musolf</td>
<td>0.0054 ± 0.0020</td>
</tr>
<tr>
<td>Hall, Blunden, Melnitchouk, Thomas, &amp; Young</td>
<td>0.00557 ± 0.00036</td>
</tr>
</tbody>
</table>
First Results: Weak Charge

\[ A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta = 0), \quad A_0 = -\frac{G_F Q^2}{4\pi \alpha \sqrt{2}} \]

Global fit of world PVES data up to \( Q^2 = 0.63 \text{ GeV}^2 \)

Data rotated to forward-angle for plotting

Remove energy- & \( Q^2 \) -dependence of \( \gamma Z \)-box

\( Q_W^p (PVES) = 0.064 \pm 0.012 \)

\( Q_W^p (SM) = 0.0710 \pm 0.0007 \)

Published 10/2/2013: PRL 111, 141803 (2013)
First Results: Quark Couplings

Black dot is SM value
Green band is Cesium APV – more sensitive to isoscalar combination
(Dzuba et al., PRL 109, 203003 (2012))
Blue ellipse is combined PVES (now with Qweak)
Red is combined APV+PVES fit

\[
\begin{align*}
C_{1u} &= -0.1835 \pm 0.0054 \\
C_{1d} &= 0.3355 \pm 0.0050
\end{align*}
\]

\[
\begin{align*}
Q^n_W(PVES + APV) &= -0.975 \pm 0.010 \\
Q^n_W(SM) &= -0.9890 \pm 0.0007
\end{align*}
\]

Published 10/2/2013: PRL 111, 141803 (2013)

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First Results: Weak Mixing Angle

At tree level: $Q_W^p = 1 - 4\sin^2\theta_W$

Each experiment sensitive to different types of new physics


4% of Qweak Data
“Teaser”

Data Rotated to the Forward-Angle Limit

\[ \frac{A_{e^p}}{A_0} = Q_w^2 (Q^2, \theta = 0) \]

This Experiment
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)

\[ Q^2 [\text{GeV/c}^2] \]

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“Teaser”

Simulation on SM with anticipated errors

Data Rotated to the Forward-Angle Limit

\[ A/A_0 = Q^p_W + Q^2 B(Q^2, \theta=0) \]
e-p transverse asymmetry

- Pasquini/Vanderhaeghen Model
  - Includes intermediate states: proton (elastic) and πN (inelastic)
  - Computed via N → πN electroproduction amplitudes from MAID
- Afanasev/Merenkov and Gorchtein Models
  - Optical theorem: relates forward Compton amplitude to total photoproduction cross section
  - Effectively includes both πN and ππN states
  - For all models, inelastic dominates over elastic

- Kinematics:
  - $Q^2 = 0.0250 \pm 0.006 \text{ (GeV/c)}^2$
  - $E = 1.155 \pm 0.003 \text{ GeV}$
  - Scattering angle $= 7.9^\circ \pm 0.3^\circ$
- Preliminary
  - $A_n = -5.30 \pm 0.07 \pm 0.15 \text{ ppm}$
  - No radiative corrections
  - Results from B. Waidyawansa Ph.D. thesis; being prepared for publication
Transverse asymmetry on nuclei

- Calculations with inelastic intermediate hadronic states agree with experimental data up to $A = 12$, but fail to describe Pb ($A = 208$).
- No calculation includes both Coulomb distortion and a full range of excited intermediate states.
- Adding data between $A = 12$ and $A = 208$ (such as Al, $A = 27$) will shed light on this issue.

Figure adapted from PREX collaboration; PRL 109, 192501 (2012)

Summary

- First published result from the Qweak experiment

\[ A_{ep} = -279 \pm 35 \text{ (stat)} \pm 31 \text{ (syst) ppb} \]

- Determination of the proton and neutron weak charge

\[
\begin{align*}
Q^p_W (PVES) &= 0.064 \pm 0.012 \\
Q^p_W (SM) &= 0.0710 \pm 0.0007 \\
Q^n_W (PVES + APV) &= -0.975 \pm 0.010 \\
Q^n_W (SM) &= -0.9890 \pm 0.0007
\end{align*}
\]

In agreement with Standard Model predictions

- Final result expected ~year from now
  - Statistical error 5 times smaller, reduced systematics, no show stoppers found
  - Additionally, many ancillary results under analysis
The Qweak Collaboration

97 collaborators  23 grad students
10 post docs   23 institutions

Institutions:
1 University of Zagreb
2 College of William and Mary
3 A. I. Alikhanyan National Science Laboratory
4 Massachusetts Institute of Technology
5 Thomas Jefferson National Accelerator Facility
6 Ohio University
7 Christopher Newport University
8 University of Manitoba,
9 University of Virginia
10 TRIUMF
11 Hampton University
12 Mississippi State University
13 Virginia Polytechnic Institute & State Univ
14 Southern University at New Orleans
15 Idaho State University
16 Louisiana Tech University
17 University of Connecticut
18 University of Northern British Columbia
19 University of Winnipeg
20 George Washington University
21 University of New Hampshire
22 Hendrix College, Conway
23 University of Adelaide


Spokespersons  Project Manager  Grad Students

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