First Results from QWEAK

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(for the QWEAK Collaboration)

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The Weak Charges

Electron-quark scattering, general four-fermion contact interaction:

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

Note “accidental” suppression of $Q_{\text{weak}}^p \rightarrow \text{sensitivity to new physics}$

<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>$Q_W^e = -1 + 4 \sin^2 \theta_W \approx 0$</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>$Q_W^p = 1 - 4 \sin^2 \theta_W \approx 0.07$</td>
</tr>
<tr>
<td>n(udd)</td>
<td>$0$</td>
<td>$Q_W^n = -1$</td>
</tr>
</tbody>
</table>

$Q_{\text{weak}}^p$ has a definite prediction in the electroweak Standard Model.
Sensitivity to New Physics

Qweak proposal: 
\[ \Delta Q^p_w / Q^p_w = 4.2\% \]

Depending on how the PV “new physics” Lagrangian is constructed, and the value of model dependent value g, the mass scale can be much greater.

Erler, Kurylov, and Ramsey-Musolf
“Dark parity violation” (Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- Introduces a new source of low energy parity violation through mass mixing between $Z$ and $Z_d$ with observable consequences.
- Complementary to direct searches for heavy dark photons.

Low-E experiments most sensitive to deviations from SM due to Dark Z
Determining $Q_p^w$

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \sim \frac{|M_{PV}|}{|M_{EM}|}$
- $A_{ep} = \left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\varepsilon G_E^\gamma G_M^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_w)\varepsilon' G_M^\gamma G_A^Z}{\varepsilon(G_E^\gamma)^2 + \tau(G_M^\gamma)^2}$

where $\varepsilon = \left[1 + 2(1 + \tau)\tan^2(\theta/2)\right]^{-1}, \quad \varepsilon' = \sqrt{\tau(1 + \tau)(1 - \varepsilon^2)}, \quad \tau = Q^2/4M^2, \quad G_{E,M}^\gamma$ are EM FFs, $G_{E,M}^Z$ & $G_A^Z$ are strange & axial FFs, and $\sin^2\theta_w = 1 - (M_W / M_Z)^2 = \text{weak mixing angle}$

- Recast $A_{ep} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_p^w + Q^2 B(Q^2, \theta)\right]$
  - So in a plot of $A_{ep}/\left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$ vs $Q^2$:
    - $Q_p^w$ is the intercept (anchored by precise data near $Q^2=0$)
    - $B(Q^2, \theta)$ is the slope (determined from higher $Q^2$ PVES data)
PVES Challenges

PVES challenges:
- Statistics
  - High rates required
  - High polarization, current
  - High powered targets with large acceptance
- Low noise
  - Electronics, target density fluctuations
  - Detector resolution
- Systematics
  - Helicity-correlated beam parameters
  - Backgrounds (target windows)
  - Polarimetry
  - Parity-conserving processes

Qweak’s goal: most precise (relative and absolute) PVES result to date.
QWEAK JLab Site

Jefferson Lab (6 GeV)

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

- **Horizontal drift chambers**
- **Quartz Cerenkov bars**
- **Vertical drift chambers**
- **Collimators**
- **Trigger scintillator**
- **Toroidal magnet spectrometer**

**Electron beam**

- $E_{\text{beam}} = 1.155 \text{ GeV}$
- $<Q^2> \sim 0.025 \text{ (GeV/c)}^2$
- $<\theta> \sim 7.9° \pm 3°$
- $\phi$ coverage $\sim 49\%$ of $2\pi$
- Current $= 145 (180) \mu\text{A}$
- Polarization $= 89\%$
- Target $= 34.4 \text{ cm LH}_2$
- Cryopower $= 2.5 \text{ kW}$
- Luminosity $2 \times 10^{39} \text{s}^{-1} \text{cm}^{-2}$

**Target**

- Red = low-current tracking mode (production current $\times 10^{-6}$)
- Blue = production (“integrating”) mode
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Electron beam

Collimators

Vertical drift chambers

Quartz Cerenkov bars

Trigger scintillator

Toroidal magnet spectrometer
Quartz Cerenkov Detectors

Azimuthal symmetry maximizes rate and decreases sensitivity to HC beam motion, transverse asymmetry.

Spectrosil 2000 (fused silica) Cerenkov radiators:
- Eight bars, each 2 m long, 18 cm hi, 1.25 cm thick
- Rad-hard. non-scintillating, low-luminescence

Simulation of MD face:
- Azimuthal direction
- Radial direction

Yield 100 pe’s/track with 2 cm Pb pre-radiators
Resolution (~10%) limited by shower fluctuations.
Target Design and Performance

- 35 cm LH$_2$ (4% $X_0$)
  - 20K, 30-35 psia
  - ~3 kW power
- Designed using CFD

Fluid Velocity Simulation

Target “Boiling” Noise:
target density fluctuations

Beam Raster Size Scan @ 182 mA

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

\[ s_b = 1.3 + (19.4/x)^{2.399} \]

Run 12104
May 2011
Measuring Asymmetry

Helicity of electron beam flipped at up to 960 times/sec. Delayed helicity reporting to prevent direct electrical pick up of reversal signal by ADC's.

Detector signal integrated
For each helicity window

Asymmetry formed by quartet (4 ms)

Statistical power is

\[ \Delta A = s_{\text{width}} \sqrt{N_{\text{quartets}}} \]

Measured asymmetry has unknown additive “blinding factor” for analysis (± 60 ppb blinding box)

236 ppm per quartet
Constructing Asymmetry

**False Asymmetries**

- \( A_{msr} = A_{raw} + A_T - A_{reg} \)
  - \( A_{raw} = (Y^+ - Y^-) / (Y^+ + Y^-) \)
    - Charge normalized ep yields for ± e-helicity
  - \( A_T = \) remnant transverse asymmetry measured with explicitly \( P_T \) beam
  - \( A_{reg} = \sum \left( \frac{\partial A}{\partial \chi_i} \right) \Delta \chi_i \), measured with natural & driven beam motion for \((x, y, x', y', E)\) using BPMs
  - \( A_Q \) driven to 0 with feedback

**Backgrounds**

- \( A_{ep} = R_{tot} \frac{A_{msr}/P - \sum_{i=1}^{4} f_i A_i}{1 - f_{tot}} \)
  - \( R_{tot} = R_Q^2 R_{RC} R_{Det} R_{Bin} = 0.98 \)
  - \( f_{tot} = \sum f_i = 3.6\% \)
  - \( f_i = \) fraction of yield from bkg i
  - \( A_i = \) asymmetry of bkg i
  - \( b_1 \) from Al windows of tgt cell (dominant bkg)
  - \( b_2 \) from beamline bkg
  - \( b_3 \) from other soft neutral bkg
  - \( b_4 \) from \( N \rightarrow \Delta \) inelastic bkg
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

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

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

Example: Detector Sensitivity to X position variation

Regression Correction from Qweak “Wien0” (PRL 111, 141803): \(A_{corr} = -35 \pm 11 \text{ ppb}\)
Transverse Asymmetry

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

- Good cancellation (symmetry factor)
- Small residual $P_T$ when running
- Correction < 4 ppb

- 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
Aluminum Window Background

Large A & f make this our largest correction. Determined from explicit measurements using Al dummy tgts & empty H₂ cell.

\[ f_{\text{Al}} = 3.23 \pm 0.24 \% \]

- Dilution from windows measured with empty target (actual tgt cell windows).
- Corrected for effect of H₂ using simulation and data driven models of elastic and QE scattering.

\[ A_{\text{Al}} = 1.76 \pm 0.26 \text{ ppm} \]

- Asymmetry measured from thick Al targets
- Measured asymmetry agrees with expectations from scaling.

\[ A_{\text{PV}}(\frac{N}{Z} X) = -\frac{Q^2 G_F}{4\pi\alpha\sqrt{2}} \left[ Q^p_W + \left(\frac{N}{Z}\right) Q^n_W \right] \]

Simulated e- profile at detector:

- Upstream window
- Downstream window
Qweak requires $\Delta P/P \leq 1\%$

Strategy: use 2 independent polarimeters

- **Use existing <1% Hall C Møller polarimeter:**
  - Low beam currents, invasive
  - Known analyzing power provided by polarized Fe foil in a 3.5 T field.
- **Use new Compton polarimeter (1%/h):**
  - High current, non-invasive
  - Continuous
  - Photon & Electron
  - Known analyzing power provided by circularly-polarized laser
Kinematics Determination

\[ A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2\pi} \alpha} \left[ Q_W^P + F(\theta, Q^2) \right] \]

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

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

**Q^2**

**Simulation**

**Data**

Goal on \( \Delta Q^2 \) is 0.5% via tracking + simulation
First Results: Asymmetry

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

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

Kinematics:
\[ \langle Q^2 \rangle = 0.0250 \pm 0.0006 \text{ GeV}^2 \]
\[ \langle E_{beam} \rangle = 1.155 \pm 0.003 \text{ GeV} \]

Q\text{weak} (4\% of data, 3 days @ 100\%)
Electroweak Corrections

\[ Q_W^p = [\rho_{NC} + \Delta_e][1 - 4 \sin^2 \hat{\theta}_W(0) + \Delta'_e] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z} \]

Table 1: \[ \Box_{\gamma Z} \] contribution to \( Q_W^p \) (Qweak kinematics)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gorchtein &amp; Horowitz [Phys. Rev. Lett. 102, 091806 (2009)]</td>
<td>0.0026 ± 0.0026</td>
</tr>
<tr>
<td>Sibirtsev, Blunden, Melnitchouk, &amp; Thomas [Phys. Rev. D 82, 013011 (2010)]</td>
<td>0.0047 ± 0.0001</td>
</tr>
<tr>
<td>Rislow &amp; Carlson [Phys. Rev. D 83, 113007 (2007)]</td>
<td>0.0057 ± 0.0009</td>
</tr>
<tr>
<td>Gorchtein, Horowitz, &amp; Ramsey-Musolf [Phys. Rev. C 84, 015502 (2011)]</td>
<td>0.0054 ± 0.0020</td>
</tr>
<tr>
<td>Hall, Blunden, Melnitchouk, Thomas, &amp; Young [Phys. Rev. D 88, 013011 (2013)]</td>
<td>0.00557 ± 0.00036</td>
</tr>
</tbody>
</table>

Calculations are primarily dispersion theory type
- error estimates can be firmed up with data!
- Qweak: inelastic asymmetry data taken at \( W \sim 2.3 \text{ GeV}, \ Q^2 = 0.09 \text{ GeV}^2 \)

The \( \Box_{\gamma Z} \) is the only \( E \) & \( Q^2 \) dependent EW correction.
→ Correct the PVES data for this \( E \) & \( Q^2 \) dependence.

~7% correction
First Results: Weak Charge

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

Data rotated to forward-angle for plotting

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

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

4% of \( Q^{\text{weak}} \) Data

\( Q_{W}^p (PVES) = 0.064 \pm 0.012 \)

\( Q_{W}^p (SM) = 0.0710 \pm 0.0007 \)

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

\[
C_{1u} = -0.1835 \pm 0.0054 \\
C_{1d} = 0.3355 \pm 0.0050
\]

\[
Q_W^n(PVES + APV) = -0.975 \pm 0.010 \\
Q_W^n(SM) = -0.9890 \pm 0.0007
\]

4% of Qweak Data

PRL 111, 141803 (2013)
Weak mixing angle

"Teaser"

Data Rotated to the Forward-Angle Limit

\[ \frac{A}{A_0} = Q_w^2 + Q^2 B(Q_*^2, \theta=0) \]

Legend:
- Red diamond: This Experiment
- Brown square: HAPPEX
- Pink cross: SAMPLE
- Green triangle: PVA4
- Blue circle: G0
- Yellow arrow: SM (prediction)
“Teaser”

Data Rotated to the Forward-Angle Limit

\[ \frac{A}{A_0} = Q_w^2 B(Q^2, \theta=0) \]

Anticipated precision of full data set
Auxiliary Measurements

Qweak has data (under analysis) on a variety of observables of potential interest for Hadron physics:

• Beam normal single-spin asymmetry for elastic scattering on proton
• Beam normal single-spin asymmetry for elastic scattering on $^{27}$Al
• PV asymmetry in the $N \rightarrow \Delta$ region.
• Beam normal single-spin asymmetry in the $N \rightarrow \Delta$ region.
• Beam normal single-spin asymmetry near $W=2.5$ GeV
• Beam normal single-spin asymmetry in pion photoproduction
• PV asymmetry in inelastic region near $W=2.5$ GeV (related to $Z$ box diagrams)
• PV asymmetry for elastic/quasielastic from $^{27}$Al
• PV asymmetry in pion photoproduction
Summary

- Measured $A_{ep} = -279 \pm 35 \text{ (statistics)} \pm 31 \text{ (systematics)} \text{ ppb}$
  - Smallest & most precise ep asymmetry measurement to date
- First determination of $Q_w(p) = -2(2C_{1u} + C_{1d})$
  - $Q_w(p) = 0.063 \pm 0.012$ (from only 4% of all data collected)
  - (SM value = 0.0710(7))
  - New physics reach $\lambda/g = (2\sqrt{2} G_F \Delta Q_W)^{-1/2} > 1.5 \text{ TeV}$
    - Based on 18% commissioning rslt, 95% CL, Erler, Kurylov, Musolf PRD68, 016006 (2003)
- First determination of $Q_w(n) = -2(C_{1u} + 2C_{1d})$:
  - By combining our result with APV: $Q_w(^{133}\text{Cs}) = -2(188C_{1u} + 211C_{1d})$
    - $Q_w(n) = -0.975 \pm 0.010$ (SM value = -0.9890(7))
- Final results from full data set (~5 times smaller $\Delta A$) in 2015
  - Expected PV new physics reach $\lambda/g$ of ~ multi TeV level
  - Very precise measurement of $Q^p_w$

Thanks to Qweak collaborators, from whom I have borrowed many slides
The Qweak Collaboration

- 95 collaborators
- 23 grad students
- 10 post docs
- 23 institutions:
  JLab, W&M, UConn, TRIUMF, MIT, UMan., Winnipeg, VPI, LaTech, Yerevan, MSU, OU, UVa, GWU, Zagreb, CNU, HU, UNBC, Hendrix, SUNO, ISU, UNH, Adelaide


¹Spokespersons  ²Project Manager  Grad Students
Extra Slides
Global PVES Fit Details

• 5 free parameters (Young, et al. PRL 99, 122003 (2007)):
  - $C_{1u}, C_{1d}, \rho_s, \mu_s, \text{ & isovector axial FF } G_A^Z$
  - $G_E^S = \rho_s Q^2 G_D, \ G_M^S = \mu_s G_D, \ & \ G_A^Z \text{ use } G_D \text{ where }$
    - $G_D = (1 + Q^2/\lambda^2)^{-2} \text{ with } \lambda = 1 \text{ GeV/c}$
• Employs all PVES data up to $Q^2=0.63 \text{ (GeV/c)}^2$
• On p, d, & $^4\text{He}$ targets, forward and back-angle data
  - SAMPLE, HAPPEX, G0, PVA4
• Uses constraints on isoscalar axial FF $G_A^Z$
• All data corrected for E & $Q^2$ dependence of $\Box_Y^Z \text{ RC}$
  - Hall et al., PRD88, 013011 (2013) & Gorchtein et al., PRC84, 015502 (2011)
• Effects of varying $Q^2, \theta, \ & \lambda$ studied, found to be small