The $Q_{\text{weak}}$ Experiment:
The First Direct Measurement of the Proton’s Weak Charge

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Overview

Motivation:
- Precision grants sensitivity to physics beyond Standard Model
- First direct measurement of $Q^P_W$

Methods & Preliminary Results:
- Experimental Overview
- Commissioning Data Results (2013)

Path to final result:
- Improved beam corrections and polarization
- Systematic effect from secondary scattering
Physics Beyond the Standard Model

- **Energy frontier**
  - Large Hadron Collider.
  - Creates particle X directly though high energy collisions.

- **Precision frontier**
  - Jefferson Lab.
  - Looks for the indirect effect of process X.

\[ e\gamma p + e\rightarrow X + p \]
Extensions to SM

Examples of TeV scale new physics that $Q_{\text{weak}}$ would be sensitive to are:

- **Dark Photon:**
  - Astrophysical motivation, observed in positron data
  - Might be linked to muon g-2 anomaly

- **Dark Parity Violation:** (Davoudiasl, Lee, Marciano, arXiv 1402.3620)
  - New source of low energy PV via mass mixing between $Z$ and $Z_d$ with observable consequences
  - Complementary to direct search for heavy dark photons
Standard Model

Standard model describes the couplings between fundamental particles.

\[
\begin{array}{c|cc}
Q & Q_W \\
u & +2/3 & 1 - 8/3\sin^2\theta_W = -2C_{1u} \\
d & -1/3 & -1 + 4/3\sin^2\theta_W = -2C_{1d}
\end{array}
\]

Proton’s electric charge:

\[
Q^p = 2 \left( +\frac{2}{3} \right) + 1 \left( -\frac{1}{3} \right) = +1
\]

Proton’s neutral weak charge:

\[
Q^p_W = 2 \left( 1 - \frac{8}{3}\sin^2\theta_W \right) + 1 \left( -1 + \frac{4}{3}\sin^2\theta_W \right)
= 1 - 4\sin^2\theta_W \approx 0.07
\]

Weak mixing angle parametrizes the mixing between the two neutral currents in the model. With the discovery of the Higgs boson, it is now predicted by the SM.

\[
\begin{pmatrix}
|\gamma\rangle \\
|Z^0\rangle
\end{pmatrix}
= \begin{pmatrix}
\cos \theta_W & \sin \theta_W \\
-\sin \theta_W & \cos \theta_W
\end{pmatrix}
\begin{pmatrix}
|B^0\rangle \\
|W^0\rangle
\end{pmatrix}
\]
**Parity-Violating Electron Scattering Measurement**

**Q\text{\_weak} experiment:** scatter longitudinally polarized electrons off of unpolarized hydrogen.

An asymmetry is formed by counting scattered electrons from each helicity state:

\[
A_{ep} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{2M^*M_Z}{|M_\gamma|^2}.
\]

\(A_{ep}\) comes from the interference of the electromagnetic and weak exchange amplitudes.
Extracting $Q_W^p$ from $A_{ep}$

\[
\mathcal{M}_Z \propto \frac{g^2}{-Q^2 + m_Z^2} \quad \mathcal{M}_\gamma \propto \frac{e^2}{-Q^2}
\]

As $Q^2 \to 0$, $\mathcal{M}_Z \sim \frac{g^2}{m_Z^2} \sim G_F$

\[
\Rightarrow \frac{\mathcal{M}_Z}{\mathcal{M}_\gamma} = \frac{G_F}{\alpha} Q^2
\]

Where $\mathcal{M}_Z$ is the weak neutral current, $\mathcal{M}_\gamma$ is the electromagnetic current, $Q^2$ is the momentum transfer, $G_F$ is the Fermi coupling constant and $\alpha$ is the fine structure constant.

\[
A_{ep} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = 2\frac{\mathcal{M}_Z}{\mathcal{M}_\gamma} = \left[ \frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \left[ Q^2 Q_W^p + F^p(Q^2, \Theta) \right]
\]

$A_{ep}$ depends on hadronic form factors

As $Q^2 \to 0, \Theta \to 0$

\[
A_{ep} = \left[ \frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \left[ Q^2 Q_{weak}^p + Q^4 B(Q^2, \Theta) \right] \approx -0.23 \text{ ppm}
\]
Jefferson Lab and CEBAF

- $Q_{\text{weak}}$ ran in Hall C of Jefferson Lab
  - Three data taking periods:
    - Run 0: Nov 2010 - Jan 2011 (Published)
    - Run I: Feb - May 2011
    - Run II: Nov 2011 - May 2012 (Analysis ongoing)

- Target:
  - Liquid H$_2$ ($\approx 34$ cm thick)
  - Al alloy windows ($\approx 0.12$ mm thick)

- Kinematics:
  - $E = 1.155 \pm 0.003$GeV
  - $I_{\text{beam}} = 180\mu A$
  - $P_L = 89\%$
  - $Q^2 = 0.0250 \pm 0.006$GeV/c$^2$
  - $\theta_{\text{lab}} = 7.9^\circ \pm 0.3^\circ$
The $Q_{\text{weak}}$ apparatus

"The $Q_{\text{weak}}$ Experimental Apparatus," NIM A 781, 105 (2015)
The $Q_{\text{weak}}$ apparatus

- Quartz Cerenkov Bars
- Horizontal Drift Chambers
- Electron beam
- LH$_2$ Target
- Collimators
- Toroidal Magnet Spectrometer
- Trigger Scintillator
- Vertical Drift Chambers
Measuring the PV Asymmetry

- Flip helicity at 960 Hz in quartet pattern
  
  \[ (+,-,-,+ \text{ or } -,+,+,+,+) \]

- Integrate PMT current for each helicity state

- Normalize integrated signal \( S \) with beam charge \( Q \) to get yield \( Y \):
  
  \[ Y = \frac{S}{Q} \]

- Form asymmetry for each quartet:
  
  \[ A_{\text{raw}} = \frac{Y_R - Y_L}{Y_R + Y_L} \]

- Correct \( A_{\text{raw}} \) for beam systematics
  
  \[ A_{\text{msr}} = A_{\text{raw}} + A_T + A_L - \sum_i \frac{\partial A}{\partial \chi_i} \Delta \chi_i \]

- \( A_T \) - Transverse polarization leakage
- \( A_L \) - PMT non-linearity
- \( \frac{\partial A}{\partial \chi_i} \) - sensitivity to helicity-correlated beam parameters
Q\textsubscript{weak} Backgrounds

There are several backgrounds that dilute the parity-violating asymmetry and need to be corrected.

\[ A_{ep} = R \frac{A_{msr}}{P} - \sum_i f_i A_i \]

- \( A_{ep} \): Parity-violating asymmetry
- \( R \): Radiative and acceptance correction
- \( A_{msr} \): Measured asymmetry by experiment
- \( P \): Measured beam polarization
- \( f_i \): Background dilution \((Y_i/Y_T)\)
- \( A_i \): Background asymmetry

Backgrounds:

1. Aluminum target windows
2. Beamline background
3. Neutral scattered events
4. Inelastic scattered events
First Results

The following results were published using the small (∼ 4%) data set taken during commissioning.

<table>
<thead>
<tr>
<th>Run</th>
<th>Dates</th>
<th>Data taken (Coulomb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 0</td>
<td>Nov 2010-Jan 2011</td>
<td>∼ 40 C</td>
</tr>
<tr>
<td>Run 1</td>
<td>Feb 2011-May 2011</td>
<td>∼ 360 C</td>
</tr>
<tr>
<td>Run 2</td>
<td>Nov 2011-May 2012</td>
<td>∼ 680 C</td>
</tr>
</tbody>
</table>


\[ A_{PV} = A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{sys}) \text{ ppb} \]
First Results


Extracted proton’s weak charge:

- $Q_W^p (PVES) = 0.064 \pm 0.012$
- $Q_W^p (SM) = 0.0710 \pm 0.0007$

Extracted neutron’s weak charge:

- $Q_W^n (PVES) = -0.975 \pm 0.010$
- $Q_W^n (SM) = -0.9890 \pm 0.0007$
Weak Mixing Angle

- Black line is Standard Model prediction based on Z-pole results.
- Black point is $\sin^2 \theta_W$ from Run 0.
- Green point is estimated error bar on final complete set.
Beamline Background
Correction is made by measuring background dilution and correcting with correlations from background detector.

Qweak Run 2 - Blinded Asymmetries
(statistics only - not corrected for beam polarization, Al target windows, \(\Delta Q^2\), etc.)

Physics Asymmetry = \((IHWP_{IN} - IHWP_{OUT})\)

Blinded Asymmetry (ppb)

Data Set #

NULL Asymmetry = \((IHWP_{IN} + IHWP_{OUT}) / 2\)

Asymmetry (ppb)

Data Set #

Correction makes improvement to fit.
Beam Polarization

Run 0: Only Møller data
Run 1 & 2: Hall-C Compton polarimeter online

Systematic uncertainties
- Compton: $dP/P = 0.59\%$
- Møller: $dP/P = 0.84\%$

Both techniques agree to < 0.8%

Expt. strategy: minimize systematics

Secondary Scattering

Spin precession of scattered electron through spectrometer magnet give some transverse polarization, $P_{\perp}$.

$P_{\perp}$ in combination with lead pre-radiators in front of quartz bars causes a transverse asymmetry that is the same order but opposite sign in the + and - PMTs.

Effect:

$$A_{\text{diff}} = A_{-} - A_{+}$$

$Q_{\text{weak}}$ measures:

$$A_{PV} = \frac{A_{-} + A_{+}}{2}$$
Secondary Scattering Effect

- **Should cancel with symmetric detectors.** We live in the real world.
- Level of cancellation is being investigated with GEANT4 simulation and bench tests.
- Each of the 8 bars has slightly different physical properties and a separate correction will be made for each.
- **Last significant systematic uncertainty before we unblind.**
Projected Final Asymmetry Error

This figure shows anticipated final uncertainty placed on the SM prediction line.
Summary

- Initial PRL published in 2013 with $\sim 4\%$ of total collected data.
- Analysis is nearing completion on the full data set. Unblinding in early spring.
- Final result is anticipated to be statistically limited.
- Ancillary physics analyses are ongoing, with future publications planned.