First Determination of the Proton’s Weak Charge – Early Results from $Q_{\text{weak}}$

A.K. Opper for the $Q_{\text{weak}}$ Collaboration

PSI – September 2013
The Weak Charges

$Q_w(p)$: neutral-weak analog of the proton’s electric charge

<table>
<thead>
<tr>
<th>Quark/Particle</th>
<th>$Q_{EM}$</th>
<th>Weak Vector Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>U quark</td>
<td>2/3</td>
<td>$-2C_{1u} = 1 - \frac{8}{3} \sin^2 \theta_w \approx 1/3$</td>
</tr>
<tr>
<td>D quark</td>
<td>-1/3</td>
<td>$-2C_{1d} = -1 + \frac{4}{3} \sin^2 \theta_w \approx -2/3$</td>
</tr>
<tr>
<td>P (uud)</td>
<td>+1</td>
<td>$1 - 4 \sin^2 \theta_w \approx 0.07$</td>
</tr>
<tr>
<td>N (udd)</td>
<td>0</td>
<td>$\approx -1$</td>
</tr>
</tbody>
</table>

$Q_{EM}$ Weak Vector Charge

$Q_{weak}$ particularly sensitive to quark vector couplings $C_{1u}$ & $C_{1d}$

- $Q_w^p$ well defined prediction in electroweak SM
- $Q_w^p$ suppressed $\Rightarrow$ sensitive to new physics
- General: $Q_w(Z,N) = -2\{C_{1u}(2Z+N) + C_{1d}(Z+2N)\}$
  - $Q_w(p) = -2(2C_{1u} + C_{1d})$ (this experiment)
  - $Q_w^{133\text{Cs}} = -2(188C_{1u} + 211C_{1d})$ (APV)

Small scattering angles

Large scattering angles
Status

• Qweak Experiment finished successfully
  – Precise measurement of $e^-p$ analyzing power @ low $Q^2$
  – 2 years on the floor, ~ 1 year of beam
    • ~ 4% of total data set analyzed (from commissioning)
    • Results presented here

1st clean determination of $Q_{W}(p), C_{1u}, C_{1d}, Q_{W}(n)$

• Remainder of data being analyzed
  – Final result by end of 2014 with ~5x better precision
  – Close to proposed goal of 4% on $Q_{W}^p$
Extract $Q_W^p$ from Elastic $e\bar{p}$ Scattering

\[ A_{ep} = \left[ \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \right] \sim \frac{|M_{weak}|}{|M_{EM}|} \]

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

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

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Extract $Q_W^p$ from Elastic $\vec{e}p$ Scattering

$\leftarrow$ Interfere $\rightarrow$

parity conserving

$\leftarrow$ $\vec{s}(+) \rightarrow p$

$e$

$\gamma$

$e$

$M_\gamma \propto \frac{1}{Q^2}$

$\rightarrow$

parity violating

$\leftarrow$ $\vec{s}(-) \rightarrow p$

$e$

$M_Z \propto \frac{1}{Q^2 + M_Z^2}$

$Q^2 \rightarrow 0$

$\theta \rightarrow 0$

$A_{ep} = \left[ \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \right] \sim \frac{|M_{weak}^{PV}|}{|M_{EM}|}$

Recast $A_{ep} = \frac{G_F Q^2}{4\pi \alpha\sqrt{2}} \left[ Q_w^p + Q^2 B(Q^2, \theta) \right]$

So in a plot of $A_{ep} \left/ \left[ \frac{G_F Q^2}{4\pi \alpha\sqrt{2}} \right] \right.$ vs $Q^2$:

- $Q_{w}^p$ 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)

This Experiment

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At tree level: \[ Q^p_w = (1 - 4\sin^2\theta_w) \approx 0.072 \]

Precision measurement: \[ \delta A = \pm 2\% \Rightarrow \delta Q^p_w = \pm 4\% \Rightarrow \delta (\sin^2 \theta_w) = \pm 0.3\% \]

Meas’d Asymmetry: \[ A(Q^2 \rightarrow 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}} \left[ Q^2 \frac{Q^p_{weak}}{Q} + Q^4 B(Q^2) \right] \]

Expected value: \[ A(0.03 \text{ GeV}^2) = A^p_{Q_w} + A^p_{B(Q^2)} = -0.19 \text{ ppm} \quad -0.10 \text{ ppm} \]

Experimental considerations:
- need high statistics \(\rightarrow\) integrating detector system
- measured asymmetry \(\sim P; \quad \rightarrow\) \(P\) must be large & well measured
- must know detector-response-weighted \(<Q^2>\) and \(<Q^4>\)
- helicity correlated systematic errors \(< 5 \times 10^{-9}\)
- need \(B(Q^2)\) so we can subtract it
- KISS \(\text{ie Keep It Simple, Stupid!}\)
Qweak Apparatus

Parameters:
- $E_{\text{beam}} = 1.165 \text{ GeV}$
- $<Q^2> = 0.025 \text{ GeV}^2$
- $<\theta> = 7.9^\circ \pm 3^\circ$
- $\phi$ coverage = 50% of $2\pi$
- $I_{\text{beam}} = 180 \mu\text{A}$
- Integrated rate = 6.4 GHz
- Beam Polarization = 88%
- Target = 35 cm LH$_2$
- Cryopower = 3 kW

Red = low-current tracking mode only
$Q_{\text{weak}}$ Apparatus (before shielding)
• **Helicity reversal frequency**: 960 Hz (“freeze” bubble motion in the target)

• **Helicity pattern**: pseudo-random “quartets” (+--+, -++, asymmetry calculated for each quartet)

\[
A = \frac{N_+ - N_-}{N_+ + N_-} + B
\]

Asymmetry is “blinded” to avoid bias

• **Insertable Half-Wave Plate**: “slow reversal” of helicity checks systematic effects cancels certain false asymmetries.
Precision Polarimetry

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)
  - Continuous, non-invasive
  - Known analyzing power provided by circularly-polarized laser
**LH₂ Target Design**

- World's highest power cryogenic target ~3 kW
- Designed with computational fluid dynamics (CFD) to reduce density fluctuations

**Specifications**

- \( I_{\text{Beam}} = 180 \text{ uA} \)
- \( L = 35 \text{ cm} \) (4% \( X_0 \))
- \( P_{\text{beam}} = 2.2 \text{ kW} \)
- \( A_{\text{spot}} = 4 \times 4 \text{ mm}^2 \)
- \( V = 57 \text{ liters} \)
- \( T = 20.00 \text{ K} \)
- \( P \sim 220 \text{ kPa} \)

**Components**

- Centrifugal pump (15 l/s, 7.6 kPa)
- 3 kW Heater
- 3 kW HX utilizing 4K & 14K He coolant
- 35 cm cell (beam interaction volume)
- Solid Tgts

**Note:**

- Beam direction is indicated in the diagram.
- Fluid velocity is shown with color intensity scales.

**Additional Information:**

- ANSYS logo is visible in the diagram.
Quartz Cerenkov Detectors

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

Spectrosil 2000:
- Eight bars, each 2 m long, 1.25 cm thick
- Rad-hard
- Non-scintillating, low-luminescence

Yield 100 pe’s/track with 2cm Pb pre-radiators
Resolution limited by shower fluctuations.
Determining the Kinematics

Required uncertainty on $Q^2$ is 0.5%

Combination of tracking & simulation

- **HDCs** upstream of magnet $\rightarrow \theta$
  
  \[ Q^2 = \frac{2E^2(1-\cos\theta)}{[1 + E/M(1-\cos\theta)]} \]

- **VDCs** & trigger scintillators after magnet $\rightarrow$ light weighted $Q^2$ across quartz bars

\[ A_{PV} = -\frac{Q^2 G_F}{4\sqrt{2} \pi \alpha} \left[ Q^p_W + F(\theta, Q^2) \right] \]
LH₂ Data Quality (blinded asymm)

Convergence to mean ~rms/sqrt(N)
Width is relevant FOM

At 165 μA, total detected rate is 5.83 GHz.

→ Pure counting statistics: 215 ppm
+ detector shower fluctuations 232 ppm
+ current normalization and target 235 ppm

Width is understood and about 10% above c.s.

Electron helicity reversed every 1 msec by electronic means
Insertable Half Wave Plate (IHWP) → optically flips the helicity before every 8 hour “slug”
→ signal changes sign

0.8 ppm statistical error in only 6.5 minutes at 165 μA
# Beam Property Requirements

<table>
<thead>
<tr>
<th>Beam value</th>
<th>Requirement</th>
<th>Run I</th>
<th>Run II</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-position at target [nm]</td>
<td>&lt;2</td>
<td>3.6 +/- 0.39</td>
<td>-0.95 +/- 0.06</td>
</tr>
<tr>
<td>Y-position at target [nm]</td>
<td>&lt;2</td>
<td>-6.9 +/- 0.39</td>
<td>-0.24 +/- 0.28</td>
</tr>
<tr>
<td>X-angle at target [nrad]</td>
<td>&lt;30</td>
<td>-0.22 +/- 0.012</td>
<td>-0.07 +/- 0.017</td>
</tr>
<tr>
<td>Y-angle at target [nrad]</td>
<td>&lt;30</td>
<td>-0.18 +/- 0.015</td>
<td>-0.06 +/- 0.011</td>
</tr>
<tr>
<td>Position at dispersion (3c12X)[nm]</td>
<td>-</td>
<td>-13.6 +/- 0.23</td>
<td>-0.83 +/- 0.30</td>
</tr>
<tr>
<td>Energy dE/E [ppb]</td>
<td>&lt;1</td>
<td>&lt;3.8 +/- 0.06</td>
<td>&lt;0.23 +/- 0.08</td>
</tr>
</tbody>
</table>
Constructing the Asymmetry

False Asymmetries

- \( A_{msr} = A_{raw} + A_T - A_{reg} \)
  - \( A_{raw} = (Y^+ - Y^-) / (Y^+ + Y^-) \)
    - Charge normalized ep yields for \( \pm e \)-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
# For “25% Commissioning Data set”

\[
A_{PV} = \frac{A_{meas}}{P} - \sum f_i A_i \\
A_{meas} = -204.6 \pm 30.5 \text{ppb}
\]

\[
A_{PV} = -279 +/- 35 \text{ (stat)} \\
+/- 31 \text{ (sys) ppb}
\]

<table>
<thead>
<tr>
<th>Source of Error (A)</th>
<th>Contribution (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A_meas Statistics</strong></td>
<td>0.0358</td>
</tr>
<tr>
<td>A_meas Systematic*</td>
<td>0.0151</td>
</tr>
<tr>
<td>Polarization</td>
<td>0.0049</td>
</tr>
<tr>
<td>Al Window Asym</td>
<td>0.0087</td>
</tr>
<tr>
<td>Al Window Dilution</td>
<td>0.0046</td>
</tr>
<tr>
<td>QTOR Transport Asym</td>
<td>0.0021</td>
</tr>
<tr>
<td>QTOR Transport Dilution</td>
<td>0.0017</td>
</tr>
<tr>
<td>Beamline Asym</td>
<td>0.0232</td>
</tr>
<tr>
<td>Beamline Dilution</td>
<td>0.0035</td>
</tr>
<tr>
<td>N→Δ Asym</td>
<td>0.0002</td>
</tr>
<tr>
<td>N→Δ Dilution</td>
<td>0.0006</td>
</tr>
<tr>
<td>Det. Bias correction**</td>
<td>0.0019</td>
</tr>
<tr>
<td>EM Rad. Corrections</td>
<td>0.0014</td>
</tr>
<tr>
<td><strong>Total Systematic</strong></td>
<td><strong>0.0302</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.0469 (16%)</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Correction</th>
<th>Correction (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>-0.0265</td>
</tr>
<tr>
<td>Aluminum Windows</td>
<td>-0.0642</td>
</tr>
<tr>
<td>QTOR transport channel (neutrals)</td>
<td>0.00000</td>
</tr>
<tr>
<td>Beamline Backgrounds (neutrals)</td>
<td>+0.0102</td>
</tr>
<tr>
<td>N→Δ electrons</td>
<td>+0.0006</td>
</tr>
<tr>
<td>EM radiative effects + Detector bias</td>
<td>-0.0088</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-0.0829</strong></td>
</tr>
</tbody>
</table>

*Includes cut dependence, regression systematics, detector non-linearities, and transverse asymmetry

**Simulation-based correction for variation in light produced across the detectors & non-uniform Q^2 distributions.
Global PVES Fit Details

- Effectively 5 free parameters:
  - $C_{1u}$, $C_{1d}$, $\rho_s$, $\mu_s$, & isovector axial FF $G_A^Z$
  - $G_E^S = \rho_s Q^2 G_D$, $G_M^S = \mu_s G_D$, & $G_A^Z$ use $G_D$ where
    - $G_D = (1 + Q^2/\lambda^2)^{-2}$ 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 $\Box_{YZ}^\gamma$ $RC$
    - Hall et al., arXiv:1304.7877 (2013) & Gorchtein et al., PRC84, 015502 (2011)
  - Effects of varying $Q^2$, $\theta$, & $\lambda$ studied, found to be small
Global Fit of $Q^2 < 0.63 \text{ (GeV/c)}^2$ PVES Data

$A = -279 \pm 35 \pm 31 \text{ ppb}$

$Q_W(p) = 0.064 \pm 0.012$

(only 4% of all data collected)

SM value = 0.0710(7)
Combined Analysis
Extract: $C_{1u}$, $C_{1d}$, $Q^n_w$

$Q^n_w = -2 (C_{1u} + 2 C_{1d})$
$= -0.975 \pm 0.010$

$C_{1u} = -0.184 \pm 0.005$
$C_{1d} = 0.336 \pm 0.005$

Remainder of experiment still being analyzed, final result before end of 2014. Expect final $\Delta A_{e-p}$ result will have $\sim 5 \times$ better precision.
Summary arXiv:1307.5275 & Status

- Measured $A_{ep} = -279 \pm 35$ (statistics) $\pm 31$ (systematics) ppb
  - Smallest & most precise ep asymmetry ever measured

- First determination of $Q_W(p)$:
  - $Q_W(p) = 0.063 \pm 0.012$ (from only 4% of all data collected)
    - (SM value = 0.0710(7))
    - New physics reach $\Lambda/g = 1/2 (\sqrt{2} G_F \Delta Q_W)^{-1/2} \sim 1.1$ TeV

- First determination of $Q_W(n) = -2(C_{1u} + 2C_{1d})$:
  - By combining our result with APV
    - $Q_W(n) = -0.975 \pm 0.010$ (SM value = -0.9890(7))

- Final results with $\sim$5 times smaller uncertainties in about a year
  - Expected physics reach of $\Lambda/g \sim 2.3$ TeV.
  - SM test, sensitive to Z’s and LQs
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

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