First Results from Q-weak

A search for parity violating new physics at the TeV scale by measurement of the Proton’s weak charge.

Roger D. Carlini
Jefferson Laboratory

(Content of this talk includes the work of students, postdocs and collaborators)

- Scatter longitudinally polarized electrons from liquid hydrogen
- Flip the electron spin and see how much the scattered fraction changes
- The difference is proportional to the weak charge of the proton
- Hadronic structure effects determined from global PVES measurements.
Precision Tests of the Standard Model

- Standard Model is known to be the effective low-energy theory of a more fundamental underlying structure. (Meaning its not complete!)

- Finding new physics beyond the SM: Two complementary approaches:
  - Energy Frontier (direct): eg. Tevatron (deceased), LHC (dry well so far)
  - Precision Frontier (indirect): Often at modest or low energy...
    - \( \mu(g-2) \), EDM, \( \beta\beta \) decay, \( \mu \to e \gamma \), \( \mu A \to e A \), \( K^+ \to \pi^+ \nu \nu \), etc.
    - \( \nu - oscillations \)
    - Atomic Parity violation
    - Parity-violating electron scattering

Hallmark of the Precision Frontier: Choose observables that are “precisely predicted” or “suppressed” in Standard Model.

If new physics is “eventually” found in direct measurements, precision measurements also useful to determine e.g. couplings...
The Weak Charges

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

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

\( C_{1q} \) and \( C_{2q} \)

Note “accidental” suppression of \( Q^{p}_{\text{weak}} \) → 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>
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<tr>
<td>e</td>
<td>-1</td>
<td>( Q^{e}_{W} = -1 + 4 \sin^2 \theta_W \approx 0 )</td>
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<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>
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<tr>
<td>d</td>
<td>-( \frac{1}{3} )</td>
<td>( -2C_{1d} = -1 + \frac{4}{3} \sin^2 \theta_W \approx -\frac{3}{3} )</td>
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<tr>
<td>p(udd)</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>
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\( Q^{p}_{\text{weak}} \) has a definite prediction in the electroweak Standard Model
Sensitivity to New Physics

The vertical axis is $\Lambda/g$

Depending on how you construct the PV “new physics” Lagrangian and select a model dependent “$g$” the mass reach can become much greater.

Eerler, Kurylov, and Ramsey-Musolf
Qweak Experiment Objectives

10 years of development + 2 years on floor (~1 year beam on target)
International Collaboration: 23 institutions, 95 Collaborators
(23 grad students, 10 postdocs)

• Measured parity-violating e-p analyzing power with high precision at $Q^2 \sim 0.025$ (GeV/c)$^2$. Determine: $Q^p_w, Q^n_w, \Lambda/g_{e-p}, C_{1u}, C_{1d}, \sin^2 \theta_W$

Ancillary / Calibration Measurements: (Will be published as standalone results.)

• Parity-violating and conserving e-C and e-Al analyzing powers.
• Parity-allowed analyzing power with transverse-polarized beam on H and Al.
• Parity-violating and allowed analyzing powers on H in the N→Δ(1232) region.
• PV asymmetries in pion photo-production.
• Transverse asymmetries in pion photo-production.
• Non-resonant inelastic measurement at 3.3 GeV to constrain γ-Z Box uncertainty.
• Transverse asymmetry in the PV inelastic scattering region (3.3 GeV).
Jefferson Lab Site

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
The Qweak experiment finished successfully
  – Precise measurement of $e^p$ analyzing power at low $Q^2$
  – 2 years in situ, ~1 year of beam
  – Commissioning run (a.k.a. Run 0 results) published in:
    PRL 111, 141803 (2013)

  • ~ 4% of total data collected
  • 1st “clean” determination of $Q^p_{\text{Weak}}, C^{1u}_{\text{1d}}, C^{1d}_{\text{1d}}, \& Q^n_{\text{Weak}}$

Remainder of experiment still being analyzed
  – Expect final results by late 2014
PVES and Hadronic Structure Effects

\[ A^{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \left[ \frac{-G_F Q^2}{\pi \alpha \sqrt{2}} \right] \left[ \varepsilon G_E^{pZ} G_E^{pZ} + \tau G_M^{pY} G_M^{pZ} - \frac{1}{2} (1 - 4 \sin^2 \theta_W) \varepsilon' G_M^{pY} G_A^p \right] \varepsilon (G_E^{pY})^2 + \tau (G_M^{pY})^2 \]

Neutral-weak form factors

Axial form factor

assume charge symmetry:

\[ 4 G_{E,M}^{pZ} = (1 - 4 \sin^2 \theta_W) \varepsilon G_E^{pY} - G_E^{pY} - G_{E,M}^{pY} - G_{E,M}^S \]

Proton weak charge (tree level)

Strangeness (Now measured to be relatively small!)

Note: Parity-violating asymmetry is sensitive to both weak charges and to hadron structure.
**$Q^p_{\text{Weak}}$ : Extract from Parity-Violating Electron Scattering**

measures $Q^p$ – proton’s electric charge

\[
A = \frac{2M_{NC}}{M_{EM}} = \left[ \frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \left[ Q^2 Q^p_{\text{weak}} + F^p (Q^2, \theta) \right]
\]

\[
\frac{Q^2 \to 0}{\theta \to 0} \Rightarrow \left[ \frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \left[ Q^2 Q^p_{\text{weak}} + Q^4 B(Q^2) \right]
\]

$Q^p_{\text{weak}} = 1 - 4 \sin^2 \theta_w \approx 0.072$ (at tree level)

Correction involving hadronic form factors.
Exp determined using global analysis of recently completed PVES experiments.

The lower the momentum transfer, $Q$, the more the proton looks like a point and the less important are the form factor corrections.
PV Measurements Relative “difficulty factor”

Technical challenges:

- **Counting Statistics**
  - High rate, beam polarization, beam current, high-power target, large acceptance detectors

- **Low noise**
  - Electronics, target density fluctuations, detector resolution

- **Systematics**
  - Helicity-correlated beam asymmetry, backgrounds, precision beam polarimetry, precise $Q^2$ determination

**Q-weak goal:** $\sim 5$ ppb on $A_{ep}$
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
The Apparatus (before shielding)
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.
Kinematics Determination

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

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

Q\textsuperscript{2} Distribution in Octant 1 (Sim & Data)

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

Track Projection on SW01 5

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<tr>
<td>Mean y</td>
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<tr>
<td>RMS x</td>
<td>12.16</td>
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<td>RMS y</td>
<td>20.09</td>
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• **Pockels cell** for fast helicity reversal
• **Helicity reversal frequency**: 960 Hz (to “freeze” bubble motion in the target)
• **Helicity pattern**: pseudo-random “quartets” (+---+ or -+++-, asymmetry calculated for each quartet)
• **Insertable Half-Wave Plate**: for “slow reversal” of helicity to check systematic effects and cancel certain false asymmetries. Less frequently, by Wien filter.
“Phase Locked” Detection Methodology

Helicity of electron beam flipped at 960 Hz, 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

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

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

- Asymmetry measured in blocks of runs “a.k.a. Slugs” of data – IHWP in/out
- Blinded Asymmetry: example Slug plot for “run 0” showing reversal

**False Asymmetry:**

\[ A_{msr} = A_{raw} + A_T + A_L + A_{reg} \]

\[ A_{raw} = \frac{(Y^+ - Y^-)}{(Y^+ + Y^-)} \]
charge normalized yields

\[ A_T = \text{remnant transverse asymmetry} \]

\[ A_L = \text{potential non-linearity in PMT} \]

\[ A_{reg} = \text{helicity-correlated false asymmetry} \]

**Backgrounds:**

\[ A_{ep} = R_{tot} \left( \frac{A_{msr}}{P} \cdot \sum_{i=1}^{4} f_i A_i \right) \]

\[ R_{tot} = \text{includes radiative correction and correction for light-variation} \]

\[ f = \text{background fraction} \]

\[ A = \text{background asymmetry} \]

(backgrounds: Al windows, beamline, neutral backgrounds, N→Δ)
Helicity-Correlated Corrections

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

Detector sensitivity to helicity-correlated beam parameters and broken symmetry can cause false asymmetry.

Sensitivity “slopes” determined from linear regression with natural beam jitter.

Regression Correction: \( A_{\text{reg}} = -31 \pm 11 \text{ ppb} \)

Order of magnitude suppression in sum
Residual 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

- 90° phase shift between vertical and horizontal

- Transverse result: nucleon structure and $2\gamma$ exchange
  - Comparison to theory models
Aluminum Window Background

Large $A$ (asymmetry) & $f$ (fraction) make this our largest correction. Determined from explicit measurements using Al dummy targets & empty H$_2$ cell.

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

- Dilution from windows measured with empty target (actual target cell windows).
- Corrected for effect of H$_2$ using simulation and data driven models of elastic and quasi-elastic scattering.

$$C_{Al} = -64 \pm 10 \text{ ppb}$$
$$A_{Al} = 1.76 \pm 0.26 \text{ ppm}$$

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

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

Simulated e- profile at detector:

Need correction for hydrogen presence

[Graph showing measured dilution factor vs. hydrogen gas density]
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 “saturated” Fe foil in a 3.5 T field.

- Compton (photon & electron) polarimeter (1\%/h)
  - Continuous, non-invasive
  - Known analyzing power provided by circularly-polarized laser
**LH$_2$ Target Design**

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

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

<table>
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<tr>
<th>Component</th>
<th>Details</th>
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<tbody>
<tr>
<td>Centrifugal pump</td>
<td>(15 l/s, 7.6 kPa)</td>
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<tr>
<td>3 kW HX utilizing</td>
<td>4K &amp; 14K He coolant</td>
</tr>
<tr>
<td>35 cm cell (beam interaction</td>
<td>volume)</td>
</tr>
<tr>
<td>Solid Tgts</td>
<td></td>
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</table>
Target Performance

Measured helicity correlated noise.

At **960 Hz reversal rate**, the target noise (< 50 ppm) is very small compared to our helicity quartet ($\pm \mp \mp \pm$) asymmetry width (∼230 ppm). (statistical power $\sim \Delta A_{\text{quartet}} / \sqrt{N_{\text{quartets}}}$)

**FFT of noise spectrum**

Need fast reversal!

At 960 Hz reversal rate, the target noise (< 50 ppm) is very small compared to our helicity quartet ($\pm \mp \mp \pm$) asymmetry width (∼230 ppm).

- **46 ppm** at 182 µA, 4x4 mm² raster!
- **42 ppm** at 169 µA, 4x4 mm² raster!

**Assumes 1/f**

$s_b = 1.3 + (19.4/x)^{2.399}$

Run 12104
May 2011

Run 11805-12095
May 2011

$s_b = 2.8 + (659/x)^{1.168}$
Determining $Q_p^{Weak}$

- $A_{ep} = \left[\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right] \sim \frac{|M^{PV}_{Weak}|}{|M_{EM}|}$, where $\sigma^\pm$ is $e^p x$-sec for $e$'s of helicity $\pm 1$

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

  - where $\varepsilon = [1 + 2(1 + \tau) \tan^2 (\theta / 2)]^{-1}$, $\varepsilon' = \sqrt{\tau(1 + \tau)(1 - \varepsilon^2)}$

  - $\tau = Q^2/4M^2$, $G_{E,M}^\gamma$ are EM FFs, $G_{E,M}^Z$ & $G_A^Z$ are strange & axial FFs,

- $\sin^2 \theta_W = 1 - (M_W / M_Z)^2$ = weak mixing angle

- 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 $A_{ep}/\left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right]$ 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
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, $G^0$, PVA4
- Uses constraints on isoscalar axial FF $G_A^Z$
- All ep data corrected for E & $Q^2$ dependence of $\square_Y Z$ 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
Electroweak Corrections

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

\( \Box_{\gamma Z} \) contribution to \( Q^p_W \) (Qweak kinematics)

\( \Box_{\gamma Z} \) contribution to \( Q^p_W \) (Qweak kinematics) ~7% correction

<table>
<thead>
<tr>
<th>Authors</th>
<th>Reference</th>
<th>Value (0.0026 ± 0.0026)</th>
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<tbody>
<tr>
<td>Gorchein &amp; Horowitz</td>
<td>PRL 102, 091806 (2009)</td>
<td>0.0026 ± 0.0026</td>
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<tr>
<td>Sibirtsev, Blunden &amp; Melnitchouk, Thomas</td>
<td>PRC 84, 015502 (2011)</td>
<td>0.0047 ± 0.0011</td>
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<tr>
<td>Rislow &amp; Carlson</td>
<td>PRD 83, 13007 (2011)</td>
<td>0.0057 ± 0.0009</td>
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<tr>
<td>Gorchein, Horowitz &amp; Ramsey-Muslof</td>
<td>PRC 84, 015502 (2011)</td>
<td>0.0054 ± 0.0020</td>
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<tr>
<td>Hall, Blunden, Melnitchouk, Thomas &amp; Young</td>
<td>arXiv:1304:7877 (2013) (calculation constrained by PVDIS data)</td>
<td>0.0052 ± 0.00043</td>
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</table>

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

\[ Q^2 \text{ Dependence} \]

\[ E \text{ Dependence} \]
First Results: Asymmetry

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

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

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

Qweak
(4% of data, 3 days @ 100%)
Global Fit of $Q^2 < 0.63$ (GeV/c)$^2$ PVES Data

Data Rotated to the Forward-Angle Limit

This Experiment
HAPPEX
SAMPLE
PVA4
G0
SM (prediction)

$A/A_0 = Q_W^p + Q_W^p B(Q^2, \theta=0)$

$A = -279 \pm 35 \pm 31$ 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.
Teaser: Simulated Fit !!
(Assuming anticipated final uncertainties and SM result)
Summary

• Measured during commissioning run:
  \( A_{ep} = -279 \pm 35 \) (statistics) \( \pm 31 \) (systematics) ppb
  – Smallest & most precise ep asymmetry ever measured

• First determination of \( Q^p_{\text{Weak}} \):
  – \( Q^p_{\text{weak}} = 0.063 \pm 0.012 \) (from only 4% of all data collected)
    • SM value = 0.0710(7)
    • New PV physics reach \( \Lambda/g > 1 \) TeV (very conservative)

• First determination of \( Q^n_{\text{Weak}} = -2(C_{1u} + 2C_{1d}) \):
  – By combining our result with APV
    • \( Q^n_{\text{Weak}} = -0.975 \pm 0.010 \) (SM value = -0.9890(7))

• Final results with much smaller uncertainties in 2014
  – Expected PV new physics reach of \( \Lambda/g \sim 2.6 \) TeV.
  – SM test, sensitive to Z’s and LQs
The Qweak Collaboration

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<tr>
<th>Institutions</th>
<th>Collaborators</th>
<th>Grad Students</th>
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95 collaborators 23 grad students 23 institutions

Spokespersons  Project Manager  Grad Students