A search for new PV physics at the TeV scale by measuring the proton’s weak charge $Q_w^p$

Greg Smith (Jefferson Lab) for the Qweak Collaboration

1.16 GeV, 7.9° $\bar{e}p$ elastic scattering asymmetry at the intensity/precision frontier

Exploits PV nature of the weak interaction

doi:10.1038/s41586-018-0096-0

https://rdcu.be/OIW2
• Commissioning result: PRL 111, 141803 (2013)
• Apparatus: NIM A781, 105 (2015)
• Final $Q_w^p$ result & SM test: Nature 557, 207 (2018)
• $Q_w^p$ cookbook & perspectives: ARNS 69, 191 (2019)
• Layman’s description: NPN 29, 15 (2019)
• 3-pass $A_{inel}$ in resonance region: PRC 101, 055503 (2020)
• $^1H$ BNSSA: PRL 125, 112502 (2020):
• $^{12}C$ & $^{27}Al$ BNSSA: to pre-readers next week, PRC
• $^{27}Al$ Longitudinal ($A_{PV}^{^{27}Al}, Q_w^{^{27}Al}, \delta R_{np}^{^{27}Al}$): partial draft
• $N \rightarrow \Delta$ Inelastic PV asymmetry ($d_\Delta$)
• $N \rightarrow \Delta$ BNSSA
• 27 students/theses, several instrumentation papers
\[ 4 \sin^2 \theta_W(0) = 1 - \frac{Q_W^p}{(\rho + \Delta_e)} - \frac{\Box_{WW} - \Box_{ZZ} - \Box_{\gamma Z}(0)}{(\rho + \Delta_e)} + \Delta_e' \]

- Precision at Z-pole is better than at low Q, BUT:
  ** Low-Q expt’s are more sensitive to new physics! **
  - Amplitudes \( A_Z \) & \( A_{\text{new}} \):
  - \(~Z\)-pole: \( A_Z \) imaginary, \( A_{\text{new}} \) ~real, so \( |A_Z + A_{\text{new}}|^2 \) has ~no interference term
  - At low Q: \( A_Z \) & \( A_{\text{new}} \) both ~real, so \( |A_Z + A_{\text{new}}|^2 \) is larger by \( 2A_Z A_{\text{new}} \)

\[ Q < 1 \text{ AVG confirms running to } 9.6\sigma \]

\[ \chi^2 / \text{dof} = 1.9 \]

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**sin^2\theta_W Sensitivity to New Physics**

- 4 sin^2 \theta_W(0) = 1 - (Q_W^p / (\rho + \Delta_e)) - (\Box_{WW} - \Box_{ZZ} - \Box_{\gamma Z}(0) / (\rho + \Delta_e)) + \Delta_e'

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Sensitivity to New Physics Coupling to the Proton

We rule out new PV SL physics below mass scales $\Lambda$, using the coupling strength “$g$” assumed for that new physics.

- Proton: $\theta_h = \tan^{-1}(1/2) = 26.6^\circ$

  $\left[ \frac{\Lambda_+}{g} = \nu \sqrt{\frac{4\sqrt{5}}{Q_w^p \pm 1.96\Delta Q_w^p - Q_w^p(SM)}} \right] = 7.5 \text{ TeV}$

  @ 95% CL, where $\nu = (G_F\sqrt{2})^{-1/2}$

For the “extreme” contact interaction corresponding to e-q compositeness (Eichten et al., PRL50, 811 (1983)),

$g^2 = 4\pi \rightarrow \Lambda_+ = 26.6 \text{ TeV}$

At the other extreme, the coupling usually assumed for leptoquarks (PDG Live)

$g^2 = 4\pi\alpha \rightarrow \Lambda_+ = 2.3 \text{ TeV}$

These are the highest mass reaches in the world for compositeness & LQs to date!
Future $Q^p_W$ Expt’s

- P2 @ MESA/Mainz: $\bar{e}p \rightarrow ep$ $A_{ep}$ & $Q^p_W$
  - Weak vector quark charges, $\Delta \sin^2 \theta_W$ to $\pm 0.00033$
  - $\Lambda/g$ to 13.8 TeV. Installs 2021? arXiv: 1802.04759.
  - $A_{ep} \sim -40 \pm 0.56$ ppb (1.4%) (requires 0.25 ppb (syst)!) $Q^2=0.0045$ GeV$^2$. 155 MeV. 60 cm LH2 (3+ kW). 150 $\mu$A.

Proposed $\Delta Q_W$ (P2 expt)
Flavor ($\theta_h$) independent Mass Reach $\Lambda/g$ (TeV) and Impact of new Experiments

\[ \theta_h \text{-ind. } \Lambda/g \sim \text{perimeter of combined Qweak & APV ellipse.} \]

Explore impact of new $Q_W(p)$ and/or APV expts with the same, $\frac{1}{2}$, or $\frac{1}{4}$ the existing uncertainties.

Because $\theta_h$-ind. $\Lambda/g$ already requires 2 precision expt’s, addition of a 3rd doesn’t help much.

<table>
<thead>
<tr>
<th>Flavor ($\theta_h$) independent Mass Reach $\Lambda/g$ (TeV)</th>
<th>Same errors</th>
<th>With errors/2</th>
<th>With errors/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing $Q_W(p)$ &amp; APV</td>
<td>3.56</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>+ New $Q_W(p)$</td>
<td>3.8</td>
<td>4.0</td>
<td>4.2</td>
</tr>
<tr>
<td>+ New APV</td>
<td>4.1</td>
<td>4.6</td>
<td>4.9</td>
</tr>
<tr>
<td>+ New $Q_W(p)$ + New APV</td>
<td>4.5</td>
<td>6.0</td>
<td>9.5</td>
</tr>
</tbody>
</table>
Systematic studies made to support our primary $A_{PV}$ result on $^1H$ are interesting in their own right:

- **PV ep $A_{inel}$ above the resonance region**

- **Elastic $^1H$ BNSSA**

- **Elastic $^{12}C$ & $^{27}Al$ BNSSA**
  - M.J. McHugh & K. Bartlett theses

- **Inelastic ep→e’$\Delta$ BNSSA**
  - Nuruzzaman thesis
  - Elastic $A_{PV}^{27Al}$, $Q_w^{27Al}$, $\delta R_{np}^{27Al}$
    - K. Bartlett thesis

- **Inelastic ep→e’$\Delta$ $A_{PV}$**
  - A. Lee, H. Nuhait, T. AlShayeb theses
Beam Normal Single Spin Asymmetries

Beam polarization orientation:
- Longitudinal $\rightarrow$ PV asymmetries $A_{PV} \rightarrow Q_w^p$
- Transverse (Vertical or Horizontal) $\rightarrow$ PC asymmetries $B_n$ or BNSSA

$B_n$ manifests itself as the amplitude of an azimuthal variation of the asymmetry when beam is polarized transverse to its incident $p$

- $B_n=0$ in OPE
- $B_n \neq 0 \rightarrow$ TPE ($\text{Im}(\text{TPE})$)
- TPE is leading explanation for proton FF puzzle (LT vs PT $G_E^p/G_M^p$)
- $\text{Re}(\text{TPE})$ from $e^\pm p$ xsecs OR from $\text{Im}(\text{TPE})$ via dispersion relations
- Test predictions of $\text{Im}(\text{TPE})$ by comparing to $B_n$
\( B_n = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{2 \Im(\mathcal{M}_\gamma \mathcal{M}_\gamma^*)}{|\mathcal{M}_\gamma|^2} \)

\[ A_{\exp}(\phi) \approx B_n \mathbf{P} \cdot \hat{n} \]

\[ R_i R_{av} B_{\exp} \sin(\phi_s - \phi_i + \phi_{off}) + C = A_{\text{raw}} - \sum \left( \frac{\partial A}{\partial \chi_j} \right) \Delta \chi_j \]

\[ B_n = R_{\text{tot}} \left[ \frac{B_{\exp}}{P - \sum_i f_i B_i} \right] + B_{\text{bias}} \]

\[ B_n = -5.19 \pm 0.07 \text{ (stat)} \pm 0.08 \text{ (syst)} \text{ ppm} \]

**Pasquini & Vanderhagen:** model intermediate hadronic state (VVCS) with electro-absorption amplitudes. Limited to \( \pi N \) states only (bad), but should apply at all angles (good).

**Afanasev & Merenkov**, and **Gorchtein** : use the optical theorem to relate the VVCS amplitude to the total photo-absorption \( \sigma \). Includes all intermediate states (good), but only strictly valid in the forward-angle limit (bad).
Predictions (open squares) at different kinematics from each group are connected by solid (Gorchtein), dashed (Pasquini & Vanderhagen) & dash-dot (Afanasev & Merenkov) lines to guide the eye.

Agreement of predictions with the far-forward angle ($\theta<10^\circ$) data (solid symbols) is better than for the $\theta>10^\circ$ data (open symbols).
**12C & 27Al BNSSA Corrections**

- **Pro:** Qweak’s 8 detectors arrayed azimuthally about the beam axis *ideal* for $B_n$ msrmnts!
  - $B_n$ is the amplitude of the azimuthal asymmetry variation
  - Statistics come in quickly compared to other expt.’s

- **Con:** Qweak apparatus was designed for $^1$H: 10% $\Delta p/p$!
  - If $A>1$, detectors don’t separate elastics from QE, Inelastic $eN \rightarrow e'\Delta$, discrete excited states, GDR, or other elements in (Al) tgt alloy
  - If $A>1$, to report an elastic $B_n$, we have to make corrections for all of these non-elastic processes, which other expt.’s don’t have to make
    - Where possible, employ our own data. Where not, use literature & sims!
    - Use conservative uncertainties for these corrections
**$^{12}\text{C}$ & $^{27}\text{Al}$ BNSSA Corrections**

- QE & Inel: dilutions from simulations using a generator based on phenomenological fits from Bosted/Mamyan, later scaled to Christy’s fits
  
  - HUGE improvement over Bosted/Mamyan at (our) low $Q^2$!

- QE $B_n$ from our $^1\text{H}$ result $\pm 10^\ast$ msrd error (to account for medium effects & n’s)

- Inel $B_n$ from our $e\text{N} \rightarrow e'\Delta$ preliminary result (Nuruzzaman’s thesis)

- Discrete state dilutions from literature $\rightarrow$ sims, $B_n \approx$ elastic $\pm 100\%$

- GDR: dilution from Goldhaber-Teller ($\text{NP}43$, 242 (1963)), $B_n \approx$ elastic $\pm 100\%$

- 8 $^{27}\text{Al}$ alloy dilutions from assay, 10% RMF calc’s, & simulation, $B_n \approx \alpha \frac{A}{Z} Q \pm 30\%$, scaled from our $^1\text{H}$ elastic $\alpha = -33$ ppm/GeV with $Q=0.157$ GeV
12C & 27Al BNSSA Data

Final B_n Results after all corrections are ~ 10%
Beam Normal Single Spin Asymmetry in $\Delta$ Resonance

Q-weak has measured Beam Normal Single Spin Asymmetry ($B_n$) in the N-to-$\Delta$ transition on $H_2$

$$B_n = \frac{\sigma_{\uparrow \downarrow} - \sigma_{\uparrow \uparrow}}{\sigma_{\uparrow \uparrow} + \sigma_{\downarrow \downarrow}} = \frac{2 \text{Im}(T_{1\gamma} \times T_{2\gamma})}{|T_{1\gamma}|^2}$$

After correcting for polarization and backgrounds

$$B_n = 43 \pm 16 \text{ ppm}$$

- $<E> = 1.16$ GeV
- $<W> = 1.2$ GeV
- $<Q^2> = 0.021$ GeV$^2$
- Unique tool to study $\gamma^*\Delta\Delta$ form factors
- Q-weak along with world data has potential to constrain models and study charge radius and magnetic moment of $\Delta$
PV ep A_{inel} above the resonance region

- Helps validate modeling of the γZ interference structure functions $F_1^{γZ}$ & $F_2^{γZ}$, used for determination of the two-boson exchange γZ box diagram contribution to PV elastic scattering measurements
- A positive PV asymmetry for inclusive π− production was observed, as well as a positive BNSSA for scattered electrons, and a negative BNSSA for inclusive π− production

Kinematics:
- $<E> = 3.35$ GeV < $W> = 2.23$ GeV
- $<Q^2> = 0.082$ GeV$^2$
- $<P_{mixed}> = 0.870 \pm 0.006$, but mixed 94% (long) & 34% (hor)

Special Corrections:
- e/π/μ/γ/n fraction (higher E → more π’s)
- 3 GeV elastics punch-thru shieldwall designed for 1 GeV elastics
Summary

- $Q_{\text{weak}}$ Expt. $\text{msrd} \, ep \ A = -226.5 \pm 9.3 \ \text{ppb} \ @ \ Q^2 = 0.0248 \ \text{GeV}^2$
  - Determined $Q_W(p) = 0.0719 \pm 0.0045$, < 0.2 $\sigma$ from SM
  - $\sin^2 \theta_W = 0.2383 \pm 0.0011_{(\text{MS-bar})}$, Avg(APV, E158, $Q_{\text{weak}}$) = 0.23861 ± 0.00077
  - Mass reach $\Lambda = 26.6 \ \text{TeV}$ (uud, $g^2=4\pi=\text{compositeness}$, 95% CL)
    - $\Lambda = 2.3 \ \text{TeV}$ (uud, $g^2=4\pi\alpha=\text{leptoquarks}$, 95% CL)
    - $\Lambda/g = 7.5 \ \text{TeV}$ (proton, ie uud, 95% CL), $\Lambda/g = 3.6 \ \text{TeV}$ (flavor-independent, 95% CL)

- BNSSA:
  - $^1H \ B_n = -5.19 \pm 0.07 \ (\text{stat}) \pm 0.08 \ (\text{syst}) \ \text{ppm}$ (published)
    - Consistent with calculations & other far-forward angle data
  - $^{12}C$ & $^{27}Al$ elastic results ready for pre-readers
  - Inelastic $ep \rightarrow e'\Delta$ preliminary (thesis) result $B_n = 43 \pm 16 \ \text{ppm}$, paper “soon”

- Elastic $A_{PV}^{27Al}, Q_W^{27Al}, \delta R_{np}^{27Al}$ paper this summer?
- Inelastic $ep \rightarrow e'\Delta$ APV at 3.3 GeV (published) and at 1.1 GeV (“soon”)
Thank you!