The Q_{weak} Experiment at Jefferson Lab- A Search for New Physics at the TeV Scale

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for the Q_{weak} Collab

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- $Q_{\text{weak}}^{\text{P}}$ - How do we extract it from our measurements?
 - How is it computed in the Standard Model?
 - How does new physics affect it?
- Brief update on construction/installation/running status

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The Q^p_{weak} Experiment: A Search for New TeV Scale Physics via a Measurement of the Proton's Weak Charge

Measure: Parity-violating asymmetry in
 $\vec{e} + p$ elastic scattering at $Q^2 \sim 0.03 \text{ GeV}^2$
to $\sim 4\%$ relative accuracy at JLab

Extract: Proton's weak charge $Q^p_{\text{weak}} \sim 1 - 4 \sin^2\theta_W$
to get $\sim 0.3\%$ on $\sin^2\theta_W$ at $Q^2 \sim 0.03 \text{ GeV}^2$

➡ tests "running of $\sin^2\theta_W$ " from M_Z^2 to low Q^2
➡ sensitive to new TeV scale physics

"Running of $\sin^2\theta_W$ " in the Electroweak Standard Model

- Electroweak radiative corrections
→ $\sin^2\theta_W$ varies with Q

PDG 2008 Review: "Electroweak Model and Constraints on New Physics"
J. Erler & P. Langacker

Neutral Current Observable - Parity-Violating Asymmetry

$$\sigma \propto \left| \begin{array}{c} \text{e} \nearrow \quad \nwarrow \text{N} \\ \gamma \quad \text{---} \quad \text{Z} \end{array} \right|^2 + \left| \begin{array}{c} \text{e} \nearrow \quad \nwarrow \text{N} \\ \gamma \quad \text{---} \quad \text{Z} \end{array} \right|^2$$

$$= \left| \begin{array}{c} \text{e} \nearrow \quad \nwarrow \text{N} \\ \gamma \end{array} \right|^2 + h_e \left| \begin{array}{c} \text{e} \nearrow \quad \nwarrow \text{N} \\ \gamma \end{array} \right| \left| \begin{array}{c} \text{e} \nearrow \quad \nwarrow \text{N} \\ \text{Z} \end{array} \right| + \left| \begin{array}{c} \text{e} \nearrow \quad \nwarrow \text{N} \\ \text{Z} \end{array} \right|^2$$

$\vec{e} + N$
(elastic scattering)

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

$$= \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \right] \times F[\text{form factors}, \sin^2 \theta_w] \approx 3 \times 10^{-7} = 0.3 \text{ ppm}$$

Q_{weak}^p : Extract from Parity-Violating Electron Scattering

As $Q^2 \rightarrow 0$

measures Q^p - proton's electric charge

measures Q_{weak}^p - proton's weak charge

$$A = \frac{2M_{NC}}{M_{EM}} \underset{\substack{Q^2 \rightarrow 0 \\ \theta \rightarrow 0}}{=} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \left[Q^2 Q_{weak}^p + F^p(Q^2, \theta) \right]$$

$$\underset{\substack{Q^2 \rightarrow 0 \\ \theta \rightarrow 0}}{\longrightarrow} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}} \right] \left[Q^2 Q_{weak}^p + Q^4 B(Q^2) \right]$$

contains hadronic structure information - strange form factors

$$Q_{weak}^p = 1 - 4\sin^2 \theta_W \sim 0.072 \text{ (at tree level)}$$

- Q_{weak}^p is a well-defined experimental observable
- Q_{weak}^p has a definite prediction in the electroweak Standard Model

$$G_E^s(Q^2)$$

$$G_M^s(Q^2)$$

Strange electric and magnetic form factors
-measure contribution of strange quark sea
to nucleon structure

Nucleon Structure Contributions to the Asymmetry

$$A = A_{Q_W^p} + A_{hadronic} + A_{axial}$$

$$= -.19 \text{ ppm} \quad -.09 \text{ ppm} \quad -.01 \text{ ppm}$$

hadronic:

(31% of asymmetry)

- contains $G_{E,M}^{\gamma}$ $G_{E,M}^Z$

Constrained by
HAPPEX, G^0 , MAMI PVA4

axial:

(4% of asymmetry) -

contains G_A^e ,
has large electroweak
radiative corrections.

Constrained by
 G^0 and SAMPLE

Constraints on $A_{hadronic}$ from other Measurements

$$A_{hadronic} = Q^4 B(Q^2)$$

Strange Form Factor Experiments - Now There's Data!

SAMPLE:

Location: MIT-Bates

Targets: p,d

Kinematics: backward angle, $Q^2 = .038, .10 \text{ GeV}^2$

See Nuclear and
Nucleon Structure -9 tomorrow
(Thomas, Souder, Beise)

Mainz PV-A4:

Location: Mainz MAMI microtron

Targets: p,d

Kinematics: forward & backward angles
 $Q^2 = .11, .23 \text{ GeV}^2$

HAPPEX I, II, III:

Location: Jefferson Lab Hall A

Targets: p, ^4He

Kinematics: forward angle, $Q^2 = .10, .48 \text{ GeV}^2$

G^0 :

Location: Jefferson Lab Hall C

Targets: p, d

Kinematics: forward & backward angles
 $Q^2 = .1 - 1 \text{ GeV}^2$

Parity-Violating Asymmetry Extrapolated to $Q^2 = 0$

(R.D. Young, R.D. Carlini, A.W. Thomas, and J. Roche, PRL 99, 122003 (2007))

$$\overline{A_{LR}^p} = A_s / (-G_F Q^2 / 4\pi\alpha\sqrt{2}) = Q_{\text{weak}}^p + Q^2 B(Q^2)$$

Anticipated Q_W^p Uncertainties

	$\Delta A_{phys} / A_{phys}$	$\Delta Q_W^p / Q_W^p$
Statistical (2200 hours production)	2.1%	3.2%
Systematic:		
Hadronic structure uncertainties	--	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2 determination	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity-correlated Beam Properties	0.5%	0.7%
Total	2.5%	4.1%

4% error on Q_W^p corresponds to $\sim 0.3\%$ precision on $\sin^2\theta_W$ at $Q^2 \sim 0.03 \text{ GeV}^2$

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

(Erler, Kurylov, Ramsey-Musolf, PRD **68**, 016006 (2003))

$Q_W^p = 0.0713 \pm 0.0008$ theoretically

1.1% error comes from QCD uncertainties in box graphs, etc.

Electroweak Radiative Corrections

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

Q_{Weak}^p	Standard Model ($Q^2 = 0$)	0.0713 ± 0.0008
Q_{Weak}^p	experiment precision goal	± 0.003

Source	Q_{Weak}^p	Uncertainty
$\Delta \sin \theta_W (M_Z)$		± 0.0006
$Z\gamma$ box		± 0.0005
$\Delta \sin \theta_W (Q)_{hadronic}$		± 0.0003
WW, ZZ box - $pQCD$		± 0.0001
Charge symmetry		0
Total		± 0.0008

Erler, Kurylov,
Ramsey-Musolf,,
PRD 68(2003)016006.

Estimates of γ -Z box diagrams on A_{PV} at Qweak Kinematics

TBE (Tjon, Blunden, Melnitchouk) 0.13% (hadronic: N and Δ)
arXiv:0903.2759

TBE (Gorchtein & Horowitz) $\sim 6\%$ (dispersion relations; PVDIS FF)
Phys. Rev. Lett. 102, 091806 (2009)

Note: Perhaps γ -W box diagrams involved in V_{ud} extraction in nuclear beta decay can provide insight? (Erler, et al.)

Energy Scale of an “Indirect” Search for New Physics

- Parameterize **New Physics** contributions in electron-quark Lagrangian

$$\mathcal{L}_{e-q}^{\text{PV}} = \mathcal{L}_{\text{SM}}^{\text{PV}} + \mathcal{L}_{\text{NEW}}^{\text{PV}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_V^q \bar{q} \gamma^\mu q$$

- A 4% Q_W^p measurement probes with 95% confidence level for new physics at energy scales to:

g : coupling constant, Λ : mass scale

$$\frac{\Lambda}{g} \sim \frac{1}{2\sqrt{\sqrt{2}G_F|\Delta Q_W^p|}} \approx 2.3 \text{ TeV}$$

- If LHC uncovers new physics, then precision low Q^2 measurements will be needed to determine charges, coupling constants, etc.

Some current and proposed mass scale Λ (TeV) lower limits

	Z' models		leptoquark		compositeness	
	$m(Z_\chi)$	$m(Z_{LR})$	$m_{LQ}(\text{up})$	$m_{LQ}(\text{down})$	$e - q$	$e - e$
Current direct search limits	0.69	0.63	0.3	0.3	–	–
Current electroweak fit	0.78	0.86	1.5	1.5	11–26	8–10
0.6% $Q_W(\text{Cs})$	1.2	1.3	5.1	5.4	28	–
13.1% $Q_W(e)$	0.66	0.34	–	–	–	13
4% $Q_W(p)$	0.95	0.45	6.5	4.6	28	–

Adapted from M.J. Ramsey-Musolf and S. Su,
Phys. Rep. **456**, 1 (2008). hep-ph/0612057

New Physics Reach

$$\mathcal{L}_{\text{SM}}^{\text{PV}} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q}^{\text{SM}} \bar{q} \gamma^\mu q$$

Erler Kurylov, Ramsey-Musolf.,
PRD68(2003)

$$\mathcal{L}_{\text{NP}}^{\text{PV}} = -\frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_V^q \bar{q} \gamma^\mu q$$

Arbitrary quark flavour dependence of new physics:

$$h_V^u = \cos \theta_h \quad h_V^d = \sin \theta_h$$

Data sets limits on: $\frac{g^2}{\Lambda^2}$

Young, Carlini, Thomas & Roche, PRL 99,
122003 (2007)

Lower Bound for “Parity Violating” New Physics

New PV physics scale $> 0.9 \text{ TeV!}$ (from 0.4 TeV)

Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)

Lower Bound for “Parity Violating” New Physics

Qweak constrains new PV physics to beyond 2 TeV

Young, Carlini, Thomas & Roche, PRL 99, 122003 (2007)

Q_{weak}^p & Q_{weak}^e - Complementary Diagnostics for New Physics

Erler, Kurylov, Ramsey-Musolf, PRD 68, 016006 (2003)

- arrows show allowed “pull” of weak charges by new physics as constrained by previous experiments
- electron and proton weak charge experiments are complementary

Relative Shifts in Proton and Electron Weak Charges due to SUSY Effects

R parity (B-L conservation)

RPC SUSY occurs only at loop level

RPV SUSY occurs at tree level

Erler, Ramsey-Musolf, Su hep-ph/0303026

See K. Kumar talk,
Precision Frontier-5, Sunday

Overview of the Q^p_{Weak} Experiment at Jefferson Lab

$\vec{e}$ -p elastic scattering

Elastically Scattered Electron

Experiment Parameters (integration mode)

Incident beam energy: 1.165 GeV
 Beam Current: 180 μ A
 Beam Polarization: 85%
 LH₂ target power: 2.5 KW

Central scattering angle: $8.4^\circ \pm 3^\circ$
 Phi Acceptance: 53% of 2π
 Average Q^2 : 0.030 GeV²
 Acceptance averaged asymmetry: -0.29 ppm
 Integrated Rate (all sectors): 6.4 GHz
 Integrated Rate (per detector): 800 MHz

Qweak overview

Q^p_{Weak} - Status of Production Mode Components

QTOR: Toroidal Magnet

High Power Cryogenic Target

Main Quartz Detector and Electronics

Collimation System

Q^P_{Weak} - Status of Calibration Mode Components

The Q^2 of the experiment is calibrated at low beam current with a tracking system.

Region 1: GEM

Region 2: HDC

Region 3: VDC

Schedule and Summary

Q_{weak}^p experiment schedule

- Installation begins in October 2009
- Commissioning/Engineering run May 2010 - July 2010
- First production run: September 2010 - April 2011
- Second production run: November 2011 - May 2012
- Beamtime end = 12 GeV upgrade shutdown in May 2012
(last experiment to run in Hall C before shutdown)

A successful Q_{Weak}^p experiment will provide:

- Precision measurement of the proton's weak charge in the simplest system.
- Sensitive search for new physics with **CL of 95%** at the **~ 2.3 TeV scale**.
- Fundamental **10σ** measurement of the running of $\sin^2\theta_W$ at low energy.