Qweak: A Precision Standard Model Test at Jefferson Lab

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Qweak uses parity-violating elastic electronproton scattering to measure the proton's weak charge at Jefferson Lab

- Precision Standard Model test
- tests "running of $sin^2\theta_W$ " from M^2_Z to low Q^2
- sensitive to new TeV scale physics



- Background: What and Why?
- The Science
- The Experiment
- Status and Outlook

* Work partially supported by the National Science Foundation



The Collaboration

Funded by DOE, NSF, NSERC

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The Q_{weak} Experiment: A Search for New Physics at the TeV Scale Via a Measurement of the Proton's Weak Charge

December 3, 2001

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Timeline

- Proposal 2001
- Design/Construction 2003 2010
- Data-taking 2010 2012
- Now ~ 100 collaborators!

The Qweak Experiment: Essentials

Elastic scattering of longitudinally polarized electrons on protons

 \overrightarrow{e} + p \rightarrow e⁻ + p



Asymmetry measured with precision of 2% \rightarrow sensitive Standard Model test

The Standard Model

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

rizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rat

matter constituents FERMIONS - 1/0 0/0 E/

| Lep | Leptons spin =1/2 | | Quarks spin =1/2 | | |
|-----------------------|-------------------------------|--------------------|------------------|---------------------------------------|---------|
| Flavor | Mass GeV/c ² | Electric charge | Flavor | Approx. Mass GeV/c ² | Electri |
| VL lightest neutrino* | (0-0.13)×10 ⁻⁹ | 0 | U up | 0.002 | 2/3 |
| e electron | 0.000511 | -1 | d down | 0.005 | -1/3 |
| M middle neutrino* | (0.009-0.13)×10 ⁻⁹ | 0 | C charm | 1.3 | 2/3 |
| µ muon | 0.106 | -1 | S strange | 0.1 | -1/3 |
| VH heaviest neutrino* | (0.04-0.14)×10 ⁻⁹ | 0 | top | 173 | 2/3 |
| T tau | 1.777 | -1 | bottom | 4.2 | -1/3 |

Spin is the intrinsic angular momentum of particles. Spin is given in units of h, which is the quantum unit of angular momentum where $h = h/2\pi = 6.58 \times 10^{-25}$ GeV s =1.05×10⁻³⁴ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10⁻¹⁹ coulombs

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c2 (remember E = mc^2) where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/ c^2 = 1.67×10^{-27} kg.

Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_{θ}, ν_{μ} , or ν_{τ} , labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos VL, VM, and VH for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0 , γ , and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles

Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons





Properties of the Interactions

aths of the inte

| Property | Gravitational Interaction | Weak Interaction (Electr | Electromagnetic Interaction | Strong Interaction |
|-----------------------------------|--------------------------------|--------------------------------|--------------------------------|-----------------------|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge |
| Particles experiencing: | All | Quarks, Leptons | Electrically Charged | Quarks, Gluons |
| Particles mediating: | Graviton (not yet observed) | W+ W- Z ⁰ | Ŷ | Gluons |
| Strength at f 10 ⁻¹⁸ m | 10-41 | 0.8 | 1 | 25 |
| 3×10 ⁻¹⁷ m | 10-41 | 10-4 | 1 | 60 |

Uni Na ph V M Wb Z Z boson

force carriers BOSONS spin = 0, 1, 2,

| ied Ele | ectroweak | spin = 1 | 6 |
|------------|----------------------------|-----------------|----------------------|
| ne | Mass GeV/c ² | Electric charge | |
| ton | 0 | 0 | |
| 7 | 80.39 | -1 | Color |
| t | 80.39 | +1 | Only qu (also c |
| osons 0 | 91 188 | 0 | color cl with the |

Strong (color) spin =1 Mass Flectric GeV/c² charge g 0 0 aluoa

Charge

arks and gluons carry "strong charge" alled "color charge") and can have strong ions. Each quark carries three types of arge. These charges have nothing to do colors of visible light. Just as electricallyarged particles interact by exchanging photons in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated - they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature mesons qq and baryons qqq. Among the many types of baryons observed are the proton (uud), antiproton (ūūd), neutron (udd), lambda A

(uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ (ud), kaon K⁻ (su), B^0 (db), and η_C (cc). Their charges are +1, -1, 0, 0 respectively.

Visit the award-winning web feature The Particle Adventure at ParticleAdventure.org This chart has been made possible by the generous support of

U.S. Department of Energy **U.S. National Science Foundation** Lawrence Berkeley National Laboratory of teachers, physicists, and educators. For more information see CPEPweb.org

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?



Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?



Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?



In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

Elastic electron-proton scattering - Standard Model "Players"

In the Standard Model, the electron and proton interact through two of the four fundamental forces - weak and electromagnetic - the unified "electroweak" force



$$\overrightarrow{e^-}$$
 + p \rightarrow e⁻ + p

Participants:

proton – 2 up quarks, 1 down quark (u u d) mass = 0.938 GeV/c²

electron - mass = $0.000511 \text{ GeV}/c^2$

Force carriers:

Electromagnetic: γ - photon - mass = 0 GeV/c²

Weak: Z⁰ boson - mass = 91 GeV/c²





Z⁰ produced virtually; Heisenberg ($\Delta E \Delta t > h$) says its okay! Elastic electron-proton scattering – Standard Model Couplings The Standard Model prescribes the couplings of the fundamental particles to each other \rightarrow Q^{γ} Q^{Z}

u +2/3
$$1 - 8/3 \sin^2 \theta_W$$

d -1/3 $-1 + 4/3 \sin^2 \theta_W$

Electromagnetic force \rightarrow proton's electric charge

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

Weak force \rightarrow proton's neutral weak charge - Q_{weak} $Q_{weak}^{p} = 2(1-8/3\sin^{2}\theta_{w}) + 1(-1+4/3\sin^{2}\theta_{w})$ $= 1-4\sin^{2}\theta_{w}$





What is $\sin^2\theta_w$ - "weak mixing angle"? \rightarrow key parameter of the Standard Model

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

 $sin^2\theta_W$ - "weak mixing angle", parameterizes the mixing between the two neutral currents in the model \rightarrow needs to be determined from experiment

"Running" of the Weak Mixing Angle - $sin^2\theta_W$



"Running" of the weak mixing angle \rightarrow key prediction of the Standard Model (Q = 4-momentum transfer between scattering particles)

- Experimental Standard Model measurements (cross sections, asymmetries, decay rates, etc. in electroweak processes) extract values of $\sin^2\theta_W$ \rightarrow success of SM is due to internal consistency of these values
- If an experiment disagrees with the SM prediction then it could be a signature of "New Physics"

The Hunt for New Physics

Isn't new physics supposed to come from energies > 1000 GeV = 1 TeV?

How can Qweak (scattering experiment with beam energy 1 GeV) hunt for New Physics?

- "Energy frontier" - like LHC - Large Hadron Collider
- \rightarrow Make new particles ("X") directly in high energy collisions





Qweak "New Physics" Sensitivity

What kinds of New Physics is Qweak sensitive to?

 \rightarrow supersymmetry, heavy Z', leptoquarks, ...



New Physics Energy Reach of Qweak

What energy scales can a precision 4% measurement of Qweak reach?

Parameterize new physics with a new contact interaction in the Lagrangian:

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

g=coupling Λ =mass scale

Arbitrary quark flavor dependence of new physics:



Historical Example: Top Quark

Past example of interplay between energy frontier and precision frontier

"Precision frontier"

Precision electroweak measurements (LEP at CERN and SLD at SLAC) were sensitive to "virtual top quarks" in loops

Prior to the direct top quark discovery, theorists predicted it would fall in a range from 145 GeV/ c^2 - 185 GeV/ c^2



Figure 4. Measurements of the top quark mass at Fermilab (CDF and D0) and indirect predictions from precision measurements (LEP1, SLD and M_W).³

m, [GeV]

Parity-Violating Asymmetry

Qweak experiment - exploit the interference between EM and weak interactions





By running at a small value of Q^2 (small beam energy, small scattering angle) we minimize our sensitivity to the effects of the proton's detailed spatial structure.

Overview of Jefferson Lab - The Parts Critical to Qweak

CEBAF Polarized Injector:

- \rightarrow Polarized electrons photoemitted from GaAs wafer
- → Laser light is polarized; reversed rapidly with high voltage pulses to "Pockels cell"
- → Much effort goes into insuring that position, angle, intensity, of laser beam doesn't change with "flip" - only circular polarization





Linear Accelerators







Overview of Qweak Apparatus



Qweak Apparatus Overview











Experimental Technique

How do we take the bulk of our data? Pretty simple actually...

- Integrate the light signal in the Cerenkov detectors, sum them, and record the value every 1 msec
- "Normalize" the integrated signal (S) to the amount of charge (Q) in the beam

$$Y = \frac{S}{Q}$$

• Flip the electron beam helicity and form the asymmetry

$$A_{PV} = \frac{Y^{+} - Y^{-}}{Y^{+} + Y^{-}}$$

• Repeat 4 billion times! (2200 hours of data-taking)

Anticipated Q^p_{weak} Uncertainties

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

Due to hadronic dilutions, a 2.5% measurement of the asymmetry is required to determine the weak charge of the proton to ~4%.

$$A_{ep} = \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}} = \left[\frac{-G_{F}}{4\pi\alpha\sqrt{2}}\right] \left[Q^{2} Q_{weak}^{p} + Q^{4}B(Q^{2})\right]$$

First - statistics on the raw measured asymmetry $A \rightarrow \rightarrow \rightarrow \rightarrow \rightarrow$

Statistical Error

To achieve our desired final statistical error the error on each 4 msec measurement of the asymmetry ("quartet") needs to be small

At 165 μA , total detected rate is 5.83 GHz $\,\rightarrow\,$ expect ~ 23 million primary events

- \rightarrow Expect 207 ppm error from "counting statistics" per quartet
- \rightarrow Observe slightly higher value (236 ppm) for understood reasons
- \rightarrow Doing this 4 billion times gives final error of ~ 5 ppb



Need to keep all other sources of random noise small compared to this. Potentially most problematic contribution was target density fluctuations BUT...

$$\Gamma_{stat} = \sqrt{\Gamma_{count}^2 + \Gamma_{electronics}^2 + \Gamma_{target}^2}$$

Qweak Target - World's Highest Power Liquid Hydrogen Target





- Target has power capacity of 2500 W adequate for 180 μA electron beam on 35 cm target
- First target of this type to use computational fluid dynamics (CFD) in its design
- Designed to minimize contribution to random noise from target density fluctuations - "boiling"



Target Density Fluctuations

Critical that target density fluctuations at our flip rate be kept less than counting statistics fluctuations ~ 236 ppm

(achieved! contribution < 46 ppm)

100 150 200 250 300 350 400 450

Frequency [Hz]

10⁻⁷

gwk md1neg.hw sum Yield Amplitude [V] 1. Versus time, two beam currents 0.0445 ... target bubble formation ? 0.044 0.0435 2. Fast Fourier transform – rapid spin flip immunizes the 0.043 experiment to low freq. noise! 0.0425 gwk_md1neg.hw_sum Yield FF1 0.042 Entries 100000 Mean 239 **10**⁻⁵ RMS 139 200 50 100 150 250 qwk_md\neg.hw_sum Yield **150 µA, 3x3, 30 Hz** Amplitude [V/µA] Amplitude [V] 20 µA, 3x3, 30 Hz 0.0418 10⁻⁶



300

350

Main detector yield

versus time

Anticipated Q^p_{weak} Uncertainties

| | $\Delta A_{phys} / A_{phys}$ | $\Delta \mathbf{Q}^{p}_{weak} / \mathbf{Q}^{p}_{weak}$ |
|--|------------------------------|--|
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| ——— Helicity-correlated Beam Properties | 0.5% | 0.7% |
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| Total | 2.5% | 4.1% |

→Helicity-correlated Beam Properties (like beam position, angle, energy):

$$A_{corrected} = A_{measured} - A_{false}$$

Two correction procedures applied:

- Linear regression using "natural beam motion"
- Beam modulation (Josh Hoskins, BC.00005)

Helicity-Correlated Beam Properties - "Natural Beam Motion" The beam parameters (like X beam position) can be different for + and - helicity $\Delta P = P_+ - P_-$ we continually measure this and correct for it

Response of detector to natural beam motion fluctuations in the X direction; Symmetry of the detector reduces sensitivity to position and angle motion





Anticipated Q^p_{weak} Uncertainties

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

→Beam Polarimetry:

$$A_{phys} = \frac{A_{correcte}}{P_{beam}}$$

Typical electron beam polarization is ~ 88%; accurately measured with two techniques:

- Moller polarimetry $\vec{e} + \vec{e} \rightarrow e' + e'$ (Josh Magee, BC.00006)
- Compton polarimetry (Amrendra Narayan, BC.00007)



Anticipated Q^{p}_{weak} Uncertainties

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

$$A_{ep} = \frac{1}{1-f} \left[A_{phys} - f A_{back} \right]$$

Physics asymmetry is corrected for asymmetries from background processes ("dilution factor" = f):

- Aluminum target windows
- Inelastic e-p scattering (John Leacock, BC.00003)
- Beamline backgrounds

Aluminum Background Asymmetry

The target cell has aluminum end windows

- Aluminum asymmetry is larger than e-p asymmetry; we must measure it in separate runs
- "dilution" f ~ 3%; anticipated asymmetry correction ~ 20%



Total Asymmetry by IHWP Setting

Anticipated Q^p_{weak} Uncertainties

| | $\Delta A_{phys} / A_{phys}$ | |
|--|------------------------------|------|
| $\Delta Q^{p}_{weak} Q^{p}_{weak}$ | 0.494 | |
| Statistical (2200 hours production) Systematic: | 2.1% | 3.2% |
| Helicity-correlated Beam Properties | 0.5% | 0.7% |
| Beam polarimetry | 1.0% | 1.5% |
| Backgrounds | 0.5% | 0.7% |
| — Absolute Q ² determination | 0.5% | 1.0% |
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| Total | 2.5% | 4.1% |

$$A_{ep} = \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}} = \left[\frac{-G_{F}}{4\pi\alpha\sqrt{2}} \int Q^{2} Q^{p}_{weak} + Q^{4}B(Q^{2}) \right]$$

→Absolute Q² determination:

Must measure Q^2 accurately in order to extract Q^2 from A_{ep}

Dedicated tracking system was built; tracks individual events at low beam current

Qweak Tracking System



Q² Measurement with Qweak Tracking System $Q^2 = 4EE'\sin^2$

Measurement of Q^2 requires

- Measurement of scattering angle θ before the magnet
- Verification of elastic scattering event after the magnet (correct E')
- Detailed measurements of spatial light distribution from detectors • ("light-weighted" Q² distribution)



Electron Profile at Detector

Simulation



Region 3 Projection:



Scattered Electron Beam Envelope After Magnet

^{weak} Animation from track reconstructed profiles from vertical drift chambers after the QTOR magnet



(yes, there is one dead wire...)

Anticipated Q^p_{weak} Uncertainties

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| Absolute Q ² determination | 0.5% | 1.0% |
| — Hadronic structure uncertainties | | 1.5% |
| Total | 2.5% | 4.1% |

$$A_{ep} = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right] \left[Q^2 Q_{weak}^p + Q^4 B(Q^2)\right]$$

→Hadronic struture uncertainties:

The "form factor" $B(Q^2)$ term - due to proton structure \rightarrow Determined by extrapolation from previous PV electron scattering at higher Q^2 to Qweak Q^2 of ~ .026 (GeV/c)²



Data Quality - Slow Reversals

We are measuring a small quantity for a long time; what diagnostics do we have to know that everything is "OK"? \rightarrow "slow" reversals are one example

- IHWP: "Insertable Half Wave Plate" at the polarized injector
 - → reverses electron beam helicity, but nothing else; real physics asymmetries should reverse sign under this reversal (timescale ~ 8 hours)



• "Double wien": Accelerator system that manipulates electron beam helicity to reverse it and nothing else; real physics asymmetries should also reverse sign under this reversal (timescale ~ 1 week)



Future Prospects at Jefferson Lab

Jefferson Lab will double its beam energy ("12 GeV Upgrade" project); with running anticipated at the new energy by ~ late 2014.

→ There are two major approved projects involving PV electron scattering MOLLER Experiment (Measurement of a Lepton Lepton Electroweak Reaction)

$$\vec{e} + e \rightarrow e' + e'$$

- Parity violating Moller scattering at 11 GeV
- Will improve E158 error by factor of 5
- Competitive $\sin^2 \theta_w$ with Z pole measurements



- Broad program built around retasked solenoidal magnet
- Electroweak couplings
- Charge symmetry
- Higher twist
- SIDIS





Summary and Outlook

- The Qweak experiment at Jefferson Lab is well underway, with ~25% of its data collected in "Run I" with the remainder expected in "Run II" from November 2011 to May 2012
- The Qweak experiment will make the first direct measurement of the weak charge of the proton, with an anticipated precision of ~ 4%.
- The expected precision on $Q^{\rm p}_{\rm weak}$ will result in the most precise measurement of the weak mixing angle at low energies



 Building on techniques developed by Qweak, further parity-violating electron scattering experiments are planned at Jefferson Lab for the "12 GeV Era"

Backups

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

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



Katherine Myers (GWU)

PAVI11 5-9 September 2011

Quark Couplings

• Qweak will fully constrain the vector quark couplings:



Radiative Corrections

Several corrections: $\Delta sin^2 \theta_W(M_Z)$, WW and ZZ box – but these have small uncertainties

Focus on: YZ Box Corrections near 1.16 GeV



* In 2009, Gorchtein and Horowitz showed the vector hadronic contribution to be significant and energy dependent.

*This soon led to more refined calculations with corrections of ~8% and error bars ranging from $\pm 1.1\%$ to $\pm 2.8\%$.

* It will probably also spark a refit of the global PVES database used to constrain G_{E^s} , G_{M^s} , G_A .



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