Eur Phys J A (2005) **24,** s2, 155–158
DOI: 10.1140/epjad/s2005-04-039-5

EPJ A direct
electronic only

Qweak: A precision measurement of the proton's weak charge

Gregory R. Smith, for the Qweak Collaboration

Jefferson Lab, Newport News, VA 23606, USA

Received: 15 October 2004 / Published Online: 8 February 2005

Abstract. The $\mathrm{Q_{weak}}$ experiment at Jefferson Lab will measure the parity-violating asymmetry in e–p elastic scattering at very low Q^2 using a longitudinally polarized electron beam and a liquid hydrogen target. The experiment will provide the first measure of the weak charge of the proton, Q_w, to an accuracy of 4%. Q_w is simply related to the weak mixing angle θ_w, providing a precision test of the Standard Model. Since the value of $\sin^2\theta_w$ is approximately 1/4, the weak charge of the proton $Q_w^p = 1 - 4\sin^2\theta_w$ is suppressed in the Standard Model, making it especially sensitive to the value of the mixing angle and also to possible new physics. The experiment employs an 85% polarized, 180 μA, 1.2 GeV electron beam, a 35 cm liquid hydrogen target; and a toroidal magnet to focus electrons scattered at $8^\circ \pm 2^\circ$, corresponding to $Q^2 \sim 0.03$ (GeV/c)^2. With these kinematics the systematic uncertainties from hadronic processes are strongly suppressed. To obtain the necessary statistics this 2200 hours experiment must run at an event rate of over 6 GHz. This requires current (integrating) mode detection of the scattered electrons, which will be achieved using synthetic quartz Cherenkov detectors. A tracking system will be used in a low-rate counting mode to determine the average Q^2 and the dilution factor of background events. The theoretical context of the experiment and the status of its design are discussed.

PACS. 24.80.+y Nuclear tests of fundamental interactions and symmetries – 25.30.Bf Elastic electron scattering

1 Introduction

We describe a new experiment at Jefferson Lab to make the world's first measurement of the weak charge of the proton. $\mathrm{Q_{weak}}$ is a well defined experimental observable with a definite prediction in the Standard Model (SM). The experiment would constitute the first SM test at Jefferson Lab. To lowest order, the weak charge can be expressed as $\mathrm{Q}_w^p = 1 - 4\sin^2\theta_\mathrm{w}$, where $\sin^2\theta_w \approx 0.23$ is the weak mixing angle. The goal of the $\mathrm{Q_{weak}}$ experiment [1] is a 4% measurement of Q_w^p (combined statistical and systematic errors), which corresponds to a 0.3% measurement of $\sin^2\theta_w$. A measurement of this precision is possible because hadronic corrections are small at low Q^2 [2], and measured by many different experiments aimed at electromagnetic and weak hadronic form factors.

2 Physics motivation

The SM makes a firm prediction for $\mathrm{Q_{weak}}$ based on the running [3,4] of $\sin^2\theta_w$ from the Z^0 pole. As shown in

---

[1] The Qweak Collaboration:
D. Armstrong[1], T. Averett[1], J. Birchall[2], T. Botto[3], J.D. Bowman[4], A. Bruell[5], R. Carlini[5], S. Chattopadhyay[5], C. Davis[6], J. Doornbos[6], K. Dow[3], J. Dunne[7], R. Ent[5], J. Erler[8], W. Falk[2], M. Farkhondeh[3], J.M. Finn[1], T. Forest[9], W. Franklin[3], D. Gaskell[5], K. Grimm[1], F.W. Hersman[10], M. Holtrop[10], K. Johnston[9], R. Jones[11], K. Joo[11], S. Kowalski[3], C. Keppel[12], M. Kohl[3], E. Korkmaz[13], L. Lee[6], Y. Liang[14], A. Lung[5], D. Mack[5], S. Majewski[5], J. Mammei[15], R. Mammei[15], D. Meekins[5], G. Mitchell[4], H. Mkrtchyan[16], N. Morgan[15], A. Opper[14], S. Page[2], S. Pentillo[4], M. Pitt[15], M. Poelker[5], T. Porcelli[13], W.D. Ramsay[2], M. Ramsey-Musolf[17], J. Roche[5], N. Simicevic[9], G.R. Smith[5], T. Smith[18], R. Suleiman[15], S. Taylor[3], E. Tsentalovich[3], W.T.H. vanOers[2], S. Wells[9], W.S. Wilburn[4], S. Wood[5], H. Zhu[10], and C. Zorn[5].
[1]College of William & Mary
[2]University of Manitoba
[3]Massachusetts Institute of Technology
[4]Los Alamos National Laboratory
[5]Thomas Jefferson National Accelerator Facility
[6]TRIUMF
[7]Mississippi State University
[8]Universidad Nacional Autonoma de Mexico
[9]Louisiana Tech University
[10]University of New Hampshire
[11]University of Connecticut
[12]Hampton University
[13]University of Northern British Columbia
[14]Ohio University
[15]Virginia Polytechnic Institute
[16]Yerevan Physics Institute
[17]California Institute of Technology
[18]Dartmouth College

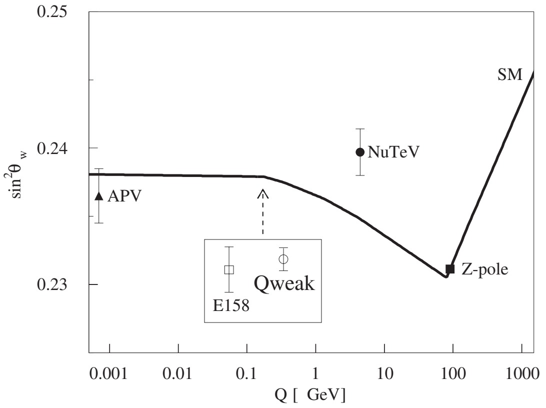

Fig. 1. Running of the weak mixing angle [3] in the Standard Model, calculated in the $\overline{\text{MS}}$ scheme. Shown are results from atomic parity violation (APV) [8–10], NuTeV [7], and the Z pole [5]. The *error bar* shown for the E158 [6] Møller experiment is that anticipated for their final result

Fig. 1 the value of the weak mixing angle is predicted to change (in the $\overline{\text{MS}}$ renormalization scheme) by $\sim 3\%$ from the energy scale of the Z pole (where a decade of precision measurements have been made at high energy colliders like SLAC and LEP [5]) to the low energy scale of Q_{weak}. With the proposed 0.3% measurement of the weak mixing angle, the Q_{weak} experiment will make a $\sim 10\sigma$ verification of this effect. A deviation from the SM prediction would imply new physics beyond the SM. In the case of the Q_{weak} experiment, there is even sensitivity to which SM extension is responsible for the deviation, especially when taken in conjunction with the results of other experiments. Should the result of this experiment agree with the prediction of the SM, then the result would dramatically constrain possible extensions to the SM.

The Q_{weak} experiment [1] at Jefferson Lab (JLab) will make such a precision measurement of the asymmetry between cross-sections for positive and negative helicity electrons in polarized elastic electron-proton scattering. The asymmetry violates parity, and arises from the interference of electromagnetic and weak amplitudes (photon and Z^0 boson exchange). At this low energy scale, the asymmetry is a measure of the weak charge of the proton, Q^p_w, which is the strength of the weak vector coupling of the Z^0 boson to the proton. At tree level the value of Q_{weak} is expected to be ~ 0.072. In the limit of small scattering angle and small momentum transfer ($Q^2 \to 0$), the asymmetry is given by [2]:

$$\begin{aligned}\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} &= [\frac{-G_F}{4\pi\alpha\sqrt{2}}][Q^2 \text{Q}^p_w + Q^4 B(Q^2)] \qquad (1)\\ &\approx\ -0.3 \text{ ppm at } Q^2 = 0.03 \text{ GeV}^2\end{aligned}$$

where $B(Q^2)$ is a contribution from electromagnetic and weak form factors. It is sensitive to $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$, the target of many recent and ongoing experiments at Jefferson Lab, Bates, and MAMI. As 1 makes clear, the B term is suppressed as Q^2 goes to zero by an extra factor of Q^2 relative to Q_{weak}. On the other hand, the experimental asymmetry grows with Q^2. At Jefferson Lab a Q^2 of ~ 0.03 GeV^2 has been chosen as the most ideal compromise between these two competing considerations.

The expected measured asymmetry A_{meas} of -0.29 ppm consists of three main terms. The biggest is the term sought in this experiment, namely A_{Qw}, the first term in 1. It has an expected value of -0.19 ppm, or about 2/3 of the expected A_{meas}. The second term comes from the hadronic form factors discussed above, and has a magnitude expected to be about 31% of A_{meas}, or about -0.09 ppm. It will be well constrained by the precise measurements provided by HAPPEX, PVA4, and G0. The third term is almost negligible, and amounts to only about 3% of the expected A_{meas}. It accounts for the axial contribution, contains $\text{G}^{\text{e}}_{\text{A}}$, and includes substantial electroweak radiative corrections. It will be constrained by SAMPLE and G0. When added in quadrature, the two background terms $\text{A}_{\text{hadronic}}$ and A_{axial} contribute only about 2% to the expected final error on Q_{weak}. We re-emphasize that the bulk of this so-called background contribution can be accounted for solely with the results of precision experiments aimed at hadronic form factors, and does not rely on theoretical calculations or models. In addition, the Q_{weak} collaboration is considering augmenting the existing experimental information on $B(Q^2)$ by performing a short independent measurement at a Q^2 slightly higher than 0.03 GeV^2. This should not be necessary if the ongoing form factor experiments achieve their proposed goals.

The Q_{weak} experiment will provide tight constraints on SM parameters associated with potential new physics. For example, the up and down quark couplings in the SM electron-quark Lagrangian:

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

are constrained by Q^p_W according to

$$Q^p_W(SM) = -2(2C_{1u} + C_{1d}) \sim 0.0721 \,.$$

This constraint is complementary to other existing constraints, and when combined with those other measurements, dramatically reduces the allowed phase space for new physics.

The physics reach of this experiment can be expressed in terms of its precision as:

$$\frac{\lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_F|\varDelta Q^p_W|}} \approx 4.6 \text{ TeV}.$$

The discovery potential of weak charge measurements will be unmatched until the LHC turns on. If new physics is uncovered at the LHC, such as an extra Z boson, then precision experiments like Q_{weak} undertaken at low Q^2 will be essential to determine the charges, coupling constants, etc.

There are many reasons to expect that the SM is a low-energy effective theory of some more fundamental description of nature. Neutral current experiments like Q_{weak} provide important consistency checks of the SM, are complementary to direct searches for new physics, and can help distinguish and characterize the new physics once it is found [3,4]. One of the most plausible extensions to the SM which can be tested for by the $Q_{\rm weak}$ experiment is the presence of extra Z′s. The present lower bound for Z′s provided by Tevatron experiments is only 0.6 TeV, which leaves plenty of discovery potential for the $Q_{\rm weak}$ experiment. Z′s would resolve the $\sim 2\sigma$ discrepancy from the SM in the generation number ($N_\nu = 2.986 \pm 0.008$) derived from the measured Z^0 lineshape. Furthermore, Z′s would improve the agreement of both the APV and NuTeV experiments with the SM. Another SM extension the $Q_{\rm weak}$ experiment is particularly sensitive to is R-parity violation, one of the most interesting varieties of SUSY. Finally, the $Q_{\rm weak}$ experiment will provide a sensitive test for leptoquarks.

Weak charge and mixing angle results can be obtained in other types of experiments. The SLAC E158 [6] experiment is a purely leptonic Møller scattering experiment recently completed at a similar Q^2. Their preliminary results are consistent with the SM. The Fermilab NuTeV experiment [7] explored νA scattering at ~ 10 GeV/c^2, and found an intriguing 3σ discrepancy with the SM. The interpretation of this discrepancy remains somewhat controversial for now. Finally, there have been atomic parity violation (APV) measurements [8–10] made of the Cs atom (Q^2=0). Those results have been plagued by extraordinarily difficult and changing theoretical corrections (see, for example [11,12]), however, at present their result is consistent with the SM. To provide some perspective, a 13% measurement of $Q^p_{\rm weak}$ in our e–p experiment would provide the same sensitivity to new physics as a 1% measure of $Q_{\rm weak}(N, Z)$ using APV, but without the theoretical uncertainties. On the other hand, our ability to test for extensions to the SM will be greatest when the results of the $Q_{\rm weak}$ experiment are combined with those from the complementary triad of experiments referred to above, especially E158.

3 The qweak experiment

The conceptual design of the $Q_{\rm weak}$ experiment is illustrated in Fig. 2. The experiment consists of scattering a longitudinally polarized 1.2 GeV electron beam by a 35 cm liquid hydrogen target. Elastically scattered electrons at $8° \pm 2°$ are selected by a collimation system, and then focused by a large toroidal resistive magnet onto a set of eight synthetic quartz Čerenkov detectors. At the average experimental momentum transfer of $Q^2 = 0.03$ GeV^2 the expected $Q_{\rm weak}$ asymmetry is small, -0.3 parts per million (ppm). The expected event rate for scattered electrons of ~ 6 GHz precludes counting the individual events. Instead, the experiment will use current mode detection and low noise front end electronics.

In brief, the various experimental systems are as follows. The liquid hydrogen target will be patterned after the successful design of the G0 and SAMPLE targets except that a centrifugal pump will deliver several times the flow velocity achieved in those targets. To meet the more challenging requirements of the $Q_{\rm weak}$ experiment, the beam will be rastered into a uniform 4mm x 4mm pattern. The target cell will be 35cm in length. With the proposed beam current of 180μA, this target will require almost 2.5kW of cooling power. The ability of the target to provide the necessary small boiling contribution to the asymmetry width will be backed up by an array of high rate, small angle quartz luminosity monitors near the end of the Jefferson Lab Hall C beam line.

The toroidal magnet consists of eight resistive coils each approximately 3.7m long and 1.5m tall composed of a double pancake of Cu conductor 3.8cm x 5.8cm in cross section, with a 2cm diameter central cooling channel. The magnet will provide an $\int \mathbf{B} \cdot d\mathbf{l} \sim 0.7$ T-m with a 9500 A, 1.2 MW DC power supply. The coils will be supported in an aluminum stand, and will permit a 1 foot diameter, Pb-shielded beam pipe to pass through the central axis. Simulations show that this magnet will cleanly separate photons and inelastic events from the elastic events of interest at the focal plane.

The detectors themselves will be relatively insensitive to γ's, n's, and π's, be capable of withstanding $\geq$ 300 kRad, and operate at counting statistics. Eight fused silica Čerenkov detectors will be used, each approximately 2m x 16cm x 2.54cm. These bars are characterized by n=1.47, $\theta_{\rm Cerenkov} = 47°$, and a total internal reflection angle of 43°. The bars will be read out by S20 photocathodes at each end, and should provide about 100 photoelectrons per event.

A tracking system will be used with the beam current reduced by four orders of magnitude, allowing individual events to be observed. This will enable both a measurement of the dilution of the Čerenkov detector signal by background and a precise determination of the average Q^2. The tracking system components will rotate to cover all octants, and will include the following sets of detectors. A gas electron multiplier closest to the target will serve as a vertex detector. Horizontal drift chambers near the magnet entrance will measure the scattering angle. These will be augmented by a mini-torus to sweep away the otherwise dominant Møller electrons. At the focal plane, vertical drift chambers will map the analog response of the Čerenkov system. Finally, large scintillation counters will provide a charged particle trigger.

Precision beam polarimetry is required in order to have a polarization contribution to the systematic error of less than 1.5%. To achieve this a two-pronged approach is being pursued. First, efforts are already underway to increase the operating current of the existing $\leq 10\mu$A, $\leq 1\%$ Møller polarimeter to 100 μA beam currents. Methods being investigated include kicking the beam across wire Møller targets, and use of rotating foil targets. In addition, a Compton polarimeter is being developed for JLab Hall C which would provide continuous relative measurement of the beam polarization, normalized by the Møller polarimeter.

Other requirements on beam properties have been determined by extensive simulations. The $Q_{\rm weak}$ beam property specifications have for the most part already been achieved at Jefferson Lab during the G0 and HAPPEX

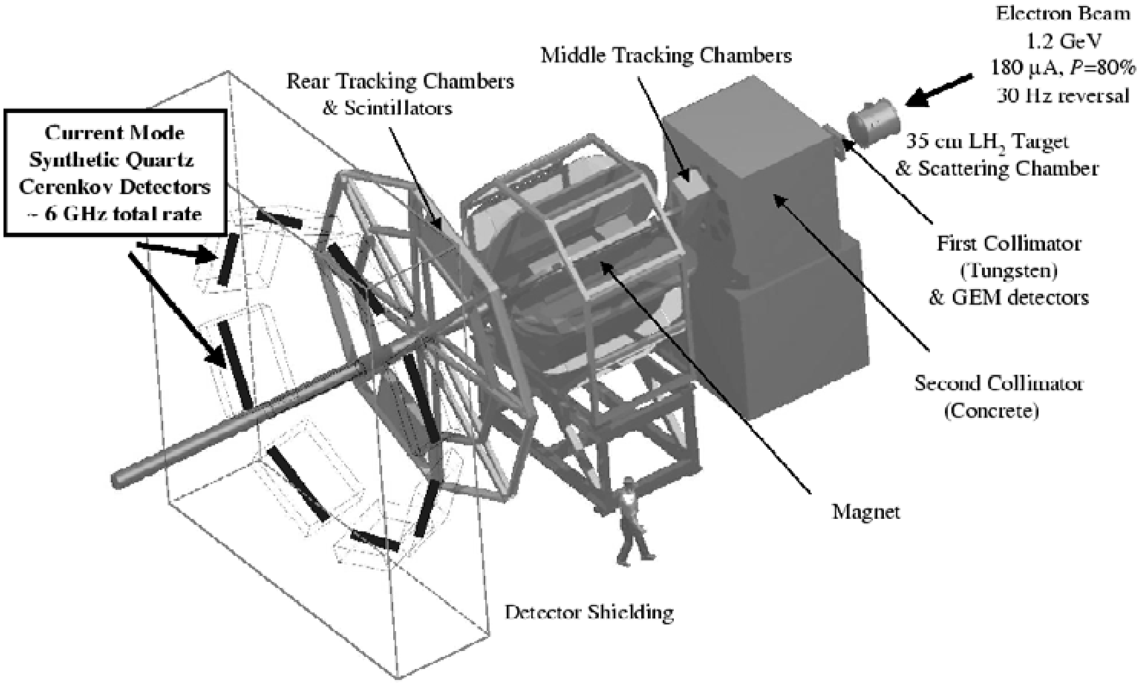

Fig. 2. Conceptual design for the Q_{weak} experimental setup, in Hall C at Jefferson Lab. The eight quartz detectors, each 2 m×16 cm×2.5 cm, are shown inside their re-entrant shielding enclosure. The spectrometer provides clean separation of elastic and inelastic electrons at its focal plane

experiments. The Q_{weak} requirements are very similar to those for HAPPEX-Pb, which runs with standard equipment and therefore should be scheduled well before Q_{weak}. That experiment, however, does not enjoy the common mode rejection inherent in a toroidal spectrometer like Q_{weak}. In addition, intensity and position feedback will be separated in the Q_{weak} experiment by making use of position information just upstream of the target. In spite of the fact that the beam properties at Jefferson Lab seem to already be very close to what is required for the Q_{weak} experiment, the collaboration is working with the JLab source group to explore the possibility of implementing helicity reversal faster than the canonical 30 Hz, which shall considerably ease the demands this experiment places on many beam properties as well as target density fluctuations, among others.

The Q_{weak} physics proposal was approved in January, 2002 by the JLab PAC, and has since become an important new thrust of the JLab scientific program. The collaboration presented a successful technical design review in January 2003. A management plan is in place for the project, and all the required funding has been secured. The project is being supported by the U.S. Department of Energy, the National Science Foundation, and the Natural Sciences and Engineering Research Council of Canada. The Q_{weak} experiment will proceed in two stages. First, a statistics limited run with a low power target will aim for a $\leq 8\%$ result on the asymmetry in 2007. This will be followed by runs totalling about 2200 hours at 180 μA in order to achieve a 4% result. The collaboration is investigating whether the absolute limits of the technique can be pushed any further, recognizing that the physics impact of an even more precise experiment would be enormous.

References

1. Qweak Collaboration, R. Carlini et al.: Jefferson Lab Proposal E-02-020.
   Proposal and collaboration member list available at `http://www.jlab.org/qweak/`.
2. M.J. Musolf et al.: Phys. Rep. **239**, 1 (1994)
3. J. Erler, A. Kurylov, M.J. Ramsey-Musolf: Phys. Rev D **68**, 016006 (2003)
4. A. Kurylov, M.J. Ramsey-Musolf, S. Su: `hep-ph/0303026`, to appear in Phys. Rev. D
5. Particle Data Group: K. Hagiwara et al.: Phys. Rev. D **66**, 010001 (2002); In particular, the section *Electroweak Model and Constraints on New Physics*
6. P.L. Anthony et al.: Phys. Rev. Lett. **92**, 181602 (2004)
7. NuTeV Collaboration, G.P. Zeller et al.: Phys. Rev. Lett. **88**, 091802 (2002)
8. N.H Edwards et al.: Phys. Rev. Lett. **74**, 2654 (1995)
9. P.A. Vetter et al.: Phys. Rev. Lett. **74**, 2658 (1995)
10. C.S. Wood et al.: Science **275**, 1759 (1997)
11. M.Y. Kuchiev, V.V. Flambaum: Phys. Rev. Lett. **89**, 283002 (2002)
12. A.I. Milstein, O.P. Sushkov, I.S. Terekhov: Phys. Rev. Lett. **89**, 283003 (2002)