The Qweak experiment: a precision measurement of the proton's weak charge

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Abstract. The Qweak experiment [1] will conduct the first precision measurement of the weak charge of the proton, Q_W^p, at Jefferson Laboratory, building on the technical advances that have been made in the laboratory's parity-violation program and using the results of earlier measurements to constrain hadronic corrections. When the results from this measurement are combined with atomic-parity violation and other PVES measurements the weak charges of the 'up' and 'down' quarks can be extracted. The experiment is basically a measurement of the parity-violating longitudinal analyzing power in e-p elastic scattering at Q^2 = 0.026 $(GeV/c)^2$ employing 150 μA's of 85% polarized electrons on a 0.35 m long liquid hydrogen target. The experiment will determine the weak charge of the proton with about 4.1% combined statistical and systematic errors. This corresponds to constraints on parity violating new physics at a mass scale of 2.3 TeV at the 95% confidence level.

Keywords: electron scattering, parity violation, proton, weak charge, weak coupling
PACS: 13.60.Hb, 24.85.+p, 24.85.+p

INTRODUCTION

The Standard Model of electroweak physics is known to be the effective low-energy theory of a more fundamental underlying structure. There exists two basic approaches to test the Standard Model. Specifically, these are the energy frontier approach such as measurements at the Tevatron and LHC and the indirect precision measurement route. The hallmark of the precision measurement approach involves choosing observables to study that are precisely predicted or suppressed in the Standard Model. This latter class of measurements include: (g-2), EDM, $\beta\beta$ decay, other rare decay processes , neutrino oscillations, atomic parity violation, parity-violating electron scattering and others.

PHYSICS GOALS AND INTERPRETATION

The Standard Model makes a firm prediction for Q_W^p, based on the running of the weak mixing angle, $sin^2\theta_W$, from the Z^0 pole down to low energies as shown in Figure 1. The average of the precise measurements at the Z^0 pole makes it possible to calibrate the curve at one specific energy. Unfortunately, the most precise leptonic and semi-leptonic measurements at the Z^0 pole differ by 3σ, a difference so far without clean explanation[2]. The shape of the curve away from this point is a prediction of the Standard Model. Consequently, to test this prediction one needs measurements away from the Z^0 pole. At the present there exist several low Q^2, precise determinations of $sin^2\theta_W$: from an atomic parity-violation measurement on ^{133}Cs[3] , and from a parity-violating

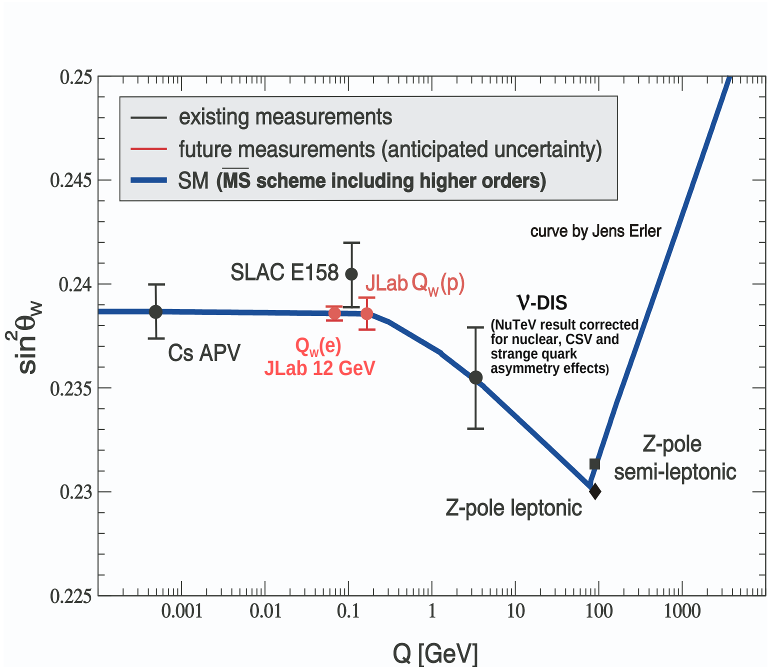

FIGURE 1. Calculated running of the weak mixing angle in the Standard Model, as defined in the modified minimal subtraction scheme[8]. The uncertainty in the predicted running is given by the thickness of the blue curve. The black points with error bars show the existing data, while the red points, with error bars (with arbitrarily chosen ordinates) refer to the JLab Qweak and a possible future 11 GeV Møller measurement. The existing measurements are from atomic parity violation, SLAC E-158 Møller scattering, the NuTeV deep inelastic neutrino scattering result corrected for nuclear, CSV and strange quark asymmetry effects, and from the LEP and SLC Z^0 pole asymmetries. The lowest point of the curve is at the W-boson mass. At lower energy (longer distance) we see screening of the weak charge, and at higher energy (shorter distance) we see anti-screening.

electron-electron, Møller scattering measurement (E158 at SLAC)[4]. The result from deep inelastic neutrino-nucleus and antineutrino-nucleus scattering (NuTeV) [5] is controversial. Recent theoretical work now strongly indicates that charge symmetry breaking quark distributions and other nuclear effects can explain the deviation of the result from the Standard Model prediction [6,7]. In the absence of physics beyond the Standard Model, the measurement of Q_W^p will provide an approximately 0.3% measurement of $sin^2\theta_W$, which will make it the most precise stand alone measurement of the weak mixing angle at low Q^2, and in combination with other parity-violation measurements, a high precision determination of the weak couplings to the 'up' and 'down' quarks, improving significantly on the present knowledge as shown in Figure 2.

The measurement of Q_W^p will be performed with statistical and systematic errors smaller than those of other existing low Q^2 data. A significant deviation from the Standard Model prediction for $sin^2\theta_W$, at low Q^2 would be a signal of new physics, whereas agreement would place new and significant constraints on possible extensions of the Standard Model. Additionally, if a Z' is discovered at the LHC and our experiment finds a significant discrepancy with the Standard Model prediction, the Q_W^p result could

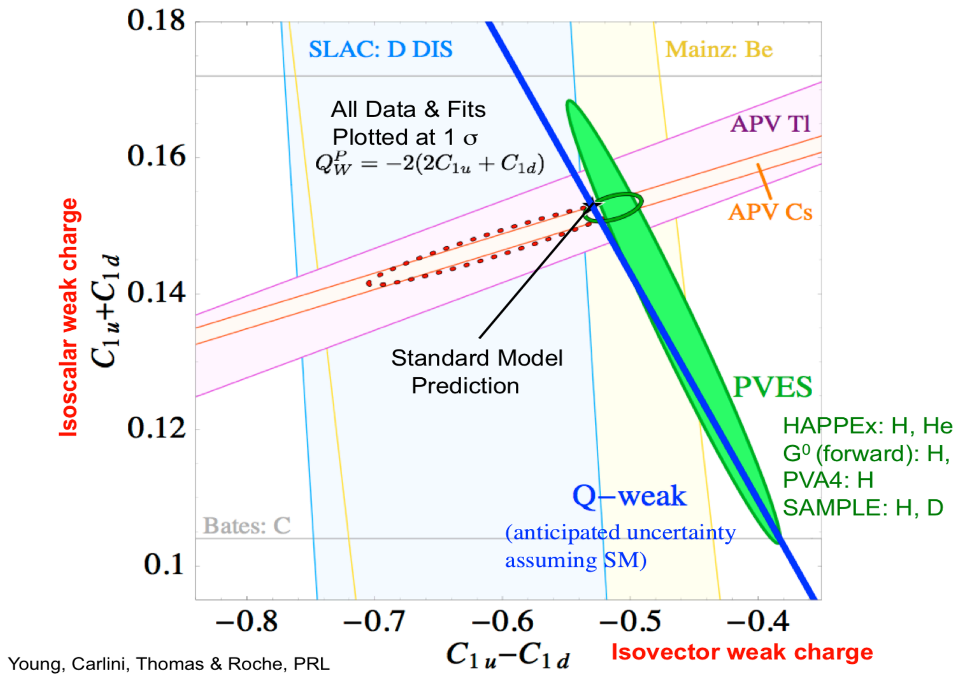

FIGURE 2. Knowledge of the neutral-weak effective coupling constants. The dotted contour displays the previous experimental limits (95% CL) reported in the PDG[9] together with the prediction of the standard model (black star). The filled ellipse denotes the present constraint provided by recent high precision PVES scattering measurements on hydrogen, deuterium, and helium targets (at 1σ), while the solid contour (95% CL) indicates the full constraint obtained by combining all results[10]. All other experimental limits shown are displayed at 1σ. The striking improvement possible from the future Jefferson Laboratory Q_W^p measurement is shown as the blue line and assuming the Standard Model.

be used to determine the sign of the coupling to light quarks associated with this new physics.

The Q_W^p measurement is anticipated to be very clean with respect to theoretical interpretability, as it relies primarily on experimental data, not theoretical calculations, to remove the residual hadronic background which is already significantly suppressed at the kinematics of the measurement. The results of this measurement in conjunction with existing parity-violation data allows a clean determination of the weak neutral current vector coupling constant (*i.e.*, Q_W^p). Once Q_W^p is determined, the extraction of information on various new physics scenarios is free from the theoretically uncertain corrections.

The quantity $A_{LR}(^1H)$ (henceforth A) is the asymmetry in the measurement of the cross section difference between elastic scattering by longitudinally polarized electrons with positive and negative helicity from unpolarized protons:

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \tag{1}$$

which, expressed in terms of Sachs electromagnetic form factors G_E^γ, G_M^γ, weak neutral form factors G_E^Z, G_M^Z and the neutral weak axial form factor G_A, has the form:

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

where

$$\varepsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}, \ \ \varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)} \tag{3}$$

are kinematical quantities, Q^2 is the four-momentum transfer, $\tau = Q^2/4M^2$ where M is the proton mass, and θ is the laboratory electron scattering angle. For forward-angle scattering where $\theta \to 0$, $\varepsilon \to 1$, and $\tau << 1$, the asymmetry can be written as:

$$A = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q_W^p + F^p(Q^2,\theta)\right] \to \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q_W^p + Q^4 B(Q^2)\right] \tag{4}$$

where F^p is a form factor. The first term, proportional to Q^2, is for a point-like proton. The second term $B(Q^2)$, proportional to Q^4, is the leading term in the nucleon structure defined in terms of neutron and proton electromagnetic and weak form factors. Ideally we would like to measure at a low enough Q^2 that the proton would look like a point and hadronic corrections would be negligible. Neglecting radiative corrections, the leading term in the equation is simply $Q_W^p = 1 - 4sin^2\theta_W$. An accurate measurement of $\sin^2\theta_W$ thus requires higher order, yet significant, corrections for nucleon structure. Nucleon structure contributions in $B(Q^2)$ can be suppressed by going to lower momentum transfer. However, this also reduces the sensitivity to Q_W^p which enters to leading order in Q^2 making it statistically more difficult to measure Q_W^p. The numerical value of $B(Q^2)$ has been determined experimentally by extrapolation from existing forward angle parity-violating data at higher Q^2. The conclusion is that the optimum Q^2 to preform the Q_W^p measurement is near 0.026 $(GeV/c)^2$ with an electron scattering angle of 8 degrees. The resulting error on Q_W^p from nucleon structure contributions is anticipated to be approximately 2%.

Electroweak radiative corrections affect the proton and electron weak charges differently. In addition to the effect from the running of $sin^2\theta_W$, there is a relatively large WW box graph contribution to the weak charge of the proton that does not appear in the case of the electron. This contribution compensates numerically for a large part the effect of the running of $sin^2\theta_W$ for the proton, which is not the case for the electron. In addition there are two boson exchange (γ and Z) contribution corrections with intermediate states described by nucleons and nucleon excitations such as the Δ [11].

Dispersion relations have been used by Gorchtein et al.[12] and Sibirtsev et al.[13] to evaluate the γZ box contribution to parity-violating electron scattering in the forward limit arising from the axial-vector coupling at the electron vertex. The calculations by Sibirtsev et al. make full use of the critical constraints from recent JLab data on electroproduction in the resonance region as well as high energy data from HERA. The total correction to Q_W^p at the Qweak experiment energy and kinematics is then $0.0047^{+0.0011}_{-0.0004}$, or $6.6^{+1.5}_{-0.6}$ % of the Standard Model value 0.0713(8) for Q_W^p. Although the shift in the central value is significant with respect to the anticipated experimental uncertainty of ± 0.0032, the additional error contribution from this correction remains minor with respect to the total measurement uncertainty. Charge symmetry violations rigorously vanish in the $Q^2 = 0$ limit and their effects at non-vanishing Q^2 can be absorbed into the hadronic "B" term that is experimentally constrained. Note that the theoretical, hadronic physics uncertainties in Q_W^p have been substantially reduced since the time of the original Qweak proposal in 2001. The current state of theoretical errors is summarized in Table 1.

TABLE 1. *Theoretical hadronic uncertainties in* Q_W^p.

Source	uncertainty
$\Delta \sin \hat{\theta}_W(M_Z)$	± 0.0006
γZ box	${}^{+0.0011}_{-0.0004}$
$\Delta \sin \hat{\theta}_W(Q)_{\text{hadronic}}$	± 0.0003
WW, ZZ box - pQCD	± 0.0001
Charge sym	0

EXPERIMENTAL METHODOLOGY

The basic concept of the experiment is shown in Figure 3. The goal is to measure the value of Q_W^p with a total uncertainty corresponding to 4.1%, or approximately 0.3% on $sin^2\theta_W$. A 1.16 GeV electron beam, longitudinally polarized to more than 85%, will pass through a 35 cm long high cryo-target built specifically for the experiment. The scattered electrons then pass through a series of Pb collimators and toroidal magnetic spectrometer with the elastic events being focused on eight symmetric detectors. To achieve the desired precision within our expected 127 days of production running demands an effective count rate of over 6 GHz, too high for conventional particle counting techniques. For this reason the main data taking for the experiment will be done in current mode, using eight detectors running at about 800 MHz each.

The detectors are synthetic quartz bars which is extremely radiation hard and insensitive to gamma, neutron and pion backgrounds. Each bar is instrumented with low gain photomultipliers (PMTs). The output signal current of these PMT's is feed into linear preamplifiers and is then digitized by custom ADC's. These detectors will operate essentially at counting statistics. Superimposed on this will be a very small parity violating signal synchronized with the spin state. A synchronous (phase locked) data acquisition system will then extract only the helicity-correlated component of the signal. Also shown in Figure 3 in the locations marked Regions 1, 2 and 3, are position sensitive detectors for dedicated low current (100 pA) counting-mode calibration runs which will be occasionally made to determine the absolute Q^2 and study the backgrounds.

The experimental asymmetry must be corrected for residual inelastic and room background contributions as well as hadronic form factor effects. Simulations indicate that the former will be relatively small, the main contribution coming from the target end caps, which will be measured and subtracted. Many experimental systematic errors are minimized by construction of a symmetric apparatus, optimization of the target design, utilization of a new rapid 1 ms spin reversal technology developed for this measurement, feedback loops in the electron source to null out helicity correlated beam excursions and

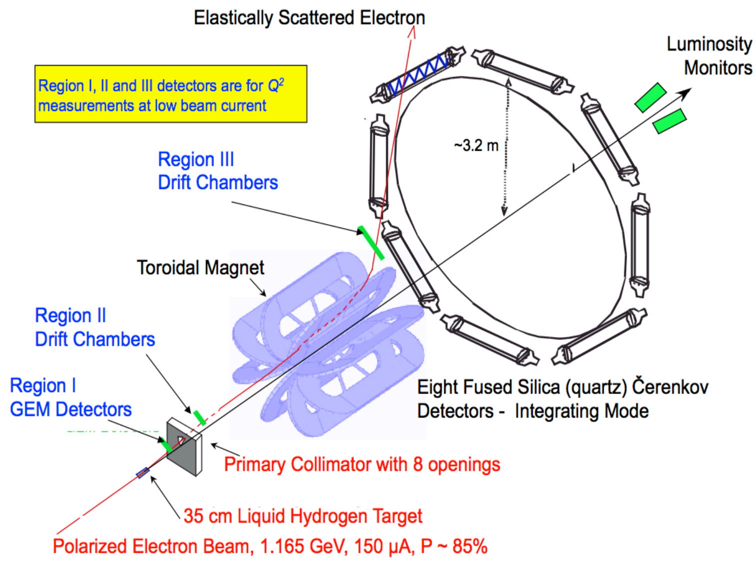

FIGURE 3. The basic experimental concept showing the target, collimation, shielding, electron trajectories, and detectors. Elastically scattered electrons (red tracks) focus on the detectors while inelastically scattered electrons (not shown), are swept away (to larger radii) from the detectors.

careful attention to beam polarimetry.

CONCLUSION

The experiment should be a highly interpretable precision measurement of Q_W^p in the simplest system. Most hadronic structure effects have already been determined from global analysis of other PVES measurements. Other theoretical uncertainties have been calculated with relatively small uncertainties. Because Q_W^p happens to almost cancel, it is very sensitive to the value of $sin^2\theta_W$, a 10σ test of the running is possible. The measurement is a sensitive search for parity violating new physics with a CL of 95% at the 2.3 TeV scale. For example: If the LHC observes a new neutral boson with mass Λ, our results could help identify it by constraining the magnitude and sign of the coupling-to-mass ratio g_{e-p}/Λ. The measurement is unique to the capabilities at JLab and is unlikely to be repeated in the foreseeable future. Construction funding was provided through NSERC, NSF, DOE and University matching contributions.

ACKNOWLEDGMENTS

This work was supported by the DOE contract No. DE-AC05-06OR23177, under which Jefferson Science Associates, LLC operates Jefferson Lab.

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