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The Qweak experiment – A search for physics and the TeV scale

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A new precision measurement of parity violation in electron scattering from the proton at very low Q^2 and forward angles is being prepared for execution at Jefferson Laboratory (JLab). The experiment is a direct challenge to the predictions of the Standard Model of quarks and leptons and is a search for new physics. There exists a unique opportunity to carry out the first precision measurement of the weak charge of the proton, $Q_W^p = 1 - 4\sin^2(\theta_W)$, by building on technical advances that have been made at Jefferson Laboratory's world-leading parity violating electron scattering program and by using the results of earlier experiments to constrain hadronic corrections. A 2200 hour measurement of the parity violating asymmetry in elastic electron-proton scattering at $Q^2 = 0.03$ (GeV/c)^2 employing 180 μA of 85% polarized beam on a 0.35 m long liquid hydrogen target will determine the proton's weak charge with 4% combined statistical and systematic errors. The Standard Model makes a firm prediction of Q_W^p, based on the 'running' of the weak mixing angle $\sin^2(\theta_W)$ from the Z^0 pole down to lower energies, corresponding to a 9 σ effect at the envisaged experiment. Any significant deviation of $\sin^2(\theta_W)$ from the Standard Model prediction at low Q^2 would be a signal of new physics, where as agreement would place new and strict constraints on possible Standard Model extensions. In the absence of new physics the envisaged experiment will provide a 0.3% determination of $\sin^2(\theta_W)$, making this a very competitive standalone measurement of the weak mixing angle indeed.

1. INTRODUCTION

Parity violating scattering of longitudinally polarized electrons from the protons in a liquid hydrogen target allows the deduction of the weak analogues of the conventional charge and magnetization distributions of the proton. In turn one may extract the individual quark contributions to these form factors. However, going to lower and lower four-momentum transfers the contributions due to the finite size of the proton become smaller and smaller and one is able to measure then the weak charge of the proton, which constitutes the sum of the weak charges of the two 'up' quarks and of the 'down' quark. A high precision measurement of the parity violating analyzing power in electron-proton scattering determines the value of $\sin^2\theta_W$ and consequently the variation of $\sin^2\theta_W$ with momentum transfer Q^2 or the 'running' of $\sin^2\theta_W$ can be established. The Standard

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Model makes a definitive prediction of the running of $\sin^2\theta_W$ taking into account electroweak radiative corrections once the value of $\sin^2\theta_W$ at the Z^0 pole has been reproduced. As with the QED and QCD couplings, $\alpha(\mu^2)$ and $\alpha_s(\mu^2)$, respectively, $\sin^2\theta_W(\mu^2)$ is an effective parameter varying with $\mu^2 \approx Q^2$. Any deviation of $\sin^2\theta_W$ from its Standard Model predicted value points to new physics which needs to be incorporated through new diagrams. Measurements at the Z^0 pole have established the value of the weak mixing angle $\sin^2\theta_W$ with great precision, although it must be remarked that the leptonic and semi-leptonic values of $\sin^2\theta_W$ differ by 3σ. The Standard Model running of $\sin^2\theta_W$ has been calculated by Erler, Kurylov, and Ramsey-Musolf [1] in the modified minimal subtraction scheme (see Fig. 1). The theoretical uncertainties ($\pm$ 0.00007) in the running of $\sin^2\theta_W$ are represented by the width of the line. Hence the interpretability is currently limited by the normalization of the curve at the Z^0 pole, which is arguably as small as ± 0.00016. Note the shift of $+0.007$ at low Q^2 with respect to the Z^0 pole best fit value of 0.23113 ± 0.00015. There have been reported several low energy measurements of the value of $\sin^2\theta_W$. The first one is an atomic parity violation measurement in ^{137}Cs [2], which agrees with the Standard Model prediction within 1σ after many refinements to the atomic structure of ^{137}Cs were introduced. The second one is through a measurement of parity violating Möller scattering [3], which again agrees with the Standard Model within 1σ. The third one is through a measurement of neutrino and antineutrino scattering from iron [4] with a roughly 3σ deviation from the Standard Model prediction. But here there remain various uncertainties with regard to the theoretical corrections that need to be applied (among other the effects of charge symmetry breaking in the quark distributions of protons and neutrons [5]). Clearly much higher precision experiments are needed to be able to constrain possible deviations from the Standard Model. A precision measurement of the weak charge of the proton, $Q_W^p = 1 - 4\sin^2\theta_W$, presently being prepared for

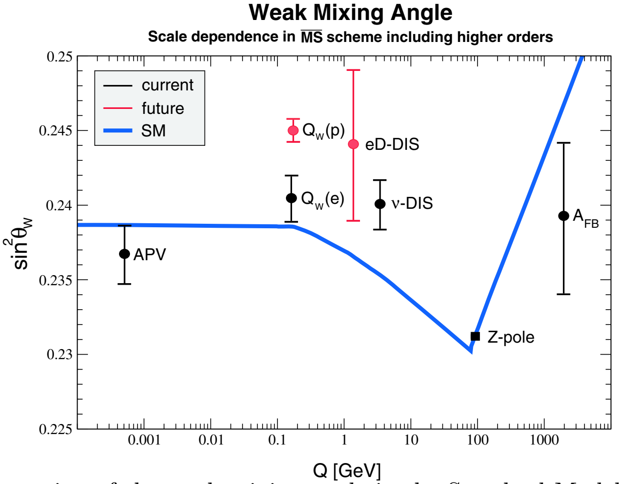

Fig. 1. Calculated running of the weak mixing angle in the Standard Model, as defined in the modified minimal subtraction scheme [1]. The black error bars show the existing experimental values, while the red error bar refers to the 4% Q_W^p measurement in preparation. A 2.5% 12 GeV Q_W^e measurement is under consideration.

execution at JLab [6], is free of many-body theoretical uncertainties and has the virtue of reaching much higher precision (note that $1 - 4\sin^2\theta_W$ at the Z^0 pole equals 0.07). The dominant hadronic effects that must be accounted for in extracting Q_W^p from the measured analyzing power are contained in form factor contributions which are sufficiently constrained from the current programs of parity violating electron scattering (at MIT-Bates, JLab, and MAMI) without reliance on theoretical nucleon structure calculations. The Standard Model evolution of $\sin^2\theta_W$ corresponds to a 10 standard deviation effect in the planned Qweak experiment at JLab. Consequently, the Qweak experiment is crucial in testing the Standard Model as it will be more precise than all other low energy measurements and is further complementary to a purely leptonic measurement as the SLAC-158 experiment [3].

2. OUTLINE OF THE QWEAK EXPERIMENT

The weak charge of the proton, $Q_W^p = 1 - 4\sin^2\theta_W$, will be deduced from a precision measurement of the parity violating analyzing power in elastic electron-proton scattering at very low momentum transfer (Q^2). The parity violating analyzing power is defined as:

$$A = (1/P)\,\frac{[\sigma^+ - \sigma^-]}{[\sigma^+ + \sigma^-]} \tag{1}$$

It was shown in [7] that for forward angle scattering, where $\theta \to 0$, the analyzing power can be written:

$$A = (1/P)\,[\frac{-G_F}{4\pi\alpha\sqrt{2}}][Q^2 Q_w^p + Q^4 B(Q^2)] \tag{2}$$

Here α is the fine structure constant and G_F the Fermi coupling constant. Note the dependence on the polarization of the incident electron beam, which requires precision polarimetry, and the dependence on the average values of $< Q^2 >$ and $< Q^4 >$ over the finite acceptance of the magnetic spectrometer based detector system for scattered electrons, which requires these average values to be determined through specific ancillary control measurements. The leading term in the equation is the weak charge of the proton, $Q_w^p = 1 - 4\sin^2\theta_W$, The quantity $B(Q^2)$ represents the nucleon structure and contains the proton and neutron electromagnetic and weak form factors. The value of $B(Q^2)$ can be determined experimentally by extrapolation from the ongoing program of forward angle parity violating experiments at higher Q^2, mentioned above, or by specific control measurements. Incident electron energy and momentum transfer (mean scattering angle) follow from careful considerations of the figure of merit. The optimum values are an incident energy of 1.165 GeV and a momentum transfer of 0.03 (GeV/c)^2. One then obtains for the longitudinal analyzing power:

$$\begin{aligned} A(0.03(\mathrm{GeV/c})^2) &= A(Q_w^p) + A(\mathrm{Had}_V) + A(\mathrm{Had}_A) \\ &= -0.19\ \mathrm{ppm} - 0.09\ \mathrm{ppm} - 0.01\ \mathrm{ppm}, \end{aligned} \tag{3}$$

where the hadronic structure contributions are separated in vector and axial vector components. Clearly, the total analyzing power is very small (-0.3 ppm) and one must arrive at an overall uncertainty of 2% to meet the precision objective of 0.3% in $\sin^2\theta_W$. Very high

Table 1
Total error estimate for the Qweak experiment. The contributions to both the physics asymmetry and the extracted Q_w^p are given. In most cases, the error magnification due to the 39% hadronic dilution is a factor of 1.64. The enhancement for the Q^2 term is somewhat larger.

Source of error	Contribution to $\Delta A_{\rm phys}/A_{\rm phys}$	Contribution to $\Delta Q_w^p\ /\ Q_w^p$
Counting Statistics	1.8%	2.9%
Hadronic structure	—	2.2%
Beam polarimetry	1.0 %	1.6%
Absolute Q^2	0.7%	1.1%
Backgrounds	0.5%	0.8%
Helicity-correlated beam properties	0.5%	0.8%
TOTAL:	2.3%	4.3%

statistics data are needed requiring high luminosity and high beam polarization, a large detector system acceptance, and an integrating low-noise detector system. As mentioned above, the beam polarization P must be precisely known as well as the hadronic structure contribution $B(Q^2)$ to be subtracted from the measured analyzing power. False analyzing power contributions result from helicity correlated changes in the incident beam parameters. The approach here is to minimize such helicity correlated changes in the beam parameters, to make the detection system as insensitive as possible to such changes, and finally to measure the sensitivities and make corrections where necessary. Feedback loops will be introduced where absolutely necessary. The Qweak experiment has set a goal of 6×10^{-9} or less for helicity correlated systematic error contributions to the analyzing power. All backgrounds cause a dilution of the actual asymmetry.

The error budgets are given in Table 1. These have been obtained through a long process of extensive simulations and fully accounts for the effects of Bremsstrahlung losses, including those inside the LH_2 target flask. A 2200 hour measurement of the parity violating analyzing power in electron-proton scattering at a momentum transfer of 0.03 $(\mathrm{GeV/c})^2$ with 180 μA of 85% polarized beam incident on a 0.35 m long LH_2 target will determine the weak charge of the proton with 4% combined statistical and systematic errors; this in turn will result into a determination of $\sin^2\theta_W$ at the 0.3% level at low energy. This is comparable to the better individual errors on $\sin^2\theta_W$ at the Z^0 pole obtained in the SLD and LEP experimental programs. A model independent analysis by Young et al. [8] of published SAMPLE, PVA4, HAPPEx, and G0 data confirmed the expected hadronic structure uncertainty listed in Table 1 for the Qweak experiment.

The layout of the experiment is shown in Fig. 2. The main elements of the Qweak experiment are a longitudinaly polarized electron beam, a LH_2 target, a precision collimator system, a resistive eight-fold symmetric toroidal magnetic spectrometer, a set of eight detectors for the forward scattered electrons, and a luminosity monitor. The toroidal magnetic field will focus elastically scattered electrons onto a set of eight ersatz quartz Ĉerenkov detectors, each coupled on either side to a photomultiplier tube allowing read

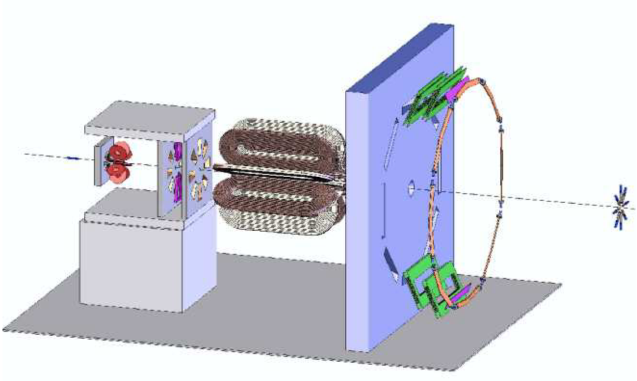

Fig. 2. Layout of the Qweak apparatus. The beam is incident from the left and scattered electrons exit the target and pass through the first collimator, the Region 1 GEM detectors, the mini-torus, the two-stage second precision collimator which surrounds the Region 2 drift chambers, the toroidal magnet, the shielding wall, the Region 3 drift chambers, the trigger scintillators, and finally the ersatz quartz Ĉerenkov detectors. The tracking system chambers and the trigger scintillators will be retracted during high current running when the Qweak asymmetry data are obtained. The Qweak luminosity monitor, which will be used to monitor target fluctuations and to provide sensitive null asymmetry tests, is located downstream of the apparatus very close to the electron beam.

out in current mode for the high statistics Qweak data taking and in pulse mode for the ancillary $< Q^2 >$ and $< Q^4 >$ determinations at greatly reduced beam intensities (around 10 nA). Inelastically scattered electrons are deflected out of the ersatz quartz detectors by the magnetic field of the toroidal spectrometer. The basic parameters of the experiment are given in Table 2. The optimized kinematics correspond to an incident energy of 1.165 GeV and scattered electron polar angles of 8.4 $\pm$ 3.0 degrees. The azimuthal angular acceptance corresponds to 8 $\times$ 24 degrees or 53% of 2π.

Experimental systematic errors are minimized by the design and construction of cylindrical symmetric apparatus, optimization of the LH_2 target layout, appropriate shielding, and as mentioned above a great deal of attention to helicity correlated fluctuations in the beam parameters. Monte Carlo simulations coupled with realistic tolerances on the apparatus has resulted in a set of helicity correlated beam property requirements which are given in Table 3.

With the very intense electron beam, radiation hardness is an issue for all instrumentation of the experiment. Other criteria for the main detector system are low sensitivity to background, uniformity of response, and low intrinsic noise. This led to the choice of ersatz quartz (Spectrosil 2000, $n = 1.47$) Ĉerenkov bars with length 2 m, width of 0.18 m, and thickness of 0.0125 m to the passing electrons, following extensive GEANT simulations. Nonlinearity in the detector plus the custom built electronics is expected to be less than 10^{-4}. A shielding hut will protect the Ĉerenkov detectors from the significant ambient room background present during running at 180 μA. The experiment is designed such that inelastic background contributing to the signal from the Ĉerenkov bars is less than 1%. With knowledge of the detector signal weighted Q^2 value the inelastic background contribution can be subtracted. The tracking system will be able to determine the $< Q^2 >$ to $\pm$ 0.7% in two opposing octants simultaneously. The retractable tracking system chambers will be mounted on rotating wheel assemblies (shown in Fig. 2). Conse-

Table 2
Basic parameters of the Qweak^p experiment.

Parameter	Value
Incident Beam Energy	1.165 GeV
Beam Polarization	85%
Beam Current	180 μA
Target Thickness	35 cm ($0.04X_0$)
Running Time	2200 hours
Nominal Scattering Angle	8.4°
Scattering Angle Acceptance	$\pm 3°$
ϕ Acceptance	53% of 2π
Solid Angle	$\Delta\Omega = 45$ msr
Average Q^2	0.030 (GeV/c)^2
Average Physics Asymmetry	-0.288 ppm
Average Expt'l Asymmetry	-0.24 ppm
Integrated Cross Section	3.9 μb
Integrated Rate (all sectors)	6.4 GHz
Statistical Error on the Asymmetry	1.8%
Statistical Error on Q_W^p	2.9%

quently four sequential measurements are required to map the entire detector system. A small quartz scanning detector will be placed directly behind the main detector bars and used as part of the acceptance mapping and linearity testing at high and low currents.

The Qweak tracking system consists of three sets of chambers. The upstream Region 1 chambers are GEM (Gas Electron Multiplier) chambers for fast response and good position resolution. The Region 2 chambers at the entrance of the spectrometer are horizontal drift chambers; a small toroidal magnet will be placed downstream of the first collimator to deflect Möller electrons out of the acceptance of the Region 2 chambers during the ancillary low current Q^2 calibration runs. The Region 3 chambers are a pair of vertical drift chambers located just upstream of the focal contour where the Ĉerenkov detectors are placed. The Region 3 chambers will momentum-analyze the particle trajectories. Finally, trigger scintillators will be installed between the Region 3 chambers and the Ĉerenkov bars in order to provide a trigger to the electronics and a timing reference. The trigger scintillators will also be retracted during high current running.

The combination of high incident electron beam current and target length demand a cooling capability of 2.5 kW. This will require additional liquid helium cooling capacity at JLab. Target density fluctuations will be minimized by careful design of the target flask, by a fast recirculation system, and by a spin flip frequency of the incident electron beam of about 250 Hz.

Downstream of the detection apparatus there will be a set of four luminosity monitors around the beam line at small angle, consisting of quartz detectors coupled to radiation hard vacuum photodiodes with external current-to-voltage converters. The small statistical error in the luminosity detector signals allows removal of sensitivities to target density fluctuations. They will also provide a valuable null asymmetry test since at their small angle the physics asymmetry has become negligible small.

Table 3
Helicity correlated (*h.c.*) beam property requirements for the Qweak experiment. The symbol x_0 refers to the DC beam position relative to the symmetry axis of the apparatus, δx refers to *h.c.* modulation x; r is the distance from the beam axis, and D is the beam diameter. These requirements should ensure that individual sources of systematic error produce false scattering asymmetries no greater than 6×10^{-9}.

H.C.	Error	Requirement	
Modulation	goes as	DC condition	*h.c.* limit
Position	$x_0 r^2 \delta x$	$x_0 < 3$ mm	$\delta x = 20$ nm
Size	$D_0^3 \delta D$	$D_0 = 4$ mm	$\delta D < 0.7$ μm
Direction	$\theta_0 \delta\theta$	$\theta_0 = 60$ μrad	$\delta\theta < 0.3$ μrad
Energy	δE	$E = 1.165$ GeV	$\frac{\delta E}{E} < 6 \times 10^{-9}$

The electron beam polarization must be measured with an accuracy at the 1% level. This will be accomplished by upgrading the existing Möller polarimeter in Hall C. Current developments place the limit of electron beam incident on the polarized iron target at 40μA. In addition, a major effort is underway to design and construct a Compton polarimeter in Hall C, which allows continuous monitoring of the polarization of the electron beam, but requires calibration against the Möller polarimeter.

3. CONCLUSION

The Qweak experiment is a major initiative at Jefferson Laboratory to measure the weak charge of the proton with a precision that provides a significant test of the Standard Model in the running of $\sin^2 \theta_W$. Installation of the Qweak instrumentation on the beam line is slated for 2008-2009. Extensive simulations coupled to a rigorous program of instrumentation design, fabrication, and testing, and the simultaneous programs of measuring the hadronic form factor contributions, point to the feasibility of a 4% measurement of the weak charge of the proton translating into a 0.3% measurement of $\sin^2 \theta_W$.

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