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The Qweak Experiment: a Search for New Physics at the TeV Scale ⋆

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Abstract

A new precision measurement of the parity violating analyzing power in longitudinally polarized electron scattering from the proton at very low Q^2 at an incident energy of 1.16 GeV is in the final stages of preparation for execution at Jefferson Laboratory (JLab). There exists an unique opportunity to carry out the first ever precision measurement of the weak charge of the proton, $Q^p_W = 1 - 4\sin^2\theta_W$, by making use of the technical advances that have been made at JLab's world-leading parity violating electron scattering program and by using the results of earlier experiments to remove hadronic contributions. 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 weak charge of the proton with 4% combined statistical and systematic errors. The Standard Model makes a firm prediction of Q^p_W, based on the 'running' of the weak mixing angle $\sin^2\theta_W$ from the Z^o pole down to lower energies. Any significant deviation of $\sin^2\theta_W$ from its Standard Model prediction at low Q^2 would constitute a signal of new physics. 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 measurement of the weak mixing angle. Complementary to the present experiment is a measurement of the weak charge of the electron in parity violating Møller scattering at 11 GeV, currently under consideration, with the upgraded CEBAF at JLab. The objective of that experiment would be a measurement of $\sin^2\theta_W$ with a precision comparable to or better than any individual measurement at the Z^o pole.

Key words: Electron scattering, Parity violation, Proton, Weak charge, Weak coupling
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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 can extract the individual quark distributions from these form factors. One should note the difference in the electromagnetic and weak couplings to the quarks (see Table 1), pointing to the reversed sensitivities of the proton and neutron. In 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 the 'down' quark. However, the analyzing power becomes zero at zero four-momentum transfer. A high precision measurement of the parity violating analyzing power in elastic electron-proton scattering determines the value of $\sin^2\theta_W$ and consequently the variation of $\sin^2\theta_W$ with four-momentum transfer Q^2 or the 'running' of $\sin^2\theta_W$. The Standard 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^o pole has been reproduced. As with the QED and QCD couplings, $\alpha(\mu^2)$ and $\alpha_s(\mu^2)$ (which exhibit screening and antiscreening, respectively), in going to higher and higher four-momentum transfer, $\sin^2\theta_W$ is an effective parameter also varying with $\mu^2 \approx Q^2$. In this case the behaviour with Q^2 is more subtle since $\sin^2\theta_W$ is a function of the electroweak couplings g_{Vl} and g_{Al}: $(g_{Vl}/g_{Al}) = 1 - 4\sin^2\theta_W$. Any deviation of $\sin^2\theta_W$ from its Standard Model predicted value points to new physics which needs to be incorporated through a set of new diagrams. Measurements at the Z^o pole have established the value of the weak mixing angle $\sin^2\theta_W$ with great precision, although it must be noted 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 (± 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^o pole, which is arguably as small as ± 0.00016. Note the shift of $+0.007$ at low Q^2 with respect to the Z^o pole best fit 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 from an atomic parity violation measurement in ^{137}Cs [2], which agrees with the Standard Model prediction within 1σ after many refinements detailing the atomic structure of ^{137}Cs were introduced. The second one is from a measurement of parity violating Møller scattering [3], which also agrees with the Standard Model prediction within approximately 1σ. This is arguably at present the better measurement in constraining extensions of the Standard Model. The third one is from a measurement of neutrino and antineutrino scattering from iron [4] with a roughly 3σ deviation from the Standard Model prediction. For this result there remain various uncertainties in the theoretical corrections that need to be applied (among other two identifiable effects of charge symmetry breaking in the quark distributions of the nucleons [5]). It is quite apparent that much higher precision experiments are needed to search for possible extensions of the Standard Model. One of these is a precision measurement of the weak charge of the proton, $Q_W^p = 1 - 4\sin^2\theta_W$, currently being prepared for execution in Hall C at JLab [6]. The extraction of the value for $\sin^2\theta_W$ is free of many-body theoretical uncertainties and has the virtue of being able to reach much

Table 1
Electroweak charge phenomenology. The accidental suppression of the weak charge of the proton in the Standard Model gives it the better sensitivity to new physics.

	Electromagnetic Charge	Weak Charge
q^{up}	+2/3	$1-(8/3)\sin^2\theta_W \approx 1/3$
q^{down}	-1/3	$-1+(4/3)\sin^2\theta_W \approx -2/3$
$Q^p = 2q^{up} + 1q^{down}$	+1	$1-4\sin^2\theta_W = 0.0716$
$Q^n = 1q^{up} + 2q^{down}$	0	-1

higher precision (note that, at a Q^2 value of $0.03(\mathrm{GeV/c})^2$, $1-4\sin^2\theta_W$ 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 (note for instance the large improvement in the knowledge of the neutral weak couplings to the valence quarks that can be deduced from the current program of parity violating electron scattering [7]). The Standard Model evolution of $\sin^2\theta_W$ corresponds to a 10 standard deviation effect in the planned Qweak experiment at JLab. The Qweak experiment, the first ever precision measurement of the weak charge of the proton and more precise than the existing low energy measurements, is crucial in testing the Standard Model. It is complementary to a parity violating Møller scattering experiment, under consideration to be performed at 11 GeV with an upgraded CEBAF at JLab, with an envisaged precision in $\sin^2\theta_W$ equal to or better than that from any individual measurement at the Z^o pole. The anticipated (1σ) uncertainties in both the Qweak experiment and a future 11 GeV Møller experiment are indicated in Fig. 1. Needless to remark: the electroweak radiative corrections to a pure leptonic measurement are more contained. In the search for physics beyond the Standard Model, precision measurements of the weak charge of the proton and of the weak charge of the electron are rather complimentary.

2. Overview 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 a very low four momentum transfer (Q^2). The parity violating analyzing power is defined as:

$$A = (1/P)[\sigma^+ - \sigma^-]/[\sigma^+ + \sigma^-]$$

where P is the polarization of the longitudinally polarized electron beam. It was shown in [8] that for forward angle scattering, where $\theta \to 0$, the analyzing power can be written:

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

Here G_F denotes the Fermi coupling constant and α is the fine structure constant. One should note the dependence on P, which requires precision polarimetry, and the dependence on the average value of Q^2 over the finite acceptance of the magnetic spectrometer based detector system for scattered electrons, which requires the average value

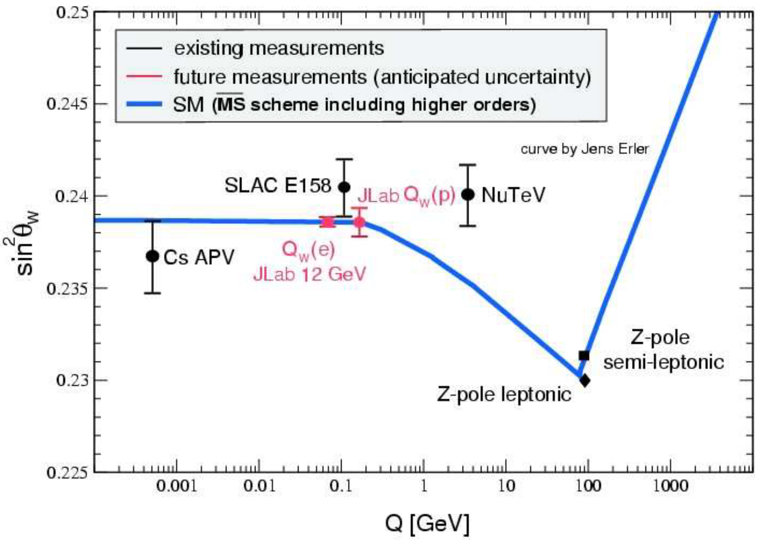

Fig. 1. Calculated 'running' of the weak mixing angle in the Standard Model, as defined in the modified minimal subtraction scheme [1]. The black points with (1σ) error bars show the existing experimental values, while the red points with error bars refer to the 4% Q_W^p measurement in preparation and a 2.5% 11 GeV Møller measurement under consideration.

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 finite size 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 electron scattering parity violating experiments at higher values of Q^2, already mentioned, or by specific control measurements. The incident energy and the momentum transfer value (mean scattering angle) followed 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 $(\mathrm{GeV/c})^2$. One can then write for the longitudinal analyzing power:

$$\begin{aligned} A(0.03(\mathrm{GeV/c})^2) &= A(Q_W^p) + A(Had_V) + A(Had_A) \\ &= -0.19\ ppm - 0.09\ ppm - 0.01\ ppm \end{aligned}$$

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 $\sin^2\theta_W$. Consequently, high statistics data are a prerequisite requiring high luminosity and high beam polarization, and an integrating low-noise detector system of large acceptance. As indicated above, the longitudinally 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 $(A(Had_V) + A(Had_A))$. A better approach may be the fitting of all forward angle elastic scattering electron-proton parity violation data as function of Q^2 which gives the value of Q_W^p at $Q^2 = 0$. As in all parity violation experiments, false analyzing power contributions result from helicity correlated changes in the incident beam parameters, e.g., incident beam momentum and polarization, intensity, position, direction, and width. The approach followed is to minimize helicity correlated changes in the beam parameters, to design and built a detector system as insensitive as possible to such changes (i.e., by introducing cylindrical symmetry), and finally to measure the sensitivities of the detector system and make corrections when necessary by measuring the helicity correlated changes in the beam parameters during data taking. Feedback loops will be introduced where and when 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 and impose longer data taking times if not yet accounted for. Backgrounds are minimized following extensive simulations to define the proper collimator system and the introduction of the appropriate shielding and optimization of the LH_2 target structure.

The defining parameters of the Qweak experiment are given in Table 2. A 2200 hour measurement of the parity violating analyzing power in elastic 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 determine $\sin^2\theta_W$ at the 0.3% level at low Q^2. This approaches (by a factor of 2) the better individual errors on $\sin^2\theta_W$ at the Z^o pole in the SLD and LEP experimental programs. A model independent analysis by Young et al. [9] of published SAMPLE, PVA4, HAPPeX, and G0 data confirmed the expected hadronic structure uncertainty entered in Table 3, which gives the error budget for the Qweak experiment. The errors have been obtained through a long process of extensive simulations and fully account for the effects of Bremsstrahlung losses, including those inside the LH_2 target flask.

3. Experiment Description

The layout of the Qweak experiment is shown in Fig. 2. The main elements of the Qweak experiment are a longitudinally polarized electron beam, a precision collimator system, a resistive eight-fold symmetric toroidal magnetic spectrometer, a set of eight detectors for the forward elastically scattered electrons, and a set of luminosity monitors. The toroidal magnetic field will focus the elastically scattered electrons onto the eight ersatz quartz Čerenkov detectors, each coupled on either side to a photomultiplier tube allowing read out in current mode for the high statistics Qweak data taking and in counting mode for the ancillary $< Q^2 >$ determination at greatly reduced beam intensities (around 1 nA). Inelastically scattered electrons are deflected out of the ersatz quartz detectors by the magnetic field of the toroidal spectrometer. The defining parameters of the experiment are as given in Table 2. The optimized kinematics correspond to an incident electron energy of 1.165 GeV and scattered electron polar angles of $8.0 \pm \approx 3.0$ degrees. The azimuthal acceptance corresponds to 53% of 2π.

The high current of the incident electron beam coupled to the length of the LH_2 target that is required demand a cooling capacity of 2.5 kW. This presents the need for particular liquid helium cooling arrangements at JLab. Target density fluctuations will be minimized by careful design of the LH_2 target flask, by fast painting of the incident electron beam over the LH_2 target (a raster of 4×4 mm in 5×10^{-5} s), by a fast circulation

Table 2
Defining parameters of the Qweak experiment.

Parameter	Value
Incident beam energy	1.165 GeV
Beam polarization	85%
Beam current	180 μA
Target thickness	0.35 m ($0.04X_0$)
Data taking time	2200 hours
Nominal scattering angle	8.0^o
Scattering angle acceptance	$\approx \pm 3.0^o$
Azimuthal acceptance	53% of 2π
Solid angle	$\Delta\Omega = 45msr$
Average Q^2	0.028 $(\mathrm{GeV/c})^2$
Average analyzing power	$-0.28ppm$
Average experimental asymmetry	$-0.24ppm$
Integrated cross section	3.9 μb
Integrated rate (eight sectors)	6.4 GHz
Statistical error on the asymmetry	1.8%
Statistical error on Q_W^p	2.9%

Table 3
Total error estimate for the Qweak experiment. The contributions to both the parity violating analyzing power and the extracted Q_W^p are given. The error magnification is due to the 39% hadronic dilution.

Source of error	Contribution to ΔA/A	Contribution to $\Delta Q_W^p/Q_W^p$
Statistical:		
Counting statistics (2200 hours)	1.8%	2.9%
Systematic:		
Beam polarimetry	1.0%	1.6%
Absolute Q^2	0.5%	1.1%
Helicity correlated beam parameter changes	0.5%	0.8%
Inelastic background uncertainty	0.2%	0.2%
Target window background	$< 0.6\%$	$< 0.8\%$
Hadronic structure uncertainties	—	1.9% - 2.4%
Radiative correction uncertainties in Q_W^p	—	$< 1\%$
Total systematic	1.4%	3.0%
TOTAL	2.2%	4.1% - 4.3%

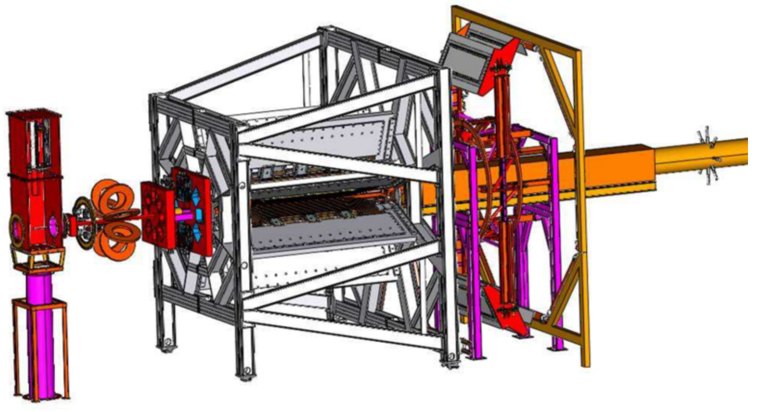

Fig. 2. Layout of the Qweak experiment. The beam is incident from the left and scattered electrons exit the target and pass through the first collimator, the region-1 GEM detectors, the two stage second precision collimator which surrounds the region-2 drift chambers, the toroidal magnet, the shielding wall, the region-3 drift chambers, the trigger scintillators, and finally the ersatz quartz Čerenkov detectors. The tracking system chambers and the trigger scintillators, mounted on rotatable wheels, will be retracted outwards during high current data taking for the Qweak experiment proper. The luminosity monitors, which will be used to monitor target density fluctuations and to provide sensitive null asymmetry tests, are located downstream of the main apparatus and are positioned very close to the through going beam.

Table 4
Helicity correlated beam parameter requirements for the Qweak experiment. The symbol x_0 refers to the DC beam position relative to the symmetry (neutral) axis of the apparatus; δx refers to the helicity correlated modulation of 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 less than 6×10^{-9}.

Helicity correlated modulation	Error goes as	Requirement DC condition	Requirement helicity correlated limit
Position	$x_0 r^2 \delta x$	$x_0 \leq 3$ mm	$\delta x = 20$ nm
Size	$D_0^3 \delta D$	$D_0 = 4$ mm	$\delta D \leq 0.7\ \mu$m
Direction	$\theta_0 \delta\theta$	$\theta_0 = 60\ \mu$rad	$\delta\theta \leq 0.3\ \mu$rad
Energy	δE	E = 1.165 GeV	δE/E $\leq 6 \times 10^{-9}$

system (many liters per second), and by a spin flip frequency of about 250 Hz. The Monte Carlo simulations coupled to realistic tolerances on the apparatus have resulted in a set of helicity correlated beam parameter requirements which are given in Table 4.

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

The requirements on the main detector system are radiation hardness, low sensitivity to different kinds of background, uniformity of response, and low intrinsic noise. Following lengthy Geant-4 simulations, the choice has been ersatz quartz (Spectrosil 2000, $n = 1.47$) Čerenkov bars of length 2.0 m, of width 0.18 m, and of thickness 0.0125 m, for the detection of the elastically scattered electrons. A shielding hut will protect the Čerenkov detectors from the significant ambient background present during data taking at 180 μA. The inelastic background contributing to the signal from the Čerenkov bars will be less than 1%. Knowledge of the detector system weighted Q^2 value will allow the inelastic background contribution to be subtracted. A small quartz scanning detector is placed directly behind the main detector bars and used as part of the acceptance mapping and linearity testing at high and low incident electron beam currents.

The Qweak tracking system consists of three sets of chambers. The upstream region-1 chambers are Gas Electron Multiplier (GEM) chambers for fast response and good position resolution. The region-2 chambers at the entrance to the spectrometer, in between the defining collimators, are horizontal drift chambers, while the region-3 chambers are vertical drift chambers just upstream of the focal contour for the elastically scattered electrons, where the Čerenkov detectors are placed. The region-3 chambers will momentum-analyze the particle trajectories. Finally, trigger scintillators are installed between the region-3 chambers and the Čerenkov bars in order to provide a trigger to the electronics and a timing reference. The tracking system will be able to determine the average Q^2 value to $\pm 0.5\%$ in two opposing octants simultaneously. The three sets of chambers as well as the trigger scintillators are mounted on three rotating wheel assemblies (shown in Fig. 2) and can be retracted outwards (towards larger radii) during high current data taking. Four sequential measurements with the tracking system are required to map the entire detector system.

The electron beam polarization needs to be measured with an accuracy less than 1%. This will be accomplished by upgrading the existing Møller polarimeter in Hall C. The scheme adopted is for the high current polarized electron beam to be deflected intermittently onto the polarized iron foil containing the electrons with known polarization. In addition, a major effort is underway to design, construct, and install a Compton polarimeter in Hall C, which will allow continuous monitoring of the polarization of the electron beam, but requires calibration against the Møller polarimeter. Both the scattered electrons and back scattered photons will be detected.

4. Conclusion

The Qweak experiment is a major undertaking 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 in Hall C is slated to be completed in 2009. Extensive simulations together with a rigorous program of instrumentation design, construction, testing, and commissioning, and the ongoing programs of measuring the hadronic form factor contributions, point to the possibility 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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