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The Q_{weak} Experiment: A measurement of the proton's weak charge at Jefferson Lab

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Summary. — The Q_{weak} Experiment at Jefferson Laboratory will make a 4% measurement of the proton's weak charge, Q_W^p, by measuring the parity-violating asymmetry in elastic electron-proton scattering at low momentum transfer, $Q^2 = 0.026\,\text{GeV}^2$. This asymmetry is proportional to the weak charge of the proton and can be related to the weak mixing angle, $\sin^2\theta_W$, a parameter in the Standard Model. Q_{weak} will measure the weak mixing angle precisely to 0.3%, challenging predictions of the Standard Model and probing certain types of new physics at the 2 TeV scale.

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1. – Introduction

The Q_{weak} experiment will measure the weak charge of the proton, Q_W^p, a fundamental property of the proton. The weak charge describes how a particle couples to the neutral weak interaction, and the Standard Model makes a firm prediction of its value. In the Standard Model (SM), the weak charge of the proton is suppressed, as shown in table I which gives the weak charges for vector coupling to the quarks. The suppression of the proton's weak charge in the Standard Model makes it an appealing candidate for a precision measurement, yielding increased sensitivity to hints of new physics. Q_{weak} aims to measure the proton's weak charge to 4%.

This measurement will help better constrain the neutral weak vector quark couplings C_{1u} and C_{1d}. Figure 1 shows the current world data on the isoscalar and isovector combinations of C_{1u} and C_{1d} from atomic parity violation and previous parity-violating electron scattering (PVES) experiments. The narrow blue band represents the constraint from the projected Q_{weak} measurement, assuming agreement with the Standard Model.

Q_{weak} will also place a new competitive constraint on the weak mixing angle at low Q^2 as shown in fig. 2. The SM prediction of the running of $\sin^2\theta_W$ is known very precisely, therefore precision measurements away from the Z^0 pole that show any significant deviations from the SM will reveal signatures of new physics. Different measurements

TABLE I. – *The electromagnetic and weak vector charge of the light quarks, proton, and neutron.*

Particle	Electromagnetic charge	Weak vector charge
u	$+2/3$	$-2C_{1u} = 1 - 8/3\sin^2\theta_W \approx 1/3$
d	$-1/3$	$-2C_{1d} = 1 + 4/3\sin^2\theta_W \approx -2/3$
p (uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0.07$
n (udd)	0	$Q_W^n = -1$

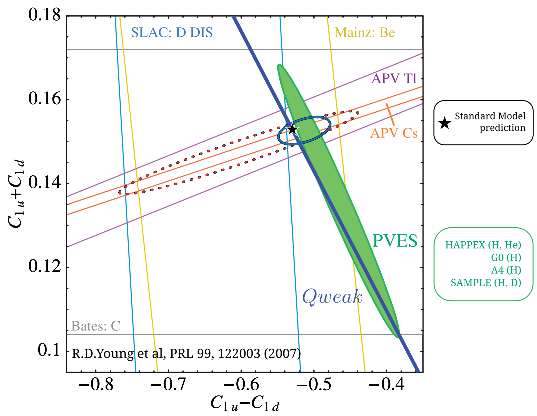

Fig. 1. – Constraints on the weak vector quark couplings C_{1u} and C_{1d} [1]. The solid open ellipse represents the current constraint from data from SLAC [2], Bates [3], Mainz-Be [4], a combination of atomic parity violation experiments [5-7], and previous PVES experiments (solid filled green ellipse) [8-11], at the 95% confidence level. The narrow blue line represents the new constraint from a 4% Q_W^p measurement assuming agreement with the Standard Model.

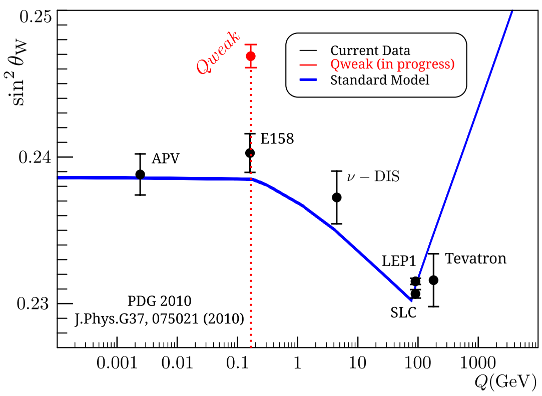

Fig. 2. – The Standard Model firmly predicts the running of the weak mixing angle from the Z^0 pole to low momentum transfer as defined in the $\overline{MS}$ renormalization scheme [12]. The thickness of the curve corresponds to the error of the prediction. The scale is set by precision measurements at the Z^0 pole [13], and several current data points exist at low Q (APV on cesium [5], SLAC E158 [14], and NuTeV [15]). The anticipated impact of a 4% Q_{weak} measurement, corresponding to 0.3% on $\sin^2\theta_W$, is shown (placed arbitrarily along the y-axis).

are complementary to each other as different types of experiments (*i.e.* lepton-lepton scattering, lepton-quark scattering, atomic parity violation) will have different sensitivities to different new physics extensions. These low-energy precision tests of the SM are also complementary to high-energy searches for new physics which can detect directly signatures of new physics but may not be able to determine how the new physics couples to matter.

This measurement is performed by measuring the parity-violating asymmetry in elastic electron-proton scattering. The parity-violating asymmetry is defined as:

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}\,, \tag{1}$$

where $\sigma_{R(L)}$ are the cross sections for right(left)-handed electrons that are polarized longitudinally to the beam. This asymmetry arises from the interference between the electromagnetic and neutral weak interactions and can be written in terms of the electromagnetic, neutral-weak, and axial form factors. At low Q^2 and forward angles, the asymmetry simplifies to

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

where the leading order term is the weak charge of the proton and the higher order term contains the hadronic structure, which is constrained by previous parity-conserving and parity-violating form factor measurements.

$Q_{\rm weak}$ will measure this asymmetry at $Q^2 = 0.026\,\mathrm{GeV}^2$, which is expected to be -230 parts-per-billion (ppb), with a beam energy of $E = 1.16\,\mathrm{GeV}$ and an average scattering angle of $7.9°$ to a statistical precision of 2.1%.

2. – Experiment overview

The $Q_{\rm weak}$ experiment is currently installed at Jefferson Laboratory. A drawing of the experimental setup (without shielding) is shown in fig. 3. Longitudinally polarized electrons, polarized up to 88%, scatter from protons in a liquid hydrogen (LH_2) target operated at 35 psia and 20 K. The target is 35 cm long, corresponding to approximately 0.04 radiation lengths, and has thin aluminum windows. Electrons scattering at $\theta = 7.9° \pm 3°$ are collimated by a set of three collimators before entering the $Q_{\rm weak}$ toroidal spectrometer (QTOR). The electrons are focused onto an array of eight azimuthally symmetric artificial fused silica Čerenkov detectors, each of which is $200 \times 18 \times 1.25\,\mathrm{cm}^3$ and made of Spectrosil 2000. The detectors are preradiated, having 2 cm of lead upstream to reduce low-energy backgrounds and amplify the signal.

The physics asymmetry, A_{phys}, is extracted from the measured asymmetry which contains contributions from backgrounds and false asymmetries:

$$A_{meas} = P\left[(1-f)A_{phys} + fA_{bkgd}\right] + A_{false}\,, \tag{3}$$

where P is the beam polarization, f is the background dilution, and A_{bkgd} and A_{false} are the asymmetry from backgrounds and false asymmetries. In order to achieve a 4% measurement of Q_W^p, these and other systematic uncertainties must be well understood and controlled. Table II shows the statistical and systematic uncertainties expected by the end of measurement.

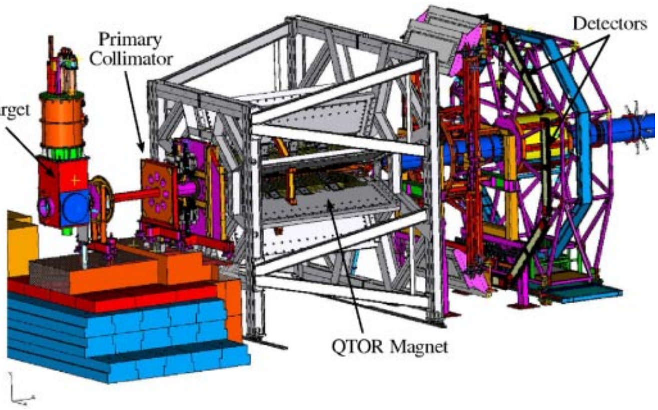

Fig. 3. – An oblique sideview drawing of the experimental setup. The experiment scatters 1.16 GeV longitudinally polarized electrons from protons in a liquid hydrogen target and detects the scattered electrons in quartz Čerenkov detectors.

3. – Results

The first phase of data taking was completed in May 2011 and about 25% of the proposed statistics have been acquired. In addition to the production data taken, several preliminary ancillary measurements have also been completed. These include measurements of the transverse asymmetry on the liquid hydrogen target, the asymmetry in the inelastic $N \to \Delta$ transition, and the asymmetry in elastic electron-aluminum scattering, the dominant background in the experiment. Each of these measurements is valuable and competitive on its own. For example, the background from scattering from the aluminum end caps of the target will be a 20% correction to the proton elastic asymmetry due to the presence of neutrons (which have a weak charge of -1), and the acceptance of elastically scattered events in the detectors. This will be the first measurement of the elastic electron-aluminum asymmetry and it will be measured to a precision of a few percent.

An example of the asymmetry data collected on LH_2 is shown in fig. 4. Each point corresponds to about 8 hours of data and the sign flip comes from a slow reversal of the electron helicity using an insertable half-wave plate. The width of the asymmetry

TABLE II. – *Breakdown of the projected uncertainties for the Q_{weak} measurement.*

Source of error	$\Delta A_{phys}/A_{phys}$	$\Delta Q^p_w/Q^p_W$
Counting Statistics	2.1%	3.2%
Hadronic structure	—	1.5%
Beam polarimetry	1.0%	1.5%
Absolute Q^2	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity-correlated beam properties	0.5%	0.7%
TOTAL:	2.5%	4.1%

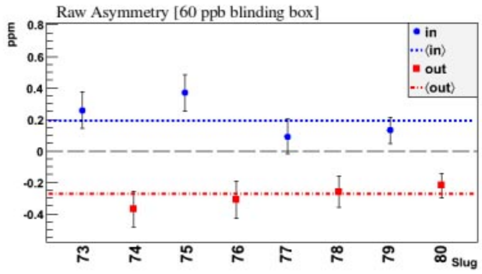

Fig. 4. – Slow helicity reversal behavior for a subset of data. For the red square points the insertable half-wave plate (IHWP) is out and for the blue circles the IHWP is in. Each point corresponds to about 8 hours of data. The dashed lines represent the averages. The data shown in this plot are raw, uncorrected asymmetries with a blinding factor applied.

distribution measured is 236 ppm and well understood. At 165 μA, the statistical width using quartets at 240 Hz is expected to be 215 ppm. When accounting for detector resolution, current normalization, and noise from target density fluctuations, the width is expected to be 235 ppm, in good agreement with what is being measured.

During phase I of data taking no major show stoppers were found and Q_{weak} is ready to begin phase II of data taking in November 2011. The measurement will be completed in May 2012 and is on track to obtaining the proposed statistics.

* * *

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