Standard Model Tests via Parity Violating Electron Scattering

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Abstract. A new generation of parity violating electron scattering measurements at high precision probe for physics beyond Standard Model. The experiments are complementary to high energy experiments and provide indirect access to TeV scale physics via electroweak one-loop effects. Data are presented from the recently completed SLAC experiment E158, which measured the weak charge of the electron Q_{weak}^e . The Qweak experiment at Jefferson Lab will measure the weak charge of the proton Q_{weak}^p to an accuracy of $\pm 4.3\%$.

Keywords: Parity Violation, Electron Scattering, Standard Model Tests

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INTRODUCTION

Parity violating electron scattering was historically important in establishing the Standard Model of the electroweak interaction. The SLAC DIS deuterium parity experiment [1] provided crucial evidence for the Weinberg, Glashow, Salam model [2]. Subsequent confirmation came from parity experiments in quasielastic scattering from ^9Be [3] and elastic scattering from ^{12}C [4]. In the past 15 years, parity experiments world-wide have been in progress to determine the strange quark contribution to the electromagnetic properties of the nucleon (for reviews see [5, 6, 7, 8]). The experimental techniques have become well established and can be applied to a new generation of high-precision Standard Model tests which measure the weak charge Q_{weak} of the electron and of the proton, described in this contribution. The electron weak charge experiment, E158 at SLAC, has completed its data taking and published the final results [9]. The proton weak charge measurement is an approved proposal at Jefferson Lab which will start in 2009 [10]. The strange quark program has had the spin-off benefit of providing tight constraints on hadronic structure uncertainties and thereby permitting a clean interpretation of proton weak charge measurements.

The asymmetry is $A = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$ where $\sigma_{R(L)}$ is the differential cross section for elastic scattering of right(*R*) and left(*L*) handed longitudinally polarized elec-

FIGURE 1. Running of the weak mixing angle. The curve is the calculation in the Standard Model from ref [16]. The black data points show the published data including E158 [9], atomic parity [11] and neutrino DIS (NUTEV) [12]. The red point with an oval around it refers to the proposed 4% Q_{weak}^p measurement.

trons from a target. This asymmetry arises from the interference of weak and electromagnetic amplitudes [13] and is sensitive to electroweak coupling constants and thus to the weak mixing parameter $\sin^2 \theta_W$. Possible physics beyond the Standard Model can manifest itself in deviations from theoretical predictions of $\sin^2 \theta_W$. The 3% variation of $\sin^2 \theta_W$ from $Q^2 = 0$ to $Q^2 = M_Z^2$ (see fig 1) is due to higher order amplitudes involving virtual weak bosons and fermions in quantum loops, referred to as electroweak radiative corrections [14]. This “running of $\sin^2 \theta_W$ ” is a key prediction of the Standard Model. Measurements at $Q^2 \ll M_Z^2$ with high enough precision to see the radiative corrections can have sensitivity to mass scales in the TeV range, making them comparable to high energy collider searches. Low energy values of $\sin^2 \theta_W$ have been extracted in atomic parity violation [11] and neutrino deep inelastic scattering [12], as shown in fig 1 together with the E158 measurement [9] and Q_{weak}^p proposed point [10].

SLAC E158: Q_{weak}^e

The E158 experiment measuring Q_{weak}^e ran at a beam energy of ~ 50 GeV in End Station A at SLAC. Final results have been published in ref [9]. The center-of-mass scattering angle was 90° and A_{PV} from Møller scattering is predicted to be 320 parts per billion (ppb) at tree level [15, 16]. Electroweak radiative corrections [14] and experimental acceptance reduce the measured asymmetry by more than 50%. A longitudinally polarized electron beam ($P_b = 90\%$) was delivered in 270 nsec pulses at 120 Hz to a 1.57 m long hydrogen target from which scattered particles passed through a magnetic spectrometer and were detected by various detectors 60 m downstream of the target [17]. The scattered Møller electrons in the range 13-24 GeV form an azimuthally-symmetric ring and are spatially separated from electrons scattered from the target protons. The primary detector is a copper/fused silica fiber sandwich calorimeter. The calorimeter provided both radial and azimuthal segmentation. The rings nearest the beamline saw the Møller electrons, while the ring furthest from the beamline were sensitive to the ep scattering flux. The signal is integrated over the beam helicity and the asymmetry A_{PV} is formed from the fractional difference between right and left helicities.

The background within the Møller rings was estimated to be 8% and was dominated by radiative ep scattering, while neutral particles and charged pions contributed less than 1%. Runs were performed over several months in 2002 and 2003 at beam energies of 45.0 and 48.3 GeV. Running at these two energies provided opposite helicity orientations because of the spin precession in the bend after the accelerator. Another slow reversal of helicity was made by insertion of a half-wave plate in the laser line at the polarized source. Roughly equal statistics were accumulated under each of these helicity flip states, suppressing many types of systematic errors.

Two methods were used to calibrate the detector sensitivity to each beam parameter and remove beam-induced random and systematic effects from the raw asymmetry. One method uses a calibration subset of the pulses, in which each beam parameter is modulated around its average value by an amount large compared to normal fluctuations. The other method utilizes a least squares linear regression analysis to determine the corrections. These two methods were consistent within 3 ppb.

The raw asymmetry is corrected for background contributions, detector linearity, and beam polarization as described in [9]. After all corrections, the asymmetry was found to be $A_{\text{PV}} = -131 \pm 14(\text{stat}) \pm 10(\text{syst})$ ppb at an average $Q^2 = 0.026\text{GeV}^2$. From this the effective weak mixing angle $\sin^2\theta_W^{\text{eff}} = 0.2397 \pm 0.0010(\text{stat}) \pm 0.0008(\text{syst})$ was extracted and is as the point labeled “ $Q_W(e)$ ” in fig 1. The result is consistent with the Standard Model expectation $\sin^2\theta_W^{\text{eff}} = 0.2381 \pm 0.0006$ and is 6.2σ away from the value of $\sin^2\theta_W$ at the Z^0 resonance, thus establishing the “running of $\sin^2\theta_W$ ” with over 6σ significance in the electron-electron scattering process which is theoretically very clean.

JLAB QWEAK: Q_{weak}^p

The proton’s weak charge $Q_W^p = 1 - 4 \sin^2\theta_W$ will be evaluated from a precision measurement of the parity violating asymmetry in elastic electron-proton scattering at very

FIGURE 2. Layout of the Q_{weak}^p apparatus. The beam and scattered electrons travel through the target, 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 through the quartz Čerenkov detectors. The tracking system chambers and trigger scintillators will be retracted during high current running when Q_{weak}^p asymmetry data are acquired. The luminosity monitor, which will be used to monitor target fluctuations and to provide a sensitive null asymmetry test, is located downstream of the apparatus very close to the beam pipe.

low momentum transfer. The experiment will begin in 2009 at Jefferson Lab.

It was shown in [8] that for forward-angle scattering where $\theta \rightarrow 0$, $\varepsilon \rightarrow 1$, and $\tau \ll 1$, the asymmetry can be written as:

$$A \sim \left[\frac{-G_F}{4\pi\alpha\sqrt{2}} \right] [Q^2 Q_w^p + Q^4 B(Q^2)] \quad (1)$$

Neglecting radiative corrections, the leading term in equation 1 is the proton's weak charge: $Q_w^p = 1 - 4\sin^2 \theta_W$. The quantity $B(Q^2)$ is the leading term in the nucleon structure defined in terms of neutron and proton electromagnetic and weak form factors. These structure contributions can be reduced by carrying out the asymmetry measurements at lower momentum transfer, but at the expense of reduced sensitivity to Q_w^p . 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 . The optimum value of Q^2 for the Q_{weak}^p experiment is near 0.03 (GeV/c)^2 based on our estimate of the anticipated final precision of the various HAPPEX [18], G^0 [19], SAMPLE [20] and Mainz A4 [21] measurements. At this momentum transfer, the parity violating asymmetry is expected to be $A = -0.3 \text{ ppm}$, and we must achieve a total uncertainty of 2% in

TABLE 1. Basic parameters of the Q_{weak}^p experiment.

Parameter	Value
Incident Beam Energy	1.165 GeV
Beam Polarization	85%
Beam Current	180 μ A
Target Thickness	35 cm ($0.04X_0$)
Running Time	2200 hours
Nominal Scattering Angle	8.4°
Scattering Angle Acceptance	$\pm 3^\circ$
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 μ b
Integrated Rate (all sectors)	6.4 GHz
Statistical Error on the Asymmetry	1.8%
Statistical Error on Q_W^p	2.9%

the measurement of A in order to meet our precision goal of 0.3% in $\sin^2 \theta_W$. A recent global analysis by Young *et.al* [22] suggests that the required accuracy in $B(Q^2)$ will be achieved.

The layout of the Q_{weak}^p experiment is given in Figure 2. A longitudinally polarized electron beam, a liquid hydrogen target, a room temperature 8-fold symmetric toroidal magnetic spectrometer, and a set of detectors for the scattered electrons at forward angles are the key elements of the experimental apparatus. The toroidal magnetic field will focus elastically scattered electrons onto a set of 8, rectangular quartz Čerenkov detectors coupled to photomultiplier tubes, which will be read out in current mode to achieve the high statistical precision required for the measurements. Inelastically scattered electrons are bent out of the detector acceptance by the spectrometer and make only a minimal contribution to the Čerenkov signal.

Basic parameters of the Q_{weak}^p experiment are summarized in Table 1. The main technical challenges result from the small expected asymmetry of approximately -0.3 ppm; we will measure this asymmetry to $\pm 1.8\%$ statistical and $\pm 1.4\%$ systematic errors. The optimum kinematics corresponds to an incident beam energy of $E_0 = 1.165$ GeV, scattered electron polar angles $\theta_e = 8.4 \pm 3$ degrees, and azimuthal detector acceptance as large as possible (8 electron detectors with acceptance $\Delta\phi_e = 24$ degrees each, totaling 53% of 2π). Fixing $Q^2 = 0.03$ (GeV/c) 2 limits nucleon structure contributions which increase with Q^2 and avoids very small asymmetries where corrections from helicity correlated beam parameters begin to dominate the measurement uncertainty. With these constraints applied, the figure-of-merit is relatively insensitive to the primary beam energy; using a higher beam energy would result in a physically longer experiment with stronger magnetic field requirements, smaller scattering angles, and the possibility of opening new secondary production channels that might contribute to backgrounds.

CONCLUSION

We have described two experiments that test the Standard Model at the level of the electroweak radiative corrections, the recently completed SLAC E158 experiment and the proposed Q_{weak}^p experiment at JLAB. These experiments measure the weak charge of the electron and proton, respectively. The weak charge is a fundamental property of these particles which can be calculated to $\sim 0.1\%$ within the Standard Model. The measurements provide significant new limits on TeV scale physics and are complementary to the best current limits on extensions of the Standard Model from high energy colliders.

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