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First result from $\mathrm{Q_{weak}}$

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Abstract. Initial results are presented from the recently-completed $\mathrm{Q_{weak}}$ experiment at Jefferson Lab. The goal is a precise measurement of the proton's weak charge Q_w^p, to yield a test of the standard model and to search for evidence of new physics. The weak charge is extracted from the parity-violating asymmetry in elastic $\vec{e}$p scattering at low momentum transfer, $\mathrm{Q}^2 = 0.025\,\mathrm{GeV}^2$. A 180 μA longitudinally-polarized 1.16 GeV electron beam was scattered from a 35 cm long liquid hydrogen at small angles, $6^\circ < \theta < 12^\circ$. Scattered electrons were analyzed in a toroidal magnetic field and detected using an array of eight Cerenkov detectors arranged symmetrically about the beam axis. The initial result, from 4% of the complete data set, is $Q_W^p = 0.064 \pm 0.012$, in excellent agreement with the standard model expectation. Full analysis of the data is expected to yield a value for the weak charge to about 5% precision.

1. Introduction

It is conventional wisdom that the enormously successful $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ standard model is actually a low-energy effective theory of some more complete higher-mass scale physics. Attempts to probe such possible new physics include direct searches at colliders (the energy frontier), and indirect searches (the precision or intensity frontier). The hallmark of the latter method is the use of observables which are well-predicted within the standard model, but for which new physics could alter those predictions, eg. via loop corrections or the exchange of new particles. One such example is the weak charge of the proton, which can be accessed in neutral-current processes such as parity-violating electron scattering (PVES) [1, 2].

The tree-level standard model expression for the proton's weak charge is

$$Q_w^p = 1 - 4\sin^2(\theta_W) \tag{1}$$

where θ_W is the electroweak mixing angle. It can also be expressed in terms of the weak vector couplings of the light quarks, $Q_w^p = -2(2C_{1u} + C_{1d})$ which are again functions of the mixing angle. These expressions are modified beyond tree level by loop corrections [3], however after recent theoretical work on the troublesome γZ box term [4–8], these are now sufficiently under control, and the standard model predictions for Q_w^p and for C_{1u} and C_{1d} are robust. The fortuitous modest suppression of the

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numerical value of Q_w^p, since $\sin^2(\theta_W)$ is near 0.23, increases the sensitivity of the measurement to potential new physics effects.

The experimental observable is the parity-violating asymmetry, the difference over the sum of the elastic scattering cross section for electrons with positive and negative helicity,

$$A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \, . \tag{2}$$

At tree level, in terms of electromagnetic, neutral-weak, and axial form factors, this is

$$A_{ep} = A_0 \left[\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1 - 4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^Z}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2} \right] \tag{3}$$

where $A_0 = \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}$, $\varepsilon = [1 + 2(1+\tau)\tan^2\frac{\theta}{2}]^{-1}$, $\varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)}$, G_F is the Fermi constant, $-Q^2$ the four-momentum transfer squared, α the fine structure constant, $\tau = Q^2/4M^2$, M the proton mass, θ the laboratory electron scattering angle and the weak charge appears as the $Q^2 \to 0$ limit of G_E^Z.

Following [9], we can recast Eq. 3 for $\theta \to 0$ as

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta), \tag{4}$$

wherein all the hadron structure dependence is subsumed in the $B(Q^2, \theta)$ factor. Thus, a measurement of A_{ep} at forward angles and low Q^2 gives access to the weak charge.

2. Experiment

The experiment built on techniques developed at Jefferson Lab over the last two decades for conducting precision parity-violating electron scattering measurements [10]. Of particular importance is the superbly small level of helicity-correlated fluctuations in beam properties available (through close cooperation with the electron-gun group and the accelerator operations group). Innovations for this experiment included the use of a very rapid reversal of the beam helicity (960 Hz) and the highest intensity beam yet used at JLab (180 μA). The measurement took place during a two year period, and was conducted in Hall C, with a dedicated apparatus [11]. A toroidal-field magnetic spectrometer with an octagonal array of radiation-hard quartz Cerenkov detectors isolated electrons elastically scattered from a high-power (3 kW) thick liquid hydrogen target [12].

The kinematics (1.16 GeV incident energy, scattering angle $\sim 8^\circ$, $Q^2 = 0.025\,\text{GeV}^2$) were chosen to suppress the hadron-structure contribution to the asymmetry (especially the axial form-factor) while maintaining an acceptable figure of merit for the expected asymmetry ($\sim$200 ppb). The anode current signals from two PMTs mounted on each Cherenkov detector were integrated over each $\sim$1 ms helicity state and digitized using 18 bit ADCs sampling at 500 kHz. The kinematics were verified in special low beam-current calibration measurements obtained using a particle tracking system based on drift chambers located before and after the spectrometer magnet.

During the experiment the beam polarization ($\sim$89%) was periodically measured using the Hall C Møller polarimeter [13] and, for the latter part of the experiment, continuously measured with a newly-developed Compton polarimeter based on a circularly polarized green laser in a low-gain cavity. The agreement between the results from the two polarimeters is excellent. For the initial results presented here, only Møller polarimeter data were available.

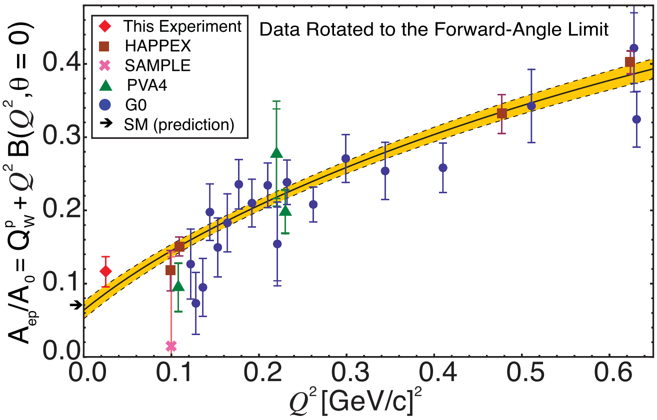

Figure 1. World data for reduced asymmetries from forward-angle PVES on the proton, including the present result, for measurements up to $Q^2 = 0.63\,(GeV)^2$, presented in the forward angle limit (see text). The solid line is the global fit based on these data as well as on forward-angle ^{4}He and deuterium data. The additional uncertainty arising from the rotation is indicated by outer error bars. The shaded region indicates the uncertainty in the fit. Q_W^p(expt) is the intercept of the fit. The standard model (SM) prediction is also shown (arrow).

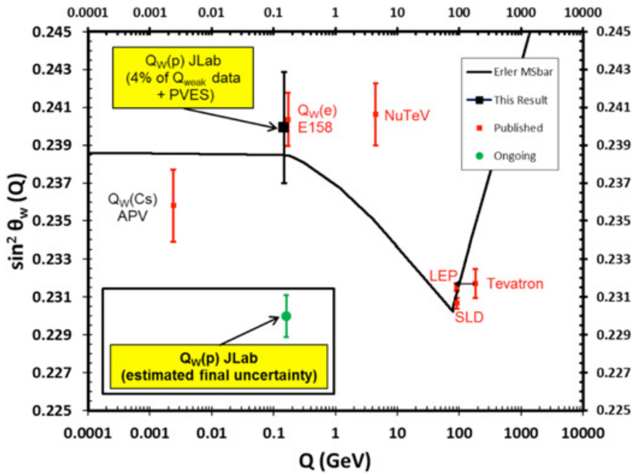

Figure 2. The running of the weak mixing angle with energy scale Q. The curve is the standard model predicted running in the $\overline{\text{MS}}$ scheme [2]. Data include collider results (LEP [17], SLD [18], Tevatron [19, 20]) at or near the Z-pole, the SLAC E158 electron-electron parity violation experiment [21], the Colorado atomic parity violation (APV) experiment on ^{133}Cs [22, 23], NuTeV [24] (this latter is controversial, we show the value from [2]), and the present result; the inset shows the anticipated final precision of our experiment.

3. Results

We report here results from initial "commissioning" data, which represent about 4% of our full data set; these results appeared in the literature the same week as this conference [14]. After all corrections, the measured asymmetry was $A_{ep} = -279 \pm 35$ (statistics) $\pm$ 31 (systematics) ppb.

In order to extract Q_w^p from the measured asymmetry A_{ep}, one needs to subtract the hadronic form factor piece in Eq. (4), *i.e.* the $Q^2 B(Q^2, \theta)$ term, which vanishes at sufficiently low Q^2. This was done by exploiting previously-measured PVES asymmetries from the SAMPLE, HAPPEX, G0, and PVA4 experiments (see Ref. [10] and references therein), all of which were at significantly higher Q^2 than the present result. These included data for hydrogen, deuterium and ^{4}He, which were combined with our result in a global fit following the method outlined in [9]. All PVES data up to 0.63 GeV^2 were used. The fit had five free parameters: the light quark weak charges C_{1u} and C_{1d}, the strange charge radius ρ_s and magnetic moment μ_s, and the isovector axial form factor $G_A^{Z\,(T=1)}$. The isoscalar $G_A^{Z\,(T=0)}$ was constrained by theory [15]. For the electromagnetic form factors G_E^γ and G_M^γ the parameterization of Kelley [16] was adopted, and the data were corrected for the γZ box diagram contributions.

To display the quality of the fit, the θ dependence of the proton-target data was removed using Eq. (3), and the asymmetries were divided by A_0, and plotted vs. Q^2; see Fig. 1. The fitted intercept is $Q_W^p(\text{expt}) = 0.064 \pm 0.012$, in excellent agreement with the standard model (SM) expectation $Q_W^p(\text{SM})=0.0710 \pm 0.0007$, and represents the first direct extraction of the proton's weak charge.

The "running" value of weak mixing angle at our kinematics can be extracted from Q_W^p [25], and is shown in Fig. 2, along with other precision determinations; again, our present result conforms well with standard model expectations.

The full analysis of the data is well underway. We anticipate a final precision on the weak charge of about 5%, which will probe certain classes of new physics at the multi-TeV scale.

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