TJNAF Letter of Intent: Search for New Physics at the TeV Scale Via a Measurement of the Proton's Weak Charge

May 31, 2001

D. Armstrong[1], T. Averett[1], J.D. Bowman[5], R. Carlini[9] (contact person), J. Erler[3], R. Ent[9], M. Finn[1], R. Jones[2], S. Kowalski[8], L. Lee[7], A. Lung[9], D. Mack[9], S. Penttila[5], M. Pitt[10], W.D. Ramsay[7] M. Ramsey-Musolf[2,4], J. Roche[1], N. Simicevic[6], G. Smith[9], W.T.H. van Oers[7], S. Wells[6], S. Wilburn[5]

[1] *College of William and Mary, Williamsburg, VA*

[2] *University of Connecticut, Storrs, Connecticut*

[3] *David Rittenhouse Laboratory, University of Pennsylvania, Philadelphia, Pennsylvania*

[4] *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

[5] *Los Alamos National Laboratory, Los Alamos, New Mexico*

[6] *Louisiana Tech University, Ruston, Louisiana*

[7] *University of Manitoba, Winnepeg, Manitoba, Canada*

[8] *Massachusetts Institute of Technology, Cambridge, Massachusetts*

[9] *TJNAF, Newport News, VA*

[10] *Virginia Polytechnic Institute, Blacksburg, Virginia*

Contents

Abstract

We propose a low energy search for new physics beyond the Standard Model. The experiment calls for a precise absolute measurement of the proton's weak charge, Q_W^p, via a measurement of the parity violating asymmetry in elastic ep scattering at $Q^2 \simeq 0.03(GeV/c)^2$. The proton's weak charge is a fundamental property of the proton which has never been measured. It is the neutral current analog of the vector coupling G_V which enters neutron and nuclear β-decay. This measurement in the semi-leptonic sector will be complementary to SLAC experiment E158 which is carrying out parity violating asymmetry measurements in the purely leptonic sector at similar Q^2 in Moeller scattering. Our proposal is similar to, but has different theoretical uncertainties than, recently completed and proposed atomic parity violation experiments which measure the weak charge of complex nuclei. The present reference design calls for a single toroidal magnet to measure electrons scattered to small angles. A 2000 hour measurement employing 180 μA of 80% polarized beam on a 35 cm liquid Hydrogen target will determine the proton's weak charge with $\simeq 4\%$ combined statistical and systematic errors. In the absence of physics beyond the Standard Model, this would be equivalent to a $\simeq$ 0.2% measurement of $\sin^2\theta_W$, making this a very competitive measurement of this quantity at low Q^2.

1 Introduction

Historically, parity-violating polarized electron-nucleon scattering played an important role in the early confirmation of the electroweak Standard Model. The pioneering parity-violating deep inelastic electron-deuteron asymmetry measurement at SLAC [1, 2] provided one of the most accurate (at that time) measurements of $\sin^2\theta_W$, which was in agreement with that obtained in other sectors and confirmed the internal consistency of the Standard Model. Since that time, the Standard Model of electroweak interactions has been tested to high accuracy at the Z^0 resonance. In the same time frame, the technical ability to carry out precise parity-violating polarized electron-nucleon asymmetry measurements has continued to improve, building on the techniques developed in the inital SLAC measurement. The physics motivation for the new generation of experiments has primarily been to measure the nucleon's strange vector form factors (see refs. [3, 4, 5] for recent reviews). However, these advances can also be exploited to significantly improve the precision of low energy Standard Model tests well below the Z^0 resonance. In this Letter of Intent (LOI), we would like to make JLab management and the wider physics community aware of our intention to propose a new measurement of parity-violating polarized elastic electron-proton scattering at a low $Q^2 = 0.03$ (GeV/c)^2. This measurement would provide a precise low energy test of the Standard Model, competitive with the SLAC E158 experiment, and it would also be a sensitive probe of possible new physics beyond the Standard Model.

An important, but not yet well-tested, prediction of the Standard Model is the variation of $\sin^2\theta_W$ with momentum transfer Q^2 (referred to as the "running of $\sin^2\theta_W$"). This behavior comes about because of calculable electroweak radiative corrections that occur in the Standard Model. The solid line in Figure 1 shows this prediction in a particular scheme for $\sin^2\theta_W$. [1] To date, this prediction has been tested at the $\sim 3\sigma$ level by the Boulder group's atomic parity violation measurement in the Cesium atom [6]. (That is, the value of $\sin^2\theta_W$ in the Cesium experiment differs from that at the Z-pole by $\sim 3\sigma$.) This experiment is currently limited by errors stemming from atomic theory calculations. The experiment described in this LOI would measure the proton's neutral weak charge, Q_W^p, to 4%. As shown in Figure 1, this precision is sufficient to determine $\sin^2\theta_W$ (effective) with a precision of 0.2%. This makes possible a test of the running of $\sin^2\theta_W$ at the $\sim 13\sigma$ level. Depending on the outcome, this measurement could provide either an impressive confirmation of an important Standard Model prediction, or it could provide evidence for new physics beyond the Standard Model. As discussed further below, this measurement is particularly sensitive to new physics which does not sit at the Z^0 resonance.

There is another high precision low energy Standard Model test proposed at SLAC (E158) [7]. This will measure the asymmetry in parity-violating Moeller scattering at $Q^2 = 0.03$ (GeV/c)^2 (see Figure 1). The expected precision implies $\sim 8\sigma$ sensitivity to the running of $\sin^2\theta_W$. This is a purely leptonic experiment, and it is complementary to the semi-leptonic experiment proposed here. Since Standard Model extensions exist that affect these sectors differently, the combination of the two measurements will provide a powerful low energy test of a variety of new physics possibilities.

The experiment proposed here is a natural next step in the parity violation program at Jefferson Lab. The current parity-violation experiments (HAPPEX, HAPPEX II, HAPPEX ^{4}He, and G^0) will provide high quality data on the strange form factors. This data is necessary to limit the errors coming from hadronic structure in the proposed measurement. Various polarized source and accelerator devel-

[1] Note that $\sin^2\theta_W$ is not strictly an observable, but depends on what has been absorbed into the definition and what has been explicitly corrected for. In any given scheme the curve is fixed; the curve representing the SM prediction is then only ambiguous at the level of the LEP+SLC error bar.

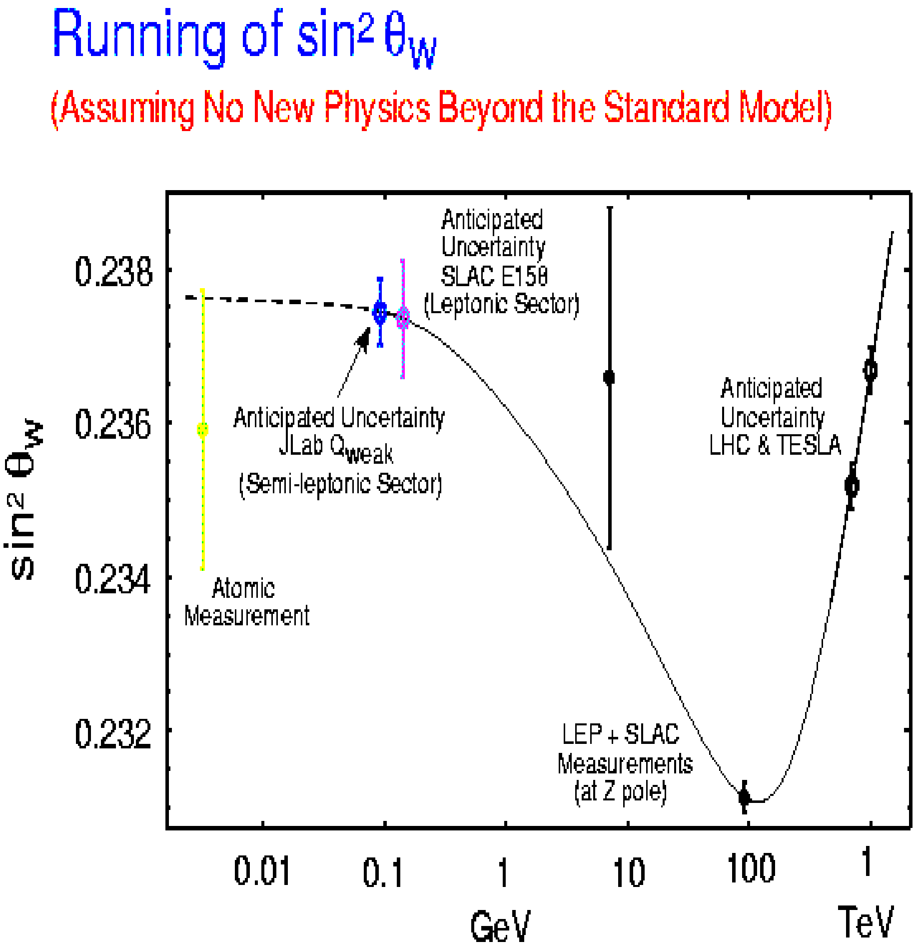

Figure 1: Current measurements (solid symbols) and anticipated errors (open symbols) of the weak mixing angle at various values of Q^2. Shown are determinations from atomic parity violation, deep inelastic neutrino-nucleus scattering, and from Z-pole asymmetries (LEP+SLC). The future measurements are for the Q^p_W determination at JLab, the SLAC E158 polarized Moeller scattering experiment, and the proposed linear collider, TESLA, in its e^+e^- ($Q^2 = 1$ TeV) and e^-e^- ($Q^2 = 0.5$ TeV) modes. Based on a figure from reference [17].

opments have led to the necessary infrastructure and beam quality to successfully carry out parity-violation measurements at Jefferson Lab. The low energy test of the Standard Model proposed here builds on the previous JLAB parity experiments by using their physics output and their technical developments.

2 Physics Motivation

The Standard Model (SM) of electroweak interactions has been confirmed with impressive precision in a variety of experiments, ranging in energies from the eV scale in atomic parity violation to a few hundred GeV in e^+e^- collisions at LEP and the SLC. Consequently, the attention of the particle physics community has turned from testing the SM and measuring its parameters to searching for possible physics which may lie beyond it. In addition to Higgs boson searches, the search for signatures of such "new" physics is one of the primary objectives of present and future high energy collider experiments.

From a theoretical standpoint, there exist strong reasons to believe that the SM is only a low energy effective theory of some larger framework. These reasons include the large number of parameters (masses, mixing angles, couplings) which must be put into the SM by hand rather than following as natural consequences of the theory; the mass hierarchy problem; and the apparent lack of coupling unification when the couplings are run perturbatively up to the expected grand unification scale. In addition, the SM does not explain why discrete symmetries such as parity and CP are violated; it simply incorporates these phenomenological observations in the structure of the model. One expects that a more complete theory will provide deeper explanations for these features of the SM and address these conceptual open questions.

There may now be experimental evidence for physics beyond the SM. The azimuthal dependence of the atmospheric ν_μ deficit observed by the Super Kamiokande collaboration implies nearly maximal mixing between the ν_μ and ν_τ. Furthermore, the very recent results for the anomalous magnetic moment of the muon[8], $(g-2)_\mu$, show a 2.5σ devision from the SM, providing tantalizing hints of supersymmetry - if questions regarding hadronic loop effects can be settled.

Confirmation of the $(g-2)_\mu$ result in other regimes is essential to determining which extensions of the SM should be pursued, so low energy experiments will continue to play an important role in the search for this more complete theory. Experiments at the Z pole are sensitive to new physics (such as modifications of the SM vector boson propagators) which affect physics at $t \simeq M_Z^2$. Low energy electroweak observables, on the other hand, are sensitive to new physics which does not sit on the Z resonance such as a Z' boson with $M_{Z'} \neq M_Z$. In particular, experiments in atomic parity violation have reached sub one-percent experimental precision, making them sensitive to new physics associated with mass scales in the TeV range. These experiments measure the "weak charge" of the nucleus, $Q_W(Z,N)$, which constitutes the $Q^2 = 0$ vector coupling of the Z^0 to the nucleus. The weak charge can be computed precisely within the SM, and any significant measured deviation from the SM value could signal the presence of new physics.

In 1997, the Boulder group reported a measurement of Q_W for ^{133}Cs which deviated from the SM prediction by 2.5σ, where the largest component of the quoted uncertainty is from atomic theory[9]. However, a recent analysis[10] of the Breit interaction in atomic structure calculations yields a value of Q_W^{Cs} which is consistent with the SM at the 1σ level. The dominant error is theoretical but the magnitude of the theoretical error is still controversial. It is clear that the overall situation in atomic parity violation is muddled; the interpretation of these precise experimental results is limited by the need for very advanced and complicated atomic structure calculations.

In the present experiment, we propose to measure the weak charge of the proton, Q_W^p, via the parity-violating asymmetry in *ep* elastic scattering at $Q^2 = 0.03(GeV/c)^2$. The proton's weak charge is a fundamental property of the proton which has never been measured. It is the neutral current analog of the vector coupling G_V which enters neutron and nuclear β-decay. In contrast to $Q_W(Z,N)$ for a heavy atom, which is a large number of order N, the observable Q_W^p is fortuitously suppressed in the SM. This is because $Q_W^p = 1 - 4\sin^2\theta_W$ and the value of the weak mixing angle, $\sin^2\theta_W$, is numerically close to $1/4$. This is characteristic for protons (and electrons) but not neutrons, and therefore absent in any other nucleus, making a Q_W^p measurement particularly sensitive to deviations arising from new physics. Consequently, *the required experimental precision is about an order of magnitude less stringent than needed for atomic parity violation new physics searches.* Roughly speaking, a 13% measurement of Q_W^p is equivalent in new physics sensitivity to a 1% measurement of $Q_W(N,Z)$. Moreover, the parity violating *ep* asymmetry, $A_{LR}(^1H)$, is sufficiently free from theoretical uncertainties at low Q^2 to make it interpretable as a new physics probe. Here we propose a 4% combined statistical and systematic error determination of Q_W^p.

We emphasize that the theoretical clarity of $A_{LR}(^1H)$ is nontrivial. In the case of Cesium atomic parity violation, the quoted atomic theory uncertainty is nearly twice as large as the experimental error. As a way of circumventing the former, several groups are planning measurements of atomic parity violation observables for atoms along an isotope chain. To a significant extent, the atomic wavefunction dependence cancels from the isotope ratios. What remains is a linear combination of Q_W^p (the neutron's weak charge cancels to first order) and shifts in $\rho_n(r)$, the neutron density, along the isotope chain [11]. Given the present level of knowledge of $\rho_n(r)$, any atomic parity violating isotope ratio measurment must be considered a measurement of $\rho_n(r)$ isotope shifts rather than of $Q_W(N,Z)$. (Although there is a JLab proposal intended to improve our knowledge of $\rho_n(r)$ for ^{208}Pb which may be useful for calibrating the theory used for other isotopes such as Cesium or Barium.[32]) By contrast, the dominant many-body effects which enter $A_{LR}(^1H)$ arise via effective nucleon form factors (see below), which can be separated from the Q_W^p term kinematically. The present program of elastic *ep* PV asymmetry measurements at Jefferson Laboratory[12, 13, 14] and Mainz[15] are expected to provide sufficient information on the form factor term to make the associated uncertainty acceptably small for our proposed measurement.

Measurements of both Q_W^p and $Q_W(N,Z)$ are important for identifying the type of new physics which may appear at low energies. Whereas $Q_W(N,Z)$ depends on a nearly isoscalar combination of possible new semi-leptonic interactions involving $u-$ and $d-$quarks, Q_W^p is twice as sensitive to new $u-$quark interactions as it is to new $d-$quark physics. Since there exist a variety of scenarios which imply different isospin content for possible new physics[11], the combination of both low energy measurements would provide powerful constraints on new physics model building. Moreover, some new physics scenarios imply large effects in both the semi-leptonic and purely leptonic sectors while others, such as $B-L$ violating supersymmetry, heavily favor the semi-leptonic sector. The Moeller experiment E158 currently running at SLAC[7] will, together with the atomic parity violation measurement of $Q_W(N,Z)$ and our proposed Q_W^p measurement, allow one to distinguish between leptonic and semi-leptonic effects. In short, our proposed measurement rounds out a triad of measurements which will constitute one of the most powerful low-energy probes of new physics at the TeV scale.

A more detailed discussion of our Q_W^p measurement as a probe of new physics will be available by the time our formal proposal is submitted[16]. Specific extensions to the SM which will be probed include extra neutral gauge bosons (ie, Z'), SUSY and leptoquarks, and lepton and quark compositeness. In the absence of new physics beyond the SM, this measurement will provide a test of the renormalization group evolution (RGE) of $\sin^2\theta_W$ (*ie*, the "running of $\sin^2\theta_W$"). To put this statement in context, we note that the strong coupling constant, α_s, is routinely subjected to analogous RGE tests: this is one of the very few arguments that QCD is the correct theory of the strong interaction. A precise test of the running of $\sin^2\theta_W$ is still missing. (See Figure 1).

3 Theoretical Interpretability

$A_{LR}(^1H)$ (henceforth simply A) is the asymmetry in the measurement of the cross section difference between elastic scattering by longitudinally polarized electrons with positive and negative helicities from unpolarized protons:

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \tag{1}$$

which, expressed in terms of Sachs electromagnetic form factors G_E^γ, G_M^γ, weak neutral form factors G_E^Z, G_M^Z and the neutral weak axial form factor G_A, has the form[4]:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\left[\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^Z}{\varepsilon(G_E^\gamma)^2 + \tau(G_M^\gamma)^2}\right] \tag{2}$$

where

$$\varepsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}, \quad \varepsilon' = \sqrt{\tau(1+\tau)(1-\varepsilon^2)} \tag{3}$$

are kinematical quantities, Q^2 is the four-momentum transfer, $\tau = Q^2/4M^2$ and θ is the laboratory electron scattering angle. It was shown in [18] that for forward-angle scattering where $\theta \to 0$, $\epsilon \to 1$, and $\tau << 1$, the asymmetry can be written as:

$$A = \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q_w^p + F^p(Q^2,\theta)\right] \to \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q_w^p + Q^4 B(Q^2)\right] \tag{4}$$

where F^p is a form factor. Neglecting radiative corrections, the leading term in the equation is simply $Q_W^p = 1 - 4\sin^2\theta_W$. The $B(Q^2)$ is the leading term in the nucleon structure defined in terms of neutron and proton electromagnetic and weak form factors. An accurate measurement of $\sin^2\theta_W$ thus requires significant corrections for nucleon structure. Nucleon structure contributions in $B(Q^2)$ (which enter to order Q^4) can be reduced by going to lower momentum transfer. However, this also reduces the sensitivity to Q_W^p (which enters to leading order in Q^2) making it statistically more difficult to measure. An optimum value of Q^2 will incorporate the measured and anticipated uncertainties on $B(Q^2)$ from the various HAPPEX, G^0, and Mainz A4 measurements. Based on simulations and estimates done so far by our collaboration, the optimum Q^2 appears to lie in the range 0.02-0.03 $(GeV/c)^2$. The reference design presented here is for Q^2= 0.03 $(GeV/c)^2$.

The remaining theoretical uncertainties are those which enter Q_W^p itself. Of these, the largest appear to be hadronic contributions to the $Z\gamma$ mixing tensor, which have been estimated to give a 3% uncertainty in Q_W^p.[19] Additional hadronic effects arise via box graphs, or "dispersion corrections", containing one or more photons. The effects of two-photon dispersion corrections vanish as $Q^2 \to 0$, and so can be included in the quantity $B(Q^2)$[20]. Measurements of $B(Q^2)$ in the present program of parity violating asymmetry measurements will, therefore, constrain uncertainties associated with these $\gamma\gamma$ dispersion corrections to be smaller than needed. The remaining $\tau-$independent dispersion correction arises from box diagrams containing one γ and one Z-boson. These corrections are proportional to the tree-level value for Q_W^p, and so enter as an $O(\alpha/4\pi)$ correction[20, 21, 22]. Hadronic uncertainties associated with this correction are, therefore, expected to be well below the projected error of this measurement.

4 The Experiment

We present here a reference design for an experiment which is already very competitive, but which is not yet completely optimized. It may be possible to do slightly better and so increase our sensitivity to new physics. To achieve the required statistical precision in an acceptable amount of running time, we propose to use a toroidal magnet to measure electrons scattered to small angles. Accurately machined and positioned collimators will define the Q^2 acceptance. The simulations presented here use the G^0 magnet but a resistive magnet (similar to the BLAST toroidal magnet) might serve as well. The electrons will be detected in quartz Cerenkov detectors and the signals will be integrated. A new high power cryotarget will be built. A 2000 hour measurement employing 180 μA of 80% polarized beam on a 35 cm liquid Hydrogen target will be used to determine the proton's weak charge to $\simeq$ 4% combined statistical and systematic uncertainty. This and other basic parameters of the experiment are presented in Table 1.

4.1 Spectrometer Magnet

With some modification, the G^0 Superconducting Magnet System (or a similar device) can be used for the measurement of the proton's weak charge. Because of their high specialization, neither the G^0 detector system nor the collimators can be

Table 1: Basic parameters of the present Q^p_{weak} experiment reference design which assumes a single toroidal spectrometer.

Parameter	**Value**
Incident Beam Energy	1.165 GeV
Beam Polarization	80%
Beam Current	180 μA
Target Thickness	35 cm
Running Time	2000 hours
Nominal Scattering Angle	9°
Scattering Angle Acceptance	±2°
Phi Acceptance	70% of 2π
Solid Angle	$\Delta\Omega = 39$ msr
Acceptance Averaged Q^2	$< Q^2 >= 0.03\ (GeV/c)^2$
Acceptance Averaged Asymmetry	$< A >$ = -0.3 ppm
Integrated Cross Section	4.3 μb
Integrated Rate (all sectors)	7.24 GHz
Statistical Error on the Asymmetry	1.90%
Statistical Error on Q^p_W	2.75%

reused for this new measurement. The G^0 Superconducting Magnet System consists of eight superconducting coils which generate the magnetic field that focuses scattered particles. This spectrometer has a field integral at maximum excitation of approximately 1.6 Tesla-meters. The spectrometer, the inner structure of which is shown in Figure 2, is designed to focus particles of the same momentum and scattering angle from the length of the extended target to a single point (zero magnification in the dispersion direction). In addition to very large solid angle and momentum acceptance, the spatial acceptance is axially symmetric and thus susceptibility to systematic uncertainties is reduced. The shape of the magnetic field is determined by the current conductors, and there is no polarized iron in the system. The target will be located upstream of the magnet.

Simulations were performed using parameters close to the reference design parameters in Table 1.[23] Elastic and inelastic electrons are shown in Figure 3, top and bottom, respectively. The elastic electrons are well-focused on the detector plane, while lower momentum electrons from inelastic processes are swept away. A similar figure for the elastic trajectories can be made using the BLAST toroid as in Figure 4.

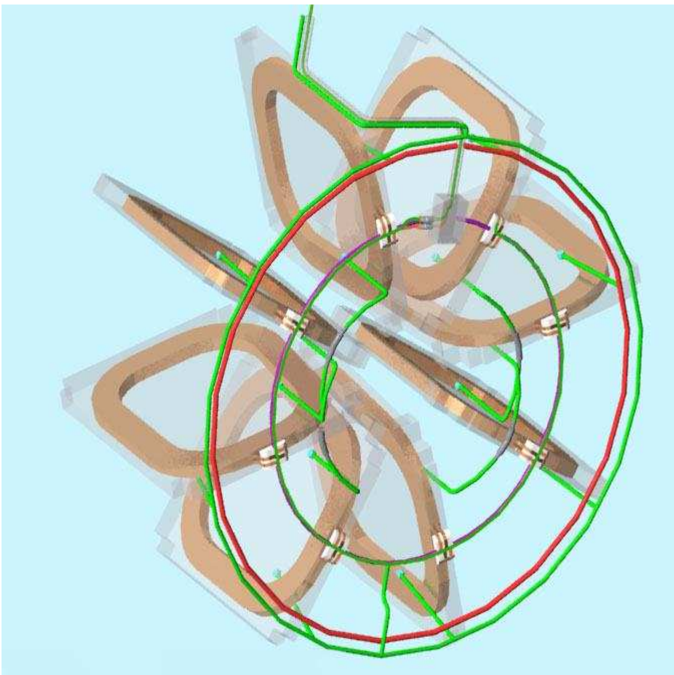

Figure 2: Inner structure of the G^0 superconducting magnet system, showing eight superconducting coils and the liquid helium plumbing between them.

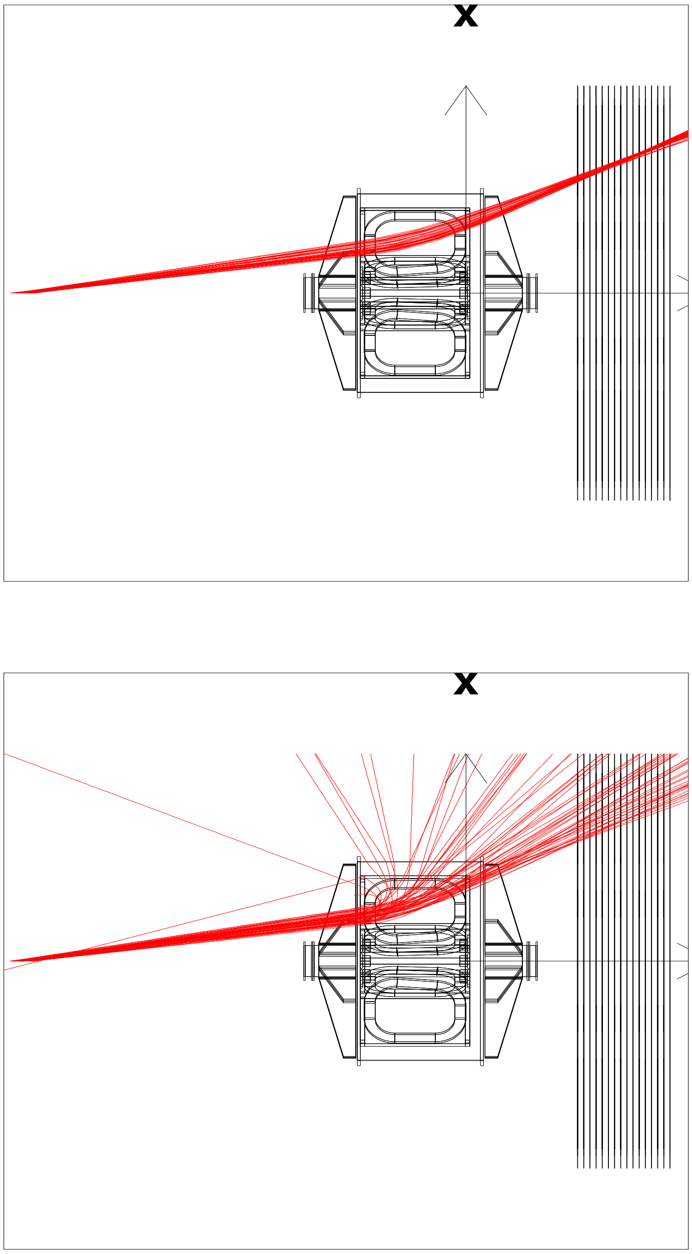

Figure 3: The side view of the test setup with a sample of elastic (top) and inelastic (bottom) trajectories restricted to $\theta_e = 9.0 \pm 1.5$ deg and $\phi_e = 0.0 \pm 15.0$ deg. The beam axis and direction is given by the horizontal arrow. The vertical arrow labeled X is a zero position along the beam axis in the standard G^0 coordinate system.

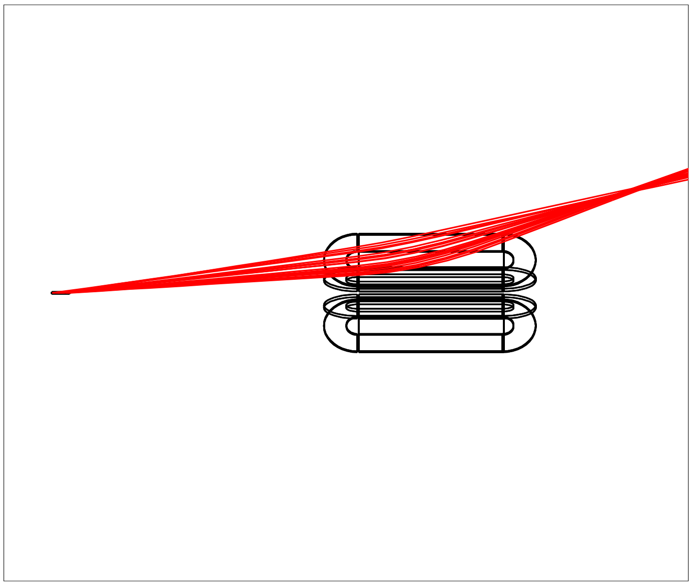

Figure 4: A good elastic focus using the BLAST toroid.

4.2 Detectors and Electronics

Several factors drive the design of the detectors:

- This precision measurement requires high statistics, therefore the rate should be as high as technically achievable. Radiation hardness will be an issue, and standard signal integrating techniques for parity experiments must be used.
- The detector system must clearly separate the elastic and inelastic channels.
- Sensitivity to backgrounds (*eg*, neutrons and pions) should be minimized.
- Noise produced by the detector (*eg*, a limited number of photoelectrons) must not significantly deteriorate the ability of the experiment to achieve counting statistics.
- Size and weight reduction are helpful for reducing backgrounds and cost, and simplifying the mounting scheme.

Our present design for the detectors consists of one rectangular quartz cerenkov bar per octant. Each will be read out on both ends by 5 inch photomultiplier tubes with S20 photocathodes. [2] In Figure 5 note the clear separation between elastic and inelastic events. (Electron radiation has not yet been enabled in these simulations.) A detector with dimensions of roughly 200 cm long by 14 cm wide is adequate for containing the elastic envelope with minimal contamination from inelastic near-threshold events. The choice of thickness is somewhat arbitrary, but for now we have selected 1.72 cm which allows us to benefit from BaBar experience with fused silica radiator bars in their DIRC detector.[25] Specifying a modest surface reflectivity of 0.997 will provide a total of about 90 photoelectrons per traversing electron when the two ends are summed.[24] The additional statistical error on the asymmetry measurement per helicity reversal due to detector photoelectron statistics, $\sqrt{1 + (\sigma_{pe}/N_{pe})^2)}$, is less than 1%.

Placing several cm of lead preradiator in front of the quartz bars has the potential to increase the already large signal without adding unduly large statistical noise due to shower fluctuations. Possible advantages of this would be to reduce the sensitivity to energetic π^-'s which can be produced in the target windows and to help shield the detectors from any background of low energy charged particles and gamma rays. Optimization of the detector design is continuing.

[2]The relatively low sheet resistance of the S20 photocathode is important for maintaining a constant voltage over the photocathode when large photocathode currents are drawn.

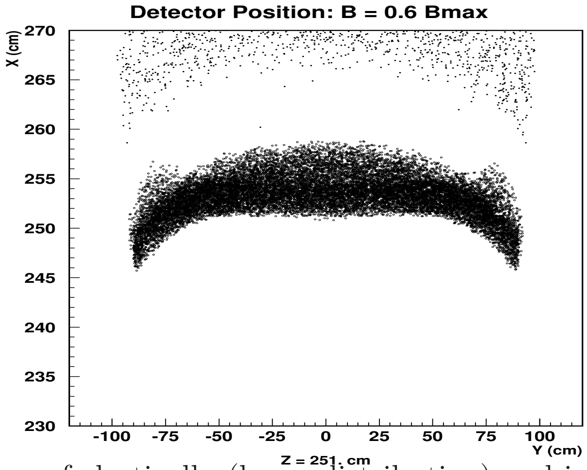

Figure 5: Separation of elastically (lower distribution) and inelastically (upper distribution) scattered electrons on selected detector position. The kinematics is restricted to $\theta_e = 9.0 \pm 1.5$ deg and $\phi_e = 0.0 \pm 15.0$ deg.

The two signals from each of the 8 sectors will be summed, input to a high gain ultra-linear op amp I-to-V (current to voltage converter), fed into a linear V/F converter, and finally digitized by scalers. The proposed helicity reversal rate would be 30 Hz with an experiment read out rate of 120 Hz. The 120 Hz readout rate is to allow for a 4 times over-sampling rejection of non-linear induced systematics from 60 Hz line couplings and prevent leakage of the reversal signal into the apparatus. The electronics are neither new nor complex, but are straightforward and have been used successfully on parity experiments at LAMPF where small asymmetries ($\simeq 10^{-8}$) were measured.

4.3 Cryotarget

It is important to note that our beam current and target length requirements lead to a target heat load of 2.1 kW, considerably over the present 1.2 kW capacity of the JLab End Station Regrigerator (ESR). This target is therefore predicated on the planned expansion of the ESR to twice its current capacity.

The design of the Q_W^p experiment LH_2 target is based on the following parameters: safe and reliable operation for sustained periods of time with a beam current=180 μA, length=35 cm, location 4.75 m upstream of the magnet, raster size $\sim$2x2 mm^2, 9°± 2° acceptance for scattered electrons, thin windows, azimuthal symmetry, no local boiling, and minimal density fluctuations.

The required He gas mass flow including a 200 Watt reserve is

$$\dot{m} = \frac{2300\ W}{(6.26\ J/gK)(20^\circ - 15^\circ)} = 75\ g/s.$$

We have studied several possible target concepts based on the above design parameters. In doing so we have considered the local temperature rise ΔT of the LH_2 in the path of the beam:

$$\begin{aligned}\Delta T &= \frac{\Delta E(J/cm)}{m_l(g/cm)\; C_p(J/gK)} \\ &= \frac{dE/dx(MeV/g/cm^2)\; I(\mu A)\; [A_{flow}(cm^2) = V_{vol}(cm^3/s)/v_s(cm/s)]}{d(cm)\; C_p(J/gK)\; V_{vol}(cm^3/s)}\end{aligned}$$

where ΔE is the beam energy deposited per cm of target length, m_l is the target mass along the beam axis, dE/dx is the beam ionization energy loss, I the beam current, A_{flow} the flow area across the beam axis, V_{flow} the volume flow provided by the recirculation fan, v_s the stream velocity transverse to the beam axis, d the raster width perpendicular to the flow direction, and C_p the specific heat of hydrogen. Therefore the only way to affect the local temperature rise is to either increase the raster size or increase the stream velocity.

In order to keep helicity correlated density fluctuations of the target at the level of 3% of the expected parity signal of 3×10^{-7}, we need to keep the helicity correlated ΔT less than about 6×10^{-7}K (since $\Delta\rho/\rho \sim -1.5\%\Delta T$). Assuming the charge asymmetry in the parity-quality beam at JLab is 10^{-6}, which is what HAPPEX obtained, and solving the above equation for the stream velocity, we find that we need $v_s \geq 700$ cm/s. This is the predicted flow velocity for the G^0 target. To reduce the helicity correlated density fluctuations to a level where they do not contribute at all to the experimental uncertainty, we need to either get a charge asymmetry better than about 2×10^{-7}, or else calculate and correct for the density fluctuations to $\leq 20\%$, which is no problem.

Beyond these considerations, it is important to ensure the target does not boil and thereby introduce noise into the system. Using the above equation with $v_s = 700$ cm/s, $I = 180\ \mu A$, and a $2\times2mm^2$ raster, we obtain $\Delta T = 0.6$K. Since we normally run 3 degrees sub-cooled (at 19K and 22 psia), the target will not boil.

Taking the above considerations into account, the target concept of choice for the Q^p_W experiment is the SAMPLE/G^0 design as illustrated in Figure 6. A high flow velocity is achieved by means of a perforated tapered cylindrical windsock, concentric to an outer cell. The flow area depends on the gap between the windsock and the target cell, as well as their respective radii, and the perforations. As a result the flow area can be made arbitrarily small and is almost independent of the length of the target. The small flow area inherent in this design contributes to the high flow velocity required by Q^p_W. A flow velocity of 500 cm/s was achieved by

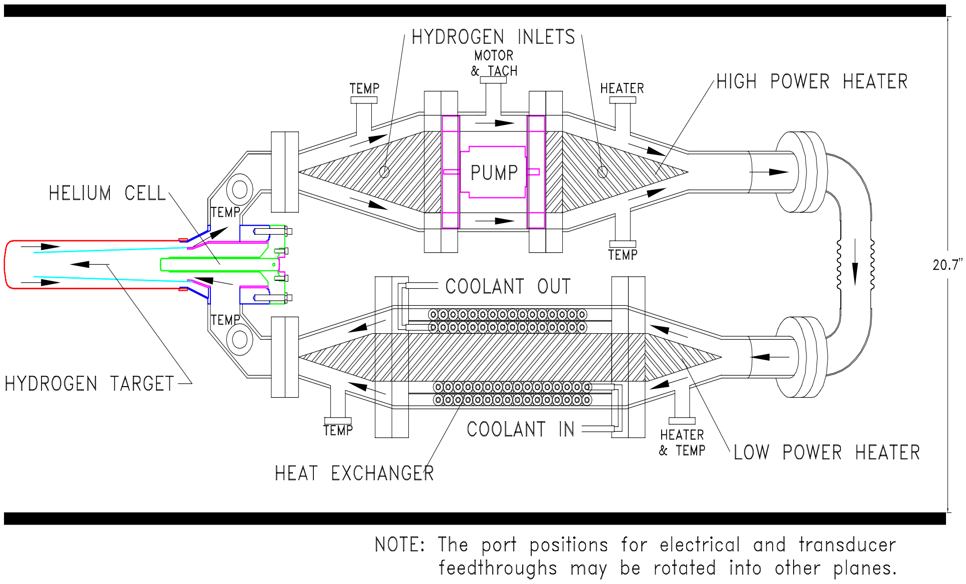

Figure 6: Schematic view of the G^0 cryotarget. The Q_W^p target will be similar but with a longer 35cm target cell.

the SAMPLE target, and as noted previously the G^0 target flow velocity is designed to be 700 cm/s. The experience gained with the G^0 target will carry over to this experiment, however, the target cell itself will need to be stretched from 20 to 35cm. In addition the heat exchanger and heater capacity will need to be increased by a factor of seven. We are currently studying the possibility of fabricating the beam entrance and exit windows from Beryllium to reduce the window backgrounds.

The impact of impurities in the LH_2 on the Q_W^p measurement has not yet been thoroughly studied. We may need to tighten our quality control at the gas panel somewhat, and take gas samples on a regular basis throughout the experiment. When no errors are made in the fill from a high purity bottle, we routinely find at JLab that the contamination of our H_2 (principally by D_2 or HD) is at most 0.1%. This would not pose a significant problem for the Q_W^p measurement.

4.4 Determination of Average Q^2

Since the PV asymmetry is proportional to Q^2, it is critical to determine the average Q^2 for the electrons from the ep elastic scattering events of interest with $\simeq$ 1% accuracy. The absolute beam energy will be known to $\leq 0.1\%$ using the Hall C energy measurement system. The central scattering angle for each collimator will be determined by redundant survey techniques to $\leq$1 mrad. Over short baselines, the JLab alignment group routinely achieves this. As was the experience from the HAPPEX experiment[26], angle errors will dominate the error in Q^2. In particular, the error for our kinematics is approximately 1.4%/mrad. Because there is essentially no loss of electrons in transport through the spectrometer, the carefully measured target and collimator geometries relative to the electron beamline will then define the Q^2 bite.

This is an integrating experiment with no event-mode data, so determination of the average Q^2 has further complications. The Q^2 dependence of the ep cross section will bias the average detected Q^2. This and any Q^2-dependent detector bias must be taken into account (since Q^2 may be correlated with position at the focal plane). Although in principle these matters can be simulated, it is important to check the experiment Monte Carlo using ancillary measurements: one to measure the shape of the focal plane distributions, and another to measure the position-dependent detector bias.

Careful thought needs to go into the choice of survey techniques. Furthermore, since survey and alignment are critical, it is important that the experiment be designed from the outset such that the beamline, cryotarget, and collimators can be accurately and redundantly surveyed.

4.5 Asymmetry Contribution from the Target Windows

The contamination of the elastic proton asymmetry from the scattering in 3.5 mil aluminum windows was estimated assuming nominal central kinematics.[27] (Here we are referring to the windows through which the primary beam enters and exits the target cell.) It was also assumed that it will not be possible to reject these backgrounds in our focal plane detectors. Both elastic scattering on the Aluminum nucleus and quasielastic scattering from the protons and neutrons in the Aluminum were considered. (Transitions to excited states of Aluminum, which may be important at $Q^2 \simeq 0.03$ $(GeV/c)^2$, have not yet been estimated.) The results are shown in Table 2. The relative contamination of the asymmetry of interest (elastic scattering from protons) is shown in the last column. Below each of these processes is considered separately, and an estimate is made of the systematic error associated with these processes using our theoretical knowledge of their asymmetries. We find that although we can make reasonable estimates of the window backgrounds, the resulting uncertainties are not comfortably below our other errors. Therefore a dedicated window background measurement will be proposed.

Table 2: Contributions of the various scattering processes in the hydrogen target and the windows at the Q_W^p central kinematics. t is the target thickness in particles/cm^2, R_{cont} is the fractional contribution to the rate in the detector, and A_{cont} is the contribution to the overall asymmetry (=-0.27 ppm) from that process. The relative contamination of the elastic proton asymmetry from each process is shown in the last column.

Process	σ (μb/sR)	A (ppm)	t (cm^{-2})	R_{cont} (%)	A_{cont} (ppm)	$\frac{A_{cont}}{(-.30)}$ (%)
Protons in LH_2 (elastic)	88	-0.31	1.3×10^{24}	97.8	-0.30	
Protons in Al (quasi-elastic)	88	-0.31	1.4×10^{22}	1.05	-0.0033	1.1
Neutrons in Al (quasi-elastic)	3	-3.1	1.5×10^{22}	0.04	-0.0012	0.4
^{27}Al nucleus (elastic)	1234	$+3.0$	1.05×10^{21}	1.1	+0.033	-11.0

4.5.1 Elastic scattering from windows

Despite the fact that the contribution of the elastic scattering on the aluminum nucleus to the overall rate is small (1.1%), the contribution to the asymmetry is large because the asymmetry from elastic scattering on aluminum is 10 times larger. This comes from the difference in the couplings: $(1-4\sin^2\theta_W)$ for elastic scattering on the proton versus $4\sin^2\theta_W$ for elastic scattering on the aluminum nucleus. The question is what is the error on a theoretical estimate of this asymmetry?

The expression for the asymmetry can be written as [31]:

$$A = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[1 - 4\sin^2\theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} + \Gamma(Q^2)\right] \tag{5}$$

where

$$F_{p,n}(Q^2) = \frac{1}{4\pi}\int d^3r j_0(Qr)\rho_{p,n}(r) \tag{6}$$

are the Fourier transforms of the proton and neutron densities. (We use the form factor $F(Q^2 = 0.03\text{ GeV}^2) = 0.27$ from [28].) There will be some uncertainty in the asymmetry due to lack of knowledge of the ratio F_n/F_p. For example, reference

[33] observes differences of about 0.1 fm in the proton and neutron radii in ^{27}Al for different choices of parameters in a mean field model. This would correspond to about a 3% uncertainty in the neutron radius.

The more significant factor is the $\Gamma(Q)$ factor in the above equation. This represents deviations from the ideal expression due to nuclear structure effects such as isospin breaking [31, 34] and Coulomb distortions [35]. At the Q_W^p q value (0.9 fm^{-1}) this factor (for the nearest calculated nucleus, ^{30}Si) varies from 0.8% to 4% depending on the shell-model space used. So we assign an uncertainty of $\simeq$ 4%.

Finally, the expression in Equation 5 is only strictly true for a spin 0 nucleus (*ie* charge scattering only). The asymmetry for ^{27}Al (spin 5/2) will contain contributions from higher multipoles as well. Fairly general expressions exist in the literature [18] from which it could presumably be derived.

Given the above uncertainties, a conservative estimate of the error bar for a theoretical calculation of this asymmetry might be about 10%, implying a 1.1% systematic error *even without a dedicated window background measurement*.

4.5.2 Quasielastic scattering from windows

For the quasielastic entries in Table 1, it was assumed that the asymmetries for the proton and neutron in aluminum are the same as the free proton and neutron. There are of course nuclear corrections to this. Parity-violating quasielastic electron scattering was considered in a general survey article in [29]. They did not consider the final state interactions in detail. These effects have been calculated by [30] in detail for deuterium. Generally, they find that the deviations from the simple picture become small ($\sim$ 1-2%) for large q ($>$ 400 MeV/c) and backward angle running. From a figure in their paper chosen to be as near to the Q_W^p kinematics as possible (q=173 MeV/c, $\theta = 9^\circ$), one finds that the difference between the asymmetry derived in a realistic final state interaction (FSI) calculation (about 0.9 ppm) and the simple picture of free proton and neutron (about 0.33 ppm) is a factor of $\simeq$ 3. The good news is that the model dependence of the FSI calculation from using very different N-N potentials is only at the 10% level.

So it would be useful to have a realistic calculation of this asymmetry. For example, if the asymmetry really changed by a factor of 3, then the proton contribution in our case would go from 1.1% to 3.3%. However, if the modeling of this asymmetry can be believed at the 10% level, then the systematic error associated with this *even without a dedicated window background measurement* would only be 0.3%.

4.5.3 Summary of window backgrounds

For aluminum end window thicknesses of 3.5 mil (front and back), quasielastic and elastic backgrounds must be taken into account. For our kinematics, the elastic contribution from the windows is dominant. In particular, the contributions to the asymmetry could be as large as 3.3% from the quasielastic and 11% from the elastic scattering. These estimates are based on what is currently available in the literature regarding these processes.

The size of the asymmetry could be measured directly by using a special empty target cell with windows 10 times thicker than the full target cell windows. Assuming the rates in Table 1, and that the empty target cell can take full production beam current, it would take only 50 hours to determine the asymmetry such that its contribution to the overall asymmetry is known at the 1% (relative) level. In practice the indirectly cooled empty target cell windows are unlikely to withstand full production beam current.

This is a work in progress. The window background, and thus the time dedicated to background measurements, could be lowered by using windows of Beryllium rather than Aluminum. Better cooling can be provided for the empty target cell windows. A reasonable goal would be to reduce the uncertainty in Q^p_W due to window backgrounds to the 1% level by making a measurement limited to a small fraction of the total beamtime request.

4.6 Beam Polarimetry

The Q^p_W experiment requires that the beam polarization be measured with an absolute uncertainty of 1%-2%. In principle, the technology to do this already exists in Hall C (for $I_{beam} < 8\mu A$) in the form of the University of Basel Moeller polarimeter.[36] While the standard $ee \rightarrow ee$ scattering process near $\theta_{CM} = 90°$ is used, the hardware configuration has several significant improvements over previous Moeller polarimeters. A superconducting solenoid with 4 Tesla, beam-axial field is used to drive a pure iron target foil into saturation. (See Figure 7.) Coincidence detection eliminates most backgrounds and the collimator design minimizes the effects of atomic Fermi motion in the target.

While the Basel Moeller polarimeter has been used to accurately measure the polarization of beam currents of several μA, most experiments run at higher currents. Experience from the last several years suggests that lowering the beam current for dedicated Moeller runs can easily introduce systematic errors which are larger than those intrinsic to the Basel Moeller polarimeter. For example, as the Hall C beam

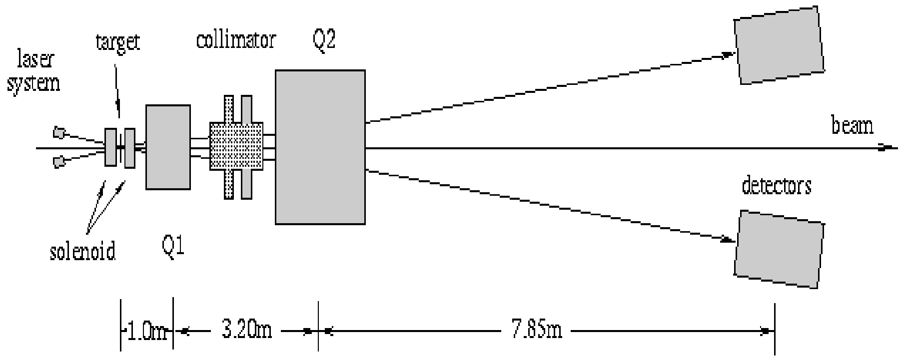

Figure 7: Layout of the Hall C Moeller polarimeter. Note especially the superconducting solenoid which is used to drive the pure iron target foil into saturation. The magnetic field is oriented parallel to the field to minimize perturbation on the beam.

current is lowered, the relative amount of cross-talk from the other Hall lasers (which may have opposite polarization) will increase. Furthermore, reducing the beam current by closing the chopper slit can change the average polarization since the beam pulse has a polarization profile. The cross talk problem can be eliminated by using a single 1.5 GHz laser in the source. The polarization profile problem can be eliminated by using the laser light attenuator rather than the chopper slit. However, since the Q_W^p experiment will run at the elevated beam current of 180μA, we will need to understand what happens to the beam polarization when the filter wheel attenuates the laser light by a factor of 100. (The laser power output is kept fixed in order to keep the frequency stable.) In principle the attenuator should have a negligible effect on beam polarization since a rotating linear polarizer is used, hence only the *quantity* of light out of the attenuator changes and not the *quality*.[37]

Another issue for the Q_W^p polarimetry group to address is whether to construct a Compton polarimeter for Hall C. The Compton polarimeter would permit *continuous* polarization measurements over a wide range in beam current. Although it would be somewhat less accurate[38] than the Basel Moeller polarimeter, the Compton polarimeter could track the beam polarization between occasional Moeller measurements. Once calibrated at low current using the Basel Moeller polarimeter as an absolute standard, a Compton polarimeter might be the ideal way to measure the beam polarization throughout the Q_W^p experiment.

4.7 Summary of Systematic Errors

We have outlined a competitive measurement of Q_W^p with combined statistical and systematic errors of approximately 4%. It may be possible to do significantly better. There are several issues the collaboration will continue to focus on while preparing a formal proposal:

- Optimization of the spectrometer design for highest rates at the selected nominal Q^2.
- Develop a comprehensive plan to reduce the uncertainty in the absolute determination of the average Q^2 to $\simeq$1%.
- Develop a plan to reduce the uncertainty in Q_W^p due to target window backgrounds to $\simeq$1%.
- Develop a plan to minimize the uncertainty due to nucleon form factors (*eg*, optimizing the choice of Q^2, extrapolating the HAPPEX, Mainz, and G^0 results

to $Q^2 = 0.03$, or by making a short measurement at higher Q^2 as part of the Q_W^p proposal).

Looking at the list of errors in Table 3 it is clear that the statistical error is presently dominant. The listed errors are goals which we believe are reasonable. If we are successful in reducing the statistical error significantly then we may give more attention to hadronic structure uncertainties.

Table 3: Total error budget for the experiment. Note: a 1% error on the asymmetry due to the uncertainty in beam polarization, for example, yields a 1.4% error in Q_W^p.

Source of error	**Contribution to $\Delta Q_W^p/Q_W^p$**
Statistical error	2.75%
Hadronic structure	2%
Absolute Q^2 determination	1.4%
Beam polarimetry	1.4%
Target window background	1%
Other backgrounds	1%
TOTAL:	4.2%

5 Summary

The Q_W^p collaboration is continuing to improve the reference design, in particular on the outstanding experimental issues mentioned above. To put our experiment in context, the Q_W^p physics asymmetry is slightly smaller than the already approved JLab neutron radius measurement E00-003 (.5 ppm versus .3 ppm) with a similar statistical error of 3%. We are enlarging the collaboration and anticipate submitting a formal proposal to PAC-21 which meets in January 2002. We believe the physics goals to be achievable and highly meritorious of consideration by the Jefferson Laboratory physics community and management.

Acknowledgements

We thank Nathan Isgur, Mark Sher, and Dirk Walecka for their helpful comments and suggestions. This work is supported in part by grants from the National Science Foundation and the US Department of Energy.

References

[1] C.Y. Prescott *et al.*, Phys. Lett. **B77**, 347 (1978).

[2] C.Y. Prescott *et al.*, Phys. Lett. **B84**, 524 (1979).

[3] D.H. Beck and R.D. McKeown, hep-ph/0102334, to appear in Annual Review of Nuclear and Particle Science

[4] D.H. Beck and B.R. Holstein, hep-ph/0102053, to be published in Int. J. Mod. Phys. E

[5] K.S. Kumar and P.A. Souder, Prog. in Part. and Nucl. Phys. **45**, S333 (2000).

[6] C.S. Wood *et al.*, Science **275**, 1759 (1997).

[7] SLAC Experiment E158 (1997), E. Hughes, K. Kumar, and P. Souder, spokespersons.

[8] H.N. Brown *et al.* [Muon g-2 Collaboration], hep-ex/0102017.

[9] S.C. Bennet and C.E. Wieman, Phys. Rev. Lett. **82**, 2484 (1999).

[10] A. Derevianko, "Reconciliation of the measurement of parity-nonconservation in Cs with the standard model," Phys. Rev. Lett. **85**, 1618 (2000) [hep-ph/0005274].

[11] M.J. Ramsey-Musolf, [hep-ph/9903264], to appear in Phys. Rev. C.

[12] TJNAF Experiment E91-010 ("HAPPEX"), P. Souder and J.M. Finn, spokespersons.

[13] TJNAF Experiment E99-115 ("HAPPEX II") K. Kumar and D. Luillitier, spokespersons.

[14] TJNAF Experiment E91-017 ("G^0") D. Beck, spokesperson.

[15] A4 Experiment at Mainz, D. von Harrach, spokesperson.

[16] J. Erler and M.J. Ramsey-Musolf, in preparation.

[17] A. Czarnecki and W.J. Marciano, Int. J. Mod. Phys. A15: 2365 (2000), hep-ph/0003049.

[18] M. J. Musolf et al., Phys. Rep. 239., 1 (1994).

[19] A. Czarnecki and W.J. Marciano, Phys. Rev **D53**, 1066 (1996).

[20] M.J. Ramsey-Musolf, [hep-ph/0003264], to appear in Phys. Rev. C.

[21] W.J. Marciano and A. Sirlin, Phys. Rev **D27**, 552 (1983); **D29**, 75 (1984).

[22] M.J. Musolf and B.R. Holstein, Phys. Lett. **242**, 461 (1990).

[23] “”Basic Design of the “Q-Weak” Experimental Setup”, N. Simicevic, LATECH-CAPS-00-06a.

[24] “Design of a Cerenkov Counter for the “Q-Weak” Experiment”, N. Simicevic, LATECH-CAPS-01-03a.

[25] I. Adam *et al.* SLAC-PUB-7707, November 1997.

[26] G. Rutledge and R. Michaels, “Systematics of Q^2 for HAPPEX”, HAPPEX internal report, available at http://www.jlab.org/ rom .

[27] This section is based on a Qweak collaboration report (including figures) entitled “Asymmetry Contributions from the Aluminum End Windows in QWEAK”, M. Pitt, Virginia Tech, August 8, 2000.

[28] T. Stovall, D. Vinciguerra, and M. Bernheim Nucl. Phys. A **91**, (1967) 513.

[29] T.W. Donnelly, M.J. Musolf, W.M. Alberico, M.B. Barbaro, A. dePace, A. Molinari, Nucl. Phys. A **541**, (1992) 525.

[30] E. Hadjimichael, G.I. Poulis, T.W. Donnelly, Phys. Rev. C **45**, (1992) 2666.

[31] T.W. Donnelly, J. Dubach, I. Sick, Nucl. Phys. A **503**, (1989) 589.

[32] TJNAF Experiment E-00-003, R. Michaels, P. Souder, G. Urciuoli, spokespersons.

[33] K. Pomorski, P. Ring, G.A. Lalazissis, A. Baran, Z. Lojewski, B. Nerlo-Pomorska, M. Warda, Nucl. Phys. A **624**, (1997) 349.

[34] W.M. Alberico, A. Molinari, page 389 of proceedings of the 1997 Paris Parity Violation Workshop

[35] C.J. Horowitz, Phys. Rev. C **57**, (1998) 3430.

[36] M. Hauger *et al.*, "A high-precision polarimeter", nucl-ex/9910013.

[37] Matt Poelker, injector group guru, private communication.

[38] Maud Baylac, These du Diplome de Doctorat, "Mesure de la polarisation du faisceau d'electrons du Jefferson Laboratory par effet Compton pour l'experience de violation de parite HAPPEX en diffusion elastique electron-proton", 2000, unpublished.