THE FIRST DIRECT MEASUREMENT OF THE WEAK CHARGE OF THE PROTON

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APPROVAL PAGE

This Dissertation is submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT PAGE

Qweak is an experiment currently running at the Thomas Jefferson National Accelerator Facility that uses parity-violating elastic electron-proton scattering to measure the weak charge of the proton Q_{weak}^P . Longitudinally polarized electrons are scattered off a liquid hydrogen target and pass through a toroidal-field magnetic spectrometer. This experiment is a sensitive test for physics beyond the Standard Model, as Q_{weak}^P is well predicted in the Standard Model. This dissertation describes the first direct measurement of Q_{weak}^P . The precision that will be generated by the final 4% measurement will allow the probing of certain classes of new physics up to 2.5 TeV. In this dissertation, the design and status of the complete experiment are discussed, including the details of the asymmetry measurements and preliminary results from several studies of experimental systematics. This dissertation also includes a full description of the design, construction, commissioning, and use of the vertical drift chambers (VDC) used in the Qweak experiment to measure the scattered electron's profile and the momentum transfer (Q^2) of the ep scattering. The Q^2 was measured to be 0.0274 $\pm 0.0013 \text{ GeV}^2/c^2$ and Q_{weak}^P was measured to be 0.102 ± 0.036 , which is consistent with the Standard Model.

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CHAPTER 1

Introduction

The Standard Model is a gauge theory based on $SU(3)_c \times SU(2)_L \times SU(1)_Y$ that describes the spontaneous symmetry breaking of the $SU(2)_L \times SU(1)_Y$ groups into the electromagnetic and weak nuclear forces we observe in the universe. The Standard Model of particle physics (SM) has been rigorously tested for over 30 years and has survived as the leading model describing both the strong nuclear force (QCD) and the electroweak forces. Despite its successes, the SM is known to be at a minimum, incomplete. The phenomena missing from the SM include dark matter, dark energy, gravity, etc., all of which are believed to exist, yet are omitted from the SM. The "holy grail" of particle physics is the discovery of "new physics" in the form of new fundamental particles or forces that would prove the SM to be either incomplete or wrong and that would help guide the choice of a more complete theory. The two principle classes of searches for the new physics are conducted using brute force high-energy collisions (TeV scale) or using precision lower-energy probes. The Qweak experiment, the subject of this thesis, follows the latter route, using parity-violating electron-proton (ep) scattering to measure the weak charge of the proton (Q_{weak}^P) . Q^P_{weak} is suppressed (very small in magnitude) in the SM allowing the probing of certain classes of physics at TeV energy scales while using GeV scale scattering because an accurate measurement of a small number is sensitive to small deviations that the new physics would cause. If Q_{weak}^P were larger, it would require an even more precise measurement to have the same new physics reach as the Qweak experiment.

In the Qweak experiment, longitudinally polarized electrons are scattered off a liquid hydrogen target. The electron beam polarization is measured using a Moller polarimeter and a Compton polarimeter. The scattering is elastic at very low 4momentum transfer (Q^2). The elastically scattered electrons are selected using a toroidal-field magnetic spectrometer (QTOR). The Q^2 is measured using pairs of Horizontal (HDC) and Vertical Drift Chambers (VDC) placed before and after QTOR. The primary detector is a Cherenkov detector made of fused silica. The complete apparatus will be described in detail in the Apparatus Chapter. Once the final 4 % precision measurement of Q^P_{weak} is complete, any significant deviation from the SM prediction will indicate new physics [1].

1.1 Brief History of Parity-Violating Scattering Experiments

Parity is a symmetry of nature that causes an object to transform to the mirror image of itself if it undergoes a parity transformation $(x \rightarrow -x, y \rightarrow -y, \text{ and } z \rightarrow$ -z). Parity violation occurs when the mirror image of a particle behaves or interacts differently than the original. Parity violation, predicted by Lee and Yang [2], was first observed by Wu et al. in the famous β -decay of ⁶⁰Co experiment where an asymmetric decay pattern was observed from a polarized nucleus [3]. After decades of theoretical developments, it was discovered that the photon (γ) of electromagnetism and the Z-boson (Z°) of the weak force are linear combinations of more fundamental gauge groups in the Standard Model. The fundamental $SU(2)_L \times U(1)_Y$ representation of the electroweak sector is rotated by an angle, known as the weak mixing angle (θ_w) , into the gauge bosons we observe in our world. The first precise measurement of θ_w came in 1978 at SLAC with E-122 [4]. E-122 was a deep-inelastic electron-deuteron scattering experiment that measured the parity-violating asymmetry to a precision of 10 ppm. Scattering experiments were done on ${}^{9}\text{Be}$ [5] and ${}^{12}\text{C}$ [6] that reduced the uncertainty on the asymmetry to ~ 1 ppm and < 1 ppm, respectively. There were other experiments that used parity-violation to study the structure of the nucleon, more specifically the strange quark's contribution to the nucleon, including SAMPLE [7] at Bates, PVA4 at MAINZ [8] and HAPPEX [9] and G0 [10] at Jefferson Lab (JLab). Fortunately for Qweak, they, including very recent HAPPEX III results [11], have all measured the electric and magnetic strange quark form factors to sufficient precision to properly account for their effects. A more detailed summary may be found here [12]. PVDIS is a JLab experiment that measured parity-violation in deep-inelastic scattering that will reduce the uncertainty on the largely unconstrained vector Z° electron coupling times the axial Z^o-quark coupling and should be published soon. PREX is another JLab experiment that is using parity-violation to map the neutron distribution of Pb. Overall, parity violation has shown itself to be a useful tool to measure a fundamental SM input parameter, measure strange contributions to the nucleon, and map neutron distributions in nuclei.

CHAPTER 2

The Weak Charge of the Proton

This section will begin with the concepts necessary to fully understand the experiment. The electroweak force will be explained in detail along with the key distinction that separates it from the other forces. A brief derivation of the parity-violating asymmetry within the Standard Model will be shown along with the formalism behind it and corrections that will be important for the final measurement.

2.1 Helicity vs. Chirality

To understand parity violation clearly, a few fundamental definitions and parameters must be well understood including parity, helicity, and chirality. Helicity is the simple relative orientation of the spin of a particle to its momentum (*helicity* = $\vec{S} \cdot \hat{p}$) as may be seen in Figure 2.1. A parity transformation is one in which all the spatial coordinates of a particle flip sign (x,y,z) \rightarrow (-x,-y,-z), like a mirror image.



FIG. 2.1: The definition of helicity. The momentum vector of a particle is shown in teal and the spin is shown in blue. If the spin and momentum vectors of a particle are aligned, the particle is known as a right-handed helicity state and similarly if the spin and momentum vectors are anti-aligned the particle is known as a left-handed helicity state.

Chirality is a more subtle concept, a chiral state is one that transforms in a left or right handed representation of the Poincaré group or similarly, a state with an unity eigenvalue when operated on by a definite chiral state operator. The left and right chiral operators are

$$\psi_{R,L} = \frac{1 \pm \gamma_5}{2} \psi \tag{2.1}$$

where ψ is a particle/state, γ_5 is a Dirac matrix, and $\psi_{R,L}$ are the right and left handed chiral states, respectively. For a massless particle, or a massive particle in the ultra-relativistic limit, a definite longitudinal helicity state becomes a definite chiral state, which can be seen by taking the inner product of the helicity eigenvector and the chiral eigenvector for a particle with the appropriate energy. From now on, any particle will be assumed to be ultra-relativistic; therefore, helicity and chirality will be equivalent. So if a longitudinal helicity state is produced and accelerated to the ultra-relativistic limit, a chiral state has been produced and can be used to measure something that is chirality dependent.

2.2 Electroweak Force

There are 4 known fundamental forces in nature: gravity, electromagnetism, strong nuclear, and weak nuclear. Gravity is very familiar but not described by the Standard Model; thus, it is not described here. The strong nuclear force is believed to be governed by quantum chromodynamics and is the source of nuclear energy and nuclear weapons. Electromagnetism is responsible for everything from the power to homes to the attraction and repulsion felt by magnets. The weak nuclear force is not responsible for much in daily human life, with one big exception, the Sun. The weak force is responsible for the reaction that takes 2 hydrogen atoms and creates deuterium, a key step for the fuel for the strong nuclear reactions that keep the Sun fusing hydrogen into helium and releasing energy.



FIG. 2.2: First order (tree-level) electromagnetic and Neutral Weak Feynman Diagrams for ep interaction. The electromagnetic force is mediated by the massless γ and the neutral weak force is mediated by the massive Z^o.

The electroweak force is a unification of the electromagnetic and weak nuclear forces. In the Standard Model, the electroweak force is described by $SU(2)_L \times U(1)_Y$ gauge groups, where L stands for left and Y stands for hypercharge. The γ is the massless mediator of electromagnetism and the Z° is one of the massive mediators of the weak force. The fact that the Z° is massive, rather than massless, causes the weak interaction to occur at higher energy scales than the electromagnetic force; thus, causes the weakness of the weak nuclear force. Table 2.1 contains the Standard Model values of the electric and weak charges of the up and down quarks as well as the neutron and proton. The proton's weak charge $(Q_{weak}^P = 1\text{-}4\sin^2\theta_w \approx 0.07)$ is accidentally suppressed in the SM allowing for the probing of new physics. Note the difference in magnitude of the weak charge of the neutron compared to the proton; any weak force scattering incident on any atom/molecule with neutrons present will be dominated by the signal from the neutrons and is relatively insensitive to Q_{weak}^P . Unlike the strong nuclear and electromagnetic forces, the weak force is stronger/weaker depending on the chirality of the particle feeling the force. A left-handed electron and a right handed electron have an identical electromagnetic coupling constant; however, they have different weak nuclear coupling constants. The difference in coupling constants creates a different cross-section for left or right handed electron scattering.

Particle	Electric Charge (L,R)	Weak Charge (L)
u quark	+2/3	$1 - \frac{8}{3}\sin^2\theta_w$
d quark	-1/3	$-1+rac{4}{3}{ m sin}^2 heta_w$
Proton (uud)	+1	$1-4\sin^2\theta_w$
Neutron (ddu)	0	-1

TABLE 2.1: Electric and Weak Charges of Quarks and Nucleons

2.3 Structure of the Proton

The proton is made of two up and down quarks along with virtual excitation of quark-antiquark pairs and gluons. The two up quarks and the one down quark are known as valence quarks as they are the leading-order contribution to the proton, and the quark-antiquark pairs are known as sea quarks and are almost exclusively uū and dd. Here strange quark effects are ignored as they have been measured to be small in HAPPEX II, G0, PVA4, and smaller still in yet to be published HAPPEX III results [8, 10, 12, 13]. Charm, beauty, and top quark effects are also not considered here as their contributions are insignificant. Form factors are parameterisations of the proton's structure as a function of Q^2 that are discussed further in the following sections. Analogous to the proton, the neutron is composed of two down quarks and one up quark. Charge symmetry, the assumption that the up quark in the proton has the same distribution as the down quark in the neutron, can be used to reduce the number of free parameters in the expressions for Feynman amplitudes in the following sections.

2.3.1 Electromagnetic Form Factors

Electromagnetic form factors are a parameterisation of the leading order electric charge and magnetization structure of the proton which are probed through the electromagnetic interaction via the exchange of a virtual γ . The amplitude of the interaction of the electron with the proton at tree level is

$$\mathcal{M}_{\gamma} = -\frac{4\pi\alpha}{q^2} J^{e\mu} J^p_{\mu}, \qquad (2.2)$$

where α is the fine structure constant, q^2 is the four-momentum transfer squared (using the definition $Q^2 = -q^2$), and $J^{e\mu}$ and J^p_{μ} are the currents of the electron and proton, respectively. The electron has no internal structure; therefore, its current is

$$J^{e\mu} = \bar{u}\gamma^{\mu}u, \qquad (2.3)$$

where \bar{u} is a Dirac spinor of the incoming particle or outgoing antiparticle spinor, u is the outgoing particle or the incoming antiparticle, and γ^{μ} are the standard Dirac

gamma matrices. The proton has internal structure, so the current takes the form

$$J^{p}_{\mu} = \bar{u} \Big[F_{1}(Q^{2})\gamma^{\mu} + iF_{2}(Q^{2})\frac{\kappa}{2M_{P}}\sigma_{\mu\nu}q^{\nu} \Big] u, \qquad (2.4)$$

where F_1 and F_2 are the Q^2 -dependent electromagnetic Dirac and Pauli form factors, respectively, M_P is the mass of the proton, κ is the anomalous magnetic moment of the proton, and $\sigma_{\mu\nu}$ is the standard Dirac algebra sigma. F_1 and F_2 may be rewritten in terms of the Sachs form factors [14] as follows

$$G_E^p(Q^2) \equiv F_1(Q^2) - \tau F_2(Q^2) \qquad \qquad G_M^p(Q^2) \equiv F_1(Q^2) + F_2(Q^2), \qquad (2.5)$$

where $\tau = \left(\frac{Q}{2M_P}\right)^2$. The form factors have a standard normalization to give the expected electric charge and magnetic moment of the proton when $Q^2 = 0$. Experimental values for the Sachs form factors are known to the necessary accuracy to complete a 25 % measurement of Q_{weak}^P [15]. The 4 % measurement of Q_{weak}^P will require a more careful choice of form factor values. The knowledge of the form factors and their relationship to the measurement will be discussed further in Section 2.6.

2.3.2 Neutral Weak Form Factors

Weak form factors are a parameterisation of the leading-order weak charge and structure of the proton when interacting weakly via the exchange of a virtual Z^{o} . The amplitude of the neutral weak interaction of the electron with the proton at tree level is

$$\mathcal{M}_Z = -\frac{G_F}{\sqrt{2}} J^{eZ\mu} J^{pZ}_{\mu}, \qquad (2.6)$$

where G_F is the Fermi constant. The electron's neutral weak current is similar to its

electric current; however, it now contains a parity-violating component and is

$$J^{eZ\mu} = \bar{u} \big[(-1 + 4\sin^2\theta_w + \gamma_5)\gamma^{\mu} \big] u.$$
 (2.7)

The proton has more complex weak internal structure, so the current takes the form

$$J^{pZ}_{\mu} = \bar{u} \Big[F^{Z}_{1}(Q^{2})\gamma^{\mu} + iF^{Z}_{2}(Q^{2})\frac{1}{2M_{P}}\sigma_{\mu\nu}q^{\nu} + \gamma_{\mu}\gamma_{5}G^{e}_{A} \Big] u, \qquad (2.8)$$

where F_1^Z and F_2^Z are the Q^2 -dependent neutral weak form factors, and G_A^e is the axial vector form factor. G_A^e is dependent on different parameters, such as the anapole moment of the proton, which describes the interaction of the virtual photon with quarks that are interacting with each other weakly, as well as higher-order radiative corrections, such as the γZ^o box diagram that will be discussed later.

2.3.3 Charge Symmetry and Form Factors

The electromagnetic and weak form factors can be taken a step further and broken down into contributions from constituent quarks, where effects due to strange or more massive quarks are being ignored as they have been shown to be small. To leading order, the electromagnetic and neutral weak form factors may be written as a linear combination of the valence quarks with the corresponding weighting by the charge of the quarks, as follows:

$$G_E^{\gamma,p} = \frac{2}{3}G_E^u - \frac{1}{3}G_E^d$$
(2.9)

$$G_M^{\gamma,p} = \frac{2}{3} G_M^u - \frac{1}{3} G_M^d$$
(2.10)

$$G_{E}^{Z,p} = \left(1 - \frac{8}{3}\sin^{2}\theta_{w}\right)G_{E}^{u} + \left(-1 + \frac{4}{3}\sin^{2}\theta_{w}\right)G_{E}^{d}$$
(2.11)

$$G_M^{Z,p} = \left(1 - \frac{8}{3}\sin^2\theta_w\right)G_M^u + \left(-1 + \frac{4}{3}\sin^2\theta_w\right)G_M^d.$$
 (2.12)

Charge symmetry in equation form is as follows

$$G_E^{u,p} = G_E^{d,n} \qquad G_E^{d,p} = G_E^{u,n}$$
 (2.13)

$$G_M^{u,p} = G_M^{d,n} \qquad G_M^{d,p} = G_M^{u,n},$$
 (2.14)

where p stands for proton and n stands for neutron. Using 2.14 and 2.14, the neutral weak form factors can be reduced to

$$G_{E,M}^{Z,p} = (1 - 4\sin^2\theta_w)G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n}.$$
(2.15)

Notice the neutral weak form factors have now been expressed completely in terms of the electromagnetic form factors of the proton, neutron, and the weak mixing angle.

2.4 Parity-Violating Asymmetry

The difference in cross-section between scattering of left and right handed electrons from the proton can be exploited to form an interference asymmetry. The cross-section of elastic scattering of longitudinally polarized electrons off an unpolarized proton target can be written in terms of amplitudes (\mathcal{M}) with a L (-) or R (+) indicating the chirality of the incident electron,

$$\sigma_{R,L} = |\mathcal{M}^{\gamma} + \mathcal{M}_{R,L}^Z|^2. \tag{2.16}$$

The full parity-violating asymmetry that can be formed is

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$
$$= \frac{|\mathcal{M}^{\gamma} + \mathcal{M}_R^Z|^2 - |\mathcal{M}^{\gamma} + \mathcal{M}_L^Z|^2}{|\mathcal{M}^{\gamma} + \mathcal{M}_R^Z|^2 + |\mathcal{M}^{\gamma} + \mathcal{M}_L^Z|^2}$$
(2.17)

$$\approx \frac{\mathcal{M}_R^Z - \mathcal{M}_L^Z}{|\mathcal{M}^\gamma|} \sim \frac{Q^2}{M_Z^2}.$$
(2.18)

Equation 2.17 is reduced to Equation 2.18 because left and right electromagnetic scattering amplitudes are equal in the numerator, so they cancel, and the leading behavior is the difference of the cross terms of electromagnetic and weak form factors. In the denominator, the amplitude of electromagnetic scattering is much larger than weak scattering, so the electromagnetic amplitude squared is the leading behavior. Equation 2.18 is the leading order term that is reduced once the electromagnetic amplitude is cancelled on top and bottom, leading to the order of magnitude estimate shown.

 A_{RL} is a function of Q^2 , to leading order, so the smaller the Q^2 , the smaller the asymmetry. The Q^2 in this experiment is $0.026 \text{ GeV}^2/\text{c}^2$ with a corresponding estimated asymmetry of ~ 200 parts per billion (ppb). In order to evaluate A_{RL} , the electromagnetic and neutral weak amplitudes from Equations 2.2 and 2.6 must be inserted into Equation 2.17 yielding

$$A_{RL} = \left(\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right) \frac{\epsilon G_E^{\gamma,p} G_E^{Z,p} + \tau G_M^{\gamma,p} G_M^{Z,p} - \frac{1}{2}(1 - 4\sin^2\theta_w)\epsilon' G_M^{\gamma,p} G_A^e}{\epsilon (G_E^{\gamma,p})^2 + \tau (G_M^{\gamma,p})^2}, \qquad (2.19)$$

where for convenience ϵ and ϵ' have been defined as

$$\epsilon = \frac{1}{1 + 2(1 + \tau)\tan^2\frac{\theta}{2}}$$
(2.20)

$$\epsilon' = \sqrt{\tau(1+\tau)(1-\epsilon^2)},\tag{2.21}$$

and where θ is the lab frame scattering angle. For Qweak the Q^2 is small; therefore, A_{RL} can be taken one step further and expanded in terms of Q^2 as $Q^2 \to 0$ and approximated by $\epsilon \to 1$ and $\epsilon' \to 0$ because of the small scattering angle. The experimental conditions in Qweak turn Equation 2.19 into the following

$$A_{RL} = \left(\frac{G_F}{4\pi\alpha\sqrt{2}}\right) \left[Q_{weak}^P Q^2 + Q^4 B(Q^2)\right]$$
(2.22)

where $Q_{weak}^P = 1 - 4 \sin^2 \theta_w$ is now isolated and $B(Q^2)$ is dependent on the electromagnetic and axial form factors. Equation 2.22 is the heart of the Qweak experiment, illustrating that if the experiment can measure A_{RL} (background corrected) and Q^2 and use previous experiments to evaluate $B(Q^2)$, it is only simple algebra to extract Q_{weak}^P . The equation also demonstrates that the approach works well only at low Q^2 ; if the Q^2 was large, $B(Q^2)$ would be the dominant term, and Q_{weak}^P would be more difficult to extract and would require even more precise knowledge of $B(Q^2)$.

2.5 Radiative Corrections

The Feynman diagrams seen in Figure 2.2 are only the leading-order terms in the parity-violating electron-proton scattering amplitude. Radiative corrections are the collective term used to describe higher-order corrections to tree level diagrams. Loop and box diagrams are functions of Q^2 and contribute to scattering amplitude calculations also as a function of Q^2 , just at smaller levels than single particle exchange diagrams. The Q^2 of Qweak is small enough that single loop and box diagrams are the highest order necessary to include; higher order than single loop corrections are not large enough to contribute to the scattering amplitude in a significant way. For the 25% measurement of Q^P_{weak} discussed here, the statistical error will be much larger than the contributions of any such radiative corrections. Radiative corrections are discussed here because they will be very important for the 4% measurement of Q^P_{weak} . Two examples of radiative corrections are seen in Figure 2.3. There are additional corrections, such as loop diagrams and simple single real γ production, that will not be discussed.

The γZ box diagram seen in Figure 2.3 is the radiative correction that was a large concern for the collaboration for a period of time when the uncertainty of the correction was estimated to be large. The γZ diagram is the exchange of both a photon and a Z° between one electron and one proton. A large correction is not a problem, so long as the uncertainty on the correction is small. At one point, the calculation was performed; the result was a large correction with a large uncertainty $(\sim 6 \pm 6)\%$ on the correction [16]. The current status of the calculation is that size of the correction is agreed upon by several groups [17], [18] and the uncertainty on the correction $(\sim 6 \pm \sim 0.8)\%$ is now more manageable [19].

The γZ box diagram will be a ~6 % correction but will not be a problem because of the theoretical advances made along side the experimental advances necessary to complete the experiment. Two- γ box diagram along will also be a significant correction, but with well understood and small uncertainties. Overall, all known contributing diagrams have been calculated and have theoretical uncertainties that are smaller than the proposed statistical uncertainties on the measurement of Q_{weak}^P .



FIG. 2.3: Two examples of radiative corrections to parity-violating electron-proton scattering. The first diagram is two-photon exchange and the second is the γZ box diagram where cross-diagrams are implied [20].

2.6 World Data

There have been numerous parity-violation experiments that have already been completed, without which Qweak would not be as meaningful theoretically or possible experimentally. There are different ways to look at the current world data and to look at the future impact of Qweak, both in terms of fundamental Standard Model parameters, quark charges, or the parity-violating asymmetry itself.

The field of parity-violating electron scattering took off with 3 large experiments: E122 at SLAC [21], the ⁹Be experiment at Mainz [5], and the ¹²C experiment at MIT-Bates [6]. E122 was a deep-inelastic electron-deuteron experiment that took place at SLAC. The experiment used 16 GeV to 22 GeV polarized electrons incident upon a liquid deuterium target and produced an asymmetry measurement with an uncertainty of 10 parts per million (ppm) and was the first precise measurement of $\sin^2 \theta_w$. The ⁹Be experiment at Mainz was a quasi-elastic scattering experiment that used 0.3 GeV polarized electrons incident upon a solid ⁹Be target and achieved an uncertainty of ~ 1 ppm on the asymmetry. The ¹²C experiment at MIT-Bates was an elastic scattering experiment that used 0.25 GeV polarized electrons incident upon



FIG. 2.4: Current world data on the running of $\sin^2 \theta_w$ vs. momentum transfer in the modified minimal subtraction scheme (\overline{MS}) [22] coming from atomic parity-violation (APV) [23], E158 [24], Z-pole measurements Z° [25], NuTeV [26], and the Tevatron [27]. The Qweak experiment is shown at an arbitrary location with expected error bars shown in red. The blue line is the "running" of $\sin^2 \theta_w$ as predicted in the Standard Model.

The most important parameter being studied is the weak mixing angle (θ_w) which is usually expressed as $\sin^2 \theta_w$. As stated previously, when electroweak symmetry breaking occurs the $SU(2)_L \times U(1)_Y$ gauge groups describing the electroweak force are rotated (broken) by the angle θ_w into the combination of massive and massless particles we observe in nature. Q_{weak}^P is directly related to $\sin^2 \theta_w$ in the Standard Model; therefore, if the Standard Model is correct, as Q_{weak}^P is measured, $\sin^2 \theta_w$ is also measured.

Select current world data on $\sin^2 \theta_w$ is shown in Figure 2.4 with the primary constraints coming from atomic parity-violation (APV) experiments done on cesium [23], the Moller scattering experiment E158 done at SLAC [24], several measurements done at the mass of the Z° (" Z° pole") [25] and the NuTeV experiment [26], each of which will be briefly discussed below. All of the world data agrees with the Standard Model, with the original exception of NuTeV which is discussed below. Qweak's anticipated smaller uncertainty will reduce the uncertainty in $\sin^2 \theta_w$ as is seen in the plot.

APV uses a laser incident on a gaseous atom (Cs) to look for transitions to occur that are only possible through weak interactions [23]. Atoms are pumped to a specific state where a transition to a state is forbidden without a weak interaction. Once the forbidden state is populated, it decays, emitting a photon, that is then counted. The amount of weak transitions that occur is proportional to the weak coupling. The major drawback of APV is the atomic many-body theory required to extract $\sin^2\theta_w$ from the transition rate measurements is quite complex.

E158 is similar to Qweak; however, at higher energy (45 GeV) where the apparatus was tuned to measure electron-electron Moller scattering with a copper and fused silica sandwich detector, rather than *ep* scattering as in Qweak [24]. The big advantage to *ee* scattering over *ep* scattering is that the electron is a fundamental particle, not a composite particle, so there is no hadronic structure to complicate the interpretation of the result. The experiment also used a half-wave plate to flip the electron beam's polarization slowly and flipped the electron polarization quickly using a Pockels cell, both of which techniques are incorporated into the Qweak experiment.

NuTeV was an experiment that used neutrino and antineutrino beams incident

on a steel target where both weak neutral and weak charged current interactions can occur. The measurement is essentially the ratio between the cross sections of weak neutral to weak charged currents, where the use of neutrino and antineutrino beams allow for the cancellation of some systematic uncertainties. The NuTeV result has been a source of controversy in the field as their original result from a blind analysis was 3 σ away from the Standard Model prediction. A blinded analysis is one in which the number being measured is altered by a small hidden constant that is later removed in order to prevent steering the result toward a preconceived result. This 3 σ result became a 1 σ (see Figure 2.4) result after further theoretical analysis (charge asymmetry effects, nuclear asymmetry effects, and strange quark asymmetry effects), external to the collaboration, was completed [28]. Overall, the NuTeV result remains a question in low-energy Standard Model tests.

SAMPLE was an experiment that took place at MIT-Bates that measured the parity-violating asymmetry from hydrogen and deuterium targets using backward electron scattering and a beam energy of 200 MeV using a Cherenkov detector in air [7]. HAPPEx was a series of experiments that took place at JLab that measured the parity-violating asymmetry from hydrogen and ⁴He at a beam energy of \sim 3 GeV using forward electron scattering and two large precision spectrometers [9]. G0 was an experiment that took place at JLab that measured the parity-violating asymmetry form hydrogen and deuterium using forward (at a beam energy of 3 GeV) and backward (at 362 and 687 MeV) electron scattering, using a custom spectrometer [10]. PVA4 was an experiment that took place at Mainz that measured the parity-violating asymmetry of hydrogen and deuterium using forward and backward electron scattering at various beam energies using a custom calorimeter [8].

A different way to view the ep parity-violating data is to look at the parityviolating asymmetry of the proton as a function of Q^2 as $\theta \to 0$, as seen in Figure

2.5. Qweak is not shown on the plot and will be located at $Q^2 = 0.026 \text{ GeV}^2/\text{c}^2$. The fit to all parity-violating electron-scattering data agrees with the Standard Model prediction when extrapolated to $Q^2 = 0$.



FIG. 2.5: Current world data on the parity-violating electron-scattering asymmetry of the proton in the low- Q^2 region with its extrapolation to $Q^2 = 0$ [29]. The Standard Model value is shown by the red star, the blue line with light blue error bars are the best fit to all parity-violating electron-scattering data. The dashed line is the fit including theoretical estimates of the anapole form factors [30]. Prior to the results of these parity-violating electron scattering experiments, the world knowledge of Q_{weak}^P was in orange. The result, incorporating all the parity-violating electron-scattering, agrees with the Standard Model to 1 σ .

Yet another way to look at parity-violating neutral current data is using the constants $C_{1u(d)}$ [31] which are defined by

$$\mathcal{L}_{NC}^{eq} = \frac{-G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q} \gamma^\mu q \qquad (2.23)$$

where the sum is over the contributing quarks. C_{1u} and C_{1d} are the weak charges of the up and down quarks, respectively. The combination of $C_{1u} + C_{1d}$ vs. $C_{1u} - C_{1d}$ is plotted in Figure 2.6. The currently allowed area is shown in the small green oval, which is primarily defined by the APV and the parity-violating electron scattering data, with the Standard Model shown as a black star. Qweak will greatly reduce the phase space with the full 4 % measurement (shown with expected uncertainty at an arbitrary location), but even the 25 % measurement (not shown) will reduce the phase space.



FIG. 2.6: Isoscalar vs. isovector combinations of the weak charges of the up and down quarks. The modern limits are set by APV and parity-violating electron scattering and lie within the small green oval [29]. Qweak is shown (thin dark blue band) located at the Standard Model values with expected final uncertainty. The experiments shown are E158 [24], Mainz ⁹Be [5], Bates ¹2C [6], APV Cs [23], and APV Tl [32].

2.7 Physics Beyond the Standard Model



FIG. 2.7: Limits on certain classes of new physics set by Qweak. A is the mass scale at which new parity-violating physics could exist, g is the coupling constant of the new physics, the ratio of the two is the model-independent mass limit of new physics, and θ_h is the flavor mixing angle of new physics. Current limits are defined from APV are set in red, parity-violating electron scattering in blue, and future Qweak (4%) limits are shown in green [29].

Qweak will reduce the phase space shown in Figure 2.6, and in doing so, will effectively probe energy scales for certain classes of new physics up to ≈ 4 TeV as seen in Figure 2.7. When Q_{weak}^P is measured, any deviation from the Standard Model prediction will indicate the presence of new physics at the TeV scale. The 25% measurement of Q_{weak}^P does not have the resolution to search for new physics that the 4% measurement will have. The area encompassed below the green line and above the blue and red lines is the area that Qweak will be able to hunt for new fundamental particles and forces. Examples of possible new physics that the final result is sensitive to include leptoquarks, Z' bosons, RPC Supersymmetry (SUSY) or RPV SUSY [33]. Leptoquarks are mediating particles that would allow the quarks and leptons to exchange lepton/baryon number with each other and become different particles. Z' bosons are generic neutral weak or new neutral force mediators. Either of the SUSY models would have loop corrections that would be observable; a few examples are shown in Figure 2.8. One class of new physics can be expressed as a contact interaction of the form

$$\mathcal{L}_{NP}^{eq} = \frac{g^2}{4\Lambda^2} \bar{e}\gamma_\mu \gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q, \qquad (2.24)$$

where g is the coupling of the new physics, Λ is the energy scale at which the new physics exists, and h_V^q is the effective coefficient of the new physics defined by setting the isospin dependence $h_V^u = \cos \theta_h$ and $h_V^d = \sin \theta_h$ [29,33].



FIG. 2.8: Potential SUSY loops that could be seen by the Qweak experiment [33]. Loops made of (a) charginos (χ^+) and sneutrinos (ν),(b) sleptons (L) contributing to γ -Z mixing, and (c) box graph containing neutralinos (χ^0), sleptons, and squarks (U) [33].

Overall, Qweak has great discovery potential only because of a strong history of other parity-violating experiments at JLab and around the world. Current and past parity-violating electron scattering has and will to continue to be a powerful tool to search for new physics in the realm that used to only be possible with the highest energy colliders.
CHAPTER 3

Apparatus

The Qweak experiment consists of almost an entirely new custom apparatus. Hall C at Jefferson Lab was cleared of nearly everything including the beamline entering the hall. There is a new Compton polarimeter, a new high-power liquid hydrogen target, a new toridal-field magnetic spectrometer, new radiation-hard quartz primary detectors, new horizontal and vertical drift chambers, new luminosity monitors, new beamline, and new collimators; each of which will be described in detail in this chapter.

3.1 Measurement Overview

The Qweak collaboration is measuring the asymmetry formed between cross sections of left- and right-handed longitudinally polarized electrons,

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto Q_{weak}^P.$$
(3.1)

To begin, the electrons are incident on a liquid hydrogen target. The polarization is

flipped at a pseudo-randomly selected pattern of quartets (pattern of 4 helicity states) at 240 Hz which is a flip speed from helicity state to helicity state of 960 Hz in order to reduce the effect of a number of systematic parameters, such as target density fluctuations, that may change when the measurement is being made. A cutaway schematic of the apparatus is located in Figure 3.1.



FIG. 3.1: Schematic of the Qweak tracking system consisting of HDCs, VDCs, high gain bases on the photomultiplier tubes of the primary quartz detectors, luminosity monitors, and the scanner.

Data are taken in the experiment in two different modes: high current or integrating mode and low current or counting/tracking mode. Integrating mode takes place at beam currents of $\approx 165 \ \mu$ A and the signals for the detectors used (primary quartz detector, up and downstream LUMIs, focal plane scanner (detector counted, not integrated), BPMs, and BCMs) are integrated over a helicity window. As was shown in Equation 2.22, the asymmetry is expanded in terms of Q^2 ; therefore, Q^2 must be accurately measured. The Q^2 is measured using the tracking system and takes place at beam currents of 50 pA to 100 nA. The signals from the detectors used (primary quartz detectors, region 2 horizontal drift chambers (HDCs), region 3 vertical drift chambers (VDCs), up and downstream LUMIs, focal plane scanner, and trigger scintillator) are all measured on an event by event basis from a single trigger (usually provided by the trigger scintillator). The only devices capable of working in both modes are the primary quartz detector, the luminosity monitors, and the scanner, and these are discussed further in Sections 3.4.3, 3.4.5, and 3.4.9, respectively.

3.2 Thomas Jefferson National Accelerator Facility

The Thomas Jefferson National Accelerator Facility (JLab) is a continuous-wave electron beam facility capable of delivering a current of up to 280 μ A total to 3 different halls (Hall A, Hall B, Hall C) with energies up to 6 GeV [34]. A full schematic of JLab is shown in Figure 3.2. JLab is a user-based facility supported by the Department of Energy. The acceleration is done by straight linear accelerators (LINACs) that increase the energy by up to 580 MeV per side, 1160 MeV total per loop. Once through both sets of LINACs, the beam can be delivered to an experimental hall or recirculated up to a total of 5 times. Polarization of up to 89 % can be delivered either longitudinal, as is the case for Qweak, or transverse to the beam's direction, and the polarization can be reversed or flipped at a rate of up to 960 Hz. The high (960 Hz) flip rate is a first for the lab, and was implemented specifically for Qweak. The beam is provided 24 hours a day, 7 days a week, for approximately 9 months a year, the remaining 3 months are devoted to maintenance and the installation of future experiments.



FIG. 3.2: Schematic of the accelerator complex at JLab, starting at the injector and ending at the experimental halls [34].

3.2.1 Injector

The injector is defined as the set of systems which provide everything from electron production to their acceleration to ≈ 60 MeV, before they make it to the LINACs. Electron production begins with a linearly-polarized laser beam that uses a Pockels cell which takes linearly-polarized photons and turns them into circularly-polarized photons. The cell is a birefringent piezoelectric crystal that changes its optical properties based on the high voltage (HV) placed on the cell. The HV is flipped between \approx -2500 V and \approx 2500 V at a rate of 960 Hz including a settle time between flips of 110 μ s (a settle time of 70 μ s but with an additional 40 μ s of time where data is not recorded). The settle time is necessary for the crystal structure to return to a stable state after a HV change. The impact of the flipping is that the polarization of the photon beam, which is responsible for the polarization of the electrons, is changed 960 times per second; however, with the high reversal rate, there is 110 μ s out of each 1042 μ s window, or 10.6%, dead-time that is lost due to settle time when data is purposely not taken. The polarization flipping at a rapid rate minimizes the effect of any slow changes in beam properties to help ensure the measured asymmetry contains as few systematic uncertainties as possible.

Once there is either a left or right circularly-polarized photon, it is incident on a strained GaAs crystal [35]. The photons optically pump the crystal and cause the subsequent excitation/ejection of electrons in a definite left- or right-handed helicity state, as is seen in Figure 3.3. The GaAs crystal is doped with Cs in order to cause the ejected electrons to only have a few meV of energy. The electron is then accelerated by a 130 kV potential between two plates. Everything from the GaAs crystal to the 130 kV acceleration is known as the "electron gun".

There are several features of the injector that are introduced in order to minimize helicity-correlated changes in beam properties during the electron production process. Before the laser is incident on the Pockels cell, there is an insertable half-wave plate, the first slow polarization flipping device, that can flip the linear polarization of the laser by 180°; thus, taking what would have been an eventual left-handed state and producing a right-handed state and vice versa for a right-handed state.



FIG. 3.3: Diagram of the energy levels present in the GaAs crystal, where the excitation is only possible with left or right circularly polarized photon as indicated by solid or dashed lines, respectively [36]. Once the crystal becomes strained, as it is in the injector, the degeneracy of the $P_{\frac{3}{2}}$ state is broken and the transition from $m_j = \pm \frac{1}{2}$ is removed. One helicity state is produced from the excitation to, and subsequent emission from, $m_j = \frac{1}{2}$ and the other helicity state is produced from the excitation to, and subsequent emission from, $m_j = -\frac{1}{2}$.

The other slow polarization flipping device is called a Wein Flipper. Where the half wave plate flips the polarization of a photon that causes the eventual flipping of the state of an electron, the Wein flips the polarization of the actual electron [37]. The Wein Flipper consists of two Wein Filters with two solenoids in the middle. The first filter rotates the electron's polarization by 90° to transverse polarization in the vertical direction. The solenoids then rotate the orthogonal polarization from vertical to horizontal. The final Wein rotates the electron's polarization so that it is longitudinal once it reaches the experimental halls, for a total rotation of 180° from the electron's original polarization, thus flipping the helicity of the electron beam. Throughout this experiment, the half wave plate is inserted or removed approximately once every 8 hours as it only takes a few minutes to complete. The Wein takes several

hours to change and is done approximately once every week. Both the half-wave plate and Wein flip are done in order to cancel the effect of helicity-correlated beam properties.

There are several other, more subtle techniques used to reduce the helicitycorrelated changes in the beam properties that include charge feedback, Pockels cell alignment, and adiabatic damping. The number of electrons produced in each individual + helicity state needs to be as close as possible to the number of electrons produced in each individual - helicity state, as to not create a false asymmetry. We actively feedback on the charge in a helicity state by measuring the integrated charge in a helicity state and then slightly altering the Pockels cell voltage to produce more or less electrons in the lacking state. The Pockels cell can also introduce a false asymmetry based on where the laser enters/exits the crystal. Proper alignment of the Pockels cell is essential in order to minimize the impact of piezoelectric and polarization effects that can lead to false asymmetries when the Pockels cell high voltage is reversed. The third technique is a byproduct of a proper energy/position setup in the machine and is known as adiabatic damping. When a bunch of electrons is accelerated through the LINACs, as long as the spatial and energy distribution is small, the bunch will be compressed; thus, reducing the possibility for a helicity-correlated property to exist.

3.2.2 Beam Current

The beam current is set using two separate devices; the first is the laser attenuator and the second is the chopper slit. Each device uses a different method to achieve the same eventual goal. The beam current is proportional to the intensity of the laser light that is incident on the crystal. The attenuator changes the beam current by increasing/decreasing the intensity of the light incident on the GaAs crystal. The chopper slit is a V-shaped slit which reduces the number of electrons by collimating some of the beam away as the slit is opened or closed. For high (μ A) current running the slit is completely open and the current is defined by the attenuator alone. For low (nA-pA) beam current the laser attenuator is turned down and the slit is closed, with the current being defined by the combination of the attenuator and the slit.

3.2.3 Beam-line

There are two main kinds of devices that noninvasively measure the beam's position and current, known as beam position monitors (BPMs) and beam current monitors (BCMs), respectively. Both devices are actively read out by the data acquisition (DAQ) system and both work with currents as high as JLab can deliver, and currents down to tenths of μ A. Each are used as diagnostics while the beam is tuned to maintain approximately the same position and current as time passes and their data are archived to watch long-term trends and to be available to help diagnose problems when they arise.

BPMs monitor the beam's position in numerous places from the injector all the way to the hall. One type of BPM consists of a set of 4 RF antennas that are parallel to the beam-line and are evenly spaced azimuthally around the beam-line. The signal in each antenna is proportional to the beam current and the distance between the beam and the antenna, by comparing the signals from the antennas the position can be determined.

The BCMs monitor the beam's current in a few places from the injector all the way to the hall. The standard BCMs consist of a pair of temperature-controlled RF cavities with a probe inside built to be coupled to a resonant mode of the cavity. As the beam passes through the cavity a transverse electromagnetic mode is excited that is then sensed by the field probe. The size of the excitation is then proportional to the beam current.

3.3 Polarimetry

The beam polarization is one of the most important parameters of the entire experiment. The polarization is measured using two devices: an invasive Moller polarimeter and a noninvasive Compton polarimeter. The error budget for polarimetry for the 4% measurement of Q^P_{weak} is 1%. For the purposes of this 25% measurement, the only device used to measure the beam polarization is the Moller polarimeter. The Compton polarimeter will be discussed as well, as it is part of the 4% measurement.

3.3.1 Moller Polarimeter

The Moller polarimeter is a device that is able to measure electron beam polarization via the process of $\vec{e} + \vec{e} \rightarrow e + e$ scattering [38]. The Hall C Moller polarimeter is a device that has been used in previous experiments, but was reconfigured for Qweak and is depicted in Figure 3.4. The polarimeter consists of a pure Fe foil target that is polarized using a 4 T superconducting solenoid along with a series of collimators and detectors to measure the scattered electrons. The Moller requires a maximum of 1 μ A of beam current and for the Moller target to be inserted into the beam path, so the measurement is completely invasive to production running.

The cross section for Moller scattering between a longitudinally polarized beam and a polarized (parallel to beam line) target in the center of mass frame is

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_o}{d\Omega} \left[1 + P_t^{\parallel} P_b^{\parallel} A_{zz}(\theta) \right], \qquad (3.2)$$

where P_b^{\parallel} is the polarization of the beam, P_t^{\parallel} is the polarization of the target, and the

unpolarized cross section $\left(\frac{d\sigma_o}{d\Omega}\right)$ and analyzing power $(A_{zz}(\theta))$ at these energies are

$$\frac{d\sigma_o}{d\Omega} = \left(\frac{\alpha(4-\sin^2\theta)}{2m_e\gamma\sin^2\theta}\right)^2 \quad \text{and} \quad A_{zz}(\theta) = -\sin^2\theta \frac{8-\sin^2\theta}{(4-\sin^2\theta)^2} \tag{3.3}$$

where θ is the scattering angle and γ is the standard Lorentz factor [38]. The cross section and analyzing power are maximized when $\theta = 90^{\circ}$. One difficulty with the Moller is that only 2 of the 26 electrons in the Fe target are polarizable, resulting in a total target polarization of only ~ 8%. Using Equation 3.2, the beam polarization can be formed by creating an asymmetry between cross-sections of parallel $\left(\frac{d\sigma^{\uparrow\uparrow}}{d\Omega}\right)$ and anti-parallel $\left(\frac{d\sigma^{\uparrow\downarrow}}{d\Omega}\right)$ target spins of

$$\epsilon = \frac{\frac{d\sigma^{\uparrow\uparrow}}{d\Omega} - \frac{d\sigma^{\uparrow\downarrow}}{d\Omega}}{\frac{d\sigma^{\uparrow\uparrow}}{d\Omega} + \frac{d\sigma^{\uparrow\downarrow}}{d\Omega}} = A_{zz}(\theta) P_t^{\parallel} P_b^{\parallel}.$$
(3.4)

When the Moller beam polarization measurement is typically made, the insertable half wave plate is inserted, resulting in the flipping of the sign of Equation 3.4. The measurement is made before and after a flip to ensure that there is no false polarization offset and that the polarization flips sign, but keeps approximately the same value.



FIG. 3.4: Diagram of the Moller polarimeter used in Hall C to measure the polarization of the electron beam [38]. Q1 is a quadrupole magnet used to focus the scattered electrons in the horizontal plane and Q2 is a quadrupole magnet rotated by 90° to defocus the scattered electrons in the horizontal plane and into the detectors. An event is recorded when there is a coincidence between both detectors.

3.3.2 Compton Polarimeter

The Compton polarimeter is a device that is able to noninvasively measure electron beam polarization via the process of $\vec{e} + \vec{\gamma} \rightarrow e + \gamma$ scattering. The Hall C Compton polarimeter is a device that was built specifically for Qweak, but will be upgraded for use in the 12 GeV physics program, and a schematic may be seen in Figure 3.5. The polarimeter consists of 4 dipole magnets to bend the beam through the Compton chicane, a 532 nm 10 W continuous wave green laser, a Fabry-Pérot cavity to increase the photon density where the electron and photon beam meets (details on a similar Compton polarimeter using a Fabry-Pérot cavity can be found here [39]), a half wave plate to produce circularly polarized photons, a photon detector, and an electron detector. The interaction region is in an area where the laser and electron beams are almost parallel and can intersect to create Compton scattering. The beam polarization is measured by backscattering a photon off the incoming electron and measuring the resulting asymmetry in the yield for different polarization states, using either the scattered photon or scattered electron to determine the yield.



FIG. 3.5: Diagram of the Compton polarimeter used in Hall C to noninvasively measure the polarization of the electron beam. D1-D4 are dipole magnets used to bend the beam into and back out of the Compton chicane interaction region. The polarization is measured using two separate detectors: an electron detector and a photon detector.

The Compton includes two different detectors, the electron and photon detectors, that run independently to have a redundant system capable of making two independent measurements of the same beam polarization. The photon detector is still in development and several types of crystals have been tried, including an undoped CsI crystal. The crystal is then connected to a photomultiplier tube that measures the energy of the back scattered photons between 10 MeV and 50 MeV. The photon detector located in downstream of the interaction region in z as seen in Figure 3.4, because the photon's energy is so small relative to the electron beam's energy that the most likely scattering is 180° backwards. The electron detector is a diamond strip detector consisting of 4 planes of 96 individual strips with a 200 μ m pitch that measures the position of the scattered electron. An electron that was hit by a photon will have slightly less (10 MeV to 50 MeV) energy than the rest of the electron beam. Both Compton scattered and unscattered electrons are then bent by D3 as seen in Figure 3.4 where the Compton electrons are bent slightly more because of their smaller energy. The Compton edge is the edge of the Compton scattered electron distribution once separated by a dipole. The combination of the known magnetic field of D3 and the absolute position of the electron detector are used together to determine the scattered electron's energy. For the Qweak experiment, with a beam energy of 1.165 GeV, the Compton edge is located 23 mm from the electron beam; therefore, the electron detector must be very radiation hard as it sees ≈ 2.5 kRad/hour of background radiation.



FIG. 3.6: Longitudinal asymmetry for Compton scattering of electrons with an incident energy of 1.165 GeV vs. scattered photon energy for 3 different laser wavelengths [40].

The cross section for Compton scattering between a longitudinally polarized electron beam and a circularly polarized photon beam is given by

$$\frac{d\sigma}{d\rho} = \frac{d\sigma_{\circ}}{d\rho} \Big[1 + P_t^{\parallel} P_{\gamma}^{\parallel} A_z(\rho) \Big], \qquad (3.5)$$

where P_{γ}^{\parallel} is the polarization of the photon beam, ρ is the scattered photon's energy normalized to the maximum photon energy, $A_z(\rho)$ is the known asymmetry of parallelantiparallel polarized $e\gamma$ scattering, and $\frac{d\sigma_o}{d\rho}$ is the unpolarized cross section, with the crossing angle of the photon beam and the electron beam being approximated to be 0° . The asymmetry (or analyzing power) A_z is given by

$$A_{z} = \frac{1}{\left[\frac{\rho^{2}(1-a)^{2}}{1-\rho(1-a)} + 1 + \left(\frac{1-\rho(1+a)}{1-\rho(1-a)}\right)^{2}\right]} (1-\rho(1+a)) \left[1 - \frac{1}{(1-\rho(1-a))^{2}}\right].$$
 (3.6)

Equation 3.6 has a maximum when $\rho = 1$ (scattered photon's energy is at its maximum) and vanishes when $\rho = 0$ (there is no energy in scattered photon) and when $\rho = \frac{1}{1+a}$ [38]. The full behaviour of A_z vs. the scattered photon's energy at E = 1.165 GeV for 3 laser wavelengths may be seen in Figure 3.6. The benefit of the shorter wavelength is clear, as A_z grows as the wavelength shrinks, and the larger asymmetry is easier to measure than the smaller asymmetry. The disadvantage of the UV laser comes in its alignment. The Compton polarimeter contains a complex grid of optical components that must be precisely located in order for the laser to "lock" and create a resonance in the cavity. This alignment is done largely by hand; therefore, a green laser was chosen because it is visible by eye, so when a mirror is moved the result is seen by eye.

Overall, the Compton polarimeter was still in development for the 25% measurement of Q^P_{weak} but will play a crucial role for the 4% measurement, as it should provide an accurate, continuous, and noninvasive measurement of the electron beam's polarization.

3.4 Qweak Apparatus



FIG. 3.7: Qweak apparatus, showing all detectors, the target, QTOR, and the full support structure for Qweak with all shielding removed. The beam originates from the left and first passes by the Compton and Moller polarimeters that are not shown. The beam then strikes the Hydrogen target inside the red rectangular box on the yellow pole. The scattered electrons pass through 3 collimators when the elastically scattered electrons are selected and bent by the large toroidal field magnetic spectrometer (QTOR) shown in white into the primary detectors shown in blue. There are two sets of drift chambers that are inserted into the scattered beam path immediately proceeding and following QTOR. There are also luminosity monitors (LUMIs) shown at the far right surrounding the dark blue beam pipe.

The entire Qweak apparatus is custom for the measurement of Q_{weak}^P and may be seen in Figure 3.7. Each component will be described in the following sections.

3.4.1 Liquid Hydrogen Target



FIG. 3.8: Qweak Target Loop. Complete Qweak target loop showing cryogenic connections at the top in orange, the impeller pump shown in silver in the middle, the heat exchanger in orange in on the left middle, the heater shown in magenta on the middle right and the LH_2 cell shown in silver at the bottom [41].

The target used for Qweak is a 2500 W, 35 cm long liquid hydrogen (LH₂) target capable of absorbing the heat deposited from 180 μ A of 1.165 GeV electrons rastered in a 4x4 mm square [41]. This target is currently the world's highest power cryogenic target. The target contains 65 l of LH₂ at 20 K being actively circulated around a closed loop by a custom impeller pump that was derived from an automotive turbo charger.



FIG. 3.9: Qweak Target Cell. The cell where the electron beam impacts the LH2 is the yellow cone in the center where the beam starts in the upper right and exits in the lower left [41]. The LH2 flow is from lower right to upper left, perpendicular to the motion of the beam.

The target cell was designed using computational fluid dynamics using the software package ANSYS FLUENT and the final design is shown in Figure 3.9 [42]. The flow of LH2 is simulated in Figure 3.10. The flow is forced to be high near the entrance window as the largest amount of heat is deposited by the beam in the entrance window; thus, high flow will limit any gaseous film build up on the window. The 2500 W of heat dissipating power comes through a complex heat exchanger. There are 4 K and 15 K liquid helium coolant lines that are woven through a web of thermal connections to lower the temperature of the LH2 by ≈ 0.25 K from the beginning to the end of the heat exchanger. 1 Kg/s of LH2 flows through the heat exchanger and the rest of the target loop. There is also a heater that serves as the replacement heat source if the beam is off.



FIG. 3.10: Qweak Target Flow Simulation. Simulation (using ANSYS FLUENT) of the flow of LH2 through the cell, where the beam starts at the bottom and exits on the top [41]. Areas of high flow are shown in red and low flow shown in blue. The LH2 flow is from right to left, perpendicular to the motion of the beam.

The true test of the target comes in studying its boiling or resistance to boiling. If the target is actively boiling, the density of the target would be changing on a time scale that would alter scattering rates and create noise in the asymmetry measurement. The basic idea behind a target boiling study is to carefully add/remove some design feature that was designed to minimize target boiling. There are numerous controllable factors that contribute to target boiling such as raster size, beam current, and pump speed. The results of one of many target boiling study may be found in Figure 3.11 where the pump speed was decreased, causing reduced LH_2 flow on the target windows, thus, inducing boiling. Overall, all of the design features introduced to mitigate target boiling are all working as planned.



FIG. 3.11: Plot of target noise (boiling) vs. circulation pump speed. The target noise is defined as the difference (subtracted in quadrature) in the width of the measured asymmetry when the target is at nominal settings and the width of the measured asymmetry when the target is at the less than nominal test setting.

There is also a solid target ladder above the LH2 cell, containing Aluminum, Carbon, and Beryllium targets of different thicknesses, shapes, and positions. The solid targets are used for various background and calibration measurements. The target has been largely successful with stable temperatures and no major leaks after the commissioning period in the fall of 2010.



FIG. 3.12: QTOR - Qweak's toroidal field magnetic spectrometer (01/21/2010). QTOR is used to azimuthally expand and radially compress the elastic beam profile onto the primary quartz detector, while removing lower energy Moller-scattered electrons and electrons from inelastic scattering.

QTOR is Qweak's 8-sector toroidal field magnetic spectrometer and is shown in Figure 3.12. A close up picture of the inside of QTOR showing the winding of the copper conductor and the two layers present on the coils is located in Figure 3.13. QTOR is a resistive magnet that bends elastically scattered electrons with a momentum of ≈ 1.165 GeV/c from a scattering angle of 8° to an angle of 21°. The required field integral is $\int \vec{B} \cdot d\vec{l} = 0.89$ T·m [43]. The spectrometer serves the primary purpose of focusing the elastically scattered electrons onto the primary quartz detectors while diverting inelastic electrons and other background particles away from the primary quartz detectors.



FIG. 3.13: QTOR's copper coils up close. The location of the coils where the two layers meet, as well as the winding, are all visible.

The azimuthal field produced by QTOR can be seen in Figure 3.14. The field rejects any particle with low energy (e.g. Moller-scattered electrons) while inelasticallyscattered electrons have slightly less energy than the elastic electrons, so they are swept just off the outer edge of the primary quartz detectors. The simulated effect of elastically-scattered, inelastically-scattered, and Moller-scattered electrons is depicted in Figure 3.16. The combination of fields shown in Figure 3.14 creates, not only an energy separation, but a radial focusing and an azimuthal defocusing. It is also important to notice that there should be no field at R = 0, so the unscattered beam should not be affected by QTOR. The elastic beam profile enters QTOR with a shape defined by the primary collimator and exits as a long thin stripe that properly fits onto the primary quartz detectors. Any neutral particle (neutrons, photons, etc.) remains unchanged by QTOR.



FIG. 3.14: Simulation of QTOR's azimuthal magnetic field. The magnetic field present in QTOR presented as a function of R and Z at fixed ϕ = median plane between a pair of coils (left) and R and ϕ at fixed Z=0 (right) [43].

The power necessary to operate QTOR comes from a custom power supply that may be seen in Figure 3.15. The supply converts 420 V AC to 9500 V DC with a total power of 1.5 MW. The supply output current is regulated to 1 part in 100000 with a ripple of \pm 5 parts in 10000 [43]. Both the power supply and magnet are water cooled, using water from the low conductivity water (LCW) supply plant at JLab.



FIG. 3.15: QTOR's power supply, the 160 V, 9500 A (1.5 MW) power supply that provides the current necessary to create the fields in QTOR.

QTOR worked well for the second half of run I (fall 2010 to spring 2011), but it was the single biggest source of down time during the first half of run I. QTOR has been responsible for over one month of time lost through numerous fuse failures, regulation control problems, and water leaks all within the power supply. I was involved in the diagnosis and eventual repair of most of the problems related to the power supply.



(a) Effect of QTOR on Moller Scattered Elec- (b) Effect of QTOR on Inelastically Scattered trons.



(c) Effect of QTOR on Elastically Scattered Electrons.

FIG. 3.16: Monte Carlo simulation of the effect of QTOR on the scattered electrons [44]. The beam is incident from the left and scattered electrons in one octant only are shown in red and photons are shown in blue. The target is the box on the far left. Moving from left to right, there are 3 collimators followed by QTOR in brown. The shield wall is next shown in gold, and the primary quarts detector is not shown, but is located twice the distance from the center of QTOR as the front of the gold shield wall. The Moller electrons are completely bent away from the detectors. The inelastic electrons mostly fall off the outside of the quartz bars but some still hit. The majority of the signal seen in the quartz bars is elastic electrons.

3.4.3 Primary Quartz Detector

The 8 primary quartz detectors in Qweak are 200 cm x 18 cm x 2.5 cm fused silica (quartz) Cherenkov detectors. The detectors are made of Spectrosil 2000 primarily because of its radiation hardness (the expected total exposure is estimated to be 100 kRad) and because it produces little light through scintillation or luminescence [43]. For cost purposes, each Cherenkov detector is made of two 100 cm long detectors optically-glued together in the center; half of one uncovered detector is shown in Figure 3.17. The detector includes a lightguide, also made of Spectrosil 2000, coupled to a photomultiplier tube (PMT) on both ends. Each complete quartz bar is enclosed in a light-tight and rigid box for protection. The detector array is divided into 8 symmetric octants as is seen in Figures 3.18 and 3.19.

Cherenkov light is a cone of light produced in a medium when a particle exceeds the speed of light within the medium, analogous to a sonic-boom being created when an object exceeds the speed of sound in a medium. In contrast, scintillation light is light produced by a simple excitation of a medium by charged particle. A Cherenkov detector has several advantages over scintillation detectors. These include the fact that low energy charged particles and photons produce very little light in a Cherenkov detector, while ultra-relativistic charged particles produce an ample amount light.



FIG. 3.17: One primary quartz detector on bench. The quartz is clear, the lightguide is the black horn, and the PMT is the silver/blue tube. Also seen are two plastic scintillator paddles, used as a trigger while testing the detectors with cosmic rays.

A Geant 3 simulation of the full evolution of the beam can be seen in Figure 3.19. The beam profile enters QTOR at approximately 8° and is bent to 21° by the end of QTOR after which, the electrons land on the primary quartz detectors. The photons are not bent, so they hit the shield wall below the quartz detectors.



FIG. 3.18: Complete primary quartz detector array. The primary detectors are inside the large black protective cases with PMTs attached on either end of the bars. The image is looking upstream towards the target. Also seen are the shield wall (yellow) and the aluminum structure used to support the primary quartz detector array.



FIG. 3.19: Quartz detector and QTOR hybrid view. A simulated projection onto the main quartz detector plane starting with the teal collimator and ending on the main quartz detectors (green rectangle), with bent electrons shown in red where (unbent) photons are shown in dark blue.

When the experiment began data taking with the hydrogen target in October 2010, the width of the primary quartz detector's summed asymmetry was larger than it should be by counting statistics alone (pure counting statistics expectation is ~ 300 ppm). After numerous studies and simulations, background sources were identified and shielding was added behind the HDCs and lintels were strengthened inside QTOR; most significantly, 2 cm thick lead pre-radiators were added to the primary quartz detectors. Lintels are pieces of material inside QTOR designed to block line of sight paths from upstream of QTOR to the primary quartz detectors. The lintels were

strengthened by increasing their size in the radial direction to block more paths to the primary quartz detectors. The thickness of the lead pre-radiator was chosen to do two jobs at once; the first is to amplify the elastically scattered electrons signal by generating an electromagnetic shower, thus maximizing the light in the quartz, and second is to stop miscellaneous low-energy particles. A Geant 3 simulation of the effect of the pre-radiators is shown in Figure 3.20.



FIG. 3.20: Simulation of the effect of a pre-radiator on the primary quartz detector. A Lead pre-radiator is shown in blue in front of the clear quartz detector with electrons shown in red and photons shown in blue [44].

Overall, the quartz detectors have been successfully operated with no detectable radiation damage and no other major problems thus far in the experiment.

3.4.4 Primary Quartz Detector Electronics

The main quartz detectors have demanding electronic needs in order to operate linearly for 2 years at high luminosity. The PMT used is the 5" Electron Tubes D753WKB which uses UV-transparent glass and an S20 photocathode [43]. The UVtransparent glass window produces a short wavelength cut off at about 250 nm to reduce the radiation damage while keeping a large number of photoelectrons. The continuous cathode current is 3 nA due to the combination of the large rate and the large number of photoelectrons per incident particle. S20 (multi-alkali) photocathodes have 3 orders of magnitude smaller resistivity than traditional bi-alkali photocathodes; therefore, they greatly reduce nonlinearities from resistive (IR) drops across the photocathode [43]. In order to use the same PMTs for the duration of the experiment, the maximum anode current must be limited to 6 μ A produced from the 3 nA photocathode current and a nominal gain of 2000 using a 7 stage dynode design.



FIG. 3.21: TRIUMF integrating ADC.

The front-end electronics, which were built at TRIUMF, take the PMT anode signal and send it to a high gain, ultralinear and low noise current to voltage (I to V) operational amplifier. With a PMT anode current of 6 μ A and a transimpedence

gain of 1 M Ω , the output is 6 V. The preamplifiers were tested at JLab for radiation hardness. No appreciable changes in the gain or DC level were discovered after 18 krad total integrated dose.

Once the signal passes through the preamplifier, it goes to a digital integrator. The integrators are triggered at the start of each helicity state and integrate for the entire helicity window (except for the 110 μ s Pockels cell hold-off). Figure 3.21 shows the layout of the 8-channel digital VME integrator. The analog signal first passes through a sharp cutoff 50 kHz anti-aliasing filter and is then digitized by an 18-bit ADC at up to 500 kilosamples per second [43]. The Field Programmable Gate Array (FPGA) then calculates the sums over the helicity window and communicates the result via VME bus using 32 bit words.

3.4.5 Luminosity Monitors

The luminosity monitors are an array of Cherenkov detectors, made of the same Spectrosil 2000 material as the primary quartz detectors, located at two positions, one on the front face of the primary collimator and the other 17 m downstream of the target. There are 4 upstream detectors read out on both ends and 8 downstream detectors readout on only one end. The luminosity monitor system serves two primary purposes: as a target boiling monitor and as a null asymmetry monitor. In Mollerscattering, the primary scattering seen by the luminosity monitors, the asymmetry is proportional to the Q^2 and Q^2 is small, so small Q^2 translates to a small asymmetry. The luminosity monitors are located in regions where the count rate is high in order to gather statistics quickly. The positions were chosen at small scattering angles where the expected asymmetry is small, so any false asymmetry should be easy to resolve. The upstream luminosity monitors are set to be sensitive mainly to Moller electrons at 6° and the downstream luminosity monitors are sensitive to mainly Moller and elastic electron-proton scattering at 0.5°. The small scattering angles make both sets of detectors relatively insensitive to beam energy and angle changes.



Collimato Aperture

(a) Upstream luminosity monitor on beamline.

(b) Upstream luminosity monitor drawing.

FIG. 3.22: Upstream luminosity monitors [45].

The upstream detectors each have an active area of 7 cm x 25 cm x 2 cm and the downstream detectors each have an active area of 3 cm x 5 cm x 2 cm. The PMTs can not live as close to the beam as the Spectrosil can, so air-core light guides coated with polished and chemically brightened anodized aluminum are used to transport the light from the quartz to the PMTs.



FIG. 3.23: Downstream luminosity monitors [45].

3.4.6 Horizontal Drift Chambers

There are two pairs of drift chambers used, one upstream of QTOR, the horizontal drift chambers (HDCs), and the others are located downstream of QTOR, the vertical drift chambers (VDCs) which are discussed in Chapter 4. Drift chambers measure the trajectory of a charged particle to hundreds of microns precision with minimal or no impact on its trajectory or energy. The HDCs are located upstream of QTOR to measure the scattering angle of the elastic electrons that make it through the collimators before they are bent by QTOR. The HDCs alone may be seen in Figure 3.24. Each HDC is made of a sandwich of aluminum-coated Mylar foils held at high voltage (HV) surrounding wires either held at ground or a small potential. The whole box is gas tight and contains argon and ethane in equal concentration in terms of partial pressures. The electron passes through the HDC causing ionization of the gas. The freed electrons are repelled by the foils and attracted to the sense wires where they generate an avalanche and thereby induce a signal on the wire. The precise timing of the signal induced on each sense wire is then recorded and the electron's path thereby measured. A much more complete description of the details of drift chambers in general is in Chapter 4.



FIG. 3.24: Horizontal drift chambers.

HDCs differ from VDCs in their intended direction of use and acceptance. HDCs are used to measure tracks that are roughly perpendicular to their wire frames while VDCs are used to measure tracks at angles near -45° relative to their wire frames. The HDCs in Qweak are required to measure a much higher particle flux, as the Moller-scattered electrons have not yet been swept away and the Moller-scattering rate is 500 times the elastic *ep* scattering rate. An HDC can typically measure the trajectory of a charged particle to better than 250 μ m accuracy and has an acceptance of any orientation that stays within the active area of the chamber from start to finish. VDCs can measure the trajectory of a charged particle to better than 200 μm accuracy, but only have an acceptance of $\pm \sim 10^\circ.$ So HDCs are typically more versatile but less accurate.



FIG. 3.25: Horizontal drift chambers on rotator model.

The two pairs of HDCs are mounted to a rotator to allow the coverage of all of the octants and is seen in Figure 3.25. The rotator saves the need for building 3 more sets of detectors. In addition, the rotator has a sliding mechanism to allow the easy insertion and retraction of the chambers into and out of the scattered beam profile.

3.4.7 Vertical Drift Chambers

The VDCs are the subject of all of Chapter 4 and will not be discussed here. There are two pairs of VDCs on a rotator similar in scope to the HDCs.

3.4.8 Trigger Scintillator

The trigger scintillators are plastic scintillators, one of which is hooked to the back of each pair of VDCs and in front of the main detector, that serve as the trigger during tracking mode running. A schematic of one scintillator may be seen in Figure 3.26. Each scintillator is made from BC408 by Bicron, is 218.45 cm x 30.48 cm high x 1.00 cm thick and completely covers the main detector, providing an additional piece of information, as the scintillator does not respond to neutral particles. The scintillator has light guides, made of UVT lucite, that were attached to either end of the rectangular scintillator, made of strands that end fully inside the acceptance of the PMT. The PMTs used are the Photonis XP4312B 3", which has a high gain (3 x 10^7) and an approximately uniform response over its photocathode [43].



FIG. 3.26: Trigger scintillator and light guide schematic.
The signal from both PMTs on a scintillator are combined using a mean-timer to create a position-independent trigger time. The mean-timer creates an output time that is the average of the two input times; this eliminates the time difference of light propagation through the scintillator. For example, if an electron hits the scintillator very close to one tube, the response in the close tube would happen earlier than the tube on the opposite side of the bar, while a hit in the center would create an equal time response in both tubes. A simple coincidence of the two examples would create a time that was hit-position dependent; a coincidence from a hit in the middle would arrive earlier than a coincidence from a hit on either end. The mean-timer removes the position dependence and produces a time signal that is approximately constant for a hit anywhere on the scintillator.

3.4.9 Focal Plane Scanner

The focal plane scanner, or scanner for short, is the only device capable of imaging the scattered electrons that can run both at beam currents as low as 50 pA and as high as 180 μ A. The scanner is a single device that is located either behind or in front of the primary quartz detector that is at the bottom of the array, closest to the floor. It consists of two 1 x 1 x 1 cm³ active area quartz detectors, one proceeding the other, each hooked to a PMT with an air light guide. The detectors are read out in coincidence in order to maximize the likelihood that the signal is from a scattered electron and not from electronic noise or room background sources. The scanner's purpose is to image the beam profile at all beam currents. The tracking system can only image the beam profile at low currents while the scanner can monitor the beam profile on a single primary quartz detector at high currents to ensure there is no difference between high and low currents. The detector is on a X and Y motion track that allows the detector to be scanned across the active area of the primary quartz Canal tack to the sense to the

detector so a signal and a coordinate are recorded for every event.

FIG. 3.27: Focal plane scanner. The active area of the scanner is located behind the main quartz detector in the photograph.

The scanner also has an extension (translation in Z) that allows the scanner to be put in front of the main quartz detectors. The extension provides the ability to study the effect the combination of the quartz and the lead pre-radiator of the main detector as well as the evolution of the beam in Z.

3.4.10 Integrating vs. Counting (Tracking) Mode

The primary quartz detectors have a challenge shared with the luminosity monitors in that they both must work in conditions of high and low beam current. This problem was solved in both cases by using easily swappable PMT bases that have high or low gain, depending on what is needed. In low current running the gain is very high, while in high current running the gain is low.

The data acquisition system (DAQ) also works in two different methods in each running mode and runs off of CEBAF Online Data Acquisition (CODA) software. The DAQ uses what is known as a trigger signal in order to start recording data and then stop recording a fixed time interval after the start. In integration mode, the trigger is the helicity window that comes from the injector at a fixed interval at a rate of 960 Hz. During the helicity trigger, all signals are summed for the approximately 1 ms window and then recorded. The only time the DAQ is not recording during integration mode is when the Pockels cell is settling between helicity flips. In tracking mode, the trigger occurs when an electron hits the trigger scintillator and is generated from the meantimer. Once the DAQ receives the tracking trigger, all signals are recorded during a 2 μ s window. For the lowest beam current (50 pA), the event rate in a single scintillator is only ~ 100 Hz, and the DAQ is easily capable of recording all of these events. For higher tracking currents (20 nA), the event rate in a single scintillator is ~ 50000 Hz, where the DAQ can not keep up with new events at that rate. The maximum rate the DAQ can run is \sim 6 KHz, with 99 % dead-time where the DAQ is unable to accept a new trigger. To handle high rates, the incoming events are pre-scaled to keep the DAQ rate between 1-2 KHz to record as many events as quickly as possible without greatly increasing the dead-time.

CHAPTER 4

Vertical Drift Chambers



FIG. 4.1: Two of the VDCs in Hall C at JLab. The bright yellow are the holes of the shield wall, the blue are LEDs on the readout electronics boards, and the VDCs are the metal boxes in the center of the image.

The region 3 Vertical Drift Chambers (VDCs) are 3' x 8' charged particle tracking detectors that were built at William and Mary. The VDCs are a sandwich of aluminized Mylar held at a potential of -3800 V and hundreds of equally spaced wires held at 0 V potential. The sandwich is gas tight and is full of argon and ethane in equal partial pressures. A charged particle causes the ionization of the gas and then the static field causes the freed electrons to travel into the wires where it can then be amplified and recorded, the details of which are contained in the following sections.



FIG. 4.2: VDC active area cross-section of one wire plane.

One of the first decisions that the collaboration faced in the design was whether to use HDCs or VDCs in the location after QTOR; each has its advantages and disadvantages. Generally, HDCs have a large angular acceptance, but poorer spatial resolution (>200 μ m) while VDCs have a much smaller angular acceptance, but higher spatial resolution (<200 μ m). HDCs expect charged particle trajectories that are approximately perpendicular to the wire planes. VDCs expect charged particle trajectories that are approximately 45° relative to the wire planes. The vertical part of the name for VDCs comes from the detectors usual orientation, VDCs are usually used flat on the ground with the charged particles being bent into them and thus, the ions inside drift vertically. Similarly, HDCs are usually oriented in an upright orientation and the ions drift horizontally. A HDC was chosen before QTOR because the large acceptance was more useful. A VDC was chosen after QTOR because after the bending/focusing of QTOR, the scattered beam had a reasonably small angular distribution.

4.1 Design

Drift chambers have been used in experiments since the late 1960s and are still in use around the world today [46]. The VDCs designed for the Qweak experiment, were based on the design of VDCs that were built at MIT and are currently in use in Hall A at JLab [47]. Several features were changed in order to make the VDCs more cost effective and leak less gas. Similar wires were used, but the foil was switched from gold to aluminum and the material was switched from Stesalit 4411W to G10-FR4. The attachment of the wires to the frame was changed from a crimped feed-through design to simple epoxy to greatly reduce the gas leak rate.

There are numerous material and design choices that were made to optimize performance of the VDCs while adhering to a tight budget. One major challenge that relates to numerous design choices, is the need to readout 558 channels (one per wire) for each VDC. The solution came via multiplexing the signals, where every 8th wire's signal is combined into the same readout chain, as is discussed in detail in Section 4.4.2. This combination of signals reduces the number of readout channels necessary by a factor of 9 while limiting the maximum track length to 8 wires per plane. The minimum number of wires hit per plane is 4 to ensure quality track reconstruction.



FIG. 4.3: Cross-section of one VDC [48]. The black dots are wires and the green lines are HV foils.

A diagram of the cross-section of a single wire plane in 2D can be seen in Figure 4.3 and in more detail in Figure 4.4 in full 3D. The number of hits from a track can be determined using

$$N_{hits} \approx \frac{l}{s} = \frac{2L}{s} \frac{1}{\tan\beta},\tag{4.1}$$

where l, s, L, and β are all geometrical parameters defined within Figures 4.3 and 4.4. The full projected track angle (β) as a function of all possible angles is

$$\beta = \tan^{-1} \left[\cos \left(\Gamma - \tan^{-1} \frac{\tan \Phi}{\tan \Theta} \right) \sqrt{\tan^2 \Phi + \tan^2 \Theta} \right]$$
(4.2)

where Φ is the azimuthal track angle, Θ is the polar track angle, and Γ is the wire stringing angle [48].



FIG. 4.4: Projected Track Angle in VDC [48].

In order to choose the proper Γ to maximize the number of hits while living comfortably under the 8 wire per plane maximum restriction, Garfield [49] and Geant 4 [50] were utilized. The results of a Garfield simulation are located in Figure 4.5 where the goal of the simulation is to determine the best Γ using the parameter known as the Garfield Track Angle ($\alpha \equiv 90^{\circ} - \beta$). Acceptable α values are $\approx 45^{\circ} - 55^{\circ}$ on both the U and V planes (the V plane is rotated 90° relative to the U plane) for some tilt angle and some wire stringing angle of the VDC and over a track range of $\pm 20^{\circ}$ in phi (shown in Figure 4.4).



FIG. 4.5: Garfield simulation of VDC hits with different track angles for different wire stringing angles and phi track angles [48].

Using the results in Figure 4.5 the optimal stringing angle was determined to be 30°. The angle was determined by looking for an angle that, with a VDC tilt angle of 45, had an α between 45° and 55° for ϕ angles of -20°, 0°, and 20°. This angle was later changed to 26.45° (tan⁻¹ $\frac{1}{2}$) to make the wire stringing jig (the device that is used to align the wires during manufacturing of the wire planes) easier to design and fabricate.

The next choice to make was the material used to support and hold the wire and foil frames. This support holds the foil frames that are under tension and holds the wires that are also under tension. The height differences across a plane of foil or wires in addition to the spacing from plane to plane are defined by the material, so it must be uniformly machineable. The material must be able to withstand the compression necessary to create a gas-tight seal with the O-rings. Where the foils and wires physically attach, the material must also be a strong dielectric as there are large potential differences within the VDCs. Another key feature is a lack of out-gassing. The material must not trap/store/release oxygen or other good electron accepters as their presence in the gas would ruin VDC performance.

A historically good material choice was known as Stesalit 4411W, as was used in the Hall VDCs [51]. It was machineable and strong; unfortunately, it is no longer manufactured, so it was not an option. The material ultimately chosen, was G10-FR4 circuit board material (the non-cryogenic version, as the VDCs will be operated at room temperature). G10-FR4 is a sandwich of compressed glass fibers and epoxy/resin. The FR4 designation stands for Flame Retardant and 4 is the type of epoxy. G10 is mechanically rigid and a good dielectric with minimal absorption/emission of gasses.

The two big drawbacks to G10-FR4 are cost and machining difficulty. A 4'x8'x0.5" sheet costs over \$ 2000 (Atlas Fiber Co., 2007). The high cost forced the rectangular construction to be made of 4 separate pieces rather than 1 solid piece. G10-FR4 is a fiberglass material that comes with safety and thickness uniformity concerns. Any machining of G10-FR4 produces dust, that if inhaled can cause lung cancer; therefore, all machining must be done in a completely enclosed air-tight system. The thickness was regulated using sand-blasting, which was determined to be the best option to create a uniform and smooth surface. The resulting surfaces were reasonably smooth across a single board, but there were thickness differences from piece to piece of as much as 1/16".

The next step was to design the different frames such that there are the fewest number of pieces possible and that everything stacks appropriately. The general design is that there is an HV foil 0.5" above a wire frame with another HV foil 0.5" below it, followed by another wire frame, with the wires rotated by 90° in their plane relative to the first wire plane. The whole system is then contained in a gas tight box. A simple diagram of the cross section of a complete VDC is located in Figure 4.6.



FIG. 4.6: Cross-Section of One VDC with the HV foils shown as pink lines and the wires shown as green lines. The spacer frame is used to keep the distance between foil and wire correct with the center foil being double-sided.

There are 5 distinct types of frames: gas, spacer, outer HV, inner HV, and wire. For simplicity, the wire frames are all strung the same; to get a wire frame to change from a U to a V frame, the wire frame is simply flipped over. The outer HV frames contain single sided aluminized (0.0005") Mylar foil, with the aluminum side always facing the wire frames to only provide a potential in the direction of the wire frame. The inner HV frame contains a double sided aluminized (0.0005") Mylar foil and is located between the two wire frames as to provide a potential both up and down. The gas and spacer frames are only to provide the appropriate spacing to keep the appropriate distances between foil and wire frames and to keep the outer aluminum frame 0.5" from the outer HV foils.

4.2 Construction

There were 5 chambers constructed named Luke, Leia, Han, Yoda, and Vader. Each G10 frame was manufactured as 4 separate pieces, two long and two short, that needed to be epoxied together to form a rectangle. The assembly was done precisely using a jig with dowel holes to align the four pieces to their proper location. The overlapping corners are held together using Araldite epoxy AY 103 resin and Hy 991 hardener (10 resin to 4 hardener mix ratio by weight; the cure time is 24 hours). A photograph of a frame during the gluing process is seen in Figure 4.7.



FIG. 4.7: Photograph of gluing the 4 pieces of a G10 frame into a rectangular frame while gluing connector cards into the frame using an alignment jig.

Once the frames were epoxied together, the excess epoxy was scraped off and the frames were cleaned with acetone to remove any dust and oils. 25μ m diameter gold-coated tungsten wires (manufactured by Luma Metall in Kalmar, Sweden) were strung and their positions measured using the procedure described in Appendix A. A wire stringing jig was used to position the wires in a precise and reproducible manner from wire frame to wire frame. The complete setup may be seen in Figure 4.8, including the G10 frame with wires attached, the wire stringing jig, and the camera system used to measure the wire positions.



FIG. 4.8: Measurement system to measure the positions of all 279 wires on a wire frame.

The tension and position of all 2790 wires (from 5 chambers) were measured and recorded using the procedures described later in this section. The wires are connected to the outside of the chamber using the custom board seen in Figure 4.9. The tension of the wires were measured using a function generator and a magnet as seen in Figure 4.10. The wire is fixed to the frame and a function generator sends an AC signal through the wire. A neodymium magnet was placed below the wire and the wire oscillated when the natural frequency was reached. The equation for tension in a wire is

$$T = (2fL)^2 \mu, \tag{4.3}$$

where T is the wire's tension, f is the lowest frequency (first harmonic) at which the wire oscillates, L is the length of the wire, and μ is the linear density of the wire.



FIG. 4.9: The wires are soldered to the pads at the bottom of the bottom of the board and passively carry the signal to the top of the green part of the board. There is a solder mask on the green portion and none on the grey portion as the mask may outgas and poison the chamber.

Wire Plane	Tension from Mass (g)	σ (g)
Luke 1	56.73	6.14
Luke 2	59.06	6.00
Leia 1	59.09	4.19
Leia 2	58.46	4.70
Han 1	57.65	5.38
Han 2	57.77	6.94
Yoda 1	58.60	5.48
Yoda 2	60.24	6.01
Vader 1	60.04	6.85
Vader 2	60.78	4.80
Average	58.84	5.65

TABLE 4.1: Measured Averages of the Tension of Wires on all 10 Wire Planes

The nominal tension of the wires was 60 g. If a wire was discovered to have a tension of less than 40 g, it was replaced and retested until it had at least 40 g of tension. The synopsis of all the tension measurements can be found in Table 4.1. The average measured tension was 58.84 ± 5.65 g. The measured tension was very close to the design and the standard deviation was within tolerance.



FIG. 4.10: Magnet below wires with an oscillating current moving through the wire, causing the wire to oscillate.

The spacing of all 2790 wires was measured using a CCD camera attached to a stepper motor with a linear encoder and was controlled by LabVIEW. The program would fit a Gaussian distribution to an image of a wire, then move by the nominal wire spacing. Each wire and position was then recorded as the amount the linear encoder moved plus or minus the deviation from center using the Gaussian fit.

Wire Plane	Spacing (mm)	σ (μ m)
Luke 1	11.092	73
Luke 2	11.077	75
Leia 1	11.087	77
Leia 2	11.073	68
Han 1	11.077	84
Han 2	11.072	80
Yoda 1	11.070	72
Yoda 2	11.059	75
Vader 1	11.058	78
Vader 2	11.074	100
Average	11.074	78

TABLE 4.2: Measured Averages of Individual Spacing of Wires on all 10 Wire Planes

The nominal wire spacing was 11.12 mm. If a wire was discovered to have a spacing from average of more than 300 μ m, it was replaced and retested until it had a spacing less than 300 μ m from the average. A synopsis of all the spacing measurements can be found in Table 4.2. The average measured spacing was 11.074 ± 0.078 mm. The average measured spacing was systematically smaller than the design by 0.04 mm, likely due to a small missalignment of the stringing jig relative to the laser table. The standard deviation of the spacings was within tolerances. A photograph of strung and tested wires may be seen in Figure 4.11.



FIG. 4.11: Wires fixed to a wire frame

Once the wires were all strung and tested, the next step in the process was to stretch and secure the HV aluminized Mylar foils onto their frames. A photograph of the foil-stretcher is located in Figure 4.12. The foil-stretcher consists of a center table to hold the G10 or the outer aluminum frame, copper pipes where the foil is wrapped around, a "U" shaped channel to hold the foil, and a frame to move the "U" frame in and out. The process began by moving all the frames in and wrapping and taping the edges of a sheet of foil around the copper pipes on all four sides. Once the foil was snug in the "U" channels, the screws that hold the channel were turned causing the foil to tighten. The foil was then epoxied to the frame using the same epoxy used throughout. A foam frame was then placed on top of the foil with weights to press down and seal the foil to the frames while the epoxy cures, as is seen in Figure 4.13.



FIG. 4.12: Jig used to stretch the aluminized Mylar foils and fix them to the HV frames.

There was no precise method used measure the foil's tension. One simply pressed on the foil with one's hand until the foil felt tight and uniform across the whole frame. The method was successful as all the foils have held HV and none have broken so far. The foil was epoxied on the inner perimeter of the frames only. Once the epoxy had cured, the foil was trimmed, leaving some loose foil around the edges.

The HV foils are held at ≈ 4000 V, so a solid electrical connection is very important. The strong electrical connection was achieved using a thin tinned copper strip that fits inside a groove around the frame. Special silicon coated wire (SIL-KOAT SK2022B-2, inner diameter = 1.52mm, outer diameter = 2.03mm, from Wiremax) that is capable of supporting 20000 V was soldered to the tinned copper to connect the outside of the chamber to the inside. The foil was then fixed to the tinned copper using Tracon BB2902 conducting silver epoxy. After the conducting epoxy was applied, the excess foil was trimmed away. The resulting frame, with a good electrical connection to the exterior of the chamber, can be seen in Figure 4.14. A row of holes in the frame allow the gas mixture inside freely travel above and below the foil planes. A similar procedure was used to attach a foil to the outer aluminum frame, but there was no metal strip used and the foil is simply electrically connected to the aluminum using conducting epoxy.



FIG. 4.13: The foil stretching process in progress, where a weight is applied to make sure the foil sticks to the frame.



FIG. 4.14: Foil frame attached to G10 frame with tin strip installed; note the perfect mirror finish.

Once the wires were strung and the foils were stretched, the only remaining task was to create a gas-tight seal with the complete stack. There are O-ring grooves on every frame that are filled with 3/16" diameter (0.210") Viton O-ring 75, chosen to compress and create a seal while not out-gassing anything that would harm the functioning of the chamber. The entire 4" stack of G10 forming the insides is held together by two 0.75" thick tooling plate aluminum frames, with center cut-outs, that also have a aluminized Mylar foil stretched across the center of the rectangular frame to hold the gas mixture inside.



FIG. 4.15: First constructed VDC at William and Mary with no shielding or electronics attached. The red wires are the Si coated wire to connect the inner HV foils to the outside of the chamber.

A photograph of the first completed chamber is located in Figure 4.15, where the outer Mylar foil is visible and before any of the external electronics or support structure is attached. A photograph with the complete readout electronics, electronics shielding, support structure, and cables may be seen in Figure 4.16. The support structure consists of aluminum, made from extra material left from the outer frame, copper to electrically shield the readout electronics, and copper bus bars to power the readout electronics.



FIG. 4.16: VDC at William and Mary with all electronics, cables, and shielding installed. The top is covered by a piece of black PVC board.

With the chamber completely assembled, the next part of the process was to fill it with gas and apply HV. The gas mixture serves two purposes: to provide a source of electrons to be the eventual signal that travels through the wires and to keep the ionization localized to the region where the ultra-relativistic particle traversed. The gas also prevents electron absorbing molecules like oxygen from being inside the chamber. The chamber is kept at a slight overpressure relative to the room using a device known as a "bubbler" that is located in Figure 4.17. There is a constant flow of gas that, with the addition of the bubbler, keeps the pressure inside the chamber slightly higher than in the room even if the room pressure changes. The chamber design also aids in preventing external gas from entering the VDCs by using a tight flow-through design. The flow-through design forces a distinct entrance and exit and causes all internal regions of the chamber to participate in the gas flow. Each foil layer has through holes only on one end opposite the end where the gas entered, so the gas enters on the left and then exits on the right, forcing flow from left to right, followed by right to left on the layer below, forcing the gas to move back and forth through the internal volume, thus preventing any pockets of gas where the flow is reduced.



FIG. 4.17: Bubbler used to prevent back-flow of atmospheric gasses into the chamber and keep the chamber slightly overpressure. The gas starts at the top, is pushed through the mineral oil with the constant gas flow, and out through the exit on the side, maintaining the chamber at a slightly higher pressure than the room even if the pressure in the room changes.

There were 3 gas mixtures tested with the VDCs: (i) 88 % argon, 10 % carbon dioxide, and 2 % methane, (ii) 65 % argon and 35 % ethane, and (iii) 50 % argon and 50 % ethane. The 88/10/2 mixture was tried with success for the HDCs [52] but was never successfully used with the VDCs. At William and Mary, pre-mixed bottles of both 65/35 and 50/50 were used with success. Both the argon and ethane provide a source of electrons and the ethane absorbs photons created during the avalanche process, which is described in detail in Section 4.3. Without the ethane the avalanche would cause ionization is regions of the chamber where the ultra-relativistic particle was not, thus causing false signals. The gas mixture that was eventually chosen was 50/50 because its range of acceptable operational parameters (HV and thresholds, described in Section 4.4.1) were larger than with the 65/35 mix. At JLab, the 50/50 mixture was bubbled through isopropanol to help slow chamber aging because a system to do this was already set up, but it was most likely unnecessary due to the infrequent use of the tracking system in our experiment.

The HV was applied to the foils using a custom built distribution/safety circuit that is depicted in Figure 4.18. An RC filter was used to minimize any spikes in current and to limit the max current drawn by the VDCs. The HV was supplied to the circuit using a Bertan 377N Power Supply (2 channels capable of outputs up to 7.5 KV with trip points from 0.1 μ A to 1 mA). The HV was supplied very slowly at first with small 50 V steps with long 1 hr settle times to allow for the system to equilibrate. Voltages of -4 KV were typically reached after several days followed by a dark current reduction over several weeks to a final value of ≈ 50 nA.

The total assembly time of a chamber starting with G10, wire, foil, etc. was 5-6 weeks, followed by a commissioning time of 2-4 additional weeks. Each wire frame took 1-1.5 weeks to string and each foil took 1-2 days to stretch. The commissioning consisted of repairing dead channels from the chamber by fixing solder joints, testing electronics, fixing poorly crimped connectors, and allowing the new HV environment to burn off any debris.



FIG. 4.18: HV distribution circuit used with $R1 = 1 M\Omega$, C1 = 330 pF and all 3 HV foils connected in parallel where red flexwire that is connected to the VDCs is located. HVPS is the high voltage power supply.

4.3 Time to Distance

One crucial piece of information necessary for reconstructing charged particle tracks is the proper mapping of the drift time to distance of the freed electrons. Once the trigger (scintillator) is triggered, the time of signal arrival on the wires is measured; see Figure 4.19. The shape is typical of a drift time spectrum, with a sharp rise at short times where the ultra-relativistic charged particle is close to the wire, followed by a flat shoulder where the constant drift-velocity region is located, away from the wire.



FIG. 4.19: Typical VDC drift time spectrum from electron beam data at JLab.

The complete process of an ultra-relativistic charged particle traversing the active area of the chamber to a signal arriving at the pre-amplifier discriminator board is more involved than would naively be assumed, even for a single wire. The active area surrounding a wire is known as a drift cell. In the Qweak VDCs, a drift cell is centered around the wire and extends 0.5" above and below the wire and 0.25 cm to the left and right of the wire in a two-dimensional cross section and exists along the full length of the wire in three dimensions. When an ultra-relativistic charged particle passes through a drift cell, the gas is ionized at points along the particle's track. The number of ionized pairs is 94 per cm for argon and 111 per cm for ethane [53]. The freed electrons experience the field set up by the HV foils at -4 KV and the wire at 0 V and travel along field lines away from the foils and towards the wire. The electrons drift at a constant velocity while away from the wire and are accelerated as they approach the wire due to the increasing electric field. As the electrons are accelerated, they ionize more of the gas; the secondary electrons generated can then ionize even more of the gas causing what is known as an avalanche, where one original electron can arrive at the wire as 10^5 to 10^6 electrons, a measurable quantity. The avalanche also produces photons that are absorbed by the ethane by turning the photon's energy into rotational energy and preventing any further ionization.

The current drawn by a chamber is

$$current = rate \times gain \times ionization + backgrounds \tag{4.4}$$

where rate is the total number of ultra-relativistic charged particles, gain is the gain from the gas in the HV potential, ionization is the number of ionization pairs that are produced along the particles path, and backgrounds are background radiation, which include everything from cosmic rays to pair production from photons to protons to low energy β s. The ultra-relativistic charged particles are incident at approximately 45° relative to the chamber and the two layers are 5.08 cm in total thickness. The total approximate path length is 8 cm. Using the average ionization pair per length of 102 produces 816 ionization pairs for a complete track. For a rate of 75 KHz, a typical VDC drew approximately 2.25 μ A of current. 816 pairs per track at 75 KHz = 6.1 x 10⁷ ionization pairs/VDC/s and 2.25 μ A of current is 1.4 x 10¹³ electrons. Dividing the total number of pairs by the total number of electrons drawn by the chamber gives an approximate gain of 2.3 x 10⁵, assuming that the ultra-relativistic electrons are the dominant source of the current drawn.



FIG. 4.20: Mapping to relate drift time to drift distance for a VDC.

Of the 100 or so electron/ion pairs produced, the electron that arrives at the wire first will be the one that is recorded and the time of which is later turned into a distance. The first electron arrival approximately comes from the ionization pairs formed at the distance of closest approach of the track to the wire. The mapping to relate the times recorded to their corresponding distance simply takes the drift time spectrum seen in Figure 4.19 and divides it up into small slices in time, mapping each slice to a distance such that all the times correspond to all the distances in a uniform way. This mapping assumes a uniform illumination of a cell. There is one additional subtlety to the time to distance, and that is that the reconstructed distance is the distance directly above or below a wire, not necessarily where the freed electron

originated. To be clear, this effect is not an issue for the central wires in a track, but is important only for wires at the end of a track. Imagine that the track only intersects a far corner of a drift cell and then exits the cell above the foil plane. The distance that needs to be mapped is the distance above the wire, where the electron was above the wire, but out of the drift cell. The effect is that any freed electron that originates in a corner, gets a distance assigned to it that is bigger than the cell width, because it is a virtual distance, where the path would have gone if the cell were larger. The resulting map can be seen in Figure 4.20. Once the map is applied to the drift time spectrum, the resulting distance spectrum is located in Figure 4.21. The electronics chain that makes the readout possible is the subject of Section 4.4.





FIG. 4.21: VDC drift distance spectra from electron beam data at JLab, resulting from applying the drift time to distance mapping to the drift time spectrum.

4.4 Electronics

A chain of electronics is responsible for the read-out of the signals from the wires of the VDCs. The chain begins with pre-amp discriminator boards (a JLab custom design) that take the analog pulses from the VDC and turn them into a low-voltage differential signal (LVDS) logic pulse, which is fed into 50' of ribbon cable, followed by 100' of shielded twisted pair cable. The LVDS signals of a chamber (36 16-channel ribbon cables, 560 channels) then all plug into the completely custom Multiplexing (MUX) crate. This crate reduces the number of cables by a factor of 9 to only four 16channel ribbon cables, carrying precisely timed emitter-coupled logic (ECL) signals from the whole VDC, which are then fed into a single 64-channel VME "F1" time to digital converter (TDC) [54] which is responsible for recording the time of arrival of all signals reaching it.

4.4.1 Preamp/Discriminator Boards



FIG. 4.22: MAD-chip based preamp/discriminator electronics board used to create LVDS signals from analog pulses.

The preamp/discriminator boards used are custom JLab electronics that take analog pulses, amplify them, and if they are above an adjustible threshold, produce LVDS logic signals from them, and may be seen in Figure 4.22. The board requires +6V for power, 0 V ground, and + and - threshold. The threshold value actually used is the difference between the + and - threshold voltage applied with small corrections able to be made using an on-board potentiometer. The 4 required voltages were supplied to all of the chambers distributed using 0.25"x0.25" copper bus bars at the chambers and fed by 1 gauge wire (+6, 0) and 18 gauge wire (thresholds) from power supplies 150' away. The board takes 16 single input channels and outputs 16 dual (twisted pair) channels. The MAD chip was chosen because of its prior success on other experiments and its ability to withstand the radiation environment where it will operate [55, 56]. Half way through the Qweak experiment, there has only been a single card out of 144 that has failed.

The only issue related to the MAD board experienced so far is the weakness of the LVDS driver. For the setup in Hall C, the LVDS signal must be driven over 150' from the MAD board to the MUX crate (which will be discussed in Subsection 4.4.2). Once the LVDS arrives at the MUX crate, it is converted to ECL; however, over 150' of twisted pair cable causes the signal to attenuate slightly differently from cable to cable causing subtle relative timing shifts from wire to wire. These shifts were acceptable, but required additional corrections applied in software to account for the timing changes. The MAD board should be limited to driving signals to no more than 70' if ultra-precise relative timing is required as is when multiplexing signals.

4.4.2 Multiplexed Readout

The MUX system was designed and built by William and Mary and the JLab fast electronics group to reduce the cost of readout electronics necessary to record data from every wire in the VDCs. To read out all of the 144 MAD cards, 144 LVDS to ECL cards would be necessary, since the F1TDCs require ECL signals, and 36 F1TDCs as well as the 4 VME crates necessary to mount all 36 of the F1TDCs. The final MUX system designed reduced the number of readout electronics by a factor of 9 down to only 4 F1TDCs and combined the LVDS-ECL conversion step into the system. There were 4 MUX crates that were built and tested, one for each VDC, each in its own VME style chassis. The LVDC to ECL conversion takes place on a removable "LEX" card. The delay lines are contained on VME backplanes that the LEX cards plug into. All 4 MUX crates were located in the shielded electronics hut beside the F1TDC crates.



FIG. 4.23: Diagram of the MUX system with MC10H188 hex buffer delay chips shown as triangles and MC100EP91 LVDC-ECL conversion chips shown as squares. One delay line is shown that contains the VDC wire information for every 9^{th} wire. As a signal passes through a delay chip, it emerges unchanged, 1.3 ns later.

For each input channel, the MUX system starts by taking the LVDS signal, splitting it into two signals, each of which is then converted into ECL (chip MC100EP91), with one going to the "left" and one going to the "right", where "left" and "right" are arbitrary ways of labelling one of the other direction on a delay line as is indicated in Figure 4.23. The next step uses hex buffer chips (chip MC10H188), which are used as delay chips, gated to always be open, causing 1.3 ns delay on average for the ECL signal to propagate through. The chambers were designed with a maximum number of hits per plane to be 8; therefore, if the signals from every 9^{th} wire was combined there would be no likely effect on track reconstruction even if a wire were misidentified with its nearest neighbor. For example, wire 1 would have 0 delay chips to the left and 18 to the right, wire 9 would be on the same delay line as wire 1 and have 1 delay chip to the left and 17 delay chips to the right and so on. After the delay chips, the left and right side of a delay line are each read out separately by a F1TDC. The signal is then processed by subtracting the time measured for the left from that from the right producing a spectrum as seen in Figure 4.24, where the first peak is the wire 1, the second peak is wire 9, the third peak is wire 17, and so on, and where each wire clearly lies within a definite time window. The σ of a typical L-R peak is 80 ps on the bench, but turned into 120 ps in Hall C.



FIG. 4.24: Time difference data between the left and right side of a delay line taken on the bench. The differences in peak heights are due to different sizes of wires, longer wires have more hits on them and the hits are only present near the scintillator paddles that were the trigger for the test setup.

The MUX data in Figure 4.24 was taken on the bench at WM using 15' cables and the data in Figure 4.25 was taken in Hall C at JLab using 150' cables. The total necessary cable length necessary to reach the electronics bunker in the hall originally estimated to be less than 95', but was actually 150'. One clear difference between the two spectra is the clean separation of the peaks in the first with the relatively poor separation for some pairs of peaks in the second. The peak shift between bench and Hall C data came from the LVDS signal degrading in a slightly different manner across the 150' span from wire to wire and when the signal was rediscriminated the weakened signals crossed the threshold at different times when the signal is split in the MUX crate. The result was slight changes in the left relative to right signal starting time causing slight shifts in the peak's locations. This effect was compensated for by making very careful maps of each left minus right spectrum and if a signal fell between two peaks, it was identified as arising from corresponding wires and ambiguity handled later in software.



FIG. 4.25: Time difference data between the left and right side of a delay line taken at JLab, note the clear separation of some peaks while other peaks are very close to their neighbors.

Overall, the MUX crates worked well enough and did not cause any problems, although it took a large amount of time to properly understand and characterize the individual effects of each and every delay line. A diagram of a complete map from VDC to MUX crate is located in Figure 4.26. If money were not a factor, it would have been much simpler to read out every wire with an individual F1TDC channel.





(b) Map of cable locations on VDC.

FIG. 4.26: MUX crate and VDC combined map.
4.5 Pattern Recognition and Track Finding

The principle by which tracks are formed from VDC data is pattern recognition. The procedure begins by placing hits onto a grid where they are matched to potential tracks in that plane, then like planes (eg. all V planes) are assembled, and finally the unlike planes (U and V) are assembled into a track in 3D. Standard least χ approaches to track finding were abandoned in favor of the pattern recognition because of the belief that the pattern recognition would decrease computational time while reducing the effect of false/missing hits.

The track reconstruction process begins by identifying all possible hit patterns within a plane that could possibly correspond to a real track. The active area of a cell is divided into an equal number of boxes above and below a wire, as a hit with a corresponding drift time could have come from either above or below a wire; this is known as the "up/down ambiguity". Before the process starts, the patterns on the grid of all tracks with all angles that would hit between 4 and 8 wires on a plane are generated and stored for reference purposes. Figure 4.27 illustrates the initial step of taking hit data, identifying the possible range of the hits, and then generating the grid pattern that corresponds to the data (note: there is still an up/down ambiguity in a single plane that will be resolved later, as a track that travels from lower left to upper right looks identical to a track that travels from upper left to lower right, so both patterns must be stored). With a pattern generated from the data, the pattern is compared to the library generated earlier and all possible matches are stored, as is seen in Figure 4.28. There are usually 10s of potential patterns found for every track in a plane.



FIG. 4.27: Pattern recognition in a single VDC wire plane, starting with a hit range on the left and ending in potential hit blocks on the right. Here 4 wires are hit in this plane. Blue lines are drift estimates and black boxes are possible hits formed on a grid.

With numerous patterns generated for all 4 wire planes in a VDC pair, the next step is to assemble like wire planes, meaning to connect U with U planes and V with V planes. The slope of every pattern in the first U (V) plane is compared to the slope of every pattern in the second U (V) plane. If the magnitude of the slope matches well enough, the hits from both planes, using complete 3D geometry, are fit to a plane. If the total residual distance between the fit and the hits is below a threshold, the plane is stored. At this step, the up down ambiguity has been resolved, because if the up/down was misidentified, the residual would be extremely large (for events with a single ultra-relativistic charged particle in them, there is usually only a single match). Once this step is complete, there is a single assembled U and a single assembled V plane. Events with multiple assembled planes are currently ignored, but they will be addressed in the future. With the equations for the U and V planes, the intersection



FIG. 4.28: Single VDC plane hits on the left with pattern matches on the right.

The complete process of pattern creation and matching through assembly into a complete VDC track is illustrated in Figures 4.27, 4.28, and 4.29. At the beam currents at which the VDCs are operated (<20 nA), multiple ultra-relativistic charged particles are not usually present in the same VDC pair. As stated previously, there is a flag that is used to identify any event with more than one ultra-relativistic charged particle in it and they are currently ignored.



FIG. 4.29: Track recognition procedure starting by matching track segments, followed by combining like wire planes (U-U, V-V), and completed by combining unlike wire plane (U-V) matches into a track.

4.6 Track Position Resolution

The current track resolution for ultra-relativistic charged particles passing between a pair of VDCs is 231 μ m σ in a single wire plane and is 266 μ m in a track; see Figure 4.30. The average residual is defined as the average distance between a fit line and the original hit. The residual has been improved by adjusting parameters such as the maximum reconstructable distance from a wire (a function of track angle), the maximum allowable drift time, the time to distance mapping, and the maximum matchable slope. Each parameter requires retuning as a different parameter is improved. The current track residual of 266 μ m is sufficient to complete all of the studies necessary for the Qweak experiment, but is still improvable with careful software refinement. The residual from a Garfield simulation of the arrival time of freed electrons is ~150 μ m, the rms of the distribution of wire locations is only ~70 μ m, and from TDC resolution is insignificant. The similarly designed Hall A VDCs have a position residual of 225 μ m, so at a minimum, 225 μ m should be achievable.



(a) VDC Residual for Individual Wire Planes.



(b) VDC Residual for Tracks.

FIG. 4.30: VDC residual for a) individual planes and b) for complete tracks.

4.7 Efficiency

The VDC efficiency can be defined in several ways. First, a package needs to be defined as a pair of VDCs (Vader+Leia = Package 1 and Yoda+Han = Package 2). The efficiency of a VDC can be defined in terms of single wires (whether or not a single wire will fire if an ultra-relativistic charged particle passes through a wire's cell) or in terms of measuring a track (wether a track is formed using the information from the fired wires).



FIG. 4.31: Relative VDC efficiency vs. discriminator threshold where efficiency is defined as the percent of events containing a VDC track out of the total triggers from the scintillator. VDC HV was 3800 V for these these data and were taken at 50 pA of electron beam current. The VDCs have approximately the relative efficiency across the thresholds tested.

The first type of efficiency we consider is a relative efficiency of the VDCs at different MAD discriminator thresholds and at different HV settings, as seen in Figures 4.31 and 4.32, respectively. Here, the efficiency is defined as the number of tracks found over the total number of triggers from the scintillator. The scintillator provides many false triggers from either very low-energy particles, light leaks, or from some other source, so the efficiency of the VDCs is only relative because there is much more than only ultra-relativistic charged particles causing triggers. The operation point of the VDCs is found from the minimum value on the relative efficiency plateau. The efficiencies between Figures 4.31 and 4.32 differ because the beam current was different between the tests, thus the clean trigger rate was different between the tests.



FIG. 4.32: Relative VDC efficiency vs. HV with a threshold of 8.0 V where efficiency is defined as the percent of events containing a VDC track out of the total triggers from the scintillator. This is only a relative measurement, as the trigger is not clean and contains many false triggers. The VDCs operate at maximal efficiency at 3750 V or higher.



FIG. 4.33: Absolute single wire efficiency using the 5-wire method (see text) for two VDCs. An efficiency of -10 % represents no data available to calculate an efficiency.

Figure 4.31 shows a study of the relative efficiency of the VDCs vs. the threshold of the MAD preamp discriminator. The highest threshold able to be set was 10 V with the electronics setup, and the lowest possible threshold was 6 V because some of the MAD cards began to oscillate below 6 V, so the study was done between 6 V and 10 V. The result of the study was an approximately flat response for both packages indicating that the VDCs operated equally well for any threshold between 6 V and 10 V. Figure 4.32 shows a study of the relative efficiency of the VDCs vs. HV, where HV was varied between -3100 V and -3800 V with a discriminator threshold of 8 V. The shape found is characteristic of drift chambers in general where the chamber is inefficient when the HV is too low and thus the gain is not large enough, the efficiency increases as the HV is raised, and levels off in efficiency after -3750 V indicating the lowest operational HV.

Wire Plane	Single Wire Efficiency (%)	σ (%)
Vader V	98.31	0.04
Vader U	99.16	0.03
Leia V	97.48	0.05
Leia U	98.69	0.04
Yoda V	99.40	0.04
Yoda U	99.33	0.04
Han V	98.14	0.09
Han U	98.16	0.09
Average	98.55	0.05

TABLE 4.3: Measured Average Single Wire Efficiency

With operational settings of -3800 V and 8 V threshold (because of intermittent noise problems), the absolute efficiency of the VDCs was studied. In a track with 5 wires hit in a particular plane, the drift time is the smallest for wire 3, is largest for wires 1 and 5, and is in the middle for wires 2 and 4. Using this information, a trigger condition can be formed by looking at wires 1,2,4,5 to measure the efficiency of wire 3. The trigger is defined as wires 1,2,4,5 all having hits and the drift times of wire 2 is less than wire 1 and 4 is less than 5 with no requirements on wire 3. This identifies events in which a particle must travel through the drift cell of wire 3. The test was ran on every wire in every chamber with the resulting data shown in Figure 4.33 for 2 of the VDCs for every wire and with VDC plane averages for all VDCs tabulated in Table 4.3. The average overall efficiency of the VDCs was measured to be 98.55 \pm 0.05 %. The short wires in the wire planes have the lowest and highest wire number, where there are relatively few tracks, thus few triggers, so the statistics on the short wires was very poor compared to central wires. There were a few wires with very low efficiency likely from a poor or damaged cable or connector along the signal's path, but the tracking software is largely unaffected by single missing wires.

4.8 Rotator



FIG. 4.34: Model of rotator used to move VDCS in and out radially as well as rotate the VDCs azimuthally to give complete coverage of all 8 primary quartz detectors.

The rotator is a device used to extend the VDCs in front of and away from the primary quartz detectors as well as to rotate the VDCs to cover all 8 primary quartz detectors, as may be seen in Figures 4.34 and 4.35. Each VDC package, consisting of 2 VDCs, plates to hold the VDCs, readout electronics, shielding, cabling, etc. weighs approximately 2500 lbs; therefore, the support structure to hold and rotate them must also be strong and is made of steel. The linear motion was performed using an Industrial Devices Corporation Electric Cylinder Model EC3-T32V-50-05B-1000-

MT4-FC2-BS24 with an S6961 Controller that uses a piston on the bottom slider rail and nothing on the top of an arm. The pair is always extended/retracted together using an automated script so as to not create any large imbalance on either side which would put torque on the rotational motor. There are two locking pins at the top and bottom of a package to reproducibly and safely secure the VDCs when they were in any position other than horizontal. The rotation was done using a Sumitomo Drive Technology LHHM1-3B120LKA-K1-B-249 1 HP rotational motor with a HF-320 α controller with a large chain around the motor and around teeth surrounding the central hub. Overall, the rotator was a complex engineering problem, that was solved using a variety of ideas and has worked successfully thus far in the experiment.



FIG. 4.35: Photograph of rotator in green with the cable guide visible that holds all ~ 200 cables while the VDCs rotate.

4.8.1 Survey and Alignment

The VDCs were installed on the rotator in 2010 and were surveyed by the JLab Survey and Alignment Group. The survey was completed using a Faro Laser Tracker that is able to locate a small fiducial marker to better than 100 μ m. The big concern with locating the VDCs in 3D in Hall C at JLab was reproducibility. As long as the chambers were in approximately the correct position (~1 cm), they would be able to accomplish their goals as long as their position was known and it was reproducible (to several mm) over time.

The linear motion of the VDCs has always been defined by pins that lock on both sides of the sliding arms. There was originally some problems getting the pins to lock, but it was eventually learned that allowing the chambers to rotate from side to side would shake the pins enough that they would seat properly; this was subsequently always done before moving the VDCs into a measurement position.

Originally, the rotational position of the chambers was defined by a pin that was in inserted into the central hub of the rotator, but the pin was smaller than the hole and the bracket that held the pin was weak. When the pin was inserted, the pin would move rather than the pin moving the chambers. We eventually went to a laser alignment system where laser pointers were rigidly fixed to the aluminum frame that holds the primary quarts detectors such they all point at the VDCs when they are in different rotational positions. The technique was simply to use the rotational motor to rotate the hub until the laser pointer lined up with markers placed on the VDCs when they were surveyed. Using the rotational pin method, the chambers were reproducible to ~ 2 mm. Once the laser alignment method was used, the chambers positions were reproducible to < 0.5 mm. The continued reproducible positioning of the VDCs using the laser alignment system will be important to remeasure as the stability of their position over months has not been studied.

CHAPTER 5

Analysis

The analysis of the Qweak experiment is made possible through the hard work and dedication of a large number of people over several years and will continue into the future as more data becomes available. Each of the following sections will discuss the error budget, the taken data, and the results for various components of the analysis. The analysis of individual sections were each completed by different people. The scope of the analysis discussed will only be for the 25% measurement. The 25% measurement is the commissioning period data where the total uncertainty on the extracted value of Q^P_{weak} will be $\approx 25\%$. The various corrections are sufficiently well known for the 25% measurement, but are not yet adequate for the final 4% measurement, as the final error budget is very tight.

It should be noted that the full analysis that follows contains a blinding factor between 0 and \pm 60 ppb that shifts the final asymmetry. At the time of this writing, the collaboration has deemed that the analysis was not yet ready to be unblinded. A blinding factor is an arbitrary constant that is introduced to shift the asymmetry so that human bias is not introduced. When measuring an asymmetry that is ~ 200ppb, human bias can shift the final measurement towards or away from a desired result, intentionally or not. For example, if the result started far below the Standard Model value, the bias would be to be to look for corrections either to move the result further, if one was looking for a disagreement, or closer, if one believed the Standard Model value. The blinding factor requires that all corrections be applied before the blinding factor is removed, so the corrections are applied in a bias-free manner.

5.1 Polarization

The electron beam's polarization was measured using the Moller polarimeter alone for the 25% statistical measurement. The Compton polarimeter was still under development and did not produce any meaningful results for the time window when the 25% measurement was taken, so no results will be shown. The error budget for a 25% measurement on polarimetry is 3.0%, while it is only 1.0% for the final 4% measurement.

5.1.1 Moller

The hardware and theory of the Moller polarimeter were discussed in Section 3.3.1. Polarization measurements were made using the Moller polarimeter approximately 3 times a week. Each measurement achieves approximately $\sim 0.3\%$ statistical precision with 6 sub-measurements (3 with the half-wave plate in and 3 with the half wave plate out; the polarization flips sign with half-wave plate setting). The polarization measured during the 25% measurement was (88.4 ± 2.4)% on average using 4 separate measurements over the 19 days when the data was taken. The first measurement shown on Figure 5.1 is still considered to be suspect by the Moller group; and the deviation from the average for this value is currently defining the estimated systematic error of 2.4 %. Note that a steady decrease of polarization vs. time is not

unexpected between activations of the GaAs crystal at the electron source.



Beam Polarization From Moller Polarimeter for 25 % Measurement

FIG. 5.1: Electron Beam polarization as measured by the Moller polarimeter for the 25% measurement.

5.2 Parity-Violating Asymmetry

The parity-violating asymmetry formed from detector yields, the parameter that is measured in the experiment, is an amalgam of the asymmetry from hydrogen, the aluminum target windows, and backgrounds from the beamline or other sources, and is dependent on electron beam current and electron beam polarization. Each of the individual components must be measured alone to allow for the eventual extraction of A_{ep} and eventually Q_{weak}^{P} .

Before A_{ep} is separated from the measured asymmetry, it is regressed against the potentially helicity-correlated beam properties of x position and angle, y position and

angle, and energy. The regression works using the following formula

$$A_{regressed} = A_{measured} - \sum_{j=x,x',y,y',E} S_j \Delta j, \qquad (5.1)$$

where S_j is the sensitivity of the variable being used, Δj is the helicity-correlated difference of the variable being used, and x, x', y, y', E are x position, x angle, y position, y angle, and energy. The sensitivity of a variable is extracted using a multivariable linear regression and extracting the dependence of the unregressed asymmetry on the variable in question. The slope is then applied to the variable to remove the dependence of the asymmetry on the variable. The differences of all 5 variables along with their sensitivities vs. runlets (every runlet is a portion of data that is ~ 6 mins of data during a run) are plotted in Figures 5.3 - 5.7 after a set of data cuts made that will be discussed next.

The following convention will be used to describe the data: "IN" = the insertable half-wave plate is in, "OUT" = the insertable half-wave plate is out, "IN + OUT" (null) = the summed result of the half-wave plate settings divided by two that should be consistent with 0, and "IN - OUT" (total) = the difference of the half-wave settings, which is also known as the total physics asymmetry. Also, a "slug" is a term used to mean the data taken during one half-wave plate setting, which is 4-8 hours long, depending on when it was taken.

	Asymmetry (ppb)	Regressed Asymmetry (ppb)
IN Asymmetry	101 ± 48	254 ± 48
OUT Asymmetry	-16 ± 47	-110 ± 48
Null Asymmetry	42 ± 34	72 ± 35
Total Asymmetry	-59 ± 34	-182 ± 34

TABLE 5.1: Asymmetries with NO Cuts Applied, Before and After Regression of Helicity-Correlated Beam Properties

Cut	< Value
Charge Asymmetry (ppm)	9.8
Energy Difference (ppm)	100
X Position (nm)	100
X Angle (nrad)	10.5
Y Position (nm)	230
Y Angle (nrad)	7

TABLE 5.2: Cuts Applied

The 25% data set consists of data taken between January 21, 2011 and February 8, 2011 and contained ~1400 runlets. Approximately 10% of the file segments were removed because the regression failed (mostly because the runlets did not contain the minimum number of events, 50,000, necessary to perform the regression), Approximately 80 more were removed because they have variables (charge asymmetry,x,x',y,y',E) which fell outside a range within their respective distributions, leaving ~ 1150 runlets. Of the 80 cut runlets, half were removed because they were outliers and the other half were removed based on statistical cuts on the 6 beam parameters that when they were removed, the IN + OUT (null) asymmetry moved closer to 0. The cuts applied are summarized in Table 5.2. It should be noted that the cuts applied did very little to the IN - OUT (total) asymmetry, the asymmetry changed by less than 3% (5 ppb change with a 35 ppb statistical error).

The change in asymmetries and errors can be tracked by looking at the differences between the values in Table 5.1 with no cuts applied and Table 5.3 with the cuts applied. With the cuts, the null asymmetry moved closer to 0 ppb, although the value of the total asymmetry changed very little. The regressed values shown are regressed and corrected on a pattern by pattern basis (asymmetry formed from individual quartets). To test the regression algorithm, corrections were instead applied on a runlet by runlet basis and the regressed asymmetry values were very similar ($\sim 3\%$ different). The size of the correction to the total asymmetry is large (~ 120 ppb) relative to the raw asymmetry (~ 60 ppb). The correction is dominated by the y position corrections as they did not cancel with the half-wave plate settings as the other variables did.

	Asymmetry (ppb)	Regressed Asymmetry (ppb)
IN Asymmetry	100 ± 50	245 ± 51
OUT Asymmetry	-41 ± 47	-130 ± 48
Null Asymmetry	29 ± 35	57 ± 35
Total Asymmetry	-70 ± 34	-187 ± 35

TABLE 5.3: Asymmetries with Cuts Applied

A summary of the 5 beam parameters differences and their respective sensitivities including errors, is located in Table 5.4. The y position differences are large relative to the other values and are responsible for the largest regression correction, as they do not cancel with half wave plate flips. The sensitivity was decreased by changing the position of the beam so it is closer to the neutral axis of the experiment. The corrections for the other 4 variables were between -25 ppb and 25 ppb. The charge asymmetry for the 25% run period is shown in Figure 5.2, which was responsible for the removal of $\sim 25\%$ of the cut data. One reason for the loss, was that the half-wave plate flipping was not being properly handled, a problem that was resolved for later running. There is a feedback loop that feeds back on the measured charge asymmetry by adjusting the Pockels cell voltage to minimize the charge asymmetry. The sign of

the half-wave plate was not properly being accounted for, so the correction was being initially applied in the wrong direction causing a large charge asymmetry.

	Waveplate IN	IN Uncertainty	Waveplate OUT	OUT Uncertainty
Charge Asymmetry (ppb)	19	82	-36	85
Energy Difference (ppm)	-21	0.8	22	0.8
X Position Difference (nm)	-6	1	6	1
X Slope Difference (nrad)	0.3	0.04	-0.1	0.04
Y Position Difference (nm)	11	1	8	1
Y Slope Difference (nrad)	1	0.07	-0.6	0.07
Energy Sensitivity (ppb/ppm)	3	0.01	0.5	0.004
X Sensitivity $(\mathrm{ppm}/\mu\mathrm{m})$	-0.6	0.01	-0.8	0.01
X Slope Sensitivity (ppm/nrad)	26	0.3	21	0.4
Y Sensitivity $(\mathrm{ppm}/\mu\mathrm{m})$	-1	0.008	-0.8	0.008
Y Slope Sensitivity (ppm/nrad)	6	0.2	-15	0.3

TABLE 5.4: Helicity-correlated differences in beam properties

The X position and angle differences and sensitivities shown in Figures 5.3 and 5.4 exhibit the same general behavior. The sensitivities are very large near run 9300 and are smaller towards the end of the data taking period. The jump and subsequent drop in sensitivities comes from a deliberate change to the axis of the beam before run 9300 the beam was in a position that was more sensitive to the changes in X, it was changed in the wrong direction near run 9300, and then it was corrected after run 9300. A similar, but larger, pattern can be seen in the Y position in Figure 5.5 and energy in Figure 5.7 and a similar, but smaller pattern, is seen in the Y angle in Figure 5.6. The beam was eventually placed in a position that minimized the Y and Energy sensitivities for the end of the running.



FIG. 5.2: Charge asymmetry vs. run number for the 25% running period.

The true measure of the data is shown in Figures 5.8 and 5.9 where the asymmetry with and without regression is plotted vs. slug number. The χ^2/dof of the unregressed data is 2.1 for the IN data and 0.8 for the OUT data and for the regressed data is 2.4 for the IN data and 0.5 for the OUT data. The regression moved the OUT data slightly closer together and the IN data slightly further apart, although the χ^2/dof is reasonable for all of the data. The regression does take the NULL value away from 0, but it is only 1.6 σ from 0, so it is still acceptable. Once the neutral axis was found, the data collected were all consistent and closely grouped as is expected.



X Position Differences vs. Run Number





Sensitivities: X Position vs. Run Number

(b) Sensitivity of asymmetry to X position beam motion differences vs. run number.

FIG. 5.3: X position differences and sensitivities for the 25% running period.



X Angle Differences vs. Run Number





Sensitivities: X Angle vs. Run Number

(b) Sensitivity of asymmetry to X slope beam motion differences vs. run number.

FIG. 5.4: X slope differences and sensitivities for the 25% running period.



Y Position Differences vs. Run Number





Sensitivities: Y Position vs. Run Number

(b) Sensitivity of asymmetry to Y position beam motion differences vs. run number.

FIG. 5.5: Y position differences and sensitivities for the 25% running period.



(a) Helicity-correlated Y slope beam motion differences vs. run number.



Sensitivities: Y Angle vs. Run Number

(b) Sensitivity of asymmetry to Y slope beam motion differences vs. run number.

FIG. 5.6: Y slope differences and sensitivities for the 25% running period.



Energy Difference vs. Run Number





Sensitivities: Energy vs. Run Number

(b) Sensitivity of asymmetry to beam energy vs. run number.

FIG. 5.7: Beam energy differences and sensitivities for the 25% running period.



(a) Measured asymmetry for *ep* scattering vs. run number.



Regressed Asymmetry vs. Run Number

(b) Regressed measured asymmetry for *ep* scattering vs. run number.

FIG. 5.8: Regressed and unregressed asymmetries for ep scattering vs. run number for the 25% run period.



(a) Measured asymmetry for ep scattering vs. slug.



(b) Regressed measured asymmetry for *ep* scattering vs. slug.

FIG. 5.9: Preliminary regressed and unregressed asymmetries for ep scattering vs. slug including the null asymmetry and the combined asymmetry for the 25% run period and with the averages shown as a horizontal line.

5.2.1 N-> Δ

One correction to the asymmetry that will be important for the 4% measurement, but is not significant for the 25% measurement, is the correction due to electrons from inelastic ep scattering that hit the primary quartz detector. The dominant inelastic process that contributes is the excitation of the nucleon into a Δ with an eventual decay into the nucleon and a π [57]. The Feynman diagrams for the inelastic scattering are located in Figure 5.13. The asymmetry of the inelastic background is measured by focusing the inelastically scattered electrons onto the primary quartz detector by reducing the magnetic field of QTOR. The asymmetry of the inelastically scattered electrons is expected to be very large in comparison with the elastically scattered electrons (~ 3 ppm vs. 0.2 ppm), but the fraction of inelastic events that hit the primary quartz detector is very small (0.001); therefore, the expected inelastic correction is ~ 3 ppb and thus is negligible for a 25% measurement where the statistical error bar is 35 ppb.



FIG. 5.10: N –> Δ Feynman Diagrams.

5.2.2 Aluminum Asymmetry and Dilution

The target is composed primarily of liquid hydrogen, but the outer vessel holding the liquid hydrogen is aluminum. The weak charge of neutrons present in aluminum is large (~ -1 vs. 0.05) and have the opposite sign compared to the asymmetry of the proton, so the aluminum asymmetry must be measured alone and removed from the primary measurement [58]. Aluminum targets of varying thicknesses were used and their asymmetry was recorded using the same apparatus as the primary measurement, just with a different target. The varying thicknesses of the targets are used so that the radiative losses through the aluminum can be measured, which is done by measuring the differences in detected rate as a function of the target's thickness. The measured asymmetry of aluminum was found to be 1.61 ± 0.16 ppm¹, where the current uncertainty is dominated by statistics. The aluminum asymmetry results from both half-wave plate settings and final results are shown in Figure 5.11.

With the aluminum asymmetry measured, the second question to answer is the quantity of electrons that scatter from the aluminum target cell windows and hit the primary quartz detectors; this will be referred to as the dilution. The dilution measurement was performed using two separate methods: an empty cell and with cold gas. The empty cell method is to simply measure the detected rate on the primary quartz detectors with the completely evacuated target cell as the target. The cold gas method uses the rate on the primary quartz detectors with the target at various hydrogen gas pressures and extrapolates to a perfect vacuum. The measured value for the dilution factor was $(0.031 \pm 0.003)^1$. The aluminum dilution factor results are depicted in Figure 5.12.

¹preliminary, not yet official collaboration result



FIG. 5.11: Preliminary measurement of the parity-violating asymmetry of aluminum.

The relationship between the measured asymmetry (A_m) and the ep scattering asymmetry (A_{ep}) is

$$A_{ep} = \frac{1}{1-f} \left[\frac{A_m}{P} - \frac{f A_{bkgd}}{P} \right]$$
(5.2)

where f is the dilution factor, P is the electron beam's polarization, and A_{bkgd} is the asymmetry of the background (aluminum). With P known from the Moller polarimeter, A_{bkgd} measured from aluminum targets, and f measured from the dilution measurements, A_{ep} can be extracted from A_m .



FIG. 5.12: Dilution factor measurement with cold gas and an empty cell measurement. The dashed line is the extrapolation of the cold gas measurements to a hydrogen gas density of 0 g/cm³.

5.3 Q^2

For the final measurement of Q^P_{weak} to 4%, the 4-momentum transfer (Q^2) must be measured to a precision of 0.5%, but for the purposes of the 25% measurement, a precision of 5% is sufficient. As a brief reminder, the physics asymmetry depends on Q^2 as

$$A_{RL} = \left(\frac{G_F}{4\pi\alpha\sqrt{2}}\right) \left[Q_{weak}^P Q^2 + Q^4 B(Q^2)\right].$$
(5.3)

The Q^2 of an ultra-relativistic collision between a particle (electron beam) and a particle at rest (liquid hydrogen target) is given by

$$Q^2 = 4EE'\sin^2\theta/2,\tag{5.4}$$

where E is the energy of the incident particle, E' is the energy of the incident particle after it has scattered, and θ is the scattering angle. The scattering that is measured in the Qweak experiment is elastic (two-body kinematics), so only 2 of the 3 variables $(E, E', \text{ and } \theta)$ are necessary to define Q^2 . E' can be written in terms of E and θ as

$$E' = \frac{E}{1 + 2\frac{E}{M_P}\sin^2\theta/2},$$
(5.5)

where M_P is the mass of the proton. Alternatively, equation 5.5 can be inserted into Equation 2.17 to form a different equation for Q^2 for the elastic ep scattering measured in terms of E and θ ,

$$Q^{2} = \frac{4E^{2}\sin^{2}\theta/2}{1 + 2\frac{E}{M_{P}}\sin^{2}\theta/2}.$$
(5.6)

The Qweak experiment will eventually choose which pair of variables to use to define Q^2 . The most well known of the three is the electron beam energy, which is discussed in Section 5.3.1, so it should be one of the two variables used. θ is measured using the tracks from the HDCs and the geometry of the experiment and is discussed in Section 5.3.2. E' is measured by solving a differential equation using the track information from both the VDCs and HDCs and the knowledge of the magnetic field of QTOR and is discussed in Section 5.3.3. The likely choice for the second variable is θ because it requires fewer pieces of information to measure; E' will be used as a verification and to ensure that the observed events are truly consistent with being from elastic ep scattering. The Q^2 analysis presented in this dissertation will use Equation 5.4.



FIG. 5.13: Plot of measured $\langle Q^2 \rangle$ with a 3x3 mm² raster.

The simulated $\langle Q^2 \rangle$ for the experiment is 0.026 GeV²/c² and the currently measured values for $\langle Q^2 \rangle$ is (0.0274 ± 0.0013) GeV²/c². A typical Q^2 distribution obtained with the beam rastered at 3x3 mm² is shown in Figure 5.13. The Q^2 uncertainty is explained in further detail in section 5.3.4.

One major source of problems in the Q^2 analysis has been the HDCs. It was discovered that the F1TDC time window has been cutting off the first ≈ 10 ns of its drift time spectrum and thus reducing its position resolution and efficiency. The problem was only recently discovered and corrected; the data already taken will be reanalyzed with the HDC drift time spectra shifted by 10 ns to put it in the correct place in time. Further refinements will include HDC geometrical corrections and improvements to the track identification algorithms.

Date	Value (GeV)	Uncertainty (GeV)
Jan 10 2011	1.16033	0.0001
May 11	1.16044	0.0001
Average	1.16038	0.0001

TABLE 5.5: Beam Energy Measurements

The beam energy is the energy of the electron beam before it hits the target and is requested to be nominally 1.165 GeV. The electron beam's energy is measured by using a defined procedure that has been used at JLab for numerous previous experiments [59]. The procedure begins by turning off the quadrupole magnets in the arc that cause the beam to be focused while leaving the eight dipole magnets on in the arc leading to the Hall C end-station. The field of one of the eight dipoles was mapped and all eight are assumed to be identical. A harp is a thin tungsten wire (~ 10 μ m) of metal that is moved transversely across the beam-line causing scattering to occur when the harp and the beam intersect [60]. The position of the harp is defined using a stepper motor and allows a measurement of the beam's position to $\sim 10 \ \mu m$ precision. There is a harp that is used to measure the position at the entrance and one at the exit of the string of dipoles. With the magnetic field known and the deflection of the beam caused by the magnetic field known, the electron beam's energy can be calculated. The results of the two beam energy measurements performed are located in Table 5.5. The two measurements only differed by 0.0001 GeV over 4 months, a very consistent result. The electron beam energy is the best well known of the 3 variables that go in to the calculation of Q^2 ; therefore, once the Q^2 equation is reduced to two variables because of the elastic scattering, beam energy should clearly be one of the two.

5.3.2 Scattering Angle

The scattering angle is the angle at which the scattered electron deviates from its original trajectory. The scattering angle is measured using the HDCs alone and is the angle of those tracks that originate from the target and still hit the trigger scintillator behind the VDCs (ensuring both the charged particle is an electron and that it has the appropriate energy as selected out by QTOR). The measured scattering angle distribution may be seen in Figure 5.14. The scattering angle is nominally 7°-9° and the central value was measured to be 8.1°.



FIG. 5.14: Scattering angle for elastic electrons in degrees for a typical tracking run.

The second factor calculated from the HDCs is the Z vertex, or Z position where the distance of closest approach to center of the beam-line exists. The measured distribution of Z vertices is shown in Figure 5.15. The hydrogen cell is 35 cm long and it is centered at -650 cm (0 cm is defined as the center of QTOR), so it begins at -667.5 cm and ends at -632.5 cm. The measured distribution is centered at -646.8 cm, so it is 3.2 cm away from nominal, but the HDC tracking software is currently under development and should improve the resolution and accuracy of the HDC tracking software, thus improving the measurement of both the scattering angle and Z vertex.



FIG. 5.15: Z Vertex in cm for a tracking run.

5.3.3 Scattered Energy

The scattered energy is the energy that the electron retains after being scattered from the proton target. The scattered electron beam's energy is measured by starting
with the known magnetic field of QTOR as simulated, and verified with selective mapping, the known entrance, using the HDCs, and exit, using the VDCs, of a charged particle into and out of QTOR's magnetic field. With the entrance and exiting trajectory known, the energy can be reconstructed by "swimming" the charged particle through the simulated magnetic field, such that it matches the measured paths. The scattered energy is the variable that Q^2 can depend on that is dependent on numerous factors from the drift chambers to QTOR's field, so it contains the most uncertainty with it and requires more accurate information to properly reconstruct. The kinetic energy is also likely to improve as the HDC software improves.



FIG. 5.16: Kinetic energy in GeV for a tracking run.

5.3.4 Q^2 Uncertainty and the Final 0.5% Measurement

The current dominant uncertainty on Q^2 comes from a presently undetermined source. All of the analysis of Q^2 is this dissertation is with the HDC software and hardware in a poorly working state and with no cuts of any kind on the variables that go into Q^2 . Initial studies were performed on the systematic effect of beam position and raster size on the measured Q^2 . The study on beam position is shown in Figure 5.17. The general trend seen in the study of Q^2 vs. beam position is that there is a minimal effect of the beam position on Q^2 with the possible exception of the +1 mm X +1 mm Y data point. The nominal position of the beam is maintained to better than 100 μ m, so to scale the effect seen in the study of ~3.5% over 1 mm down to the nominal changes it would be ~0.35% over 100 μ m.



FIG. 5.17: Q^2 vs. beam position in X and Y.

A similar study was done of Q^2 vs. raster size, shown in Figure 5.18, that

yielded no significant deviation in the nominal raster range of 2 mm to 4 mm. The raster study did however, reveal an uncontrolled systematic error that is presently the dominant source of error of Q^2 . During unstable beam conditions (the event rate was falling and the chopper slit was adjusted to increase the event rate), the Q^2 was measured with the raster at 1x1 mm and values were recorded that were 5% different (6 σ) from each other while all controllable parameters were the same, although it should be noted that the data points were at a raster setting where production data is never taken.



FIG. 5.18: $\langle Q^2 \rangle$ vs. beam position in X and Y.

A third study was completed by measuring the effect of the field of QTOR on Q^2 . As was previously stated, the equation used here for Q^2 is Equation 5.4 (which depends on E'). The study varied QTOR's field thus, moved the elastic scattered beam profile radially in response to the field change, and then normalized the measured Q^2 by QTOR's current. The general behavior is as expected; once normalized by QTOR's current, the distribution is approximately flat. The important thing to notice is the relatively small changes in Q^2 over the full current range. The running conditions during this study were much more stable than during the position study described earlier. Over the run range between QTOR = 8900 A to 8940 A (nominal is 8921 A), the difference between the smallest and largest values are only 0.5%.



FIG. 5.19: Q^2 vs. QTOR current.

From the results of the studies, there is no known systematic effect studied thus far that will prevent the measurement of $\langle Q^2 \rangle$ to 0.5% precision from being reached. There are two possibilities that could explain the random behavior differences between the QTOR study and the raster study: small fluctuations in scattering angle or an increase in leakage current from the other halls that were amplified by unrefined tracking software that cuts and improvements will remove or a real systematic difference between the running conditions in the studies. The beam position and current are not monitored or used to feed back on during tracking mode running, unlike the case of production running, so there may always be some instabilities in the beam that are a product of the pA beam, that are not present in high current running.

The only way a measurement of $\langle Q^2 \rangle$ to 0.5% precision will be possible is if the random differences from run to run are better understood and if beam time is given to allow for those studies. The likely culprit is beam current, which if is better understood using techniques that are still being developed (like the luminosity monitors) and improved software, the deviations should shrink to ranges that will be necessary for the 0.5 % measurement. There has been clear times when conditions are stable and can produce reproducible Q^2 values, so stability is possible, it simply must be studied more carefully.

The likely choice for the Q^2 measurement variables are E and θ which only require properly working HDCs (primarily software), which is not the current situation, the measurement of E' from the VDCs is for verification purposes only. The VDCs are, however, essential for an additional aspect of the $\langle Q^2 \rangle$ measurement. They must measure the light distribution across the primary quartz detectors, which they are presently capable of doing, so the variance in light produced by track positions and angles is removed in software, as will be discussed in Section 5.3.6. Overall the VDCs are in a position to make the 0.5% measurement, once we have better control on the beam quality and parameters at ultra low currents, and the HDCs are a work in progress that should be complete in the near future.

5.3.5 Projections

The tracks measured by the VDCs may be projected to any location along the beam line as long as there is no magnetic field that would have caused the charged particles to bend from a straight path. These projections can be used to learn about the overall shape of the scattered electron's profile, determine what does or does not hit a detector, or to determine what does or does not hit a detector to measure the accuracy of the projections.



FIG. 5.20: VDC Projection on to the (x,y) plane of the scanner in a run triggered by the scanner. The color scale indicates the number of tracks projected to the pixel. The expected diamond shape of the detector is seen.



FIG. 5.21: Projection of all tracks seen by the VDCs onto the position of the primary quartz detectors with the color scale as logarithmic indicating the number of tracks in the pixel. The primary quartz detectors lie between -100 cm and 100 cm on the y axis and 325 cm to 343 cm on the x axis.

As a reminder, the focal plane scanner is a movable 1 cm × 1 cm × 2 cm quartz crystal located in one octant that has been surveyed to sub-millimeter accuracy by the survey and alignment group at JLab. Figure 5.20 is a projection of the tracks on to the plane of the scanner, measured by the VDCs in a data run when the scanner provided the trigger. Assuming the scanner is a perfect trigger, which of course it is not, the accuracy of the tracking can be measured. The projection in Figure 5.20 is a $\sqrt{2}$ cm × $\sqrt{2}$ cm plot because the detector is a rotated square. The $\sqrt{2}$ cm × $\sqrt{2}$ cm projection contains 93% of the tracks reconstructed in the run with the remaining 7% presumably coming from a combination of false triggers from the scanner and falsely reconstructed tracks. The other piece of information gained from the scanner projection is the geometrical accuracy of the VDCs. The scanner is located at X = 323 cm and Y = 0 cm, so the projection is off by 5 mm in the Y direction and 2 mm in the X direction, which suggests that the knowledge of the geometry of the VDCs is not yet perfect and will be refined and improved with time.

Figure 5.21 is a projection of the scattered electron's profile projected to the Z of the primary quartz detector in a data run triggered by the trigger scintillator. The shape seen is the "moustache" shape as expected from previous experiments and simulations from the focusing in the X direction and defocusing in the Y direction produced by the toroidal magnetic spectrometer and causing the profile to land on the primary quartz detector as desired. The primary quartz detectors lies between Y = 100 cm and -100 cm and X = 326 cm and 343 cm. The portion of the profile that falls onto the detector and off the detector is explored further in Section 5.3.6. The profile is not centered in X in order to suppress the detection of scattering from the front Al window of the target cell.

5.3.6 Light-Weighting

The projections of Section 5.3.5 can be weighted by the signal size of a detector to determine which tracks do and do not hit a detector in question. Figure 5.22 contains a copy of Figure 5.21 for reference and a copy of the same figure weighted by the summed response of both of the PMTs attached to the primary quartz detector behind the VDC used to make the projection. From this light-weighted projection the portion of the scattered profile that interacts in the primary quartz detector is clearly separated from the non-interaction portion and the size of the primary quartz detector is measured. The detector is $2 \text{ m} \times 18 \text{ cm}$, exactly as seen in the figure.

A second weighting method became a powerful yet unexpected tool. Figure 5.23 contains the same type of plot as seen in Figure 5.22 for primary quartz detector number 1 but is weighted by the PMT response of only one of the two tubes. The

glue joint between the two halves of the detector is clearly visible. When the same plot is made for any primary quartz detector other than number 1, the glue joint is far less visible. It was discovered that primary quartz detector number 1 was losing more light across the glue joint than the others; therefore, either somewhat separating or the glue became opaque. The problem was discovered and tracked with time and it was learned that the problem was not getting worse and, more importantly, it was not affecting the parity analysis.

Light-weighting will also be important to make a correction to the amount of light produced as a function of where, and with what angle, the electron impacts the primary quartz detector. The distribution of number of photoelectrons seen in Figure 5.22 is clearly not uniform. This correction, that is currently under development, will come in the form of a small ~1.5% (from simulation) change in the effective Q^2 distribution across the primary quartz detector. This correction is necessary because the main measurement is the integration over a time window. The light weighting breaks up a summed amount of light into its average distribution across the primary quartz detector. The events that hit the center of the primary quartz detector will produce some amount of light and have an associated Q^2 and will come at a fixed rate; similarly, events that hit the ends of the primary quartz bars will have a different amount of light produced, a different Q^2 , and come at a different rate.



FIG. 5.22: Top: Typical VDC track projection (octant 5) to the primary quartz detectors weighted by the response of the sum of their PMTs. The color scale is the number of photoelectrons measured by both PMTs. The shape of the detectors is clearly visible. Bottom: The same projection as above with no weighting. The color scale indicates the number of tracks in a pixel.



FIG. 5.23: VDC track projection to the primary quartz detectors, weighted by the response of only one of the PMTs on the primary quartz detector in octant 1. The number of photoelectrons drastically changes when going over the glue joint at the center of the y axis. The color axis is number of photoelectrons measured by only one PMT.

5.4 Q_{weak}^P

In order to extract Q_{weak}^P from the measured parameter A_m , corrections for experimental backgrounds and beam polarization must be applied using Equation 5.2 which yields A_{ep} . A summary of the measured parameters used to calculate A_{ep} are located in Table 5.7. Once A_{ep} is isolated from the measured parameters, the axial and vector hadronic corrections are applied using

$$A_{ep} = A_{QW} + A_{had}^V + A_{had}^A \tag{5.7}$$

where A_{had}^V is the vector hadronic asymmetry correction and A_{had}^A is the axial hadronic

asymmetry correction. Equation 5.7 to finally produce the base asymmetry A_{QW} . A_{QW} has no remaining contribution from hadronic structure. Q^P_{weak} is then calculated using Equation 5.3 where the "B" term has been properly accounted for using the hadronic corrections applied earlier.

Source	$\Delta Q_w^P / Q_w^P$
Counting Statistics	23.3~%
Beam Polarization	3.6~%
Aluminum Asymmetry	4.5 %
$Q^2~({ m GeV^2/c^2})$	10.0~%
Hadronic Structure	$1.5 \ \%$
Blinding Factor	23.3~%
Total with Blinding	35~%

TABLE 5.6: Contributions to Uncertainty of Q_{weak}^P

The largest and dominant uncertainty is the statistical uncertainty on the asymmetry measurement of 35 ppb combined with the 60 ppb blinding factor create the error on the asymmetry of 50 ppb if the blinding factor is treated as an rms. The BLINDED value of Q_{weak}^P is 0.102 \pm 0.036. The blinding factor has been treated like an additional random error on the measurement and has created a final error on Q_{weak}^P of ~35%. Once the blinding factor is removed and the precision on the aluminum asymmetry is increased, the data will have a 25% uncertainty as was originally estimated.

	Value	Uncertainty
$A_m (ppb)$	-187	50
Beam Polarization (%)	88.4	2.4
Aluminum Asymmetry (ppb)	1610	160
Aluminum Dilution Factor	0.031	0.003
$Q^2~({ m GeV^2/c^2})$	0.027	0.0013

TABLE 5.7: Values Used to Extract Qweak

CHAPTER 6

Conclusions and the Path Forward

The Qweak experiment has been through many different challenges and trials, but is on the way to collect the necessary statistics in the allotted running time. It has been through power supply failures, beamline failures, failures to deliver quality beam, and shielding redesigns, and have still collected ~25% of the data necessary to make it to the 4 ppb error bar. The data-collecting progress of the experiment can be seen in Figure 6.1. In order to achieve the desired error on the final measurement, the experiment will need to run at ~70% efficiency. By the end of Run 1, the experiment had achieved a steady state and was simply collecting statistics, so ~70% efficiency is achievable so long as there are no major failures to deliver high-quality (low halo), highly polarized (85+ %) electron beam at the high currents (180 μ A) the experiment requires.

The polarimetry is now actively being measured using both the Moller and Compton polarimeters and are yielding results that should be able to provide the necessary 1% required precision. To date, the aluminum measurement is good to 10% and will require 30 to 70 more days of data taking, depending on the beam current, to reach 0.35% precision. The N $\rightarrow \Delta$ measurement is good to $\sim 15\%$ and will require only several more hours of data, or a better understanding of the data already collected, to reach the needed precision. There are a few other backgrounds (beam-line, transverse polarization, etc.) that were not discussed that are also on track to be measured precisely enough for the final measurement. The Q^2 is conservatively measured to 5% and will require several more ~1 day long periods spread out over the running period to measure the stability of Q^2 as well as several dedicated days to understand the fluctuations observed.



FIG. 6.1: Summary of the statistics collected during Run 1 with projections to future statistics using various efficiencies. The experiment will need to run at $\sim 70\%$ efficiency for Run 2 to achieve the desired statistical goal.

6.1 World Data + Qweak's Data

The blinded result for the ep asymmetry is $-(277 \pm 63)$ ppb (treating the blinding factor as an uncertainty) and for Q_{weak}^P is 0.102 ± 0.036 . The measured value for Q_{weak}^P is consistent with the Standard Model within 1 σ . The ep asymmetry result along with current world data vs. Q^2 is plotted in Figure 6.2 and the isoscalar vs. isovector combinations of the weak charges result including world data is shown in Figure 6.3. The most important result shown is that the Qweak experiment is on its way to making the 4 ppb measurement that will be able to accept or reject various new physics models and that the currently measured value is consistent with the Standard Model to 1σ .



FIG. 6.2: Current world data on the parity-violating asymmetry of the proton in the low- Q^2 region with its extrapolation to $Q^2 = 0$ [29] including the new point from Qweak shown in orange. The Standard Model value is shown by the red star, the blue line with light blue error bars is the best fit to all data. The newest point from Qweak has moved the global fit directly on top of the Standard Model Value.



FIG. 6.3: Isoscalar vs. isovector combinations of the weak charges of the up and down quarks with new results. The previous modern limits are set by APV and parity-violating electron scattering and lie within the small green oval [29]. The new limits from this measurement shift the parity-violating electron scattering data from the green ellipse to the gray ellipse.

Once the presented measurement is unblinded, the measurement of Q^P_{weak} will be accurate to ~25% as desired. The current world data on Q^P_{weak} including all parityviolating electron scattering data was 0.0589 \pm 0.0231 and is now, including this measurement, 0.0743 \pm 0.0185 and the precision generated from the 25% measurement will further increase the world knowledge of Q^P_{weak} . The unblinded asymmetry measurement will be good to 17% and will be a strong standalone measurement in the unmeasured region of $Q^2 = 0.027 \ (\text{GeV/c})^2$ as seen in Figure 6.2. Overall, QTOR is properly manipulating the scattered electron's profile, the primary quartz detectors are measuring data at counting statistics rates, the tracking system is measuring the Q^2 distribution which agrees with simulation, the measured asymmetry has the correct sign and magnitude for aluminum and hydrogen and when adding the half-wave plate states together, the result is consistent with 0, and JLab has been delivering the appropriate polarization, quality, and current electron beam to the experiment.

BIBLIOGRAPHY

- M. J. Ramsey-Musolf and S. Su, "Low-energy precision tests of supersymmetry," Phys. Rep., vol. 456, no. 1-2, pp. 1–88, 2008.
- [2] T. D. Lee and C. N. Yang, "Question of parity conservation in weak interactions," Physical Review, vol. 104, no. 1, p. 254, 1956.
- [3] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, "Experimental test of parity conservation in beta decay," <u>Phys. Rev.</u>, vol. 105, no. 4, p. 1413, 1957.
- [4] C. Y. Prescott, W. B. Atwood, R. L. A. Cottrell, H. Destaebler, E. L. Garwin, A. Gonidec, R. H. Miller, L. S. Rochester, T. Sato, D. J. Sherden, <u>et al.</u>, "Further measurements of parity non-conservation in inelastic electron scattering," <u>Phys.</u> Lett. B, vol. 84, no. 4, pp. 524–528, 1979.
- [5] W. Heil, J. Ahrens, H. G. Andresen, A. Bornheimer, D. Conrath, K. J. Dietz, W. Gasteyer, H. J. Gessinger, W. Hartmann, J. Jethwa, et al., "Improved limits on the weak, neutral, hadronic axial vector coupling constants from quasielastic scattering of polarized electrons," Nucl. Phys. B, vol. 327, no. 1, pp. 1–31, 1989.
- [6] P. A. Souder, R. Holmes, D. H. Kim, K. S. Kumar, M. E. Schulze, K. Isakovich, G. W. Dodson, K. W. Dow, M. Farkhondeh, S. Kowalski, <u>et al.</u>, "Measurement of parity violation in the elastic scattering of polarized electrons from ¹²C," <u>Phys.</u> Rev. Lett., vol. 65, no. 6, pp. 694–697, 1990.
- [7] E. J. Beise, M. L. Pitt, and D. T. Spayde, "The Sample experiment and weak nucleon structure," Prog. Part. Nucl. Phys., vol. 54, pp. 289–350, 2005.
- [8] S. Baunack, K. Aulenbacher, D. Balaguer Ríos, L. Capozza, J. Diefenbach, B. Glaser, D. Von Harrach, Y. Imai, E. M. Kabuß, R. Kothe, et al., "Measurement of strange quark contributions to the vector form factors of the proton," Phys. Rev. Lett., vol. 102, no. 15, p. 151803, 2009.
- [9] K. A. Aniol, D. S. Armstrong, T. Averett, H. Benaoum, P. Y. Bertin, E. Burtin, J. Cahoon, G. D. Cates, C. C. Chang, Y. C. Chao, et al., "Parity-violating

electron scattering from ⁴He and the strange electric form factor of the nucleon," Phys. Rev. Lett., vol. 96, no. 2, p. 22003, 2006.

- [10] D. S. Armstrong, J. Arvieux, R. Asaturyan, T. Averett, S. L. Bailey, G. Batigne, D. H. Beck, E. Beise, J. Benesch, L. Bimbot, et al., "Strange-quark contributions to parity-violating asymmetries in the forward G0 electron-proton scattering experiment," Phys. Rev. Lett., vol. 95, no. 9, p. 92001, 2005.
- [11] Z. Ahmed, K. Allada, K. A. Aniol, D. S. Armstrong, J. Arrington, P. Baturin, V. Bellini, J. Benesch, R. Beminiwattha, F. Benmokhtar, et al., "New precision limit on the strange vector form factors of the proton," <u>Arxiv preprint</u> arXiv:1107.0913, 2011.
- [12] K. Paschke, A. W. Thomas, R. Michaels, and D. S. Armstrong, "Strange vector form factors from parity-violating electron scattering," <u>J. Phys. Conf. Ser.</u>, vol. 299, no. 012003, 2011.
- [13] A. Acha, K. A. Aniol, D. S. Armstrong, J. Arrington, T. Averett, S. Bailey, J. Barber, A. Beck, H. Benaoum, J. Benesch, et al., "Precision measurements of the nucleon strange form factors at Q² ~ 0.1 GeV²," <u>Phys. Rev. Lett.</u>, vol. 98, no. 3, p. 32301, 2007.
- [14] R. G. Sachs, "High-energy behavior of nucleon electromagnetic form factors," Phys. Rev., vol. 126, no. 6, p. 2256, 1962.
- [15] C. E. Hyde-Wright and K. de Jager, "Electromagnetic form factors of the nucleon and compton scattering," Rev. Nucl. Part. Sci, vol. 54, pp. 217–267, 2004.
- [16] M. Gorchtein and C. Horowitz, "Dispersion gamma z-box correction to the weak charge of the proton," Phys. Rev. Lett., vol. 102, p. 091806, 2009.
- [17] B. C. Rislow and C. E. Carlson, "Contributions from γz box diagrams to parity violating elastic ep scattering," <u>Physical Review D</u>, vol. 83, no. 11, p. 113007, 2011.
- [18] A. Sibirtsev, P. G. Blunden, W. Melnitchouk, and A. W. Thomas, "gamma-z corrections to forward-angle parity-violating ep scattering," <u>Physical Review D</u>, vol. 82, no. 1, p. 013011, 2010.
- [19] P. G. Blunden, W. Melnitchouk, and A. W. Thomas, "New formulation of gamma-z box corrections to the weak charge of the proton," <u>Arxiv preprint</u> arXiv:1102.5334, 2011.

- [20] A. V. Afanasev and C. E. Carlson, "Two-photon-exchange correction to parityviolating elastic electron-proton scattering," <u>Phys. Rev. Lett.</u>, vol. 94, p. 212301, Jun 2005.
- [21] C. Y. Prescott, W. B. Atwood, R. L. A. Cottrell, H. Destaebler, E. L. Garwin, A. Gonidec, R. H. Miller, L. S. Rochester, T. Sato, and D. J. Sherden, "Parity non-conservation in inelastic electron scattering," <u>Phys. Lett. B</u>, vol. 77, no. 3, pp. 347–352, 1978.
- [22] K. Nakamura, "Particle data group," J. Phys., vol. G37, 2010.
- [23] J. S. M. Ginges and V. V. Flambaum, "Violations of fundamental symmetries in atoms and tests of unification theories of elementary particles," <u>Phys. Rep.</u>, vol. 397, no. 2, pp. 63–154, 2004.
- [24] P. L. Anthony, R. G. Arnold, C. Arroyo, K. Baird, K. Bega, J. Biesiada, P. E. Bosted, M. Breuer, R. Carr, G. D. Cates, <u>et al.</u>, "Observation of parity non-conservation in moeller scattering," <u>Phys. Rev. Lett.</u>, vol. 92, no. 18, p. 181602, 2004.
- [25] K. Abe, K. Abe, T. Abe, I. Adam, H. Akimoto, D. Aston, K. Baird, C. Baltay, H. Band, T. Barklow, et al., "High-precision measurement of the left-right Z boson cross-section asymmetry," <u>Physical Review Letters</u>, vol. 84, no. 26, pp. 5945– 5949, 2000.
- [26] G. P. Zeller, K. S. McFarland, T. Adams, A. Alton, S. Avvakumov, L. de Barbaro, P. de Barbaro, R. H. Bernstein, A. Bodek, T. Bolton, J. Brau, D. Buchholz, H. Budd, L. Bugel, J. Conrad, R. B. Drucker, B. T. Fleming, R. Frey, J. A. Formaggio, J. Goldman, M. Goncharov, D. A. Harris, R. A. Johnson, J. H. Kim, S. Koutsoliotas, M. J. Lamm, W. Marsh, D. Mason, J. McDonald, C. McNulty, D. Naples, P. Nienaber, A. Romosan, W. K. Sakumoto, H. Schellman, M. H. Shaevitz, P. Spentzouris, E. G. Stern, N. Suwonjandee, M. Tzanov, M. Vakili, A. Vaitaitis, U. K. Yang, J. Yu, and E. D. Zimmerman, "Erratum: "effect of asymmetric strange seas and isospin-violating parton distribution functions on sin² θw measured in the NuTeV experiment"," <u>Phys. Rev. D</u>, vol. 67, p. 119902, Jun 2003.
- [27] M. Carena, A. Daleo, B. Dobrescu, and T. Tait, "Z' gauge bosons at the fermilab tevatron," Physical Review D, vol. 70, no. 9, p. 093009, 2004.
- [28] I. Cloet, W. Bentz, and A. Thomas, "Isospin dependence of emc effect explains nutev anomaly," <u>Physical Review Letters</u>, vol. 102, no. JLAB-THY-09-933; DOE/OR/23177-0606, 2009.

- [29] R. D. Young, R. D. Carlini, A. Thomas, and J. Roche, "Testing the standard model by precision measurement of the weak charges of quarks," <u>Phys. Rev.</u> Lett., vol. 99, no. 12, p. 122003, 2007.
- [30] S.-L. Zhu, S. J. Puglia, B. R. Holstein, and M. J. Ramsey-Musolf, "Nucleon anapole moment and parity-violating ep scattering," <u>Phys. Rev. D</u>, vol. 62, p. 033008, Jul 2000.
- [31] W. M. Yao, C. Amsler, D. Asner, R. M. Barnett, J. Beringer, P. R. Burchat, C. D. Carone, C. Caso, and O. Dahl, "Review of particle physics," <u>J. Phys. G</u>, vol. 33, no. 1, p. 164, 2006.
- [32] T. Mossberg, A. Flusberg, and S. R. Hartmann, "Optical second-harmonic generation in atomic thallium vapor," <u>Optics Comm.</u>, vol. 25, no. 1, pp. 121–124, 1978.
- [33] J. Erler, A. Kurylov, and M. J. Ramsey-Musolf, "Weak charge of the proton and new physics," Physical Review D, vol. 68, no. 1, p. 016006, 2003.
- [34] C. W. Leemann, D. R. Douglas, and G. A. Krafft, "The continuous electron beam accelerator facility: CEBAF at the jefferson laboratory," <u>Ann. Rev. of Nuc. and</u> Part. Sci., vol. 51, no. 1, pp. 413–450, 2001.
- [35] T. Nishitani, T. Nakanishi, M. Yamamoto, S. Okumi, F. Furuta, M. Miyamoto, M. Kuwahara, N. Yamamoto, K. Naniwa, and O. Watanabe, "Highly polarized electrons from GaAs–GaAsP and InGaAs–AlGaAs strained-layer superlattice photocathodes," J. of App. Phys., vol. 97, p. 094907, 2005.
- [36] M. Poelker, P. Adderley, J. Clark, A. Day, J. Grames, J. Hansknecht, P. Hartmann, R. Kazimi, P. Rutt, and C. Sinclair, "Polarized source performance and developments at jefferson lab," in AIP Conf. Proc., pp. 943–948, 2001.
- [37] J. Grames, P. Adderley, J. Benesch, J. Clark, J. Hansknecht, R. Kazimi, D. Machie, and M. Poelker, "Two wien filter spin flipper," <u>Proceedings of 2011</u> Particle Accelerator Conference, 2011.
- [38] M. Hauger, A. Honegger, J. Jourdan, G. Kubon, T. Petitjean, D. Rohe, I. Sick, G. Warren, H. Wohrle, and J. Zhao, "A high-precision polarimeter," <u>Nucl. Instr.</u> Meth. A, vol. 462, no. 3, pp. 382–392, 2001.
- [39] J. Jorda, M. Authier, M. Baylac, E. Burtin, C. Cavata, J. Chen, N. Colombel, P. Deck, A. Delbart, and N. Falletto, "A new type of compton polarimeter for

jefferson lab hall a," tech. rep., Thomas Jefferson National Accelerator Facility, Newport News, VA (US), 1998.

- [40] W. Deconinck, "A precise compton polarimeter for hall c at jefferson lab." Presentation at April APS Meeting, Feb. 2010.
- [41] G. Smith, "High power targets." PAVI 2009 Talk, http://web.mit.edu/pavi09/, June 2009.
- [42] A. Fluent, "12.0," Theory Guide, 2009. http://www.ansys.com/.
- [43] Q. Collaboration, "Qweak proposal v2." Proposal to PAC, www.jlab.org/qweak, 2004.
- [44] K. Myers Private Communication.
- [45] J. Leacock Private Communication.
- [46] G. Charpak, "Evolution of the automatic spark chambers," <u>Annual Review of</u> Nuclear Science, vol. 20, no. 1, pp. 195–254, 1970.
- [47] K. G. Fissum, W. Bertozzi, J. P. Chen, D. Dale, H. C. Fenker, J. Gao, A. Gavalya, S. Gilad, C. R. Leathers, and N. Liyanage, "Vertical drift chambers for the hall a high-resolution spectrometers at jefferson lab," <u>Nucl. Instr. and Meth. A</u>, vol. 474, no. 2, pp. 108–131, 2001.
- [48] K. Grimm Private Communication.
- [49] R. Veenhof, "Garfield, a drift chamber simulation program," <u>CERN program</u> library W, vol. 5050, 1984.
- [50] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, and G. Barrand, "Geant4-a simulation toolkit," <u>Nucl. Instr.</u> and Meth. A, vol. 506, no. 3, pp. 250–303, 2003.
- [51] A. Stesalit, "Ch-4234 zullwil switzerland."
- [52] M. L. Pitt, "VT HDC group." Virginia, USA.
- [53] A. Sharma and R. Veenhof, "Properties of some gas mixtures used in tracking detectors," tech. rep., CERN, 1990.

- [54] F. J. Barbosa, E. Jastrzembski, J. Proffitt, and J. Wilson, "The jefferson lab high resolution tdc module," in <u>Nuclear Science Symposium Conference Record</u>, IEEE, vol. 1, pp. 135–139, 2002.
- [55] F. Gonella and M. Pegoraro, "The mad, a full custom asic for the cms barrel muon chambers front end electronics," in <u>Proc. 7th Workshop Electronics for</u> LHC Experiments, p. 204, 2001.
- [56] F. Gonella and M. Pegoraro, "Bicmos frontend asic for the readout of the drift tubes of cms barrel muon detector," tech. rep., CERN, 2000.
- [57] M. J. Musolf, T. W. Donnelly, J. Dubach, S. J. Pollock, S. Kowalski, and E. Beise, "Intermediate-energy semileptonic probes of the hadronic neutral current," Physics Reports, vol. 239, no. 1-2, pp. 1–178, 1994.
- [58] T. Donnelly, W. Musolf, M. Barbaro, et al., "Parity-violating quasielastic electron scattering* 1," Nuclear Physics A, vol. 541, no. 4, pp. 525–577, 1992.
- [59] C. Yan, R. D. Carlini, and D. Neuffer, "Beam energy measurement using the hall c beam line," in Proc. Particle Accelerator Conference, p. 2136, 1993.
- [60] C. Yan, P. Adderley, D. Barker, J. Beaufait, K. Capek, R. D. Carlini, J. Dahlberg, E. Feldl, K. Jordan, B. Kross, et al., "Superharp-a wire scanner with absolute position readout for beam energy measurement at cebaf," <u>Nucl. Instr. and Meth.</u> A, vol. 365, no. 2-3, pp. 261–267, 1995.

Appendix

Appendix A: Wire Stringing Instructions

(need 2 people)

1.Both people must be wearing gloves, masks, and hair nets at all times

2. Raise the stringing jig so that any new wires will clearly not touch the G10

3. Carefully place the wire on the spool holder

4.Attach a washer to the end of the wire with two dots of UV glue, hardening a dot for 5 seconds very close to the dot and 15 seconds touching the dot

5.Hand the washer to your partner and place the wire in its correct position with the washer hanging several inches above the table and not touching any other washers and the spool set on the table directly below the wire's slot (PAY CLOSE ATTEN-TION TO SET THE WIRE STRAIGHT DOWN, DO NOT PULL IT WHILE IT IS ON THE JIG)

6.Push down on the wire to make sure it is in contact with the jig at every dowel pin

7.UV glue the wire to the jig (20 Seconds) at the end closest to the spool, once hardened, cut the wire between the glue and the spool

8. Attach the glued together weight to the washer

9.Push down on the wire to make sure it is in contact with the jig at every dowel pin

Appendix

10.UV glue the end of the wire with the weights on it to the jig (do not put any glue on the jig until the weight has been added and is not moving)

11.Cut the weight free

12.Once the days wires have been strung, lower the jig until the wires are just barley resting on the G10

13. Epoxy the wires to the G10 $\,$