The QWeak Experiment:
Searching for Physics Beyond the Standard Model by A Measurement of the Weak Charge of The Proton

A Prospectus

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Buddhini P. Waidyawansa

Department of Physics and Astronomy
Ohio University

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Advisory and Examination Committee

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Prof. Julie Roche (advisor)

____

Prof. Daniel Phillips

____

Prof. Kenneth Hicks

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Prof. Greg Van Patten

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Graduate Coordinator

Abstract

The QWeak experiment at Jefferson Lab will make a measurement of the weak charge of the proton up to a combined statistical and systematic error of 4% by using parity violating e-p scattering. Any deviation observed in this calculation from its prediction in the Standard Model (SM) of the particle physics could reveal new physics and agreement could constrain any possible extensions of SM. As a QWeak thesis student being part of the QWeak Data Acquisition and Software group, my contributions to the experiment will be related to hardware, software and the physics measurement of the systematic error, transverse asymmetry, that I intend to present in my thesis. This proposal contains a brief introduction to the QWeak experiment and an outline of my future contributions to it as a thesis student.

Contents

1. INTRODUCTION

The QWeak experiment [1] at the Thomas Jefferson Laboratory [2] plans to make the world's first precision measurement of the proton's weak charge via parity violating (PV) elastic electron-proton scattering. The experiment will measure the parity violating asymmetry of longitudinally polarized electron beam of 180μA elastically scattering off a liquid hydrogen target at a $Q^2 = 0.026(\text{GeV}/c)^2$. This will determine the protons weak charge to a 4% combined statistical and systematic errors. Any deviation observed in this value may reveal new physics beyond the Standard Model (SM) [3] of the particle physics. In addition, this measurement will provide a 0.3% measurement of the $\sin^2\theta_w$.

This proposal contains a brief overview of the QWeak experiment, its goals and my involvement on it as a thesis student. It is intended as an insight to the work I plan to present in my thesis.

2. PHYSICS MOTIVATION

Despite its continuing success in describing various phenomena in nuclear and particle physics [3], there are theoretical and experimental reasons [4] to believe that the Standard Model (SM) of the particle physics is only a low energy approximation of a more fundamental theory. For decades experiments have been carried out to search for this more fundamental theory by either building high energetic colliders, like the Large Hadron Colllider at CERN which can excite matter in to new forms, or by performing precision measurements at low energies, like the QWeak experiment, which can reveal new physics in the form of deviations from SM predictions.

Low energy precision measurements can be used to test many features of the SM that are hard to observe at much higher energies. One of the experimental techniques used for this kind of measurements is the parity violating phenomena of the weak interaction. Parity violation in polarized lepton nucleon scattering allows the contribution from the weak interaction to be extracted experimentally by measuring the experimental asymmetry. This asymmetry includes low energy electroweak observables such as the "weak charge" which have a definite SM prediction. Therefore, a measurement of this kind allows the SM predictions to be tested experimentally. The QWeak experiment will utilize the parity violation observed in electron proton scattering to make a precision measurement of the "weak charge" of the proton.

The "weak charge" is a terminology used in describing the weak currents created by particles that interact via the weak interaction in an analogy with the electromagnetic interaction, where the interaction occurs between electrically charged particles [5]. The weak charge of the proton Q^{p}_{weak}, is a well defined experimental observable with a firm SM prediction given by

$$Q^{p}_{weak} = 1 - 4sin^{2}\theta_{w} \approx 0.0716 \pm 0.0006 \text{ (at } Q^{2}{=}0)[6], \qquad (1)$$

using radiative corrections and the value of weak mixing angle $\sin^{2}\theta_{w}$ given by SM, which is ≈ 0.2385 at Q^{2}=0 [7]. The suppression of Q^{p}_{weak} due to the value of $\sin^{2}\theta_{w}$ is a property observed only in protons and electrons. Since a measurement of a value which is known to be close to zero is technically more easier than that of a one which has a larger magnitude, it is comparatively easier to extract the value of Q^{p}_{weak} at low Q^{2}. It can then be used to extract the value of $\sin^{2}\theta_{w}$ at low Q^{2} using equation 1.

The weak mixing angle $\sin^{2}\theta_{w}$ determines the coupling of the neutral currents to the helicity of the fermions and the electric charge. The SM predicts the value of the weak mixing angle based on its "running"(variation with Q^{2}) from the Z-pole. Figure 1 contains a plot of the SM predictions for "running" of $\sin^{2}\theta_{w}$ in the $\overline{MS}$ renormalization scheme and experimental results from existing and proposed world data. As can be seen from the graph, previous experimental results have been successful in verifying the general form of the "running" predicted by the SM. The purposed QWeak measurement will be performed with significantly smaller statistical and systematic errors than the existing low Q^{2} data. QWeak minimize the effect of theoretical uncertainties by utilizing existing experimental results to calculate hadronic contribution [8] . All of these experiments use PV electron proton scattering to measure the PV asymmetry to extract different hadron form factors contained in it (see equation 6 in section 3) whereas Qweak use it to extract the weak charge. Hence this similarity between Qweak and those experiments makes the calculation of hadronic contribution in to Qweak asymmetry possible.

All of the techniques used to minimize the error in the Qweak measurement makes it highly probable that any significant deviation of the observed value of Q^{p}_{weak} from the SM prediction would be a signal of new physics [9],[10],[11] whereas an agreement with SM would place new and significant constraints [12] on possible SM extensions.

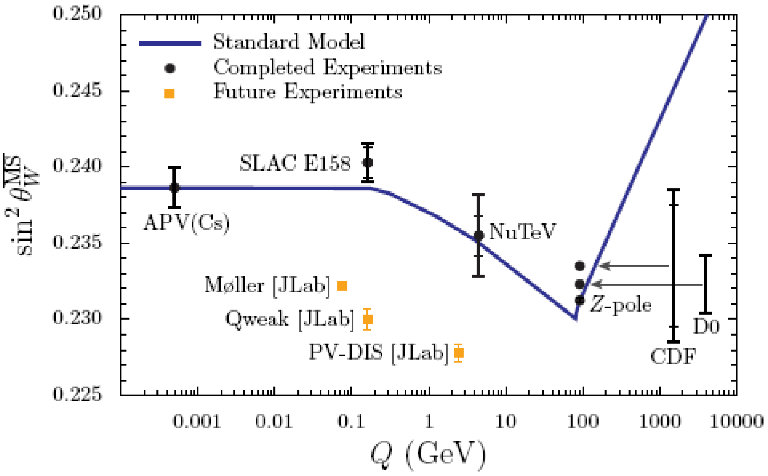

FIG. 1: *The running of the weak mixing angle* $\sin^2\theta_w$ *as a function of the momentum transfer* Q^2 *[13]. The SM prediction is based on the* $\overline{MS}$ *renormalization scheme and it has a minimum which corresponds to* $Q = M_Z$*, the mass of the Z boson [4]. The width of the curve reflects the theory uncertainty from strong interaction effects which is at the level of* $7{\pm}10^{-5}$ *[7]. The current experimental results shown are from APV (Atomic parity Violation) [14], deep inelastic* ν *scattering (NuTeV) [15] [16], the Z pole(LEP and SLAC) [17], D0 [18] and CDF [19] collaboration results, and SLAC E158[20]. The predicted results are for the Qweak, Moller and PV-DIS experiments at JLab. The PV-DIS experiment is scheduled to be run at the end of 2009 and the Moller experiment is scheduled to be run after the 12GeV upgrade (May 2012).*

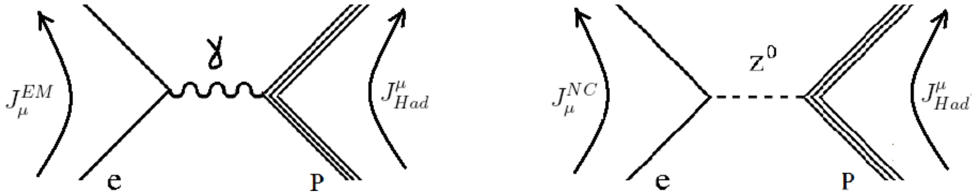

FIG. 2: *The first order Feynman diagrams of the electron proton interaction. The diagram on the left indicates the exchange of a photon via the electromagnetic interaction and the diagram on the right indicates the exchange of the Z boson via the weak interaction.*

3. FORMALISM

3.1. The Longitudinal Asymmetry

The Parity Violating Electron Scattering (PVES) between electrons and nucleons occurs via the electromagnetic interaction and the weak interaction. Figure 2 presents the lowest-order Feynman diagrams for the two interactions. Using Quantum Electrodynamics and applying the Feynman rules of electroweak interaction to theses diagrams one can derive (to the first order) the invariant amplitude of the electromagnetic interaction between the electron and the proton to be

$$\mathcal{M}^{EM} = \frac{4\pi\alpha}{Q^2} e J^{\mu}_{Had} J^{EM}_{\mu} \tag{2}$$

and the invariant amplitude of the weak interaction to be

$$\mathcal{M}^{NC} = \frac{G_F}{2\sqrt{2}} J^{\mu}_{Had} \gamma^{\mu} (g_V - g_A \gamma_5) J^{NC}_{\mu}. \tag{3}$$

(Summation over the indices is implied). Here J^{μ}_{Had}, J^{EM}_{μ} and J^{NC}_{μ} represent the hadronic (Had), electromagnetic (EM) and neutral currents (NC) respectively. α is the fine structure constant and Q is the four-momentum of the electron. g_A and g_V represents the axial and vector coupling constants given by $g_V = -(1 + 4sin^2\theta_w)$ and g_A = - 1 and G_F is the Fermi constant.

Since the electron and the proton scattering can occur via either of these interactions, the total cross section σ for the scattering process is obtained as the summation and the interference of the two exchange processes. i.e.

$$\sigma \approx |\mathcal{M}^{EM} + \mathcal{M}^{NC}|^2 = |\mathcal{M}^{EM}|^2 + |\mathcal{M}^{NC}|^2 + 2(\mathcal{M}^{EM})^* \mathcal{M}^{NC}. \tag{4}$$

The interference term makes the neutral current amplitude accessible via an asymmetry calculation using polarized electrons which can be written as

$$A_{Phys} = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \approx \frac{2|\mathcal{M}^{NC}|}{|\mathcal{M}^{EM}|} \tag{5}$$

with $\overrightarrow{\sigma}(\overleftarrow{\sigma})$ representing cross sections for electrons polarized parallel (anti-parallel) to the direction of motion. By substituting equations 2 and 3 in to equation 5 and using protons EM vector form factors, G$_{Ep}$ and G$_{Mp}$, and the protons neutral vector and axial form factors, G$^{Z}_{Ep}$,G$^{Z}_{Mp}$ and G$^{Z}_{A}$, the physics asymmetry can be derived[21, pgs 59-68] to be,

$$A_{Phys} = \frac{-G_F}{4\pi\alpha\sqrt{2}} \left[\frac{\eta G_{Ep} G^{Z}_{Ep} + \tau G_{Mp} G^{Z}_{Mp} + (1 - 4sin^2\theta_w)\acute{\eta} G_{Mp} G^{Z}_{A}}{(\tau G^{2}_{Mp} + \eta G^{2}_{Ep})} \right] \tag{6}$$

with

$$\tau = \frac{Q^2}{4M_p^2} \tag{7}$$

$$\eta^{-1} = 1 + 2(1+\tau)tan^2\theta \tag{8}$$

$$\acute{\eta} = \sqrt{\tau(1+\tau)(1-\eta^2)}. \tag{9}$$

Here M_p is the mass of the proton and θ is the scattering angle of the electron. By neglecting higher order terms associated with radiative corrections, the parity-violating physics asymmetry for a small momentum transfer in the forward scattering direction ($\theta \rightarrow 0, \varepsilon \rightarrow 0$ and $\tau \ll 1$) is found to be [11]

$$A_{Phys} = \frac{-G_F}{4\pi\alpha\sqrt{2}}[Q^2 Q^p_{weak} + Q^4 B(Q^2)]. \tag{10}$$

The leading order term of equation 10 is just the weak charge Q^p_{weak} and the next-to-leading order term $B(Q^2)$ is the leading term in the nucleon structure defined in terms of neutron and proton electromagnetic and weak form factors[22]. Hence it is evident that an accurate measurement of Q^p_{weak} depends on the accuracy of A_{Phys}, $B(Q^2)$ and Q^2. At very low Q^2, Q^p_{weak} will dominate over $B(Q^2)$. Therefore one can reduce the effect from $B(Q^2)$ by going in to lower Q^2 values. But this will result in a measured asymmetry that is smaller than ppb (parts per billion), which is statistically more difficult to measure. Therefore, an optimum value for $Q^2 = 0.026(\mathrm{Gev/c^2})$ has been determined for QWeak such that it minimizes the effect of $B(Q^2)$ without minimizing the measurable asymmetry. The value of $B(Q^2)$ for this chosen Q^2 value will be obtained by using the existing measurements of A_{Phys} at moderate Q^2 and fitting them (see figure 3) [23] [8]. The accuracy of A_{Phys} is dependent on the accuracy of the experimental asymmetry and polarimetry as discussed in the next paragraph.

Experimentally, the asymmetry of the scattering process is obtained by

$$A_{Exp} = \left[\frac{N_+ - N_-}{N_+ + N_-}\right], \tag{11}$$

where $N = \sigma q L \Omega$ represent the detected number of electrons of positive ($N_+, \overrightarrow{\sigma}$) or negative ($N_-, \overleftarrow{\sigma}$) helicity with luminosity L and charge q deposited on target over a solid angle of Ω. Under the assumption that the luminosity, charge and solid angle remain constant within consecutive helicity states, the measured experimental asymmetry A_{Exp} is related to the physics asymmetry by the relation

$$A_{Exp} = PA_{Phys} \tag{12}$$

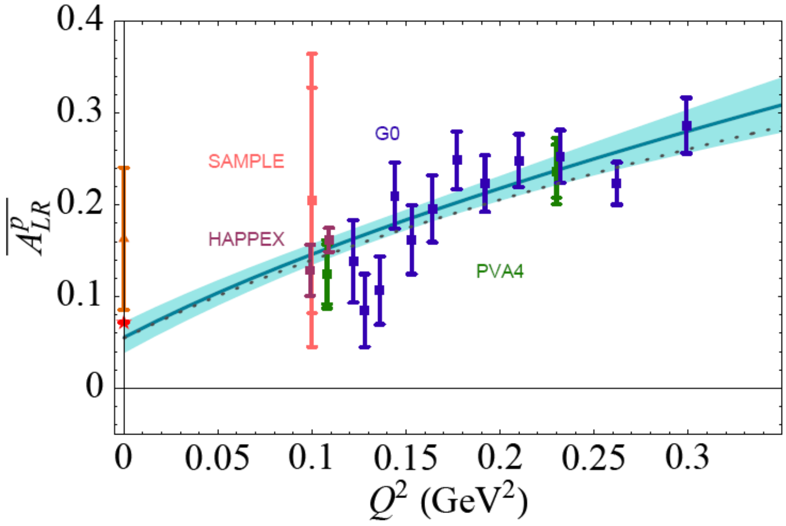

FIG. 3: *The plot illustrates the anticipated methodology to extract Q^p_{weak} from the results of the QWeak experiment. It contains the normalized PVES asymmetry measurements, extrapolated to the forward angle limit using all current world data. The triangular data point represents the previous experimental limit on Q^p_{weak} and the star represents the SM prediction. The solid curve and shaded region indicate the best fit and 1 σ bound, respectively based upon a global fit to all world data. [1]*

with P being the polarization of the electron beam.

The extraction of Q$^p_{weak}$ from the measured A$_{Phys}$ is carried out by first normalizing it as $\overline{A^p_{LR}} = A_{Phys}/Q^2\left(\frac{-G_F}{4\pi\alpha\sqrt{2}}\right)$, and then plotting as a function of the momentum transfer Q^2 along with the existing PVES asymmetry measurements as shown in figure 3. The extrapolation to Q^2=0 of the fitted curve will yield Q$^p_{weak}$. Once Q$^p_{weak}$ is calculated the calculation of sin$^2\theta_w$ using equation 1 will be trivial.

3.2. The Transverse Asymmetry

In addition to measuring the parity-violating longitudinal asymmetry required for the extraction of Q$^p_{weak}$, the QWeak experiment will also perform a measurement of the transverse asymmetry A$_{Trans}$, during a short run, in order to determine its contribution to the longitudinal experimental asymmetry. I will be determining this asymmetry as the physics measurement in my thesis.

The parity conserving transverse asymmetry is a possible systematic error in PVES experiments because it arises due to residual transverse polarization in the beam. In general, the polarization of the beam entering an experimental hall consists of three components of polariza-

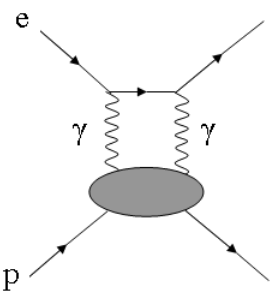

FIG. 4: *Feynman diagram of the two-photon exchange process in the elastic electron proton scattering.*

tion : a longitudinal component parallel to the beam direction and two transverse components normal to the beam direction. The transverse components are created by the residual vertical components of polarizations created in the injector and by the precession of the longitudinal spin component in the horizontal plane of the beam as the beam travels through the arcs [24]. A Wien filter is often used to preset the direction of the beam polarization exiting the injector by rotating the polarization vector by a pre-determined angle such that the spin direction on the experimental target is longitudinal. But the magnitude of this angle is determined to a defined precision. Therefore, there is always some amount of transverse polarization left in the beam hitting the target that will result in a transverse asymmetry[24]. Since the polarimeters in the halls which are only sensitive to the longitudinal polarization, a maximum polarization measurement yields a minimum transverse polarization in the beam [25].

The transverse asymmetry is generated by the two-photon exchange process and other higher order processes in the scattering of transversely polarized electrons from protons [26]. In general, for PV experiments, the longitudinal asymmetry is derived by considering only the first order processes that occur in the interaction as I have discussed in previous section. But as we venture to measure experimental asymmetries with magnitudes of ppm, these higher order processes becomes a significant systematic uncertainty that cannot be neglected. It is known [26] that at 1GeV energy range A_{Trans} can measure up to be about 1 to 10 ppm which is comparable to the expected longitudinal asymmetry of 0.3 ppm for QWeak.

Figure 4 presents the Feynman diagram for the two-photon exchange process which involve the exchange of two photons with an intermediate hadronic state [25]. The real part of this asymmetry is given by [26]

$$A_{Trans}^{Theory} = \frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} = \frac{2ImT_{2\gamma}.T_{1\gamma}^{*}}{|T_{1\gamma|}}, \tag{13}$$

with $T^*_{1\gamma}$ being the one-photon exchange amplitude and $T^*_{2\gamma}$ being the two-photon exchange amplitude. Here, $\sigma \uparrow$ ($\sigma \downarrow$) represents the cross-section for the scattering of an electron polarized parallel(anti-parallel) to a direction normal to the direction of motion. Since the theoretical calculation of A_{Trans} is made difficult by the lack of information on the inelastic hadronic intermediate states required to calculate $T^*_{2\gamma}$, the experimental approach is used instead for its determination by using equation 11 for a transversely polarized electron beam scattering off a proton target. The experimental setup (figure 5) used for this measurement will be the same that is used for the measurement of the longitudinal asymmetry with the few differences discussed next.

Since the polarimeters used in the hall are sensitive only to the longitudinal polarization, the magnitude of the transverse polarization required for the calculation in equation 12 will be determined by fitting the measured longitudinal polarization for a range of Wien filter angels and obtaining the Wien setting/angle that gives the minimal longitudinal polarization. Also, the dependence of the transverse asymmetry in the azimuthal angle results in a transverse asymmetry measured by a *Čerenkov* detector located at a particular angle ϕ to be [25]

$$A^{\phi}_{Trans} = |A_{Trans}| sin(\phi + \phi_0), \tag{14}$$

with $|A_{Trans}|$ being the magnitude of the transverse asymmetry and ϕ_0 being a phase dependent on the direction of the transverse beam polarization. Therefore, to determine the magnitude $|A_{Trans}|$, we need to perform a fit for the measured transverse asymmetry from each of the eight *Čerenkov* detectors as a function of the detector angle on the azimuthal plane.

In addition to being a systematic error for the QWeak experiment, the Transverse asymmetry extracted using the QWeak setup along with many of the existing experimental measurements at different Q^2 will provide means to extract the intermediate hadronic states required for the theoretical calculation of the imaginary part of the two photon process [25].

4. EXPERIMENT OVERVIEW

The QWeak experiment is scheduled to be run in Hall C at Jefferson Laboratory from 2010 to 2012. The main technical challenge to this measurement results from the small expected asymmetry of ≈ -0.3 ppm (parts per million) which is planned to be measured with a 2.1% statistical and 1.3% systematic error [1]. Table I contains the distribution of the expected sources of statistical and systematic errors of the experiment that will contribute to this asymmetry

TABLE I: *Total Error estimate for the QWweak experiment[1]. Includes the contribution to both the physics asymmetry and the extracted. Using this the error of the* $sin^2\theta$ *calculation is found to be 0.3%.*

Source of Error	Contribution to $\frac{\Delta A_{Phys}}{A_{Phys}}$	Contribution $\frac{\Delta Q^p_{weak}}{Q^p_{weak}}$
Counting Statistics	2.1%	3.2%
Hadronic Structure	-	1.5%
Beam Polarimetry	1.0%	1.5%
Absolute Q^2	0.5%	1.0%
Backgrounds	0.5%	0.7%
Helicity Correlated Beam Properties	0.5%	0.7%
TOTAL:	2.5%	4.1%

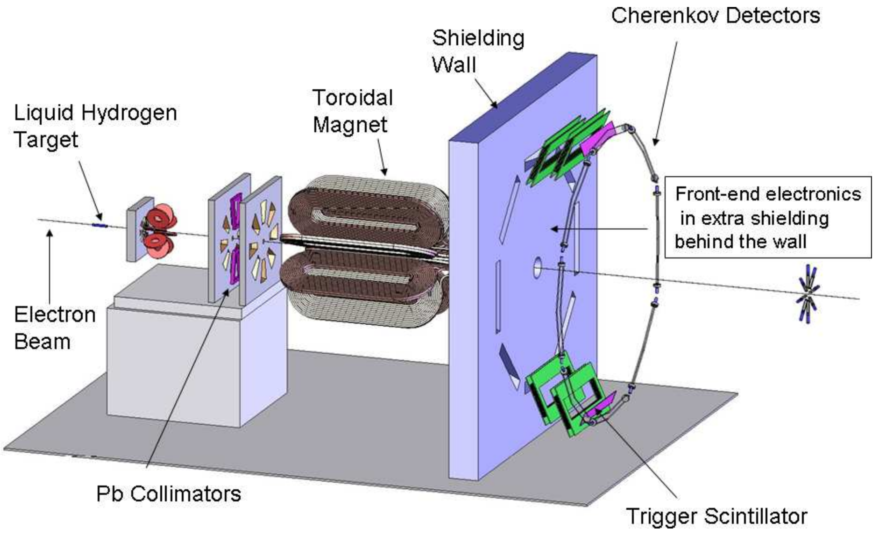

FIG. 5: *Schematic diagram of the Qweak apparatus indicating the main parts of the experimental setup [27].*

and the final Q^p_{weak} measurement. In order to achieve these precisions QWeak will build upon technologies that already exists at Jefferson lab as a result of previous parity violation programs, like G0 and HAPPEX, by adding new hardware and software to accommodate QWeak parameters.

Figure 5 presents a schematic of the QWeak experimental setup and table II contains a summary of basic parameters of the experiment. In general, an 85% longitudinally polarized electron beam with an energy of 1.165GeV will be scattered off from a 35 cm liquid hydrogen cryo-target and a combination of Pb collimators and a toroidal magnet will act as a spectrometer to select and focus elastically scattered electrons with a $Q^2 = 0.026(GeV/c)^2$ and a scattering angle of 7.9^o on to the *Čerenkov* main detectors located azimuthally around

TABLE II: *Basic parameters of the Qweak experiment [1]*

Parameters	Value
Incident Beam Energy	1.165 GeV
Beam Polarization	85%
Beam Current	180 μA
Target Thickness	35 cm
Full Current Production Running	2544 hours
Nominal Scattering Angle	7.9 deg
Acceptance Averaged Q^2	$\langle Q^2\rangle$=0.026 (GeV/c)^2
Acceptance Averaged Physics Asymmetry	$\langle A\rangle$=-0.234 ppm
Acceptance Averaged Experimental Asymmetry	$\langle A\rangle$=-0.200 ppm
Integrated Cross Section	4.0 μb
Integrated Rate (all sectors)	6.5 GHz

the beam. These detectors will be read out using PMTs (Photo-Multiplier Tubes) connected to custom made TRIUMF ADCs (Analog to Digital Converters) manufactured by TRIUMF specially for this experiment[28].

The experiment will collect data in two operational modes called the integrating mode and the tracking mode. The integrating mode will be used to collect data for the experimental asymmetry (equation 11) measurement using a high current of 180μA. It will be the primary mode of running for the experiment. The low current ($\approx$100nA) tracking mode operation will be carried out to measure the Q^2 acceptance and the apparatus will be partially instrumented with a tracking detector system for this purpose.

The CODA (CEBAF Online Data Acquisition)[29][30] based DAQ (Data Acquisition) system of the experiment will be implemented separately for the two experimental modes. The data analysis will be carried out by the specially developed analysis software called the Qw-Analysis software which is capable of both real-time and online analysis.

5. ACHIEVING PARITY QUALITY BEAM

Attaining and maintaining parity quality beam by accurate polarization measurements and minimization of Helicity Correlated Beam Asymmetries (HCBA) (see section 5.2), is very important for PVES precision experiments. As shown in table I, polarimetry and helicity correlated beam asymmetries (HCBA) are the beam related systematics that have considerable effects on the final measurements. In addition, if not properly guided, the electron beam scraping on the beamline apparatus could generate soft photons that will add up to the amount of backgrounds[31]. Also, the control of random noise from beam parameters is important to achieve the desired statistical precision. In order to achieve these, the injector and the Hall C beamline are instrumented with devices such as the Beam Position Monitors (BPMs), Beam Charge Monitors (BCMs), Luminosity Monitors (LUMIs), Polarimeters and other optical devices that can control and guide the beam[32].

5.1. Precision Polarimetry

The dominant experimental systematic uncertainty in the QWeak physics asymmetry measurement will result from corrections due to beam polarization [1] which is expected to be 1% absolute error (see table I). The technology to do this already exists in Hall C in the form of the Basel Mϕller Polarimeter. Even though the Basel Mϕller Polarimeter can provide accurate absolute polarization measurements, its operation is limited to low beam currents up to $2\mu A$ [1]. In order to handle high currents of the QWeak experiment, it is being upgraded with a beam kicker to extend the operatability to currents up to a maximum value of 100μA [1]. Because of the operational limitations of the Basel Mϕller Polarimeter, the QWeak experiment requires an additional polarimeter which can be operated continuously during the 180μA parity runs to measure the beam polarization continuously. This is achieved by using a Compton polarimeter which will be newly installed on the Hall C beamline for the use of QWeak.

The Compton polarimeter uses Compton scattering of electrons and photons to measure the polarization of the electron beam. While it will provide the continuous polarization measurement during the parity runs, the Basel Mϕller Polarimeter will be used as a reference polarimeter to cross-check the Compton measurements and for its low-current calibrations. The Compton polarimeter uses an electron detector and a photon detector for its measurements. As a summer project I was involved in designing and completing the event identification and triggering circuit for the electron detector. I describe my work on this in bit more detail under section 8.

5.2. Helicity Correlated Beam Asymmetries

One of the areas I am working in as a part of my research work on the QWeak DAQ is the minimization of the Helicity Correlated Beam Asymmetries. Therefore I will go in to more detail here about HCBA and techniques used to minimize them.

TABLE III: *Summary of the requirements for minimization of HCBA [1]. This contains the averaged expected values of HCBA for the duration of the experiment and expected HCBA during a quartet spin cycle. A quartet spin cycle can be either + - - + or - + + - and it is averaged over during the calculation of A_{Meas} (see Appendix)*

Parameter (P_i)	Max. run-averaged helicity correlated value (2544 hours at 180μA)	Max. noise during quartet spin cycle (4ms)
Beam Intensity	$A_Q < 10^{-7}$	$A_Q < 10^{-4}$
Beam Energy	$\frac{\Delta E}{E} \lesssim 10^{-9}$	$\frac{\Delta E}{E} \lesssim 10^{-6}$
Beam Position	$\langle \delta x \rangle \lesssim 2nm$	7μm
Beam Angle	$\langle \delta \theta \rangle \lesssim 30mrad$	100μrad
Beam Diameter	$\langle \delta \sigma \rangle < 0.7\mu$m	$< 2mm$

HCBAs are asymmetries generated when beam parameters for the two helicity states are different. Since the measured detector yield Y has a linear dependence on the beam parameters P ($Y = \alpha P$), a false asymmetry is generated when HCBA are present. It is related to the physics asymmetry by [33]

$$A_{Meas} = A_{Exp} + \Sigma_{i=1}^{n} \alpha \frac{\delta P_i}{2\langle Y \rangle}. \tag{15}$$

In equation 15, the last term represents HCBA arising from the ith beam parameter P_i, which changes on helicity reversal by $\delta P_i = P_i^+ - P_i^-$ and $\langle Y \rangle = \frac{1}{2}(Y^+ + Y^-)$ is the average detector yield. The subscripts + and - indicate the value at positive and negative helicity.

Table III contains the beam parameters that are expected to generate HCBA for the QWeak experiment and the upper limits set on them to keep any HCBA generated to be below 0.006 ppm for all the beam parameters except for the beam modulation which it is about 0.06 ppm[1].

In general, the minimization of the HCBA are carried out in two steps. The first step involves fine tuning hardware used in the beamline to make the helicity correlated effects on the beam parameters as small as possible. This is usually done prior to the experiment, before data taking, as a part of the configuration of the beam line instrumentation in the injector beamline. In this step, we minimize the charge asymmetry A_Q which arises due to the imperfect polarization generated by the intrinsic birefringence of the Pockels cell[1] or the PITA (Polarization Induced Transport Asymmetries) Effect[32], other birefringence beam line

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[1] A Pockels cell is an optical device that is used to covert linear polarization in to circular polarization

elements and laser divergence in the Pockels cell, by adjusting the phase induced by the Pockels cell by means of applying a voltage offset called the PITA voltage. Helicity correlated beam position differences are created by the steering effects of the Pockels cell, phase gradients in the laser spot, cathode analyzing power gradients and beam divergences. Steering effects and phase gradients can be minimized by using a Rotatable Half Wave Plate (RHWP) and using a Pockel cell with a small phase gradient. Beam divergence effects can be controlled by using an Insetible Half Wave Plate(IHWP), centering the beam through the PC to minimize steering effects, reducing beam spot size at PC [34].

The next step is carried out during the running of the experiment by using feedback mechanisms to further minimize the helicity correlated effects on beam parameters. The charge asymmetry is further minimized by performing PITA scans [2] during the experiment between 10-100 s[1] time intervals to calculate the required PITA voltage to null A_Q. This value along with the position differences calculated will be updated on to the setup using feedback system. For each quartet, the measured asymmetry will be updated using equation 15. This is also refered to as performing linear regression on the final asymmetry calculation of the events.

In order to familiarize my self in the techniques used in the first step to minimize HCBA I have been working with the collaborators of HAPPEX III experiment in their beam related studies. More details on this work will be mentioned in section 8. The implementation of the linear regression inside the QwAnalysis software is my next task to complete in this area.

6. DATA ACQUISITION SYSTEMS

QWeak CODA-based Data Acquisition (DAQ) systems consists of two distinct modes called Integrating mode DAQ and Tracking mode DAQ. These will be implemented as two independent systems with separate crates and analysis software[1]. As a part of the DAQ group of the QWeak collaboration, my research will be based on working on the implementation of the Integrating mode DAQ system.

6.1. Integrating Mode

The experimental asymmetry measurement will be made using the integrating mode DAQ which is based on reading TRIUMF ADCs that digitize signals from the main detector, the

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[2] Measuring A_Q for different values of the PITA voltage. The PITA voltage will then be plotted as a function of the measured A_Q to obtain the PITA voltage value that can null A_Q.

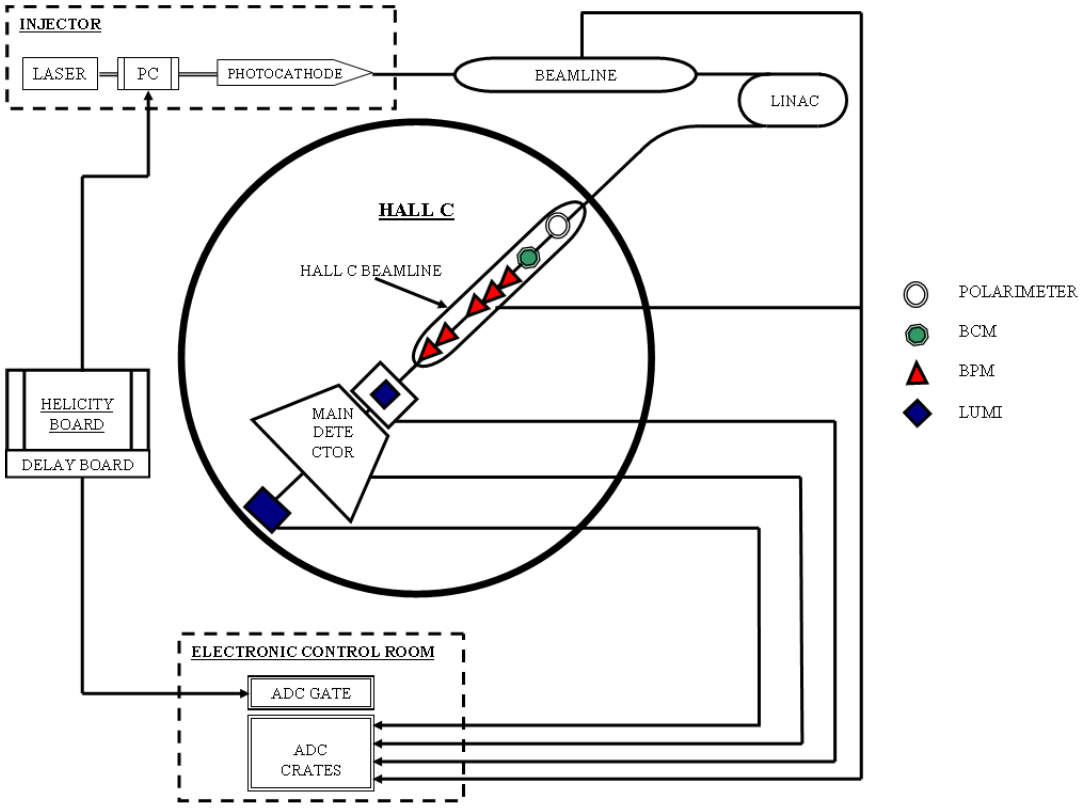

FIG. 6: *Schematic showing the layout of the QWeak Integrating mode DAQ system (not to scale). The devices shown here are just for reference. The actual number of the devices vary depending on the experimental requirement.*

injector and the Hall C beamline monitors. Figure 6 contains a rough layout of the QWeak Integrating mode DAQ system. As shown, the systems of the experiment which will be implemented with integrating mode DAQ are the main detectors, beamline instruments, Pockels cell, helicity board and the delay board.

The helicity board[35] is responsible for generating the pseudo-random helicity pattern that is sent to the Pockels cell to flip the helicity. The pattern consists of multiplets (a pattern of n number of helicities) and are determined with the purpose of cancelling the 60Hz background noise contribution. Currently, the selected pattern for QWeak is called a "quartet". A quartet consists of four helicity bits with the second pair of bits carrying the opposite helicity of the first pair of bits. Figure 7 contains the quartet pattern of + - - + or - + + -. The delay board is responsible for delaying the actual helicity of an event that is being sent to the integrating mode DAQ such that the helicity reported with the event is actually the helicity of an event some predetermined events ago. This is done in order to prevent helicity signal pick-up on the main detector signals and it is usually set as a delay of eight events.

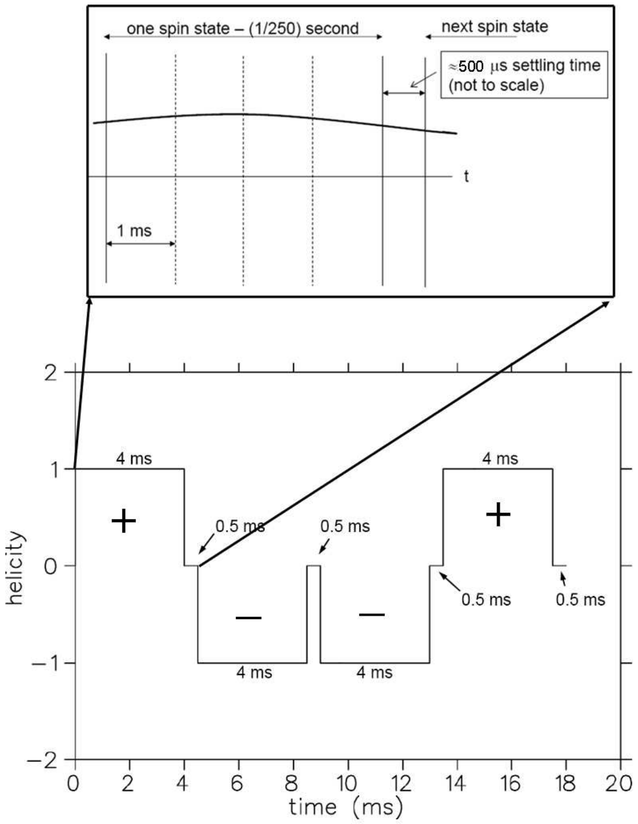

FIG. 7: *Timing signals showing the integrating output(top graph) of the TRIUMF ADC during a helicity window(bottom graph)[27]. The helicity pattern shown is called a "quartet".*

Except for the helicty board and the delay board, each of the systems in figure 7 are connected to TRIUMF ADCs that are located in the Electronics Control room crates and each ADC is provided with an ADC gating signal that is being sent by the helicity board. In normal operation the ADCs will allow a four-fold oversampling of the planned 250 Hz helicity rate as shown in figure 7. Once a new helicity window begins the helicity board will send a notification signal to the ADC to begin integrating signals during the 4 ms helicity window which corresponds to an "event" in the integrating mode. At the end of the window the DAQ will be triggered and within the 0.5 ms settling time of the Pockels cell, the ADCs will be read out by CODA which collects the integrated data flux from the main detector and beam properties from beamline monitors for that event.

7. QWEAK ANALYSIS SOFTWARE

The QwAnalysis software is the data analyzer for the Qweak experiment which will determine the experimental asymmetry and the momentum transfer Q^2 required to extract the weak charge of proton. It is being developed by using C++ and ROOT (an objected oriented framework built by CERN for large scale analysis [36]) and consists of two main parts called the parity analysis engine and tracking analysis engine named after the two required calculations. In terms of processing speed for online analysis, for example, if one expects to calculate and update the PITA voltage for some 50K events within 10-100s, QwAnalysis should be able to process those events within that time period and preferably less than 10s. During the 2544 hrs run with an acquisition rate of 250 Hz, the QWeak data rate would be about 1500 kBytes/s [1] resulting in final data set of about 13 TB. QwAnalysis should be able to process and store this data for quick access for calculating the physics asymmetry and Q^2.

7.1. Parity Analysis Engine

The Parity Analysis Engine or the parity analyzer will be used to determine the experiment asymmetry given by equation 11. Figure 8 contains the basic flow chart of the parity analysis engine. The analysis is carried out by first creating subsystems to store data corresponding to each logical group of the instruments used, for example, in the injector beamline, hall beamline, main detector and helicity board. Once the subsystems are created, input data corresponding to the ROC configurations and the calibration factors for beamline instruments such as BPMs and BCM and parameters of histograms are loaded in. Next the CODA file is loaded on to the system to be decoded. For each event, all the information in CODA will be allocated to relevant subsystems. Once the decoding is done the system will check for hardware consistency, apply calibration factors to the beamline instrumentation and then calculate the yields and the sums required to perform the asymmetry extraction. Event cuts are applied to the data to select "clean data"(usable data) by removing data, for example, associated with low beam currents and beam trips. Once a quartet is processed, the asymmetry will be extracted and corrected for helicity correlated beam asymmetries. All the asymmetries extracted from the quartets will be stored in to the data base for determination of the averaged experimental asymmetry.

For QwAnalysis I work in the implementation of the methods to handle the beamline devices and the helicity information where the helicity related routines are coded in. The analysis

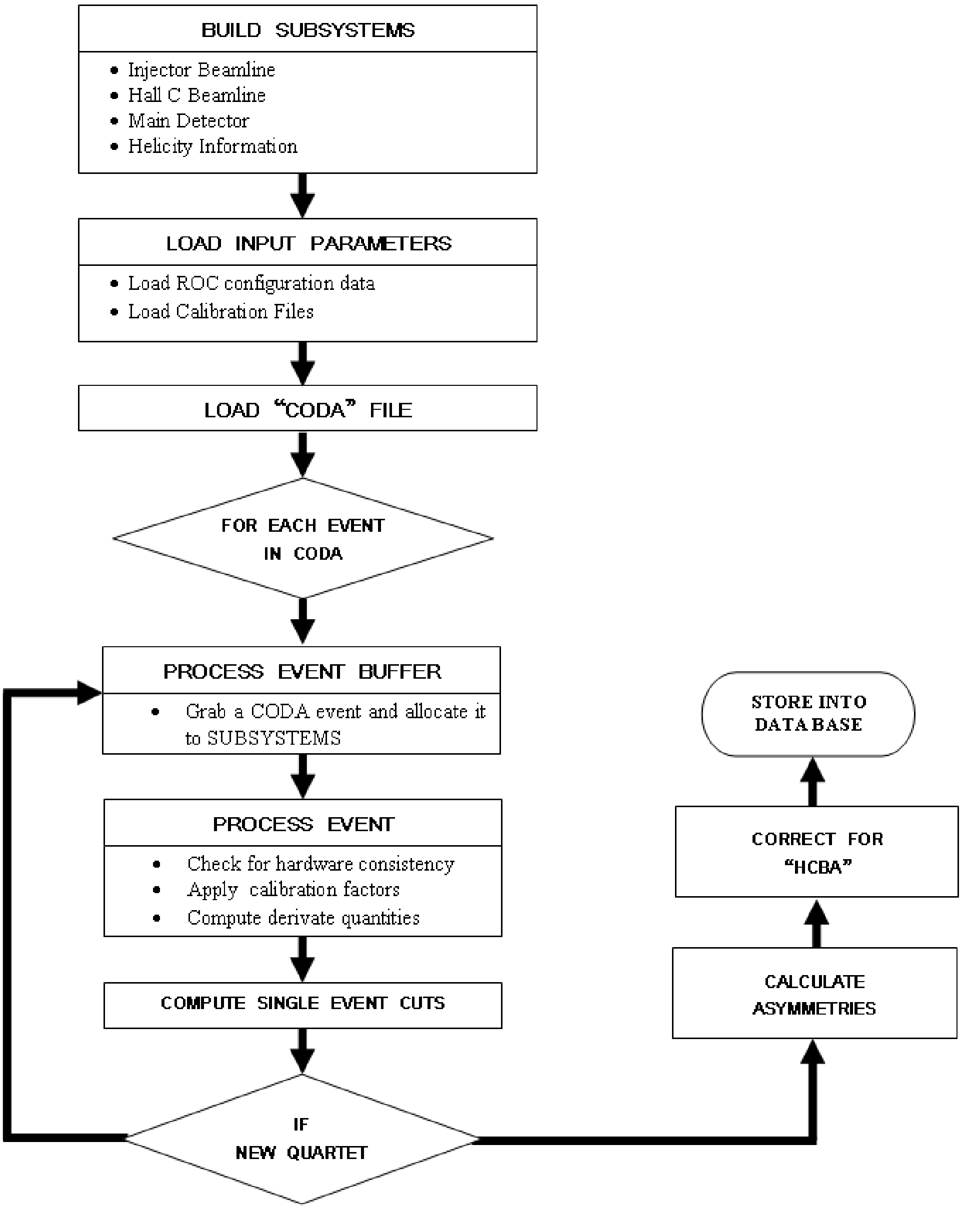

FIG. 8: *The flow digram of the parity analysis engine of the QwAnalysis software.*

frame work currently handles bcm data and bpm data from the beamline and needs to have methods to handle the lumis and the cavity monitors and to perform the linear regression for the asymmetries. My future work on the QwAnalysis will be done on these areas mostly in addition to working on general parts. The Qwanalysis software is written as a group effort by the Analysis group.

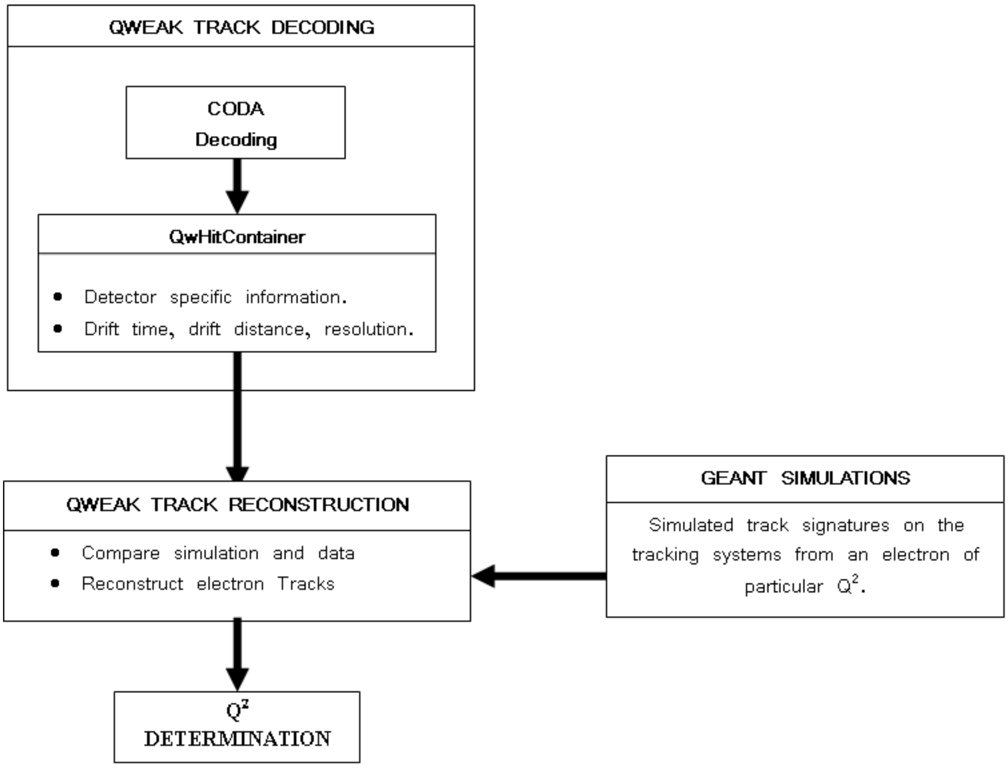

FIG. 9: *The basic architecture of Tracking Analysis Engine of QwAnalysis software.*

7.2. Tracking Analysis Engine

The Tracking analysis engine will be used for path reconstruction of electrons needed for Q^2 determination. It consist of two parts called the Qweak Track Decoding and Qweak Track Reconstruction[37]. The Qweak Track decoding will decode CODA events to extract information such as detector specific information, number of hits on wires, drift time, etc. and pass them on to the Qweak Track Reconstruction routine. The track reconstruction routine will obtain Q^2 for different events by comparing the data sent by the decoder with the simulated data from tracking detectors[38] obtained from GEANT simulations [39] carried out at different Q^2. Once all the tracks are regenerated and the momentum transfers for each event are calculated, they will be fitted to obtain the mean Q^2 of the experiment.

8. MY CONTRIBUTIONS TO QWEAK

As a member of the QWeak DAQ and Software group my future and current research is based on working on those two areas, mainly handling the hardware the Integrating mode DAQ and developing the parity analysis engine of the QwAnalysis software.

During the summer-fall 2008, as a part of a special-study, I was involved in programming of the front-end electronics for the electron detector for the Compton polarimeter during summer-fall 2008. The project goal was to use VHDL (VHIC Hardware Description Language)[40] to design a circuit which can identify electrons that hit a 4-plane semiconductor detector using the signals coming from each of the four detector planes as electrons pass through them. The outputs from this circuit contains information related to the path of the electron and its a status i.e if its an indeed electron that went Compton scattering via a photon or not. More information on my work can be found on the technical report titled *Designing the detection circuit using VHDL for the electron detector of the Compton Polarimeter of Qweak experiment* submitted by me to the Qweak document data base[3] (Qweak-doc-853). It is attached as Appendix 1 of this document.

Currently I am involved in both studying techniques to minimize HCBAs as described in section 5.2 and performing noise studies on the parity DAQ. As a part of the studies on HCBA minimization techniques, I have been collaborating with the HAPPEx III experiment on their studies in HCBA minimization. This involves using Qwanalysis software to reproduce the charge asymmetries, RHWP studies and PITA Scan studies produced by the HAPPEx collaboration on the injector beam studies they have done. In addition to being useful as a cross-check for the performance of the QwAnalysis software these studies have been very important in improving my technical knowledge about performing these studies and taking the required data. The noise studies carried out on the Parity DAQ tests the amount of noise that get add up to the ADC inputs due to background sources and the cables. Before the initial setup we have to be certain that the signals we are measuring via the ADCs are not distorted extensively by noise. This is very important as the Parity DAQ is the DAQ system that handles the main detector signal that are used to generate the physics asymmetry.

In the future, I will be engaged in embedding the linear regression techniques inside the QwAnalysis software to be used to correct the measured asymmetry for the HCBAs as described in section 5.2. Also my work on the Parity DAQ will include over seeing many technical details such as developing maps, identifying hardware requirements etc.

The physics result I intend to put forward in my thesis is the measuring and determination of the transverse asymmetry for the QWeak which is considered to be possible systematic correction for the final physics asymmetry as described in section 3.2. This will use similar techniques used to measure the longitudinal asymmetry used for the calculation of the weak

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[3] To access this data base: go to http://qweak.jlab.org/doc-public/DocumentDatabase

charge but with a transversely polarized beam on a very short run.

Following table contains the time line of my thesis and research work.

Task	2009		2010		2011		2012	
	01-06	07-12	01-06	07-12	01-06	07-12	01-06	07-12
QWeak Installation	✓	✓	✓					
Production running			✓	✓	✓	✓	✓	
Data Analysis					✓	✓	✓	✓
Thesis Writing							✓	✓
Thesis Submission								✓

I joined the Physics PhD program at the Department of Physics and Astronomy at Ohio University in fall of 2007 and attained my PhD candidacy in fall of 2008. So far I have been able to complete four out of the seven required courses for my PhD and plan to complete the remaining three while being located at the Jefferson Labs in Virginia.

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