TJNAF Letter of Intent: Probing QCD Symmetry Breaking Effects via the Parity Violating $N \to \Delta$ Asymmetry at Low Q^2

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April 28, 2003

Abstract

We intend to measure the parity violating asymmetry in the $N \to \Delta$ transition at low Q^2 using the Q_{weak} apparatus. A measurement of this asymmetry will be used to determine the low energy constant, d_Δ, responsible for substantially shifting the asymmetry at low Q^2 such that the asymmetry is non-zero at the photon point. The constant d_Δ was uncovered while investigating hadronic weak radiative corrections and corresponds to the parity violating electric dipole transition matrix element. This same transition drives the asymmetry parameter in radiative hyperon decays which have been found to deviate from their expected values by up to 6 standard deviations in the case of the $\Sigma^+ \to p\gamma$ decay. The same weak Lagrangians used to describe weak radiative hyperon decays are also used to couple the intermediate state resonances to hyperons and daughter nucleons in non-leptonic hyperon decays. It was recently shown that the parameters of the weak Lagrangian fit to simultaneously reproduce the s- and p- wave amplitudes in non-leptonic hyperon decays, itself a long standing puzzle in hyperon physics, brought the radiative hyperon decay asymmetry into better agreement with experiment. These results have led to the prediction that d_Δ may be 100 fold larger than previously assumed. This proposed experiment will measure d_Δ to a precision of 2.5%. A measurement of d_Δ will provide a unique window into the underlying dynamics of the unexpectedly large QCD symmetry breaking effects observed in hyperon decay measurements as well as support a complete understanding of hadronic electroweak radiative corrections which is needed for a proper interpretation of precision electroweak measurements such as those involving strange quark contributions to nucleon form factors, neutron β-decay, and the anomalous magnetic moment of the muon.

1 Introduction

While much has been learned about the nature of the strong interaction and the structure of matter through Quantum Chromodynamics (QCD), we still do not have a thorough understanding of the mechanisms which break the fundamental symmetries on which QCD is based. Symmetry breaking effects are known to be present in this theory, but are often put in "by hand" or parameterized in QCD inspired models, without an understanding of the dynamics which causes those effects.

The parity violating asymmetry in the $N \to \Delta$ transition at very low Q^2 has been shown to be sensitive to an as yet unmeasured and theoretically uncertain low energy constant (d_Δ) which may provide new insight into the dynamics of the breaking of certain QCD symmetries [1]. This observable in these kinematics is dominated by a hadronic electroweak radiative correction that is driven by the same matrix element responsible for the large SU(3) breaking effects observed in hyperon decays, phenomena which have puzzled hyperon physicists for decades.

Additionally, a thorough and complete understanding of hadronic electroweak radiative corrections is necessary for a proper interpretation of precision electroweak measurements such as those involving strange quark contributions to nucleon form factors, neutron β-decay, and the anomalous magnetic moment of the muon, $(g-2)_\mu$. Because the parity violating asymmetry in the $N \to \Delta$ transition at low Q^2 is dominated by such a radiative correction, a precise measurement of this quantity would provide a new handle on understanding hadronic electroweak radiative corrections in general.

Finally, the measurement proposed here will have an impact on two PAC approved experiments to be performed at JLab: the Q_{weak} experiment (E02-020 [2]) and the parity violating asymmetry measurement of the $N \to \Delta$ transition using the G0 apparatus in its backward angle mode (E01-115 [3]). For the Q_{weak} elastic measurements, there will be a small contribution to the elastic asymmetry from inelastic events (due to rescattering effects within the spectrometer). Thus, the measurement proposed here will constrain through direct measurement the contribution to the elastic asymmetry from the inelastic events. For the backward angle $N \to \Delta$ asymmetry measurements, the radiative correction to which the observable proposed here is directly sensitive, introduces a large theoretical uncertainty in the extraction of the axial transition form factor of the proton, $G^A_{N\Delta}$, from the parity violating asymmetry measurements of this reaction at larger Q^2 values. Thus, the measurement proposed here, when combined with the data from experiment E01-115, will considerably sharpen the interpretability of those measurements, providing a more complete understanding of the axial response of the proton.

2 Physics Motivation

2.1 QCD Symmetries and Symmetry Breaking

Quantum Chromodynamics (QCD) is firmly believed to be the correct theory of the strong interaction. At the heart of this theory are fundamental symmetries ranging from flavor and color symmetries such as SU(2), SU(3), etc., discrete symmetries such as P, C, T, etc., to chiral symmetry. All of these symmetries are included in the Standard Model of fundamental particles and interactions, of which QCD is a significant component.

While these symmetries form the basis of QCD, they are known to be broken at some level under certain circumstances. The baryon mass spectrum, for example, is not degenerate due to the breaking of SU(3) and SU(4) flavor symmetries, which is responsible for the mass splittings in this spectrum. The expected size of such symmetry breaking effects can be estimated and/or measured for certain reactions, depending upon which symmetry is broken in those reactions. The mass difference between the nucleon N and Δ states, for example, results from the breaking of spin-flavor SU(4) symmetry (in the large N_c limit), and is measured quite precisely. At higher masses in the baryon spectrum are strange baryons, such as Σ^+, which would be degenerate with the nucleon under SU(3) symmetry, which is expected to be broken at the level $(m_s - m_u)/\Lambda_\chi \sim 15\%$, where $\Lambda_\chi = 4\pi F_\pi \sim 1$ GeV is the scale of chiral symmetry breaking [1] ($F_\pi = 92.4$ MeV is the pion decay constant). Flavor symmetry breaking effects have also been investigated where implications for meson-baryon scattering observables [4] and strangeness in the nucleon [5] have been studied.

The measurement of observables involving both strange baryons and non-strange baryons in the same reaction would therefore be expected to scale with the size of SU(3) breaking of order 15%. There exist, however, examples of such reactions where the experimental observations imply surprisingly large SU(3) violation. One long standing puzzle in hyperon decay physics involves the asymmetry parameters in radiative hyperon decays, such as $\Sigma^+ \to p\gamma$. In such decays, the asymmetry parameter is driven by a parity violating electric dipole transition, which would vanish in the exact SU(3) limit, a result known as Hara's theorem [6]. Given the expected scale of SU(3) breaking of order 15% [1], one would expect the size of the asymmetry parameters to be of this order, yet the experimentally observed quantities are five times larger. Specifically, the asymmetry parameter for the $\Sigma^+ \to p\gamma$ decay is measured to be -0.76$\pm$0.08, corresponding to roughly a 6 standard deviation effect from the expected size of SU(3) breaking effects. As we show below, the parity violating asymmetry in the $N \to \Delta$ transition at very low Q^2, which would vanish in the SU(4), large N_c limit, is driven by the same parity violating electric dipole matrix element, and a precise measurement of this quantity would provide a unique window into the dynamics of the unexpectedly large QCD symmetry breaking effects seen in hyperon decays.

2.2 The $N \to \Delta$ Asymmetry, Hyperon Decays, and Intermediate State Resonances

The axial response of the proton is a fundamental quantity necessary for constraining models of nucleon structure. In particular, the axial response during the proton's transition to its first excited state, the Δ resonance, has been investigated both theoretically and experimentally [1, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16] with significant questions remaining as to the true nature of this transition. Given the vector-axial vector nature of the weak interaction, the parity violating asymmetry in the $N \to \Delta$ transition is directly sensitive to the axial, or intrinsic spin response of the proton during this transition. The $N \to \Delta$ matrix elements of the vector and axial-vector currents can be written [1]

$$\langle \Delta^+(p')|V^3_\mu|N\rangle = \bar{\Delta}^{+\nu}(p')\{[\frac{C_3^V}{M}\gamma^\lambda + \frac{C_4^V}{M^2}p'^\lambda + \frac{C_5^V}{M^2}p^\lambda](q_\lambda g_{\mu\nu} - q_\nu g_{\lambda\mu}) + C_6^V g_{\mu\nu}\}\gamma_5 u(p), \quad (1)$$

and

$$\langle \Delta^+(p')|A^3_\mu|N\rangle = \bar{\Delta}^{+\nu}(p')\{[\frac{C_3^A}{M}\gamma^\lambda + \frac{C_4^A}{M^2}p'^\lambda](q_\lambda g_{\mu\nu} - q_\nu g_{\lambda\mu}) + C_5^A g_{\mu\nu} + \frac{C_6^A}{M^2}q_\mu q_\nu\}u(p), \quad (2)$$

respectively. Presently, there exist considerable data on the vector current transition form factors C_i^V which have been obtained with electromagnetic probes. A comparison of these experimentally determined quantities to theoretical predictions points to significant disagreement (see Ref. [11]). Both lattice QCD calculations [17] and spin-flavor SU(6) based constituent quark models [9], for example, underpredict the data by $\sim 30\%$. In contrast, only a limited amount of data exist for the axial transition form factors C_i^A, obtained from charged current experiments, and these data have considerably larger uncertainties than the vector current form factors. Despite these larger uncertainties, QCD inspired models tend to underpredict the central values for the axial matrix elements by $\sim 30\%$, just as for the vector form factors. More recently, calculation of the C_i^A form factors has been performed in chiral quark models [18] (a linear σ model and a cloudy bag model), giving quite different predictions depending on whether pion pole or non-pole terms are included in the reaction. Thus, a more precise determination of the axial transition form factor will considerably sharpen our present knowledge of the axial vector transition amplitude. This is the physics motivation for the JLab PAC approved experiment E01-115 [3], which will use the G0 apparatus [19] in its backward angle mode to measure the parity violating asymmetry in the $N \to \Delta$ transition and extract the axial vector transition form factor over the range $0.1 < Q^2 < 0.6$ (GeV/c)^2. In this proposal, we focus on the parity violating asymmetry in the $N \to \Delta$ transition at much lower Q^2, which is sensitive to different physics than that just discussed but nonetheless impacts the measurements to be made in E01-115.

In the language of [1], the parity violating asymmetry in the $N \to \Delta$ transition can be written

$$A_{LR}^{PV} = -\frac{G_F}{\sqrt{2}}\frac{Q^2}{4\pi\alpha}[\Delta^{\pi}_{(1)} + \Delta^{\pi}_{(2)} + \Delta^{\pi}_{(3)}], \tag{3}$$

where G_F is the Fermi constant, α is the electromagnetic coupling constant,

$$\Delta^{\pi}_{(1)} = 2(1 - 2\sin^2\theta_W),$$

$\Delta^{\pi}_{(2)}$ contains the non-resonant contributions to this asymmetry [11], and $\Delta^{\pi}_{(3)}$ is proportional to the axial vector transition form factor $G^A_{N\Delta}(Q^2)$ [3], which is a linear combination of the individual C_i^A form factors (for a full mathematical connection between $G^A_{N\Delta}$ and the C_i^A's, see the appendices of [3]). With the inclusion of electroweak radiative corrections, and in the notation of Ref. [1], $\Delta^{\pi}_{(3)}$ can be written

$$\Delta^{\pi}_{(3)} = 2(1 - 4\sin^2\theta_W)(1 + R_A^{\Delta})F(Q^2, s), \tag{4}$$

where $F(Q^2, s)$ is the same linear combination of the C_i^A form factors as $G^A_{N\Delta}$, normalized to the electromagnetic response function, s is the square of the total energy in the center of mass, and R_A^{Δ} is the overall electroweak radiative correction (to order α) of the axial response (to order G_F). This proposal seeks to measure the parity violating $N \to \Delta$ asymmetry at very low Q^2; consequently, we focus on the dominant radiative correction to this asymmetry found by the authors of Ref. [1].

During a thorough investigation of weak radiative corrections to the PV asymmetry in the $N \to \Delta$ transition, the authors of Ref. [1] uncovered a new type of radiative correction for inelastic reactions that does not contribute to elastic parity violating electron scattering. Although formally originating from the same Feynman diagram describing the so called "anapole" contributions [1] (i.e., a photon coupling to a parity violating hadronic vertex), this particular radiative correction involves a parity violating $\gamma N\Delta$ electric dipole transition, which has no analog in the elastic channel, where the recent SAMPLE results [20] indicate that anapole contributions in that channel are significantly larger than theoretically predicted. As a consequence of Siegert's theorem [21], the leading component from the contribution of this transition amplitude is Q^2 independent (a $1/Q^2$ from the photon propagator cancels the leading Q^2 dependence from the anapole term) and is proportional to ω ($\omega = E_f - E_i$) times the parity violating electric dipole matrix element, which is characterized by a low energy constant d_Δ. This results in a non-vanishing parity violating asymmetry at $Q^2 = 0$, whereas all other contributions to this asymmetry vanish at $Q^2 = 0$. Thus, a measurement of the parity violating asymmetry in the $N \to \Delta$ transition at the photon point, or at very low Q^2, henceforth called the Siegert contribution, would provide a direct measurement of the low energy constant d_Δ.

Although introduced in the context of a radiative correction to the PV asymmetry in the $N \to \Delta$ transition, the quantity d_Δ is tied to interesting physics in its own right. As mentioned above, d_Δ is given by the PV electric dipole matrix element, the same transition which drives the asymmetry parameter in radiative hyperon decays, e.g. $\Sigma^+ \to p\gamma$. A long standing puzzle in hyperon decay physics has been understanding the large values obtained for these parameters, which, according to Hara's theorem, would vanish in the exact SU(3) limit. While typical SU(3) breaking effects are of order $(m_s - m_u)/1\text{GeV} \sim 15\%$, experimentally the asymmetry parameter for $\Sigma^+ \to p\gamma$ is found to be 6 standard deviations away from its predicted value assuming SU(3) is broken at the 15% level. The authors of Ref. [22] proposed a solution to this puzzle by including high mass intermediate state resonances ($1/2^-$), where the weak Lagrangian allows the coupling of both the hyperon and daughter nucleon to the intermediate state resonances, driving the asymmetry parameter to large negative values. This same reaction mechanism was also shown to simultaneously reproduce the s and p wave amplitudes in nonleptonic hyperon decays, which has also been an unsolved puzzle in hyperon decay physics. Thus, if the same underlying dynamics is present in the non-strange sector ($\Delta S = 0$) as is present in the strangeness changing sector ($\Delta S = 1$), one would expect d_Δ to be enhanced over its natural scale ($g_\pi = 3.8\times10^{-8}$, corresponding to the scale of charged current hadronic PV effects [23, 24]). The authors of [1] estimate that this enhancement may be as large as a factor of 100, corresponding to an asymmetry of ~ 4 ppm, comparable to the size of the effects due to the axial response and therefore easily measurable. Thus, a measurement of this quantity could provide a unique window into the underlying dynamics of the unexpectedly large QCD symmetry breaking effects seen in hyperon decays.

To more formally establish a connection between these different reactions, we write out the amplitudes for each of the processes considered here. The amplitude for the

Siegert contribution to the parity violating $N \to \Delta$ asymmetry may be written as[1]

$$M^{PV}_{\text{Siegert}} = -\frac{4\pi\alpha}{Q^2}\frac{d_\Delta}{\Lambda_\chi}\bar{e}\gamma_\mu e \bar{\Delta}_\nu[(M - M_\Delta)g^{\mu\nu} - q^\nu\gamma^\mu]N, \tag{5}$$

where up to numerical factors,

$$\frac{d_\Delta}{\Lambda_\chi} \propto -\frac{\sqrt{2}}{3}\omega\langle f|\int d^3x x Y_{1\lambda}(\Omega)\hat{\rho}(x)|i\rangle, \tag{6}$$

which, according to Siegert's theorem, is the leading component of matrix elements of the transverse electric multipole operator $\hat{T}^E_{J=1\lambda}$. This term is Q^2 independent and proportional to $\omega = E_f - E_i$, showing explicitly that this contribution vanishes in the elastic case, but contributes to the parity violating $N \to \Delta$ asymmetry.

The amplitude for the radiative hyperon decay $\Sigma^+ \to p\gamma$ may be written as [22]

$$M(\Sigma^+ \to p\gamma) = \bar{u}_p(p')\frac{i}{2(M_{\Sigma^+} + M)}\sigma_{\mu\nu}F^{\mu\nu}(A_{p\Sigma^+} + \gamma_5 B_{p\Sigma^+})u_{\Sigma^+}(p), \tag{7}$$

where $F^{\mu\nu}$ is the electromagnetic strength tensor, $A_{p\Sigma^+}$ is the parity conserving M1 amplitude, and $B_{p\Sigma^+}$ is the parity violating E1 amplitude. This latter amplitude is proportional to d_Δ, just as is the amplitude for the Siegert contribution given above. The asymmetry parameter in polarized $\Sigma^+ \to p\gamma$ is related to the decay amplitudes via

$$\alpha_\gamma = \frac{2\Re\{A_{p\Sigma^+}B^*_{p\Sigma^+}\}}{|A_{p\Sigma^+}|^2 + |B_{p\Sigma^+}|^2}, \tag{8}$$

so this observable is driven by the parity violating E1 matrix element characterized by d_Δ. The "G-parity" associated with the U-spin subalgebra of SU(3) requires the vanishing of electric dipole transitions for this decay [22], and as a consequence, α_γ should vanish as well, in contradiction to its large experimentally measured value. This is the origin of one long standing puzzle in hyperon decay physics for the past three decades.

Another long standing puzzle in hyperon decay physics has been the simultaneous description of the $s-$ and $p-$ wave amplitudes in nonleptonic hyperon decays, such as $\Sigma^+ \to n\pi^+$. The amplitude for such a decay can be written [22]

$$M(\Sigma^+ \to n\pi^+) = \bar{u}_n\{A^s_{\Sigma^+ n} + \gamma_5 A^p_{\Sigma^+ n}\}u_{\Sigma^+}, \tag{9}$$

where $A^s_{\Sigma^+ n}$ and $A^p_{\Sigma^+ n}$ are the parity violating $s-$wave and parity conserving conserving $p-$wave amplitudes, respectively. It has been the simultaneous description of

$A^s_{\Sigma^+ n}$ and $A^p_{\Sigma^+ n}$ (and similar amplitudes for other non-leptonic hyperon decay channels) that has evaded theorists for many years. The authors of Ref. [22] proposed a solution to this dilemma by including heavy intermediate state $1/2^-$ resonances for these decays in a heavy baryon chiral perturbation theory formalism. The strong and weak Lagrangians incorporated allowed both the hyperons and daughter nucleons to couple to the intermediate state resonances, where the parameters of the strong Lagrangians were determined from the strong decays of the resonances included, while the parameters of the weak Lagrangians were adjusted to fit both the $s-$ and $p-$ wave amplitudes for the hyperon decays. Within the context of this formalism, a much more satisfactory agreement with experiment was obtained.

In a following work, the same authors applied this formalism to radiative hyperon decays, with considerable success [22]. It is important to emphasize that the *same* weak Lagrangians which couple the intermediate state resonances to the hyperons and daughter nucleons in the description of the non-leptonic hyperon decays are used in the description of radiative hyperon decays. The parameters determined in the fit of the $s-$ and $p-$ wave amplitudes from the former were used for the latter. It is these hyperon-resonance and daughter nucleon-resonance couplings which generate non-zero values for the parity violating E1 amplitudes, and consequently drive the asymmetry parameters in these decays to large values in much better agreement with experiment. Thus, a dynamic mechanism for large SU(3) violating effects seen in the strangeness changing $\Delta S = 1$ sector goes a long way toward solving two long standing puzzles in hyperon decay physics. If this same mechanism plays an important role in the parity violating E1 amplitude in the $\Delta S = 0$ sector (i.e., d_Δ), the measurement described here would provide a unique window into the dynamics of QCD symmetry breaking effects.

3 Experimental Apparatus and Technique

The experiment will be performed using the Q_{weak} apparatus in Hall C. The Q_{weak} experiment [2] was approved at the 21st meeting of the Jefferson Lab Program Advisory Committee in January, 2002, and has adopted the goal of installing the apparatus in 2006. This experiment intends to measure the inclusive inelastic parity violating asymmetry, not the elastic channel proposed in Q_{weak}, by scattering and intense (180 μA) beam of 1.165 GeV electrons, polarized to 80%, from a 35 cm long extended liquid hydrogen target. The scattered electrons are detected using a set of Čerenkov detectors located at a mean scattering angle of 9^o with a ϕ acceptance of $4\pi/3$. The experiment will use the Q_{weak} apparatus, designed to measure the Q_{weak} asymmetry

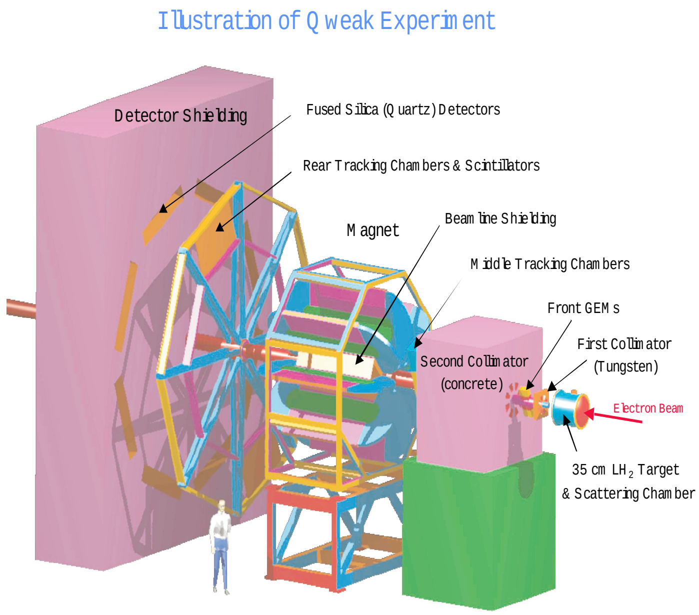

Figure 1: *The Q_{weak} apparatus.*

of 0.3 ppm with a statistical uncertainty of 8% and a systematic uncertainty of 3.4%, to measure the inelastic asymmetry in the Δ resonance region, expected to be an order of magnitude larger than the Q_{weak} asymmetry, by simply reducing the magnetic field strength of the Q_{weak} spectrometer "QTOR".

A sketch of the Q_{weak} apparatus is shown in Figure 1. A double collimator system, appearing just after the target, has been designed to restrict the electron scattering angle to $9^o \pm 2^o$. Two of the three tracking system elements, designed for use at low beam current to measure and confirm the Q^2 distribution defined by the collimator, are located such that the first tracking element, based on gas electron multiplier technology, is attached to the back side of the primary collimator with the second tracking element placed approximately 1.8 meters away behind the secondary collimator and just in front of the main spectrometer magnet "QTOR". The main spectrometer magnet will focus elastically scattered electrons onto a set of eight rectangular fused silica (synthetic quartz) detectors that are coupled to photomultiplier tubes at both ends which are operated in current (integration) mode during production operation to achieve the high statistical precision required for such asymmetry measurements. The third tracking element lies between the magnet and the Čerenkov detector completing the tracking system.

The design of the Q_{weak} liquid hydrogen target calls for a cooling power of 2500 Watts to accommodate the 2120 Watts of power deposited by a 180 μA electron beam that is rastered over a 16 mm^2 area as well as several hundred Watts of load from conductive heat losses, circulation fan heat load, reserve heat load for feedback control, etc. [25]. Since this cooling power requirement exceeds the capacity of the JLAB ESR, an alternative solution has been developed in consultation with the JLAB cryogenics groups which employs the CHL backup refrigerator. The target design will be based on the vertical target loop used in the SAMPLE experiment with a heat exchanger that is basically a stretched version of the existing $\sim$ 1000 Watt G0 design. Additional improvements to the SAMPLE design involving the cryogenic pump and target cell windows are described in the Q_{weak} TDR [25]. Although the Q_{weak} target will establish the highest power cryotarget in the world by today's standards, it is clear that the refrigeration demands can be met and that the laboratory is committed to the development of this target.

A two stage collimation system is placed after the target in order to establish the desired scattering angle for elastically scattered electrons in the Q_{weak} experiment. The primary collimator will be constructed of machinable tungsten while the second collimator will be constructed from sections of cast lead alloy and serve as a "clean up" collimator. A GEANT simulation indicates that mechanical tolerances and assembly errors should be constrained to the 1mm level.

A toroidal magnet ("QTOR") will be used to focus elastically scattered electrons onto a set of eight quartz Čerenkov detectors. An axially symmetric resistive toroidal spectrometer has been chosen with magnetic field integral ($\int \vec{B} \cdot d\vec{l}$) of approximately 0.67 T·m. The basic layout of the eight magnetic field coils is shown in Figure 2. A detailed description of the magnet optics, coil design, electrical and mechanical specifications as well as a field mapping apparatus appears in the Q_{weak} TDR [25].

Fused silica (synthetic quartz) bars will be used as Čerenkov detectors in each of the eight octants to measure the electron asymmetry which results when polarized electrons are scattered from the liquid hydrogen target (see Figure 3). Simulations indicate that a total of 100 photo-electrons will be generated by an electron traversing an octant containing a 2.5 cm thick quartz bar which has been rotated along its long axis by 12.5^o. The quartz thickness was chosen to optimize light production and minimize noise from electromagnetic showering. The angle of rotation was chosen to minimize the position dependence along the detector by increasing the light capture efficiency on one side of the Čerenkov cone at the expense of overall light loss. The effects of detector dimensions, orientation, surface polishing, and photocathode quantum efficiency were considered in optimizing Čerenkov detector parameters and are described in the Q_{weak} TDR [25].

Figure 2: *The Q_{weak} magnetic field coils.*

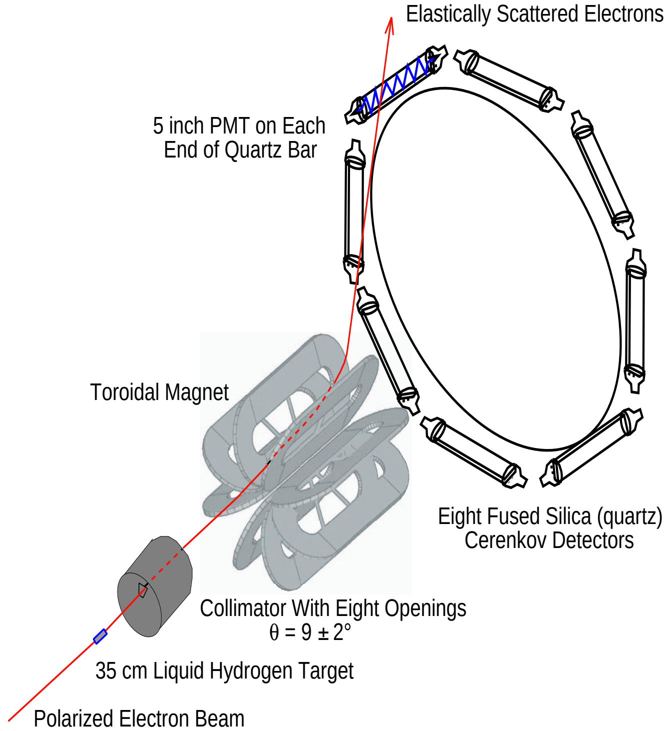

Figure 3: *The Q_{weak} Čerenkov detector relative to the spectrometer magnet, collimator and liquid hydrogen target.*

A tracking system has been designed for use at low beam currents which moves into position to evaluate the Q^2 distribution defined by the collimator. The tracking system will reconstruct particle trajectories based on measurements made in three separate regions of the Q_{weak} apparatus. An ionization chamber, equipped with a gas electron multiplier (GEM) preamplification stage, will be placed just behind the primary collimator. This element of the tracking system has well established properties of resistance to radiation damage, spatial resolution and high rate operation which are well suited to the needs of the region 1 tracking chamber for Q_{weak}. The region 2 tracking chamber, patterned after the HERMES front chambers and the Hall C SOS drift chambers, will be located just before the spectrometer and will provide an accurate measurement of the particles entrance angle into the magnet. An accurate measurement of the target vertex and scattering angle will be accomplished by combining the region 1 and region 2 measurements. The final element of the tracking system will be a vertical drift chamber, designed after the Hall A VDC, placed in front of the Čerenkov detectors. The scattered particle momentum may be determined by combining the entrance angle measurement from region 2 with the exit angle measurement made by the region 3 detectors and a field map of the magnet. Using a scintillation detector placed near the Čerenkov detector as the trigger, the tracking system will provide a complete characterization of the particle trajectories which enter the Čerenkov detector. A more complete description of the system may be found in the Q_{weak} TDR [25].

4 Kinematics and Rates

The kinematics for this measurement are determined by the incident beam energy (1.165 GeV), collimator ($9 \pm 2\ ^o$) and spectrometer setting. The kinematics have been chosen to be compatible with the Q_{weak} experiment in order to take advantage of the infrastructure which will be established to measure the order of magnitude smaller Q_{weak} asymmetry. Only the magnetic field will be changed, to a smaller field ($B \sim 0.85 B_{el}$), such that the portion of the Delta resonance just above single pion threshold and just below double pion threshold will be focused onto the Čerenkov detectors, while the elastically scattered electrons will be directed to the region between the quartz detectors and the beamline (see Fig. 3). This will minimize the impact of higher resonances on the measured asymmetry.

As a result of lowering the magnetic field, an inclusive electron which traverses the collimator and is focused on the Čerenkov detector will have an average $Q^2 = 0.024\ GeV^2/c^2$. The Q^2 and missing mass (W) distributions are shown in Figure 4.

Unless the collimator is changed, only altering the beam energy would provide the means to accessing different Q^2 values in this same missing mass region.

The inelastically scattered electron rate is defined as

$$Rate = \int_{E'_{min}}^{E'_{max}} \int_{\Delta\Omega} \frac{d\sigma}{dE' d\Omega} dE' d\Omega \tag{10}$$

where $\frac{d\sigma}{dE' d\Omega}$ is the double differential inelastic electron cross section, E'_{min} and E'_{max} are the lower and upper limits of the detected electron momentum, and $\Delta\Omega$ represents the detector solid angle. The same GEANT [26] simulation used for the Q_{weak} proposal [2] was modified to estimate the inelastic counting rate. The phase space density of the three particle final states was calculated numerically using the CERN library routine GENBOD [27]. The commonly used algorithm "PFC" [28] was implemented to estimate the double differential cross section $\frac{d\sigma}{dE' d\Omega}$. The Čerenkov detector was binned according to intervals of the scattered electron momentum range $\Delta E'$ and solid angle $\Delta\Omega$ which were small enough such that Equation 10 may be replaced by

$$Rate = \sum_{i,j} \frac{\overline{d\sigma}}{dE'_i d\Omega_j} \Delta E'_i \, \Delta\Omega_j, \tag{11}$$

where $\frac{\overline{d\sigma}}{E'_i d\Omega_j}$ the average inelastic electron cross section for electrons having a momentum range $\Delta E'_i$ detected in the solid angle $\Delta\Omega_j$.

The counting rate shown in Figure 6 was determined using the above differential cross section and the effective luminosity of $1.76 \times 10^{39} cm^{-2} s^{-1}$. Also shown is the dominant background due to elastically scattered electrons which radiate and enter the acceptance. The elastic radiative tail rates contribute about 34% to the signal. Fortunately the parity violating asymmetry for elastic scattering is an order of magnitude smaller than the expected inelastic asymmetry thereby further reducing its impact on the proposed measurement.

4.1 Statistical Error

As in the Q_{weak} experiment, this experiment will integrate the detector signals at a 30 Hz frequency which is synchronized with the pseudo-random beam helicity reversal. The detector yield for a given incident electron helicity state (Y_h) is

$$Y_h = \frac{Rate \times T_h}{Q_h} = \frac{N_h}{Q_h}, \tag{12}$$

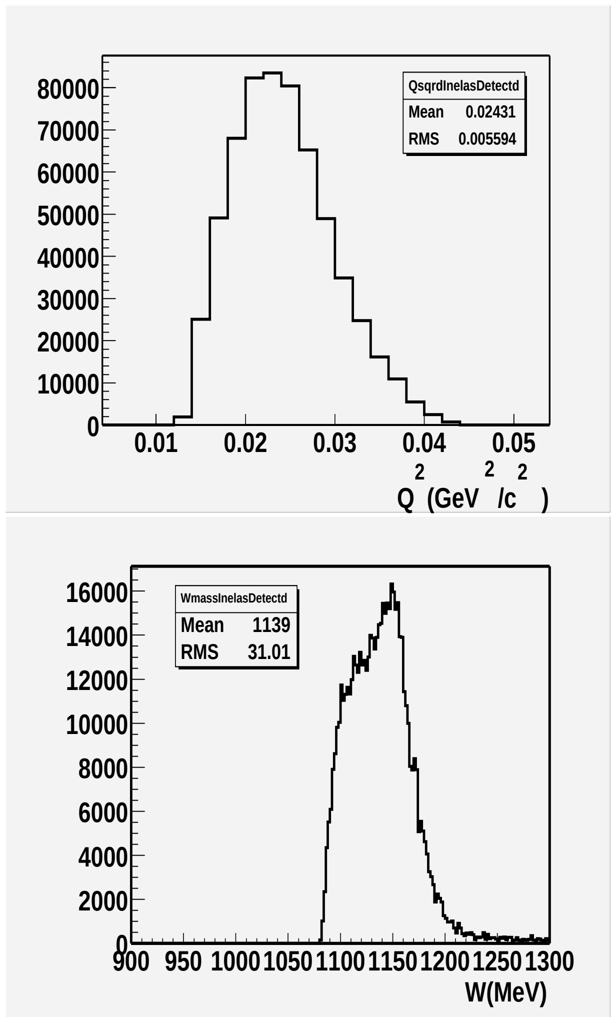

Figure 4: *The cross section weighted Q^2 and W distributions for detected inclusive inelastic electrons based on an incident beam energy of 1.165 GeV.*

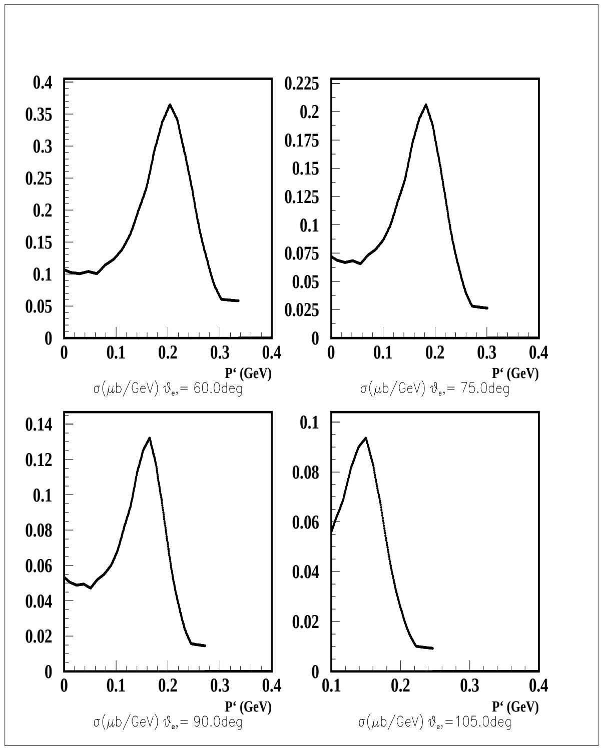

Figure 5: *Inelastic electron-proton cross section calculation for E=0.585 GeV, at four electron scattering angles.*

Parameter	Value
Incident Beam Energy	1.165 GeV
Beam Polarization	80%
Beam Current	180 μA
Target	35 cm (0.04 X_o)
Nominal Scattering Angle	9^o
Scattering Angle Acceptance	$\pm 2^o$
ϕ Acceptance	$\frac{4}{3}\pi$
Solid Angle $\Delta\Omega$	45.7 msr

Table 1: Basic Parameters of the Q_{weak} apparatus.

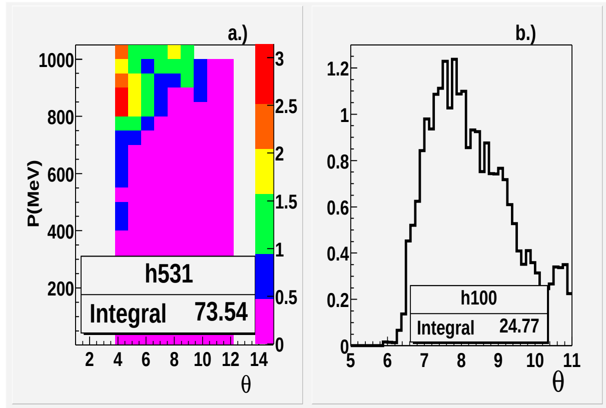

Figure 6: *a.) Inelastic rates as a function of the electron scattering angle and momentum in MHz. b.) Elastic radiative tail rates in MHz which enters the detector acceptance during the inelastic measurement. The radiative tail rates are the dominant background for the inelastic measurement.*

where the "Rate" is given in Equation 11, T_h is the helicity reversal timescale, and Q_h represents the beam charge passing through the target in time T_h. An asymmetry is measured by subtracting the yield associated with a negative incident electron helicity from a positive helicity electron and dividing by their sum:

$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}. \tag{13}$$

The statistical error for each "pulse pair" asymmetry measurement arising from counting statistics may be written as:

$$\Delta A_{pp} = \frac{1}{\sqrt{2N_e}}\sqrt{1 + \left(\frac{\sigma_{N_{pe}}}{N_{Pe}}\right)^2} \tag{14}$$

The "pulse pair" error during the higher rate elastic measurements made by Q_{weak} is 5.0×10^{-5} while the expected inelastic rates for this proposal increase this error to 1.5×10^{-4}. As indicated in the Q_{weak} proposal, other sources of random noise such as the beam charge measurement, detector electronics noise, and target density fluctuations, will be constrained to have minimal impact on the 5.0×10^{-5} "pulse pair" error. Constraining the random noise to this level will be more than adequate for the measurement described here. As a result, the statistical uncertainty in the measured asymmetry A_{meas} assuming a runtime of 7 full days would be 5.1×10^{-8} or 0.05 ppm.

The measured asymmetry may be expressed as

$$A_{meas} = \frac{A_{inel}N_{inel} + A_{back}N_{back}}{N_{inel} + N_{back}}, \tag{15}$$

where A_{inel} (A_{back}) and N_{inel} (N_{back}) are the asymmetry and yield for the inelastic (background) events, respectively; the inelastic asymmetry can be extracted from the measured asymmetry via

$$A_{inel} = A_{meas}(1 + R) - A_{back}R, \tag{16}$$

where $R = N_{back}/N_{inel}$ is the ratio of the background to inelastic yield. A simulation using a magnetic field that is 85% of the Q_{weak} field strength indicates that elastic radiative tail is the dominant background and amounts to 34% of the inelastic counting rate. The background will be measured using the detector tracking system to a relative accuracy of 1% and the elastic background asymmetry will be measured in Q_{weak} to an absolute accuracy of 0.006 ppm. The combination of these uncorrelated errors will increase the statistical uncertainty for the inelastic asymmetry to 0.066 ppm.

5 Corrections due to Finite Q^2 and W Effects

The Siegert term as discussed throughout this proposal is the contribution to the parity violating $N \to \Delta$ asymmetry at $Q^2 = 0$, while the measurement described here is at finite Q^2. Additionally, due to the finite acceptance of the spectrometer and detector system, a range of Q^2 values will be accepted for the inelastic electrons, as well as a range of W values due to the three body final state. The cross section weighted Q^2 distribution as shown in Figure 4 gives the accepted Q^2 range of $0.014 < Q^2 < 0.042 (GeV/c)^2$, and has a mean value of 0.024 GeV^2/c^2. Similarly the cross section weighted W distribution as shown in Figure 4 gives a range of W values between $1078 < W < 1200$ MeV (with an inelastic radiative tail extending to $W \sim$ 1300 MeV), i.e. from single pion threshold to just below the peak of the Δ resonance, with a cross section weighted mean value of 1139 MeV.

While the Siegert contribution is Q^2 independent, the other factors contributing to the asymmetry measured at finite Q^2 are Q^2 dependent, and that dependence must be taken into account. As seen from Eq. (3), the leading dependence is linear in Q^2 for contributions other than the Siegert contribution. In addition to that, the individual $\Delta^{\pi}_{(i)}$ contributions are in general Q^2 dependent. These effects were thoroughly investigated in Ref. [11]. The dominant contribution to the asymmetry from the $\Delta^{\pi}_{(i)}$ terms comes from $\Delta^{\pi}_{(1)}$, whose only Q^2 dependence arises from the running of $\sin^2\theta_W$, which will be measured to a high precision by the Q_{weak} elastic experiment at a Q^2 very close to the mean Q^2 for the measurement described here. The remaining two contributions, $\Delta^{\pi}_{(2)}$ and $\Delta^{\pi}_{(3)}$, involve transition form factors which have additional Q^2 dependence. The authors of Ref. [11] performed calculations of the contributions of each of these terms to the total asymmetry as a function of Q^2 very near the kinematics of intended measurement, and found that the non-resonant contribution $\Delta^{\pi}_{(2)}$ varied from $\sim 0.5-1.0\%$ of the total asymmetry over the Q^2 range covered by our acceptance (corresponding to asymmetry contributions from 0.009 to 0.058 ppm), while the relative contribution of the axial term $\Delta^{\pi}_{(3)}$ (without the Siegert term) remained nearly constant between 11-12% of the total asymmetry over this range (corresponding to asymmetry contributions from 0.21 to 0.52 ppm). These variations are small relative to the variation of the expected asymmetry without the Siegert contribution, which varies from -1.7 to -4.8 ppm over this range, suggesting that taking the values of the asymmetry and the contributions of the $\Delta^{\pi}_{(i)}$ at the mean value of our Q^2 range is a good approximation for estimating expected errors from these terms. Additionally, we will measure the Q^2 distribution of the inelastic electrons to 1.5% using the same tracking system that the elastic Q^2 distribution will be measured for the Q_{weak} elastic experiment. Finally, it also shows that the axial $\Delta^{\pi}_{(3)}$ term dominates over the $\Delta^{\pi}_{(2)}$ term by a factor of 10-20 over this range, and that the non-resonant contributions will have little impact on the extraction of the Siegert term (and therefore d_Δ) from these measurements.

6 Expected Results

The effects discussed in the previous section will enter into the extraction of d_Δ. We rewrite Eq. (3) isolating the Siegert contribution ($A_{Sieg} = A^{PV}_{N\Delta}(Q^2=0)$),

$$A_{meas} = -\frac{G_F}{\sqrt{2}}\frac{Q^2}{4\pi\alpha}[\Delta^{\pi}_{(1)} + \Delta^{\pi}_{(2)} + \Delta^{\pi,\prime}_{(3)}] + A_{Sieg}, \tag{17}$$

where $\Delta^{\pi\prime}_{(3)}$ contains all contributions to the axial term except A_{Sieg}, so that

$$\delta A_{Sieg} = \sqrt{\delta A^2_{meas} + (\frac{G_F Q^2}{\sqrt{2}4\pi\alpha})^2[(\delta\Delta^{\pi}_{(1)})^2 + (\delta\Delta^{\pi}_{(2)})^2 + (\delta\Delta^{\pi}_{(3)})^2] + (A_{meas} - A_{Sieg})^2(\frac{\delta Q^2}{Q^2})^2}. \tag{18}$$

The uncertainties for each of the contributions in Eq.(18) can be taken and estimated from various places. The uncertainty on the measured asymmetry is taken to

Contribution	Expected Error (ppm)
Statistical (w/dilution)	0.066
$\Delta^{\pi}_{(1)}$	0.018
$\Delta^{\pi}_{(2}$	0.0015
$\Delta^{\pi}_{(3}$	0.027
P_{beam}	0.03
Q^2	0.045
Total	0.091

Table 2:

be the statistical uncertainty assuming a 7 day run period, and taking into account the dilution due to the elastic radiative tail. Because $\Delta^{\pi}_{(1)}$ involves only $\sin^2\theta_W$, $\delta\Delta^{\pi}_{(1)}$ will be constrained by the Q_{weak} elastic measurements. The $\Delta^{\pi}_{(2)}$ contribution is from non-resonant multipoles, which will be constrained by various Hall B single pion production measurements involving polarization and angular correlation observables. The uncertainties on these multipoles have been estimated to be at the 5% level [31], so we assume 5% uncertainty from the $\Delta^{\pi}_{(2)}$ contribution. The dominant error associated with the $\Delta^{\pi}_{(3)}$ contribution is due to the overall normalization of the axial form factor. This issue has been addressed employing the Off-Diagonal Goldberger Trieman Relation [33] (and see Section 8.3 of this proposal), which can constrain this normalization at the 10% level. The uncertainty in the beam polarization will be 1% as described in the Q_{weak} TDR and dilutes the measured asymmetry. Based on the expected asymmetry the beam polarization uncertainty will contribute 0.03 ppm to the overall error. Finally, due to the leading Q^2 dependence of the asymmetry (without the Siegert contribution), our uncertainty in our Q^2 distribution will contribute to the overall error. As discussed above and in the Q_{weak} proposal, this distribution will be measured at the 1.5% level. Combining all of these effects, we expect a total uncertainty on the Siegert asymmetry of 0.091 ppm. The break down of the contribution from all effects is summarized in Table 2 and the expected measurement is compared with the range of d_Δ values in Figure 7.

What has not been included in the error estimate is the effects due to finite W acceptance. While this is possible in principal for the non-resonant $\Delta^{\pi}_{(2)}$ contribution (via analysis of eg. MAID [30] non-resonant multipoles over this W range), calculations of the axial $\Delta^{\pi}_{(3)}$ multipoles have to date only been performed on the peak of the Δ resonance (i.e. $M_\Delta = 1232$ MeV), so that this analysis needs further theoretical input to proceed. Nonetheless, given the small relative sizes of both the $\Delta^{\pi}_{(2)}$ and

$\Delta^{\pi}_{(3)}$ contributions relative to the expected size of the Siegert contribution at this small value of Q^2, and the small W variation over our acceptance, the errors from the variation of the multipoles with W should have little impact on the error extracted on d_Δ from these measurements.

7 Impact on the Q_{weak} Elastic Measurements

Although the Q_{weak} experiment has been designed in such a way that the spectrometer and quartz Čerenkov detector system only accepts elastically scattered electrons, while inelastically scattered electrons are swept out of the acceptance of the system, rescattering effects in the collimators, etc. will result in some small fraction of inelastically scattered electrons reaching the detector. Extensive simulations indicate that this inelastic contamination to the elastic yield is at the 0.03% level [25]. Because we will have measured the inelastic asymmetry to high precision, this effect can be easily subtracted from the elastic asymmetry, with negligible impact on the extraction of Q^p_W from those measurements.

Writing the measured asymmetry for the Q_{weak} elastic program as

$$A_{meas} = \frac{A_{el}N_{el} + A_{inel}N_{inel}}{N_{el} + N_{inel}}, \tag{19}$$

where A_{el} (A_{inel}) and N_{el} (N_{inel}) are the asymmetry and yield for the elastic (inelastic) events, respectively, the elastic asymmetry can be extracted from the measured asymmetry via

$$A_{el} = A_{meas}(1 + R) - A_{inel}R, \tag{20}$$

where $R = N_{inel}/N_{el}$ is the ratio of the inelastic yield to the elastic yield. Now, because the signal to background ratio will be measured at a different time and with different running conditions than the asymmetries, the ratio R and the measured asymmetry A_{meas} are uncorrelated. Additionally, this measurement of the inelastic asymmetry will be made at a nearly identical Q^2 value as the inelastic Q^2 expected during the elastic measurements. This allows us to incorporate the error on the inelastic asymmetry measurement to constrain this contribution to the elastic asymmetry to be measured during Q_{weak} via

$$\delta A_{el} = \sqrt{(\delta A_{meas})^2(1 + R)^2 + A^2_{meas}\delta R^2 + \delta A^2_{inel}R^2 + A^2_{inel}\delta R^2}, \tag{21}$$

where A_{meas}, δA_{meas}, R, and δR are parameters from the Q_{weak} elastic program, and A_{inel} and δA_{inel} are associated with these measurements here. While the estimate on

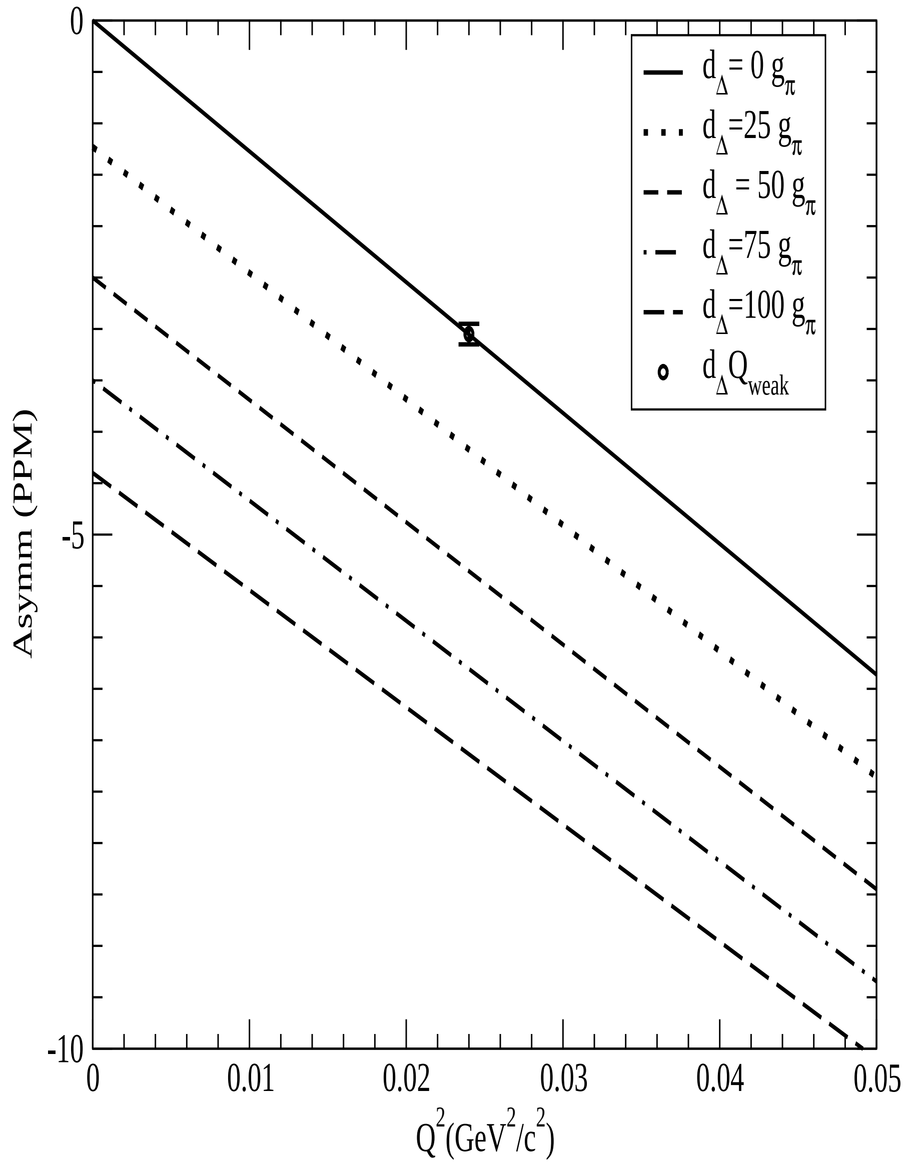

Figure 7: Expected precision of the measured asymmetry compared with the expected asymmetry for several values of the low energy constant d_Δ.

the contribution from the inelastic contamination to the elastic asymmetry for the Q_{weak} experiment was made at 0.2% [25], we find using Eq. (21) that the precision with which the measurements will be made, the contribution from the inelastic yield to the elastic asymmetry will be $< 0.1\%$, and therefore negligible compared to the statistical and other systematic errors expected from those measurements.

8 Impact on the Axial Vector Transition Form Factor $G^A_{N\Delta}(Q^2)$

8.1 The Axial Vector Transition Form Factor $G^A_{N\Delta}(Q^2)$ and the axial mass M_A

In the PAC approved experiment E01-115 [3], the parity violating asymmetry in the $N \rightarrow \Delta$ transition will be measured as a function of Q^2 over the range $0.1 < Q^2 < 0.6$ (GeV/c)^2 at backward scattering angles. As demonstrated in Ref.[1], the "Siegert" asymmetry discussed throughout this proposal corresponds to a radiative correction to this asymmetry, and introduces a theoretical uncertainty in extracting the axial vector transition form factor $G^A_{N\Delta}(Q^2)$. Employing the results of Ref. [22], who include higher intermediate state resonances in both radiative and non-leptonic hyperon decays, the authors of Ref. [1] find that the asymmetry from the Siegert contribution could be as large as $100 g_\pi$ or ~ 4 ppm. This introduces an overall normalization uncertainty in extracting the axial transition form factor $G^A_{N\Delta}(Q^2)$ and translates into a larger uncertainty in the axial mass parameter M_A in the Adler parameterization of this form factor [32]. Thus, a precise measurement of d_Δ will significantly reduce the theoretical uncertainty in the extraction of axial transition form factor $G^A_{N\Delta}(Q^2)$ from experiment E01-115.

To quantify this effect, we reanalyze our expected statistical precision on the axial mass parameter M_A that will be extracted from E01-115 first ignoring the Siegert term, then constraining the parametrization with a predicted value and finally constrain the fit with this measurement. In the original proposal for E01-115, our estimates were performed assuming that the parity violating asymmetry in the $N \rightarrow \Delta$ transition vanished at the photon point (i.e., no Siegert contribution). We rewrite Eq. (3),

$$A^{PV}_{LR} = -\frac{G_F}{\sqrt{2}} \frac{Q^2}{4\pi\alpha} [\Delta^\pi_{(1)} + \Delta^\pi_{(2)} + \Delta^\pi_{(3)}], \tag{22}$$

where

$$\Delta^{\pi}_{(1)} = 2(1 - 2\sin^2\theta_W),$$

$\Delta^{\pi}_{(2)}$ contains the non-resonant contributions to this asymmetry [11], and $\Delta^{\pi}_{(3)}$ is proportional to the axial vector transition form factor $G^A_{N\Delta}(Q^2)$. Without the Siegert contribution, we can directly extract $G^A_{N\Delta}(Q^2)$ by subtracting $\Delta^{\pi}_{(1)}$ and $\Delta^{\pi}_{(2)}$ from the measured asymmetry. This was the analysis technique used for predicting our expected results on $G^A_{N\Delta}(Q^2)$ as proposed for E01-115. The results of this analysis are shown in Figure 8, where we expect an uncertainty on the axial mass of $\delta M_A = 0.043$ GeV, which is a factor of two better than the best neutrino results for the corresponding axial mass parameter in the charged current sector of the weak interaction. These results are based on 700 hours of 75% polarized beam time for each of three beam energies: 0.424 GeV, 0.585 GeV, and 0.799 GeV, corresponding to elastic Q^2 values of 0.3, 0.5, and 0.8 $(\mathrm{GeV/c})^2$, respectively, for the G0 backward angle program [19].

8.2 The Axial Mass M_A and the Siegert Contribution

If we now include the contribution from the Siegert term, an overall offset to the measured asymmetry would be introduced due to the non-zero value of the Siegert term at the photon point. Because each data point from E01-115 would be shifted in a correlated way, it is not correct to simply increase the error on each expected data point from E01-115 by an amount consistent with the size of the Siegert term. In addition, it is not possible to subtract off an unknown piece of the measured asymmetry to extract $G^A_{N\Delta}(Q^2)$ as before (cf. Eq. (17)). Instead, we fit the expected asymmetry with two parameters: the value of the asymmetry at the photon point $A^{PV}_{N\Delta}(Q^2 = 0)$ (i.e., the Siegert contribution), and the axial mass M_A. In Figure 9, the parameter of this fit is shown in the caption, where we assume that the measurement is NOT performed, and the photon point asymmetry is fixed at -4 ppm (corresponding to $d_\Delta = 100 g_\pi$), which results in a determination of the Siegert term with an uncertainty of 1.23 ppm (corresponding to $\delta d_\Delta = 30 g_\pi$), and an uncertainty on the axial mass of $\delta M_A = 0.13$ GeV: a factor of three increase relative to the expected results without the Siegert contribution. Thus, the Siegert term introduces a significant theoretical uncertainty in the extraction of the axial mass parameter M_A in $G^A_{N\Delta}(Q^2)$.

If we now include the expected results from this measurement, we see that this theoretical uncertainty is significantly reduced. Plotted in Figure 9 is the fit to the expected parity violating asymmetry in the $N \to \Delta$ transition from both E01-115, and from these measurements. With a Siegert contribution of $A^{PV}_{N\Delta}(Q^2 = 0) = -4$ ppm,

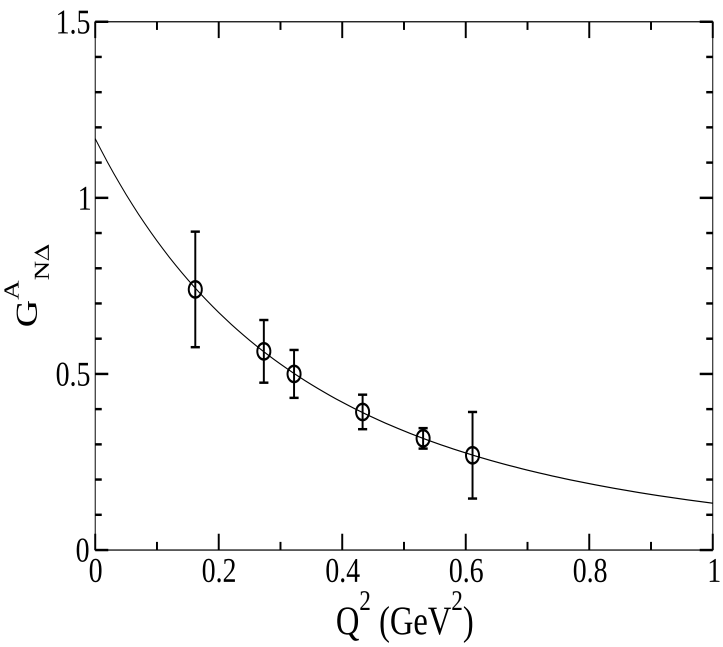

Figure 8: Expected results for the axial mass parameter in the axial vector transition form factor $G^A_{N\Delta}$ where we have plotted $G^A_{N\Delta}$ vs. Q^2 assuming the Adler parameterization without including the Siegert contribution. In this case, we would achieve a statistical uncertainty on the axial mass of $\delta M_A = 0.043$ GeV

Data	δd_Δ	$\delta M_A(GeV)$
Q_{weak}	2.5 g_π	
G^0	30 g_π	0.13
$Q_{weak} + G^0$	2.2 g_π	0.042

Table 3: Impact of the Q_{weak} and G^0 experiments on the uncertainty of d_Δ and M_A individually and when taken together.

an expected asymmetry of -7.5 ppm at a Q^2 value of 0.024 (GeV/c)^2 would result. With the expected statistical precision of 0.091 ppm for the $N \to \Delta$ asymmetry at $Q^2 = 0.024$ (GeV/c)^2, this adds a significant data point to be included in this fit. A fit to all of these expected data, shown in Fig. 9, yields an uncertainty on the Siegert term of $\delta A^{PV}_{N\Delta}(Q^2 = 0) = 0.092$ ppm (corresponding to $\delta d_\Delta = 2.3 g_\pi$), and an uncertainty on the axial mass M_A of $\delta M_A = 0.042$ GeV, recovering the proposed precision in M_A from E01-115, and a factor of 2 better than the best neutrino results on the corresponding axial mass parameter determined in the charged current sector of the weak interaction. Thus, these measurements will constrain d_Δ to $\sim\ 2g_\pi$, whereas the enhancement of this quantity due to dynamical SU(3) breaking effects is predicted to be as large as $100g_\pi$. If such effects are present, this measurement will constrain them at the 2% level.

8.3 Anapole Effects (a_Δ), $C_5^A(0)$, and the ODGTR

In addition to the contribution of the Siegert term to the parity violating $N \to \Delta$ asymmetry, another many quark radiative correction involving the photon coupling to a parity violating interaction inside the nucleon is that of "anapole" contributions. Similar effects have been studied, both theoretically and experimentally [20], for parity violating elastic *ep* and quasielastic *ed* scattering. For both the elastic case considered in Ref. [20] and the $N \to \Delta$ case considered here and in Ref. [1], the anapole contributions have a leading Q^2 dependence which follows that of the tree level neutral current. They can be included in the axial contributions to this asymmetry through [1]

$$\Delta^{\pi}_{(3)}(\mathrm{TOT}) = 2(1 - 4\sin^2\theta_W)(1 + R^{\Delta}_A)F(Q^2, s), \tag{23}$$

where R^{Δ}_A includes both the Siegert and anapole contributions (along with other much smaller and theoretically understood contributions), and $F(Q^2, s)$ includes the axial

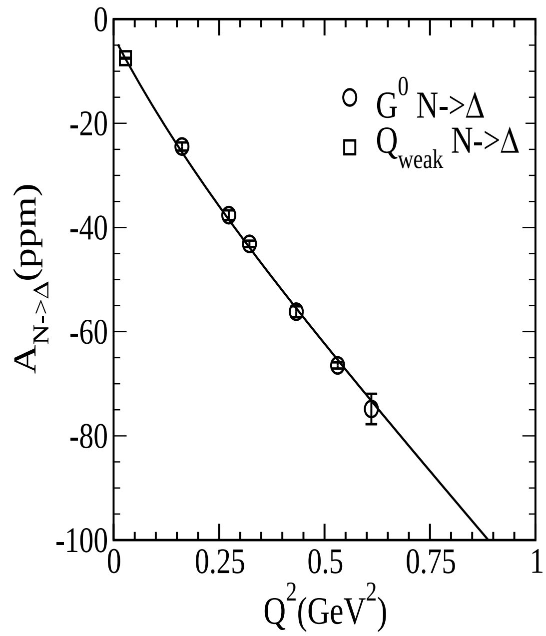

Figure 9: Expected results for the axial mass parameter in the axial vector transition form factor $G^A_{N\Delta}$ and the Siegert contribution, where we have plotted the expected asymmetry vs. Q^2 assuming the Adler parameterization including the Siegert contribution of -4 ppm at $Q^2 = 0$. Using the measurement described here, we would achieve a statistical uncertainty on the axial mass of $\delta M_A = 0.042$, and an uncertainty on the Siegert term of 0.092 ppm corresponding to $\delta d_\Delta = 2.3 g_\pi$. Without this measurement, we would achieve a statistical uncertainty on the axial mass of $\delta M_A = 0.13$ GeV, and an uncertainty on the Siegert term of 1.23 ppm (corresponding to $\delta d_\Delta = 30 g_\pi$).

vector transition form factor $G^A_{N\Delta}(Q^2)$. The authors of Ref. [1] show that R_A^{anapole} is proportional to another low energy constant, a_Δ, which can also be expressed in terms of g_π, and is also theoretically uncertain. The "reasonable range" given for a_Δ in [1] is $-15g_\pi < a_\Delta < 70g_\pi$, corresponding to a range in radiative corrections due to this term of $0.06 > R_A^{\text{anapole}} > -0.29$ in the kinematic range covered by these measurements (both those described here and those of E01-115). It is also shown in [1] that R_A^{anapole} is a very slowly varying function of Q^2, and therefore manifests itself as a change in normalization of $G^A_{N\Delta}$. Now, $G^A_{N\Delta}$ is written in terms of the C_i^A's [3], and the contribution from C_5^A is found to dominate from phenomenological fits to charged current data. Because the radiative corrections always come in tandem with the axial vector transition form factor, i.e.

$$\Delta^\pi_{(3)} \propto (1 + R_A^\Delta)G^A_{N\Delta}, \tag{24}$$

R_A^{anapole} and C_5^A cannot be determined independently; only the product $(1+R_A^{\text{anapole}})C_5^A$ can be determined.

There exists, however, a relation between the form factor $C_5^A(0)$ and the strong $\pi N\Delta$ coupling, namely, the Off Diagonal Goldberger Trieman Relation (ODGTR) [33], which will allow us to constrain C_5^A at $Q^2 = 0$. The ODGTR reads [33]

$$C_5^A(0) = -\sqrt{\frac{2}{3}}\frac{G_{\pi N\Delta}(m_\pi^2)P_\pi(m_\pi^2)}{m_N m_\pi^2}(1 - \Delta_\pi), \tag{25}$$

where

$$G_{\pi N\Delta} = \frac{g_{\pi N\Delta} m_N}{F_\pi}, \tag{26}$$

and $P(m_\pi^2)$ is the coupling of the pseudoscalar current to pions at the pion mass. The Off Diagonal Goldberger Trieman Discrepancy (ODGTD) Δ_π arises from the fact that the ODGTR is truly valid only at $Q^2 = 0$, while the couplings $G_{\pi N\Delta}$ and P_π cannot be measured at $Q^2 = 0$, and Δ_π embodies the corrections to the approximations replacing these couplings at $Q^2 = m_\pi^2$ rather than at $Q^2 = 0$.

From the experimental values of $G_{\pi N\Delta}$ and P_π, the authors of Ref. [33] find the leading order prediction of the ODGTR to be

$$C_5^A(0) = 0.93 \pm 0.10, \tag{27}$$

thus constraining this form factor at the 10% level, with the ODGT Descrepency consistent with zero within errors, and in line of their prediction that the ODGTD be of order a few percent at most. Thus, this constraint can be used for the overall normalization of $G^A_{N\Delta}$, with the axial mass M_A characterizing its Q^2 evolution. Any deviation from this normalization could then be attributed to anapole effects. These effects have recently taken on added interest in light of the SAMPLE results [20], which imply that R_A^{anapole} for the elastic channel may be considerably larger than implied by theory. Understanding these corrections could have important implications for other precision electroweak measurements, such as neutron β-decay, so it is of interest to study them in both the elastic and inelastic channels.

9 Beam Time Requirement

The statistical uncertainties have been calculated under the assumption of an 8 day allocation of beam time in Hall C using 180 μA of 80% polarized electrons that have been accelerated to 1.165 GeV. Evaluation of the Q^2 distribution and beam polarization as well as other calibrations will consume 1 day of beam time while the remaining 7 days will be dedicated to a measurement of the inelastic asymmetry. Our preference would be to have the allocated time scheduled to coincide with the first Q_{weak} run. Ideally the beam time would occur after the Q_{weak} facility development period has established the run conditions acceptable to run the Q_{weak} experiment.

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