A Program to Study Hadronic Matter using Electromagnetic Probes at JLab

We are requesting continuing NSF support for our established program studying hadronic matter using electromagnetic probes. This program currently supports three graduate students who are in mid stride towards completing their Ph.D.s in experimental nuclear physics. Even though the group was recently formed at Idaho State University, each of the senior-level participants have an established history of intense involvement in the Jefferson Lab physics program from their research at their former universities. The PIs, moreover, have a strong record of constructing scientific instrumentation with NSF funding and each has made substantial impacts to the field. The significance of our research and the objectives for the proposed work period are described in section 1. In section 2 we discuss our continued recruitment of underrepresented groups in physics through our well established partnership with several universities in the Americas. The requested funding will not only enable our graduate students to complete the JLab data analysis in a timely manner and obtain their Ph.D. degrees, but these monies will further provide the necessary support to enable Idaho State University to construct the six inner drift chambers for the 12 GeV upgrade to Hall B of JLab; these tracking chambers being a critical-path item for the upgrade.

1 Intellectual Merit of the Proposed Activity

1.1 The ISU Physics Program

1.1.1 Q_{weak}

The Q_{weak} experiment (E05-008), scheduled for installation in 2010, will use parity violating (PV) electron-proton scattering at very low momentum transfers ($Q^2 \sim 0.03$ GeV^2) to measure the weak mixing angle $\sin^2(\theta_W)$. The dominant contribution to the PV asymmetry measured by Q_{weak} is given by the weak charge of the proton, $Q_W^p = 1 - 4\sin^2\theta_W$, with small corrections of order Q^4 from nucleon electromagnetic form factors. This measurement will be a standard model test of the running of the electroweak coupling constant, $\sin^2(\theta_W)$. Any significant deviation of $\sin^2\theta_W$ from the standard model prediction at low Q^2 would be a signal of new physics, whereas agreement would place new and significant constraints on possible standard model extensions including new physics. A brief description of the physics behind the Q_{weak} experiment and the crucial contributions of this proposal to the Q_{weak} experiment are given below.

An essential prediction of the Standard Model is the variation of $\sin^2\theta_W$ with Q^2, often referred to as the "running of $\sin^2\theta_W$." Testing this prediction requires a set of precision measurements at a variety of Q^2 points, with sufficiently small and well understood theoretical uncertainties associated with the extraction of $\sin^2\theta_W$. It also requires a careful evaluation of the radiative corrections to $\sin^2\theta_W$ in the context of the renormalization group evolution (RGE) of the gauge couplings. Such tests have been crucial in establishing QCD as the correct theory of strong interactions [1]. The RGE evolution of the QED coupling has also been demonstrated experimentally [2, 3, 4, 5]. The gauge coupling of the weak interaction, however, represented at low energies by the weak mixing angle $\sin^2\theta_W$, has not yet been studied successfully in this respect.

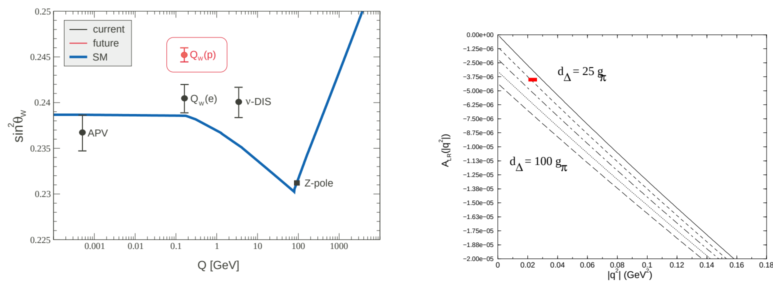

Figure 1: The dependence of $\sin^2\theta_W$ as a function of Q^2 cast in the MS bar scheme of reference [6]. The solid line represents the Standard Model prediction. The results from four experiments (APV [7], $Q_W(e)$ [8], ν-DIS [9], Z-pole [10] are shown together with the expected precision from the Q_{weak} experiment ($\mathrm{Q}_W(p)$) [11]. Expected precision of an inelastic asymmetry measured in one week using the Q_{weak} apparatus compared with the expected asymmetry for several values of the low energy constant d_Δ. The rectangular box indicates both the Q^2 bin and the asymmetry uncertainty.

Figure 1 shows the Standard Model prediction in a particular scheme [12] for $\sin^2\theta_W$ versus Q^2 along with existing and proposed world data. As seen in this Figure, the very precise measurements near the Z^0 pole merely set the overall magnitude of the curve; to test its shape one needs precise off-peak measurements. Presently, there are only three off-peak measurements of $\sin^2\theta_W$ which test the running at a significant level: one from APV [7], one from high energy neutrino-nucleus scattering [9], and the recently completed SLAC experiment E-158 (Q_w(e)) [8]. The measurement of Q_W^p described here will be performed with smaller statistical and systematic errors and has a much cleaner theoretical interpretation than existing low-Q^2 data. In addition, this measurement resides in the semi-leptonic sector, and is therefore complementary to experiment E-158 at SLAC, which resides in the pure leptonic sector and has determined $\sin^2\theta_W$ from PV $\vec{e}e$ (Møller) scattering to roughly a factor of two less precision at low Q^2 [8]. The total statistical and systematic errors anticipated on Q_W^p from these measurements is around 4% [11], corresponding to an uncertainty in $\sin^2\theta_W$ of ± 0.0007. This would establish the difference in radiative corrections between $\sin^2\theta_W(Q^2 \approx 0)$ and $\sin^2\theta_W(M_Z)$ as a 10 standard deviation effect.

ISU's role in Q_{weak}

PI Forest is currently the work package manager of the Region 1 detector and front end electronics for Q_{weak}. The Region 1 tracking system detectors are being assembled and will be tested by the end of 2008. This proposal will support the installation of a front end electronics system from CERN to digitize the analog output of the detectors. PI Forest has been using his startup funds to develop the infrastructure needed to implement this system in Q_{weak}. A critical milestone in the work plan, outlined in Table 1, will be the testing of the integrated tracking system during the summer of 2009 at JLab in preparation for the installation of the system in early 2010. Support from this proposal will be used to complete the front end electronics installation and maintain the Region 1 tracking system during the calibration phase of the Q_{weak} experiment currently scheduled to begin installation in JLab's Hall C in early 2010.

In addition to providing a key component to the Q_{weak} tracking system, PI Forest has also outlined a week-long experiment to measure d_Δ using the Q_{weak} apparatus [11] to a statistical precision of less than 0.1 ppm as shown in Figure 1 [13]. This low energy constant d_Δ was discovered while evaluating the radiative corrections for the PV $N \to \Delta$ transition [14]. The authors in Ref. [14] used Siegert's theorem to show the presence of a non-vanishing PV asymmetry at $Q^2 = 0$ which is proportional to d_Δ. A measurement of the PV asymmetry in the $N \to \Delta$ transition at the photon point, or at very low Q^2 would provide a direct measurement of the low energy constant d_Δ.

The low-energy constant d_Δ is a fundamental constant which has implications to other long-standing physics questions. The same PV electric dipole matrix element which results in d_Δ also drives the asymmetry parameter (α_γ) in radiative hyperon decays, e.g. $\Sigma^+ \to p\gamma$. Although Hara's theorem [15] predicts that the asymmetry parameter ($\alpha_\gamma(\Sigma^+ \to p\gamma)$) should vanish in the exact SU(3) limit, the Particle Data Group [16] reports a measured value of $\alpha_\gamma(\Sigma^+ \to p\gamma) = -0.72\pm$ 0.08. While typical SU(3) breaking effects are of order $(m_s - m_u)/1\text{GeV} \sim 15\%$, the above asymmetry parameter is experimentally found to be more than four times larger. A solution proposed by the authors of Ref. [17] involves 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 non-leptonic hyperon decays, which has also been a long standing puzzle in hyperon decay physics. If the same underlying dynamics is present in the non-strange sector ($\Delta S = 0$) as 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 [18, 19]). The authors of Ref. [14] estimate that this enhancement may be as large as a factor of 100, corresponding to an asymmetry of $\sim$ 4 ppm. This is 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 window into the underlying dynamics of the unexpectedly large QCD symmetry breaking effects seen in hyperon decays.

1.1.2 Vector Meson and Hyperon Photoproduction with Linearly Polarized Photons

The probe afforded by a beam of linearly-polarized photons allows one to gain access to several observables in photonuclear reactions, which otherwise would not be measurable. The polarization axis defines a unique direction in space whereby the angular distributions of the final-state particles can be uniquely referenced. The polarization axis of the photon beam breaks the azimuthal symmetry of the reaction, thereby introducing an azimuthal (Φ) dependence to the differential cross section. This additional information on the angular dependence opens the door to the measurement of a host of observables which are accessible only with a beam of linearly-polarized photons; consequently it provides important constraints on the nature of the photon-nucleon reaction. Such polarization observables are necessary for extracting the spin/parity of the broadly overlapping baryon resonances and measuring such parameters over a large energy range with full angular coverage is crucial for disentangling such contributions. CoPI Cole is the contact person of the experiments which comprise the g8 run [20, 21, 22, 23, 24, 25]. The scientific purpose of g8 is to improve the understanding of the underlying symmetry of the quark degrees of freedom in the nucleon, the nature of the parity exchange between the incident photon and the target nucleon, and the mechanism of associated strangeness production in electromagnetic reactions. With the high-quality beam of the tagged and collimated linearly-polarized photons and the nearly complete angular coverage of the Hall-B spectrometer, we seek to extract the differential cross sections and polarization observables for the photoproduction of vector mesons and kaons at photon energies ranging between 1.10 and 2.20 GeV.

In preparation for the g8a run, we commissioned the Coherent Bremsstrahlung Facility [26], which was essentially a new beamline in Hall B for producing a tagged and collimated beam of linearly polarized photons, where the mean polarization in the energy range of 1.8 to 2.2 GeV was 71%. We enjoyed a reasonably successful two-month run for g8a, which so far, has culminated in two Ph.D. theses [27, 28], two master's theses [29, 30], and one of the two NSF graduate research fellowships [31] awarded in nuclear physics in 2003. We seek to build upon our earlier work and investigate the nature of resonant baryon states by probing protons with polarized photons. The set of experiments forming the first phase of the g8 run took place in the summer of 2001 (6/04/01 - 8/13/01) in Hall B of Jefferson Lab. These experiments made use of a beam of linearly-polarized photons produced through coherent bremsstrahlung and represents the first time such a probe was employed at Jefferson Lab. The second time this probe was used took place in the summer of 2005 (6/20/05 - 9/01/05) for the second phase of g8 (g8b), followed by g13b (3/08/07 - 6/29/07) and g9a (10/17/07 - 2/11/08). The g8 set of experiments, therefore, was a vital first step for establishing the Coherent Bremsstrahlung Facility and this experience paved the way for the successful runs with linearly polarized photons in Hall B of JLab: g13b ($\vec{\gamma}d$), and g9a ($\vec{\gamma}\vec{p}$). The lessons learned in calibration and cooking for g8b have accelerated the analyses for the g13a/b and g9a. And in the three years since the end of the g8b run, we have or are near completion of three Ph.D. theses: a) Craig Paterson [32], University of Glasgow, $\vec{\gamma}p \to K\Lambda, K\Sigma^{\circ}$, Aug. 2008), b) Patrick Collins [33], Arizona State University, $\vec{\gamma}p \to p\eta, p\eta'$, Nov. 2008, and c) Julián Salamanca [34, 35], Idaho State University, $\vec{\gamma}p \to p\phi$, May 2009.

Photoproduction of the $\phi(1020)$

Vector meson photoproduction at high energies, as is well known, proceeds primarily through pomeron exchange rather than by π or η meson exchange, which are respectively termed natural and unnatural parity exchange. In the baryon resonance energy regime ($E_{\vec{\gamma}} \sim 2.0$ GeV) and at low four-momentum transfer squared, t, the peak structure of the coherent ϕ-meson photoproduction cross section is not well explained at threshold by a pure pomeron-exchange-based model [36]. The extraction of the Spin Density Matrix Elements (SDMEs) from ϕ-meson decay angular distributions will shed light on the proportion of natural and unnatural parity exchange involved in the reaction mechanism [37] at low t, which is further to be compared to the predicted values of the Vector Dominance Model (VDM) [38]. We have several thousand ϕ mesons at both low and high t in the baryon resonance regime of $2.02 < \sqrt{s} < 2.11$ GeV. With the exception of this g8 dataset, there are no photoproduced phi mesons with linearly polarized photons measured in the central region in the world data set. Extracting the SDMEs for the phi channel at high $|t|$ will therefore hold discovery potential for non-VDM mechanisms at higher four-momentum transfers squared. After making the necessary momentum, timing, particle ID, and Dalitz mass cuts we separate the data into unpolarized (AMO), perpendicular (PERP) polarization, and parallel (PARA) polarization. We fit a Breit-Wigner to the phi meson peak constrained with a decay width Γ of 4.26 MeV with a second-order polynomial for fitting the background and a gaussian for representing the detector uncertainties. Below we display the phi peak obtained from extracting the K^- from missing mass and then forming the invariant mass of the K^+K^- separated in PERP and PARA orientations for the cms energy of $2.11 < \sqrt{s} < 2.20$ GeV.

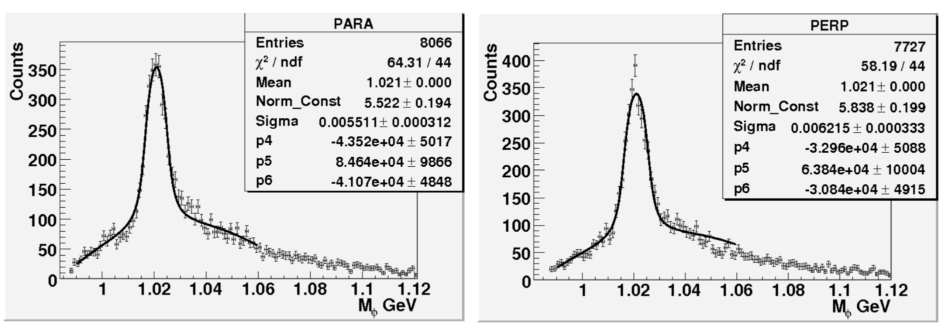

Figure 2: K^+K^- invariant mass in the cms energy range of $2.11 < \sqrt{s} < 2.20$ GeV fit with a Breit-Wigner + Gaussian + 2nd order polynomial. The decay width is fixed at 4.26 MeV. (RHS) parallel (LHS) perpendicular polarizations.

Below we plot the combination of parallel (PARA) and perpendicular (PERP) photoproduced phi mesons for all t to obtain the photon beam asymmetry parameter:

$$\Sigma = (W^{PARA} - W^{PERP})/(W^{PERP} + W^{PARA}).$$

These values are consistent with what we would expect from the Vector Dominance Model. We are presently working on separating the data into low- and high-$|t|$ regimes, but are not prepared to show it until we have authorization from the CLAS collaboration.

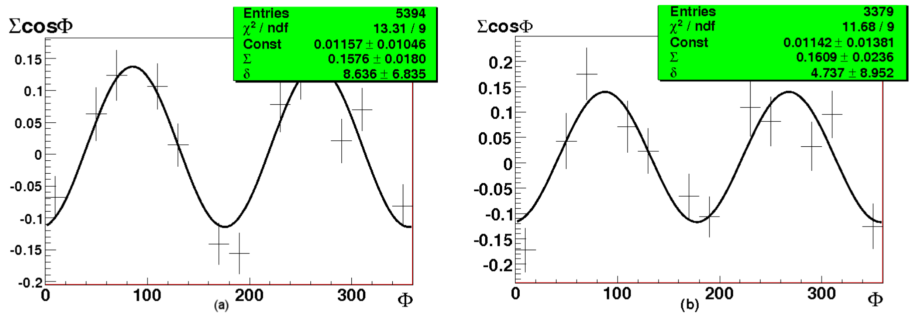

Figure 3: Beam asymmetry for the phi meson channel over the full range of t for (a) $1.9 < E_\gamma < 2.1$ GeV and (b) $1.7 < E_\gamma < 1.9$ GeV. The photon beam polarization is 75%.

1.1.3 The *PrimEx* Experiment

CoPI Dale is a spokesperson for the *PrimEx* Collaboration. At present, the scientific goal of the Collaboration is to perform a high precision measurement of the neutral pion lifetime as a test of the chiral anomaly in QCD, along with different approaches to corrections to the anomaly.

The two-photon decay mode of the π^0 reveals one of the most profound symmetry issues in quantum chromodynamics, namely, the explicit breaking of a classical symmetry by the quantum fluctuations of the quark fields coupling to a gauge field [39]. This phenomenon, called anomalous symmetry breaking, is of pure quantum mechanical origin. The axial anomaly of interest to us involves the corresponding coupling of the quarks to photons [40]. In the limit of exact isospin symmetry, the π^o couples only to the isotriplet axial-vector current $\bar{q}I_3\gamma_\mu\gamma_5 q$, where $q = (u,\ d)$, and I_3 is the third isospin generator. In the limit of two quark flavors, the electromagnetic current is given by $\bar{q}(1/6+I_3/2)\gamma_\mu q$. When coupling to the photon, the isosinglet and isotriplet components of the electromagnetic current lead to an anomaly that explicitly breaks the symmetry associated with the axial-vector current $\bar{q}\ I_3\ \gamma_\mu\gamma_5\ q$, and this in turn directly affects the coupling of the π^o to two photons. The conservation of the axial U(1) current, to which the η' meson couples, as well as the $\bar{q}\frac{1}{2}\lambda_8\gamma_\mu\gamma_5 q$, to which the η meson couples, are similarly affected by the electromagnetic field.

For vanishing quark masses, the anomaly leads to the predicted width of the $\pi^o \to \gamma\gamma$ decay:

$$\Gamma = M_\pi^3 \frac{\mid A_{\gamma\gamma} \mid^2}{64\pi} = 7.725 \pm 0.044 \text{ eV}, \tag{1}$$

where the reduced amplitude is

$$A_{\gamma\gamma} = \frac{\alpha_{em}}{\pi F_\pi} = 2.513 \cdot 10^{-2} \text{ GeV}^{-1} \tag{2}$$

In this expression, there are no free parameters. Since the mass of the π^0 is the smallest in the hadron spectrum, higher order corrections to this prediction are small and can be calculated

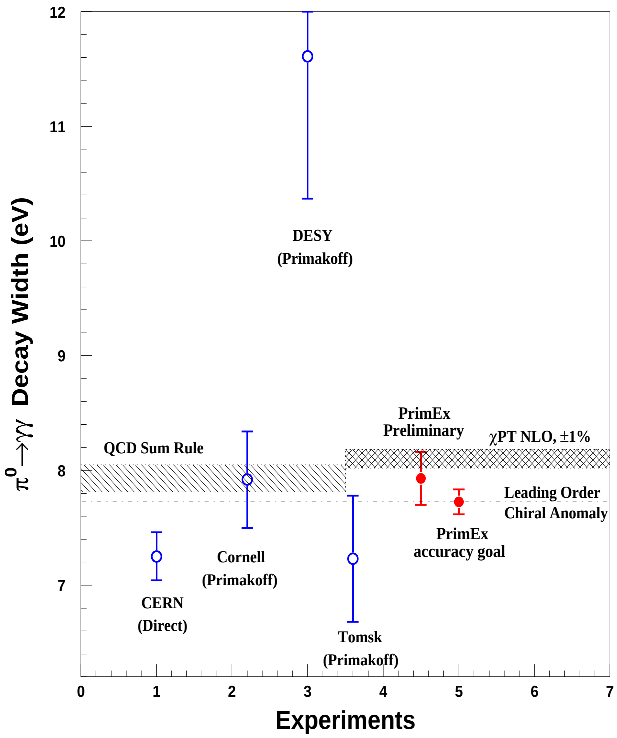

Figure 4: $\pi^o \to \gamma\gamma$ decay width in eV. The dashed horizontal line is the leading order prediction of the axial anomaly [39, 40]. The left hand side shaded band is the recent QCD sum rule prediction and the right hand side shaded band is the next-to-leading order chiral theory predictions. The experimental results with errors are for : (1) the direct method [41]; (2, 3, 4) the Primakoff method [42, 43, 44]; (5) the preliminary result from the first *PrimEx* data set; (6) the expected error for the final goal of the *PrimEx* experiment, arbitrarily plotted to agree with the leading order prediction. prediction.

with sub-percent accuracy. The current experimental value is 7.84 ± 0.56 eV [51] and is in good agreement with the predicted value with the chiral limit amplitude. This number is an average of several experiments [51]. Even at the 7% level quoted by the Particle Data Book [16], the accuracy is not sufficient for a test of the new calculations which take the finite quark masses into account. The level of precision of $\simeq 1.4\%$, which is the goal of *PrimEx*, will satisfy these requirements. Stimulated by the *PrimEx* project, several new theoretical calculations have been published in recent years, and are shown in Figure 4. The first two independent calculations of the chiral corrections were performed in the combined framework of chiral perturbation theory (ChPT) and the $1/N_c$ expansion up to $\mathcal{O}(p^6)$ and $\mathcal{O}(p^4 \times 1/N_c)$ in the decay amplitude [52] [53]. The η' is explicitly included in the analysis as it plays as important a role as the η in the mixing effects. It was found that the decay width is enhanced by about 4% with respect to the value stated in equation (1). This enhancement is almost entirely due to the mixing effects. The result of this next-to-leading order analysis is $\Gamma_{\pi^0\to\gamma\gamma} = 8.10$ eV with an estimated uncertainty of less than 1%. Another theoretical calculation based on QCD sum rules [54], also inspired by the *PrimEx* experiment, has recently been published with a theoretical uncertainty less than 1.5%. Here, the only input parameter to the calculation is the η width.

We are using quasi-monochromatic photons of energy 4.6-5.7 GeV from the Hall B photon tagging facility to measure the absolute cross section of small angle π^o photoproduction from the Coulomb field of complex nuclei. The invariant mass and angle of the pion are reconstructed by detecting the π^o decay photons from the $\pi^o \to \gamma\gamma$ reaction. For unpolarized photons, the Primakoff cross section is given by:

$$\frac{d\sigma_P}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\pi \tag{3}$$

where $\Gamma_{\gamma\gamma}$ is the pion decay width, Z is the atomic number, m, β, θ_π are the mass, velocity and production angle of the pion, E is the energy of incoming photon, Q is the momentum transfer to the nucleus, and $F_{e.m.}(Q)$ is the nuclear electromagnetic form factor, corrected for final state interactions of the outgoing pion. As the Primakoff effect is not the only mechanism for pion photoproduction at high energies, some care must be taken to isolate it from competing processes. In particular, the full cross section is given by:

$$\frac{d\sigma}{d\Omega_\pi} = \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_C}{d\Omega} + \frac{d\sigma_I}{d\Omega} + 2 \cdot \sqrt{\frac{d\sigma_P}{d\Omega} \cdot \frac{d\sigma_C}{d\Omega}} cos(\phi_1 + \phi_2) \tag{4}$$

where the Primakoff cross section, $\frac{d\sigma_P}{d\Omega}$, is given by equation (4). The nuclear coherent cross section is given by:

$$\frac{d\sigma_C}{d\Omega} = C \cdot A^2 |F_N(Q)|^2 \sin^2\theta_\pi \tag{5}$$

and the incoherent cross section is:

$$\frac{d\sigma_I}{d\Omega} = \xi A(1 - G(Q)) \frac{d\sigma_H}{d\Omega} \tag{6}$$

where A is the nucleon number, $C \sin^2\theta_\pi$ is the square of the isospin and spin independent part of the neutral meson photoproduction amplitude on a single nucleon, $|F_N(Q)|$ is the form factor for the nuclear matter distribution in the nucleus, (corrected for final state interactions of the outgoing pion), ξ is the absorption factor of the incoherently produced pions, $1 - G(Q)$ is a factor which reduces the cross section at small momentum transfer due to the Pauli exclusion principle, and $\frac{d\sigma_H}{d\Omega}$ is the π^o photoproduction cross section on a single nucleon. The relative phase between the Primakoff and nuclear coherent amplitudes without final state interactions is given by ϕ_1, and the phase shift of the outgoing pion due to final state interactions is given by ϕ_2. The angular dependence of the Primakoff signal is different from the background processes, allowing $\Gamma(\pi^0 \to \gamma\gamma)$ to be extracted from a fit to the angular distribution of photoproduced π^0. Measurements of the nuclear effects at larger angles are necessary to determine the unknown parameters in the production mechanism and thus make an empirical determination of the nuclear contribution in the Primakoff peak region. Consequently, this experiment uses a π^o detector with good angular resolution to eliminate nuclear coherent production, and good energy resolution in the decay photon detection will enable an invariant mass cut to suppress multi-photon backgrounds.

We submitted our first proposal (E-99-014) to PAC15 in December of 1998. It was approved by PAC15 and reconfirmed in jeopardy review later by PAC22 with an "A" rating. An NSF MRI proposal for \$970k was awarded (PIs: D.S. Dale, A. Gasparian, R. Miskimen, S. Dangoulian) for the construction of a multichannel neutral pion calorimeter. This was successfully designed, constructed, and commissioned over the period 2000-2004. The first experiment on two targets (^{12}C

and ^{208}Pb) was performed in 2004. A second run (E-08-023, spokespersons: D. Dale, A. Gasparian, M. Ito, R. Miskimen) was approved by PAC33 with an $A-$ rating for 20 days of running to reach the proposed goal of $\sim 1.4\%$ accuracy. While the CoPI of this funding proposal has been involved in all aspects of this program, he has taken primary responsibility for the flux normalization. This has involved the design, construction, and commissioning of the *PrimEx* pair spectrometer. In addition, along with his students, he has been responsible for the analysis of the resulting data. This has also included a high precision measurement of the absolute cross section of a well known QED process, pair production, to verify that the flux determination was correct.

1.2 Prior use of NSF funds

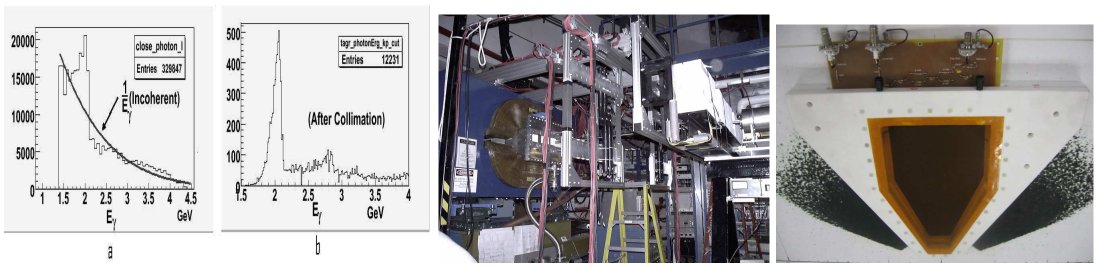

Figure 5: The histograms show the improvement to Hall B's linearly polarized photon beam using the collimator designed and calibrated by CoPI Cole. The middle picture shows the pair spectrometer system installed in Hall B by CoPI Dale and his collaborators. The right most picture is of an assembled GEM detector for Q_{weak}'s Region 1 tracking system designed, machined and assembled by PI Forest and his students at ISU.

The PIs in this proposal have a strong record of receiving external funding from the NSF and a history of effectively using those funds to make substantially contributions to the infrastructure of the nuclear physics program described in this proposal, as summarized in Figure 5. The bremsstrahlung facility in JLab's Hall-B is one example of CoPI Cole's efforts to enhance the capabilities of Hall B's photon physics program. CoPI Dale has used NSF funds to install a pair spectrometer facility in Hall B. The Region 1 tracking system for Q_{weak} was constructed by PI Forest using NSF funds.

<u>Coherent Bremsstrahlung Facility</u>

An instrumented collimator, having an aperture of 2.0 mm in diameter, is installed in the Hall-B beamline downstream of the tagger magnet and is located 22.9 m away from the diamond radiator. The collimator [45], designed and calibrated by CoPI Cole, forms part of the Coherent Bremstrahlung Facility [26]; it serves to enhance the degree of linear polarization, P_γ, within the coherent peak. As shown in Figure 5, the coherent distribution, peaked at 2.1 GeV, is considerably enhanced by tightly collimating the photon beam to one half of a characteristic angle. The spectra were taken with an electron beam energy of 4.5 GeV. Since the merit function inversely scales with the photon polarization squared, the collimation as shown in Figure 5 enhances the quality of the polarization data by at least 30%.

Pair Spectrometer

In 2000, an NSF MRI proposal (grant # PHY-0079840) for $970k was awarded (PIs: D.S. Dale, A. Gasparian, R. Miskimen, S. Dangoulian) for the construction of a multichannel neutral pion calorimeter, a pair spectrometer for flux monitoring, as well as a number of other pieces of experimental instrumentation for the *PrimEx* experiment. CoPI Dale was involved in all aspects of the experimental design and construction, and was the lead on the design, construction, and testing of the pair spectrometer. This pair spectrometer was successfully commissioned in 2002, and is now a part of the standard beamline instrumentation in Hall B.

Q_{weak} Detector Construction

The design, construction, and testing of the Region 1 tracking system for the Q_{weak} experiment at Jefferson Lab has been the main research activity supported by PI Forest's previous NSF grant. The Q_{weak} Region 1 tracking system is one of three tracking systems designed to measure the Q^2 profile of elastically scattered electrons as well as background contributions to the parity violating signal [11]. The Region 1 tracking system is located behind the first collimator at a distance of about 550 cm from the main torus magnet (200 cm from the target). The high radiation flux and the small detector footprint are two of the biggest challenges facing the Region 1 tracking system. As a result, an ionization chamber equipped with Gas Electron Multipliers (GEM) [46] was chosen in order to accommodate the high radiation flux near the target. The GEM preamplifiers allow smaller ionization cell sizes thereby resulting in ionization chamber rise times of 50 nanoseconds or less. Figure 5 below shows the custom designed GEM detector for the Q_{weak} Region 1 tracking system [47]. Engineers from the Idaho Accelerator Center (IAC) designed the GEM preamplifiers. This is a clear example of how the infrastructure at the IAC can be leveraged in support of our physics mission. The remaining detector design, machining, and assembly was completed using both graduate and undergraduate students.

1.3 Future Use of NSF funds

Work Plan

The work undertaken to satisfy the objectives for the funding cycle of this proposal involves the completion of the Region 1 tracking system for Q_{weak} and the construction of drift chambers for the Hall B 12 GeV upgrade according to the milestones shown in Table 1. The construction of the

Q_{weak} Region 1 tracking system detector will be completed before the current NSF funding cycle expires. The R1 tracking system is expected to be delivered to JLab during the summer of 2009 and be integrated with other tracking system components to test the system before the scheduled installation in early 2010. PI Forest will play a critical role integrating the detector and front end electronics into the rest of the tracking system during the first few months of this proposal as well as during the installation and operation of the system in the two years that follow. During the same time frame, CoPIs Cole and Dale will be responsible for installing a clean room facility at ISU which will be used to construct drift chambers for JLab's Hall B starting in early 2010 (please see attached letter from the JLab 12 GeV Upgrade Assistant Project manager). The class-10,000 clean room for this project has been designed in collaboration with JLab's drift chamber management group and bids have been received. The drift chamber construction for Hall B is a critical component in support of the 12 GeV upgrade program at JLab and will support the ISU physics program.

ISU's 12 GeV Physics Program

The ISU group is currently the spokespersons on two experiments proposed for a 12 GeV upgraded Hall B. The first experiment, PR12-06-109, will make measurements that contribute substantially to our knowledge of polarized parton distribution functions for all quark flavors and even the polarized gluon distribution Δg. One particular outcome, shown in Figure 6, will improve

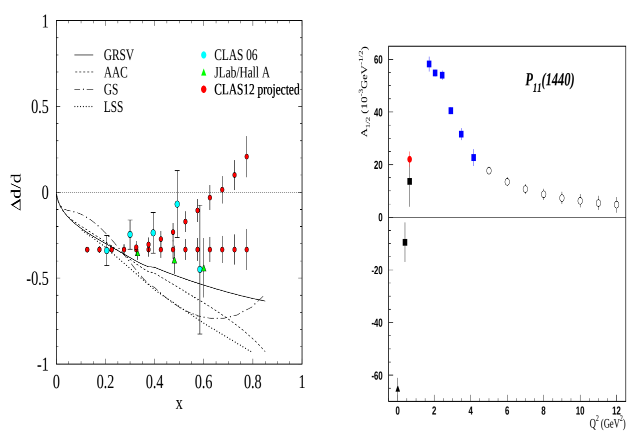

Figure 6: The left figure represents a comparison between the measurement to be made using an energy upgraded JLab with fits of the world data set for $\frac{\Delta d}{d}$. The expected data have been drawn along the pQCD and CQM prediction. The right figure represents the high Q^2 measurements that are possible after the upgrade to Hall B. Projected N^* electrocoupling for the Roper $P_{11}(1440)$ as a function of Q^2 where the open circles with error bars are from our expected experiment [48], the closed squares are from the available CLAS data on single pion electroproduction [49], and the solid blue squares are the preliminary data from analysis of e1-6 run overlaid with the results from the combined analysis of single and double pion electroproduction off protons [50].

Date	Objective
06/09	Begin installing a clean room for constructing Hall B R1 Drift Chambers at the Idaho Accelerator Center
09/09	Complete testing of the Q_{weak} Region 1 tracking system at JLab
01/10	Begin Construction of R1 Chambers
03/10	Complete installation of Q_{weak} Region 1 tracking system in JLab's Hall C
06/10	Quality Assurance Tests for the First R1 Drift Chambers
10/12	Install all R1 chambers in Hall-B
08/09 - 07/11	Continue efforts with the Americas
08/09 - 07/11	Analyze g8b and g13a/b data: omega and charged rho production.

Table 1: Work Plan Timeline

our ability to test the high-x prediction made by pQCD and the constituent quark model. While pQCD predicts that $\frac{\Delta d}{d}$ should go to unity at $x_{bjk} = 1$, the constituent quark model, with hyperfine interactions, predicts a value closer to $-1/3$. A second component to ISU's 12 GeV program will seek to measure the exclusive single- and double-pion channels produced when 11-GeV electrons are directed onto a proton target with an upgraded CLAS detector. The goal will be to perform measurements of resonances, like the $P_{11}(1440)$ resonance shown in Figure 6, which will be used as input to models describing such transitions. The Excited Baryon Analysis Center (EBAC) at JLab is one such effort which will use an advanced coupled-channel approach in these fits. These studies will afford us the means to sample the transition from the hadronic to partonic regime.

List of Currently supported students

Student	Major (Year of Degree)	Projected
Julian Salamanca	Ph.D.	2009
Tamar Didberidze	Ph.D.	2010
Danny Martinez	Ph.D.	2012
Oleksei Kosinov	Ph.D.	2012
Adrianne Spilker	M.S.	2009
Shadike Saitiniyazi	M.S.	2009
Jordan Keough	B.S.	2011
Nathan Lebaron	B.S.	2012

Table 2: Currently supported students

2 The Broader Impact of the Idaho State University Nuclear Physics Research Program

2.1 The Americas

Our broader impacts activities are directed towards the Americas, central and south. Over the past nine years, the two CoPIs have have been active in outreach towards Latin America. CoPIs Dale and Cole can both communicate in Spanish. Indeed, this past year CoPI Cole successfully completed Spanish 201 and 202 at ISU, as a Freshman with an undeclared major, and he is presently enrolled in an advanced Spanish composition course at the 300-level in the effort to attain fluency. Speaking Spanish is necessary for our broader impacts activities. South American physics students tend to read English rather well, but speaking good English is entirely another matter. To attract students, one needs to present the many research opportunities in medium energy nuclear physics in the United States while dispelling subtle and not-so-subtle misconceptions, which abound. And to communicate these matters, it is imperative to speak good Spanish.

We seek to promote dialogue between faculty members of North-American and Latin-American institutions by finding common interests in research which will allow for coordinating our programs in nuclear physics research. Through this effort, we expect to strengthen existing links and forge new ones within the broad scope of the international nuclear physics community. CoPI Cole has been a PI four times and a CoPI twice on six separate Americas Program grants, which amounts in $130k in funding.

Funding History

- The III Latin American Workshop on Nuclear and Heavy Ion Physics (PI: Phil Cole) NSF-INT-9907453 for $15,000
- A Collaborative Effort between the U.S. and Colombia on the Physics with Linearly Polarized Photons. (PI: Phil Cole) NSF-OISE-0101815 for $32,590.
- Americas Program: Student Sponsorship at the Fourth Latin American Symposium on Nuclear Physics, Mexico City, Mexico, September 24-28, 2001. (PI: Phil Cole) NSF-OISE-0117545 for $23,369
- US-Brazil Student Sponsorship at the Fifth Latin American Symposium on Nuclear Physics; Santos, Brazil, September 1-5, 2003 (PI: Phil Cole, CoPI Jorge Lopez) NSF-OISE-0313656 for $18,000
- U.S.-Argentina Collaborative Workshop in Nuclear Physics and Its Applications (PI: Chaden Djalali, CoPI: Phil Cole) NSF-OISE-0527110 for $32,200.

- US-Peru Workshop in Nuclear Physics and Its Applications, June 11-16, 2007, Cusco, Peru (PI: Chaden Djalali, CoPI: Phil Cole) NSF-OISE-0652360 for $32,200. See: VII Latin American Symposium on Nuclear Physics and Applications, AIP Conference Proceedings 947 (2007), Editors: Ricardo Alarcon, Philip L. Cole, Chaden Djalali, and Fernando Umeres.

Recent outcomes of our links with the Latin American community include Mr. Tulio Rodrigues' visit to Jefferson Lab in August 2004 to work with CoPI Dan Dale on theoretical calculations for the *PrimEx* experiment. At the time CoPI Dale was at the University of Kentucky. Mr. Rodrigues was supervised by Dr. Arruda-Neto, head of the Nuclear Reactions and Structure Research Group at the Physics Institute of the University of São Paulo and received his Ph.D. in 2006. Dr. Rodrigues has visited ISU twice in the past two years to work on *PrimEx*-related physics. Another graduate student, Mr. Vladimir Montealegre from the Universidad de los Andes in Bogotá, Colombia, entered the Ph.D. program at the University of South Carolina. Our recruitment efforts are paying off. Our group now has two strong Ph.D. students, Julián Salamaca and Danny Martínez, from Colombia and upon processing the necessary paperwork, two more Ph.D. students from Colombia will join us in January, 2009.

The Need

Lack of modern equipment is one of the main obstacles to research in the less-developed Latin American countries. There is, however, considerable variation in the size and influence of the physics community by individual countries [55]. A few groups have managed to pursue successful experimental programs in countries with comparatively long traditions in applied and basic research in the nuclear sciences; the chief examples being Argentina, Brazil, Chile, and Mexico, countries where research is fostered through collaborative efforts through annual national nuclear physics conferences. Two of these countries Brazil, site of the V LASNP, and Argentina, site of the VI LASNPA, have launched initiatives to construct large facilities allowing for their use by the wider international nuclear physics community: the Brazilian National Synchrotron Light Laboratory (LNLS) in Campinas (about 70 miles west of São Paulo) and the Tandar heavy ion accelerator in Buenos Aires, Argentina. Other countries in the region which have recently initiated activities aimed to improve their academic and scientific infrastructure in the nuclear sciences include Bolivia, Colombia, Peru and Venezuela.

The Opportunity

There is ample room for collaborative overlap between the two hemispheres. Establishing links between the United States and Latin America will provide a means for recruiting high-caliber graduate-level students and post-doctoral fellows to pursue research at US institutions and laboratories such as JLab, RHIC, ORNL, RIA, and IAC. Such an academic relationship between North and South America will further strengthen the scientific endeavors of the nuclear physics communities of both continents. There is at present a dearth of graduate students pursuing advanced degrees in experimental and theoretical nuclear physics at US universities. This shortage is keenly felt at the national laboratories and facilities, where there is an abundance of Ph.D. theses topics and a paucity of graduate students. The goal is to build ties with faculty and students. While attracting students to US graduate programs, we also wish to build new groups and infrastructure in Latin America that would give the students an attractive career option in their home country after graduation.

The Means and the Goals

We seek to grow these outreach efforts and our group will continue to write funding grants to the NSF Americas Program for sponsoring students to attend future interactions of the Latin American Symposium for Nuclear Physics and Applications. CoPI Cole was recently elected to the ten-member board International Organizing Committee of the VIII Latin American Symposium on Nuclear Physics and Applications to be held in Santiago, Chile, December 15-19, 2009. As in the past, the Committee's responsibilities include the scientific program, formation of an International Advisory Board, and some key aspects of the overall organization of the Symposium. Of this membership, three members are from Universities in the United States. With a colleague in Argentina, CoPI Cole further will write a grant to the International Atomic Energy Agency to help defray travel expenses for non-U.S. students in Latin America, where typically funding from the NSF cannot be obtained.

2.2 Graduate Student Training and Marketability

The role graduate students play in the experiments which take place within our program provide them with marketable skill sets. Maria Novovic and Jena Kraft are clear examples of the impact members of this group have had training an underrepresented group in physics. Maria Novovic was trained in data acquisition, scintillator construction, and data analysis. She is currently a staff physicist at the University of Southern Alabama and is responsible for the undergraduate physics laboratories in addition to her undergraduate instructor role. The graduate training and experiences in PI Forest's lab were instrumental in securing her current position. Jena Kraft, who found a position in industry, reported that her design skills acquired while making a high pressure gas chamber for the GEM detector during her thesis were a key ingredient to her current position. The detector construction and instrumentation projects described in this proposal will continue to be effective in training graduate students for the market place. The Intermediate Energy Nuclear Physics Group at Idaho State University currently has three graduate students, listed in Table 2, working on JLab physics. Our expectation is that this number will increase with the addition of two faculty with JLab projects and the annual influx of more than 10 incoming graduate students per year.

References

[1] I. Hinchcliffe, Eur. Phys. J. C **15**, 85 (2000).

[2] TOPAZ Collaboration: I. Levine *et al.*, Phys. Rev. Lett. **78**, 424 (1997).

[3] VENUS Collaboration: S. Odaka *et al.*, Phys. Rev. Lett. **81**, 2428 (1998).

[4] OPAL Collaboration: G. Abbiendi *et al.*, Eur. Phys. J. C **13**, 553 (2000).

[5] L3 Collaboration: M. Acciarri *et al.*, Phys. Lett. B **476**, 40 (2000).

[6] J. Erler and M. J. Ramsey-Musolf, arXiv:hep-ph/0409169; hep-ph/0005084.

[7] A. Derevianko *et al.*, Phys. Rev. Lett. **85**, 1618 (2000).

[8] P.L. Anthony *et al.*, Phys. Rev. Lett. **95**, 081601, (2005) hep-ex/0504049.

[9] NuTeV Collaboration: G. P. Zeller *et al.*, Phys. Rev. Lett. **88**, 091802 (2002); Erratum-ibid. **90**, 239902 (2003) hep-ex/0110059.

[10] M. Chanowitz, Phys. Rev. Lett. **87**, 231802 (2001); Phys. Rev. D **66**, 073002 (2002).

[11] Q_{weak} Experiment, JLab Experiment E05-008, R. Carlini spokesperson (www.jlab.org/Qweak).

[12] Q_{weak} Experiment, JLab Experiment E02-020 Appendices, J. Erler and M.J. Ramsey-Musolf.

[13] Letter of Intent (LOI-03-105) to JLab PAC24.

[14] Shi-Lin Zhu, C.M. Mackawa, G. Sacco, B.R. Holstein, and M.J. Ramsey-Musolf, Phys. Rev. D **65**, 033001 (2002).

[15] Y. Hara, Phys. Rev. Lett. **12**, 378 (1964).

[16] Particle Data Group, W.-M. Yao *et al.*, Journal of Physics G **33**, 1 (2006) (www.pdg.lbl.gov).

[17] B. Borasoy and B.R. Holstein, Phys. Rev. D **59**, 094025 (1999), hep-ph/9902431.

[18] B. Desplanques, J.F. Donoghue, and B.R. Holstein, Ann. Phys. **124**, 449 (1980).

[19] Shi-lin Zhu, S.J. Puglia, B.R. Holstein, and M.J. Ramsey-Musolf, hep-ph/0012253 (2000).

[20] "Photoproduction of ρ Mesons from the Proton with Linearly Polarized Photons," Jefferson Lab E-94-109, P.L. Cole and K. Livingston, cospokespersons.

[21] "Photoproduction of ϕ Mesons with Linearly Polarized Photons," Jefferson Lab E-98-109, D.J. Tedeschi, P.L. Cole, and J.A. Mueller, cospokespersons.

[22] "Photoproduction of ω Mesons off Protons with Linearly Polarized Photons," Jefferson Lab E-99-013, F.J. Klein and P.L. Cole, cospokespersons.

[23] "Photoproduction of Associated Strangeness using a Linearly Polarized Beam of Photons," CLAS Approved Analysis 2001, J.C. Sanabria, J. Kellie, and F.J. Klein, cospokespersons.

[24] "Proposal for CLAS Approved Analysis (CAA) for Beam Asymmetry in η', $\pi^{\circ}p$, and $\pi^{+}n$ Photoproduction with g8b Data, "P. Collins J. Ball, M. Dugger, E. Pasyuk, B.G. Ritchie, W.J. Briscoe, I.I. Strakovsky, and R.L. Workman. Oct. 27, 2006.

[25] See: http://www.jlab.org/exp_prog/generated/apphallb.html to view the above approved proposals in pdf and click on the experiment number (E-94-109, E-98-109, and/or E-99-013). These pdf files can also be found in: http://www.physics.isu.edu/∼cole/g8/experimental-proposals/.

[26] P.L. Cole, J. Kellie, F.J. Klein, K. Livingston, J.A. Mueller, J.C. Sanabria, and D.J. Tedeschi, Proceedings of the Int'l Symp. of Electromagnetic Interactions in Nuclear and Hadron Physics (World Scientific), ISBN 981-238-044-2. (2002).

[27] Christopher Gordon, "ρ° Photoproduction using Linearly Polarised Photons with the CLAS Detector," University of Glasgow, Ph.D. Thesis, May 2004.

[28] Joseph Melone, "Measurement of the Photon Asymmetry for the $p(\vec{\gamma}K^{+})\Lambda$ Reaction at CLAS from 1.6 to 2.0 GeV," University of Glasgow, Ph.D. Thesis, Dec. 2004.

[29] Alejandro Puga, "Calibration of the UTEP/Orsay Instrumented Collimator via the LabVIEW-based Data Acquisition System," University of Texas at El Paso, Master's Thesis, Dec. 2001.

[30] Julián Salamanca, "Cálculo de la aceptancia del detector CLAS para la reacción $\vec{\gamma}p \rightarrow K\Lambda$," Universidad de los Andes, Bogotá, Colombia; Master's Thesis: Dec. 2004. The PI was the external committee member and attended the defense in Bogotá in November, 2004. He also used this opportunity to recruit Mr. Salamanca to Idaho State University.

[31] Russell Mammei, NSF Graduate Research Fellowship, 2003. He worked on the calibration of the Hall-B instrumented collimator. Juliette Mammei, NSF Graduate Research Fellowship, 2003. She worked on the Hall-C 12 GeV upgrade.

[32] Craig Paterson, "Polarization Observables in Strangeness Photoproduction with CLAS at Jefferson Lab," Ph.D. Thesis, University of Glasgow, Sept. 2008.

[33] Patrick Collins, "Beam Asymmetry in Eta(547) and Eta(958) Meson Photoproduction off the Proton," Ph.D. Thesis, Arizona State University, Nov. 2008.

[34] Julian Salamanca, "ϕ-Meson Photoproduction with Linearly Polarized Photons at Threshold Energies," Ph.D. Thesis, Idaho State University, expected: May, 2009.

[35] Julian Salamanca, Philip L. Cole, and the CLAS Collaboration, "ϕ-Meson Photoproduction with Linearly Polarized Photons at Threshold Energies," VII Latin American Symposium on Nuclear Physics and Applications, AIP Conf. Proc. 947 (2007).

[36] T. Mibe, "Measurement of ϕ-meson photoproduction near production threshold with linearly polarized photons," Ph.D. Thesis, Osaka University, Japan (2004);
T. Mibe *et al.* Phys. Rev. Lett. **95**, 182001 (2005).

[37] K. Schilling, P. Seyboth, and G. Wolf, Nucl. Phys. B **15**, 397 (1970).

[38] J.J. Sakurai, Ann. Phys. **11**, 1 (1960).

[39] See *e.g.* Dynamics of the Standard Model, J.F. Donoghue, E. Golowich, and B.R. Holstein, Cambridge University Press (1992).

[40] J.S. Bell and R. Jaciw, Nuovo Cimento A **60**, 47 (1969). S.L. Adler, Phys. Rev. **177**, 2426 (1969).

[41] H.W. Atherton *et al.*, Phys. Lett. B **158** 81 (1985).

[42] A. Browman *et al.*, Phys. Rev. Lett. **33**, 1400 (1974).

[43] G. Bellettini *et al.*, Il Nuovo Cimento **66**, 243 (1970).

[44] V.I. Kryshkin *et al.*, Sov. Phys. JETP **30**, 1037 (1970).

[45] P.L. Cole, Design Note (1999) unpublished; A. Puga, M.S. Thesis, University of Texas at El Paso (2001). The device was designed and constructed by IPN-Orsay and Univ. of Texas at El Paso under grant NSF-PHY-9874653.

[46] F. Sauli,Nucl. Instr. and Meth., **A 386**, 531-534 (1997).

[47] http://www.iac.isu.edu/mediawiki/index.php/Qweak

[48] "Nucleon Resonance Studies with CLAS12 in the Transition from Soft to Partonic Physics," Spokespersons: V.I. Mokeev, R.W. Gothe, V.D. Burkert, P.L. Cole, K. Joo, and P. Stoler. Proposal to be submitted in Jan. 2009.

[49] I.G. Aznauryan *et al.*, Phys. Rev. C **71**, 015201 (2005).

[50] I.G. Aznauryan *et al.*, Phys. Rev. C **72**, 045201 (2005).

[51] R.M. Barnett *et al.*, Review of Particle Physics, Phys. Rev. D **54**,1 (1996).

[52] J. L. Goity, A. M. Bernstein, J. F. Donoghue, and B. R. Holstein, manuscript in preparation; J. L. Goity, talk at Baryons 2002.

[53] B. Ananthanarayan and B. Moussallam, preprint hep-ph/0205232.

[54] B.L. Ioffe and A.G. Oganesian, Phys. Lett. B **647**, 389 (2007).

[55] Jose Luis Morán-López, *Physics in Latin America Comes of Age*, Physics Today, Oct. 2000 Vol. 53, Number 10, online at http://www.aip.org/pt/vol-53/iss-10/p38.html.