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 four graduate students, three of whom 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 (JLab) 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. Through our well established partnership with several universities in the Americas, we discuss in section 2 our continued recruitment of underrepresented groups in physics. 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 five of the six inner Region1 (R1) 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 Jefferson Lab 12 GeV Program

In this section we discuss the N* and EG1 programs and how the construction of R1 at ISU helps realize those physics goals.

The physics Ph.D. students at ISU are currently analyzing data, taken by the CLAS collaboration, to elucidate the structure of a nucleon using polarization observables. The extraction of photonuclear asymmetries and measurements of a nucleon's polarized quark distribution functions have been the group's two central objectives. The next step in the pursuit of these objectives will require the use of a 12-GeV energy upgrade to CEBAF. The ISU group has taken on the construction of five drift chambers for the Hall-B detector upgrade (CLAS12) as a means to achieve the above objectives and as a service to the research community in intermediate energy nuclear physics.

1.1.1.1 CLAS12 RegionI Drift Chamber Construction The ISU group has been contracted by Jefferson Science Associates to construct five drift chambers for the 12 GeV upgrade to Hall B. Two members of the group, Dr. Dustin McNulty and Dr. Tony Forest, constructed a Class-10,000 clean room this past summer for the project. The first chamber is currently being strung with wires, as shown in the figure below, and is expected to be completed by January 2011. Each chamber takes less than 6 months to construct. A team of stringers and a lead stringer have been hired for this task with the ISU group taking the role of management and quality control. We expect to complete the last chamber before October, 2013.

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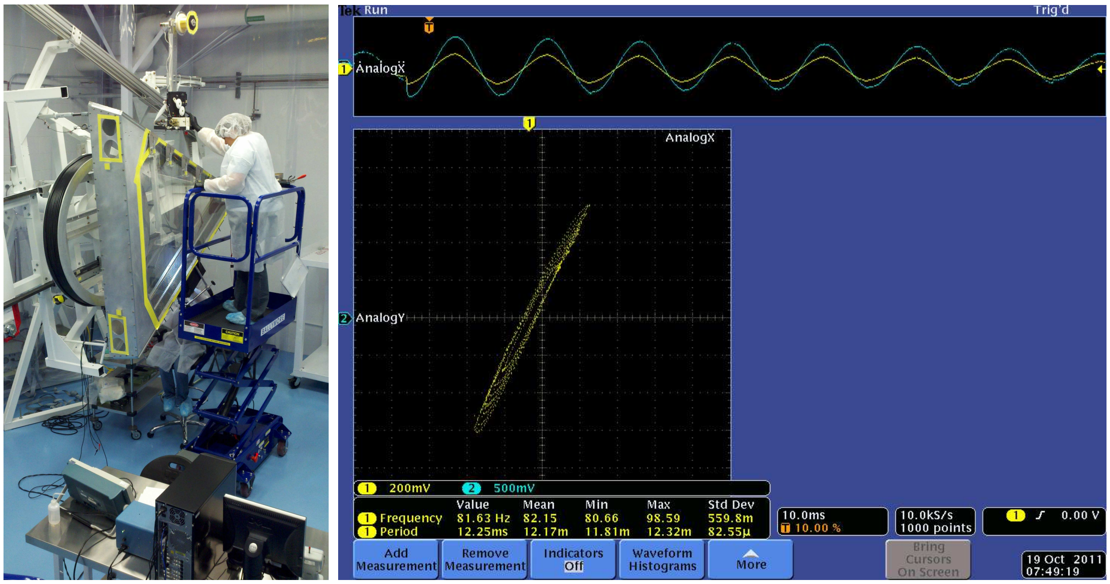

Figure 1: The left figure shows a photograph of two technicians constructing one of the R1 drift chambers in the ISU physics clean room. The right figure is an illustration of the signal observed during the wire tension measurements [1].

1.1.1.2 EG1 Program Spin structure functions of the nucleon have been measured in deep inelastic lepton scattering (DIS)for nearly 30 years since the first experiments at SLAC. Interest increased substantially in the 80s when the EMC collaboration reported that the quark helicities only made a small contribution to the overall helicity of the proton, according to their data. This "spin crisis" led to a vigorous theoretical and experimental effort over the next 20 years, with a large data set collected at CERN, SLAC, DESY, and Jefferson Lab.

Interest in the quark contributions to a nucleon's structure continues unabated. At large-x, new data from JLab address for the first time the question of the helicity structure of the nucleon in a kinematic realm where sea quark and gluon contributions are minimal thereby making one mostly sensitive to valence quarks. Examples of these results are shown in Fig. 2. To extend this region to higher x and moderate Q^2, one needs higher beam energies than presently available at JLab. In particular, to test various models of the asymptotic value of the virtual photon asymmetry $A_1(x)$ as $x \to 1$, one needs the upgraded CEBAF with 12 GeV beam energy.

The comprehensive data set to be collected by experiment PR12-06-109 will contribute substantially to our knowledge of polarized parton distribution functions for all quark flavors and even the polarized gluon distribution Δg. Through Next-to-Leading Order (NLO) analysis of the world data on inclusive DIS (using the DGLAP evolution equations), one can constrain these distribution functions and their integrals. Existing CLAS data from 6 GeV have already made an impact on these fits. The expected data from the proposed experiment at 11 GeV will yield further dramatic reductions in the errors on these distributions. Semi-inclusive DIS (SIDIS) data will also be collected, where, in addition to the scattered electron, we will also detect some of the leading hadrons produced after the struck quark hadronizes. These data will further constrain the NLO fits and improve the separation of the various quark flavors' contribution to nucleon observables.

1.1.1.3 N*s at 12 GeV For the foreseeable future, the CLAS12 detector will be the sole facility worldwide capable of delivering comprehensive information on the $\gamma_v NN^*$ transition helicity amplitudes – and thereby the electrocouplings – at photon virtualities of $Q^2 > 5.0$ GeV^2 and in the mass range up to 2 GeV. Electrocouplings will be extracted from the electroproduction of the primary meson reaction channels ($n\pi^+$, $p\pi^0$, $p\eta$, and $p\pi^+\pi^-$) as is discussed in our approved CLAS12 proposal [2]. Through our recent work [3, 4] at $Q^2 < 5.0$ GeV^2, we have found consistent results on the $\gamma_v NN^*$ electrocouplings in both the single- and double-pion modes as can be seen in the left plot of Fig. 3. Investigating the evolution of the $\gamma_v NN^*$ electrocouplings for several prominent excited states at $Q^2 > 5.0$ GeV^2 will offer direct access to the quark structure of the nucleon (see right plot of Fig. 3). The data for our approved experiment (PR12-09-003) [2] will, for the first time, allow one to study the kinematic regime for momenta running over the quark

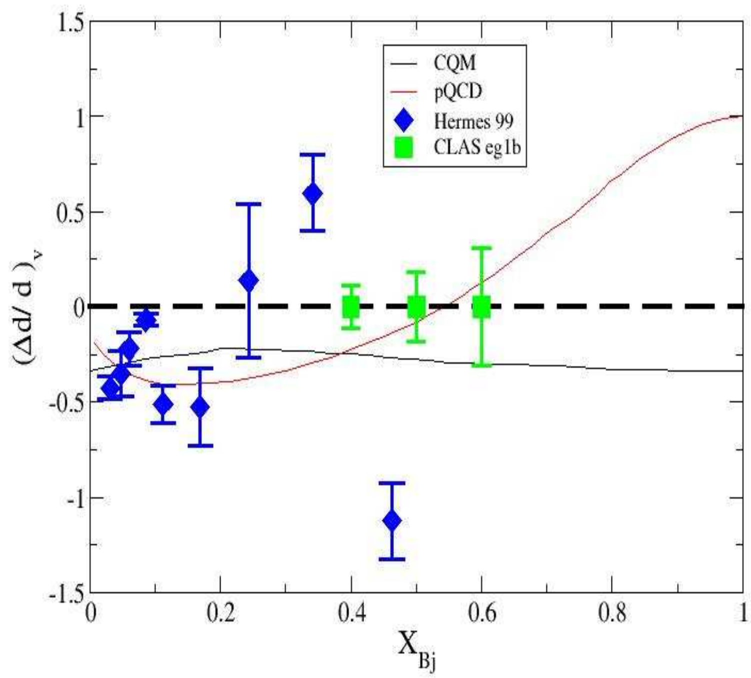

Figure 2: The expected statistical uncertainty of a $\Delta d/d$ measurement using CLAS12.

propagator for momenta $p < 1.1$ GeV, which spans the transition from almost-completely dressed constituent quarks to the almost-completely undressed current quarks. At these distance scales, meson-baryon cloud contributions are expected to be small or negligible. In conjunction with detailed information on the nucleon ground state structure from the other experiments at 12 GeV, a comprehensive dataset, allowing us to access quark contributions to the spectrum of nucleon states, will be available for the very first time. The results from our experiment will provide:

- access to the dynamics of non-perturbative strong interactions among dressed quarks and to shed light on their emergence from QCD and the subsequent N^* formation.
- information on how the constituent quark mass arises from a cloud of low-momentum gluons which constitute the dressing to the current quarks. This process of dynamical chiral-symmetry breaking accounts for over 97% of the nucleon mass.
- enhanced capabilities for exploring the behavior of the universal QCD β-function in the infrared regime.

As new theoretical developments emerge, we shall certainly follow up on them as we did in documenting the detailed plan on theory support for our proposal in the 62-page White Paper entitled, *Theory Support for the Excited Baryon Program at the JLab 12 GeV Upgrade*, which appeared as a preprint [5].

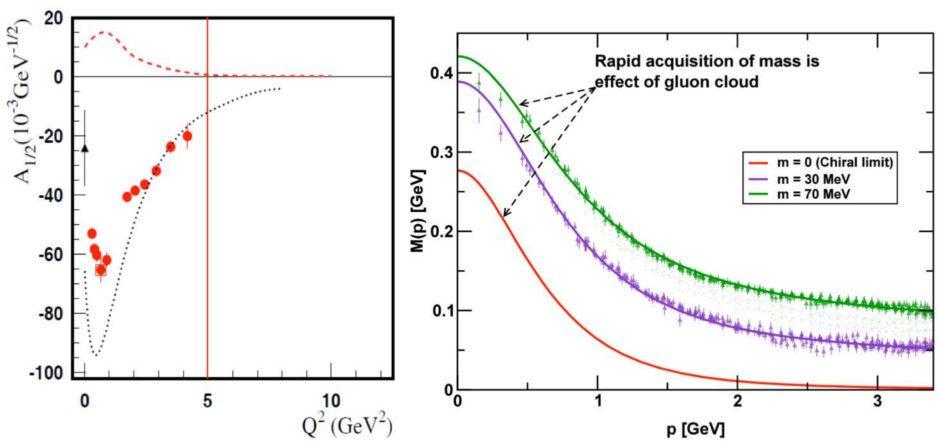

Figure 3: Left side: Electrocouplings for $D_{13}(1520)$ state determined from the CLAS data on $N\pi$ electroproduction [3] (red points) from a combined analysis of the $N\pi$ and $N\pi\pi$ channels. Differences between the data at $Q^2 < 1.0$ GeV^2 and quark model [6] calculations (dotted curve) highlight possible contributions from meson-baryon dressing (red dashed curve) [7]. Right side: Dressed quark mass as a function of momentum for light-quarks, obtained in the Landau gauge: solid curves are the Dyson Schwinger Equation results, including the chiral-limit [8, 9]; points with error bars are the results from unquenched LQCD [10].

1.1.2 A Precision Measurement of the Neutral Pion via the Primakoff Effect

CoPI Dan Dale is a spokesperson for an experiment at Jefferson Laboratory to perform a precision measurement of the lifetime of the neutral pion using the Primakoff production mechanism. The PI of this proposal, Dr. Dustin McNulty, has recently joined the Idaho State University group, and is also an active member of the PrimEx Collaboration. Dr. McNulty played a major role in the construction and installation of the experiment at JLab, and also led a major data analysis effort.

The $\pi^o \to \gamma\gamma$ decay represents an important process in the anomaly sector in that it reflects an explicit breaking of a classical symmetry by the quantum fluctuations of the quark fields coupling to the electromagnetic field[11]. In the limit of vanishing quark masses (the chiral limit), the leading order (LO) amplitude is precisely specified in terms of the fine structure constant, the pion decay constant, and the number of colors in QCD. Namely,

$$\Gamma(\pi^o \to \gamma\gamma) = \frac{\alpha^2 M_\pi^3}{576\pi^3 F_\pi^2} N_c^2 = 7.73eV \tag{1}$$

This prediction contains no unknown low-energy constants or form factors and is in agreement with the currently accepted experimentally determined value for the radiative width of $7.74 \pm 0.46eV$[12], thus confirming the number of colors in QCD, N_c, to be three. Corrrections, however, arise due to the fact that the physical current quark masses are not zero, *viz.*, $m_u \simeq 4MeV$ and $m_d \simeq 7MeV$. Because of the low level of precision of the current experiments, the NLO theoretical predictions for the $\pi^o \to \gamma\gamma$ decay width are yet to be tested. The level of precision of $\simeq 1.4\%$, which is the goal of the PrimEx experiment, will satisfy these requirements.

Since the original PrimEx proposal, several new theoretical calculations have been published and are shown in Fig. 4. The calculation labeled NLO in Fig. 4 represents an analysis performed in the framework of Chiral Perturbation Theory (ChPT). This result derives from an approach utilizing a combined framework of chiral perturbation theory 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[13]. As can be seen in the figure, these corrections result in an enhancement of about 4.5% to the π^o decay width with respect to the case without state mixing, indicated by LO in the figure. The uncertainty in the ChPT prediction is estimated to be 1%. Corrections to the chiral anomaly have also been performed using dispersion relations and QCD sum rules [14], and are indicated by “Ioffe07” in the figure. Here, the only input parameter in this calculation is the η width.

The PrimEx experiment seeks to perform a high precision measurement of the neutral pion radiative width to test these state-of-the-art calculations. We are using quasi-monochromatic photons of energy 4.6-5.8 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:

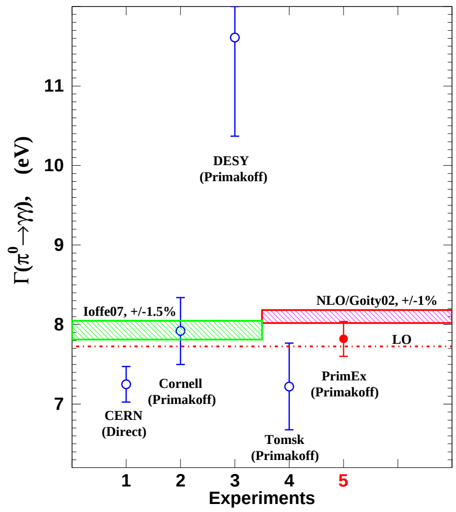

Figure 4: $\pi^o \rightarrow \gamma\gamma$ decay width in eV with theoretical predictions of Ioffe and Goity. The result of PrimEx I is indicated.

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

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:

$$\frac{d\sigma}{d\Omega_\pi} = \frac{d\sigma_P}{d\Omega} + \frac{d\sigma_C}{d\Omega} + \frac{d\sigma_I}{d\Omega} + 2\cdot\sqrt{\frac{d\sigma_P}{d\Omega}\cdot\frac{d\sigma_C}{d\Omega}}cos(\phi_1+\phi_2) \tag{3}$$

where the Primakoff cross section, $\frac{d\sigma_P}{d\Omega}$, is given by equation 2. The nuclear coherent cross section is given by:

$$\frac{d\sigma_C}{d\Omega} = C\cdot A^2|F_N(Q)|^2\sin^2\theta_\pi \tag{4}$$

and the incoherent cross section is:

$$\frac{d\sigma_I}{d\Omega} = \xi A(1-G(Q))\frac{d\sigma_H}{d\Omega} \tag{5}$$

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 $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ to be extracted from a fit to the angular distribution of photo-produced neutral pions. 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. Data were taken for this second phase in the Fall of 2010 on carbon and silicon targets, during which time one of the CoPI's served as run coordinator for the beginning of the run. The CoPI (DSD) of this funding proposal has been involved in all aspects of this program, and 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.

The PI of this proposal, Dustin McNulty worked extensively on the initial installation of the experiment, and performed a significant portion of the data analysis for PrimEx I. Together, the PI (Dr. McNulty) and a CoPI (Dr. Dale) have taken on the responsibility for the aspects of the analysis for PrimEx II which involve the luminosity measurements. This includes analysis of the pair spectrometer data, TAC normalization runs, and electron counting in the photon tagger.

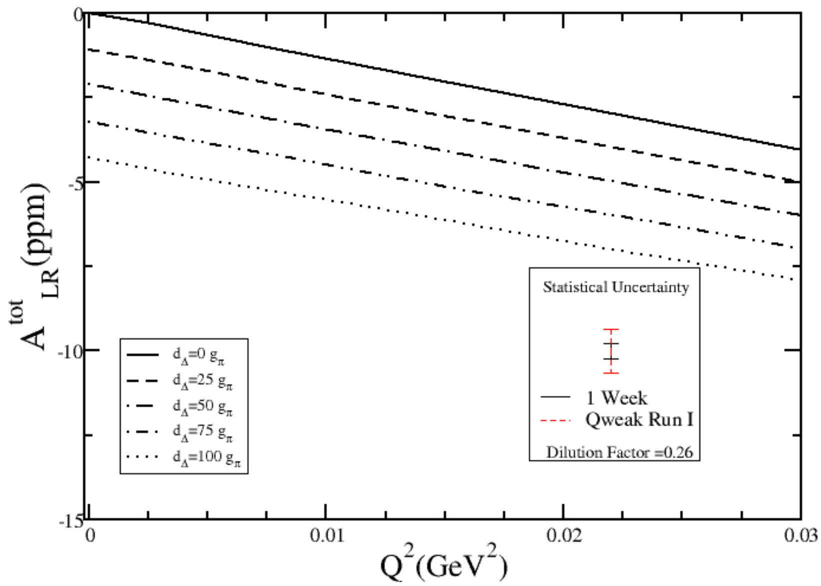

Figure 5: The expected statistical uncertainty for a measurement of d_Δ using the current data set from the last Qweak run and assuming a full week of beam time.

1.1.3 Parity Violation Measurements

1.2 Results from Prior NSF Support

1.2.1 PrimEx I

Substantial progress has been made in the PrimEx project during the preceding funding period. First, analysis of the PrimEx I run was completed and the resulting radiative decay width, $\Gamma(\pi^o \rightarrow \gamma\gamma) = 7.82 \pm 0.14(stat) \pm 0.17(syst.)$ was published in Physical Review Letters[15]. Figures 6 and 7 show elasticity, pion invariant mass, and angular distributions obtained in PrimEx I as an indication of the quality of the data obtained.

Second, a draft of a paper describing the techniques by which the PrimEx Collaboration attained a 1% uncertainty in the luminosity has been prepared by a CoPI (D. Dale) and is presently circulating in the Collaboration. In 1990, Owens published a paper describing the techniques for analyzing tagged photon experiments[16]. Building on this work, the PrimEx Collaboration has developed a number of new techniques for luminosity monitoring including the implementation of multi-hit TDC's, electron counting via a sampling method involving clock triggers, and online beam diagnosis with a pair production spectrometer. We expect to submit this paper to NIM in the next couple of months.

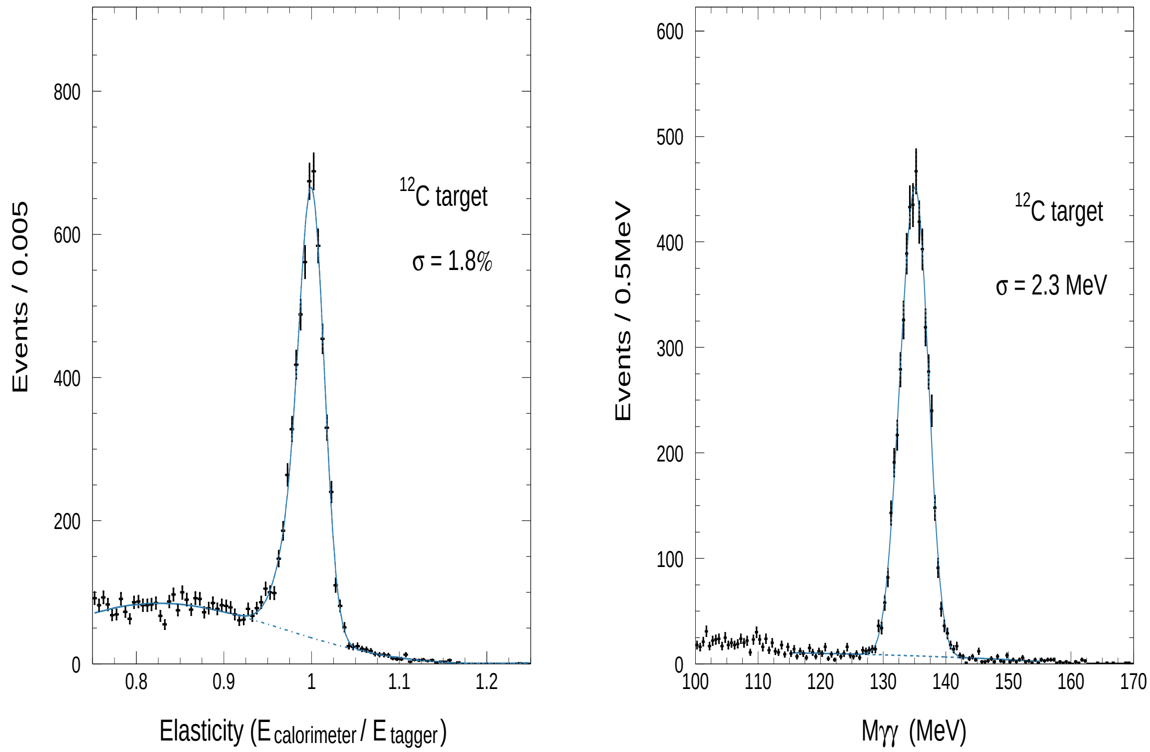

Figure 6: Typical distributions of reconstructed elasticity (left) and $m_{\gamma\gamma}$ (right) for one angular bin.

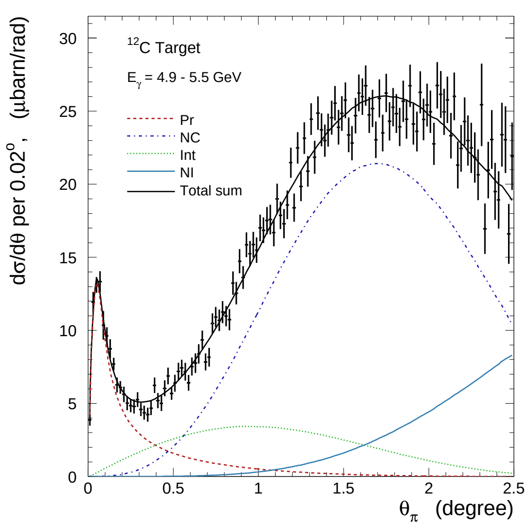

Figure 7: Differential cross section as a function of π^o production angle for ^{12}C together with fit results for the different physics processes.

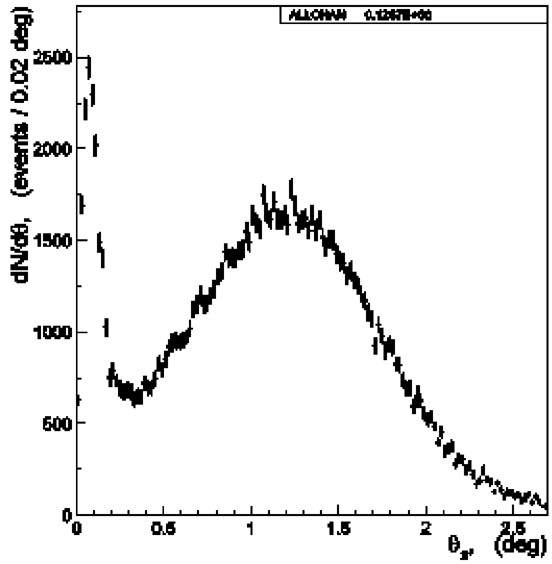

Figure 8: Preliminary angular distribution as a function of π^o production angle for the silicon target in the PrimEx II run.

1.3 PrimEx II

During the Fall of 2010, the PrimEx Collaboration had their second data taking run. In this run, there were several improvements to the experimental setup as compared to PrimEx I. These included some modifications to the beamline, individual TDCs on the inner modules of the HYCAL pion calorimeter, and increased charged particle veto channels on the pion detector. High quality data were taken on both carbon and silicon targets where approximately 8000 and 20000 pions were obtained in the two targets, respectively. An example of a preliminary pion angular distribution for the silicon target is shown in Fig. 8.

1.3.1 Graduate Student Analysis Results

The probe afforded by a beam of linearly-polarized photons allows one to gain access to several observables in photonucleon 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.

The scientific purpose of g8 [17, 18, 19, 20, 21, 22] seeks 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 afforded by the Coherent Bremsstrahlung Facility (CBF) 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.

The first phase of the g8 run marked the commissioning of the CBF. It took place in the summer of 2001 (6/04/01 - 8/13/01) in Hall B of Jefferson Lab and provided the Ph.D. thesis work for two students [23, 24] and the material for two master's theses [25, 26]); g8b followed four years later culminating in four PhD theses [27, 28, 29, 30] and one is on the way [31].

These experiments made use of a beam of linearly-polarized photons produced through coherent bremsstrahlung and marked the first time such a probe was employed at Jefferson Lab. The g8 set of experiments, therefore, was a vital first step in establishing the CBF and this experience paved the way for several subsequent successful runs with linearly polarized photons in Hall B of JLab: g13b ($\vec{\gamma}d$), and g9a/b ($\vec{\gamma}\vec{p}$). At the time of this writing, HDIce (g14) is poised to run; HDIce is a search for N*s using polarized photons directed onto a separably-polarizable proton and deuteron target and will be closing experiment for CLAS6. The lessons learned in calibration and cooking for the earlier g8 experiments have accelerated the analyses for the g13a/b, g9a, and presumably g14. Currently three students at ISU are playing key roles in calibrating detectors for g13 and will continue to give such assistance with g14. Danny Martínez, ($\vec{\gamma}p \to \omega p$ from g8b), and Olga Cortés ($\vec{\gamma}n(p) \to \omega n(p)$) and Charles Taylor ($\vec{\gamma}n(p) \to K^0_s\Lambda(p)$ are analyzing g13 data).

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 [32]. 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 [33] at low t, which is further to be compared to the predicted values of the Vector Dominance Model (VDM) [34].

In his PhD thesis [29], Julián Salamanca, extracted over eight thousand ϕs mesons from the g8b dataset at both low and high t in the baryon resonance regime of $2.02 < \sqrt{s} < 2.11$ GeV. Extracting the SDMEs for the phi channel at high $|t|$ holds discovery potential for non-VDM mechanisms at higher four-momentum transfers squared. On the right hand side of Fig. 9, the fitted ϕ-meson peaks are shown for two orientations of the polarization vector, $\vec{E}$. And on the left hand side are the respective angular distributions in the rest frame of the ϕ meson with the quantization axis point

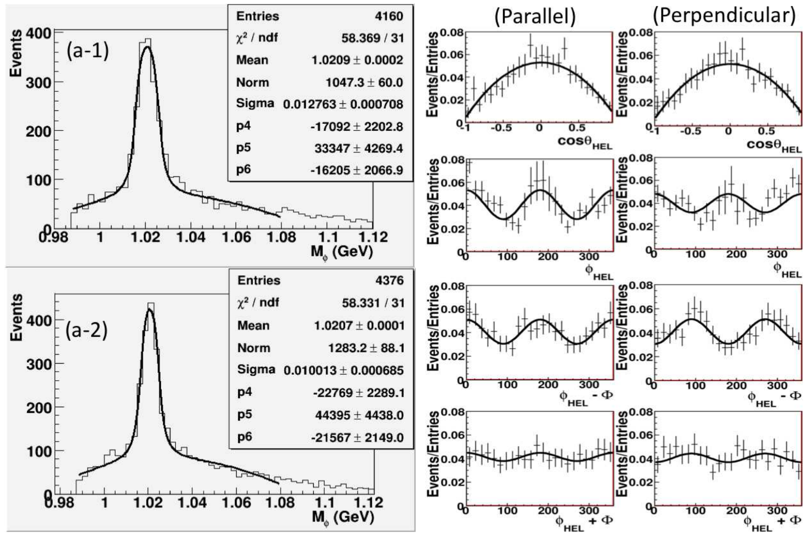

Figure 9: $\vec{\gamma}p \rightarrow \phi p$ and $1.7 < E_\gamma < 1.9$ GeV. Left plot: ϕ-meson distribution fit with a Breit-Wigner convoluted with a Gaussian peak ($\sigma \sim 11$ MeV) and a 2$^{\text{nd}}$ order polynomial background. Here, the direction of the polarization vector ($(vecE)$: (a-1) Parallel and (a-2) Perpendicular to the floor in the CLAS lab frame. Right plot: Angular distributions of the ϕ-meson in the Helicity frame. First (second) column is for $\vec{E}_\parallel$ ($\vec{E}_\perp$. Of especial interest are the angular distributions as a function of $\cos\theta_{Hel}$ showing the expected $\sin^2\theta_{Hel}$-like behavior and the modulation as a function of azimuth $(\phi_{Hel} - \Phi)$.

opposite the direction of the recoil proton, i.e. the Helicity frame). Five SDMEs were extracted in this thesis work of Dr. Salamanca. CLAS requires all analyses to be thoroughly reviewed by expert committee before a paper may be submitted. We have just answered the last few questions from the CLAS review committee. Once this ϕ analysis note is approved – and that should be soon we will prepare a paper for PRL or PRC on the extracted SDMEs from the photoproduction of phi mesons off protons with linearly-polarized photons.

The analysis of the photoproduction of ω mesons off hydrogen is an absolute must before this channel may be analyzed from neutrons in deuterium. Danny Martínez has made significant progress in extracting the Beam Asymmetry parameter Σ by fitting the ratio $\frac{N_\perp N_\parallel}{N_\perp N_\parallel}$ to a $\cos 2\phi$-like function for each $\cos\theta$ bin and E_γ bin (see Fig. 10):

$$\begin{aligned}
\sigma_\perp &= \sigma_0(1 + P_\perp \Sigma \cos 2\phi) \\
\sigma_\parallel &= \sigma_0(1 + P_\parallel \Sigma \cos 2\phi + \pi) \\
\sigma_\parallel &= \sigma_0(1 - P_\parallel \Sigma \cos 2\phi)
\end{aligned}$$

$$\frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{(\frac{N_\perp}{N_\parallel} - 1) - (\frac{N_\perp}{N_\parallel} P_\perp + P_\parallel)\Sigma\cos(2(\phi))}{(\frac{N_\perp}{N_\parallel} + 1) - (\frac{N_\perp}{N_\parallel} P_\perp - P_\parallel)\Sigma\cos(2(\phi))}$$

This ϕ bin method compares well with the results from the method of moments [28, 35]. The extracted Σ will constrain combinations of the SDMEs. Further, this analysis on the proton will be the starting point for the photoproduction of omega mesons off neutrons.

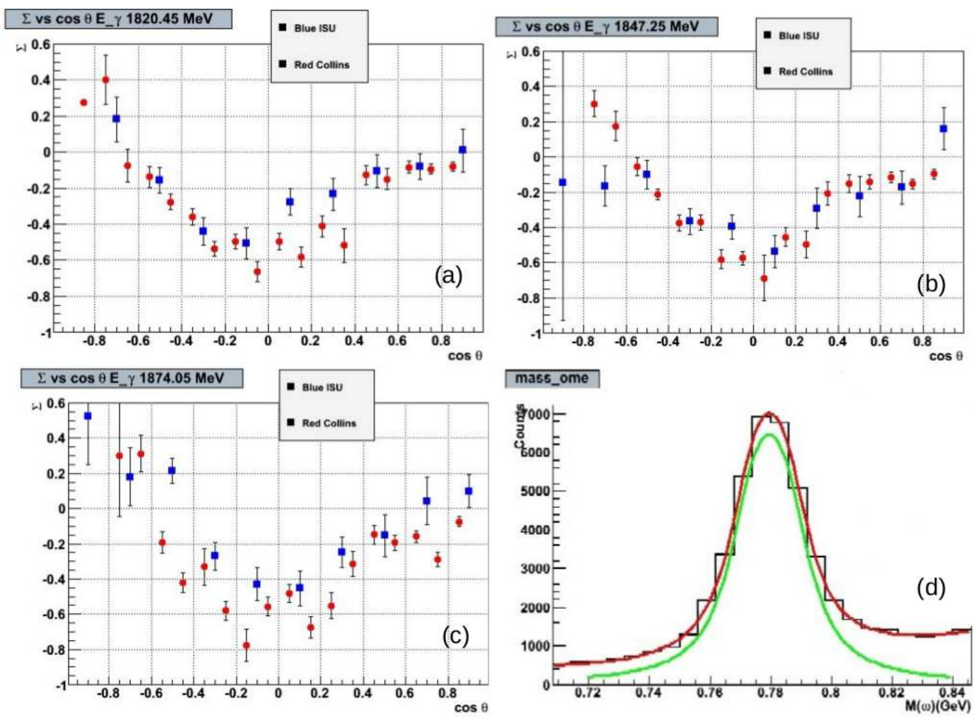

Figure 10: $\vec{\gamma}p \to \omega p$ and $\omega \to \pi^+, \pi^-, \pi^0$. Plotted are the beam asymmetry parameters, Σ, for the three separate photon energies: (a) $1.81 < E_{vec\gamma} < 1.83$ GeV, (b) $1.83 < E_{vec\gamma} < 1.85$ GeV, and (c) $1.85 < E_{vec\gamma} < 1.87$ GeV. For each $\cos\theta_{\rm cm}$ bin there are 18 ϕ bins from which Σ is extracted. The solid squares correspond to the ϕ bin method from ISU and the closed correspond to method of moments from a separate analysis [28, 35]. (d) ω meson signal: Voigtian (Breit Wigner + Gaussian) with a 4th-degree polynomial for the background.

Tamuna's Exclusive Pion Production Comparison with Joo's et. al. Publication

Figure 11 shows a comparison of the relative exclusive pion production ($\vec{e}p \to en\pi^+$) rates measured using a liquid hydrogen target in E99-107 to the measurements using a polarized ammonia (NH_3) target. The comparison was done as part of T. Didberidze's SIDIS analysis for the purpose of cross checking pion identification methods used in CLAS. The kinematics of single pion

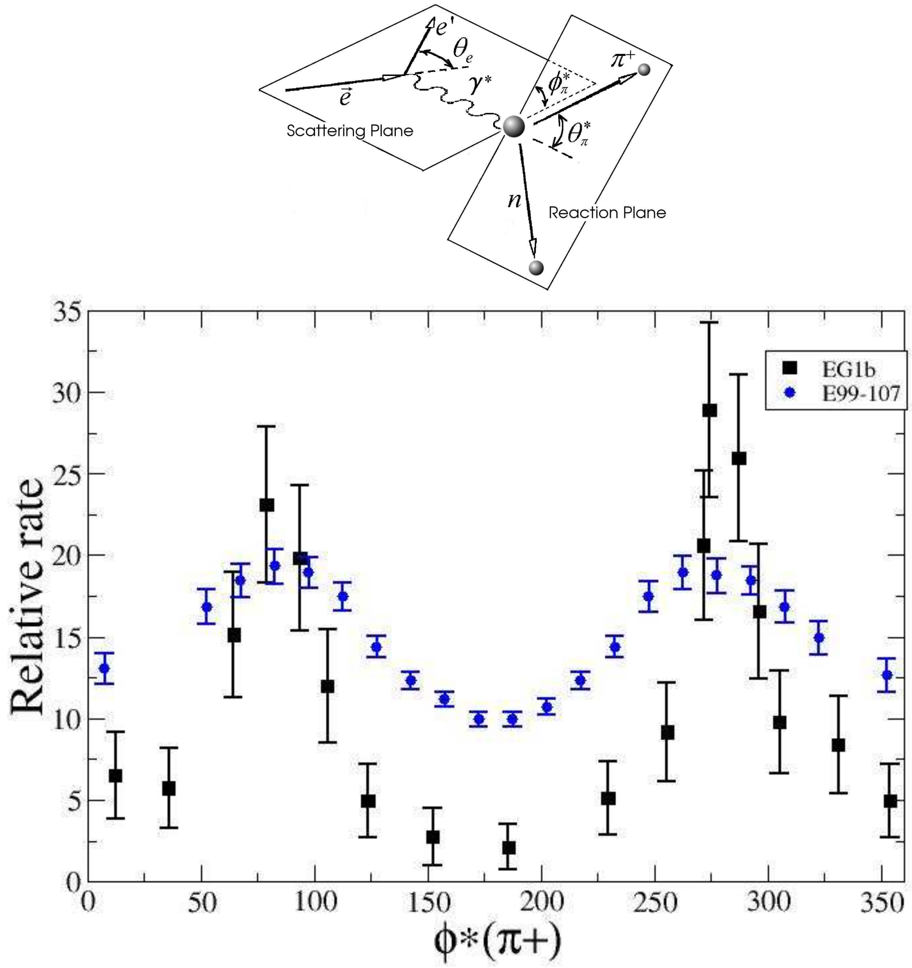

Figure 11: Top: An illustration of the kinematic quantities used to describe exclusive single pion production. Bottom: A comparison of the inclusive pion production measured using and NH_3 target to the published results from CLAS experiment E99-107 which used a liquid hydrogen target.

electroproduction can be described by five variables: the virtual photon negative four-momentum transferred squared Q^2, W invariant mass of the photon-nucleon system, θ_π^* the polar and ϕ_π^* the azimuthal angle of the outgoing pion in center of mass frame and ϕ_e the scattered electron azimuthal angle. The five-fold differential cross section can be written in the following way for a single pion electroproduction:

$$\frac{\partial^5\sigma}{\partial E_f \partial\Omega_e \partial\Omega_\pi{}^*} = \frac{1}{2\pi}\Sigma\frac{1}{L_{int}A_{cc}\epsilon_{CC}\Delta W\Delta Q^2\Delta cos\theta_\pi{}^*\Delta\phi_\pi{}^*}\frac{d(W,Q^2)}{d(E_f, cos\theta_e)} \quad (6)$$

where L_{int} represents the integrated luminosity, A_{cc} is the acceptance factor, ϵ_{CC} represents the efficiency of the Cerenkov detector and the Jacobian term can be expressed in terms of the initial and final energy of lepton:

$$\frac{d(W,Q^2)}{d(E_f,cos\theta_e)} = \frac{2M_pE_iE_f}{W} \quad (7)$$

The E99-107 measurement shown in Figure 11 used the following kinematic cuts; $0.9 < M_x < 1.1$, invariant mass $1.44 < W < 1.46$ and $0.4 < cos\theta_\pi^{CM} < 0.6$. Despite the low statistics available for the kinematic region shared by both experiments, the rate dependence on ϕ_π^* that is reproduced using the NH3 target is an excellent cross check that increases confidence in the standard methods used by CLAS to identify the π^+.

1.4 Future Use of NSF Funds

Work Plan

List of Currently supported students

Student	Major (Year of Degree)	Projected
Tamar Didberidze	Ph. D.	2011
Danny Martínez	Ph. D.	2013
Charles Taylor	Ph. D.	2013
Olga Cortés	Ph. D.	2015

Table 1: 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, particularly South America where we especially have good contacts. Over the past eleven years, two of the CoPIs have been active in outreach towards Latin America. CoPIs Dale and Cole can both communicate in Spanish. 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 unfortunately abound. And to communicate these matters effectively, one must speak Spanish at a reasonable level. We seek to promote dialog 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. Venues as the Latin American Symposia on Nuclear Physics and Applications, which convene every two years in alternating countries in Latin America, offer great opportunities for strengthen existing links and forging new ones within the broad scope of the international nuclear physics community. Members of our group have attended every one of these biennial symposia since 1999; CoPI Cole has been an editor twice on the proceedings and is on the standing organizational executive committee. In the six years that the ISU Physics Department has had a PhD, we have attracted four talented students from Colombia to Pocatello, Idaho. We are closing the loop and, in the process, we are strengthening our ties to Colombia. Dr. Salamanca graduated in December, 2009, our first PhD in JLab physics at ISU. He recently became an Assistant Professor at Universidad Distrital in Bogotá, Colombia. We can only expect to draw more students to the ISU graduate physics program from this excellent connection.

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 skills. In the past three years, the ISU group has graduate a Ph.D. student and a Masters student. As mentioned in the previous section, Julian Salamanca graduated from ISU's program with a Ph. D. thesis based on the CLAS and is now an Assistant Professor at Universidad Distrital in Bogotá, Colombia. Another student, Warren Parsens, graduated from ISU with a masters degree and is now employed in the technology sector. Both graduates have stated that the construction projects undertaken using the facilities at ISU were instrumental to their success after graduation. These two examples are not unique but rather representative of the well rounded education students receive when doing research which combines projects at ISU and Jefferson Lab. We intend to continue using this bridge as a means to train students with marketable skills that increase their chances for success after graduation.

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