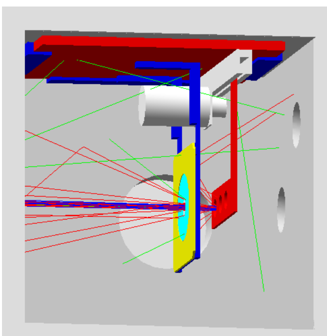
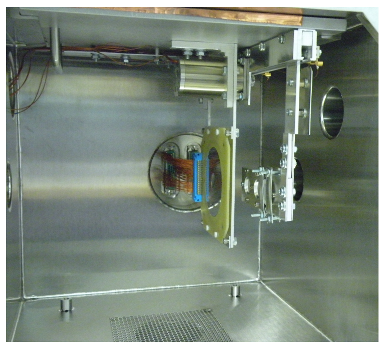
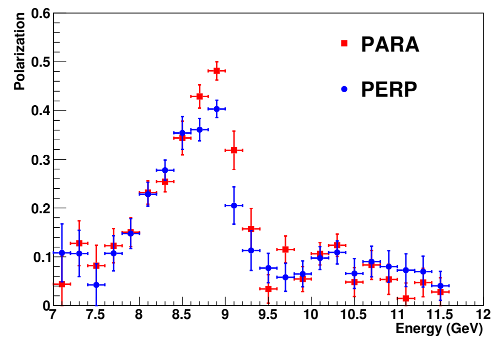
Project Narrative

Experimental Medium Energy Physics at Arizona State University

September 2018







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The figure above (left) is a snapshot of a simulation representing the ASU-built triplet polarimeter TPOL, designed to measure the polarization of the photon beam in Hall D at Jefferson Lab. Within the simulation snapshot, 100 photon events were thrown, where blue lines represent photoproduced positrons, electrons are shown as red lines, and green lines are secondary photons. The photograph in the center shows TPOL as installed by ASU in the Hall D beamline. The plot at far right shows the photon beam polarization of the Hall D beam as a function of photon energy, as measured by TPOL during Spring 2016 running.

Contents

Abstract

Using the newly-upgraded experimental facilities of Jefferson Lab in Halls B and D, the Arizona State University (ASU) Meson Physics Group will conduct experiments to search for and characterize (1) excited baryons containing two or more strange quarks and (2) hybrid meson states. Both these types of particles have been specifically predicted by hadron models based on quantum chromodynamics (QCD), exploiting flavor symmetry and gluonic excitations. The detailed knowledge of the spectrum of these states that will be obtained is essential for meeting the goals of NSAC Long-Range Plan.

1 Introduction

As stated in the current NSAC Long-Range Plan [**?**]: "[t]he new capabilities of the 12-GeV era facilitate a detailed study of baryons containing two and three strange quarks. Knowledge of the spectrum of these states will further enhance our understanding of the manifestation of QCD in the three-quark arena." Concerted efforts over the past several decades have helped identify and characterize many excited states for the lightest baryon - the nucleon - and for the lightest mesons. The vast amount of information gleaned for the lightest hadrons has led to tremendous progress in arriving at a description of those particles using QCD. Yet, these very same detailed measurements have deepened the mystery of why such QCD-based descriptions of nucleon excited states invariably predict many more states than observed—the so-called "missing resonance" problem.

Going beyond the lightest hadrons, progress towards a clearer understanding of heavier hadrons containing one or more strange quarks arguably has been much slower. Flavor symmetry predicts a spectrum of excited states for heavier baryons at least as rich as that for the nucleon. Furthermore, the existence of hybrid mesons are a natural extension of the constituent quark model when real excitations of gluonic fields are allowed. Naively, with the presence of one or more strange quarks, one might think QCD-based descriptions for those heavier particles would be more straightforward, robust, and successful than those currently attainable for the nucleon and the lightest mesons. However, comparatively very little data exists for those heavier particles, and experimental evidence for predicted hybrid and other exotic meson states remains tenuous and controversial. Major improvements in our empirical knowledge of the properties of these states should lead directly to advances in QCD descriptions of all hadrons, including better predictions for the lightest particles consisting solely of up or down quarks.

This proposal seeks support for a program of measurements that will provide major improvements in our knowledge of hadron spectroscopy, focused on activities at Jefferson Lab (JLab) (1) within Hall B using the CEBAF Large Acceptance Spectrometer (CLAS) newly upgraded for experiments using the 12 GeV beam at JLab (CLAS12) and (2) within Hall D using the GlueX detector. ASU will conduct investigations with two large international collaborations to provide data which will be critical to advancing our understanding of how quarks and gluons assemble into mesons and baryons. Both the Hall B and the Hall D activities outlined below seek to identify heretofore unobserved excited states of multi-quark systems and to clarify the properties of those states so that theoretical models of those multi-quark systems will be informed by the most accurate and complete database possible.

We will obtain and analyze data using the newly-built CLAS12 detector to explore the spectrum of multi-strange-quark ("very strange") baryons. ASU simulations already have helped establish the initial running configuration for CLAS12, and confirmed the feasibility of our experimental program. Our extensive experience in meson photoproduction with CLAS during the 6 GeV era and our interests in hybrid and exotic mesons led us to extend our program to the Hall D facilities, which we have helped bring to full operation, because those facilities were specifically tailored to carry out searches for those particles.

Based on our prior experience with polarized photon beams in Hall B during the 6 GeV era, the ASU Meson Physics Group successfully proposed, designed, built, and now operates a first-of-its-kind triplet-photoproduction photon-polarimeter (TPOL) for the Hall D linearly-polarized photon beam. The TPOL device, discussed more fully in section 2.2.2, precisely characterizes the degree of polarization of the photon beam in Hall D. Thus, beyond the fundamental physics goals of our research program described above, our group will remain responsible for determining the polarization of the photon beam for all experiments in Hall D. This contribution is critical: only precise knowledge of the Hall D photon beam can empower the full exploitation of Hall D's capabilities to probe the physics of hybrid and exotic hadrons with GlueX, as well as to carry out the studies proposed here.

The program outlined in the following sections, will obtain precise, extensive data detailing the excitation spectra of two- and three-quark systems, including previously unobserved or poorly-measured three-quark states, as well as hybrid mesons. No comprehensive QCD-based description of how hadrons are built from quarks and gluons can be achieved without such information. Two complementary approaches will be pursued:

1. Working with the CLAS Collaboration, ASU will lead an experiment with the newly-installed CLAS12 detector in Hall B to study excitations of Ω^- and Ξ baryons using quasi-real incident photons. These data will produce the largest sample of photoproduced Ξ baryons ever, elucidating the excitation spectrum for that hadron, and also yield the first data on photoproduced Ω^- baryons. The availability of a large sample of excited Ξ states will allow measurement of poorly-known decay modes, many of which are currently listed simply as "seen" or "small" within the current PDG summary [**?**].

2. Working with the GlueX Collaboration, the ASU group will participate in the search for exotic hadrons with masses up to 2.5 GeV, with a particular emphasis on identifying the η_1' hybrid meson to rule out potential tetra-quark states. Identifying such particles requires the determination of exotic quantum numbers J^{PC} that do not correspond to those seen in the traditional constituent quark model. Accurate knowledge of the energy and degree of polarization of the tagged photon beam is mandatory for all analyses in Hall D, and ASU's TPOL will provide direct measurements of the photon beam polarization for all experiments in Hall D.

Currently, the ASU Meson Physics Group is comprised of the principal investigator Associate Professor Michael Dugger, co-investigator Professor Barry Ritchie, Graduate Research Associate Sebastian Cole, and sophomore undergraduate student Eric Bryan. The proposal seeks steady-state funding for supporting the principal investigator (PI), co-investigator, two graduate students, and an undergraduate student.

2 Research to be undertaken under proposed award

The ASU Meson Physics Group played a central role in designing, building, commissioning, and exploiting the past and current generation of experimental facilities at JLab by leading and collaborating in experiments in Hall B that advanced understanding of the nucleon. The ASU group subsequently led and participated in a program of experiments that provided the bulk of the current database for non-strange meson photoproduction data, which underpin the current understanding of the nucleon. This program included the development and exploitation of polarized photon beams and polarized proton targets. ASU-led experiments and analyses using CLAS are summarized in Table 1. (Remaining 6 GeV CLAS analyses will be completed by the start of the requested funding period.)

Table 1: ASU-led research in the CLAS 6 GeV program. Citation statistics from INSPIRE (8/22/2018). (The project marked with "∗" has statistics insufficient for publication.)

Reaction	Observable	Status [Presentations, publications]
$\gamma p \to p\pi^0$	$d\sigma/d\Omega$	Completed. Published August 2007. [?] (cited 87 times)
	Σ	Completed. Published December 2013. [?] (cited 32 times)
$\gamma p \to n\pi^+$	$d\sigma/d\Omega$	Completed. Published June 2009. [?] (cited 103 times)
	Σ	Completed. Published December 2013. [?] (cited 32 times)
	T, F	Analysis note being drafted.
	P, H	Analysis note being drafted.
$\gamma p \to p\eta$	$d\sigma/d\Omega$	Completed. Published November 2002. [?] (cited 129 times)
	Σ	Completed. Published March 2017. [?] (cited 13 times).
	E	Completed. Published April 2016. [?] (cited 23 times)
	T, F	Dissertation of Ross Tucker successfully defended April 2016. ∗
$\gamma p \to p\eta'$	$d\sigma/d\Omega$	Completed. Published February 2006. [?] (cited 65 times)
	Σ	Completed. Published March 2017. [?] (cited 13 times)
$\gamma p \to p\omega$	Σ	Completed. Published June 2017. [?] (cited 3 time s)

This proposal capitalizes on the momentum and experience of the ASU group to pursue a vigorous experimental program with the newly-upgraded facilities at JLab. We will use the CLAS12 detector to study multi-strange-quark baryons in Hall B, and will employ the GlueX detector in Hall D to search for hybrid mesons, while also providing precise and reliable characterization of the Hall D photon beam for all Hall D experiments using the ASU triplet polarimeter (TPOL).

2.1 Probing the Ω^- and Ξ baryon spectra with CLAS12

As noted above, studies of two and three-strange-quark baryons have great potential to enhance our understanding of the QCD structure within baryons. The "computational cost" for predictions using lattice QCD are greatly influenced by the number of light quarks (u and d) present in the baryon studied. For that reason, studies that extend our knowledge of the properties of states with two and three strange quarks should be extremely useful in deepening insight into how all baryons are assembled from quarks.

The ASU group is leading an experiment which will provide the largest-ever sample of photoproduced cascade Ξ baryons, as well as the first photoproduction measurements of Ω^- [?]. This "very strange particle" search represents part of the suite of experiments approved to run during Run Group A. Using the CLAS12 detector, our measurements should greatly enhance knowledge of the excitations of these baryons, which in turn will provide an empirical "proving ground" for QCD-based descriptions of baryons with varying numbers of heavy quarks.

While the "missing resonance" problem for the nucleon system is much discussed, the missing resonance problem is even more striking when looking at the Ξ sector. For example, the Isgur and Capstick relativistic constituent quark model [?] predicts 44 Ξ states with masses below 2.5 GeV, yet the PDG [?] only lists *six* cascade resonances with ratings of three or four stars, as indicated in Table 2.

Table 2: "Well-known" Ξ resonances listed in the PDG summary [?].

State	J^P	Width (MeV)	PDG rating
$\Xi(1318)$	$\frac{1}{2}^+$		****
$\Xi(1530)$	$\frac{3}{2}^+$	9.1±0.5	****
$\Xi(1690)$	$\frac{1}{2}^-$?	10±6	***
$\Xi(1820)$	$\frac{3}{2}^-$	24±6	***
$\Xi(1950)$	?	60±20	***
$\Xi(2030)$	$\geq \frac{5}{2}$?	21±6	***

Looking more closely at the Ξ states, photoproduction cross sections for Ξ resonance states are observed to be much smaller than for nucleon resonances. However, the widths of the Ξ excitations are much narrower than those for the nucleon, which should make them easier to identify [?]. As seen in Table 2, the well-known cascade resonances also have mass separations that are greater than the resonance widths, which again should make identification of excited Ξ states far easier than for the N^* and Δ states (with widths of $\sim$150 MeV). Even with those advantages, however, no new cascade states have been discovered in the last 20 years. The 1989 discovery of $\Xi(1690)$ [?] was plagued by backgrounds from a $\Sigma^-(C, Cu) \to \Xi^-\pi^+$ inclusive reaction. The large solid angle of the CLAS12 detector (discussed further in the next subsection) will permit using exclusive reactions to markedly reduce backgrounds. Moreover, the CLAS12 detector will simultaneously measure Ξ^* decay modes, allowing for the determination of branching ratios that are, as shown in Table 3, not well determined for most of the three and four star Ξ^* states [?]. Of particular interest is the apparent suppression of the excited cascades going to $\Xi\pi$. For the $\Xi(1530)$, the branch to $\Xi\pi$ is given in the PDG as 100%, but for all other cascades, the observed decay branches are merely characterized as "small" or "seen". Measuring the Ξ^* branching ratios for states that decouple from $\Xi\pi$ can help shed light on why the Ξ^* have such narrow widths.

As for the Ω situation, as indicated in Table 4, only four Ω states have been seen: the ground state, one three-star excited Ω baryon state, and two additional excited states with two-star ratings. Photoproduction reactions for Ω^- and its excited states have yet to be measured; a SLAC experiment provided an upper limit for $\gamma p \to \Omega^- X$ of $\sigma_t < 17$ nb [?] Yet, predictions from Roberts, Afanasev, and Shklyar suggest that the photoproduced Ω^- cross section should be about 0.3 nb.

Table 3: PDG values for branching ratios of excited Ξ states [?].

State	ΛK	ΣK	$\Xi\pi$
$\Xi(1530)$			100 %
$\Xi(1690)$	seen	seen	seen
$\Xi(1820)$	large	small	small
$\Xi(1950)$	seen	seen?	seen
$\Xi(2030)$	20%	80%	small

We intend to measure the cross section for the reaction $\gamma p \to \Omega^- K^+ K^+ K^0$. Assuming a cross section of 0.3 nb, our simulations estimate $\sim$7000 Ω^- baryons and several million

Ξ states will be observed in 80 days of beam time at high luminosity. Supplemental to the approved 80 days of high-luminosity data, an additional 39 days approved at low-lunimosity should boost statistics to an equivalent of 100 days at high-luminosity. Moreover, 20 additional days allocated with the torus at reversed polarity will increase statistics even further.

In recognition of the ASU role in the analysis effort towards the measurement of multi-strangeness baryon production, PI Dugger has been designated by the CLAS Collaboration as the coordinator for Ω^- and Ξ baryon analyses. ASU's leading role in the analysis of multi-strangeness baryon production positions our group well to participate fully in the analysis of data to be obtained. Currently, PI Dugger and undergraduate student Eric Bryan are working on the analysis of newly obtained CLAS12 data.

Table 4: Status of known Ω^- states from the PDG summary [?].

State	J^P	Width (MeV)	PDG rating
Ω^-	$\frac{3}{2}^+$		****
$\Omega(2250)^-$	?	55 ± 18	***
$\Omega(2380)^-$	?	26 ± 23	**
$\Omega(2470)^-$	?	72 ± 33	**

The information obtained on mass splittings within these Ω^- and Ξ systems will be extremely useful in testing lattice QCD and QCD-inspired models of these baryons. At present, the only baryonic mass splittings available come from the ground state octet and decuplets (e.g. n-p splitting or ground state Δ splitting). All the data will help address the issue of how quarks and gluons assemble into the hadrons observed in nature.

2.1.1 The CLAS12 detector

A brief overview of the CLAS12 detector to be used for the Ω^- and Ξ measurements is provided here to provide context for the preliminary ASU results discussed in the next subsection. While the CLAS12 detector is designed primarily to measure deeply exclusive scattering using electron beams, a forward tagger has been installed within CLAS12 that enables quasi-real photon experiments with q^2 as low as 0.01 GeV^2. The ASU efforts in Hall B make use of this forward tagger to perform photoproduction measurements for the Ξ and Ω from the cryogenic hydrogen target within the CLAS12 detector. In addition to the presence of the forward tagger, another key experimental consideration for using CLAS12 for our studies is that, at present, the particle identification for kaons should be better than that expected for the current configuration of the GlueX detector in Hall D. This superior particle identification for CLAS12 is the primary motivation for our use of that detector in the search for Ω^- and Ξ baryons states. With the availability of both tagged photons and good kaon identification, Hall B is well-suited for the measurements we propose to make.

As seen in Fig. 1, CLAS12 is composed of two main detector arrays: the Central Detector (CD) and the Forward Detector (FD). The FD covers the range of 5° to 40° in polar angle, whereas the CD covers the polar angles from 40° to 135°. The FD is expected to provide separation of identified $K^\pm$ and $\pi^\pm$ having momenta less than 3 GeV/c, and separation of protons and $K^\pm$ with momenta less than 4.5 GeV/c – the key capability required for this experiment noted above.

A cryogenic target cell is located at the center of the cylindrically-symmetric CD. Surrounding the cryogenic target cell is a Silicon Vertex Tracker (SVT) yielding 1 mrad angular resolution in azimuthal angle and 15 mrad in polar angle for charged tracks, as well as providing vertex resolution better than 2 mm. Outside the SVT is the cylindrically-symmetric

Central Time-of-Flight system (CTOF). The CTOF scintillator array has a timing resolution of 50 ps. The Central Electromagnetic Calorimeter forms the next cylindrical layer, consisting of a scintillating-fiber/tungsten-powder array. These detectors are housed within a 5-T superconducting solenoid magnet of aperture 0.78 m. The original CLAS superconducting toroidal magnet has been repurposed for CLAS12, with the same six-sector azimuthal symmetry as the original detector.

Downstream of the SVT are the High Threshold Cherenkov Counters and the Forward Tagger (FT) arrays. Electrons that scatter with angles between 2.5° and 4.5° are detected in the FT, enabling quasi-real photon experiments such as those we will undertake in this work. Beyond the FT are three regions of drift chambers, forming the Forward Tracking Chamber (FTC). The chambers are arranged in a fashion similar to the original CLAS design, with Region 1 drift chambers located before the torus magnet, Region 2 within the torus magnet, and Region 3 behind the torus. Ultimately, the spatial resolution for this chamber package is expected to be a factor of 3 better than the original CLAS system. Downstream of the FTC are the Low Threshold Cherenkov Counters (LTCC), which are modified versions of the original CLAS Cherenkov counters with the same external geometry. As with the LTCC, the Forward Time-of-Flight (FTOF) system has the same geometry as the original CLAS system, but has been upgraded to obtain 80-ps timing resolution. The detector furthest downstream is the Forward Electromagnetic Calorimeter, an array retained and repurposed from the original CLAS detector.

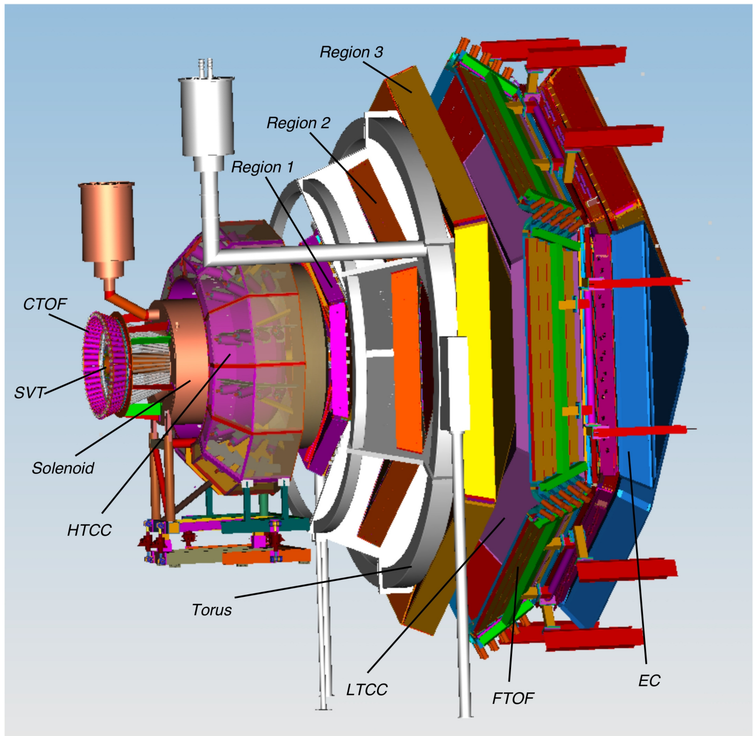


Figure 1: Schematic diagram for CLAS12. The labeled subsystems are described in the text.

2.1.2 ASU preliminary analysis of Spring 2018 CLAS12 data

During the Spring 2018 (2/6/2018 through 5/6/2018), the first physics runs were taken at JLab with the CLAS12 detector. For that running period, over 3.8×10^7 triggers were accumulated at incident electron energies of 2.2, 6.8 and 10.4 GeV, with the lower energy runs used for commissioning the detector.

As of this writing, the first pass of calibrated cooking has yet to be started for the Spring 2018 data. Thus far, a handful of runs processed for calibration purposes are also available for collaboration members to analyze. The Very Strange Group analyzed a single run from the 6.8 GeV data for an initial glance at the data. From that early look, Fig. 2

shows the measured mass for charged tracks hitting the forward time-of-flight array (FTOF). Even though the calibrations were still being made at that point, charged kaons are already visible between the pion and proton peaks. The particle identification (PID) scheme will be further optimized when the current cooking has completed, but for the preliminary analyses discussed next, pions were defined as having a mass between zero and 0.45 GeV, and protons were taken in the mass range between 0.65 and 1.2 GeV.

Owing to the large cross section and large beam symmetry of photoproduced ρ^0 mesons, the PI performed a beam asymmetry measurement for the reaction $\gamma_v p \to p\rho^0$, where $\rho^0 \to \pi^+\pi^-$ and γ_v represents the nearly-real virtual photon. For the identification of the ρ^0 meson, the missing mass from the reaction $\gamma_v p \to p\pi^+\pi^- X$, where X is the missing particle was chosen such that -0.02 $<$ Mass$^2(X)$/GeV $<$ 0.0 (The center of the squared missing-mass is shifted slightly towards the negative at the moment). The ρ^0 mesons were then binned in a single 100 MeV wide bin in γ_v energy with center at 2.5 GeV, three $|t|$ bins with centers ranging from 0.1 to 0.4 GeV^2, and 18 bins in the angular variable Ψ, where Ψ is the azimuthal direction of the resulting π^+ as seen in the ρ^0 rest frame with the x-axis defined along the polarization direction (defined below). An example of the ρ^0 mass for $|t| = 0.15$ GeV^2 integrated over all Ψ angles and fit to a Breit-Wigner-plus-zero-order polynomial is given in Fig. 3.

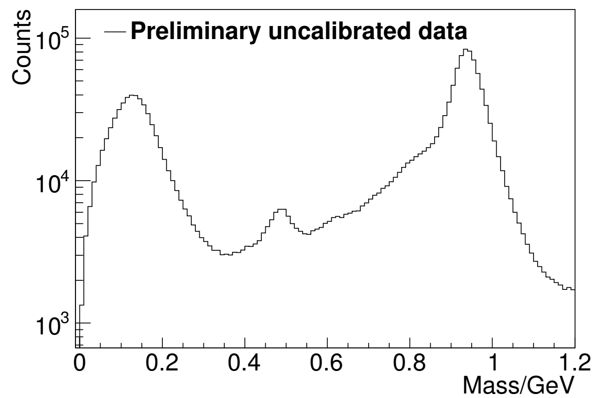


Figure 2: Initial PID previous to full calibration for events hitting the FTOF.

Unlike the case for the real photons in the GlueX experiment, the determination of the polarization for virtual photons in CLAS12 does not require a dedicated device. For the determination of the photon polarization using CLAS12, knowledge of the 4-vectors of the incident and scattered electron is sufficient to determine the virtual photon polarization. The polarization direction is orthogonal to the scattering plane with the longitudinal component being negligible for nearly-real photons. The value of the virtual polarization ε is given by

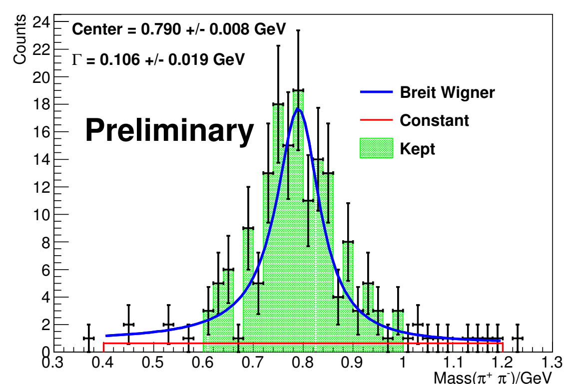


Figure 3: Mass of the $\pi^+\pi^-$ system for $E_\gamma = 2.5$ GeV and $|t| = 2.5$ GeV^2

$$\varepsilon = \left[1 + 2\left(\frac{Q^2+\nu^2}{Q^2}\right)\tan^2\left(\frac{\theta_{e_F}}{2}\right)\right]^{-1},$$

where $-Q^2$ is the squared-mass of the virtual photon, ν is the energy of the virtual photon, and θ_{e_F} is the scattering angle of the scattered electron relative to the incident electron.

For each of the three values of $|t|$ used, we created 18 bins in the Ψ variable to obtain the Ψ distribution of the ρ^0 yields. These yields were then fit to the function $A[1-B\cos(2\Psi-2\Psi_0)]$, where A, B and Ψ_0 were varied. To extract the beam asymmetry (Σ), the value of B from the fitting routine was divided by the polarization P, which yields Σ. For all $|t|$-bins, Ψ_0 was within 1.16 standard deviations of the expected value ($\Psi_0 = 0$). An example of the Σ extraction from a Ψ-distribution is provided n Fig. 4.

Once the beam asymmetry Σ was determined for each $|t|$-bin, a plot of Σ versus $|t|$ was produced. The energy and $|t|$ ranges we chose for this analysis permit a comparison to existing world data. In 1970 DESY reported beam asymmetries using two counter-wire telescopes [?], while in 1972 SLAC published ρ^0 beam asymmetries using a bubble chamber [?]. A comparison of the preliminary CLAS12 ρ^0 asymmetries compared to SLAC and DESY is shown in Fig. 5.

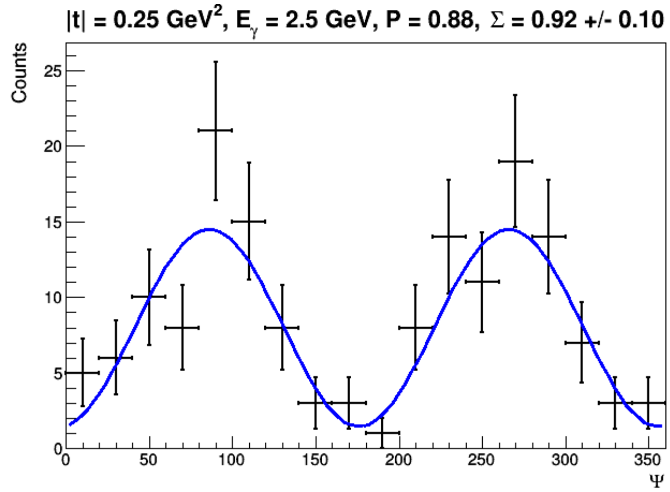


Figure 4: The Ψ distribution for the reaction $\gamma_v p \to p\rho^0$, where $\rho^0 \to \pi^+\pi^-$ at $|t| = 0.25$ GeV and a fit to $A[1 - B\cos(2\Psi - 2\Psi_0)]$, where A, B and Ψ_0 were variables of the fit.

Our preliminary Σ results from a *single CLAS12 run (that was still being calibrated)* agree quite well with the previous results. When calibrated full statistics are available for all Spring 2018 runs, our CLAS12 results for Σ for $\gamma_v p \to p\rho^0$, where $\rho^0 \to \pi^+\pi^-$, will cover a wider range in $|t|$ with smaller bin widths and smaller statistical uncertainties than the few published data.

Though we are not primarily interested in the physics associated with ρ^0 photoproduction, this ρ^0 analysis may lead to CLAS12's first physics publication. We are acting quickly and opportunistically with respect to this reaction observable. If the analysis of the fully cooked Spring 2018 data goes as smoothly as the single run used thus far, ASU could complete the analysis of ρ^0 beam asymmetries early in the requested grant period. Regardless, these ρ^0 results confirm that ASU is fully capable of carrying out the analyses for the proposed Ω^- and Ξ baryons studies outlined above.

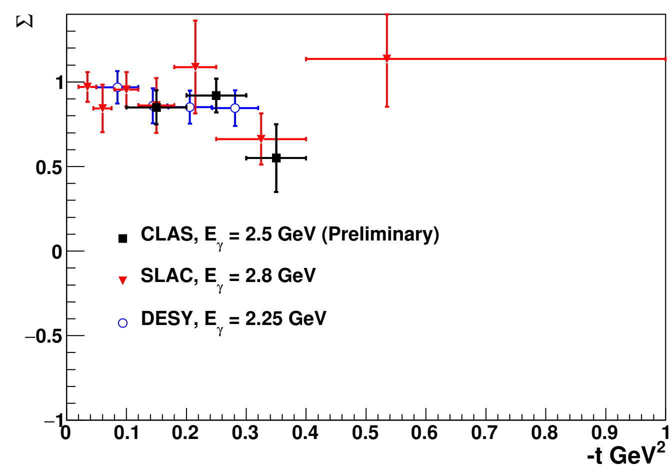


Figure 5: Beam asymmetry Σ for ρ^0 photoproduction on the proton. Black filled squares are from the ASU preliminary analysis of CLAS12 data from a single run, while red filled triangles are from SLAC [?] and blue open circles represent results from DESY [?].

2.2 Exotic hadrons

Improving our understanding of quark confinement in hadrons requires deepening our insight into the gluonic fields within those particles. Exploration of the spectrum and properties of exotic hybrid mesons has emerged as a key path forward for exploring quark confinement. Indeed, that topic was a major motivation for the upgrade of JLab, and is specifically mentioned multiple times in the 2015 NSAC Long-Range Plan [**?**].

To deepen understanding of how confinement arises, ASU is working with the GlueX Collaboration in Hall D to search for exotic hybrids with masses up to 2.5 GeV. Exotic hadrons ("exotics") are classified as one of three types: glueballs, tetraquarks, and hybrids. Glueballs are states that completely lack valence quarks. The lightest glueballs should have $J^{PC} = 0^{++}$ or 2^{++}, and are expected to mix with constituent quark states with the same quantum numbers. Tetraquarks are comprised of two $q\overline{q}$ states, and are the product of two $SU(3)$ octets that can be represented as

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8_1} \oplus \mathbf{8_2} \oplus \mathbf{1}.$$

Hybrid states in a constituent $q\bar{q}g$ model are built from the usual $q\overline{q}$ constituent-quark representation with the promotion of one or more gluons from virtual to real. For a hybrid state, a $q\overline{q}$ colored state interacts with real constituent colored gluon(s) to form an overall colorless state. In contrast to glueballs and tetraquarks, hybrids are only expected to exist in nonets similar to those for the constituent quark model. Exotics, however, can have quantum numbers J^{PC} that differ from those of hadrons constructed with the simple constituent quark model. Finding particles with exotic quantum numbers J^{PC} serves as the "smoking gun" for determining if a state is exotic.

Some guidance in the search for hybrid states has come from lattice QCD predictions. For example, a lattice calculation performed by the Hadron Spectrum Collaboration (HSC) in 2013 [**?**] found hybrid states in supermultiplets with $J^{PC} = 0^{+-}$, 1^{-+}, 2^{+-}, and 1^{--}. This HSC model description suggests that those hybrids have the structure $([\mathbf{q\overline{q}}]_{\mathbf{8_c}} \otimes \mathbf{G_{8_c}})$. States of particular importance for the search of hybrids have the exotic quantum numbers of $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$.

Table 5 shows several possible decays of exotic mesons of interest for the GlueX experiment. Currently, there are two exotic $J^{PC} = 1^{-+}$ states ($\pi_1(1400)$ and $\pi_1(1600)$) listed by the Particle Data Group [**?**]. For the $\pi_1(1400)$, the decay modes that have been seen are $\eta\pi^0$ and $\eta\pi^-$, while for $\pi_1(1600)$ the decays seen are $b_1\pi$, $\eta'\pi^-$ and $f_1\pi$. The interpretation of the $\pi_1(1400)$ as a hybrid is problematic [**?**, **?**, **?**]. A hybrid meson ($q\bar{q}g$) state can either have an angular excitation between the quark+anti-quark system and the gluon (said to be "gluon excited") or the excitation can be exclusively between the quark and anti-quark ("quark excited"). For the gluonic angular-excitation, within the $q\bar{q}g$ constituent model, a decay of a hybrid into two fundamental mesons is suppressed. This would make the $\pi(1400) \to \eta\pi$ decay unlikely in the gluon-excited case. However, a quark excitation can proceed into two fundamental mesons, though the branch into the η-singlet is favored over the η-octet. Since no search for $\pi(1400) \to \eta'\pi$ has been successful, there is some doubt that the $\pi_1(1400)$ is a hybrid. Instead, some have suggested that the $\pi_1(1400)$ is a tetraquark state [**?**, **?**, **?**].

In addition to the π_1 exotic states, there should be corresponding isospin $I = 0$ nonet members if the π_1 is a hybrid. Establishing these isoscalar members for the nonets is

Table 5: Possible decay modes of exotic hybrids that will be explored by GlueX.

Hybrid meson	J^{PC}	Reachable with limited running	Reachable with longer running	Challenging even with longer running
b_0	0^{+-}	—	—	$\pi(1300)\pi$, $h_1\pi$, $f_1\pi$, $b_1\pi$
h_0	0^{+-}	—	$b_1\pi$	$h_1\eta$
h_0'	0^{+-}	—	$K_1(1270)K$	$K(1460)K$, $h_1\eta$
π_1	1^{-+}	$\pi\rho$	πb_1, πf_1, $\pi\eta'$	ηa_1
η_1	1^{-+}	ηf_2, $a_2\pi$	ηf_1, $\eta\eta'$	$\pi(1300)\pi$, $a_1\pi$
η_1'	1^{-+}	K^*K	$K_1(1270)K$, $K_1(1410)K$, K_2^*K, $\eta\eta'$	—
b_2	2^{+-}	$\omega\pi$, $a_2\pi$, $\rho\eta$	—	$f_1\rho$, $a_1\pi$, $h_1\pi$, $b_1\eta$
h_2	2^{+-}	$\rho\pi$	$b_1\pi$, $\omega\eta$	$f_1\omega$
h_2'	2^{+-}	—	$K_1(1270)K$, $K_1(1410)K$ K_2^*K, $\phi\eta$	$f_1\phi$

important in order to verify these exotics as being hybrids. The tetraquark state with $J^{PC} = 1^{-+}$ excludes the presence of an isosinglet, and is fully contained within the **20**-plet $(\mathbf{10} \oplus \overline{\mathbf{10}})$. Thus, identifying an isosinglet state with $J^{PC} = 1^{-+}$ excludes that state as being a tetraquark.

As detailed further below, we participated in GlueX analyses of single meson final states with the initial data obtained in the Spring 2016 running. The first GlueX physics paper has been published for the photon beam asymmetry Σ from $\gamma p \to p\pi^0$ and $\gamma p \to p\eta$ reactions [**?**]. This paper was made possible by the photon beam polarization measurements determined by the ASU group using TPOL, described further below. No other measurement of the photon beam polarization was available since the coherent bremsstrahlung spectral analysis (CBSA) approach originally envisioned proved unreliable. PI Dugger, who spearheaded the triplet polarization analysis, served on the three-member GlueX analysis/paper review committee.

The collection of physics results we intend to focus on in Hall D and those from other analyses by our collaborators in the GlueX Collaboration, will clarify the existence of exotic states, determine the properties of any such particles found, and, in turn, lead to progress in understanding how quarks and gluons assemble into hadrons.

2.2.1 The GlueX detector in Hall D

The Hall D GlueX detector is being used to search for gluonic excitations within mesons with masses up to 2.5 GeV [**?**, **?**]. As noted above, distinguishing states with gluonic excitations from other meson states will require the determination of exotic quantum numbers, J^{PC} that are unlike the assignments possible with traditional constituent quark models of meson states. A full partial wave analysis will be needed to obtain J^{PC} for the observed states. To minimize possible ambiguities in obtaining the required J^{PC} information from the partial wave analysis, all decay products from the candidate hybrid meson must be identified with good resolution. The identification of all decay products is greatly enhanced when the detector has a full acceptance in decay angles. For these reasons the GlueX detector (Fig. 6) was designed to have 4π solid angle coverage, with nearly full hermeticity, and good momentum and energy resolution of photons and charged particles.

Electrons with energies of 12 GeV incident on a thin (50 or 20 μm) diamond radiator produce a beam of linearly polarized photons ($\approx$40% polarization) with E_γ = 8.5-9 GeV. The tagging of the post-bremsstrahlung electron determine the photon energy to within 0.1%. The photons strike a 30-cm-long liquid hydrogen target surrounded by a start counter. Past the start counter, the next detector elements are cylindrical drift-chambers, which are surrounded by a cylindrical electromagnetic calorimeter made of lead and scintillating fibers. The target, start counter, drift chambers, and electromagnetic calorimeters are all contained within a refurbished 2.25 T superconducting solenoid that provides the momentum-analyzing magnetic field. On the downstream side of the solenoid is a time-of-flight system and a 3000-element lead-glass electromagnetic calorimeter. For 9 GeV incident photons, the GlueX detector has 4π acceptance for photons and charged particles to facilitate the partial-wave analyses of many-particle final states. The acceptance of final-state particles is typically better than 95%, and is very uniform over the detector. Moreover, the near hermetic design of the detector is well suited for determining the masses and J^{PC} for mesons with masses from 1.5 to 2.5 GeV/c^2.

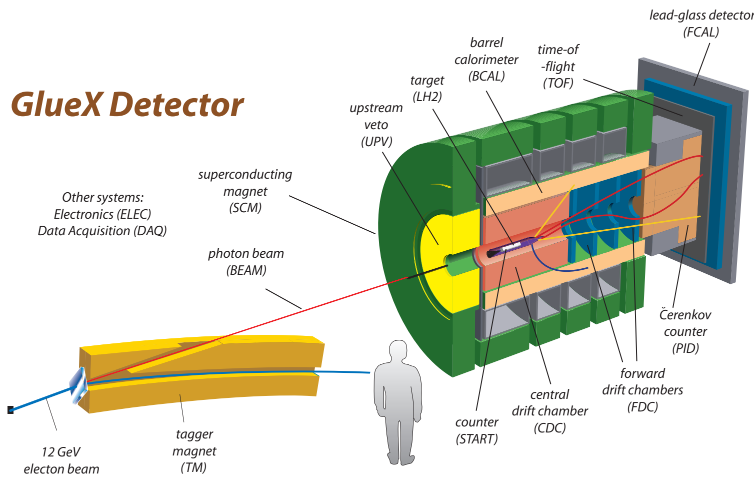


Figure 6: Diagram of Hall D and the GlueX detector.

For increased precision in kaon particle identification, the newly acquired DIRC (Detection of Internally Reflected Cherenkov) is placed just in front of the FCAL. The DIRC has as the main component four boxes filled with fused silica bars from the BaBar experiment. When installed in the BaBar experiment, these boxes provided good kaon separation up to 4 GeV [**?**]. Similar performance is expected when utilized for the GlueX experiment, greatly improving kaon identification, which will facilitate many analyses including those ASU is particularly targeting.

2.2.2 TPOL: the ASU triplet polarimeter

The partial-wave analyses to be undertaken in the GlueX search for hybrid mesons require an absolute uncertainty of $\pm$0.04 in the photon beam polarization. When ASU joined the GlueX Collaboration, we proposed a direct measurement of the photon polarization through pair production from an atomic electron ("triplet photoproduction") as a method to determine this critical parameter. In triplet production, the photon interacts with the field of an atomic electron to produce an electron-positron pair; the recoil atomic electron has a relatively low momentum, and can attain large polar angles that correlates with the production plane. The process is a straightforward QED process for which the primary contributing diagrams are given in Fig. 7. The large polar angle for the recoil atomic electron simplifies its detection.

The azimuthal angular distribution of the recoil electron yields information on the beam polarization. For polarized photons, the cross section for the triplet photoproduction process can be written as $\sigma = \sigma_0 [1 + P\Sigma\cos(2\phi)]$, where σ_0 is the unpolarized cross section, P is the photon beam polarization, Σ is the photon beam asymmetry, and ϕ is the recoil electron azimuthal angle. For GlueX, the photoproduced pair is detected in the existing pair spectrometer located downstream of the triplet polarimeter. A QED calculation of the beam asymmetry arising from scattering from an orbital electron yields the analyzing power Σ for the reaction, which with the Hall D beamline and geometry is approximately 0.2. To determine the photon beam polarization, the azimuthal distribution of the recoil electrons is fit to the function $A [1 + B\cos(2\phi)]$, where the variables A and B are fit parameters. Once B has been extracted from the data, the polarization is $P = B/\Sigma$.

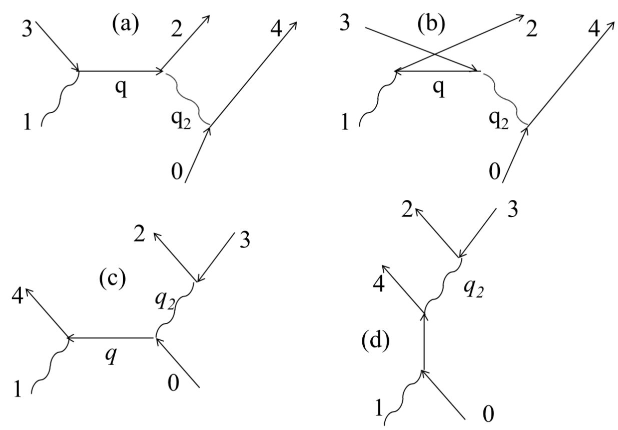


Figure 7: Half the Feynman QED diagrams for the triplet photoproduction process. Remaining diagrams are obtained by swapping electron 2 with electron 4.

Our group designed and constructed a detector system (called TPOL) that measures photon beam asymmetries with this triplet production process, and installed the system in the Hall D beamline prior to the Spring 2015 test run. TPOL uses an S3, double-sided silicon strip detector (SSD) manufactured by Micron Semiconductor to measure timing, energy deposition, and the azimuthal distribution of recoil electrons coming from the triplet production process. Fig. 8 shows the interior of the TPOL vacuum chamber; the beam transits that figure from right to left. The SSD has 32 azimuthal sectors on the ohmic side and 24 concentric rings on the junction side, with an outer active diameter of 70 mm and an inner active diameter of 22 mm.

The TPOL installation in the Hall D beamline is shown in Fig. 9, seen from beam right. The housings consist of three boxes attached to one another. The largest rearmost box in the figure is the vacuum chamber, the middle box is the preamp enclosure, and the smallest box is the distribution box that routes voltages and signals to and from the preamps. Cables attached to the distribution box include the signal lines (white), high voltage bias (red) and low voltage (gray) lines.

To determine the degree of photon beam polarization P in practice, the value of B obtained from fitting the azimuthal distribution to $A [1 + B\cos(2\phi)]$ is divided by the analyzing power Σ. A plot showing the polarization for PARA and PERP orientations (i.e., photon beam polarization parallel and perpendicular to the floor of the experimental area) as a function of incident photon energy is given in Fig. 10, where the red points are for PARA and the blue points are for the PERP orientation. For the Spring 2016 runs, the degree of polarization P, in the energy range used for the published π^0 and η beam asymmetries [?] ($8.4 > E_\gamma < 9.0$ GeV) in the next subsection was found to be $P_\gamma^{\rm PARA} = 0.440 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$ and $P_\gamma^{\rm PERP} = 0.382 \pm 0.008(\text{stat.}) \pm 0.006(\text{syst.})$. Additional information on the TPOL detector can be found in our recently published paper [?].

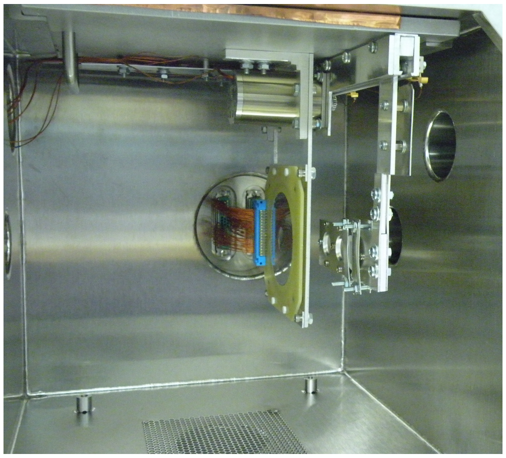


Figure 8: Interior of TPOL vacuum chamber with SSD and production target ladder assembly (from beam left).

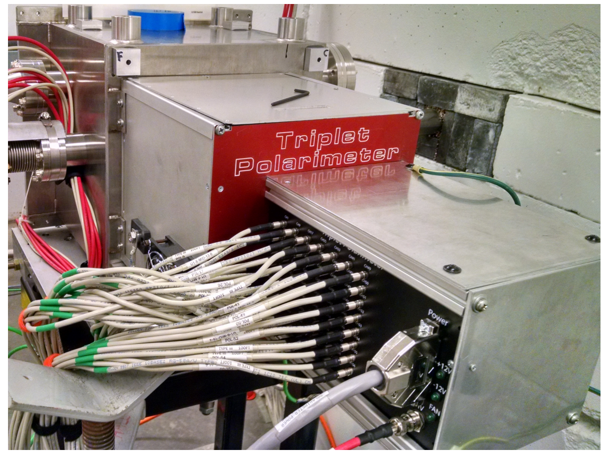


Figure 9: TPOL vacuum chamber and electronics housings installed in Hall D beamline (from beam right).

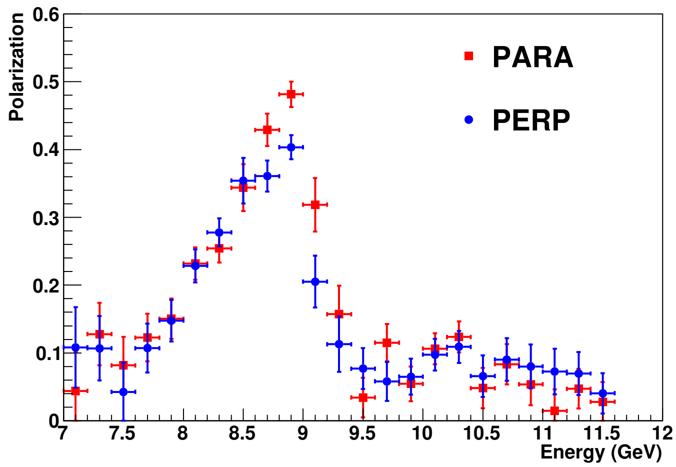


Figure 10: Polarization versus E_γ. Red squares represent results from the PARA setting, while blue circles represents PERP results.

Thus far, we have only instrumented the 32 sectors on the ohmic side of the SSD. During the proposed award period, we plan on upgrading the TPOL device to include readout for the ring side of the SSD. The readout of the ring side will give us access to additional polar angle information for the recoil electron that will allow us to further understand and reduce systematic uncertainties. The preamplifiers required for the upgrade have already been obtained, and JLab will produce the ASU-designed filter electronics. In order to house the additional electronics, the distribution box (smallest box shown in Fig. 9) has to be expanded, and part of the preamp enclosure (middle box in Fig. 9) has to be modified. JLab will fabricate the new distribution box, while the ASU group will be responsible for the modifications to the preamp enclosure.

To our knowledge, no other photon beam polarimeter operates at such energies. Motivated by our success with TPOL, the ASU group has begun conversations with the University of Glasgow on the possibility of designing a polarimeter utilizing pixel detectors to measure photon polarization through asymmetries in pair production. The advantage of using the pair production process, as opposed to the triplet process, is that the statistical precision and analyzing power for a pair production asymmetry measurement could be much better than that of a TPOL type device owing to the larger production cross section. The difficulty, however, in using the pair process, is that the opening angle between the photoproduced leptons is very small and requires high precision in the spatial resolution of the pair-detector elements.

The ASU group has provided the Glasgow group with our event generator and GEANT simulation software, and they have modified that package for the purpose of exploring a pair production polarimeter (PPOL). From their studies, the Glasgow group found that the PPOL concept should work and has obtained funding through a grant from the Science and Technology Facilities Council (United Kingdom). The Glasgow development of a PPOL will begin in earnest starting this year. In the meantime, the ASU group has performed additional feasibility studies of the PPOL concept using GlueX data and simulations. The results of the ASU analysis look promising, and Ken Livingston of the Glasgow group is working with us on the possibility of installing several pixel detectors in the GlueX pair spectrometer as a way to have a hybrid TPOL/PPOL polarization measurement.

ASU is thus positioned to continue providing the important polarization information for all Hall D experiments with TPOL during the proposed award period, as well as primed to further exploit new approaches in photon beam polarimetry that might be extended to other photon beams around the world.

2.2.3 The first physics publication from GlueX

As an example of the performance of the GlueX detector, TPOL, and an example of ASU's participation in the collaboration, we briefly discuss here the first physics publication arising from GlueX analyses.

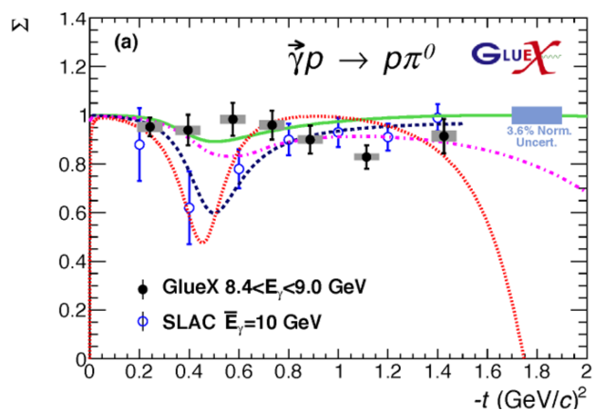


Figure 11: Beam asymmetry Σ for π^0 photoproduction from the proton with 8.4 to 9 GeV linearly-polarized photons from the first GlueX physics publication [?].

The Spring 2016 running period in Hall D coincided with the JLab accelerator providing its first 12 GeV electron beam. A 50-micron-thick diamond was placed in the beamline using a goniometer, and polarized photons with a coherent edge energy of 9 GeV were produced. Most of the running period was consumed by commissioning activities, but 45 data runs with polarized photons had conditions sufficient for physics production. From those 45 polarized photon-beam runs, 21 were taken with the polarization parallel to the lab floor and 24 with the polarization perpendicular.

Using this small initial sample of production data, the GlueX collaboration was able to obtain photon beam asymmetries Σ for π^0 and η photoproduction from the proton (π^0 results are shown in Fig. 11), which included the first Σ measurements for η photoproduction at 9 GeV. The π^0 results possessed much higher precision than any previous measurement. These Σ measurements became the first physics publication for the GlueX Collaboration [?]. The results would not have been possible without the TPOL work of the ASU group that provided the polarization measurements illustrated above in Fig. 10 since no other approach to determine the beam polarization attempted by the GlueX Collaboration was successful.

The dip in the SLAC π^0 results shown in Fig. 11 occurs where large corrections were required due to Compton backgrounds. In the SLAC article [?], the authors stated "The extracted π^0 cross section in the dip depends very critically on this correction. For example, at 15 GeV and t = -0.5 (GeV/c), two-thirds of the observed yield is due to Compton scattering." In terms of physics, a large positive value of the beam asymmetry corresponds to the expected case, where the π^0 is created through a t-channel process with a vector meson acting as a messenger particle. This particular type of exchange results in a natural parity exchange. The dip shown in Fig. 11, however, would correspond to a large contribution from a pseudovector meson exchange, like a b or h meson. Such a pseudovector exchange would lead to an unnatural parity exchange. This sensitivity to the reaction mechanism is illustrative of how polarization information can be useful in determining, in this case, the type of meson being exchanged. Such information is critical for extracting the J^{PC} information required for the classification of a t-channel produced meson as being exotic.

These first results illustrate that progress toward understanding the GlueX detector has been swift, that the triplet polarization approach to measuring the photon beam polarization is sound, and that the partial wave analyses needed in the search for exotics will not be hampered by ambiguities in measurements of the photon beam polarization. As additional data is obtained in future running periods during the proposed award, the searches undertaken in Hall D should proceed apace, with ASU both participating in those analyses and providing the beam polarization information essential for achieving the physics goals for Hall D.

2.2.4 Example of ASU analysis of GlueX data

To illustrate the types of analysis we can currently perform with GlueX data, we discuss here portions of the analysis of multi-kaon states undertaken by ASU graduate student Sebastian Cole on the existing GlueX dataset. In ASU's Hall B studies, the group extensively utilized the η and η' to filter out $I = 3/2$ resonances from the nucleon resonance spectrum. For Hall D, we will similarly use the η_1' to filter out tetraquark states from the spectrum of exotic meson states. The K^*K branch is a prime candidate for early detection of the η_1' hybrid.

Since the $K^* \to K\pi$ 100% of the time, the detected particles necessary for the reconstruction of the $\eta_1' \to K^*K$ are $KK\pi$. The particular branches that Cole is isolating in his search for the η_1' are $K^+K^-\pi^0$ and $K_s^0K^\pm\pi^\mp$. To begin his search, he has reconstructed the well-known $\phi \to K^+K^-$ meson decay, as well as the $\Lambda(1520) \to pK^-$ baryon decay. This work will assist in improving pre-DIRC kaon identification in order to search for η_1'. Fig. 12 shows the invariant mass of pK^- versus the invariant mass of K^+K^- from the August 2018 reconstruction of

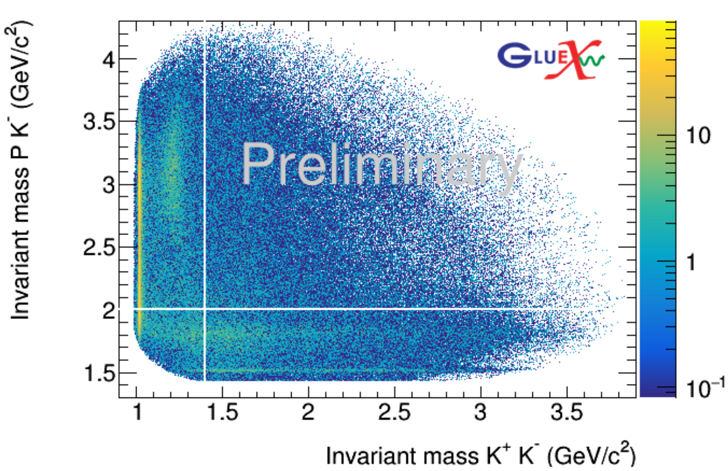


Figure 12: Invariant mass of pK^+ versus the invariant mass of K^+K^-. The white lines denote different cut selections (described in text).

Spring 2016 GlueX data. Fig. 12 shows strong enhancement bands ~ 1.02 GeV in the vertical direction, and ~ 1.52 GeV and ~ 1.8 GeV in the horizontal direction. (The vertical enhancement at ~ 1.2 GeV due to the misidentification of pions with low opening angles and high momentum as kaons.) Also shown in Fig. 12 is a vertical white line at 1.4 GeV and a horizontal white line at 2 GeV, which indicate the location of cuts on the data to further isolate $\phi(1020)$ and $\Lambda(1520)$.

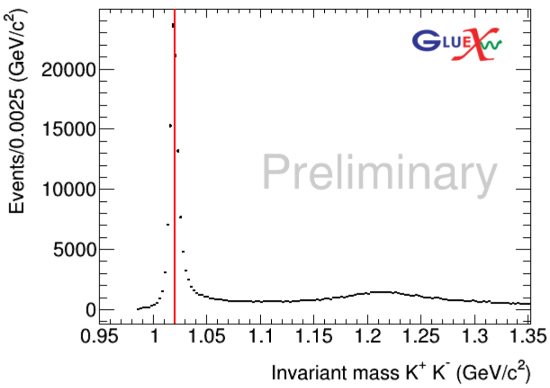


Figure 13: Invariant mass of pK^-. The vertical red line shows the PDG value for the mass of the ϕ meson.

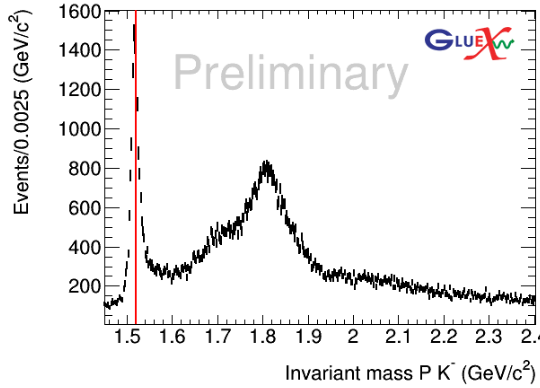
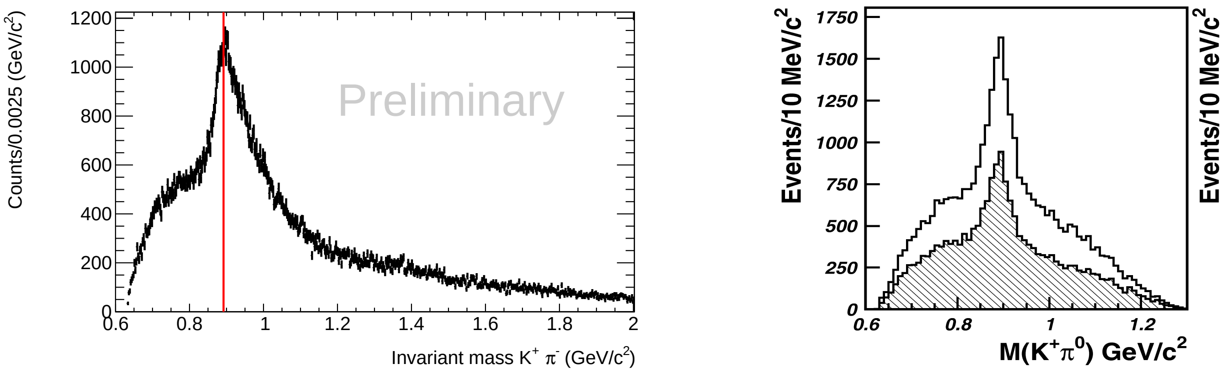


Figure 14: Invariant mass of pK^-. The vertical red line shows the PDG value for the mass of the $\Lambda(1520)$ baryon.

By taking events above the horizontal white line shown in Fig. 12, a plot of the K^+K^- invariant mass shows a strong ϕ signal, as seen in Fig. 13. Likewise, by selecting events to the right of the vertical white line, the $\Lambda(1520)$ is clearly visible in Fig. 14.

At the time of this writing, we await $pK^+K^-\pi^0$ and $pK^\pm 2\pi^\mp\pi^\pm$ skims of the GlueX data from the August reconstruction launches of 2016 and 2017 data, as well as the first reconstruction launch of 2018 data to occur in Fall 2018, to dig deeper into this search. These reconstruction launches are critical for analyses in GlueX due to major improvements to GlueX tracking, and energy deposition determination in the CDC and FDC, leading to a recovery of approximately 30% more events than current analysis efforts. A subset of the $pK^+K^-\pi^0$ and $pK^\pm 2\pi^\mp\pi^\pm$ skims containing $K^* \to K\pi$ candidate events will be identified and the η_1' hybrid search will begin in earnest. In preparation for this newly reconstructed data, Cole has begun analyzing $pK_s^0K^+\pi^-$, where $K_s^0 \to \pi^+\pi^-$, skims from the initial reconstruction of low and high intensity 2017 data. Fig. 15a shows evidence of $K^*(892)$ in the high intensity 2017 running of GlueX. The reconstruction of a $K^*(892)$ is a necessary step in the search for η_1' in $K^*K_s^0$. While still at a relative early stage of analysis, this spectrum is remarkably similar to prior published data on this channel [**?**], as seen in Fig. 15b.

The next 12 months is a particularly exciting time for the exploration of reaction signatures that include kaons. Recently, the GlueX Collaboration installed a DIRC for in-beam commissioning slated for Fall 2018, with DIRC-included production runs starting in Fall 2019. The DIRC will greatly improve the particle identification for kaons needed for the search of the η_1' hybrid.



(a) (b)

Figure 15: (a) Invariant mass of $K^+\pi^-$. The vertical red line indicates the PDG value for the mass of the $K^*(892)$. (b) Missing mass spectrum from Ref. [?]. The shaded area indicates results where $|t| > 0.1$ GeV^2.

3 Impact of other work on this grant's resources

PI Associate Professor Dugger and Co-Investigator Professor Ritchie are tenure-track and tenured (respectively) faculty members at ASU with academic year contracts. ASU requires all tenured and tenure-track faculty members to contribute effort during the academic year in the areas of teaching, research, and service. Both the PI and Co-Investigator will fully commit their entire research effort during the academic year to the research to be undertaken in this proposal, and all effort during the summer months will be allocated to this proposal. Neither PI nor Co-Investigator have any effort committed to any other proposal.

4 Research plan

A timeline is presented here for the activities discussed above based on the assumptions that the proposed award will be funded at the requested level and that the accelerator schedule at JLab will proceed as planned. While this plan represents a "good faith" estimate of the schedule for the funding period, major unscheduled downtime at JLab or budget reductions may push events beyond the timeline discussed here. Regardless, our entire effort is dedicated to this proposal, and work will proceed as rapidly as practical.

During Year 1, additional data will be taken with both Halls B and D. In addition to normal service responsibilities expected of collaborations in both the CLAS and GlueX Collaborations, we will continue our responsibility for polarization characterization in Hall D. An upgrade for the triplet polarimeter is scheduled for the Summer 2019. Developments related to the polarization measurement work with the University of Glasgow should result in tests of the devices developed for Mainz during the first year of the award, with a possible additional installation for testing purposes in Hall D. The PI will have finished the first pass at uncovering existing and new Ξ states, and a second graduate student funded by the new award will start pursuing Hall B cascade production. The data collected from Hall D will be the first production data from that hall to include the DIRC. Mentored by the Co-Investigator, ASU Graduate Research Associate Sebastian Cole will finish his analysis regarding the isolation of $\eta_1' \to K^*K$ candidates, including background subtractions, determination of cross sections and beam asymmetries using all non-DIRC data available. The Cole analysis will form the basis of future ASU analyses for that reaction; those studies will form his dissertation project. By the end of the first year of the award period, Sebastian Cole will have received his Ph.D.

During Year 2, all data for the physics discussed in Section 2 will be in hand and under full analysis. A new graduate student (replacing Sebastian Cole) will have started modifying the analysis developed by Cole to include the newly obtained and calibrated DIRC data from Hall D. The Hall B analyses related to cascade production should be well underway, with preliminary data presented at workshops and meetings.

During Year 3, the analysis of Ξ states from Hall B should be nearing completion, and the ASU graduate student related to that project will have begun assisting in the Ω^- search. The Hall-D search for the η_1', including all DIRC and non-DIRC data, will be undergoing partial wave analysis (PWA) using the mature and robust PWA tools developed by the GlueX Collaboration; the graduate student by this award (who replaced Cole) will be fully engaged in that work. Opportunistic physics analyses likely will present themselves as these analyses proceed, which may spawn projects for undergraduate and graduates students. As analyses progress, preliminary data will be presented at workshops and meetings.

5 Roles and responsibilities

Since the ASU Meson Physics Group is a relatively small research group, both the PI and Co-Investigator will be involved and cognizant of work undertaken in all analyses related to the work discussed in this proposal. There will, however, be separate lead responsibilities held by each for the work undertaken. PI Dugger will be responsible for leadership of the analyses and publications related to the Hall B/CLAS12 data, as well as implementation of the upgrades to the TPOL device. He will also serve as the mentor for any graduate or undergraduate students working on the CLAS12 analyses. Co-Investigator Ritchie will hold lead responsibility for the analyses and publications of Hall D/GlueX data, and will serve as mentor for any graduate or undergraduate students working on that data. Both the PI and Co-Investigator will share in the responsibility of maintaining the TPOL, manning shifts for both halls, and in the mentoring of students. Weekly group meetings will assist in coordinating and synchronizing all efforts and to provide "cross-training" for the students working with the group.

6 Human resource development

Based at one of the nation's largest and most diverse major public research universities, instruction and mentoring form a central feature of this project. As has been true for over a third-of-a-century, the training of graduate and undergraduate students in science and technology through work with the ASU Meson Physics Group during the project will enhance the nation's scientific workforce. Mentoring and training of students is an essential feature of this proposal: the activities described above cannot be carried out without their training, development, and participation.

Faculty members of the ASU Meson Physics Group have continuously mentored graduate and undergraduate students since Ritchie joined the faculty of ASU in 1984. While the PI has not yet graduated any Ph.D. students, he has been fully involved in mentoring graduates students for nearly 20 years. Focusing solely on the time since the PI became a member of the ASU Meson Physics Group as a graduate student in 1997, five graduate students working with the group have obtained their Ph.D degrees with Co-Investigator Ritchie as their advisor, and 60% of those graduate students remain in physics. The most recent graduate, Ross Tucker, chose to pursue his love of teaching and is currently a Lecturer in Physics at ASU. David Lawrence is a staff scientist at Jefferson Lab working on GlueX physics, and Michael Dugger is a tenure-track Associate Professor at ASU and the PI of this grant application.Of the remaining Ph.D. students, Brian T. Morrison went straight into industry as a software developer, while Patrick Collins completed a nuclear physics postdoctorial position with The Catholic University of America before leaving the field.

Among the undergraduate students who have worked with the group, most have gone on to graduate school and careers in physics. One such example is Professor Todd Averett, currently a faculty member in Physics at William and Mary working in JLab Hall A, who worked with the group as an undergraduate analyzing LAMPF data. A number of undergraduates students have written honors theses on work with the group. For example, the most recent undergraduate student to work with the group, Robert J. Lee, was mentored by the PI, and graduated in Spring 2018 and has begun graduate studies in physics at the University of California at San Diego. Robert was an exceptional student that the PI worked closely with for three years. His honors thesis was on the analysis of FROST (Frozen Spin target) data from JLab CLAS data. He analyzed the spin observables associated linearly polarized photons incident on transversely polarized protons for the reaction $\gamma p \to \pi^+ n$. Robert's thesis is being turned into a CLAS analysis note and we expect this to lead to a publication by the beginning of the proposed grant period. Currently, The PI has a sophomore undergraduate student, Eric Bryan that he is mentoring in the analysis of CLAS12 data, while the Co-Investigator is advising a Ph.D student, Sebastian Cole, that is returning from a 1-year stint at JLab working on GlueX data, maintenance of the TPOL and analysis of TPOL data.

Students fully participate in weekly group meetings, making presentations on their own work while asking questions about the work of others. This provides them frequent opportunities to hone their scientific presentation skills. As expected, the scientific results of the investigations outlined in Section 2 will be broadly disseminated through national and international conference presentations, workshops, reports, and refereed publications, and will be archived in public databases. Presenters will include these junior scientists in the group - both undergraduate and graduate students - to increase their adeptness in scientific communication, as well as to build their own scientific collaborator networks.

7 Requested resources and justification

The justifications for the items listed in the proposal budget are provided here.

7.1 Senior personnel

Summer salary support is being sought for the Principal Investigators to enable their effort to continue during the summer months when their full time can be devoted to the research described above. Michael Dugger (PI, two summer months/year) has extensive experience working in both Halls B and D at Jefferson Lab. While active in all areas of the project, he will particularly focus on leadership of the very strange meson production experiments in Hall B for the group, mentoring the graduate student and undergraduate student working on the cascade production efforts in Hall B. Barry Ritchie (Co-Investigator, one summer month/year) has been active in the field of medium energy physics beginning with postdoctoral work in 1980, with extensive participation in experiments at LAMPF, PSI, and JLab. While active in all group activities during the award period, Ritchie will focus particularly on the meson photoproduction work in Hall D, including direction of the graduate student and undergraduate student associated with the exotic meson production efforts in Hall D. As noted above, both investigators will participate jointly and collaboratively in all mentoring activities for the junior personnel of the group.

7.2 Other Personnel

7.2.1 Graduate Research Associates

Support is sought for a steady-state group size with two graduate students. The funding requested encompasses for each supported student 4.5 academic months per academic year and 1.5 summer months per calendar year. At ASU, this translates to 20 hours/week during the academic year and summer, which is considered 100% effort for a graduate student. As a graduate student completes his program at ASU, a new graduate student will assume the vacated line. Student participation will greatly enhance the productivity of the group beyond the efforts of the investigators, and also deliver the human resource benefits noted above, enhancing the nation's supply of well-trained scientists. Graduate student salaries listed in the budget are based on the standard rate for graduate research associates in the Department of Physics with an additional three months of summer support.

7.2.2 Undergraduate students

As noted in the prior section, undergraduate student participation is a key feature of our group's activities, equipping those students to move into science and technology fields as junior researchers. Support is requested to provide funding for an equivalent of one 10-hour-per-week undergraduate students per academic year and 20-hour-per-week during the summer, at an hourly rate of $12, with the intention of that student being in residence at Jefferson Lab for a portion of that summer period. At ASU, this translates into 3.75 calendar months per year -$12/hour for 10 hours/week for during the academic year and 20 hours/week for 3 months/year in the summer. Very likely, there will be more than one undergraduate working with the group, but we will only support our most advanced undergraduate with the funds from this award.

7.3 Fringe benefits.

Arizona State University defines fringe benefits as direct costs, estimates benefits as a standard percent of salary applied uniformly to all types of sponsored activities, and charges benefits to sponsors in accordance with the federally-negotiated rates in effect at the time salaries are incurred. Benefit costs are expected to increase approximately 3% per year; the rates used in the proposal budget are based on the current Federally-Negotiated Rate Agreement plus annual escalation for out-years. The proposal's Fringe Benefits were negotiated and approved by the U.S. Department of Health and Human Services. For purposes of this proposal the following rates are being used:

- Faculty members: 28.12%, 28.96%, and 29.83% of salary for Year 1, 2, and 3, respectively.
- Graduate research assistants/associates: 7.31%, 7.53%, and 7.76% of salaries for Year 1, 2, and 3, respectively.
- Undergraduate students (hourly): 2.16%, 2.22%, and 2.29% of wages for Year 1, 2, and 3, respectively.

7.4 Total salaries, wages and fringe benefits

A cost-of-living increase of 3% has been calculated in years 2 – 3 for each year of this project. The total request for salaries, wages and fringe benefits: Year 1 -$105,981, Year 2 -$109,632, Year 3 -$113,423.

7.5 Equipment

No funds are requested for equipment.

7.6 Travel

The travel budget was estimated in accordance with the University's travel policy based on current air fares, current federal and ASU authorized per diem rates, airport shuttle services, and, if applicable, conference registration fees and/or car rental. At the time of this proposal, ASU's travel system software provider, Concur Technologies, assesses a minimal charge per person for each travel expense report submitted. This expense is a direct cost charged per trip.

For each year of support, we have allocated six trips to Jefferson Lab, with four of those trips having a duration of ten days and nine nights, and the remaining two JLab trips having durations of six days and 5 nights. These trips will enable at least one additional person from ASU beyond the on-site graduate student(s) to participate in collaboration activities, meet service obligations, discuss analyses and results with collaborators, and make presentations at collaboration meetings. In addition to the JLab trips, we have allocated two trips per year for giving talks at conferences. The travel funds being requested: Year 1 -$15,902, Year 2 -$16,379, Year 3 -$16,870.

7.7 Other direct costs

Funds for materials and supplies are requested at the level of approximately $4,000 per year for computing equipment replacement and repair, (including upkeep of the computer clusters owned by the group), plus additional funds for miscellaneous supplies and consumables. The breakdown per year is as follows: Year 1 -$4,025, Year 2 -$3,811, Year 3 -$4,042.

Tuition remission for graduate students is a required charge at ASU for graduate students supported by external funding. The remission is charged to projects in proportion to the amount of effort the graduate student will work on the project, and those tuition charges are exempt from Facilities and Administrative Costs. The tuition charge per graduate student is based upon the currently approved university tuition and fee schedules and is calculated as follows: Year 1 - $19,178; Year 2 - $20,712; Year 3 - $22,369.

No participant costs or equipment purchases are budgeted.

7.8 Total direct costs

The total direct costs for each budget year of this award will be $164,264, $171,246, and $179,073 for Years 1, 2, and 3, respectively.

7.9 Indirect costs

Indirect costs are calculated on Modified Total Direct Costs (MTDC) using Facilities and Administrative Costs rates approved by DHHS on August 21, 2018. Items excluded from the indirect cost calculation include are capital equipment, subcontracts over the first $25,000, tuition remission, participant support costs, rental/maintenance of off-campus space, and patient care fees. The off-campus research rate of 26% is applied for all years of the project.

7.10 Total Direct and Indirect costs

The total direct and indirect costs being requested for each 12-month period of this award amount to $197,000, $205,000, and $214,000 for Years 1, 2, and 3, respectively. The total over the requested three-year periods $616,000.

8 Institutional support

Arizona State University provides support to to ASU Meson Physics Group at both the Tempe campus and the Polytechnic campus (located in Mesa, AZ). At both locations, ASU provides utilities, basic telecommunication service, 1 Gbs internet access, approximately 500 square feet of dedicated lab space, and sufficient office space for the principal investigators. At the Tempe campus, there are two additional dedicated offices for use by the members of the group. These institutional resources are sufficient to support the research efforts related to this proposal for all group members with the proposal funded at the level requested.

Appendices

A Data management plan

The ASU Meson Physics Group, as a member of the CLAS Collaboration and the GlueX Collaboration, adheres to the data management practices of those groups, which are consistent with best practices in the field. As is common in experimental hadronic physics, the data obtained from experiments pass through three stages: raw data, calibrated (or "cooked") data, and final results. Data in the first two stages are kept in the storage facilities at Jefferson Lab, where those data can be accessed and utilized by institutions, like ASU, that are in the particular collaboration within which the data were taken. As analyses proceed to the results stage, preliminary results are disseminated in talks and presentations. With final collaboration approval, the results are published in refereed journals and placed in collaboration archives for public access.

Expected data: Raw and cooked data are stored physically at JLab. Those JLab storage resources are multiply redundant in order to prevent any data loss. As is the case for other groups, the ASU Meson Physics Group makes copies of portions (or, in some cases, the entirety) of the cooked data for a given running period temporarily using hard drives on computer resources local to the group; that temporary storage also is usually on redundant devices. Thus, at any point in the raw and cooked stages, a given set of data may exist on many other sites than JLab, so preservation is robust. There generally is no attempt by a local group to permanently store cooked data on local resources. In case of local hardware failures or human error leading to the loss of data on local resources, those data are re-copied onto local hardware from the original copies at JLab. Once final results are published, those results are placed on archives accessible to the general public (e.g. Refs. [**?**, **?**]).

Data format: The data format for raw and cooked data for the GlueX and CLAS collaborations, called EVIO, was developed by JLab; documentation describing the EVIO format is available in Ref. [**?**].

Access and data sharing: Raw and cooked data are accessible to members of each collaboration. A person or institution desiring access to the raw and cooked data must apply and be accepted for membership within the CLAS or GlueX collaborations. The final data products of the ASU Meson Physics Group, consisting primarily of cross sections and spin observables, are made publicly available through publications, talks, and presentations, as well as in databases such as the SAID database [**?**] and CLAS Archive [**?**].

Policies for re-use and re-distribution: Preliminary results often are presented at open national and international scientific conferences. These preliminary results are internally reviewed within the respective collaboration prior to presentation, with permission obtained to present the preliminary results required by the collaboration prior to the presentation. Such preliminary results are useful in the the initial development of physical interpretations, and comparison with other world data. Reproduction of preliminary results is not permitted without explicit permission of the respective collaborations. Once results have been through the full internal review process within each collaboration, the results are deemed “final”. The data products are submitted to professional journals and made available in public databases such as the SAID database [?] and the CLAS Archive [?].

Archiving of data: As noted above, the raw and cooked data for data runs are archived on tape on-site at JLab. Final results are archived in databases such as the SAID database [?] and the CLAS Archive [?].

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C Publications

Table 6: Summary of Publications

Name	Letter Publications	Other Refereed Journals	Invited Talks
Faculty/Permanent Staff			
M. Dugger	3(3)	9(2)	1
B.G. Ritchie	7(3)	11(1)	
Total	7(3)	11(2)	1

D Principal collaborators

D.1 Close collaborators

Hall B/CLAS/CLAS12: B. Briscoe (George Washington University), V. Burkert (JLab), V. Crede (Florida State University), L. Elouadrhiri (JLab), D. Glazier (University of Glasgow), L. Guo (Florida International University), K. Hicks (Ohio University), F. Klein (George

Washington University), K. Livingston (University of Glasgow), E. Pasyuk (JLab), J. Price (CSU Dominguez Hills), D. Sober (CUA), I. Strakovsky (George Washington University) S. Strauch (University of South Carolina).

Hall D/GlueX: E. Chudakov (JLab), S. Dobbs (Florida State University), P. Eugenio (Florida State University), R. Jones (University of Connecticut), D. Lawrence (JLab), C.A. Meyer (Carnegie Mellon University), M. Shepherd (Indiana University), E. Smith (JLab), J. Stevens (College of William and Mary), S. Taylor (JLab).

D.2 Advisors and postdoctoral sponsors of the investigators

MRD: B.G. Ritchie (ASU); **BGR**: F.T. Avignone, III (University of South Carolina), B.M. Preedom (University of South Carolina), P.G. Roos (University of Maryland).

D.3 Former post-doctoral participants in academic and lab positions

E.A. Pasyuk: Senior Staff Scientist, Jefferson Lab; M.R. Dugger: Associate Professor, ASU.

D.4 Former Ph.D. students in academic and lab positions

M. Dugger: Associate Professor, ASU; D. Lawrence: Staff Scientist, JLab; R. Tucker: Lecturer, ASU.

E Biographical sketches

E.1 Michael R. Dugger

Professional preparation

	Institution	Major/Conc.	Degree, Year
Undergraduate:	Northern Arizona State University	Physics/Mathematics	B.S., 1993
Graduate:	Arizona State University	Physics	Ph.D., 2001
Postdoctoral:	Arizona State University	Physics	2002-2006

Appointments

Associate Professor (tenure-track)	Arizona State University	2017 to present
Associate Research Professor	Arizona State University	2013 to 2017
Assistant Research Professor	Arizona State University	2006-2013
Postdoctoral Research Associate	Arizona State University	2002-2006

Invited talks over the last three years

"Overview of Spectroscopy Results in Meson Photoproduction with Polarization Observables," HADRON, Newport News, VA., Septrmber 14, 2015.

Synergistic activities

GlueX Collaboration Board member, 2013-2015; Division of Nuclear Physics, Conference Experience for Undergraduates, Review Committee member, 2018; International Advisory Committee, MENU 2019 Conference, 2018-Present; CLAS Collaboration, Analysis Coordinator for Ξ and Ω^- photoproduction, 2017-Present.

Publications over the last three years

E.2 Barry G. Ritchie

Professional preparation

	Institution	Major/Conc.	Degree, Year
Undergraduate:	Appalachian State University	Physics	B.S., 1975
Graduate:	University of South Carolina	Physics	M.S., 1977
	University of South Carolina	Physics	Ph.D., 1979
Postdoctoral:	University of South Carolina	Physics	1979-1983
	University of Maryland	Physics	1983-1984

Appointments

Professor	Arizona State University	1996-present
Senior Advisor to the Provost	Arizona State University	2015-2016
Vice Provost for Academic Personnel	Arizona State University	2012-2015
Interim Dean and Vice President	Arizona State University	2006-2007
Chair	Arizona State University	2000-2006
Associate Professor	Arizona State University	1990-1996
Visiting Associate Professor	University of Virginia	1990-1991
Assistant Professor	Arizona State University	1984-1990

Synergistic activities

Technical Advisory Panel Representative, Hall B, CEBAF, 1990-92; Member, Board of Directors, LAMPF Users' Group, Inc., 1992-94; LAMPF Experimental Facilities Panel member, 1990-94; Chair, CLAS Real Photon Physics Working Group and Member, CLAS Coordinating Committee, 1995-99; Member, External Visiting Committee, Physics Department, New Mexico State University, 2001-2005; Referee: Physical Review C, Physical Review Letters, Journal of Physics G; Proposal Reviewer: Department of Energy, National Science Foundation.

Publications over the last three years

F Student tracking information

Table 7: Student tracking information

Student	Date Entered Graduate School	Date Joined Group	Degree Program	Date Degree Awarded / (Expected)	Advisor
Sebastian Cole	August 2015	August 2016	Ph.D.	(May 2020)	B.G. Ritchie

G Current and pending support

The PI and Co-Investigator currently are not supported by any funding agency. Beyond the current proposal, which has not been submitted to any other agency, the PI and Co-Investigator have no other pending support.

H Facilities and resources

H.1 Laboratory facilities

Sufficient lab space for small equipment assembly, fabrication of computer systems, and detector testing has been committed to the ASU Meson Physics Group by ASU within the Department of Physics on the Tempe campus and within the College of Integrated Sciences and Arts (CISA) on the Polytechnic campus. A laboratory space of approximately 500 square feet in size has been committed on both campuses to the group, and contain cluster computers that were built by the group. The lab spaces also include electronic test benches, as well as workstations for those group personal that are on site at either ASU locations. As needed, on-site fabrication and assembly of instrumentation at JLab can also take place in areas provided by JLab for that work.

H.2 Computer facilities

The ASU Meson Physics Group has built cluster computers for data analysis and Monte Carlo simulations. At the Tempe campus, there is a 136 core cluster, while at the Polytechnic location, the core count is currently at 40. The initial reduction and calibration of data taken at JLab is performed on a computer farm provided by that laboratory, and ASU group members are provided full access to those facilities.

H.3 Office space

On the Tempe campus, sufficient office space is available both in the laboratory space provided to the ASU Meson Physics Group, and in two offices adjacent to the laboratory space provided by the Department of Physics. On the Polytechnic campus, sufficient office space is provided for Prof. Dugger, as well. For those members of the group located on-site at JLab, office space has been allocated by JLab sufficient for our group.

H.4 Major instrumentation

Unique and specialized instrumentation are required for performing the research of the ASU Meson Physics Group described in Section 2 of this proposal. Working with collaborators from other institutions, this equipment has been designed and constructed within the experimental halls at Jefferson Lab, specifically Hall B and Hall D. Both halls will provide polarized tagged photon beams, the cryogenic targets, and the associated detector systems which will enable the experiments described.

H.5 Other resources

The ASU College of Liberal Arts and Sciences Mechanical Instrument Shop (MIS) is one of the most capable university machine shops in the nation, designing and building items as simple as special purpose housings (as in the case of the original ASU-designed CLAS tagger electronics) to equipment as complex as spacecraft instruments (as in the case of devices on several Mars missions, including components of the Mars landers). MIS was responsible for the pair spectrometer vacuum box for PrimEx, assisted in fabrication of the instrumentation for the triplet polarimeter, and will be available for small projects related to this proposal, as needed. In addition to the MIS, there is a machine shop available for faculty and student use, and this shop was utilized in construction the triplet polarimeter. The Electronics Instrument Shop provides support for small-scale design and fabrication projects. In the past, this has included, for example, much of the original Hall B CLAS photon tagger focal plane electronics.