BARYON SPECTROSCOPY
THROUGH PARTIAL-WAVE ANALYSIS AND MESON PHOTOPRODUCTION

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by

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Abstract

The principal goal of this project is the experimental and phenomenological study of baryon spectroscopy.

The PI's group currently consists of himself and three graduate students, ChandraSekhar (Chandra) Akondi, Brian Hunt, and Haoran Sun. Chandra is analyzing liquid deuterium data measured at MAMI-C in Mainz, Germany with the goal of measuring the cross sections for $\gamma n \to K^0\Lambda$, $\gamma n \to K^0\Sigma^0$, and $\gamma p \to K^0\Sigma^+$. Brian's dissertation project is to make a partial-wave analysis of all available data for $\gamma p \to \eta p$, $\gamma n \to \eta n$, and $\gamma p \to K^+\Lambda$. Chandra and Brian both presented contributed talks on their research at the Spring meeting of the Ohio-Region Section of the American Physical Society (OSAPS), which was held at Kent State University on March 27 and 28, 2015. On April 7, 2016, Brian gave a CNR Seminar at Kent State, on April 16, 2016, he gave a contributed talk on his research at the APS April meeting in Salt Lake City, UT, and on May 18, 2016, he gave a contributed talk on his research at Baryons 2016, the 14th International Conference on the Structure of Baryons, held in Tallahassee, FL. The PI helped him prepare his presentations for all of these talks. The PI's newest student, Haoran Sun, joined his group in August 2016. His dissertation project will be a coupled-channel partial-wave analysis of the reactions $K^-p \to K^-p$, $K^-p \to \overline{K^0}n$, $K^+p \to K^+p$, $K^0_Lp \to K^0_Sp$, and possibly also $K^+n \to K^0p$.

During the period March 1, 2015 through August 14, 2016, the PI co-authored 11 published journal papers and one proceedings article. The PI also co-authored and edited the professional obituary for Dr. Gerhard Höhler, which was published in the July-August 2015 issue of the CERN Courier. The PI also contributed to a Letter of Intent on "Physics Opportunities with Secondary K^0_L Beam at JLab", which was submitted to Jefferson Lab PAC-43 in May 2015.

The PI gave an invited talk on $\gamma p \to \eta p$ and $\gamma p \to K^+\Lambda$ at PWA8/ATHOS3, the International Workshop on Partial Wave Analysis for Hadron Spectroscopy held in Ashburn, VA during April 13-17, 2015. He also served as a Convenor and Session Chair for this meeting. During September 7-12, 2015, the PI traveled to Mainz, Germany to attend a meeting of the A2 Collaboration, where he gave an invited talk on "Partial-Wave Analysis of η and $K^+\Lambda$ Photoproduction." On February 1, 2016, the PI gave an invited talk on "K^0_Lp Scattering to 2-Body Final States" at KL2016, a Workshop on Physics with Neutral Kaon Beam, held at Newport News, VA. He also served as a Session Chair for this meeting.

During December 12-19, 2016, the PI traveled to Mainz, Germany to take five shifts to test a new transverse active polarized target.

1 Introduction

In the sections below, we summarize recent work done by the PI and his current Ph.D. students. Our general interest is the investigation of the baryon resonance spectrum up to masses of $\sim$2 GeV.

2 Neutral Kaon Photoproduction

Photoproduction of neutral kaons off nucleons is a fundamental process and an important tool for gaining insight into nucleon resonances. There are only three elementary neutral kaon photoproduction reactions:

$$\begin{array}{ll} (1) & \gamma + p \to K^0 + \Sigma^+, \\ (2) & \gamma + n \to K^0 + \Lambda, \\ (3) & \gamma + n \to K^0 + \Sigma^0. \end{array}$$

There have been limited measurements for reaction (1) using both liquid hydrogen and liquid deuterium targets, however, until very recently, there were no experimental measurements for the reactions involving a neutron target. The first published work for $\gamma n \to K^0\Lambda$ on a liquid deuterium target was by K. Tsukada *et al.* [1]. The measurements were performed at the Laboratory for Nuclear Science (LNS) in Sendai, Japan using incident photons up to 1.1 GeV. Final-state neutral kaons were identified by detecting the positive and negative pions emitted in the decays of $K^0_S \to \pi^+\pi^-$. These measurements were insufficient to extract differential or integrated cross sections, but the measured inclusive momentum distributions were useful in constraining some of the free parameters in the isobar models with which the data were compared.

In December 2007 we had about two weeks of measurements with a 5-cm liquid deuterium target at MAMI-C in Mainz, Germany. Final-state photons were detected using an electromagnetic calorimeter composed of the Crystal Ball (CB) and TAPS detectors. The 672 NaI crystals of the CB covered the full azimuthal angle for polar angles between $20°$ and $160°$ around the target, which was mounted in the center of the CB. TAPS covered polar angles between $1°$ and $20°$ as a hexagonal wall of 510 $\mathrm{BaF_2}$ crystals, mounted 1.75 m downstream from the target. The event trigger was based on a subdivision of the CB and TAPS detectors into logical sectors. The trigger required signals in two or more logical sectors of the calorimeter above a threshold of 20 MeV and an analog energy sum of the CB modules above 50 MeV. Once a valid trigger had been generated, thresholds for the readout of individual modules were 5 MeV in TAPS and 2 MeV in the CB.

The invariant-mass spectrum of photon pairs can be used to identify neutral pions or η-mesons (from the $\pi^0 \to \gamma\gamma$ or $\eta \to \gamma\gamma$ decays). In addition, η-mesons can also be identified from the invariant-mass spectrum of six photons from the $\eta \to 3\pi^0 \to 6\gamma$ decays. Similarly, neutral kaons may be identified from the invariant-mass spectrum of four photons from the $K^0 \to \pi^0\pi^0 \to 4\gamma$ decays. Photons in the CB and TAPS detectors are identified through the deposition of energy in neutral "clusters" of adjacent crystals in either the CB or TAPS detectors.

In Summer 2011, Mr. ChandraSekhar Akondi joined the PI's group and began learning the necessary skills to analyze CB data. He first had to learn C++ programming. Then he traveled to Mainz, Germany in September 2011 where he stayed until the end of the year. While there, he met with various local experts to learn about various aspects of data analysis and he also participated in ongoing measurements of meson photoproduction with the CB and TAPS setup. He returned to Kent State at the beginning of the Spring 2012 semester and began analyzing the LD_2 data for the $\gamma n \to K^0\Sigma^0$ reaction. His analysis was later extended to include the $\gamma n \to K^0\Lambda$ and $\gamma p \to K^0\Sigma^+$ reactions. All three reactions require the identification of three neutral pions in the final state (two from $K^0 \to \pi^0\pi^0$ plus one from either $\Lambda \to \pi^0 n$, $\Sigma^+ \to \pi^0 p$, or $\Sigma^0 \to \gamma\Lambda \to \gamma\pi^0 n$). To identify $\gamma n \to K^0\Lambda$ and $\gamma p \to K^0\Sigma^+$, we must then detect six neutral clusters (corresponding to photons from three $\pi^0 \to 2\gamma$ decays) if the final-state nucleon goes undetected. If the final-state nucleon is detected, we must detect seven clusters. The final-state nucleon most commonly goes forward and, if detected, would most likely be seen as a cluster in TAPS. In the case of $\gamma n \to K^0\Sigma^0$, we must detect seven neutral clusters (six from π^0 decays plus an unpaired photon from $\Sigma^0 \to \gamma\Lambda$ decays) if the final-state neutron goes undetected. We must detect eight neutral clusters if the final-state neutron is detected. This cluster would most commonly appear in TAPS. It is possible to distinguish nucleons from photons in TAPS using pulse-shape analysis [2]. This method, however, is only applicable to experimental data because the two scintillation light components of BaF_2 were not simulated in the Monte Carlo analysis.

We are also using signals from the cylindrical Particle Identification Detector (PID), which surrounds the target. The PID can be used to identify charged particles (e.g., protons) via dE/dx information. For a cluster in the CB to be identified as a photon or neutron candidate, it must produce no PID signal. In addition, the missing mass of all the other clusters (which are photon candidates) must be consistent with a nucleon. We required the missing mass of the other clusters to be between 900 and 1200 MeV in order to accept a cluster as a nucleon candidate.

Monte Carlo (MC) simulations have been used extensively to refine our analysis methods. Numerous algorithms were investigated to optimize our techniques without introducing bias into our K^0 identification method. Identification of the three final-state pions is a formidable task because of the large combinatoric background. For example, if we consider the simplest case of $\gamma n \to K^0\Lambda$ and $\gamma p \to K^0\Sigma^+$, when the final-state nucleon goes undetected, we must detect six photons from decays of three neutral pions. For events in which six neutral clusters are detected, there are 15 ways to combine the clusters into distinct two-cluster combinations (corresponding to π^0 candidates). For events in which seven neutral clusters are detected, there are 105 ways to combine the clusters into distinct two-cluster combinations.

The best method that we have found involves forming all possible combinations of three π^0 candidates for each event. In order to be a valid π^0 candidate, we require the invariant mass $m_{\gamma\gamma}$ of two neutral clusters to be in the range 100 to 150 MeV. We first accept events with a unique set of three π^0 candidates. For events in which there is more than one set of three π^0 candidates, we choose the combination that has the smallest average opening angle $\theta_{\gamma\gamma}$ for $\pi^0 \to 2\gamma$ decays. This criterion is based on the fact that it is much more likely for the opening angle to be smaller than 90° than greater. Once we have identified all π^0 candidates for each event, we then applied the correction

$$E' = E \cdot \frac{m_{\pi^0}}{m_{\gamma\gamma}}$$

to the reconstructed energy E, where $m_{\gamma\gamma}$ is the invariant mass of the decay photons, thus obtaining the energy E' that has a better resolution. We then used the scaled four-momenta of the clusters to calculate the invariant mass $m_{2\pi^0}$ corresponding to each distinct pair of two π^0 candidates. Neutral kaons should appear as a peak near 498 MeV (the K^0 mass) in the histogram of the $m_{2\pi^0}$ distribution.

We identified π^0 candidates by their decays $\pi^0 \to 2\gamma$, we identified K^0 candidates by their decays $K^0 \to 2\pi^0 \to 4\gamma$, we identified Λ candidates by their decays $\Lambda \to \pi^0 n \to 2\gamma n$, we identified Σ^+ candidates by their decays $\Sigma^+ \to \pi^0 p \to 2\gamma n$, and we identified Σ^0 candidates by their decays $\Sigma^0 \to \gamma\Lambda \to \gamma\pi^0 n \to 3\gamma n$. The first step in our analysis is then to select events with six or seven photon candidates from crystals in both the Crystal Ball and TAPS detectors:

$$\begin{aligned} \gamma + n &\to K^0 + \Lambda \to 3\pi^0 + n \to 6\gamma + n \, , \\ \gamma + p &\to K^0 + \Sigma^+ \to 3\pi^0 + p \to 6\gamma + p \, , \\ \gamma + n &\to K^0 + \Sigma^0 \to \gamma + 3\pi^0 + n \to 7\gamma + n \, . \end{aligned}$$

The next step is to identify all possible distinct three π^0 combinations by requiring the $m_{\gamma\gamma}$ to be between 100 and 150 MeV, where $m_{\gamma\gamma}$ is the invariant mass of two neutral clusters identified as photon candidates. We include events having a unique set of three π^0 candidates for further analysis but, for non-unique combinations, we select the combination having the smallest opening angle for $\pi^0 \to 2\gamma$ for further analysis.

For real data, there is a sizeable background from η photoproduction in which the η meson decays into three π^0s. This background can be almost completely eliminated by requiring that $IM_{6\gamma}$ *not* be between 500 and 600 MeV, where $IM_{6\gamma}$ is the invariant mass of the six photon clusters associated with the three π^0 candidates.

We also investigated the angular dependence of the unpaired cluster. For $\gamma n \to K^0\Lambda$ events, the unpaired cluster should be a detected neutron, which is expected to go forward and will possibly be detected in the TAPS detector. Our work with MC simulations suggested that most of the background to $\gamma n \to K^0\Sigma^0$ from $\gamma p \to K^0\Sigma^+$ and $\gamma p \to K^0\Lambda$ events can be eliminated by using a combination of the PID to veto events with a final-state proton (coming from $\Sigma^0 \to \pi^0 p$ decays) and a forward-angle cut on the polar angle of the unpaired cluster (which should be a proton for $\gamma p \to K^0\Sigma^+$ decays and a neutron for $\gamma p \to K^0\Lambda$ decays).

In the past year, we finalized our fitting algorithm and developed a method to carry out simultaneous constrained fits of the missing-mass and invariant-mass distributions, which is needed to determine the number of neutral kaons and associated hyperons produced in each energy/angle bin. Figure 1 shows Monte Carlo simulations for $\gamma n \to K^0\Lambda$ events. The left panel shows $IM_{4\gamma}$, the invariant mass of four photons associated with all three combinations of two π^0 candidates. A peak corresponding to K^0 mesons is clearly visible at 498 MeV. The right panel shows $MM_{4\gamma}$, the missing mass of four photons associated with all three combinations of two π^0 candidates. A peak corresponding to Λ hyperons is clearly visible at 1116 MeV. The curves shows the result of a simultaneous fit in which the signal events are represented by Gaussian distributions centered at fixed masses with appropriate kinematic thresholds.

This work is the Ph.D. project of Mr. ChandraSekhar Akondi, who is expected to complete his dissertation research by August 2017. Chandra attended the 2015 Reaction Theory Summer School held at Indiana University, Bloomington, IN, USA, June 8-19, 2015.

3 Partial-Wave Analyses of $\gamma p \to \eta p$, $\gamma n \to \eta n$, and $\gamma p \to K^+\Lambda$

We have initiated multipole analyses of $\gamma p \to \eta p$, $\gamma n \to \eta n$, and $\gamma p \to K^+\Lambda$. All three reactions have pure isospin $I = 1/2$ and the η production reactions are dominated near threshold

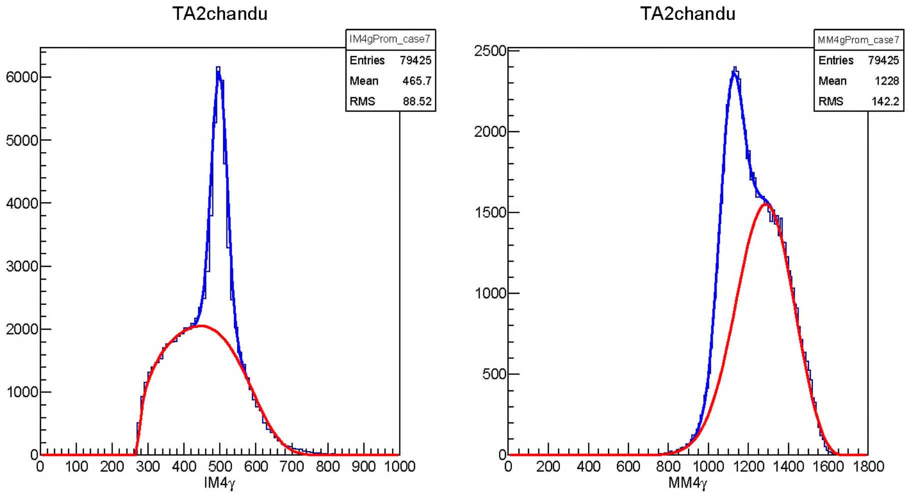

Figure 1: Monte Carlo simulations for $\gamma n \to K^0\Lambda$ events. *Left:* The invariant mass of all three combinations of four photons (IM$_{4\gamma}$) corresponding to two π^0 candidates. A peak can be seen at the K^0 mass (498 MeV). *Right:* The missing mass of four photons (IM$_{4\gamma}$). A peak can be seen at the Λ mass (1116 MeV). The curves were obtained by simultaneously fitting the two distributions with the constraint that the signal contributions in the two distributions must have the same number of events.

by the $S_{11}(1535)$ resonance.

Some of the measurements included in our database for $\gamma p \to \eta p$ are differential cross-section ($d\sigma/d\Omega$) measurements from MAMI [3–5], GRAAL [6], LNS [7], ELSA [8], and JLab [9, 10], beam asymmetry (Σ) measurements from GRAAL [6, 11] and ELSA [12], transverse target asymmetry (T) measurements from MAMI [13] and ELSA [14], and beam-target asymmetry (F) measurements from MAMI [13]. We also include preliminary results for the double-polarization observable E from JLab [15], some older measurements of the proton recoil polarization (P) [16] and some as yet unpublished C_x data [17]. C_x is a double polarization observable in which the polarization transferred from a circularly polarized photon beam to the recoiling proton is measured.

The measurements included in our database for $\gamma p \to K^+\Lambda$ are differential cross-section ($d\sigma/d\Omega$) measurements from JLab [18–20], SPring-8 [21,22], ELSA [23–25], DESY [26], and the Tokyo INS [27], beam asymmetry (Σ) measurements from SPring-8 [21, 22] and GRAAL [28], hyperon recoil polarization (P) measurements from JLab [18, 20], GRAAL [28], ELSA [23–25], the Tokyo INS [27], and Frascati [29], beam-recoil observables O_x, O_z, and target asymmetry T from GRAAL [30], and beam-recoil observables C_x and C_z measurements from JLab [31].

To minimize model bias, we first carried out binned single-energy partial-wave analyses. We currently have the capability to include various constraints, such as fitting an amplitude with either the real or imaginary part held fixed, or with the phase held fixed. We have obtained single-energy solutions for $\gamma p \to \eta p$ from threshold to c.m. energies of $W = 1927.5$ MeV (central bin energy). The highest partial wave included is F_{15}. For $\gamma p \to K^+\Lambda$, we have obtained solutions up to $W = 2250$ MeV (central bin energy) with G_{17} and G_{19} partial waves included above 2000 MeV.

Once we obtained initial single-energy solutions for the partial waves, we used them as input into multichannel energy-dependent fits . The single-energy amplitudes are fitted using a unitary parametrization of the partial-wave S-matrix developed by the PI (commonly referred to as the “KSU model”). Our current energy-dependent fits include partial-wave amplitudes for $\gamma N \to \pi N$, $\pi N \to \pi N$, $\pi N \to \eta N$, $\pi N \to K\Lambda$, and the quasi-two-body $\pi N \to \pi\pi N$ channels [32].

We first used preliminary single-energy fits to determine the modulus of the S_{11} (or E_{0+}) multipole, which was then incorporated into our multichannel energy-dependent fits. For our single-energy fits, we determined multipoles in units of mfm following the usual expansions for observables. However, for our energy-dependent fits, we converted these multipoles into dimensionless amplitudes (with a bar over E or M) using the relationships:

$$\begin{aligned}
|\overline{E}_{\ell+}|^2 &= qk(\ell+1)(\ell+2)|E_{\ell+}|^2, \\
|\overline{M}_{\ell+}|^2 &= qk\ell(\ell+1)|M_{\ell+}|^2, \\
|\overline{E}_{(\ell+1)-}|^2 &= qk\ell(\ell+1)|E_{(\ell+1)_-}|^2, \\
|\overline{M}_{(\ell+1)-}|^2 &= qk(\ell+1)(\ell+2)|M_{(\ell+1)_-}|^2,
\end{aligned}$$

where k is the initial c.m. momentum of the incident photon and proton and q is the final c.m. momentum of the outgoing η and proton. With this choice, the integrated cross section for $\gamma p \to \eta p$ and $\gamma p \to K^+\Lambda$ takes the simple form:

$$\sigma = \frac{2\pi}{k^2}\sum_{\ell=0}^{\infty}(\ell+1)[|\overline{E}_{\ell+}|^2 + |\overline{M}_{\ell+}|^2 + |\overline{E}_{(\ell+1)-}|^2 + |\overline{M}_{(\ell+1)-}|^2].$$

It is well known that partial-wave analyses are fraught with ambiguities. Only by directly fitting experimental data (i.e., cross sections and spin observables) can we hope to obtain multipole amplitudes that reliably describe the experimental data for these channels. This fact became very clear a few years ago when the first precise data for $\gamma p \to \eta p$ were published, which resulted in a large helicity-1/2 amplitude for the $S_{11}(1535)$ resonance that was inconsistent with prior analyses based only on information from the $\pi N \to \pi N$ and $\gamma N \to \pi N$ reactions [33]. In particular, a 1996 analysis [34] of $\gamma N \to \pi N$ gave $A_{1/2} = 0.060 \pm 0.015$ GeV$^{-1/2}$ whereas a simple analysis of $\gamma p \to \eta p$ the following year by Krusche *et al.* [33] found $A_{1/2} = 0.120 \pm 0.011 \pm 0.015$ GeV$^{-1/2}$. More recently, the BnGa Collaboration found $A_{1/2} = 0.105 \pm 0.010$ GeV$^{-1/2}$ [35]. In our recent multichannel fit of the S_{11} partial waves, we found $A_{1/2} = 0.093 \pm 0.002$ GeV$^{-1/2}$, which disagrees with the values obtained by Arndt *et al.* and Krusche *et al.* but agrees with the value obtained by the BnGa Collaboration.

Based on our early success fitting the S_{11} amplitude, we did several rounds of single-energy fits holding the dominant S_{11} multipole fixed at the values determined from our energy-dependent fit.

Another important issue that we investigated and confirmed is the claim [5, 36, 37] that a small contribution from D_{13} is necessary to describe the $d\sigma/d\Omega$ and Σ data for $\gamma p \to \eta p$. This claim stems from low-energy expansions based on the assumption that dominance of the $S_{11}(1535)$ allows one to keep only terms proportional to the E_{0+} multipole. We have carefully rechecked the expansion to keep all S, P, and D-waves with terms proportional to the E_{0+} multipole. The resulting differential cross section has the form

$$\frac{d\sigma}{d\Omega} = \frac{q}{k}[a + b\cos(\theta^*) + c\cos^2(\theta^*)] \ ,$$

where q is the η center-of-mass (c.m.) momentum, k is the incident photon c.m. momentum, and θ^* is the c.m. polar angle of the η mesons. We find

$$\begin{aligned} a &= E_{0+}^2 - \mathrm{Re}[E_{0+}^*(E_{2-} - 3M_{2-} + 6E_{2+} + 3M_{2+})] \ , \\ b &= 2\mathrm{Re}[E_{0+}(3E_{1+} + M_{1+} - M_{1-})] \ , \\ c &= 3\mathrm{Re}[E_{0+}(E_{2-} - 3M_{2-} + 6E_{2+} + 3M_{2+})] \ . \end{aligned}$$

Previous papers [5,36,37] did not include the contributions from E_{2+} and M_{2+}, which are associated with the D_{15} partial wave. Because the $D_{15}(1675)$ resonance is a “stretched state” in which the constituent quarks couple their intrinsic spin ($S = 3/2$) and orbital angular momentum ($L = 1$) maximally, the M_{2+} multipole amplitude should be much larger than the E_{2+} amplitude. (A similar situation holds for the $P_{33}(1232)$ and the $F_{37}(1950)$ resonances.) We found [32] that the D_{13} partial wave couples very weakly to ηN (but strongly to γp), whereas the D_{15} partial wave couples fairly strongly to ηN (but less strongly to γp) even at energies as low as $W = 1550$ MeV. Our present analysis finds very little evidence for the $D_{15}(1675)$ in either $\gamma p \to \eta p$ or $\gamma p \to K^+\Lambda$. Our observations are consistent with what is expected from the Moorhouse selection rule [38], which predicts that the $S_{11}(1650)$, the $D_{13}(1700)$, and the $D_{15}(1675)$ should decouple from γp to first order.

As mentioned above, after obtaining single-energy solutions for the multipole amplitudes, we included them in our multichannel energy-dependent fits. This procedure allows us to obtain energy-dependent solutions that are consistent with two-body unitarity. In addition, the energy-dependent solutions allow us to extract resonance parameters determined consistently to describe several hadronic reactions in addition to the meson photoproduction reactions.

In 2007, a narrow structure at $W \approx 1680$ MeV was reported in GRAAL measurements for quasi-free η photoproduction on neutrons bound in a deuterium target [39]. A narrow structure at this energy was also observed in inclusive measurements, $d(\gamma, \eta)pn$, performed at the LNS (now ELPH) at Tohoku University [40], and in quasi-free measurements of η photoproduction on the neutron at Bonn [41,42] and at MAMI [43,44]. This peak is not observed in $\gamma p \to \eta p$, and a good deal of speculation and controversy has arisen concerning its interpretation. We are finding that the narrow structure at $W \approx 1680$ MeV likely has contributions from more than one partial wave. One resonance that seems to contribute is the $D_{15}(1675)$ resonance, which decouples from γp due to the Moorhouse selection rule [38]. However, there is no rule to suppress its coupling to γn, so it appears in the cross section for that reaction. The $P_{11}(1710)$ resonance also likely plays a role. This state is only seen weakly in πN elastic scattering because it is rather inelastic (i.e., it has a small branching ratio to πN). In our fits, this state is rather narrow for an N^* resonance, but that is not surprising when one thinks about it. For a state to be wide, it must have a strong coupling to one or more hadronic channels. In the case of the $P_{11}(1710)$, it does not seem to couple strongly to πN or $\pi\pi N$ channels, which leads to a relatively narrow resonance. The same thing is expected for the $D_{13}(1700)$, which is often not observed in πN elastic scattering analyses.

In summary, we are currently comparing the results of our energy-dependent solutions with observables for both $\gamma p \to \eta p$ and $\pi^- p \to \eta n$ and with observables for both $\gamma p \to K^+\Lambda$ and $\pi^- p \to K^0\Lambda$. Our analysis so far indicates that the $S_{11}(1535)$ plays a very important role in $\pi^- p \to \eta n$, the $S_{11}(1650)$ plays an important role in $\pi^- p \to K^0\Lambda$, and the P_{13} partial wave plays an important role in $\gamma p \to K^+\Lambda$ and $\pi^- p \to K^0\Lambda$. It will be of interest to compare our results with those being done by the BnGa Collaboration, who recently published results of an energy-independent PWA of $\gamma p \to K^+\Lambda$ [45]. Our plan is to continue to iterate between the single-energy and energy-dependent fits until we obtain a successful energy-dependent solution for all the important multipoles. The partial-wave analyses of the world data for $\gamma p \rightarrow \eta p$, $\gamma n \rightarrow \eta n$, and $\gamma p \rightarrow K^+\Lambda$ is the dissertation project of Brian Hunt. Brian has already written drafts of the first two chapters of his dissertation.

4 Publications and Presentations During Project Period

This sections lists all research-related work that has either been published or presented during the period March 1, 2015 through August 14, 2016.

4.1 Papers in Refereed Journals

1. *Measurements of Double-Polarized Compton Scattering Asymmetries and Extraction of the Proton Spin Polarizabilities*, A2 Collaboration: P.P. Martel, R. Miskimen, P. Aguar-Bartolome, J. Ahrens, C.S. Akondi, J.R.M. Annand, H.J. Arends, W. Barnes, R. Beck, A. Bernstein N. Borisov, A. Braghieri, W.J. Briscoe, S. Cherepnya, C. Collicott, S. Costanza, A. Denig, M. Dieterle, E.J. Downie, L.V. Fil'kov, S. Garni, D.I. Glazier, W. Gradl, G. Gurevich, P. Hall Barrientos, D. Hamilton, D. Hornidge, D. Howdle, G.M. Huber, T.C. Jude, A. Kaeser, V.L. Kashevarov, I. Keshelashvili, R. Kondratiev, M. Korolija, B. Krusche, A. Lazarev, V. Lisin, K. Livingston, I.J.D. MacGregor, J. Mancell, D.M. Manley, W. Meyer, D.G. Middleton, A. Mushkarenkov, B.M.K. Nefkens, A. Neganov, A. Nikolaev, M. Oberle, H. Ortega Spina, M. Ostrick, P. Ott, P.B. Otte, B. Oussena, P. Pedroni, A. Polonski, V. Polyansky, S. Prakhov, A. Rajabi, G. Reicherz, T. Rostomyan, A. Sarty, S. Schrauf, S. Schumann, M.H. Sikora, A. Starostin, O. Steffen, I.I. Strakovsky, T. Strub, I. Supek, M. Thiel, L. Tiator, A. Thomas, M. Unverzagt, Y. Usov, D.P. Watts, L. Witthauer, D. Werthmüller, and M. Wolfes, Phys. Rev. Lett. **114**, 112501 [5 pages]; DOI: 10.1103/PhysRevLett.114.112501 (19 March 2015).
2. *A new measurement of the neutron detection efficiency for the NaI Crystal Ball detector*, A2 Collaboration: M. Martemianov , V. Kulikov, B.T. Demissie, Z. Marinides, C.S. Akondi, J.R.M. Annand, H.J. Arends, R. Beck, N. Borisov, A. Braghieri, W.J. Briscoe, S. Cherepnya, C. Collicott, S. Costanza, E.J. Downie, M. Dieterle, M.I. Ferretti Bondy, L.V. Fil'kov, S. Garni, D.I. Glazier, D. Glowa, W. Gradl, G. Gurevich, D. Hornidge, G.M. Huber, A. Kaeser, V.L. Kashevarov, I. Keshelashvili, R. Kondratiev, M. Korolija, B. Krusche, A. Lazarev, J.M. Linturi, V. Lisin, K. Livingston, I.J.D. MacGregor, D.M. Manley, P.P. Martel, D.G. Middleton, R. Miskimen, A. Mushkarenkov, A. Neganov, A. Neiser, M. Oberle, M. Ostrick, P. Ott, P.B. Otte, B. Oussena, P. Pedroni, A. Polonski, S. Prakhov, G. Ron, T. Rostomyan, A. Sarty, D.M. Schott, S. Schumann, V. Sokhoyan, O. Steffen, I.I. Strakovsky, Th. Strub, I. Supek, M. Thiel, A. Thomas, M. Unverzagt, Yu. A. Usov, S. Wagner, D.P. Watts, J. Wettig, D. Werthmüller, L. Witthauer, and M. Wolfes, JINST **10**, T04001 [11 pages]; DOI: 10.1088/1748-0221/10/04/T04001 (7 April 2015).
3. *Photoproduction of the ω meson off the proton near threshold*, A2 Collaboration at MAMI: I.I. Strakovsky, S. Prakhov, Ya. I. Azimov, P. Aguar-Bartolomé, J.R.M. Annand, H.J. Arends, K. Bantawa, R. Beck , V. Bekrenev, H. Berghäuser, A. Braghieri, W.J. Briscoe, J. Brudvik, S. Cherepnya, R.F.B. Codling, C. Collicott, S. Costanza, B.T. Demissie, E.J. Downie, P. Drexler, L.V. Fil'kov, D.I. Glazier, R. Gregor, D.J. Hamilton,

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4.2 Papers in Conference Proceedings

1. *K^0_L Scattering to Two-Body Final States*, D. M. Manley, in *Workshop on Physics with Neutral Kaon Beam at JLab (KL2016) Mini-Proceedings* (Newport News, VA, February 1-3, 2016), arXiv:1604.02141v1 [hep-ph] 42-48 (2016).

4.3 Invited Talks and Seminars

1. *Partial-wave analysis of $\gamma p \to \eta p$ and $\gamma p \to K^+\Lambda$*, PWA8/ATHOS3: The International Workshop on Partial-Wave Analysis, Virginia Campus, The George Washington University, Ashburn, Virginia (April 13, 2015).
2. *Partial-Wave Analysis of η and $K^+\Lambda$ Photoproduction*, A2 Collaboration Meeting, Johannes Gutenberg University, Mainz, Germany (September 9, 2015).
3. *$K^0_L p$ Scattering to 2-Body Final States*, KL2016: Workshop on Physics with Neutral Kaon Beam at JLab, Newport News, VA (February 1, 2016).

5 Project Personnel

The PI's group currently consists of himself and three graduate students, ChandraSekhar Akondi (from India), Brian Hunt (from the United States), and Haoran Sun (from China).

ChandraSekhar Akondi entered the graduate program at Kent State University in Fall 2009 and began working with the PI in Summer 2011. His dissertation project is an analysis of K^0 photoproduction data from MAMI-C. Brian Hunt entered the graduate program at Kent State University in Fall 2011 and began working with the PI in Summer 2012. His dissertation project is a partial-wave analysis of all world data for $\gamma p \to \eta p$, $\gamma n \to \eta n$, and $\gamma p \to K^0\Lambda$. Further details are given in Table 1. Haoran Sun entered the graduate program at Kent State University in Fall 2012 and began working with the PI in August 2016. His dissertation project is a coupled-channel partial-wave analysis of all world data for $K^-p \to K^-p$, $K^-p \to \overline{K^0}n$, $K^+p \to K^+p$, $K^0_L p \to K^0_S p$, and possibly also $K^+n \to K^0 p$ measured on a deuterium target. Further details are given in Table 1.

Name	Gender	Entered Program	Joined Group	Advisor	Expected Grad. Date
C. Akondi	M	Aug 2009	Aug 2011	Manley	Aug 2017
B. Hunt	M	Aug 2011	Apr 2013	Manley	Aug 2017
H. Sun	M	Aug 2012	Aug 2016	Manley	Aug 2019

Table 1: Student Tracking Information.

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