The Differential Cross Section and Λ Recoil Polarization from $\gamma d \rightarrow K^0 \Lambda(p)$

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This dissertation titled
The Differential Cross Section and Λ Recoil Polarization from $\gamma d \rightarrow K^0 \Lambda(p)$

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ABSTRACT

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The Differential Cross Section and Λ Recoil Polarization from $\gamma d \rightarrow K^0 \Lambda(p)$ (181 pp.)

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Presented is the analysis of the differential cross section and Λ recoil polarization from the reaction $\gamma d \rightarrow K^0 \Lambda(p)$. This work measured these observables over beam energies from 0.90 GeV to 3.0 GeV. These measurements are the first in this channel to cover such a wide range of energies. The data were taken using the CEBAF Large Acceptance Spectrometer (CLAS) at Jefferson Laboratory (JLAB) along with a tagged photon beam. This analysis was completed by identifying events of interest that decayed into the final state topology of $\pi^- \pi^+ \pi^- p(p)$. Through conservation of energy and momentum, the K^0 , Λ , and missing mass of the spectator proton were reconstructed. Utilizing the same analysis techniques, the observables were measured on two different experiments with good agreement.

Photoproduction of strange mesons from the neutron are difficult to measure, consequently there are only a few measurements of this kind. Despite that, these reactions supply essential complementary data to those on the proton. The differential cross sections and the recoil polarization extracted, span the region where new nucleon resonances have been found from studies of the reaction $\gamma p \rightarrow K^+ \Lambda$. Comparisons between the $K^+ \Lambda$ and $K^0 \Lambda$ cross section demonstrate that possible interference terms near 1900 MeV are less pronounced in the latter. This unexpected result inspired a partial wave analyses (PWA) to be fitted to the data. The fit solution shows that this measurement fostered an improvement on the knowledge of observed resonance parameters, necessary to understanding these excited states. The study of nucleon resonances is a key motivating factor since the resonance masses can be calculated from the theory of the strong nuclear force, called quantum chromodynamics, or QCD.

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1 INTRODUCTION

It is well established that the nucleus can be described in terms of protons and neutrons, or more generically nucleons. At one time, it was thought that these nucleons were the fundamental building blocks of nuclei that interacted via photons (electromagnetism) and pions (strong force). It is now known that the fundamental building blocks of most visible matter are quarks, which interact via gluons. Many experiments show that these quarks and their properties relative to each other create a rich structure inside matter. To learn more about this structure, investigations were carried out in the same manner as they were for that of the atom. That is to say, properties of the valence particles were explored. The atom contains valence electrons which contribute spin and energy, whereas nucleons are typically described by three constituent quarks.

The electrons in an atom have very specific properties available to it depending on neighboring electron attributes and the nucleus itself. Confirming that one of these properties was the orbital level, which depends on its spin and angular momentum, required an enormous amount of effort. Moreover, the exploration of the atom and electron orbitals are heavily reliant on its spectroscopy. This spectroscopy, or measurement of electron energy levels, made the modeling of a simple atom possible. Similarly, the spectroscopy of the nucleon can be used to identify how the valence quarks behave relative to each other (Figure 1.1).

Atomic spectroscopy often consists of the excitation of an electron within the atom (absorption), followed by any number of possible de-excitation paths (emission). These energetic states only exist at discrete energy levels above the ground state. The energies of these levels depend on the potential well provided by the nucleus. The transition from one state to another only requires the absorption or emission of a photon, which is used to determine the initial and final states of the transition. From these studies, the presence of specific spectral lines can determine the element composition of material given an external

Figure 1.1: Shown is the spectroscopy of excitation states: (a) When electrons in an atom de-excite, they emit a photon with a discrete energy. (b) Resonances differ by having a natural decay width (wide and overlapping) as well as decay into many final states (πN , ρN , KY , ...).

energy source. Utilizing this knowledge, one can then infer information about the orbital structure within an atom; in turn this determines the attributes and transitions of the atomic electrons. These data were key to understanding the inner workings of the atom including the quantum numbers, like spin. This is thought to be the case for spectroscopy of the nucleon as well.

By adding energy to a nucleon, the valence quarks are able to arrange themselves in such a way that they form an unbound excited state, called a resonance. As with the atomic case, this energetic state is likely to transition into a lower energy configuration. This configuration is usually obtained through the emission of a quark-antiquark pair rather than a photon. In order to study this spectroscopy, one must look at the ground state baryon (qqq) along with the emitted meson ($q\bar{q}$). There are two complications with this analogy. The first is that there are multiple ground state baryons as well as emitted mesons. This means that possible resonance lines may show up in some spectral channels, but not others depending on the coupling or branching ratio of that resonance. The second complication, comes from

the fact that unlike atomic spectroscopy where the spectral lines are discrete, resonances are described by probabilistic wave mechanics. This means that these “resonant spectral lines” (represented over a number of events) form a broad peak rather than a discrete energy that is constant for all events. Nonetheless, this spectroscopy is a powerful tool to determine the existence and properties of these energetic states.

Spectroscopy provides information about how the nucleon is formed from quarks and gluons. The theory developed based on this insight is called Quantum Chromodynamics (QCD). Any strong interaction between quarks and gluons is governed by the equations of QCD. In other words, QCD encapsulates the current understanding of how these strong interactions work. It has had much success as a predictive tool at high energy regimes, where approximations and perturbative methods can be used (as in charmonium level diagrams [Gri12]). Despite those successes, direct calculations to describe a nucleon, or other low energy regimes are still out of the reach using approximate methods. This is mainly due to the non-linearity of the problem. Therefore, the spectrum of the nucleon can not be calculated analytically, and must be explored using empirical measurements coupled with phenomenological models. In many ways these phenomenological models can be thought of as an analogy to the shell model of the nucleus. Many of the models used to predict excited states of the nucleon suggest that there are still several unobserved states. This “missing resonance” problem demonstrates that there is much to be learned in non-perturbative QCD. To truly understand how quarks inside the nucleon interact with each other, one must map out the production and decay channels of these resonances, which will give new input to existing models.

The goal of this work is to investigate the phenomena in the “resonance region” as denoted by Figure 1.2. In general, this is done by adding energy to the nucleon while measuring the probability of specific output channels. Using multiple channels as input, a

Figure 1.2: Shown is a rough outline on where the phenomenological “resonance region” is in comparison to the perturbative region (pQCD). This figure was made in the likeness of a figure in [Cor07]

partial wave analysis (PWA)¹ can help determine which resonances are coupled to specific decays. This thesis outlines the process of impinging a high-energy photon beam upon a deuterium target to create a K^0 meson and Λ baryon, or simply written $\gamma d \rightarrow K^0 \Lambda(p)$. The data used for this measurement were taken using the CLAS detector at JLAB. By measuring observables from this reaction, we are making data available that will advance our understanding of nucleon resonances through the interpretation of PWA fits. Extracted fit results will then be able to be applied to models within the theoretical framework of QCD, which is beyond the scope of this thesis. As in the case of atomic structure, spectra and resonances may be key to understanding the nucleon.

¹ More about PWA in Section 1.4.

1.1 Quantum Chromodynamics (QCD)

There are four fundamental forces in physics: gravity, weak force, electromagnetism, and strong force. For this thesis the focus will mainly be on the strong force, drawing parallels to electromagnetism. QCD is the theory that describes the strong force, similar to how Quantum Electrodynamics (QED) describes the electromagnetic force. QED is the theory that describes how charged particles (electrons, protons, etc.) interact with each other. They interact through the exchange of massless bosons known as photons. Similarly, QCD describes how the subatomic particles with color (quarks and gluons) interact with each other. Quarks interact with each other via gluons. The property of color is often referred to as color charge to more closely parallel QED. However, this parallel stops rather quickly as an electric charge only has two states (positive or negative), whereas the color charge has six possible states (red, blue, green, or the their respective anti-colors). Each quark has an electric and color charge with anti-quarks having the opposite charges such as anti-red, anti-blue, or anti-green. Moreover, the introduction of color causes several more challenges, including the fact that gluons are also sensitive to color change. This combined with the fact that the strong coupling constant is not sufficiently small at low energies for perturbative methods, proves difficult to model computationally without phenomenological input. Recently, there have been significant improvements with Lattice Gauge Theory², in which select known states can be reproduced and even predict new states. Even with improvements, lattice work still has limits and the produced predictions must be verified with experiment. Therefore, input from cross sections and other polarization observables³ from reactions off a nucleon creating appropriate hadronic final states are helpful to both

² Lattice Gauge Theory is a theory where all possible paths taken are discretized onto a lattice. As the density of nodes and volume of the lattice increase, paths from one point to another approach the limit of a continuous trajectory. By summing over all possible stochastic paths, the probability of specific excitations can be computed. This is very computationally expensive, and has only recently become reliable.

³ More about polarization observables in Section 1.3.

lattice work and phenomenological models. The measurement of these observables coupled with subsequent PWA results will set or improve limits on theories inspired by QCD.

1.1.1 Hadrons

Particles that are made up of quarks and gluons are referred to as hadrons, where the known quarks and their properties can be seen in Table 1.1. Initially, it was expected that only a handful of hadrons would be found (i.e. neutron, proton, and pion). By attempting to find all the possible hadrons that could be created by combinations of quarks and gluons, it became apparent that several more confined states could be formed. Combining group theory with each quark type, or flavor, offers a straight forward way to represent all known hadrons.

These hadrons are classified into two groups, baryons and mesons. Baryons are composed of three quarks (qqq), whereas mesons are composed of a quark and an anti-quark ($q\bar{q}$). Only six unique quark flavors are needed to create any found hadron with qqq or $q\bar{q}$ combinations. These quark flavors are up, down, strange, charm, bottom, and top, with each having its own antiparticle.

Table 1.1: The six fundamental quarks along with their respective anti-particle as quoted from [Gri12]

Family	Flavor	Charge	Mass (MeV)
First Generation	$u(\bar{u})$	$+2/3(-2/3)$	3
	$d(\bar{d})$	$-1/3(+1/3)$	6
Second Generation	$c(\bar{c})$	$+2/3(-2/3)$	1300
	$s(\bar{s})$	$-1/3(+1/3)$	100
Third Generation	$t(\bar{t})$	$+2/3(-2/3)$	175000
	$b(\bar{b})$	$-1/3(+1/3)$	4300

By allowing a unique color to be associated to each quark the Pauli Exclusion Principle⁴ does not prevent baryons containing three bound quarks from having the same

⁴ The Pauli Exclusion Principle is the quantum mechanical principle that states: two identical particles with half-integer spin can not occupy the same quantum state simultaneously.

flavor and spin. For example the particle Δ^{++} is made up of three constituent up quarks with aligned spins. In other words, the wavefunction of a baryon can be described by the factorization of its parts:

$$\Psi = \psi_{space}\psi_{spin}\psi_{flavor}\psi_{color}. \quad (1.1)$$

Without color, this particle should not exist since all up quarks are in the same space.

1.1.2 QCD Spectrum

The best way to study QCD interactions would be by viewing an individual quark. Although internal structure can be seen in hadrons, no individual quark has explicitly been seen. This failure led to the rule of what is now called quark confinement. At short distances the interactions are expected to behave Coulomb-like, $V \sim 1/r$. As the distance increases to account for this confinement phenomenon, the potential must increase without limit. Therefore, the overall potential has the form of something similar to

$$V(r) = -\frac{4}{3} \frac{\alpha_s \hbar c}{r} + kr, \quad (1.2)$$

where α_s is the strong coupling constant, k is a constant, and r is the distance from the central potential. It should be noted that a commonly accepted explanation for this rule is attributed to the overall color state. It is thought that all matter must be in a color neutral bound state. Thus, if enough energy was given to a hadron, no single quark would emerge; rather a colorless meson would result along with a final state hadron. These facts encouraged the continued study of meson production experiments.

Energy can be injected into hadrons through several methods. Initially the majority of our knowledge involving nucleon excitations came from pion beam experiments. This was preferred at the time due to the large rates given by the large cross sections (millibarns). Although these data were large statistically and gave an initial look into this field, the number of observables to define the processes seen were limited. Two other methods used for adding energy to a nucleon include electro- and photo- production. Both of

these two methods allow many polarization observables to be extracted that describe the intermediate processes. These could allow insight into intermediate states that may not be allowed in pion data. Photoproduction allows the elimination of a few dependent variables, namely longitudinal polarizations and photon virtuality (Q^2). Photoproduction is a process where photons bombard an initial state baryon. The photons are able to interact with the internal quarks via electric charge or magnetic moment, which results in several final state possibilities. A universal picture of this process can be seen in Figure 1.3. The idea is then

Figure 1.3: Shown is the lab frame and center of mass (CM) frame of a photoproduction process, where R represents the recoil baryon. Image is taken from [SHKL11].

Figure 1.4: Shown are the three Mandelstam interactions. These include the (a) s-channel, (b) t-channel, and (c) u-channel processes. Resonance production is represented by the s-channel diagram.

to make the final observable state available in order for theories and models to untangle what might possibly be happening during photoproduction. Some examples are shown in Figure 1.4. Several of these processes are happening at once. One such process which is described by the s-channel diagram, would correspond to an intermediate state being formed or, in this context, resonance formation.

1.1.3 Missing Resonances

A major tool in finding and identifying baryon resonances is measuring cross sections combined with partial wave analysis techniques. This can be done on proton or deuterium targets. Many experiments have been done on proton targets, however, each unique initial and final state could affect the scattering or resonant amplitude. An example of pion-proton cross sections can be seen in pion scattering (Figure 1.5).

Figure 1.5: Shown are the total cross sections from πp scattering experiments. The N^* states that are given a four star rating by [O⁺14] are labeled. It should also be noted that these units should be [mb] not [μ b]. This image is taken from [Wil07].

Photoproduction, along with pion scattering, can result in useful information about resonant states. Numerous predictions exist for resonant states of the nucleon that have not yet been found. Although some of these predictions are based on a simplification of all the interactions, multiple resonant states follow these models quite well. According to these predictions, whether it included a few assumptions or was obtained from lattice work (Figure 1.6), there are still several resonant states predicted, but not yet seen by experiment (“missing”). A handful of states may have been found, but are categorized by the Particle Data Group (PDG)[O⁺14] to be less than a four star rating, meaning that more evidence is needed to claim a likely resonance as outlined in Table 1.2.

Figure 1.6: Shown are predicted resonance states based on lattice QCD using $m_\pi = 391$ MeV. This figure is taken from [EMRW13].

The coupling to many resonance states are unknown. Most of the N^* spectrum quoted as four star rating by the PDG was obtained through pion-nucleon final state results. It is theorized that many of the “missing resonances” couple weakly to pion-nucleon decays. Due to that theory many experimental measurements have been focused on other exit channels including $K\Lambda$ or $K\Sigma$. Based on results from the channel $\gamma p \rightarrow$

Table 1.2: The PDG[O⁺14] rates their confidence in the existence of each resonance based on a star rating system.

Star Rating	Explanation
****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

$K^+\Lambda$ [BSM⁺06, MBM⁺10], a resonance of $N(1900)_{\frac{3}{2}}^+$ was shown to have a prominent branching ratio into the $K\Lambda$ channel[MK12, KR10]. The entrance channel may also result in different resonances excited due to the difference in photocoupling of the neutron versus proton, as stated by the Moorhouse selection rule[Clo79]. It is evident that more measurements need to be done covering as many decay and entrance channels as possible. This analysis focuses on the channel: $\gamma d \rightarrow K^0\Lambda(p)$.

1.2 The Reaction $\gamma d \rightarrow K^0\Lambda(p)$

The measurements performed on this channel can only be interpreted accurately by using a PWA fit to the data. Although a cross section could show a “bump” indicating a resonance contribution, a further analysis would be required to verify and extract the corresponding couplings and quantum numbers. It should be noted that all the diagrams seen in Figure 1.4 could present itself in the cross section, although the t-channel contribution should be non-existent until K^* exchange is kinematically possible. Measuring this channel allows a unique opportunity to relate the assumed branching ratios of $N^* \rightarrow K^+\Lambda$ to $N^* \rightarrow K^0\Lambda$ through relative isospin factors, thus allowing a look into the production differences of $\gamma p \rightarrow N^*$ and $\gamma n \rightarrow N^*$. The reaction explored by this analysis can be visually seen in Figure 1.7.

Figure 1.7: A pictorial representation of the reaction of interest for this thesis, $\gamma n \rightarrow K^0 \Lambda$. This diagram represents the known initial state (γ, n), measured final state (K^0, Λ), and the sum of the unknown intermediate mechanisms (?) which are inferred based on the other two.

1.2.1 The K^0 and Λ Hadrons

The K^0 meson in terms of the constituent quark model is represented by the two valence quark combination of $d\bar{s}$, where $\bar{s}$ denotes a strange anti-quark. This meson is especially interesting due to the fact it has a mixture of two states with opposite quantum numbers. These quantum states are referred to as K_S^0 and K_L^0 , where the S stands for short lifetime, and the L stands for long lifetime⁵. An approximation of the distance traveled in the lifetime is often noted by $c\tau$, where c is the speed of light and τ is the mean lifetime. Using this approximation the difference in travel distance of these hadrons can be compared in sensible units (i.e. $c\tau_{K_S^0} = 0.0268$ m and $c\tau_{K_L^0} = 15.34$ m). Beyond decay time, these kaons also have a slightly different mass on the order of 10^{-12} MeV. Although this mass

⁵ Technically, there are two mass eigenstates, K_1 and K_2 , where K_S^0 and K_L^0 are superpositions, or linear combinations, of the two states (i.e. $|K_S^0\rangle = \frac{1}{\sqrt{1+\epsilon^2}} [|K_1\rangle + \epsilon |K_2\rangle]$). To a very good approximation, $|K_S^0\rangle \approx |K_1\rangle$; therefore, for simplicity, this detail is omitted.

difference is small, it allows an oscillation between the neutral kaon states to occur. The magnitude of this oscillation period can be written as

$$T_{osc} = \frac{2\pi\hbar}{\Delta m} \approx 1.2 \times 10^{-9}\text{s}, \quad (1.3)$$

where Δm is the mass difference. If a K^0 is created, it can be represented by $|K^0(t=0)\rangle = \frac{1}{\sqrt{2}} [|K_S^0\rangle + |K_L^0\rangle]$. As mentioned above the K^0 is really a superposition of two mass eigen states that will evolve over time. Therefore, when time progresses it is known that

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} \left(\theta_S(t) |K_S^0\rangle + \theta_L(t) |K_L^0\rangle \right), \quad (1.4)$$

where θ_i is the mixing angle of the i^{th} type, and $|K_S^0\rangle/|K_L^0\rangle$ are represented by

$$|K_S^0\rangle = |K_1\rangle = \frac{1}{\sqrt{2}} (|K^0\rangle - |\bar{K}^0\rangle) \quad (1.5)$$

and

$$|K_L^0\rangle = |K_2\rangle = \frac{1}{\sqrt{2}} (|K^0\rangle + |\bar{K}^0\rangle). \quad (1.6)$$

These oscillation/decay rates can be seen in Figure 1.8. It should be noted here that this is not a problem experimentally as the number of K_S tracks from a K^0 beam can be seen by

$$N_{K_S}(t) = N_{t=0} |\langle K_S | \psi(t) \rangle|^2 = \frac{N_{t=0}}{2} |\theta_S(t)|^2 = \frac{N_{t=0}}{2} e^{-t/\tau_{K_S^0}}, \quad (1.7)$$

which is equivalent to considering $K^0 \rightarrow K_S^0$ as a decay, with a branching ratio of 50%. Furthermore the decay $K_S^0 \rightarrow \pi^+\pi^-$ has a branching ratio of 69.2% [O⁺14], making it an ideal channel for any K^0 studies.

The Λ_s baryon, generally referred to as Λ , in terms of the constituent quark model is represented by the three valence quark combination of uds. This quark combination can be part of an isospin triplet or isospin singlet. The convention of naming Λ refers to the cases of isospin singlets, which means in the instance of the strange sector the Λ is always neutral. This is unlike the Σ being named for the triplet states (i.e. Σ^+ (uus), Σ^0 (uds), Σ^-

Figure 1.8: The decrease in the red curve represents the events lost either through K_S^0 or K_L^0 decays. At long time scales the majority of any undecayed kaons (black), or anti-kaons (blue), should be consistent with K_L^0 , or $\bar{K}_L^0$.

(dds)). This naming convention extends over all flavors (1 u-quark, 1 d-quark, and 1 other flavored quark), although the charge states may change. For example, the $\Lambda_c^+(udc)$ baryon has a net positive charge due to its charm quark (See Table 1.1 for the charges associated with each quark). The Λ baryon is the lowest mass baryon that contains at least one higher generation quark. For this reason, all decays of Λ must change the net flavor contribution. In other words, it decays through the weak force. The primary decay channel is $\Lambda \rightarrow p\pi^-$ with the branching ratio quoted as 63.9% [O⁺14].

1.2.2 Self-Analyzing Power α

When a particle decays via the weak force, parity violation is allowed. This was demonstrated by the famous experiment done with Cobalt-60 [WAH⁺57]. This experiment proved that parity is not always conserved in weak decays, and in fact can vary based on

the reaction. The amount of violation, so to speak, is recorded in decay parameters. These can be found in such texts as the PDG[O⁺14].

Consider the case of the Λ particle. It decays into a proton- π^- pair 63.9% of the time. This is a weak decay that can be viewed as a strange quark decaying into an up quark giving off a weak boson, W^- . This W^- is grounds for the creation of the π^- ($\bar{u}d$). If this Λ is now left in a field, such that it is polarized in one direction, say up, then by looking at the trajectories of the decay products, one can directly measure the decay parameter. If this process completely violated parity the proton would always be directed into the upper hemisphere. If there was no parity violation, then the amount of protons projected upward would be equivalent to the number of protons projected in the downward direction. The percentage of violation is labeled as the decay parameter α . In this specific scenario, it is $\alpha = 0.642 \pm 0.013$. Using the above results, if Λ particles are created and polarized in the same direction every time with respect to the reaction plane, then roughly 64% more of the daughter protons would have a positive component along the direction of polarization.

1.3 Photoproduction Observables

To maximize the capabilities of QCD models, a set of observables is formulated to correspond to complex helicity amplitudes and form factors of a given meson photoproduction reaction mechanism. These observables present themselves with different polarizations with respect to the beam ($P_{L,C}^\gamma$), target ($\vec{P}_{x,y,z}^T$), and recoil baryon ($\vec{P}_{x',y',z'}^R$) of a specific experiment. In all, there are 16 observables that completely describe a meson photoproduction experiment (although only a select 8 are needed to determine the rest). A measurement of all observables would form what is referred to as a “complete experiment”. The derivation of the observables relate to trajectories ($\vec{q}, \vec{k}$) and polarizations ($P^\gamma, \vec{P}^T, \vec{P}^R$) as outlined by Figure 1.9.

Figure 1.9: Photoproduction process in terms of possible polarization quantities in the center-of-mass frame. These diagrams represent (a) initial polarizations of the photon and nucleon as well as (b) the final polarizations of a produced Kaon and Λ pair. Schematics are taken from [SHKL11].

The most general form of the cross section can be written as

$$\begin{aligned}
 \frac{d\sigma^{B,T,R}}{d\Omega}(\vec{P}^\gamma, \vec{P}^T, \vec{P}^R) = & \frac{1}{2} \left\{ \frac{d\sigma_0}{d\Omega} [1 - P_L^\gamma P_y^T P_{y'}^R \cos(2\phi_\gamma)] + \check{\Sigma} [-P_L^\gamma \cos(2\phi_\gamma) + P_y^T P_{y'}^R] \right. \\
 & \check{T} [P_y^T - P_L^\gamma P_{y'}^R \cos(2\phi_\gamma)] + \check{P} [P_{y'}^R - P_L^\gamma P_y^T \cos(2\phi_\gamma)] \\
 & \check{E} [-P_c^\gamma P_z^T + P_L^\gamma P_x^T P_{y'}^R \sin(2\phi_\gamma)] + \check{G} [P_L^\gamma P_z^T \sin(2\phi_\gamma) + P_c^\gamma P_x^T P_{y'}^R] \\
 & \check{F} [P_c^\gamma P_x^T + P_L^\gamma P_z^T P_{y'}^R \sin(2\phi_\gamma)] + \check{H} [P_L^\gamma P_x^T \sin(2\phi_\gamma) - P_c^\gamma P_z^T P_{y'}^R] \\
 & \check{C}_{x'} [P_c^\gamma P_{x'}^R - P_L^\gamma P_y^T P_{z'}^R \sin(2\phi_\gamma)] + \check{C}_{z'} [P_c^\gamma P_{z'}^R + P_L^\gamma P_y^T P_{x'}^R \sin(2\phi_\gamma)] \\
 & \check{O}_{x'} [P_L^\gamma P_{x'}^R \sin(2\phi_\gamma) + P_c^\gamma P_y^T P_{z'}^R] + \check{O}_{z'} [P_L^\gamma P_{z'}^R \sin(2\phi_\gamma) - P_c^\gamma P_y^T P_{x'}^R] \\
 & \check{L}_{x'} [P_z^T P_{x'}^R + P_L^\gamma P_x^T P_{z'}^R \cos(2\phi_\gamma)] + \check{L}_{z'} [P_z^T P_{z'}^R - P_L^\gamma P_x^T P_{x'}^R \cos(2\phi_\gamma)] \\
 & \check{T}_{x'} [P_x^T P_{x'}^R - P_L^\gamma P_z^T P_{z'}^R \cos(2\phi_\gamma)] + \check{T}_{z'} [P_x^T P_{z'}^R + P_L^\gamma P_z^T P_{x'}^R \cos(2\phi_\gamma)] \Big\}, \tag{1.8}
 \end{aligned}$$

as quoted by [SHKL11] where $\frac{d\sigma_0}{d\Omega}$ is the unpolarized cross section, the variables outside each square bracket are profile functions, the terms inside the square brackets describe the initial and final polarization states. Each profile function is a specific measured asymmetry multiplied by the cross section, for instance $\check{A} = A \frac{d\sigma_0}{d\Omega}$. When extracting information from the system of a specific reaction, a common tool used is PWA. This tool has several variable parameters that could potentially fit one cross section measurement by including an arbitrary number of resonances. Each resonance has its own phase, and can interfere with other resonances, which will alter the asymmetries represented by the profile functions in Equation 1.8. Therefore, by measuring each observable for a specific channel, each PWA can identify and put limits on baryon resonances that contribute to that channel. For instance, one could think about measuring the cross section with different polarizations employed instead of measuring the asymmetries themselves, which would result in something like Figure 1.10. Generally, measuring the profile functions as asymmetries is a cleaner measurement. Among the asymmetries in Equation 1.8, two observables can be measured without any polarization on the target or beam. The first is the unpolarized differential cross section as discussed in Section 1.3.1. The second is the recoil polarization of the baryon as discussed in Section 1.3.2. Currently there is great interest in measuring complete experiments in the KY channels [LtCC12, Wer16].

Figure 1.10: The total cross sections of photons absorbed on the proton with different polarization states, $\sigma_{3/2}$ and $\sigma_{1/2}$ [A⁺00, A⁺01a, DHK⁺03]. These polarization states were obtained through the alignment and anti-alignment of the photon ($\vec{P}^\gamma = \vec{1}$) and the proton ($\vec{P}^T = 1/2$) spins respectively. This image is taken from [KR10].

1.3.1 Differential Cross Section

The differential cross section governs the probability by which a given reaction will take place at a given energy and scattering angle. This information can be crucial to providing insight into production mechanisms for specific intermediate and final states. Although pion beam experiments can offer cross sections on the order of millibarns, photon beam experiments are typically on the order of microbarns as seen by Figure 1.11.

Generally, if a center-of-mass (CM) energy is reached that corresponds to a known resonance, that resonance will be produced along with any other scattering reaction. If this resonance also decays to the same final state, the overall cross section will increase due to the added s-channel mechanism (the resonance formation). The angular, or differential, component will also contain information about the resonances' quantum

Figure 1.11: Example of total cross sections of several γp reactions. This image is taken from [KR10].

numbers. Although the differential cross section alone, or “bump hunting”, does not give enough information to verify that a resonance exists, it does provide a foundation and absolute scale of the contribution. Coupling a partial wave analysis study with the measured differential cross section can result in crucial information when searching for resonances, due to the restriction provided by fitting over several observables at once. To evaluate a photoproduction cross section one needs to create the events in a laboratory (Chapter 2), identify the final state tracks (Chapter 4), determine the absolute normalization (Chapter 5), and isolate the events of the specific reaction (Chapter 6). The equations used in this evaluation can be seen in Chapter 7. Performing this calculation greatly restricts the

theoretical models applied to any data on a given reaction channel, which is explained more in Section 1.4.

1.3.2 Λ Recoil Polarization

The asymmetry associated with the recoil polarization of the baryon is isolated by setting all P^T and P^γ variables to zero in Equation 1.8; thus reducing the formal expression to

$$\left(\frac{d\sigma}{d\Omega}\right)^{(0,0,\vec{P}^R)} = \frac{1}{2} \frac{d\sigma_0}{d\Omega} (1 + PP_{y'}^R), \quad (1.9)$$

where P is the asymmetry from the recoil polarization of the Λ , $\vec{P}_{y'}^R$. To extract P from experiments with an unpolarized beam and target, one needs to know $\vec{P}_{y'}^R$. Although $\vec{P}_{y'}^R$ is not known on an event by event basis, an average can be found over a large set of events by utilizing the self analyzing power of Λ , as discussed in Section 1.2.2. Therefore, access to the Λ polarization information is described by

$$\vec{P}_{y'}^R = \alpha \cos \theta_{y'} \hat{y}', \quad (1.10)$$

where $\alpha = 0.642$ is the self analyzing power, $\cos \theta_{y'}$ is the cosine of the angle between the proton⁶ and the normal of the reaction plane, $\hat{y}' = \hat{y}^{CM}$. Both $\cos \theta_{y'}$ and $\hat{y}'$ are defined with more detail in Appendix B. To transform

$$\left(\frac{d\sigma}{d\Omega}\right)^{(0,0,\vec{P}^R)} = \frac{1}{2} \frac{d\sigma_0}{d\Omega} (1 + P\alpha \cos \theta_{y'} \hat{y}'), \quad (1.11)$$

into something more easily measured it should be noted that the number of events is proportional to the cross section as seen by

$$N(\cos \theta_{y'}, W, \theta_{K^0}^{CM}) \propto \left(\frac{d\sigma}{d\Omega}\right)^{(0,0,\vec{P}^R)}, \quad (1.12)$$

and

$$N(W, \theta_{K^0}^{CM}) \propto \frac{d\sigma_0}{d\Omega}, \quad (1.13)$$

⁶ This is the proton from the $\Lambda \rightarrow p\pi^-$.

where $N(\cos \theta_{y'}, W, \theta_{K^0}^{CM})$ is the number of events as a function of $\cos \theta_{y'}$ and $N(W, \theta_{K^0}^{CM})$ is the integrated number of events. Applying these relations, transforms Equation 1.11 into a similar relationship,

$$N(\cos \theta_{y'}) = \frac{N}{2} (1 + P \alpha \cos \theta_{y'}), \quad (1.14)$$

where $N(\cos \theta_{y'})$ and N are implicitly dependent on W and $\theta_{K^0}^{CM}$. From Equation 1.14, it follows that the measurement of P can be done by binning events in $\cos \theta_{y'}$ at a specific W and $\cos \theta_{K^0}^{CM}$. Following a few more algebraic steps (as done in Chapter 7), it can be seen that P can be found two different ways without considering polarized experiments.

Measurement of the asymmetries seen in Equation 1.8 give useful information to better describe the relative contributions from each process that contributes to the cross section. For example, a t-channel process may be modeled to result in a different recoil polarization of the Λ than an s-channel process. Furthermore, each resonance contributing to the cross section may preferentially decay into a specific polarization of the Λ . The amount of contribution to a specific polarization observable from the individual resonances may vary depending on the observable and on the quantum numbers associated with the intermediate state. The observable P , has no published results on the reaction $\gamma d \rightarrow K^0 \Lambda(p)$, making this measurement a high impact measurement performed and reported in this thesis.

1.4 Models Fitted to Measured Data

Two of the models used in identifying resonances based on asymmetry or cross section measurements include KAON-MAID[MBHT] and BoGa[ABK⁺12]. In simplistic terms these models fit the data by adding in contributions from observed resonances. They then do systematics on their fits to determine if the model must be missing something in order to get a reasonable fit to the data. These fits could then separate out contributions from resonances or t-channel processes as seen by Figure 1.12. If a fit can not represent the data, a new resonance could be added in allowing interference terms to take effect.

Figure 1.12: An example of KAON-MAID fitting the cross section of $\gamma p \rightarrow K^+ \Lambda$ and identifying specific contributions. Image taken from [MK12].

Each state in the model has a branching ratio to each channel and helicity amplitude (phase and strength in the complex energy plane). This amplitude combined with the other known production amplitudes could interfere with each other, either bolstering or hindering apparent strength to the naked eye. An added factor of constraint comes from fitting multiple channels at once, each having several measurements associated with it as is done routinely by the BoGa Group [ABK⁺12]. This method allows the determination of the helicity amplitudes when fitting neutron and proton data at the same time. The fact that the states obtained from a proton (i.e. $\gamma p \rightarrow K^+ \Lambda$) versus the neutron (i.e. $\gamma n \rightarrow K^0 \Lambda$) creates new constraints which show where interference is the greatest. With this knowledge one can: A) determine a more accurate helicity amplitude, as well as B) categorize resonances in the group theory model as worked out using the Moorhouse selection rule[Clo79]. This process requires several variables on one channel to act as constraints and is quite

complicated. The definition given was only meant to get the general idea across, but in reality is more robust than the simplistic explanation above.

1.5 Summary

The reaction $\gamma d \rightarrow K^0 \Lambda(p)$ offers a unique opportunity to gather insight into the “missing resonance” problem. This is due in part to a neutron reaction, production/decay into the strange sector, the self analyzing power of Λ decay, and finally that these results will be the first measurements on this channel that covers anywhere near this kinematic coverage. The measured differential cross section and recoil polarization will lay the foundation for other measurements on this channel. Published data on each observable (i.e. $\frac{d\sigma_0}{d\Omega}$ or P) in this channel will allow several different models to incorporate these data into their fits to better understand the properties of the nucleon and therefore non-perturbative QCD. These final results can be found in Chapter 7.

2 EXPERIMENTAL SETUP

This analysis uses data from two different experiments, the g10a and g13a datasets. These datasets were collected in Experimental Hall B at the Thomas Jefferson National Accelerator Facility (TJNAF), also sometimes referred to as Jefferson Laboratory (JLAB). The g10a experiment was initially intended for a high statistic measurement of a hypothesized pentaquark, Θ^+ . Although the run did not see evidence of the Θ^+ , an upper limit was quoted. Moreover, the run utilized an unpolarized liquid deuterium target bombarded by an unpolarized beam, leaving this run as one of the high statistic datasets for reactions on the deuteron. The g13 run was proposed[NTBI⁺06] using data from the g10 dataset in order to outline a plan exploring the reaction $\gamma n \rightarrow K^0 \Lambda$, or more rigorously it is written as $\gamma d \rightarrow K^0 \Lambda(p)$, where the proton (p) is a spectator to the main reaction. The g13 experiment also used an unpolarized liquid deuterium target. However, the beam was circularly polarized in g13a and linearly polarized in g13b. The detector in both experiments employed the CEBAF Large Acceptance Spectrometer (CLAS), which was optimized for multi-particle final state detection. Although CLAS surrounds the target and is referred to as a 4π detector, the gaps between the individual components reduce the coverage to about $60\% \times 4\pi$. The photon beam was produced and tagged with a tagger hodoscope array. Together, the CEBAF accelerator, tagger, CLAS, and target were vital in both the g10a and g13a datasets.

2.1 CEBAF

An electron beam is delivered to Hall A, B, C, and D at JLAB from the Continuous Electron Beam Accelerator Facility (CEBAF). Superconducting radio frequency (RF) cavities were used to accelerate the electron bunches. In general, RF cavities can be molded to a variety of shapes and sizes to allow electromagnetic waves to resonate inside. The cavities were tuned such that the frequency of the cavity charge was inline with the

electron bunches. This was only possible with the use of superconducting material, which provided a resistance free channel to oscillate at the optimum frequency. This oscillation along the cavity provided a positive electric force to each electron that travels through the beam pipe. The linear particle accelerators (LINACs) were each composed of 168

Figure 2.1: Shown is a schematic of CEBAF before the addition of Hall D. There are two LINACs, one per side. These accelerate each electron pulse that then gets passed through the tracks several times (max of 5). This image was taken from [M⁺03].

superconducting cavities. The LINACs can be seen on two sides of CEBAF in Figure 2.1. Every cavity is kept extremely cold (-271°C) by the liquid Helium that cycles through the Helium Refrigerator. After the beam passes through the LINACs (roughly $7/8$ mile) it is then split based on its energy allowing a total of 5 passes through the racetrack-like design of CEBAF. These 5 passes allow a maximum of ~ 6 GeV to be delivered to any of the experimental Halls. JLAB is currently finishing an upgrade to allow the maximum beam energy to be closer to 12 GeV. Although 6 GeV beam was achievable, many experiments were able to extract beam off of an earlier pass to have a lower beam energy delivered. After a beam bunch was directed towards a specific Hall, that Hall could then measure and control the beam position and focus points. The experiments analyzed in this report

all were done with CLAS, located in Hall B. The general layout of Hall B can be seen in Figure 2.2.

Figure 2.2: Shown is a schematic of Hall B. The beam comes in from the left, passes through the pipe until it hits a gold foil to radiate photons that continue onto the target. Any remaining electrons are bent down to the beam dump at the bottom of the figure. This image was taken from [M⁺03].

2.2 Photon Tagger

Many experiments at JLAB, including experiments in Hall B, look at electro-production. One complication of electro-production, is the fact that the resulting polarization of the electron must be identified and accounted for in order to extract more observables from a specific reaction channel. A useful method to eliminate the complications associated with electron polarization to the final measurements is to use a real photon beam. To ensure that the measured reaction observables were created with real photons, the electron beam is converted to photons through bremsstrahlung radiation. The bremsstrahlung radiation process is done by bombarding a high-Z nucleus, such as a gold

foil, with the initial electron beam, producing a scattered electron along with a produced photon, $e^- + Au \rightarrow Au + e^- + \gamma$. The gold foil is often called the radiator, and the scattered electron can be detected to identify, or tag, the energy of the outgoing photon. The tagger used in Hall B to tag each photon can be seen in Figure 2.3. The tagger itself detects scattered electrons in the range of roughly 20%-95% times the incident electron energy, E_0 .

Figure 2.3: Shown is a schematic of the Tagger used in Hall B. The tagger “tags” each photon by detecting the scattered electron. The scattered electron is bent out of the beamline and into hodoscope of E-counters and T-counters by a dipole magnet. This image is taken from [S⁺00]

This process creates photons with a range of energies, which are tagged from measuring the outgoing electron energies. Measuring the electron energies is accomplished through the use of a dipole magnet to bend these electrons through “E” and “T” scintillators (energy and time respectively) within the tagger. These scintillators planes are often referred to as E- and T- counters, and are constructed as hodoscopes. These hodoscopes are

placed such that there is overlap between them. An example is that of the E-counters where 384 counters are placed at 1/3 overlap giving 767 bins (EID) of electron energy. There are 61 wider T-counters placed with non-uniform overlap creating 121 smaller time bins (TID). The electrons that are roughly between 20% – 95% of E_0 will be directed toward these counters by the dipole magnet spectrometer. The full energy electrons were directed away from the beam line into a separate beam dump, leaving only the generated photons to continue onto the deuterium target. The photon energy was calculated by $E_\gamma = E_0 - E_{e'}$, where $E_{e'}$ is the energy of the scattered electron. This energy is known to a resolution of $10^{-3}E_0$, due to the overlap of the E-Counters. Trajectories of the bent electrons also allow the determination of whether the event was a good geometrical hit in the hodoscopes, or good status. Each photon then has an energy (from its EID), time (from its TID), and status associated with it recorded in each event.

2.3 The CLAS Detector

The CEBAF Large Acceptance Spectrometer (CLAS) is comprised of several detector components designed to work concurrently with one another. The components include, but are not limited to the target cell, start counter, drift chambers (three regions), TOF panels, and magnets providing a toroidal field. Many of the components surround the target resulting in very good angular coverage to detect a multi-particle final state. The coverage in ϕ_{LAB} helps increase the acceptance of tracks per event. CLAS has an intrinsic six-fold symmetry about the beam line. Each one of these six regions is often referred to as a sector and is intended to be as identical as possible and can be seen in Figure 2.4.

(a) Shown is a side view of CLAS, with the beamline directed from left to right.

(b) Shown is a view down the beam line, which highlights the location of the torus coils and drift chambers (R1, R2, and R3).

(c) Shown is a three dimensional view of CLAS, where the beam would be coming out and to the right of the page.

Figure 2.4: Shown are several views of CLAS. Each view offers a slightly different perspective of the components within CLAS. Images taken from [M⁺03] and [M⁺00].

2.3.1 Target

The target used in CLAS can be changed depending on the experiment proposed. In general, the longer the target, the higher the luminosity for that experiment. However, increasing the target also increases the background due to Moller scattering and could negatively affect the acceptance for a given experiment as a function of production vertex. Both the g10 and g13 experiments utilized an unpolarized liquid deuterium target. The g10 experiment had a cylinder target, four centimeters in diameter with a length of 24 cm, centered 25 cm upstream from CLAS center. This location was chosen to maximize the acceptance for the proposed channels of study. The g13 experiment employed a newer start counter, and a slightly bigger target setup. This target was still a cylinder four centimeters

in diameter, however, it was 40 cm in length and centered 20 cm upstream from CLAS center.

2.3.2 Start Counter

The start counter is responsible for recording the start time of any particle traversing CLAS originating in the target. This event start time is crucial to measure an accurate time-of-flight using this and the TOF scintillator wall. The triggering of an event typically required at least one hit recorded from the start counter and two hits in TOF counters in two different sectors. To maximize acceptance of events, the start counter had an angled cone near the beam line to detect tracks with a small opening angle from the beam line. Since CLAS extends on the scale of a meter, a very small increase in acceptance on the start counter could have a large effect by the time a track reaches the outskirts of CLAS. The g10 start counter was fashioned using 3 pieces of scintillator, each covering two sectors. The nose of the start counter was angled inward forward of the target. Each sector had its own PMT to receive a signal. The start counter was replaced after the g10 experiment, making a finer-segmented start counter. Each sector was composed of four strips of scintillator, each with its own PMT. This new start counter was used in the g13 experiment where the triggering required hits in two different sectors of the start counter.

Figure 2.5: Shown are several views of the g10 start counter. These images are taken from [TAD⁺01]

Figure 2.6: Shown are several views of the g13 start counter. These images are taken from [SBB⁺06]

2.3.3 Toroidal Magnet

One main tool of CLAS is its toroidal magnetic field. The coils for these magnets are placed in between each of the six sectors. The toroidal field shape will bend charged particle tracks towards or away from the beam line depending on the polarity. The azimuthal angle essentially is unchanged. The maximum setting on these are roughly 4000 Amps. The

g10 experiment used two field settings: one at +2250 Amps and one at +3375 Amps. The positive current curves negatively charged tracks towards the beam line. The g13 experiment had several settings, but mainly used a -1495 Amp setting on the current. This setting curved the negative charged particles away from the beam line. The idea was that this would increase the acceptance of low momentum pions, for example from the decay $\Lambda \rightarrow \pi^- p$.

Figure 2.7: Shown is a side view of the magnetic field used. Also shown are equipotential field lines. This image is taken from [M⁺03].

2.3.4 Drift Chambers

The multi-layered drift chambers (DC) were designed to be in 18 separate pieces, three regions per sector, each piece to be mounted between two toroid coils. The 18 components house over 35,000 individual hexagonal drift cells. An effort to maximize active area was carried out by mounting all inactive parts in the “shadows” of the superconducting toroid [M⁺00]. The placement and coverage of these chambers provided excellent tracking resolution, efficiency, and acceptance. Beyond maximizing the effective area, the resolution was slated to be on the order of 0.5% for $\delta p/p$ and 2 mrad for the angular trajectory ($\delta\theta$ and $\delta\phi$) of the reconstructed tracks at a nominal momentum of 1 GeV/c. To accomplish this,

the location of tracks within the chamber had to be known to an accuracy of $100\ \mu\text{m}$ in the plane of bending (due to the magnetic field) and 1 mm orthogonal to the bending plane.

2.3.5 Time-Of-Flight Wall

The time-of-flight (TOF) wall of CLAS was designed to measure the laboratory time of the charged tracks leaving CLAS. The difference in the time recorded from the TOF wall and the event start time can be used to identify the mass of specific tracks in an event. This TOF wall was built using several scintillating strips that are connected to PMTs on at each end of the strip. The unit was built again in six components, one for each sector. Each scintillator within one sector was positioned at a unique θ , to cover CLAS in an arc-like fashion. The size of each scintillator varies as a function of θ , as allowed by the structure of CLAS. The TOF structure can be seen in Figure 2.8.

Figure 2.8: Shown is one of the six sectors of TOF scintillation arrays. Logically there are 48 paddles, even though there are physically more (some are connected to the same PMT). Figure taken from [S⁺99].

2.3.6 Cherenkov Counters

The Cherenkov Counters (CC) are used to trigger on electrons and separate electrons from pions[ABC⁺01]. This is most useful in electroproduction experiments, where the electron flux inside CLAS is much higher. These detectors use Cherenkov radiation given from the tracks traveling through the trapped gas. The emitted light is reflected through a process of curved mirrors allowing a cone of light to be detected. The information obtained from this unit is collected only in the ϕ direction, thus preserving the polar angle trajectory determined by the charge, momentum, and magnetic field.

2.3.7 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (EC) is broken down into six sectors similar to the other components. The only difference is that the EC is not curved around the target, instead each sector is built as a triangular prism. The purpose of this is to trigger on high energy electrons or detect neutral particles that are not bent by the magnetic field[A⁺01b]. This prism is composed of 13 sandwiched layers of lead, scintillator strip, scintillator strip, scintillator strip, and lead. Each neighboring layer of scintillator strip is rotated by 120° to assist in the location of the track hit. This location not only gives information for event building, but also is critical when determining the attenuation correction needed to approximate the deposited energy inside the unit. Each layer of lead is intended to create electromagnetic showers in an effort to stop the ionizing radiation allowing the scintillators and corresponding PMT's to collect the light output.

2.4 Summary

This chapter outlined the capabilities of CLAS, as far as the usefulness of this detector to observe hadronic final states. The tagger combined with CLAS results in a great tool to investigate many reaction channels such as $\gamma d \rightarrow K^0 \Lambda(p)$. The advantage being mutli-track

detection over the greater part of 4π . Both the g10 and g13 experimental setups utilized the the photon tagger along with many components of CLAS. The main difference between the two experiments being opposite polarity of the magnetic field and different start counters. The next Chapters will describe in detail the extraction of the $K^0\Lambda$ signal as well as the connection to CLAS as a detector.

3 CLAS12 PRESHOWER CALORIMETER

The CLAS Collaboration is only able to take data with calibrated detectors due to the constant service work provided by its members. This service work can come in the form of taking shifts, setting up hardware, or creating software for technical or calibration services. Due to the size and sophistication of the CLAS detector, it takes several service projects to set-up even one experiment. It is impossible to set-up an experiment by oneself, let alone prepare for future experiments. During my time as a member of the CLAS Collaboration, the detector has been offline. This downtime has left several experimental measurements to be analyzed using the existing data. This time has also allowed the current service work to be directed to the upgrade of CLAS. The work I contributed to this process is partially described in Section 3.2. Building on the work of others, a calibration method must be implemented using data taken on each detector system. I have created and implemented this method and software (in C/C++) on data taken by Cole Smith and many others. I have also helped translate this method into CLAS created software (based in JAVA) to better visualize calibration data in a graphical format. This calibration method is necessary in order to reduce backgrounds and improve calibrations to the desired accuracy for data taking. To describe this method and results, additional information describing the added hardware is given below and in Section 3.1.

The detector described in Chapter 2 was the set-up during both the g10 and g13 experiments. However, since the completion of these experiments, Jefferson Lab has upgraded its facility to increase its maximum beam energy from 6 GeV to 12 GeV. This upgrade, consequently, is capable of producing particles at a much higher energy. This correlates to more forward going (boosted) tracks. Considering this, the classic CLAS layout will not be as effective. To solve this problem CLAS is also being upgraded to what is now called CLAS12, with the old set-up referred to as CLAS6. The bulk of CLAS12 was created to look more like a wall of detectors downstream of the target, rather than

encapsulating the target (Figure 3.1). Along with re-positioning detector components, other features have also been addressed. For instance, the tracks with higher energies will not be stopped by the CLAS6 EC alone. Another problem is the capability of determining a neutral particle's position, specifically pertaining to photons originating from the π^0 decay ($\pi^0 \rightarrow \gamma\gamma$). Many research opportunities that utilize the calorimeter depend on identifying a topology containing these π^0 s. To maximize this capability, a new calorimeter is being added to CLAS12 in front of the previous calorimeter (EC). This new preshower calorimeter (PCAL) will increase the positioning resolution as well as increase the detection efficiency of high momentum pions when both systems (EC + PCAL) are utilized.

Figure 3.1: Shown is a schematic of CLAS12 and its subsystems. Image taken from [CLA]

3.1 Geometry

The PCAL is triangular in shape. The triangular form was chosen in order to be lined up with each sector of CLAS12. A diagram of the front and side view of the PCAL with respect to the EC can be seen in Fig. 3.2. The PCAL box encapsulates layers of scintillator

Figure 3.2: This diagram demonstrates the dimensions of the PCAL unit. This figure has been taken directly from the PCAL geometry note[A⁺b].

strips and lead sheets. Between each lead sheet there are three different orientations of scintillating strips. These orientations are described as the U, V, and W layers. Each layer is parallel with one side of the PCAL box. The sequencing of the lead sheet, U layer, V layer, and W layer is repeated five times within each sector of the PCAL unit. This results

in fifteen layers of scintillator strips. Each repeating layer signal is coupled to the same PMT. A UVW view of the PCAL can be seen in Fig. 3.3.

Figure 3.3: This is a schematic of how each orientation of scintillator is laid out. This figure is also taken directly from the PCAL geometry note[A⁺b].

There are 84 U strips, 77 V strips, and 77 W strips in each corresponding layer. The last 32 U strips are grouped into one PMT per pair. The first 30 V and W strips are also grouped in pairs within their respective layer. This pattern of scintillators can be seen in Fig. 3.3. Strips in each view can be numbered for ease. Lower numbered strips are the shorter strips while higher numbered strips are longer. For example, V1 is the shortest and V62 is the longest strip in the V view. This strip convention is used throughout this document and is taken from the PCAL geometry note[A⁺b]. Using this convention, the layout of the PMT readout can easily be understood from Fig. 3.4 which shows PMT readout of a strip in each view. As a consequence there is better spatial resolution at low strip numbers in the U layer and at high strip numbers in the V and W layers.

Figure 3.4: This is a cartoon showing the layout of the PMT readout for different views. Image created by T. Chetry.

The construction of the PCAL unit itself has had multiple parts including measuring thicknesses, cutting scintillation strips, cutting fibers, testing of each component, and positioning of all the materials inside the unit. This was an intensive project, and was contributed in part from Ohio University funding and select graduate students service projects (W. Tang and S. Chandavar). The construction and testing was carried out at JLAB for all six sectors. All sectors were stored until they were mounted in December, 2013. The final mounted view of all six sectors is shown in Figure 3.5.

Figure 3.5: Shown are all six sectors of the PCAL mounted to the supports. Image taken from [Ste]

Our goal is to calibrate the PCAL unit of the CLAS12 detector. One can think of dividing each PCAL module into bins based on the overlapping shapes. The overlap shapes/pixels are of two types: a 3-strip pixel, shape formed when all the views are superimposed together, and a 2-strip pixel formed from the overlap of two strips where the strips are part of different views. Maps of different overlap conditions are shown in Fig. 3.6.

Figure 3.6: Shown are the different ways overlaps can be considered in a single PCAL module.

Although in general a 3-strip pixel can be odd shaped, a 2-strip pixel can be straightforward. This two layer correlation creates trapezoidal bins formed by the overlap of two different strip orientations. An example of one of these trapezoids outlined in black can be seen in Fig. 3.7. Each one of these trapezoids should have a ADC readout value. The width of this physical bin can be found by

$$s = \frac{w}{\sin \alpha} \quad (3.1)$$

where w is a single scintillator strip width ($\approx 4.5\text{cm}$). Statistically one might expect some sort of peak describing the distribution of values. The centroid of this distribution is used as a data point along with the distance from the PMT to the center of that physical bin, or overlapping region.

Figure 3.7: Shown is an outline of a generic intersection of a U and W strip. The distance between the trapezoidal area and the PCAL edge can be represented by a linear function of s .

3.2 Calibration

The data used for calibration is from cosmic ray muons. These cosmic rays hit randomly throughout the PCAL unit. The distribution of these events although expected to be uniform, don't guarantee a good hit or detected signal in all three layers. Moreover, due to the strange pixel shapes and varying sizes, different pixels have large fluctuations in the number of counts. As the muons traverse the scintillating strips, light is emitted. This light is kept inside the strip through a reflective coating surrounding the strip. Ultimately, this produced light only has a small attenuation length and in some cases would have to traverse several of these lengths to reach the corresponding PMT. To solve this problem,

and ensure a signal is detected, wavelength shifting fibers were used inside the scintillators. These fibers converted the original blue light into green light that has an attenuation length on the scale of three meters or more. This length coincides more closely with the maximum distance from a scintillation event and the corresponding PMT position ($\approx 400\text{cm}$).

The first step of the calibration process then is utilizing a known event position to find the distance that the signal traveled to each PMT. This position, and therefore distance, is determined based on the two or three strip pixel position and the edge of the the PCAL unit. To reduce the contribution of non-perpendicular physical tracks in the calibration process, a multiplicity and a valid pixel cut were applied to the data (Section 3.2.1). The second step in the calibration process required obtaining the correct signal peak location for each analyzed pixel. However, the data sample still included an unknown background in the ADC spectrum. The third step in the calibration process was to plot the detected signal strength versus distance traversed allowing an attenuation curve to be fit to the data. This attenuation fit shape is not known *a priori*, but is expected to have some form of decaying strength. In the end, the attenuation functional form was found empirically to be consistent with the form

$$I(x) = Ae^{-Bx} + C, \quad (3.2)$$

where A , B , and C are the fit parameters that describe the attenuation coefficients.

The final step in the calibration process was to repeat steps two and three with cuts about the ADC signal spectra until convergent results were obtained. These cuts were made on all ADC layers, meaning that a two strip pixel, made by the U layer and W layer, had both ADC cuts applied to it. With this iteration process, convergent results were obtained as shown in Sections 3.2.2 and 3.2.3.

3.2.1 The Initial Cuts

To ensure a more accurate calibration, a multiplicity cut was applied to the collected data. The multiplicity cut removed any event that contained more than three PMT readouts (one in each layer). This reduces the number of cosmic ray events that are not relatively perpendicular to the face of the PCAL unit. This is due to the fact that if a cosmic ray trajectory is not perpendicular to the PCAL face, it could clip multiple strips in one orientation (*i.e.*, strips U30 and U31 both receive a signal). Therefore, by restricting the calibration to one perpendicular hit, calibration constants could be better determined. The accepted range of incident angles (different from perpendicular to the PCAL face) varies as a function of strip number and is not uniform in all directions. This multiplicity cut also helps to remove events when multiple cosmic rays hit the detector within the same time interval, due to possible firing of more PMTs.

An investigation into the types of backgrounds was performed. Looking at an occupation number (events within a pixel), some recorded hits were unphysical if only one cosmic ray was considered to prompt the signal. Examples can be seen by Figures 3.8b and 3.9.

Some of the unphysical events can be spotted easily because low U and low V strip numbers should never correlate to just one incident cosmic ray. To investigate in more detail, a program outlining the PCAL detector by strip number was generated. This was generated using α , β , number of strips, and strip width (w) as defined by Figure 3.7. This outline or pixel mapping can be seen in Figure 3.8a. This ideal outline of the system was then used in combination with a random number generator to verify which strip numbers could correlate to a physical perpendicular trajectory through the system. These correlation numbers were then stored in tables and recalled in the analysis. Neighboring pixels in all directions were also marked as valid to account for uncertainties. Removing any event that did not end up in correlated PMTs results in the elimination of the obvious unphysical

Figure 3.8: Shown is a rough outline of the PCAL system including (a) the pixel map and (b) one example of an event that would pass a multiplicity cut, but is clearly from either multiple rays or other noise.

Figure 3.9: The left histogram shows the U and V strip correlation after the multiplicity cut was applied. The right histogram shows the U and V strip correlation after rejecting all known unphysical background.

signals is seen in figure 3.9. However, looking at the signal distribution, an exponential background still appears. This demonstrates that either different cuts and/or a very good fitting routine needed to be put in place.

3.2.2 Signal Shape and Attenuation Curve

The desired outcome is to approximate the ADC signal by a simple function, for instance a Gaussian function. Upon investigation, the integrated values appear to be a combination of a Gaussian and exponential fits (Figure 3.10). This type of background can be seen for every physical two layered bin along any strip.

Figure 3.10: Shown is an example of the distribution of the ADC readout from one u/w trapezoidal bin (specifically the logical numbers u =67, w=50). The red line is a fit to an exponential combined with a Gaussian distribution.

The exponential is background/noise in most cases, whereas the Gaussian represents near perpendicular cosmic ray hits. The centroid of the Gaussian is extracted and determined to be the primary light intensity in that trapezoidal bin. This plan works well for

most interior physical bins. However, after looking at the strips corresponding to the edges of the PCAL unit, more can be done. Two improvements were utilized to better extend the calibration to the outer edges.

1. **Cut on each fit Gaussian signal:**

Using the fact that each bin in one scintillating strip corresponds to the other two, a cut on one affects the others. By making an iteration over all events, a three sigma cut can be placed on each signal. This reduces the exponential background, improving the fits to some edge pixels.

2. **Cut on the overall energy deposited:**

Assuming that the signal is from the same minimum ionizing cosmic ray, and if that event doesn't participate in corner clipping, then the event should deposit the same amount of energy into each layer. After cutting on the original signal and fitting attenuation curves, individual gains can be approximated. Using the empirically found gains, a cut on the sum of ADC signals can be performed. This also helped extend good fits to the edges of the PCAL unit. This is the case due to the fact that two intersecting medium range strips (other layers) set limits on the possible events on the outer most strips. By improving the ADC distribution of the outer-most strips, they can be used to set limits on the overlapping shorter strips.

An iteration process was employed to improve the signal extraction. Every iteration, this process cuts out events based on ADC values determined by either the most recent signal fits or by attenuation fits. This allows for a converging result because each cut on one layer affects the other two. Therefore, the raw signal fit keeps improving as the attenuation fit and gains improve. To illustrate how the process works, the first and last iteration (pass) results are shown below for six different pixels. The cuts used on that pass are also described.

- **First Pass:**

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.

- Valid hit or near neighbor hit: Using generated events on a calculated skeleton of the PCAL, each pixel was determined to be valid or not. Extra uncertainty was allowed by also marking nearest neighboring pixels.
- The ADC spectrum was fit with a Gaussian plus exponential form.

Figure 3.11: Shown is the ADC signal corresponding to signals from multiple U-strips (5, 15, 30, 45, 67, and 68) and a projection of the W60 strip.

Figure 3.12: Shown is the overall attenuation fits to the selected U-strips (5, 15, 30, 45, 67, and 68).

- **Last Pass:**

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.
- Valid hit: Using generated events on a calculated skeleton of the PCAL, each pixel was determined to be valid or not.
- 3σ Cut on Signal: Each signal was fit to a Gaussian from the previous pass. The parameter σ from the Gaussian fit was used to cut out the events that did not lie within this range.
- Attenuation Corrected Intensity Cut: The ADC value measured was corrected with the attenuation curves obtained from the previous pass. The corrected value was summed over each layer (U, V, and W). A cut on this intensity was placed generously about the expected summed value (Figure 3.15).

Figure 3.13: Shown is the ADC signal corresponding to signals from multiple U-strips (5, 15, 30, 45, 67, and 68) and a projection of the W60 strip.

Figure 3.14: Shown is the overall attenuation fits to the selected U-strips (5, 15, 30, 45, 67, and 68).

Figure 3.15: Shown is the sum of the attenuation corrected ADC values from the U, V, and W layers (expected to be at the peak location of 1950). The signal loss between (a) and (b) was minimal when applying the three σ cut.

3.2.3 Results

After several iterations the ADC signal fits appeared to be fairly Gaussian (Figure 3.13). Using the Gaussian centroids and corresponding uncertainties, reliable attenuation coefficients were obtained (Figure 3.14). These coefficients A, B, and C from Equation 3.2 were then saved to the CLAS12 database. Utilizing the functional form and saved parameters, it is expected that CLAS12 tracks (from EM showers) can be corrected to the appropriate incident energies. These energies and positions can then be combined with the EC energies where valid to obtain total momentum and directionality values inline with the expected CLAS12 resolution. This will mainly help with high momentum tracks especially when reconstructing π^0 creation events.

3.3 Summary

As a CLAS Collaboration member, I have contributed a portion of my time in the form of calibrating a new detector, the Preshower Calorimeter. The calibration on this unit was problematic, as an unknown background was seen in the data. Using an iterative technique,

I was able to clean up the signal, and fit the attenuation curve. Knowing this attenuation curve and the location of any track in the calorimeter, the deposited energy is now able to be calculated in relative comparison. This functional fit is especially important to be known where better resolution is needed (reconstruction of π^0 s) or where more energetic particles would not be stopped by the electromagnetic calorimeter alone. This calibration is bound to change over time, and the created program has been automated to be used in a standalone C++ format. The current parameters have been saved to the database. The routine is currently being streamlined into an embedded JAVA program that will be compatible in all CLAS12 detector subsystem interfaces. Documentation of what I completed has also been written and given to the PCAL group to be updated as the current software versions evolve.

4 EVENT PROCESSING

The photon beam for the g10 experiment was created by colliding an electron beam into a gold foil that caused a range of photon energies to be sent down the beam pipe to a unpolarized liquid-deuterium target. The target chamber measured 24 cm in length with a 4 cm diameter. The center of the target was positioned 25 cm upstream from the CLAS center. The energy of the photons emitted from the target were calculated by identifying the corresponding electron in the tagging spectrometer [S⁺00]. The incident electron energy was $E_e \sim 3.779$ GeV. The outgoing electron traveled through a magnetic field and into the tagger that separated the electrons based on energy.

The analysis on this dataset was limited to photon energies between 1.0 GeV and 3.0 GeV where event rates are the largest. The g10 run period used the detection of two charged particles in different TOF sectors along with a hit in the electromagnetic calorimeter [A⁺01b] as a trigger. The magnetic settings in this run period had two different settings. The first part had the torus magnet set at +2250 Amps, while the second part was set at +3375 Amps [CMD⁺09]. Each magnet setting was kept for roughly half of the g10 beam time. This analysis only investigated the data set with the torus magnet set at +2250 Amps. This setting was chosen in the analysis to increase the probability of detecting low momentum pions. Both cases were positive polarity, which bend negatively charged pions towards the beam line, resulting in the possibility of a low momentum (< 200 MeV/c) π^- to curl up before reaching the outer TOF wall.

The g13 experiment was split into two parts called g13a and g13b [NTBI⁺06]. Both used specialized radiators to transform the electron beam into a polarized photon beam. The g13a data used a circularly polarized photon beam, created from a longitudinally polarized electron beam. The g13b experiment used a diamond target with tight collimation to produce a linearly polarized photon beam. A 40 cm unpolarized liquid-deuterium target was used for both g13a and g13b. The target was 4 cm in diameter while positioned 20

cm upstream from CLAS center. A current of -1497 Amp was used in the torus magnet to bend negatively charged particles away from the beamline, in contrast to g10's positive polarity. This set-up was intended to maximize the acceptance of low-momentum π^- that resulted from the decays of hyperons. Only data from the g13a portion of the experiment were used for this analysis.

The g13a portion of the experiment was in itself broken up into two parts. The first part was 3-pass data (three passes through the accelerator loop). These data utilized an incident electron beam of 1.996 GeV to create the photon beam. The second part was 4-pass data, utilizing a beam energy of 2.65 GeV. The 4-pass data was used in this analysis to provide a measurement with higher statistics, complimentary to that of the g10 results.

4.1 Experimental Runs

Both the g10 and g13 datasets were collected in shorter increments, called runs. Every run was tracked in the experimental log book⁷. A sample collection of the details found in the logbook for g10 data set is shown in Table 4.1. The runs used in the g10 part of this analysis are any runs not labelled as

- junk
- test
- cosmic
- changing threshold

all while having

- the target type as D_2
- beam energy of 3.779 GeV
- and torous field setting as $+2250$ Amps.

⁷ This log book can be found at <http://clasweb.jlab.org/clasonline/prodrunsearch.html>.

These selected runs have shown to be reliable in reproducing previously measured cross sections (Appendix D). Similarly the runs used in the g13 part of this analysis are any run that shares the g10 rejection conditions all while having

- the target type as D_2
- beam energy of 2.65 GeV
- and torous field setting as -1497 Amps.

The overall run ranges can be seen in Table 4.2. Both collection of runs have shown to have reliable flux-normalized yields (Section 5.5).

Table 4.2: A quick summary of the g13 data runs. The red refers to the data investigated by this analysis.

Run Number		Label	Target	Beam Energy (GeV)	Mag. Field (Amps)
Begin	End				
53095	53148	g13a (3 pass)	H_2	Circular (1.987 GeV)	-1497A
53164	53326	g13a (3 pass)	D_2	Circular (1.987 GeV)	-1497A
53333	53532	g13a (3 pass)	D_2	Circular (1.996 GeV)	-1497A
53538	53624	g13a (4 pass)	D_2	Circular (2.654 GeV)	-1497A
53625	53625	g13a (4 pass)	Empty	Circular (2.654 GeV)	-1497A
53626	53862	g13a (4 pass)	D_2	Circular (2.654 GeV)	-1497A
53863	53967	-	Empty		-1497A
53970	53994	g13a (3 pass)	H_2		-1497A
53998	54035	g13a (3 pass)	D_2		-1497A
54042	55001	g13b (5 pass)	D_2		-1497A
55147	55173	g13b (5 pass)	H_2		-1497A
55175	55204	g13b (5 pass)	H_2		+1497A

4.2 Tripped Events

Over the duration of beam delivery to a hall, the accelerator sometimes trips. This results in a loss of incident energy on the target. In order to try to maintain a constant incident flux, events that occur during a beam trip were removed. Figure 4.1 shows an example from Hall A, where the time intervals with low current (red) before and after the beam trips are cut from the stable beam currents (black).

These beam trips then can still create physics events within the data files. All event numbers are recorded in associated trip files for each run indicating whether the event occurred during a beam trip or not. To remove these trip events, the events flagged as beam trip events are cut out of the analysis. More documentation on how this flag was determined can be found at [Mat14b]. A sample of the contents of such a file is seen in Table 4.3. Any event where the event number from the “HEAD” bank is between the “1stEvent#” and “LastEvent#” where the “Flag” is set to zero, is used as a good trip region. The fact that the flux consistency study (Section 5.5) resulted in consistent results throughout the

experiment, is an indicator that the bad trip regions as denoted by these files were removed correctly. Only good trip regions were used in when extracting yield.

Figure 4.1: Red events are beam tripped events and black events are good beam events for single run. Image taken from [Aa].

Table 4.3: A portion of a trip file created for an experimental run.

TripF	TripR	Flag	1stEvent#	LastEvent#	#Events	...	LiveTime
0	611	-1	50007706	50015057	7352	...	0.982799
1	612	0	50015058	50109862	94805	...	0.838968
2	613	0	50109863	50205159	95297	...	0.839715
3	614	1	50205160	50266178	61019	...	0.895645
⋮	⋮	⋮	⋮	⋮	⋮	⋮	

4.3 Energy and Momentum Corrections

Every experiment in CLAS has its own corrections on momenta and energies. These corrections originate from several sources including the sagging of the tagger, sagging of DC wires, broken detector components, or losing energy through ionization. These corrections are often on the order of 1%. The applied changes will modify each detected

tracks momenta, most readily seen on reconstructed particles. This is due to the fact that the directly detected tracks are assigned their correct mass. Any reconstructed particle is built through four vector algebra, conserving energy and momentum. Therefore, if the detected momentum is not equal to its true value the missing or invariant mass quantities are shifted from the expected values. To illustrate this effect, imagine that a Λ at rest decayed to a π^- and proton along the $-\hat{z}$ and the $\hat{z}$ axes, respectively. If the proton's z-momentum were perturbed slightly from the true value, the reconstructed Λ mass would be incorrect. Figure 4.2 demonstrates this simple example up to a 10% variation of the given proton's momentum. The result of this small simple perturbation could cause up to a 1 MeV shift in the reconstructed Λ mass, $M(p\pi^-)$. In reality a created Λ would not be at rest and has components in the $\hat{x}$, $\hat{y}$, and $\hat{z}$ directions. To reduce this effect, any known momentum corrections were applied to the data as described in the next section.

Figure 4.2: Shown is the effect on the invariant mass of the Λ , given a perturbation of the proton's momentum in the decay of $\Lambda \rightarrow \pi^- p$.

4.3.1 Tagger Corrections

Every photon that gets identified by the tagger gets assigned a specific energy. This energy is determined by the physical location of the detector component, along with the

strength of the magnetic field applied to the tagger. Noted originally by M. Williams [Wil07], by detecting a kinematically complete sample of events, he showed that the tagged energies were slightly skewed. Further more, these energies were skewed in such a way that the location of the supports which hold the tagger could be seen. This means that over time the tagger components began to sag (less so at the support locations) causing the scattered electrons to hit different hodoscopes. Several studies were performed, and a study used to outline these corrections is given by [S⁺05]. These corrections were done based on the overlap of the E-Counters in the tagger, referred to as EID, and can be seen in Figure 4.3. The EID has a specific range of energy tagged in each hodoscope which is roughly 2-4 MeV wide (based on experimental beam energy). These corrections were part of the data calibrations of the g13 experiment, and were manually added into the g10 experiment.

Figure 4.3: Corrections obtained by the magnetic pair spectrometer [S⁺05]. Approximate photon energies are also given to offer a sense of scale.

4.3.2 Energy Loss Corrections

While the particles pass through matter (i.e. the target, start counter, and other parts of CLAS), they lose energy from dE/dx losses and multiple scattering. This loss can be approximated by the Bethe-Bloch equation [O⁺14], which can be calculated with the “eloss” software package[Pas07]. This package has standard corrections built in given the target material, a map of CLAS components, the particle mass, and the particle momentum. The application of these corrections essentially add momentum to each identified particle. This corrected momentum and energy gives a more accurate representation of reconstructed invariant and missing masses, providing better peak location of the given signals. The energy loss correction was applied to each particle during the reconstruction of the neutral Lambda and kaon particles from the charged daughter products. This correction shifted the mass peaks of the reconstructed hadrons closer to the expected PDG [O⁺14] values as seen (for g13) in the Figures 4.4, 4.5, and 4.6. Results from g10 were similar in the fact that all signal peaks shifted 0-3 MeV in the invariant masses and roughly 10 MeV in the missing mass,

$$MM(\gamma d, \pi^+ \pi^- \pi^- p) = \sqrt{(P_\gamma + P_d - P_{\pi^+} - P_{\pi^-} - P_{\pi^-} - P_p)^2}, \quad (4.1)$$

spectrum.

Figure 4.4: The missing mass distributions with (blue) and without (red) the eloss correction. The solid black line is at 0.93827 GeV (known mass of the proton).

Figure 4.5: The invariant Λ mass distributions with (blue) and without (red) the eloss correction. The solid black line is at 1.1157 GeV (known mass of the Λ).

Figure 4.6: The invariant K^0 mass distributions with (blue) and without (red) the eloss correction. The solid black line is at 0.4976 GeV (known mass of the K^0).

4.3.3 Momentum Corrections

Often, additional momentum corrections are also applied to the detected tracks inside CLAS. These corrections account for sag in the drift chambers and improve the overall accuracy and resolution of the recorded momentum. Due to different magnetic fields and target set-up, each experimental run was in charge of their own momentum corrections. It has been shown that these corrections are small compared to the energy loss corrections. Therefore, when analyzing the g10 data (where these corrections were unavailable) the momentum corrections were not applied.

4.4 Event Topology: $\gamma d \rightarrow K^0 \Lambda(p) \rightarrow \pi^- \pi^+ \pi^- p(p)$

The reaction of interest for this analysis is $\gamma n \rightarrow K^0 \Lambda$. Of course, a neutron target is not feasible. Therefore, to measure this one must look at the reaction $\gamma d \rightarrow K^0 \Lambda(p)$, where the proton (p) is a spectator. This channel is slightly more complicated due to the requirement that a kinematic complete set of particles must be detected for the K^0 and Λ . The absence of the spectator proton in the final detection means that one track is already missing, which requires the detection of all K^0 and Λ daughter particles. These come from $K^0 \rightarrow \pi^- \pi^+$ and $\Lambda \rightarrow \pi^- p$. A more subtle reoccurring point throughout this work is that the target neutron is not at rest, and has a non-trivial Fermi Momentum balanced by the neighboring proton. The Fermi Momentum peaks near 70 MeV and dies exponentially to a negligible percentage by a few hundred MeV. The threshold of proton detection within CLAS is roughly 350-400 MeV making the likelihood of detecting the spectator proton insignificant without considering final-state interactions (FSI). These FSI events are when the created K^0 or Λ interact with the neighboring proton, causing a re-scattering. This re-scattering could either redistribute momentum ($\Lambda p \rightarrow \Lambda p$) or even change final states ($\Lambda p \rightarrow \Lambda^* p$, etc.). Moreover, FSI events with other original topologies could be redistributed into this channel (i.e. $\gamma d \rightarrow pp\pi^-$ then $\pi^- p \rightarrow K^0 \Lambda$). The FSI effects are

assumed to be small throughout this analysis⁸. Although it is unknown how many events were lost or gained through FSI events it is known from other measurements at CLAS that at low missing momenta, the Quasi-Free process (where minimal re-scattering is present) dominates the number of events. The best topology to use for this reaction is to detect 3 pions and a proton through $\gamma d \rightarrow K^0 \Lambda(p) \rightarrow \pi^- \pi^+ \pi^- p(p)$, while identifying the event through the fitting of the missing mass for the remaining proton.

4.4.1 Photon Selection

The photons tagged in the experiment can be tracked to specific beam bunches. From the given times between the tagged photon to the target and the event start time given by the detected particle tracks, a timing cut can be placed of ± 1 ns from the time difference peak. Selecting a photon for each event was done based on a good hit status, timing, and a missing mass cut. Given that a photon could be created that does not produce a specific event, a very loose missing mass cut was also place to reduce the photon multiplicity.

4.4.2 Particle Identification

Particle Identification (PID) was done based on the difference in time-of-flight, δt . The path of a particle track was mapped inside CLAS using the drift chamber, which results in a measured distance, D , for each track. The momentum of each particle, p , was also determined using the bend of the track through the magnetic field. The measured time-of-flight, t_{tof}^{meas} , was obtained by using the event time and time readout of the hit in the TOF paddles. Combining all of these one can get a the difference in times, by assuming a specific mass. This can be written as:

$$\delta t = t_{tof}^{meas} - t_{tof}^{calc} = t_{tof}^{meas} - \frac{D}{\beta c} = t_{tof}^{meas} - \frac{D \sqrt{p^2 + m^2}}{pc}, \quad (4.2)$$

⁸ This is discussed in more detail in Appendix D.2

where t_{tof}^{calc} is the calculated time-of-flight using an assumed mass m and the speed of light c . The mass of pions and protons result in different distributions for δt , which should center near zero if the assumption is correct. This can be seen in Figure 4.7.

Figure 4.7: An example of the difference in the time-of-flight distribution versus the track's momentum from one data file. The event tracks shown here are not filtered by any cuts, and only differ by charge and assumed mass. Simulation is not directly comparable to the data at this stage in the analysis, because recreating these momenta distributions would require knowledge of the dominating reaction channels.

Figure 4.8: G13 distributions of the time difference versus momentum for real data (a,c,e) and the simulation (b,d,f). A 2σ cut was made about each Gaussian centroid (red line) for each particle. The events have several cuts employed to reduce the background, making a better comparison between the data and simulation of $\gamma d \rightarrow K_S^0 \Lambda(p)$.

4.4.3 Determination of π_{Λ}^{-}

When detecting the final state of $\pi^+\pi^-\pi^-p$, there exists some ambiguity of which π^- belongs to which parent particle (K^0 or Λ). Several studies were done to find acceptable ways of determining the correct pairing. It has been shown using data and simulation that the π^-p pair that best recreates the mass of Λ is likely the correct pair, only being incorrect $<1\%$ of the time. This is likely due several factors, including the low momentum of the π_{Λ}^{-} from the hyperon decay versus the kaon decay, the sharp resolution of the Λ peak, as well as kinematic restrictions.

4.4.4 Signal Spectrum

Although every event has the tracks corresponding to $\pi^+\pi^-\pi^-p$, only a small fraction of these events are from $K_S^0\Lambda$ decays. As seen from Figures 4.9-4.10, the events of interest will make peaks at both m_{K^0} and m_{Λ} . The simulation agrees with the data remarkably well, showing less than a 1 MeV difference between the extracted centroids. The resolution of the m_{K^0} and m_{Λ} signals were roughly 5 MeV and 2 MeV, respectively.

By cutting on both masses, although non-strange backgrounds still exist and will be addressed in Chapter 6, the data sample is dominated by events from $K_S^0\Lambda$ decays. Again as discussed later there are still other strange particle background contributions which are outlined by Figure 4.11. The subtlety of this figure is that the missing mass can be calculated two different ways: assuming a neutron target (without Fermi momentum) or assuming a deuteron target and identifying a missing proton. The first option, although tempting, is only really useful for demonstration purposes, as the unaccounted Fermi momentum blurs the signal peaks.

When projecting the events on to the missing mass, $MM(\gamma d, \pi^+\pi^-\pi^-p)$, one can clearly see the complication in isolating $K\Lambda$ events from $K\Sigma^0$. This is shown in Figure 4.12.

Figure 4.9: Shown is the invariant mass of the $\pi^- p$ pair for both (left) the data and (right) simulation. The red lines represent a first order polynomial along with a Gaussian fit allowing the extraction of a centroid and σ . The blue lines represents 4σ from the centroid.

Figure 4.10: Shown is the invariant mass of the $\pi^+ \pi^-$ pair after a 4σ cut on $M(\pi^- p)$ for both (left) the data and (right) simulation. The red lines represent a first order polynomial along with a Gaussian fit allowing the extraction of a centroid and σ . The blue lines represents 4σ from the centroid.

Figure 4.11: (g13 data) The missing mass phase space for the $MM(\gamma n, \pi^+ \pi^-)$ versus $MM(\gamma d, \pi^+ \pi^- p)$. The lower left corresponds to $K^0 \Lambda$ channel, while the other two are the background channels $K^0 \Sigma^0$ and $K^0 \Sigma^*$, from left to right. The black dotted line is drawn at $MM(\gamma d, \pi^+ \pi^- p) = 1.08 \text{ GeV}/c^2$.

Figure 4.12: The missing mass distribution peaks about the proton mass due to the creation of $K_S^0 \Lambda$. Another signal can be seen from a missing proton plus photon which was largely associated with the $K_S^0 \Sigma^0$. An extra missing pion would result in the missing mass moving to the right of the black dotted line (drawn at the same location as in Figure 4.11).

4.5 Detector Performance Cuts

To correct for a specific reaction rate, corrections need to be applied to account for the geometry of the reliable detector components. These corrections are obtained through computer simulation and are referred to as detector acceptance. The acceptance is determined using a Monte Carlo (MC) simulation to generate events containing the reaction of interest (Chapter 5). These events are then propagated through CLAS based on an accurate model and decay probabilities. Typically the acceptance would correct for event kinematics (which kinematics can be seen by CLAS), signal smearing, and dead/inefficient drift chamber regions. However, as CLAS ages, many components and regions of CLAS are less reliable than were not modeled in the simulation. Due to this some regions of the detector were removed from the data as well as from the simulated events. The two major types of cuts used to account for these effects are bad TOF paddle knock outs and the removal of events near the toroidal magnets (edges of CLAS). The TOF paddles can become hot (always reading a signal) or inefficient (rarely seeing a signal). These paddles can be cut out individually. The tracks near the edges of CLAS are slightly more involved and dependent on momentum, charge, θ , ϕ , and production vertex due to the applied magnetic field. These tracks are often cut due to the possibility of clipping the edge of the detector (not resulting in a full signal) coupled with the increase in the field gradient in the particle's path.

4.5.1 TOF Paddle Knock Outs

Over time the paddles in the TOF wall can appear to go bad. These bad paddles can be found multiple ways, but in general can be connected to a low number of events within a specific time-of-flight cut. The paddles cut from the analyses can be found in Table 4.4. More documentation of g13a bad SC timing information can be found at [Mat14a].

Table 4.4: SC paddles that are determined to have unreliable timing information for g10a and g13a. The listed paddles were removed from both the real and simulated data.

Data Set	Sector	All Particles	Neg. Charged	Pos. Charged
G10, $E_0 = 3.779$ GeV	1	27	-	-
	2	-	-	-
	3	11, 23, 31	-	-
	4	35	-	-
	5	23, 29	-	-
	6	-	-	-
G13, $E_0 = 2.655$ GeV	1	6, 10, 17, 23, ≥ 40	35, 39	22
	2	8, 39, ≥ 40	-	22
	3	11, 23, ≥ 40	24, 30, 32	22
	4	23, ≥ 40	-	22
	5	17, 23, ≥ 40	37	22
	6	10, 23, ≥ 40	31	21, 22

4.5.2 Fiducial Angle Cuts

To remove events containing tracks that hit the edges of CLAS one must first bin the data into the variables wanted. Figure 4.13 demonstrates the angular distributions of π^- tracks within the spectrometer at different momentum bins. It is clear from the distributions where the six sectors are located in LAB coordinates. This figure also shows exponential fits of

$$\phi = Ae^{B\theta} + C, \quad (4.3)$$

where A , B , and C are fit parameters. These fits are obtained by fitting points from the θ bins onto the ϕ axis, as shown in Figure 4.14. These points themselves are extracted at a 50% level as shown in Figure 4.15. Using this fit as a cut, the results are shown in Figure 4.16. This now clean distribution contains a hard cut based on momentum, particle, and trajectory information. As one can imagine this is only a small effect on any extracted result, as the majority of tracks are within the main portion of the sector. However, this cut ensures that the simulation edges match that of the data, making the results more reliable.

Figure 4.13: The distribution of events over the azimuthal and polar angles for the proton. The red lines indicate the fit for the cuts. The points for fitting were determined by projecting onto the axis of the polar angle within each azimuthal and momentum bin.

Figure 4.14: Projection of the azimuthal angles onto the polar, binned by momentum range.

Figure 4.15: Projection of the azimuthal angles onto the polar, binned by momentum range.

Figure 4.16: The cuts were performed on a randomly generated phase space over all angles to verify that the cutting routine was functioning properly.

4.6 Summary

The experimental parameters and runs for both the g10 and g13 data outline the useful triggering information as well as beam conditions while taking data. Knowing the beam energy allowed the application of tagger corrections to obtain correct photon energies. Combining this with other momentum and energy corrections increased the resolution and accuracy of calibrations seen in the missing and invariant mass spectra. Every particle reconstruction in $\gamma d \rightarrow K^0 \Lambda(p)$ provided a comparison of how well these momentum corrections were determined. This included the reconstruction of the Λ , K^0 , and spectator proton. The decays $\Lambda \rightarrow p\pi^-$ and $K^0 \rightarrow K_S^0 \rightarrow \pi^-\pi^+$ were also used to isolate the events of interest. This is the highest statistic decay mode to detect, given that the spectator proton is never detected by CLAS at low momenta. Instead the spectator proton was constructed via missing mass to correctly account for the unknown Fermi momentum. This means that four reliable tracks must be detected by CLAS. To increase this reliability, tracks that hit components with efficiencies not modeled in simulation were excluded, thus vetoing that event. By removing these events from the data and simulation the effective fiducial volume was decreased, but the remaining events were deemed more dependable. A more in depth analysis can then be done on the surviving signals and backgrounds. The normalization factors can also be determined using these detector cuts on the simulation as discussed in the next Chapter.

5 ACCEPTANCE AND NORMALIZATION

The previous Chapter outlined the method in which events of interest were filtered out from the billions of triggers. However, obtaining the correct events from the data is only part of the story. Finding a more meaningful measurement, in this case the differential cross section, also consists of other quantities. These parts include the detector acceptance and beam normalization. To get the detector acceptance one must simulate events through the detector, compare the quality of events to the data, then process the events to correct for the loss of signal at specific energies and angles. The beam normalization also has several components. These include knowing the number of photons that hit the target (or photon flux), knowing the quality or consistency of this number (flux-normalized yield), and finally knowing the target density as a function of number per area to get a final luminosity with an associated uncertainty.

5.1 Detector Simulation

To simulate events through CLAS one has to:

- Generate Events (program name: fsgen)
 - Model specific decays (i.e. $K^0 \rightarrow \pi^+ \pi^-$)
 - Model realistic kinematics (i.e. cross section weighted)
- Track events through CLAS (program name: GSIM)
 - Register hits in detectors
 - Use interactions with detector material
 - Use particle decay lifetimes
- Produce data-like results (program name: GPP)
 - Smear resolution to match measured detector quantities
 - Knock out known inefficient tracking components (i.e. drift chamber sections)

5.1.1 Fsgen

Events were generated with a Monte Carlo phase space generator called *fsgen* [Ste06]. This program generates events with intended decay branching ratios. The first step used in doing this is declaring a beam energy range. This energy range is weighted by a bremsstrahlung distribution, roughly $1/E_\gamma$ to more accurately model event weighting in the data. Next, the Fermi momentum is taken into account for the relative nucleon motion, which is also weighted to model experimental data. These two quantities allow for the calculation of the event kinematics, which distributes energy to the outgoing parent particles proportionally while conserving momentum and energy. If a specific decay is selected, the parent particle will decay uniformly into its daughter particles. The tracks are then saved in an event file to be sent through the CLAS simulation.

5.1.2 GSIM

The generated events are then propagated through CLAS using GEANT [BBM⁺87] and a map of the CLAS detector and its materials using a program called *GSIM* [Hol]. The GEANT routine follows the particle through the detector mapping and decays the particle based on its lifetime and a random number generator. As the track passes through each component, appropriate signals are fired, as well as simulated energy loss on each track. The output from this is then saved into CLAS data format (information banks).

5.1.3 GPP

The banks of information obtained through GSIM are now smeared in the GSIM post processor (GPP) [Hol]. This also knocks out any tracks recorded as hitting inefficient drift chamber portions. Once the simulated events pass through GPP, the event information is then saved and analyzed through the same routines as for the general data files. Although

GPP parameters could potentially be changed from one analysis to another, the default g10 and g13 parameters were used in the generation of the simulation.

5.2 Simulation Comparison with Data

Several quantities can be compared to the data when simulating the reaction $\gamma d \rightarrow K^0 \Lambda(p)$. The invariant mass quantities $M(\pi^+ \pi^-)$ and $M(\pi^- p)$ were already shown in Figures 4.9-4.10. These average peak values and peak widths were shown to be within a small uncertainty of each other. Another check can be done with the momentum distribution. This could easily disagree with the data for every detected particle separately. To obtain reasonable agreement between the simulation and data one can use preliminary cross section results to weight the trajectories of the K^0 and Λ . The agreement between the simulation and data momentum distributions suggest the line shape of the preliminary cross section is very close to the real cross section.

The original simulation used was $\gamma d \rightarrow K^0 \Lambda(p)$ generated with a t-slope of 0. This resulted with a near uniform distribution in $\cos \theta_{CM}^{K^0}$ (red line in Figure 5.1). Using the uniform distribution of $\cos \theta_{CM}^{K^0}$, it can be seen that each particle's momentum range was covered by the simulation. However, when the simulation was scaled to match the data, it was clear that the momentum ranges did not peak at the same location, as seen by the red lines in Figures 5.2, 5.3, and 5.4 (this is most apparent from the proton's momentum distribution). This demonstrates that the momentum distribution is clearly dependent on $\cos \theta_{CM}^{K^0}$. Therefore, using preliminary cross section estimates, the events were selectively thrown out based on the generated $\cos \theta_{CM}^{K^0}$. Here, when an event is thrown out, it is thrown from the generated and simulated events. This is sometimes referred to as rejection weighting. The new distributions seen by the green lines in Figures 5.1-5.4 confirm that the Monte Carlo events can reproduce the momentum distributions if the correct generated $\cos \theta_{CM}^{K^0}$ is used. In every momentum comparison, the simulations (weighted and

unweighted) were scaled to the data separately using the full integral of each distribution compared to the data. To best compare simulated $\gamma d \rightarrow K^0 \Lambda(p)$ to the data, signal isolating cuts were applied, including a cut on the missing mass of $0.91 < MM(\gamma d, \pi^+ \pi^- \pi^- p) < 0.97$. The missing mass cut was used to exclude most of the Σ^0 production events. There is still a slight contamination of $\gamma d \rightarrow \pi^+ \pi^- \pi^- p(p)$ (phase space) events in the sample, but is small compared with the signal of interest.

Figure 5.1: The generated $\cos \theta_{CM}^{K^0}$ distribution used in simulation binned by energy. The red line indicates the generated uniform $\cos \theta_{CM}^{K^0}$, and the green line indicates the subset of events kept by the rejection weighting.

Figure 5.2: The comparison of the π^- momenta between the data (black points with blue error bars), the unweighted simulation (red, scaled by integration), and the the weighted simulation (green, scaled by integration) binned by energy.

Figure 5.3: The comparison of the π^+ momenta between the data (black points with blue error bars), the unweighted simulation (red, scaled by integration), and the the weighted simulation (green, scaled by integration) binned by energy.

Figure 5.4: The comparison of the p^+ momenta between the data (black points with blue error bars), the unweighted simulation (red, scaled by integration), and the the weighted simulation (green, scaled by integration) binned by energy.

5.3 Acceptance

The acceptance is used to correct for the loss of events due to kinematic limitations from CLAS. For instance, there are gaps in between each sector along with inefficient or dead detector components. The cuts employed on the data, to remove unreliable events must also be done to the simulation in order to correctly apply acceptance values. Both data sets of the g10 and g13 experiments were taken using CLAS; however, each had different components removed from the analysis along with distinct magnetic field settings. This offers two completely different behaviors within CLAS, which will have a large impact

on each acceptance calculation. In general the g13 experiment is thought to have better acceptance than g10 for $\gamma d \rightarrow K^0 \Lambda p \rightarrow \pi^- \pi^+ \pi^- p(p)$, in part due to the direction of bend on low momentum pions. These low momentum pions are produced from the decay $\Lambda \rightarrow \pi^- p$. The separate nominal values used for the acceptances are shown in Figure 5.5. Although these results are important, it should be noted that these are highly dependent on the cuts used in the analysis and in the end, the accepted events should mirror the distributions in the data.

Figure 5.5: Shown are the acceptances of $\gamma d \rightarrow K_S^0 \Lambda p \rightarrow \pi^- \pi^+ \pi^- p(p)$ from both the g10 and g13 experiments. These values do not contain correction for the branching fractions.

5.4 Photon Flux

An important part of measuring any cross section is the number of incident photons on the target. This quantity is measured using the tagger [S⁺00] and recorded in gflux files. These files were created during the cooking procedure, using CLAS gflux software

Figure 5.6: Photon flux for the four-pass ($E_e = 2.65$ GeV) runs. There are 767 points on this plot representing the calculated energy centroids given by the overlap of the E-Counters. It can be seen that there are a few sharp rises and decreases caused by the bad E or T counters. The zero values correspond to the dead E-Counters, and the overlapping hits causes an increase in the neighboring energy values, making increases in the flux for those bins.

[BP05]. Every experimental run has a corresponding gflux file. If the flux file does not exist, the corresponding data file must be (and was) excluded from the analysis. Two main points were looked into for the inclusion of these files. The first point was to test the flux consistency throughout the experiment, which is described in more detail in Section 5.5. Analysis of this consistency allowed an estimate of how consistent the run was within itself. The second point was to match the tagger bins up to the energies found in the data file. An example of an integrated flux (over several runs) for each tagger energy bin can be seen by Figure 5.6. Analysis of these bins allowed an exclusion of simulated events within specific energy ranges, corresponding to bad tagger bins.

5.5 Flux-Normalized Yields

Measuring how consistent an experiment is within itself can be done with a specific extracted yield and the corresponding photon flux. On the most basic level, as the measured

Figure 5.7: Shown is the normalized yield for (a) the g10 low field data and (b) g13a 4pass data versus run number with the calculated means (red).

photon flux increases, the extracted yield should also increase. This yield could in general be from an arbitrary set of cuts employed on all detected tracks. By utilizing a preliminary $K^0\Lambda$ skim, a specific yield was obtained for the number of events with the set of π^+ , π^- , π^- , p^+ per run. The events that correspond to beam instability “trips” were subtracted from this subset. The resultant yield was normalized, or divided, by the total number of incident photons in the run. An example of this can be seen in Figure 5.7. The fluctuation of the normalized yield is in part due to systematic and statistical uncertainties. Both data sets are considered to fluctuate less than 7% from the nominal value. Figure 5.7 demonstrates the integrated (over all energies) normalized yield (showing <2% fluctuation in g13a). This was also done in bins of the measured cross section energies. There the statistical uncertainties dominate and can not typically be assigned an uncertainty of less than 3%.

5.6 Target and Luminosity

As discussed previously, the two experiments g10 and g13 both used different targets. The g10 experiment used a 24 cm long target centered 25 cm upstream from CLAS center.

The g13 experiment used a 40 cm long target centered 20 cm upstream from CLAS center.

Luminosity can be calculated in both cases by

$$L(E_\gamma) = \frac{N_\gamma(E_\gamma)\rho_d\ell N_A}{d_{MM}}, \quad (5.1)$$

where $N_\gamma(E_\gamma)$ is the number of incident photons (for a given energy), ρ_d is the density of deuterium, ℓ is the length of the target, N_A is Avagadro's number, and d_{MM} is the molar mass of deuterium. The g10 values are seen in Table 5.1 and are consistent with previous calculated luminosities from g10 [MGH⁺06]. The g13 values are seen in Table 5.2.

Table 5.1: Calculated luminosities from the g10 experiment. The luminosity is considering runs 42344-42922.

Energy Range (GeV)	$N_\gamma(\Delta E) (\times 10^{12})$	Luminosity (pb^{-1})
1.0 to 1.2	4.34	5.26
1.2 to 1.4	3.56	4.32
1.4 to 1.6	3.03	3.68
1.6 to 1.8	2.64	3.20
1.8 to 2.0	2.13	2.58
2.0 to 2.2	2.01	2.44
2.2 to 2.4	1.86	2.26
2.4 to 2.6	1.62	1.96
2.6 to 2.8	1.61	1.95
2.8 to 3.0	1.92	2.33
1.0 to 3.0	2.47	29.98

Table 5.2: Tabulated luminosity for g13a. The 4pass luminosity is considering runs 53538-53862. The 3pass luminosity is considering runs 53333-53532.

Energy Range (GeV)	4 Pass		3 Pass	
	$N_\gamma(\Delta E) (\times 10^{12})$	Lum. (pb^{-1})	$N_\gamma(\Delta E) (\times 10^{12})$	Lum. (pb^{-1})
0.90 to 1.00	2.42	4.88	1.69	3.41
1.00 to 1.10	2.42	4.90	1.33	2.68
1.10 to 1.20	2.34	4.73	1.35	2.73
1.20 to 1.30	2.03	4.11	1.19	2.40
1.30 to 1.40	1.79	3.61	1.14	2.31
1.40 to 1.50	1.60	3.24	1.07	2.17
1.50 to 1.60	1.64	3.31	1.03	2.08
1.60 to 1.70	1.51	3.05	0.95	1.92
1.70 to 1.80	1.31	2.66	0.96	1.93
1.80 to 1.90	1.38	2.80	0.92	1.86
1.90 to 2.00	1.30	2.62	-	-
2.00 to 2.10	1.24	2.50	-	-
2.10 to 2.20	1.23	2.50	-	-
2.20 to 2.30	1.12	2.26	-	-
2.30 to 2.40	1.16	2.34	-	-
2.40 to 2.50	1.15	2.32	-	-
0.90 to 1.90	17.07	34.50	11.62	23.50
0.90 to 2.50	25.61	51.76	-	-

5.7 Summary

The calculated acceptance has been completed by using simulation of $\gamma d \rightarrow K^0 \Lambda(p)$ events through CLAS. These events are tracked utilizing GSIM, which incorporates GEANT modeled trajectories inside the detector systems. Tracks were finally smeared to resemble real data input using a post processor (GPP). The CLAS geometry, detector cuts, and the knowledge of the number of generated events, allows an appropriate correction to the yield from the data. This acceptance corrected yield in combination with the luminosity result in the capability of measure an absolute normalization in the cross section. The uncertainty in the luminosity is seen to be dominated by the variance in flux as a function of run number, or time. The uncertainty in the simulation is folded into the systematic uncertainties found by the difference in cross sections in later chapters. Reproduction of

previously measured cross sections can also demonstrate that the overall normalization capability as seen in Appendix D.

6 YIELD EXTRACTION

Before identifying backgrounds, it is useful to know what the signals from $\gamma d \rightarrow K^0 \Lambda(p)$ will look in each mass projection. Simulated distributions (Figure 6.2) are offered as examples of what the signal should look like compared to what is seen in the data (Figure 6.1).

Figure 6.1: The events of interest are clearly visible in the data without any invariant mass cuts applied.

As expected the data events do not represent a completely clean signal. Background processes complicate the analysis. These backgrounds are explored in more detail in Section 6.2. Utilizing the characteristics of the background processes they can be separated from the signal yield.

Figure 6.2: The simulated distributions demonstrate where the events of interest are located without any invariant mass cuts applied.

6.1 Isolation Cuts and Systematics

A large portion of background and unreliable events in the data were removed by employing a set of cuts as seen in Table 6.1. The acceptance is determined using the same cuts in order to properly correct for event losses. The detector cuts were discussed in Section 4.5.

Several studies were performed in estimation of the systematic uncertainties. These include particle identification cuts, energy/momentum corrections, kaon and lambda candidate selections, fitting methods, acceptance uncertainties, and bin width effects. Each systematic uncertainty is found by adjusting fits, cuts, or other variables to observe how the final results change. The overall effect of these observations can be quantized by the

Table 6.1: A rough outline and description of each cut used to reduced the background contamination is reported here.

Label	Type of Cut	Description of Cut
A	PID,4 tracks, tag photon	Section 4.4
B	Energy Range	$0.9 \leq E_\gamma \leq 3.0$ (GeV)
C	Tagger Cuts	Section 5.4
D	Bad Paddles	Section 4.5
E	Fiducial	Section 4.5
F	Beam Trip	Section 4.2
G	Z Vertex	Around Target
H	Missing Momentum	$ p_{miss} \leq 0.3$ GeV
I	$M(\Lambda)$	4σ , Section 4.4
J	$M(K^0)$	8σ , Section 4.4
K	$M(K^0)$	4σ , Section 4.4

relative difference,

$$\text{Relative Difference} = \frac{y_B - y_A}{y_A}, \quad (6.1)$$

where y_A represents the nominal (differential cross section) results and y_B represents the differential cross section with a slightly varied cut applied. Obtaining a point-to-point systematic uncertainty may not be all that reliable due to low statistics near extreme angles, where statistical uncertainties may dominate. Therefore, where deemed appropriate an average point-to-point uncertainty is used as an estimate of the overall systematic effect. This is done by calculating the relative difference for all data points, and histogramming the results. If enough data points exist (and an uncorrelated effect is present) the distribution should look Gaussian in nature. The shift of this distribution represents the systematic effect, and the width of it represents the statistical fluctuations. A summary of these results [CHC14, CTC⁺16] can be seen in the Tables 6.2 and 6.3.

Table 6.2: Summary of the g10 systematic effects, estimating a total average point-to-point uncertainty.

Investigated Cut/Correction	Systematic Uncertainty
Luminosity	5.0%
Acceptance	1.6%
Yield Extraction	6.3%
Detector	5.0%
Branching Ratios	<1.0%
Total	10%

Table 6.3: Summary of the g13 systematic effects, estimating a total average point-to-point uncertainty.

Investigated Cut/Correction	Systematic Uncertainty
Luminosity	2.6-7.0%
Acceptance	1.9-2.1%
Yield Extraction	4.5-11.4%
Detector	3.2%
Branching Ratios	<1.0%
Total	7% - 14%

6.2 Backgrounds

The reaction of interest is $\gamma n \rightarrow K^0 \Lambda$. To measure this process the decay products of K_S^0 and Λ are detected. Therefore the final state particles that are detected contain $\pi^- \pi^+ \pi^- p$. The four tracks could be produced several different ways. The backgrounds can be attributed to two categories. The first category is a five (or more) track background, where one (or more) tracks were missed by CLAS. The second category of background processes are from a four track background, where no strange quarks were produced.

6.2.1 Five Track

By extracting the yield through the missing mass, it is likely that any process producing an extra pion (or other massive particle) is well separated from the spectator proton missing mass measured (in 4-vector notation) by $MM(K^0 \Lambda) = \sqrt{(P_d + P_\gamma - P_{K^0} - P_\Lambda)^2}$.

Near the missing mass signal, the most prevalent five track background is identified as $\gamma d \rightarrow K^0 \Sigma^0 p \rightarrow K^0 \Lambda(\gamma p) \rightarrow \pi^- \pi^+ \pi^- p(\gamma p)$.

The $K^0 \Sigma^0$ background can't be separated from the $K^0 \Lambda$ signal except through the missing mass, as both reactions will produce a peak at the Λ and K^0 masses. The characteristic shape of this background is explored through simulation. When extracting the yield for the $K^0 \Lambda$ channel, a fit to this background shape from simulations is used to subtract the $K^0 \Sigma^0$ events. This fit is described in more detail in Section 6.3. As seen from Figure 6.3, this background combined with simulated $K^0 \Lambda$ events can represent the data fairly well.

Figure 6.3: Shown is the missing mass distribution for the data (left, black), simulated $K_S^0 \Lambda$ (middle, red), simulated $K_S^0 \Sigma^0$ (middle, green), and the comparison between the data (right, black) and scaled simulations (right, blue)

Other five track backgrounds include $\gamma d \rightarrow K^* \Lambda p \rightarrow K^0 \Lambda(\pi p)$, $\gamma d \rightarrow K^0 \Sigma^* p \rightarrow K^0 \Lambda(\pi p)$, and $\gamma d \rightarrow \pi^- \pi^+ \pi^- p(\pi^+ n)$. Although select backgrounds are capable of creating real K^0 or Λ peaks, the missing mass signal presented by such a background would be separated from the signal by a large missing mass. From simulation studies, the small probability of the missing mass to be near the spectator proton mass shows that these channels are not contaminating the data set.

6.2.2 Four Track

Although obtaining these four final state particles through the strange sector is likely only from K^0 and Λ decays, other processes from non-strange production mechanisms may contribute to the four-track background. There are several processes to produce this final state. The easiest to consider is the production channel of $\gamma d \rightarrow \rho \Delta^0 p \rightarrow \pi^- \pi^+ \pi^- p(p)$. This process is hard to identify due to the decay width of the ρ and Δ . These widths are extremely large (~ 150 MeV), producing a vast kinematic coverage concerning each track's momentum. It is worth while to note that there are several other production channels that could result in the final state of $\pi^- \pi^+ \pi^- p(p)$. These mechanisms also yield a large sample of kinematic possibilities. The general trend of such a process would result in a missing mass peak at the value of the proton mass, but would not produce a peak at the kaon or Λ mass. The absence of these peaks can be seen in Figure 6.4. This plot compares the data to simulated $\gamma d \rightarrow \pi^- \pi^+ \pi^- p(p)$ events. This event generation utilized a uniform phase space distribution to model the kinematics. Similar results were seen when an intermediate $\rho \Delta$ state was simulated. The events with π^- and proton tracks that result in an invariant mass between 1.09 GeV and 1.14 GeV seem to match the background shape near the Λ signal. Likewise, the events with π^- and π^+ tracks that result in an invariant mass between 0.430 GeV and 0.570 GeV seem to match the background shape near the K^0 signal (after a cut on $M(\pi^- p)$) as seen by Figure 6.4. Identifying the characteristics of the contributing backgrounds make it possible to account for them through subtraction or fitting techniques.

(a) Shown is $M(\pi^- p)$ for the data (solid blue) and a scaled simulated pion background (dashed red). (b) Shown is $M(\pi^- \pi^+)$ after a cut on $M(\pi^- p)$ for the data (solid blue) and a scaled simulated pion background (dashed red).

Figure 6.4: A demonstration that a phase space representation for a pion background can reproduce the background seen in the data.

6.3 Fit to Σ^0 Background

A hyperbolic tangent fit was used to describe the $\gamma d \rightarrow K^0 \Sigma^0 p \rightarrow K^0 \Lambda(\gamma p)$ background. It was necessary to combine this $K^0 \Sigma^0$ fit with a Gaussian function describing the proton peak in order to extract the $\gamma d \rightarrow K^0 \Lambda(p)$ yield (Section 6.4). When reconstructing an incomplete reaction (*i.e.* missing a γ and proton), the resulting missing mass will not produce a sharp peak. Instead, the two missing 4-vectors tend to smear out the peak depending on the kinematics of the event. Although describing the whole $K^0 \Sigma^0$ signal shape would be complex, the edge of the distribution is more reliable. To approximate the edge of this smeared out peak the parameters to the background function were obtained by fitting simulated $K^0 \Sigma^0$ events. This only requires that the simulated distributions of this channel are well understood near the expected missing mass peak for $K^0 \Lambda$. The modified

hyperbolic tangent function used is represented by

$$h(x) = A \times \left(\frac{1.0 - \exp(-C \times (x - B))}{1.0 + \exp(-C \times (x - B))} + 1.0 \right), \quad (6.2)$$

where x is the missing mass, A is the height, B is the shift of the half max to the right of zero (ranges from approximately 0.97 to 1.0), and C controls the slope of the hyperbolic tangent. It is important to know that Equation 6.2 is only meant to be valid at missing mass values less than 1.05 GeV. Considering this, the sigmoidal function is able to describe the simulation quite well (Figure 6.5). The scaled shape also appears to represent the data appropriately (Section 6.4 and [CHC14, CTC⁺16]).

Figure 6.5: Example fits obtained on the missing mass of $\gamma d \rightarrow K^0 \Sigma^0 p \rightarrow \pi^+ \pi^- \pi^- p (\gamma\gamma)$ simulations. The fit used was a hyperbolic tangent as seen by Equation 6.2.

6.4 Fit to Signal

The fit to the $K^0 \Lambda$ signal must be parameterized simultaneously with the $K^0 \Sigma^0$ background distribution. This is due to the fact that the $K^0 \Sigma^0$ background can not be removed with any simple cut. These events will produce a peak at the Λ and K^0 invariant masses along with the desired $K^0 \Lambda$ events. Fitting a background shape combined with a Gaussian signal function to the the missing mass is capable of extracting the $\gamma d \rightarrow K^0 \Lambda(p)$ yield, despite the fact that the event distributions fade into one another. The characteristic shape of this background was explored through simulation, described in Section 6.3. When

extracting the yield for the $K^0\Lambda$ channel, a fit to this background shape was used to subtract the $K^0\Sigma^0$ events, which can be seen in Figure 6.6. Other five track backgrounds that do not produce real K^0 's or Λ 's are significantly reduced by invariant mass cuts and, more importantly, are separated from the signal by a large missing mass.

(a) Shown is a hyperbolic tangent curve fit to $\gamma d \rightarrow K^0\Sigma^0 p \rightarrow \pi^-\pi^+\pi^-p(\gamma p)$ simulation. (b) Shown is a fit to one data bin. The fit uses a Gaussian and a hyperbolic tangent shape that is parameterized from the simulation.

Figure 6.6: This is an example of a fit to the g13 data to extract the number of events that are missing only one proton.

6.5 Non-Strange Background Subtraction

Background from $\gamma d \rightarrow X \rightarrow \pi^-\pi^+\pi^-p(p)$, where X could be any combination of particles, is expected to exist in the data with a missing mass of the proton. The nature of these production channels are described in Section 6.2.2. To account for these non-strange backgrounds, the sidebands of K^0 were projected onto the missing mass plane. The number of events that are consistent with the desired missing mass can be found in each region noted in Figure 6.7. To obtain the correct number of $K^0\Lambda$ events, subtraction is used based on the sidebands of the K^0 distribution. The events in Region 2 of Figure 6.7 can be

written as

$$N_2^{K^0\Lambda} + N_2^{K^0\Sigma^0} + N_2^{\pi^-\pi^+\pi^-p}, \quad (6.3)$$

where $N^{K^0\Lambda}$ is the number of $\gamma d \rightarrow K^0\Lambda(p)$ events, $N^{K^0\Sigma^0}$ is the number of $\gamma d \rightarrow K^0\Sigma^0(p)$ events, and $N^{\pi^-\pi^+\pi^-p}$ is the number of $\gamma d \rightarrow \pi^-\pi^+\pi^-p(p)$ events that do not follow from the decays of K^0 or Λ . To correct for the overestimate of $K^0\Lambda$ yield, $\pi^-\pi^+\pi^-p$ events in Region 1 and Region 3 of Figure 6.7,

$$N_1^{\pi^-\pi^+\pi^-p} + N_3^{\pi^-\pi^+\pi^-p}, \quad (6.4)$$

were subtracted from the events of Region 2. A 1-D representation can also be seen in Figure 6.8. This resulted in the raw yield of $K^0\Lambda$ after subtraction of $K^0\Sigma^0$ events. An estimation of 0-20% of non-strange background contamination within the data is made which depends on kinematics.

Figure 6.7: Shown is the invariant mass of the $\pi^+\pi^-$ pair that is marked as a possible kaon versus the missing mass. This figure demonstrates where non-strange $\pi^-\pi^+\pi^-p$ background is contributing to any extracted yield. The signal and the K^0 sidebands are outlined by the dashed lines.

Figure 6.8: The events in the data within the K^0 peak (between the two blue lines) can be described as $N_A = N_{K^0\Lambda} + N_{K^0\Sigma^0} + N_{\pi^-\pi^+\pi^-p}$. The events within the K^0 sideband (between the blue and red lines), assuming $N_{K^0\Lambda} = N_{K^0\Sigma^0} = 0$, can be described as $N_B = N_{\pi^-\pi^+\pi^-p}$.

6.6 Summary

In summary, the data clearly show that $K^0\Lambda$ events exist. Extracting the yield corresponding to these events required the consideration of several background channels. Many production channels that could have potentially complicated this process had a negligible effect due to their non-overlapping missing mass distribution. These channels included K^* , Λ^* , and Σ^* backgrounds. The two main backgrounds that need special attention in order to obtain the correct number of events are $\gamma d \rightarrow K^0\Sigma^0(p)$ and $\gamma d \rightarrow \pi^-\pi^+\pi^-p(p)$. The nature of the $K^0\Sigma^0$ background was investigated and was removed based on shape fitting in each kinematic bin. The non- K^0 producing events were isolated and subtracted from the total yield by studying the side bands of the $K^0\Lambda$ events. This demonstrated that up to 20% of the events originated from background channels. The corrected yield can then be combined with the appropriate acceptance and normalization

factors to obtain the polarization observables of $\frac{d\sigma}{d\cos(\theta)}$ and P , which is the topic of the next Chapter.

7 CROSS SECTION AND Λ RECOIL POLARIZATION

Outlined in Chapter 1, cross sections and polarization observables are essential to identifying nucleon resonant states. As the databases of these observables grow, the more we constrain models based on non-perturbative QCD. Complete experiments of coupled channels will yield the best results when fitted with partial wave analyses. The differential cross section ($\frac{d\sigma}{d\Omega}$) and Λ recoil polarization (P) on the channel $\gamma d \rightarrow K^0 \Lambda(p)$ will be one of the first measured observables published for this channel.

7.1 Differential Cross Section

The differential cross section for the $\gamma d \rightarrow K^0 \Lambda(p)$ reaction can be written in experimental quantities as:

$$\frac{d\sigma_0}{d\cos\theta_{K^0}^{CM}} = \frac{1}{L(E_\gamma)\Delta\cos\theta_{K^0}^{CM}} \frac{Y(E_\gamma, \cos\theta_{K^0}^{CM})}{\alpha(E_\gamma, \cos\theta_{K^0}^{CM})} \times B.F., \quad (7.1)$$

where $L(E_\gamma)$ is the luminosity, $\Delta\cos(\theta_{K^0}^{CM})$ is the bin width of $\cos\theta_{K^0}^{CM}$, $Y(E_\gamma, \cos\theta_{K^0}^{CM})$ is the corrected yield, $\alpha(E_\gamma, \cos\theta_{K^0}^{CM})$ is the acceptance, and $B.F.$ is the branching fraction or inverse branching ratios of the decay channels for the neutral hadrons ($K^0 \rightarrow K_S^0$, $K_S^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow \pi^- p$). The luminosity, as explained in Section 5.6, is measured as a function of beam energy in each experiment. The differential cross section in Equation 7.1 is related to the differential cross section in Equation 1.8 by the relation

$$\frac{d\sigma_0}{d\Omega} = \frac{1}{2\pi} \frac{d\sigma_0}{d\cos\theta_{K^0}^{CM}}. \quad (7.2)$$

The cross section here is binned and measured as a function of E_γ . Analyses that measure cross sections on proton targets can easily convert back and forth to the center of mass energy (W or $\sqrt{s}$) by a simple formula. Assuming the neutron is at rest in the reaction $\gamma n \rightarrow K^0 \Lambda$ one can use the equation

$$W = \sqrt{s} = \sqrt{m_n^2 + 2E_\gamma m_n}, \quad (7.3)$$

where m_n is the neutron mass and E_γ is the beam energy. Since the neutron is not necessarily at rest, there will be a spread in W for a given E_γ . In general this distribution should still peak at the value obtained from Equation 7.3. A simple test with the data can also be done to show the correlation of W with E_γ . This is done by measuring the invariant mass of all detected particles,

$$W = M(\pi^-\pi^+\pi^-p) = \sqrt{\left(\sum P_i\right)^2}, \quad (7.4)$$

where P_i is the four vector of each detected track (assuming no missing tracks). This quantity should be equivalent to W for all events that are **only** missing the spectator proton and have perfect momentum correction. This distribution can be seen in Figure 7.1 for the data, simulated $K^0\Lambda$, and simulated $K^0\Sigma^0$. The spread in W for a specific E_γ is why the cross section is measured in bins of E_γ .

(a) Shown is $M(\pi^+\pi^-\pi^-p)$ for the data, with a restrictive missing mass cut. Thus, $M(\pi^+\pi^-\pi^-p)$ is likely to be equal to W . (b) Shown is $M(\pi^+\pi^-\pi^-p)$ for the simulated $K^0\Lambda$, where all the decay tracks are detected. Thus $W = M(\pi^+\pi^-\pi^-p)$. (c) Shown is $M(\pi^+\pi^-\pi^-p)$ for the simulated $K^0\Sigma^0$, where there is an additional missing γ . Thus $W \neq M(\pi^+\pi^-\pi^-p)$.

Figure 7.1: Shown is $M(\pi^+\pi^-\pi^-p)$ versus E_γ . The peak (not nec. mean or median) of the W distribution at each energy matches that of Equation 7.3, when there are no missing tracks.

Using the g13 data set, Figure 7.2 shows the differential cross section of the $\gamma d \rightarrow K^0 \Lambda(p)$ reaction with respect to $\cos(\theta_{CM}^{K^0})$ for 0.1 GeV photon energy bins between 0.9 to 2.5 GeV. In figure 7.3, the cross section was binned by the center-of-mass energy for various $\cos(\theta_{CM}^{K^0})$ bins for both g10 and g13 data sets. Close agreement is seen between the two experiments, with some discrepancies in the forward bin: $0.7 < \cos(\theta_{CM}^{K^0}) < 0.8$. The Kaon-Maid model is also shown, assuming no contribution from the $K^*(892)$ and $K_1(1270)$. These parameters were chosen for the model as this provided the best agreement with data. From this it is seen that this data will be essential to better constrain parameters associated with t-channel contributions. The complementary nature of $\gamma d \rightarrow K^0 \Lambda(p)$ to that of $\gamma p \rightarrow K^+ \Lambda$ will also help sort out the interference effects between known resonances. A preliminary PWA fit from the BoGa group is also shown in Figure 7.3. They achieved two different solutions during their fitting procedures. The solutions are drawn as a shaded region to demonstrate where they deviate the most from each other.

Figure 7.2: The g13 differential cross sections in bins of $\cos(\theta_{CM}^{K^0})$ for each beam energy.

Figure 7.3: The g10 (circles) and g13 (squares) differential cross section in bins of W (GeV) for each $\cos(\theta_{CM}^{K^0})$. The Kaon-Maid model (dashed line) is shown, assuming no contribution from the $K^*(892)$ and $K_1(1270)$ along with the possible the preliminary BoGa $K^0 \Lambda$ fit (shaded curve). The inner error bars represent the statistical uncertainty. The outer error bars are the statistic and systematic uncertainties added in quadrature.

7.2 Total Cross Section

The total cross section can be found by integrating over all $\cos(\theta_{CM}^{K^0})$ of the differential cross section. However, it can be seen from Figure 7.2 that all of the energies investigated lack tight constraint at extreme angles. This presents two sources of uncertainty, the uncertainty of the fit to the points, as well as an uncertainty associated with the absence of points at extreme angles. The absence of these points makes this integration more sensitive, but it does not prevent a reasonable estimation of the total cross section to be obtained. Although one individual fit function may fit the data within the measured angular region quite well, it may not be fully representative of the overall uncertainty. To obtain an estimate on the uncertainty attributed with extrapolations to extreme $\cos(\theta_{CM}^{K^0})$ regions, many functions were tried. These functions include (where $z = \cos \theta_{CM}^{K^0}$):

- A second order Legendre Polynomial

$$\frac{d\sigma}{dz} = A_0 + A_1z + A_2(1.5z^2 - 0.5)$$

- A third order Legendre Polynomial

$$\frac{d\sigma}{dz} = A_0 + A_1z + A_2(1.5z^2 - 0.5) + A_3(2.5z^3 - 1.5z)$$

- A second order Legendre Polynomial multiplied by an exponential

$$\frac{d\sigma}{dz} = (A_0 + A_1z + A_2(1.5z^2 - 0.5))e^{Bz}$$

- A third order Legendre Polynomial multiplied by an exponential

$$\frac{d\sigma}{dz} = (A_0 + A_1z + A_2(1.5z^2 - 0.5) + A_3(2.5z^3 - 1.5z))e^{Bz}$$

- A third order Legendre Polynomial with linear extrapolations

$$\frac{d\sigma}{dz} = \begin{cases} m_0z + b_0, & \text{if } z < -0.45 \\ A_0 + A_1z + A_2(1.5z^2 - 0.5) + A_3(2.5z^3 - 1.5z), & \text{if } -0.45 < z < 0.50 \\ m_1z + b_1, & \text{if } z > 0.50 \end{cases}$$

Assuming these functions can fit the data well and have realistic behaviors near the forward and backward angles, the fits could be used for comparisons of total cross section

results. Figure 7.4 demonstrates several fits to the data with integrated cross sections shown in Figure ???. The integrated cross section is obtained using *root*'s *Integral()* and *IntegralError()* functions, which uses the covariant matrix given by the fit when calculating the error. If the uncertainty of the integral is larger than the integral itself, it is not used in calculating the variance. Using the third order Legendre Polynomial as the base fit, the total cross section can be computed and is shown in Figure 7.5. The inner error bars are the error estimates from the third order Legendre Polynomial integration. The outer error bars represent the computed standard deviation (between third order polynomial and all other fits) added in quadrature with the inner error bars.

Figure 7.4: The left panel shows different fits of the g13 differential cross sections (at $E_\gamma = 1.65$ GeV) using five different fits. The shaded regions represent a 1σ band of the fit to the data. The right panel shows the integration of the each fit used on the g13 differential cross sections for all energies.

(a) The total cross section results from both g13 (squares) and g10 (circles) experiments. Also shown is the Kaon-Maid prediction given two different input parameters (brown and light blue). This prediction clearly is not very constrained in this channel, in reference to contributions from higher mass kaons.

(b) The total cross section results from both g13 (squares) and g10 (circles) experiments. Also shown is the total cross section of $\gamma p \rightarrow K^+ \Lambda$ and the corresponding BoGa PWA fit solutions BG2014-02[GCS⁺14] (dot/dashed curve), $K^0 \Lambda$ solution 1 (solid curve), and $K^0 \Lambda$ solution 2 (dashed curve).

Figure 7.5: Shown is (a) the theoretical predictions and (b) the complimentary reaction channel $\gamma p \rightarrow K^+ \Lambda$ compared to the total cross section of $\gamma d \rightarrow K^0 \Lambda(p)$.

7.3 Λ Recoil Polarization

The polarization observable P , is associated with the recoil baryon polarization. In the case of $\gamma d \rightarrow K^0 \Lambda(p)$ this is referring to the Λ . This polarization can be found by looking at the average angle between the proton from $\Lambda \rightarrow p\pi^-$ and the reaction plane (outlined in Section 1.3.2). There are several ways to measure this quantity, as this variable is a part of most other polarization observables. With an unpolarized beam, there still exist two methods to obtain this value as discussed in Sections 7.3.1 & 7.3.2.

7.3.1 Integrated Two Bin

Starting from Equation 1.14 in Section 1.3.2 the number of protons with a positive $\hat{y}'$ component is

$$N^+ = \int_0^1 N(\cos \theta_{y'}) d(\cos \theta_{y'}) = \frac{N}{2} \left(1 + \frac{\alpha}{2} P\right). \quad (7.5)$$

Likewise, the number of protons with a negative $\hat{y}'$ component is

$$N^- = \int_{-1}^0 N(\cos \theta_{y'}) d(\cos \theta_{y'}) = \frac{N}{2} \left(1 - \frac{\alpha}{2} P\right). \quad (7.6)$$

Combining Equations 7.5 and 7.6, a P dependent difference can be created,

$$N^+ - N^- = \frac{N}{2} \alpha P. \quad (7.7)$$

Clearly, the total number of Λ decays can be represented by

$$N = N^+ + N^-. \quad (7.8)$$

Finally, solving for P , one can come to the asymmetry:

$$P = \frac{N^+ - N^-}{\frac{\alpha}{2}(N^+ + N^-)}. \quad (7.9)$$

If acceptance correction is used, each N^+ and N^- would be acceptance corrected individually, before calculating P . The acceptance correction is expected to be small for a two bin approach, as the systematic effects should cancel in the asymmetry measurement. If more bins were used, this would no longer be the case.

7.3.2 Fit Distribution

The fit to the $\cos \theta_{y'}$ distribution should be linear and dependent on the total number of events, following from Equation 1.14. Writing this equation a different way to better extract P given the graph in Figure 7.7 we can obtain

$$\begin{aligned} N(\cos \theta_{y'}) &= \frac{N}{2} (1 + P \alpha \cos \theta_{y'}) \\ &= A + ABC \cos \theta_{y'}, \end{aligned} \quad (7.10)$$

where A is a free parameter that represents the average number of counts/binsize, B is a fixed parameter equal to α , and C is an extracted parameter equal to P . The acceptance as a function of $N(\cos \theta_{\gamma'})$ can be seen in Figure 7.6. This demonstrates that events are more likely to be accepted at the extremes of $\cos \theta_{\gamma'} = \pm 1$ by as much as a factor of 7 in the kinematic bin of $E_\gamma = 1.20$ GeV and $\cos \theta_{K^0}^{CM} = -0.30$.

Figure 7.6: Shown is the acceptance as a function of $\cos \theta_{\gamma'}$ at $E_\gamma = 1.20$ GeV and $\cos \theta_{K^0}^{CM} = -0.30$.

Figure 7.7: Shown is the acceptance corrected yield as a function of $\cos \theta_{\gamma'}$ at $E_\gamma = 1.20$ GeV and $\cos \theta_{K^0}^{CM} = -0.30$ fit to a first order polynomial. This demonstrates that extracting P from a linear fit requires acceptance correction.

7.3.3 Results

By utilizing both methods (described in Sections 7.3.1-7.3.2) to find P for each E_γ and $\cos(\theta_{CM}^{K^0})$ bin, the results can be plotted just like the cross section in bins of one variable as a function of the other. Any disagreement between the two methods would indicate a possible bias from acceptance correcting or bad fits to the data. The results for both methods can be seen in Figure 7.8. A comparison can be done between the methods to

Figure 7.8: Shown are the results of P , given the two different methods. Agreement is seen between the two methods: 2-bin (blue squares) and 6-bin (black circles).

provide a first order estimate of the systematic uncertainty within the experiment.

7.4 Summary

In summary, the observables $\frac{d\sigma}{d\cos(\theta)}$ and P have been measured on the channel $\gamma d \rightarrow K^0 \Lambda(p)$. Although the target used was not a collection free neutrons, these results are estimated to be consistent with such a channel as $\gamma n \rightarrow K^0 \Lambda$. This is due to the overpowering signal from the quasi-free process. This process can be equated to a spectator approximation combined with minimal secondary scattering. Keeping this in mind, PWA fits can be utilized in order to model which resonances are contributing to the final results along with the coupling strength. These fits must be multi-channel to appropriately constrain all free parameters. If these resonances exist in both $\gamma p \rightarrow K^+ \Lambda$, then the branching ratios must also be consistent given that the Λ is an isospin singlet. If there are resonances missing in the fit to $\gamma n \rightarrow K^0 \Lambda$ observables, then these states can be classified into specific multiplets. The aim of this work was to make two observables ($\frac{d\sigma}{d\cos(\theta)}$ and P) on this channel available for higher level PWA, which can in turn be compared with theoretical models of the N^* spectrum.

8 CONCLUSIONS AND OUTLOOK

The goal of understanding non-perturbative QCD is a difficult undertaking. Initial studies of particle physics brought new comprehension and continues to show that there is so much more to learn. Chapter 1 illustrated that continual progress can be made in this regime by looking at the baryon excitation spectrum. Although some of these spectroscopic states can be seen effortlessly, many are undetectable without other tools. The complication arises from the observed nature in which these resonances present themselves (*i.e.* in differential cross sections and spin observables), and are commonly quoted as “wide and overlapping” in masses. The typical energy width of a single resonance can be on the order of 200 MeV to 400 MeV. The multiplicity of these states within 400 MeV, along with the fact that these have complex amplitudes, allow the resonances to hide broad peaks as they interfere with one another.

Previously, the main mechanisms used to identify such states were from elastic pion scattering $\pi N \rightarrow \pi N$. This reaction had great success in finding new resonances due to the high statistics and ability to model/fit the resulting measurements. The successes eventually hit limitations including the possibility that specific resonances may have small branching ratios into the final state of πN . To address the restrictions of pion data, facilities such as JLAB have put effort into investigating other scenarios achieved through photo- and electro-production. Using these production techniques and several 2-body observable quantities, a new high statistics reaction framework was created in which resonances could be found and verified (discussed in Section 1.3).

The polarization observables defined by this framework depend on the contributing mechanism to a final state at each beam energy and production angle. This final state could be of any type including πN , ηN , ρN , ωN , $K\Lambda$, or $K\Sigma$. The most talked about final states are often the $K\Lambda$ and $K\Sigma$ channels. This is partially due to the parity violating decays $\Lambda \rightarrow p\pi^-$ and $\Sigma^+ \rightarrow p\pi^0$. With enough statistics the recoil polarization can be

measured from the decay angular distributions without too much complication. This opens the door for the measurements of double polarization observables that depend on this recoil polarization, P . A complete experiment within one channel or even a family of channels (like KY) could provide tight constraints on any PWA solution's included resonances. The current state of the KY channel experimental results can be seen in Tables 8.1 and 8.2. The completion of this thesis project will be essential in order to achieve this goal.

Table 8.1: Possible kaon production channels and the corresponding Single and Beam-Target observables. The table shows previously published work (✓), this work (✓), data acquired by CLAS (✓).

Channel	Single				Beam-Target			
	σ	Σ	T	P	E	F	G	H
$\gamma p \rightarrow K^+ \Lambda$	✓	✓	✓	✓	✓	✓	✓	✓
$\gamma p \rightarrow K^+ \Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓
$\gamma p \rightarrow K^0 \Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓
$\gamma n \rightarrow K^0 \Lambda$	✓	✓		✓	✓	✓	✓	
$\gamma n \rightarrow K^+ \Sigma^-$	✓	✓						
$\gamma n \rightarrow K^0 \Sigma^0$	✓	✓		✓	✓	✓	✓	

Table 8.2: Possible kaon production channels and the corresponding Beam-Recoil and Target-Recoil observables. The table shows previously published work (✓) and data acquired by CLAS (✓).

Channel	Target-Recoil				Beam-Recoil			
	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$\gamma p \rightarrow K^+ \Lambda$	✓	✓	✓	✓	✓	✓	✓	✓
$\gamma p \rightarrow K^+ \Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓
$\gamma p \rightarrow K^0 \Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓
$\gamma n \rightarrow K^0 \Lambda$			✓	✓	✓	✓	✓	✓
$\gamma n \rightarrow K^+ \Sigma^-$								
$\gamma n \rightarrow K^0 \Sigma^0$			✓	✓	✓	✓	✓	✓

Previous analyses on $\gamma p \rightarrow K^+ \Lambda$ have shown that there are resonances originally not observed from pion data. Therefore, the channel $K^0 \Lambda$ should be able to confirm these found states. For example, Figure 7.5b clearly shows a “bump” in the $\gamma p \rightarrow K^+ \Lambda$ channel near

1900 MeV often attributed to the $N(1900)3/2^+$ resonance. However, this enhancement is not seen in $\gamma d \rightarrow K^0 \Lambda(p)$. This suggests that this effect is due to missing interference terms. One interpretation is to view these missing terms as contributing to the excess $K^+ \Lambda$ cross section through the interference of a resonant state, $N(1900)$, and t-channel background processes. This is assumed since $\gamma d \rightarrow K^0 \Lambda(p)$ has a suppression of t-channel terms[LWB92] described by kaon exchange, which should make this reaction ideal for identifying resonances. This implies that partial wave analyses combined with the nature of $\gamma d \rightarrow K^0 \Lambda(p)$ production will be able to provide constraints for models describing nucleon resonances that couple strongly to $K \Lambda$ decay channels. Therefore, these data contain unique information which can be extracted to help with resonance classification and determination of helicity amplitudes.

Collaboration with the Bonn-Gatchina (BoGa) group has shown that the $\gamma d \rightarrow K^0 \Lambda(p)$ data can indeed yield valuable information to our understanding of currently known resonances. The present BoGa PWA fit has resulted in two unique solutions. Both solutions result in a reliable fit to the $\gamma d \rightarrow K^0 \Lambda(p)$ cross section, and in the very near future can be sorted out through continued study on the other polarization observables in this channel. These solutions also depend on observables found in other channels as well, and is referred to as a coupled channel analysis. Although the channel $\gamma p \rightarrow K^+ \Lambda$ has been well studied and therefore constrains resonance branching ratios, it does not provide any information on resonance formation on the neutron. Constraints on resonance photoproduction were provided based on other neutron reactions, which can be seen in Table 8.3. Although neutron data is sparse, every observable contributes helpful information. Table 8.3 outlines the reduced chi-squared, χ_v^2 , before and after the inclusion of this thesis work. It is seen that the fit quality results in a χ_v^2 value near one for the $K^0 \Lambda$ cross section. Due to this, it can be concluded that the known resonances are able to describe the current data. Moreover, because the neutron photocoupling and kaon t-channel terms are different than $\gamma p \rightarrow K^+ \Lambda$,

the shape of the cross section is partially defined by the interference effects between these production terms. Therefore, the PWA is able to better define the γN helicity amplitudes and the pole positions of the contributing resonances. These helicity amplitudes alone can be used to suggest how to label the excited states in a corresponding multiplet, thus allowing conjectures of where to look in order to find more of the so-called “missing” resonances.

Table 8.3: Data from neutron photoproduction experiments used by the BoGa coupled channel PWA fit [ABC⁺pt].

Channel	Observable	$\chi^2_v(\text{old})$	$\chi^2_v(\text{new})$
$\gamma d \rightarrow \pi^- p(p)$	$d\sigma/d\Omega$	3.08	3.10
	Σ	3.08	2.99
	T	3.18	1.88
	P	3.17	1.55
$\pi^- p \rightarrow \gamma n$	$d\sigma/d\Omega$	1.53	1.60
	P	3.11	1.96
$\gamma d \rightarrow \pi^0 n(p)$	$d\sigma/d\Omega$	2.98	2.97
	Σ	1.90	1.85
$\gamma d \rightarrow \eta n(p)$	$d\sigma/d\Omega$	-	1.01
	Σ	2.17	1.85
$\gamma d \rightarrow K^0 \Lambda(p)$	$d\sigma/d\Omega$	-	0.96
$\gamma d \rightarrow K^+ \Sigma^-(p)$	$d\sigma/d\Omega$	-	0.72

This work has been done in order to obtain measurements that will influence the search for missing resonances. Reactions produced on either protons or neutrons should yield the same evidence for N^* and Δ^* states. These states have specific pole positions in the complex energy plane and decay couplings, should restrict our modeling of the interfering background terms which can otherwise be a complication in the PWA process. The results of this thesis along with private communications with the BoGa group has led to an important follow up publication (in manuscript). This higher level analysis attempts to find the helicity couplings to the known resonances contributing to $\gamma d \rightarrow K^0 \Lambda(p)$. Two initial helicity amplitudes are possible ($A^{1/2}$ and $A^{3/2}$) without orbital excitation based on the orientation of the photon spin ($\vec{1}$) and the nucleon spin ($\vec{\frac{1}{2}}$). Relating these to electric

(E) and magnetic (M) multipoles allows a connection in the observed production and drives the fit of helicity amplitudes associated to each spectroscopic state. For example, the E/M ratio is small for $N(1975)\frac{3}{2}^{+}$ and $N(2000)\frac{5}{2}^{+}$ suggesting they belong to a spin-quartet. This categorization is only possible utilizing neutron production data including the measurements presented in this document. The contribution of this new data along with the coupled channel analysis can extract helicity couplings and pole positions for all the N^{*} s in Table 8.4. Knowing these parameters could increase the significance of the states listed to three or four star ratings. It is expected that the continued study of observables in these KY channels will result in the ability to parameterize contributing resonances to a higher precision and possibly even predict which resonances are still missing through the use of PWA fits.

The PWA fits and corresponding N^{*} properties are necessary to understand the non-perturbative portion of QCD within the nucleon. Although the constituent quark model can recover select resonances using simplistic assumptions, the vast majority of the spectrum can not be reproduced. In fact, this area of nuclear physics has no reliable analytic solution, making the comparison from experiment to theory more difficult. Utilizing known interactions, lattice gauge theory is often attributed as the main predictive tool of baryon excitations. As lattice results improve (through computing power and enhanced algorithms), it may eventually be able to describe the majority of non-perturbative QCD. To verify the predictions from these models, they will have to reproduce all of the found resonance states of the nucleon. These comparisons, of course, are between the PWA results and lattice predicted properties of resonances. The importance of locating these excited baryons, can be recognized in many aspects. One scenario is to view these states as the transition between the quark-gluon plasma, described in hot QCD, and the confinement of quarks and gluons in nucleons, described in strong QCD. Clearly, knowledge of N^{*}

Table 8.4: Resonances status given by [O⁺14], but able to be parameterized by the BonnGa coupled channel PWA fit with the inclusion of this thesis work.

Resonance	Overall Status	ΛK Status
N(1440) $\frac{1}{2}^{+}$	****	-
N(1520) $\frac{3}{2}^{-}$	****	-
N(1535) $\frac{1}{2}^{-}$	****	-
— ΛK Threshold —		
N(1650) $\frac{1}{2}^{-}$	****	***
N(1675) $\frac{5}{2}^{-}$	****	*
N(1680) $\frac{5}{2}^{+}$	****	-
N(1710) $\frac{1}{2}^{+}$	***	***
N(1720) $\frac{3}{2}^{+}$	****	**
N(1875) $\frac{3}{2}^{-}$	***	***
N(1880) $\frac{1}{2}^{+}$	**	*
N(1895) $\frac{1}{2}^{-}$	**	**
N(1900) $\frac{3}{2}^{+}$	***	***
N(1975) $\frac{3}{2}^{+}$	-	-
N(1990) $\frac{7}{2}^{+}$	**	-
N(2000) $\frac{5}{2}^{+}$	**	**
N(2060) $\frac{5}{2}^{-}$	**	-
N(2100) $\frac{1}{2}^{+}$	*	-
N(2120) $\frac{3}{2}^{-}$	-	-
N(2190) $\frac{7}{2}^{-}$	****	**

physics is essential to correctly describe the formation of hadrons in the early universe or any other hadronization conditions.

In summary, the goal of this thesis was to study N*s on the neutron that contribute to $K^0\Lambda$. This measurement is not only very important to accomplish that goal, but will likely be the worlds first published data on this reaction channel. The results alone are surprising considering that one resonance, N(1900) $\frac{3}{2}^{+}$, is not noticeable for $K^0\Lambda$, but is clearly seen for $K^+\Lambda$. This study inspired PWA researchers to include this channel in their fit scenarios, providing enough input to produce a follow-up publication. This higher level analysis will improve the world knowledge of nucleon resonance parameters. It is evident that further

studies of double-spin observables for $\gamma d \rightarrow K^0 \Lambda(p)$ (in progress by other members of the CLAS Collaboration) will continue to enhance our understanding of N^* physics.

REFERENCES

- [Aa] Hall A. Analysis tools wiki. URL: https://hallaweb.jlab.org/wiki/index.php/Analysis_Tools
- [A⁺b] G. Asryan et al. The geometry of the clas12 pre-shower calorimeter. Technical report, Jefferson Laboratory. CLAS-Note. URL: https://clasweb.jlab.org/wiki/images/d/d0/Pcal_geometry_note.pdf
- [A⁺00] J. Ahrens et al. Helicity dependence of $\gamma p \rightarrow N\pi$ below 450 mev and contribution to the gerasimov-drell-hearn sum rule. *Phys. Rev. Lett.*, 84:5950–5954, Jun 2000. URL: <http://link.aps.org/doi/10.1103/PhysRevLett.84.5950>, doi:10.1103/PhysRevLett.84.5950
- [A⁺01a] J. Ahrens et al. First measurement of the gerasimov-drell-hearn integral for 1h from 200 to 800 mev. *Phys. Rev. Lett.*, 87:022003, Jun 2001. URL: <http://link.aps.org/doi/10.1103/PhysRevLett.87.022003>, doi:10.1103/PhysRevLett.87.022003
- [A⁺01b] M. Amarian et al. The CLAS forward electromagnetic calorimeter. *Nucl. Instrum. Meth.*, A460:239–265, 2001. doi:10.1016/S0168-9002(00)00996-7
- [ABC⁺01] G. Adams, V. Burkert, R. Carl, T. Carstens, V. Frolov, L. Houghtlin, G. Jacobs, M. Kossov, M. Klusman, B. Kross, M. Onuk, J. Napolitano, J.W. Price, C. Riggs, Y. Sharabian, A. Stavinsky, L.C. Smith, W.A. Stephens, P. Stoler, W. Tuzel, K. Ullrich, A. Vlassov, A. Weisenberger, M. Witkowski, B. Wojtekowski, P.F. Yergin, and C. Zorn. The {CLAS} cherenkov detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 465(23):414 – 427, 2001. URL: <http://www.sciencedirect.com/science/article/pii/S0168900200013139>, doi:[http://dx.doi.org/10.1016/S0168-9002\(00\)01313-9](http://dx.doi.org/10.1016/S0168-9002(00)01313-9)
- [ABC⁺pt] A.V. Anisovich, V. Burkert, N. Compton, K. Hicks, E. Klempt, V.A. Nikonov, A.V. Sarantsev, and U. Thoma. Neutron helicity amplitudes. *Phys. Rev. C*, (in manuscript).
- [ABK⁺12] A. V. Anisovich, R. Beck, E. Klempt, V. A. Nikonov, A. V. Sarantsev, and U. Thoma. Properties of baryon resonances from a multichannel partial wave analysis. *The European Physical Journal A*, 48(2):1–13, 2012. URL: <http://dx.doi.org/10.1140/epja/i2012-12015-8>, doi:10.1140/epja/i2012-12015-8
- [BBM⁺87] R. Brun, F. Bruyant, M. Maire, A. C. McPherson, and P. Zancarini. GEANT3. 1987. URL: <https://cds.cern.ch/record/1119728/files/CERN-DD-EE-84-1.pdf>

- [BP05] J. Ball and E. Pasyuk. Photon flux determination through sampling of “out-of-time” hits with the hall b photon tagger. Technical Report 002, Jefferson Laboratory, 2005. CLAS-Note 2005-002.
- [BSM⁺06] R. Bradford, R. A. Schumacher, J. W. C. McNabb, L. Todor, et al. Differential cross sections for $\gamma + p \rightarrow K^+ + y$ for Λ and Σ^0 hyperons. *Phys. Rev. C*, 73:035202, Mar 2006. URL: <http://link.aps.org/doi/10.1103/PhysRevC.73.035202>, doi:10.1103/PhysRevC.73.035202
- [CHC14] N. Compton, K. Hicks, and M. Camp. Cross sections of $\gamma d \rightarrow k^0 \Lambda(p)$ from g10. Technical report, Jefferson Laboratory, 2014. URL: https://www.jlab.org/Hall-B/shifts/admin/paper_reviews/2014/k0lamv4-9309054-2014-11-18-v8.0.PDF
- [CLA] CLAS12. Clas12 wiki. URL: <https://www.jlab.org/Hall-B/clas12-web/>
- [Clo79] F. E. Close. *An Introduction to Quarks and Partons*. Academic Press Inc., 111 Fifth Avenue, New York, New York 10003, 1979.
- [CMD⁺09] W. Chen, T. Mibe, D. Dutta, H. Gao, J. M. Laget, M. Mirazita, P. Rossi, S. Stepanyan, I. I. Strakovsky, et al. Measurement of the differential cross section for the reaction $\gamma n \rightarrow \pi^- p$ from deuterium. *Phys. Rev. Lett.*, 103:012301, Jul 2009. URL: <http://link.aps.org/doi/10.1103/PhysRevLett.103.012301>, doi:10.1103/PhysRevLett.103.012301
- [Cor07] Tamara Corthals. *Regge-Plus-Resonance Approach to Kaon Production from the Proton*. PhD thesis, University of Gent, Department of Physics and Astronomy, Proeftuinstraat 86, 9000 Ghent, Belgium, 6 2007.
- [CTC⁺16] N. Compton, C. E. Taylor, P. Cole, Y. Ilieva, N. Zachariou, and P. Nadel-Turonski. $k^0 \Lambda$ photoproduction on the neutron within the resonance region. Technical report, Jefferson Laboratory, 2016. URL: https://www.jlab.org/Hall-B/shifts/admin/paper_reviews/2016/g13k0lambdav4-4961210-2016-10-10-v9.pdf
- [DHK⁺03] H. Dutz, K. Helbing, J. Krimmer, T. Speckner, G. Zeitler, et al. First measurement of the gerasimov-drell-hearn sum rule for ^1H from 0.7 to 1.8 gev at elsa. *Phys. Rev. Lett.*, 91:192001, Nov 2003. URL: <http://link.aps.org/doi/10.1103/PhysRevLett.91.192001>, doi:10.1103/PhysRevLett.91.192001
- [EMRW13] Robert G. Edwards, Nilmani Mathur, David G. Richards, and Stephen J. Wallace. Flavor structure of the excited baryon spectra from lattice qcd. *Phys. Rev. D*, 87:054506, Mar 2013. URL: <http://link.aps.org/doi/10.1103/PhysRevD.87.054506>, doi:10.1103/PhysRevD.87.054506

- [GCS⁺14] E. Gutz, V. Crede, V. Sokhoyan, H. van Pee, et al. High statistics study of the reaction $\gamma p \rightarrow p\pi^0 \eta$. *The European Physical Journal A*, 50(4):1–27, 2014. URL: <http://dx.doi.org/10.1140/epja/i2014-14074-1>, doi:10.1140/epja/i2014-14074-1
- [Gri12] David Griffiths. *Introduction to Elementary Particles*. WILEY-VCH, 2 edition, 2012.
- [Hol] M. Holtrop. Gsim: Clas geant simulation. URL: http://nuclear.unh.edu/~maurik/Gsim/gsim_info.shtml
- [KR10] Eberhard Klempt and Jean-Marc Richard. Baryon spectroscopy. *Rev. Mod. Phys.*, 82:1095–1153, 2010. arXiv:0901.2055, doi:10.1103/RevModPhys.82.1095
- [LtCC12] Ken Livingston and the Clas Collaboration. Recent progress in n^* physics from kaon photoproduction experiments at clas. *Journal of Physics: Conference Series*, 381(1):012026, 2012. URL: <http://stacks.iop.org/1742-6596/381/i=1/a=012026>
- [LWB92] Xiaodong Li, L. E. Wright, and C. Bennhold. Kaon photoproduction on the neutron using deuterium. *Phys. Rev. C*, 45:2011–2014, Apr 1992. URL: <http://link.aps.org/doi/10.1103/PhysRevC.45.2011>, doi:10.1103/PhysRevC.45.2011
- [M⁺00] M. D. Mestayer et al. The CLAS drift chamber system. *Nucl. Instrum. Meth.*, A449:81–111, 2000. doi:10.1016/S0168-9002(00)00151-0
- [M⁺03] B. A. Mecking et al. The CEBAF Large Acceptance Spectrometer (CLAS). *Nucl. Instrum. Meth.*, A503:513–553, 2003. doi:10.1016/S0168-9002(03)01001-5
- [Mat14a] P. Mattione. Sc efficiency studies, 2014. URL: https://clasweb.jlab.org/rungroups/g13/wiki_secure/index.php/Mattione_SCEfficiencyStudies
- [Mat14b] P. Mattione. Trip studies, 2014. URL: <https://clasweb.jlab.org/rungroups/g13/wiki/index.php/TripFixer>
- [MBHT] T. Mart, C. Bennhold, H. Haberzettl, and L. Tiator. Kaonmaid 2000. URL: <http://portal.kph.uni-mainz.de/MAID//kaon/kaonmaid>
- [MBM⁺10] M. E. McCracken, M. Bellis, C. A. Meyer, M. Williams, et al. Differential cross section and recoil polarization measurements for the $\gamma p \rightarrow K^+ \Lambda$ reaction using clas at jefferson lab. *Phys. Rev. C*, 81:025201, Feb 2010. URL: <http://link.aps.org/doi/10.1103/PhysRevC.81.025201>, doi:10.1103/PhysRevC.81.025201

- [MGH⁺06] T. Mibe, H. Gao, K. Hicks, K. Kramer, S. Stepanyan, and D. Tedeschi. Coherent ϕ -meson photoproduction on deuterium. Technical report, Jefferson Laboratory, 2006. CLAS-Note 2006. URL: <https://www.jlab.org/Hall-B/secure/g10/mibe/phi/note/v2.1/note.pdf>
- [MK12] T. Mart and M. J. Kholili. Origin of the second peak in the cross section of $K^+\Lambda$ photoproduction. *Phys. Rev. C*, 86:022201, Aug 2012. URL: <http://link.aps.org/doi/10.1103/PhysRevC.86.022201>, doi:10.1103/PhysRevC.86.022201
- [NTBI⁺06] P. Nadel-Turonski, B.L. Berman, Y. Ilieva, A. Tkabladze, D.G. Ireland, et al. Kaon production on the deuteron using polarized photons. Technical report, Jul 2006. Jefferson Lab PAC30 Proposal: PR-06-103.
- [O⁺14] K. A. Olive et al. Review of Particle Physics. *Chin. Phys.*, C38:090001, 2014. doi:10.1088/1674-1137/38/9/090001
- [Pas07] E. Pasyuk. Energy loss corrections for charged particles in clas. Technical Report 016, Jefferson Laboratory, 2007. CLAS-Note 2007-016.
- [S⁺99] E.S. Smith et al. The time-of-flight system for {CLAS}. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 432(23):265 – 298, 1999. URL: <http://www.sciencedirect.com/science/article/pii/S0168900299004842>, doi:[http://dx.doi.org/10.1016/S0168-9002\(99\)00484-2](http://dx.doi.org/10.1016/S0168-9002(99)00484-2)
- [S⁺00] D. I. Sober et al. The bremsstrahlung tagged photon beam in Hall B at JLab. *Nucl. Instrum. Meth.*, A440:263–284, 2000. doi:10.1016/S0168-9002(99)00784-6
- [S⁺05] S. Stepanyan et al. Energy claibraton of the hall b bremsstrahlung tagging system using a magnetic pair spectrometer. Technical Report 012, Jefferson Laboratory, 2005. URL: <https://misportal.jlab.org/ul/Physics/Hall-B/clas/viewFile.cfm/2005-012.pdf?documentId=179>
- [SBB⁺06] Y.G. Sharabian, M. Battaglieri, V.D. Burkert, R. DeVita, L. Elouadrhiri, L. Guo, D. Kashy, V. Kubarovsky, G.S. Mutchler, M. Ostrick, M. Ripani, P. Rossi, A. Rottura, E. Pasyuk, and D. Weygand. A new highly segmented start counter for the {CLAS} detector. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 556(1):246 – 258, 2006. URL: <http://www.sciencedirect.com/science/article/pii/S016890020501942X>, doi:<http://dx.doi.org/10.1016/j.nima.2005.10.031>
- [SHKL11] A M Sandorfi, S Hoblit, H Kamano, and T-S H Lee. Determining pseudoscalar meson photoproduction amplitudes from complete experiments. *Journal*

of Physics G: Nuclear and Particle Physics, 38(5):053001, 2011. URL: <http://stacks.iop.org/0954-3899/38/i=5/a=053001>

[Ste] S. Stepanyan. Clas12 pre-shower calorimeter (pcal) project. URL: https://userweb.jlab.org/~stepanya/clas12/preshower/PCAL_Summary.pdf

[Ste06] S. Stepanyan. fsgen, 2006.

[TAD⁺01] S. Taylor, S. Ahmad, J. Distelbrink, G. S. Mutchler, E. Smith, and T. Smith. The CLAS start counter. *Nucl. Instrum. Meth.*, A462:484–493, 2001. doi:10.1016/S0168-9002(00)01125-6

[WAH⁺57] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson. Experimental test of parity conservation in beta decay. *Phys. Rev.*, 105:1413–1415, Feb 1957. URL: <http://link.aps.org/doi/10.1103/PhysRev.105.1413>, doi:10.1103/PhysRev.105.1413

[Wer16] Dominik Werthmüller. Strangeness Photoproduction on Quasifree Neutrons. *JPS Conf. Proc.*, 10:032008, 2016. arXiv:1510.01660, doi:10.7566/JPSCP.10.032008

[Wil07] Mike Williams. *Measurement of Differential Cross Sections and Spin Density Matrix Elements along with a Partial Wave Analysis for $\gamma p \rightarrow p\omega$ using CLAS at Jefferson Lab*. PhD thesis, Carnegie Mellon University, 11 2007.

APPENDIX A: DATA TABLES

The extracted results of this thesis are that of the differential cross section, an estimate of the total cross section, and the Λ recoil polarization (P). These results are shown in tabular form in Sections A.1, A.2, and A.3 respectively. These measurements arise following the procedure given throughout this document. Fits to distributions and intermediate yields can be found in [CHC14] and [CTC⁺16].

A.1 $\frac{d\sigma}{d\cos\theta_{CM}^{K^0}}$ Measurements

Table A.1: Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g10 data.

E_γ (GeV)	$\cos\theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta} (\mu b)$	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.10	-0.65	1.00013	0.39197	0.10001
1.10	-0.55	1.22589	0.27443	0.12259
1.10	-0.45	0.71969	0.18661	0.07197
1.10	-0.35	0.78350	0.14200	0.07835
1.10	-0.25	0.82721	0.12747	0.08272
1.10	-0.15	0.72508	0.10020	0.07251
1.10	-0.05	0.77049	0.09670	0.07705
1.10	0.05	0.52375	0.08326	0.05238
1.10	0.15	0.59885	0.07771	0.05989
1.10	0.25	0.60626	0.08459	0.06063
1.10	0.35	0.66305	0.07958	0.06631
1.10	0.45	0.61605	0.09009	0.06161
1.10	0.55	0.37751	0.08750	0.03775
1.10	0.65	0.31476	0.10235	0.03148

Table A.1: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g10 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.10	0.75	0.23623	0.10792	0.02362
1.30	-0.65	0.84988	0.28049	0.08499
1.30	-0.55	0.88767	0.17588	0.08877
1.30	-0.45	0.69275	0.09751	0.06927
1.30	-0.35	0.57456	0.06604	0.05746
1.30	-0.25	0.59504	0.05872	0.05950
1.30	-0.15	0.53502	0.05056	0.05350
1.30	-0.05	0.71023	0.04659	0.07102
1.30	0.05	0.60923	0.04677	0.06092
1.30	0.15	0.58598	0.04683	0.05860
1.30	0.25	0.62218	0.05072	0.06222
1.30	0.35	0.60768	0.04693	0.06077
1.30	0.55	0.70114	0.06825	0.07011
1.30	0.65	0.56572	0.07038	0.05657
1.30	0.75	0.48735	0.09389	0.04874
1.50	-0.65	0.44312	0.16679	0.04431
1.50	-0.55	0.30142	0.08267	0.03014
1.50	-0.45	0.18577	0.04228	0.01858
1.50	-0.35	0.19701	0.03086	0.01970
1.50	-0.25	0.22659	0.02968	0.02266
1.50	-0.15	0.24699	0.02800	0.02470
1.50	-0.05	0.23696	0.02521	0.02370

Table A.1: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g10 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.50	0.05	0.29974	0.02627	0.02997
1.50	0.15	0.25251	0.02437	0.02525
1.50	0.25	0.35535	0.02824	0.03554
1.50	0.35	0.39293	0.03049	0.03929
1.50	0.45	0.43659	0.03435	0.04366
1.50	0.55	0.45310	0.04106	0.04531
1.50	0.65	0.38425	0.04451	0.03843
1.50	0.75	0.35311	0.05939	0.03531
1.70	-0.55	0.15057	0.05422	0.01506
1.70	-0.45	0.11339	0.02715	0.01134
1.70	-0.35	0.14933	0.02108	0.01493
1.70	-0.25	0.09314	0.01801	0.00931
1.70	-0.15	0.10314	0.01543	0.01031
1.70	-0.05	0.12015	0.01516	0.01202
1.70	0.15	0.18413	0.01695	0.01841
1.70	0.25	0.28597	0.02109	0.02860
1.70	0.35	0.29966	0.02143	0.02997
1.70	0.45	0.34241	0.02653	0.03424
1.70	0.55	0.40805	0.03285	0.04081
1.70	0.65	0.49763	0.04392	0.04976
1.70	0.75	0.36749	0.05521	0.03675
1.90	-0.55	0.11043	0.03719	0.01104

Table A.1: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g10 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.90	-0.45	0.05705	0.01839	0.00571
1.90	-0.35	0.10543	0.01779	0.01054
1.90	-0.25	0.09800	0.01350	0.00980
1.90	-0.15	0.05759	0.01111	0.00576
1.90	-0.05	0.05927	0.01208	0.00593
1.90	0.05	0.09919	0.01287	0.00992
1.90	0.15	0.12653	0.01322	0.01265
1.90	0.25	0.14384	0.01510	0.01438
1.90	0.35	0.19756	0.01787	0.01976
1.90	0.45	0.21230	0.01875	0.02123
1.90	0.55	0.33042	0.02857	0.03304
1.90	0.65	0.41433	0.03976	0.04143
1.90	0.75	0.32115	0.05167	0.03211
2.10	-0.55	0.05985	0.03258	0.00598
2.10	-0.45	0.02499	0.01678	0.00250
2.10	-0.35	0.04487	0.01100	0.00449
2.10	-0.25	0.04053	0.00926	0.00405
2.10	-0.15	0.03574	0.00842	0.00357
2.10	-0.05	0.04052	0.00825	0.00405
2.10	0.05	0.02846	0.00848	0.00285
2.10	0.15	0.06472	0.01016	0.00647
2.10	0.35	0.12534	0.01356	0.01253

Table A.1: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g10 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
2.10	0.45	0.17897	0.01659	0.01790
2.10	0.55	0.27612	0.02319	0.02761
2.10	0.65	0.32914	0.03134	0.03291
2.10	0.75	0.46576	0.05962	0.04658
2.30	-0.55	0.09393	0.02631	0.00939
2.30	-0.45	0.03974	0.01434	0.00397
2.30	-0.35	0.01601	0.00850	0.00160
2.30	-0.25	0.03098	0.00773	0.00310
2.30	-0.15	0.01400	0.00632	0.00140
2.30	-0.05	0.01652	0.00612	0.00165
2.30	0.05	0.02725	0.00635	0.00272
2.30	0.15	0.03218	0.00675	0.00322
2.30	0.25	0.06879	0.00908	0.00688
2.30	0.35	0.10418	0.01186	0.01042
2.30	0.45	0.14920	0.01497	0.01492
2.30	0.55	0.18561	0.01928	0.01856
2.30	0.65	0.23703	0.02506	0.02370
2.30	0.75	0.28270	0.04309	0.02827
2.50	-0.55	0.04511	0.02009	0.00451
2.50	-0.45	0.03033	0.00999	0.00303
2.50	-0.35	0.01442	0.00675	0.00144
2.50	-0.25	0.01399	0.00549	0.00140

Table A.1: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g10 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
2.50	-0.15	0.01566	0.00544	0.00157
2.50	-0.05	0.01149	0.00374	0.00115
2.50	0.05	0.00996	0.00572	0.00100
2.50	0.15	0.02832	0.00729	0.00283
2.50	0.25	0.04826	0.00821	0.00483
2.50	0.35	0.07632	0.01049	0.00763
2.50	0.45	0.11663	0.01322	0.01166
2.50	0.55	0.17365	0.01968	0.01736
2.50	0.65	0.22403	0.02580	0.02240
2.50	0.75	0.29691	0.04540	0.02969
2.70	-0.45	0.01367	0.01099	0.00137
2.70	-0.35	0.03146	0.00891	0.00315
2.70	-0.25	0.00871	0.00492	0.00087
2.70	-0.15	0.00528	0.00365	0.00053
2.70	-0.05	0.00695	0.00407	0.00070
2.70	0.05	0.00555	0.00455	0.00056
2.70	0.15	0.01532	0.00523	0.00153
2.70	0.25	0.02582	0.00634	0.00258
2.70	0.35	0.06135	0.00945	0.00614
2.70	0.45	0.07578	0.01138	0.00758
2.70	0.55	0.09083	0.01279	0.00908
2.70	0.65	0.13890	0.01846	0.01389

Table A.1: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g10 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
2.70	0.75	0.17514	0.03573	0.01751
2.90	-0.55	0.02295	0.01465	0.00230
2.90	-0.35	0.01680	0.00546	0.00168
2.90	-0.25	0.00971	0.00376	0.00097
2.90	0.05	0.00359	0.00222	0.00036
2.90	0.15	0.01019	0.00284	0.00102
2.90	0.25	0.01012	0.00403	0.00101
2.90	0.35	0.02945	0.00543	0.00294
2.90	0.45	0.04284	0.00702	0.00428
2.90	0.55	0.04900	0.00873	0.00490
2.90	0.65	0.08143	0.01379	0.00814
2.90	0.75	0.10337	0.02153	0.01034

Table A.2: Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
0.97	-0.65	0.75255	0.35076	0.06867
0.97	-0.55	0.77160	0.33467	0.07040
0.97	-0.45	0.86497	0.24008	0.07892
0.97	-0.35	0.74992	0.17343	0.06843
0.97	-0.25	0.72369	0.17066	0.06603

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
0.97	-0.15	0.59180	0.11788	0.05400
0.97	-0.05	0.70802	0.11000	0.06460
0.97	0.05	0.78103	0.11056	0.07126
0.97	0.15	0.64846	0.10411	0.05917
0.97	0.25	0.57306	0.09379	0.05229
0.97	0.35	0.57949	0.09745	0.05287
0.97	0.45	0.70460	0.10752	0.06429
0.97	0.55	0.44682	0.09608	0.04077
0.97	0.65	0.51625	0.12026	0.04710
0.97	0.75	0.51830	0.14436	0.04729
1.05	-0.55	1.33875	0.23334	0.10225
1.05	-0.45	1.05646	0.12457	0.08069
1.05	-0.35	1.05996	0.10028	0.08096
1.05	-0.25	0.86644	0.08602	0.06618
1.05	-0.15	0.88866	0.07516	0.06788
1.05	-0.05	0.82451	0.06602	0.06298
1.05	0.05	0.82510	0.06255	0.06302
1.05	0.15	0.75963	0.05883	0.05802
1.05	0.25	0.77430	0.05987	0.05914
1.05	0.35	0.67270	0.05781	0.05138
1.05	0.45	0.71069	0.06013	0.05428
1.05	0.55	0.57955	0.05932	0.04427

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.05	0.65	0.55457	0.07076	0.04236
1.05	0.75	0.70325	0.09656	0.05372
1.15	-0.65	1.11443	0.18921	0.07850
1.15	-0.55	1.08909	0.12420	0.07672
1.15	-0.45	1.03075	0.08920	0.07261
1.15	-0.35	0.88525	0.06737	0.06236
1.15	-0.25	0.79475	0.05571	0.05598
1.15	-0.15	0.71598	0.04944	0.05043
1.15	-0.05	0.75928	0.04681	0.05348
1.15	0.05	0.74950	0.04504	0.05279
1.15	0.15	0.63681	0.03979	0.04486
1.15	0.25	0.76139	0.04296	0.05363
1.15	0.35	0.66951	0.04196	0.04716
1.15	0.45	0.67394	0.04344	0.04747
1.15	0.55	0.69452	0.04952	0.04892
1.15	0.65	0.71138	0.05281	0.05011
1.15	0.75	0.70978	0.06620	0.05000
1.25	-0.65	1.41869	0.18279	0.09557
1.25	-0.55	1.02626	0.10700	0.06913
1.25	-0.45	0.92005	0.07879	0.06198
1.25	-0.35	0.80255	0.05824	0.05406
1.25	-0.25	0.76759	0.05021	0.05171

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.25	-0.15	0.70174	0.04323	0.04727
1.25	-0.05	0.72802	0.04088	0.04904
1.25	0.05	0.62247	0.03618	0.04193
1.25	0.15	0.65450	0.03824	0.04409
1.25	0.25	0.77066	0.03968	0.05191
1.25	0.35	0.77760	0.03932	0.05238
1.25	0.45	0.72072	0.04070	0.04855
1.25	0.55	0.62717	0.04325	0.04225
1.25	0.65	0.67817	0.04858	0.04568
1.25	0.75	0.68653	0.06194	0.04625
1.35	-0.65	0.79066	0.14608	0.05183
1.35	-0.55	0.70911	0.08701	0.04649
1.35	-0.45	0.70095	0.06063	0.04596
1.35	-0.35	0.60235	0.04678	0.03949
1.35	-0.25	0.59899	0.04013	0.03927
1.35	-0.15	0.56432	0.03514	0.03700
1.35	-0.05	0.56618	0.03263	0.03712
1.35	0.05	0.53946	0.03094	0.03537
1.35	0.15	0.54716	0.03028	0.03587
1.35	0.25	0.58681	0.03221	0.03847
1.35	0.35	0.52749	0.03141	0.03458
1.35	0.45	0.56359	0.03440	0.03695

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.35	0.55	0.57093	0.03933	0.03743
1.35	0.65	0.59598	0.04497	0.03907
1.35	0.75	0.67498	0.06028	0.04425
1.45	-0.55	0.48669	0.07164	0.03173
1.45	-0.45	0.52218	0.05000	0.03460
1.45	-0.35	0.40599	0.03659	0.02647
1.45	-0.25	0.35432	0.02933	0.02310
1.45	-0.15	0.37073	0.02726	0.02417
1.45	-0.05	0.40146	0.02634	0.02617
1.45	0.05	0.37243	0.02412	0.02428
1.45	0.15	0.35336	0.02461	0.02304
1.45	0.25	0.35558	0.02463	0.02318
1.45	0.35	0.42516	0.02640	0.02772
1.45	0.45	0.52429	0.03086	0.03418
1.45	0.55	0.53086	0.03503	0.03460
1.45	0.65	0.50279	0.03859	0.03277
1.45	0.75	0.61126	0.05597	0.03984
1.55	-0.55	0.28879	0.05107	0.01964
1.55	-0.45	0.24327	0.03220	0.01633
1.55	-0.35	0.20305	0.02309	0.01362
1.55	-0.25	0.19669	0.01976	0.01320
1.55	-0.15	0.18372	0.01760	0.01233

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.55	-0.05	0.17685	0.01688	0.01193
1.55	0.05	0.23188	0.01803	0.01559
1.55	0.15	0.27718	0.01856	0.01865
1.55	0.25	0.30317	0.01888	0.02034
1.55	0.35	0.31162	0.02078	0.02092
1.55	0.45	0.32393	0.02346	0.02173
1.55	0.55	0.38605	0.02834	0.02589
1.55	0.65	0.43859	0.03520	0.02941
1.55	0.75	0.43297	0.04882	0.02904
1.65	-0.55	0.18039	0.03551	0.01216
1.65	-0.45	0.19119	0.02561	0.01243
1.65	-0.35	0.15919	0.01849	0.01034
1.65	-0.25	0.12044	0.01560	0.00784
1.65	-0.15	0.12797	0.01427	0.00831
1.65	-0.05	0.12656	0.01391	0.00827
1.65	0.05	0.15465	0.01498	0.01005
1.65	0.15	0.20314	0.01597	0.01322
1.65	0.25	0.21709	0.01689	0.01409
1.65	0.35	0.26907	0.01870	0.01750
1.65	0.45	0.32082	0.02180	0.02082
1.65	0.55	0.40120	0.02820	0.02604
1.65	0.65	0.45581	0.03610	0.02958

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.65	0.75	0.57200	0.05412	0.03713
1.75	-0.55	0.16534	0.03194	0.01111
1.75	-0.45	0.17897	0.02230	0.01203
1.75	-0.35	0.09317	0.01530	0.00629
1.75	-0.25	0.08305	0.01289	0.00559
1.75	-0.15	0.08291	0.01206	0.00561
1.75	-0.05	0.08655	0.01213	0.00585
1.75	0.05	0.15390	0.01382	0.01036
1.75	0.15	0.17531	0.01541	0.01184
1.75	0.25	0.16149	0.01470	0.01089
1.75	0.35	0.23698	0.01728	0.01593
1.75	0.45	0.27890	0.02071	0.01874
1.75	0.55	0.35337	0.02587	0.02375
1.75	0.65	0.44786	0.03696	0.03009
1.75	0.75	0.66910	0.06598	0.04495
1.85	-0.55	0.06010	0.02025	0.00409
1.85	-0.45	0.08868	0.01599	0.00592
1.85	-0.35	0.09077	0.01371	0.00609
1.85	-0.25	0.08972	0.01144	0.00600
1.85	-0.15	0.08442	0.01091	0.00564
1.85	-0.05	0.08094	0.01062	0.00550
1.85	0.05	0.09120	0.01044	0.00611

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
1.85	0.15	0.11921	0.01208	0.00797
1.85	0.25	0.13622	0.01293	0.00913
1.85	0.35	0.18348	0.01470	0.01226
1.85	0.45	0.27127	0.01847	0.01812
1.85	0.55	0.27746	0.02227	0.01853
1.85	0.65	0.36097	0.03286	0.02411
1.85	0.75	0.45618	0.05999	0.03046
1.95	-0.55	0.07889	0.02144	0.00520
1.95	-0.45	0.08362	0.01455	0.00557
1.95	-0.35	0.06207	0.01126	0.00407
1.95	-0.25	0.06722	0.01060	0.00441
1.95	-0.15	0.05209	0.00908	0.00342
1.95	-0.05	0.07212	0.00919	0.00475
1.95	0.05	0.07863	0.00974	0.00516
1.95	0.15	0.07853	0.01053	0.00527
1.95	0.25	0.13154	0.01223	0.00863
1.95	0.35	0.15496	0.01353	0.01018
1.95	0.45	0.20197	0.01687	0.01325
1.95	0.55	0.25252	0.02099	0.01654
1.95	0.65	0.31196	0.03198	0.02044
1.95	0.75	0.33056	0.05756	0.02165
2.05	-0.55	0.08179	0.01988	0.00541

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
2.05	-0.45	0.07376	0.01232	0.00484
2.05	-0.35	0.05625	0.01004	0.00369
2.05	-0.25	0.05190	0.00905	0.00342
2.05	-0.15	0.04399	0.00838	0.00289
2.05	-0.05	0.04490	0.00883	0.00295
2.05	0.05	0.04106	0.00909	0.00274
2.05	0.15	0.06679	0.00953	0.00450
2.05	0.25	0.10552	0.01140	0.00696
2.05	0.35	0.14621	0.01330	0.00961
2.05	0.45	0.21218	0.01649	0.01393
2.05	0.55	0.21077	0.02012	0.01383
2.05	0.65	0.31704	0.03580	0.02079
2.05	0.75	0.35042	0.06888	0.02320
2.15	-0.55	0.05246	0.01674	0.00358
2.15	-0.45	0.04878	0.01137	0.00327
2.15	-0.35	0.03869	0.00911	0.00263
2.15	-0.25	0.04184	0.00779	0.00281
2.15	-0.15	0.02167	0.00702	0.00147
2.15	-0.05	0.02822	0.00731	0.00190
2.15	0.05	0.04655	0.00874	0.00313
2.15	0.15	0.04077	0.00771	0.00276
2.15	0.25	0.07932	0.00974	0.00546

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
2.15	0.35	0.11273	0.01140	0.00756
2.15	0.45	0.14085	0.01349	0.00944
2.15	0.55	0.24018	0.02003	0.01609
2.15	0.65	0.24749	0.02982	0.01658
2.15	0.75	0.25732	0.06418	0.01761
2.25	-0.65	0.02567	0.02226	0.00180
2.25	-0.55	0.02952	0.01342	0.00207
2.25	-0.45	0.03718	0.00992	0.00261
2.25	-0.35	0.03327	0.00812	0.00232
2.25	-0.25	0.02416	0.00730	0.00167
2.25	-0.05	0.01092	0.00615	0.00076
2.25	0.05	0.02809	0.00760	0.00194
2.25	0.15	0.02312	0.00776	0.00160
2.25	0.25	0.05048	0.00915	0.00350
2.25	0.35	0.10989	0.01185	0.00758
2.25	0.45	0.14907	0.01409	0.01029
2.25	0.55	0.18725	0.01990	0.01292
2.25	0.65	0.34181	0.03665	0.02358
2.35	-0.65	0.03675	0.02146	0.00345
2.35	-0.55	0.01943	0.01110	0.00183
2.35	-0.45	0.01774	0.00968	0.00116
2.35	-0.35	0.02601	0.00736	0.00171

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta}$ (μb)	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
2.35	-0.15	0.01446	0.00687	0.00096
2.35	-0.05	0.00745	0.00587	0.00049
2.35	0.05	0.01752	0.00583	0.00115
2.35	0.15	0.02863	0.00707	0.00188
2.35	0.25	0.06421	0.00835	0.00422
2.35	0.35	0.09907	0.01024	0.00648
2.35	0.45	0.14870	0.01386	0.00973
2.35	0.55	0.18374	0.01835	0.01201
2.35	0.65	0.21345	0.03008	0.01397
2.45	-0.55	0.02850	0.01312	0.01366
2.45	-0.45	0.02657	0.00862	0.00176
2.45	-0.35	0.01547	0.00692	0.00104
2.45	-0.25	0.01802	0.00650	0.00118
2.45	-0.15	0.01117	0.00549	0.00090
2.45	-0.05	0.00628	0.00609	0.00042
2.45	0.05	0.00882	0.00631	0.00057
2.45	0.15	0.02063	0.00613	0.00135
2.45	0.25	0.04485	0.00731	0.00292
2.45	0.35	0.06794	0.00913	0.00442
2.45	0.45	0.11035	0.01167	0.00718
2.45	0.55	0.16248	0.01689	0.01057
2.45	0.65	0.19303	0.02777	0.01260

Table A.2: (continued) Listed is the $\gamma d \rightarrow K^0 \Lambda(p)$ differential cross section as measured with g13 data.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	$\frac{d\sigma}{d\cos\theta} (\mu b)$	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
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A.2 σ_{total} Measurements

Table A.3: Listed is the estimate of the $\gamma d \rightarrow K^0 \Lambda(p)$ total cross section for each experiment.

E_γ (GeV)	Experiment	$\sigma_{total} (\mu b)$	Stat. Uncertainty (μb)	Syst. Uncertainty (μb)
0.97	g13	1.3086	0.1931	0.1954
1.05	g13	1.8266	0.1589	0.3225
1.10	g10	1.4756	0.1775	0.2636
1.15	g13	1.8040	0.0850	0.1104
1.25	g13	1.8368	0.0766	0.2091
1.30	g10	1.3805	0.1124	0.2634
1.35	g13	1.3172	0.0620	0.0623
1.45	g13	1.0657	0.0598	0.0843
1.50	g10	0.7118	0.0556	0.1678
1.55	g13	0.7054	0.0417	0.0918
1.65	g13	0.6369	0.0328	0.0480
1.70	g10	0.6231	0.0411	0.1598
1.75	g13	0.5746	0.0294	0.0348
1.85	g13	0.3962	0.0220	0.1188
1.90	g10	0.4225	0.0295	0.1056

Table A.3: (continued) Listed is the estimate of the $\gamma d \rightarrow K^0 \Lambda(p)$ total cross section for each experiment.

E_γ (GeV)	Experiment	σ_{total} (μb)	Stat. Uncertainty (μb)	Total Uncertainty (μb)
1.95	g13	0.3585	0.0211	0.0452
2.05	g13	0.3602	0.0198	0.0554
2.10	g10	0.3189	0.0250	0.0532
2.15	g13	0.2831	0.0174	0.0785
2.25	g13	0.2757	0.0159	0.0504
2.30	g10	0.2765	0.0202	0.0826
2.35	g13	0.2363	0.0143	0.0395
2.45	g13	0.2039	0.0143	0.0271
2.50	g10	0.2202	0.1400	0.0233

A.3 P_Λ Measurements

Table A.4: Listed is the g13 measurement of the Λ recoil polarization (P) from the reaction $\gamma d \rightarrow K^0 \Lambda(p)$.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	P	Stat. Uncertainty	Syst. Uncertainty
1.00	-0.70	0.72452	0.84384	0.33560
1.00	-0.50	-0.63113	0.18577	0.13480
1.00	-0.30	-0.15100	0.12943	0.04170
1.00	-0.10	-0.32028	0.10209	0.02040
1.00	0.10	-0.37591	0.09087	0.04405
1.00	0.30	-0.36505	0.09962	0.06745

Table A.4: (continued) Listed is the g13 measurement of the Λ recoil polarization (P) from the reaction $\gamma d \rightarrow K^0 \Lambda(p)$.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	P	Stat. Uncertainty	Syst. Uncertainty
1.00	0.50	0.07528	0.11062	0.01970
1.00	0.70	0.01015	0.16196	0.01325
1.20	-0.70	-0.21471	0.19299	0.03295
1.20	-0.50	-0.65846	0.09167	0.06100
1.20	-0.30	-0.65395	0.06822	0.11010
1.20	-0.10	-0.55164	0.06046	0.09150
1.20	0.10	-0.40288	0.05673	0.03305
1.20	0.30	-0.29225	0.05105	0.04495
1.20	0.50	-0.41988	0.06148	0.07295
1.20	0.70	-0.17233	0.07280	0.02795
1.40	-0.70	0.08595	0.24121	0.09865
1.40	-0.50	-0.47398	0.09169	0.04005
1.40	-0.30	-0.38755	0.06980	0.10215
1.40	-0.10	-0.45669	0.06057	0.07010
1.40	0.10	-0.30468	0.05624	0.06260
1.40	0.30	-0.17102	0.05685	0.02790
1.40	0.50	-0.04174	0.05889	0.00575
1.40	0.70	0.08974	0.07592	0.01250
1.60	-0.50	-0.19781	0.12700	0.00385
1.60	-0.30	-0.52125	0.09911	0.04655
1.60	-0.10	-0.19415	0.08499	0.03855
1.60	0.10	-0.09090	0.06782	0.00070

Table A.4: (continued) Listed is the g13 measurement of the Λ recoil polarization (P) from the reaction $\gamma d \rightarrow K^0 \Lambda(p)$.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	P	Stat. Uncertainty	Syst. Uncertainty
1.60	0.30	-0.07601	0.06696	0.02510
1.60	0.50	0.10292	0.06614	0.02370
1.60	0.70	0.19547	0.08395	0.01850
1.80	-0.70	-0.16236	0.49348	0.11535
1.80	-0.50	0.06998	0.14383	0.03390
1.80	-0.30	-0.13309	0.12117	0.01265
1.80	-0.10	-0.28133	0.10712	0.04760
1.80	0.10	-0.45829	0.08078	0.05555
1.80	0.30	-0.24088	0.07175	0.04715
1.80	0.50	-0.23948	0.06939	0.02095
1.80	0.70	-0.02770	0.09763	0.07945
2.00	-0.50	0.18133	0.16945	0.06670
2.00	-0.30	0.44713	0.13734	0.09970
2.00	-0.10	-0.18677	0.12377	0.15445
2.00	0.10	-0.36403	0.09970	0.00080
2.00	0.30	-0.43333	0.08086	0.00420
2.00	0.50	-0.31477	0.07707	0.01430
2.00	0.70	-0.03569	0.13141	0.01185
2.20	-0.50	0.83187	0.19750	0.09675
2.20	-0.30	0.39472	0.17015	0.05470
2.20	-0.10	0.60368	0.21355	0.22950
2.20	0.10	-0.40039	0.14711	0.08820

Table A.4: (continued) Listed is the g13 measurement of the Λ recoil polarization (P) from the reaction $\gamma d \rightarrow K^0 \Lambda(p)$.

E_γ (GeV)	$\cos \theta_{CM}^{K^0}$	P	Stat. Uncertainty	Syst. Uncertainty
2.20	0.30	-0.40521	0.09542	0.06200
2.20	0.50	-0.38888	0.08616	0.02210
2.20	0.70	-0.10674	0.13453	0.06450
2.40	-0.50	1.00833	0.38693	0.00450
2.40	-0.30	0.41012	0.24563	0.16210
2.40	-0.10	0.14624	0.24978	0.13070
2.40	0.10	0.76730	0.18726	0.04665
2.40	0.30	-0.41219	0.10225	0.04625
2.40	0.50	-0.56127	0.09692	0.00150
2.40	0.70	-0.35810	0.16467	0.05785

APPENDIX B: DEFINITION OF AXES AND $\cos \theta_{y'}$

Given the momentum vectors of the photon ($\vec{p}_\gamma$), neutron ($\vec{p}_n$), K^0 ($\vec{p}_{K^0}$), and Λ ($\vec{p}_\Lambda$), one can define several coordinate systems. A useful quantity to account for the Fermi momentum is the effective incident vector ($\vec{p}_{\gamma,eff}$). This can theoretically be obtained either by adding up the initial vectors (which is impossible due to the random distribution of the Fermi momentum) or by adding up the detected momentum vectors

$$\vec{p}_{\gamma,eff} = \vec{p}_\gamma + \vec{p}_n = \vec{p}_{K^0} + \vec{p}_\Lambda. \quad (\text{B.1})$$

This is also demonstrated visually in Figure B.1a. Although the blue and red vector(s) are all in one plane, and the green and red vector(s) in another plane, those two planes may not necessarily be the same.

After boosting $\vec{p}_{\gamma,eff}$, $\vec{p}_{K^0}$, and $\vec{p}_\Lambda$ to the Center-of-Mass (CM) frame using the four momenta, P_Λ and P_{K^0} , there are three co-planar vectors that define the CM reaction plane and corresponding axes. The z-axis is defined as $\vec{p}_{\gamma,eff}^{CM}$. The y-axis is defined as $\vec{p}_{\gamma,eff}^{CM} \times \vec{p}_{K^0}^{CM}$. Leaving the x-axis as $\hat{y}^{CM} \times \hat{z}^{CM}$. This is illustrated in Figure B.1b. Here, the z-axis is re-aligned with the effective incident photon vector (due to Fermi momentum) and the Kaon is back to back in direction with the Λ . By definition the momentum vectors of the effective incident, K^0 , and Λ are all co-planar with the normal vector corresponding to $\hat{y}^{CM}$.

In order to extract $\cos \theta_{y'}$ the dot product between the proton from the Λ decay and the $\hat{y}^{CM}$ must be found. However, this dot product should be computed using the proton momentum ($\vec{p}_p$) in the Λ rest frame (L.R.F.). Note: When boosting to this frame $\hat{y}^{CM}$ should be equivalent $\hat{y}^{L.R.F.}$; unlike the relative magnitudes in the $\hat{x}^{L.R.F.}$ and $\hat{z}^{L.R.F.}$ directions. Thus the extraction of $\cos \theta_{y'}$ is obtained by

$$\cos \theta_{y'} = (\hat{p}_{\gamma,eff}^{CM} \times \hat{p}_{K^0}^{CM}) \cdot \hat{p}_p^{L.R.F.} = \hat{y}^{CM} \cdot \hat{p}_p^{L.R.F.}, \quad (\text{B.2})$$

where $\theta_{y'}$ can be seen in Figure B.1c.

Figure B.1: A pictorial representation of commonly used reference frames including the (a) Lab Reference Frame (LAB), (b) CM Reference Frame (CM), and (c) Λ Reference Frame (L.R.F.).

APPENDIX C: UNCERTAINTY DERIVATION OF P

Starting with the asymmetry measurement,

$$P = \frac{N^+ - N^-}{\frac{\alpha}{2}(N^+ + N^-)}, \quad (\text{C.1})$$

one can derive the equation of uncertainty. The independent variables consist of N^+ , N^- , and α . These variables are defined in sections 7.3.1 and 1.2.2 respectively. Although σ_α is a systematic uncertainty, it is left in the derivation for completeness (values can be found in [O⁺14]). The following uncertainty derivation utilizes the uncertainty in the number of counts, σ_{N^+} and σ_{N^-} . These intermediate uncertainties are determined using counting statistics (*i.e.* $\sigma_{N^+} = \sqrt{N^+}$).

$$\sigma_P^2 = \left(\frac{\partial P}{\partial N^+} \right)^2 (\sigma_{N^+})^2 + \left(\frac{\partial P}{\partial N^-} \right)^2 (\sigma_{N^-})^2 + \left(\frac{\partial P}{\partial \alpha} \right)^2 (\sigma_\alpha)^2 \quad (\text{C.2})$$

$$\left(\frac{\partial P}{\partial N^+} \right)^2 = \frac{4N^{-2}}{\left(\frac{\alpha}{2} \right)^2 (N^+ + N^-)^4} \quad (\text{C.3})$$

$$\left(\frac{\partial P}{\partial N^-} \right)^2 = \frac{4N^{+2}}{\left(\frac{\alpha}{2} \right)^2 (N^+ + N^-)^4} \quad (\text{C.4})$$

$$\left(\frac{\partial P}{\partial \alpha} \right)^2 = \frac{(N^+ - N^-)^2}{\left(\frac{\alpha^2}{2} \right)^2 (N^+ + N^-)^2} \quad (\text{C.5})$$

$$\sigma_P^2 = P^2 \left[\frac{4N^{+2}\sigma_{N^-}^2 + 4N^{-2}\sigma_{N^+}^2}{(N^+ - N^-)^2 (N^+ + N^-)^2} + \left(\frac{\sigma_\alpha}{\alpha} \right)^2 \right] \quad (\text{C.6})$$

$$\sigma_P^2 = P^2 \left[\frac{4N^{+2}\sigma_{N^-}^2 + 4N^{-2}\sigma_{N^+}^2}{(N^{+2} - N^{-2})^2} + \left(\frac{\sigma_\alpha}{\alpha} \right)^2 \right] \quad (\text{C.7})$$

APPENDIX D: DATA CHECKS

Although measuring observables on the reaction $\gamma d \rightarrow K^0 \Lambda(p)$ is crucial to provide more constraint to our models, there is not a convenient known quantity to check procedures and data quality. For example, when measuring a cross section on the proton, different topologies can be used or it can be compared to other world data. The topology used in this measurement (which was necessary with CLAS) consisted of three charged pions and a proton. These tracks must've been created off the neutron or another track must be missing. Therefore, a check on different topologies was not an option to check procedures. Moreover, there is minimal world data using deuterium targets to check normalization methods. Due to these reasons simple studies were done to compare cross sections of $\gamma d \rightarrow \pi^- p(p)$ (Section D.1) and $\gamma d \rightarrow K^+ \Lambda(n)$ (Section D.2) to previously measured data using developed procedures from the analysis on $\gamma d \rightarrow K^0 \Lambda(p)$. It is suggested that by matching these cross section data using the same techniques as in the case of $K^0 \Lambda$ that the luminosity, data, and procedures were all verified to be correct.

D.1 $\gamma d \rightarrow \pi^- p(p)$

The simplest cross section to measure (that would trigger events inside CLAS) with a deuterium target is that of $\gamma d \rightarrow \pi^- p(p)$. This has been measured using g10 data (mostly high field) and was published in 2012[CMD⁺09]. The aim of this study was to reproduce the published cross section, using only the low field data of g10. However, the data released to the CLAS database were corrected for final state interactions which are likely larger in the case of $\gamma d \rightarrow \pi^- p(p)$ rather than $\gamma d \rightarrow K^0 \Lambda(p)$ ⁹. A copy of the pre-corrected data points which were sent by the author to Igor Strakovsky was used to compare with this cross section¹⁰.

⁹ More about final state interactions on $\gamma d \rightarrow K^0 \Lambda(p)$ in Section D.2

¹⁰ It should be noted that these data differ 0-10% from the data which the BoGa group has in their database (http://pwa.hiskp.uni-bonn.de/BG2014.02_gn_int.htm).

The direct detection of the π^- and p , make for a straight forward and high statistic measurement. The likelihood of a missed photon is nowhere near the total amount of $\gamma d \rightarrow \pi^- p(p)$ events, making it a negligible contribution. The next lowest mass particle that could be missed (besides the spectator proton) is another pion, which is well separated from the missing mass peak of the spectator proton. Figure D.1 shows examples of the missing mass distributions within one energy bin. To resemble the previous g10 work the data was fit to a Gaussian that determined the integration limits calculating the yield. This yield was not background subtracted as the long tails could be mis-calibrated proton tracks.

Figure D.1: Shown are the peaks of the missing proton in the reaction $\gamma d \rightarrow \pi^- p(p)$. The extra pion peak is faintly visible at higher masses (>1.05 GeV). The green vertical lines represent the yield extraction integration region.

The acceptance was found to range up to 40%, creating a large statistic reaction. This acceptance was generated with the same software as it was for the reaction $\gamma d \rightarrow K^0 \Lambda(p)$. The t-slope used in this generation was 0.65, meaning this generated cross section was not uniform in $\cos(\theta_{CM}^{\pi^-})$. Instead the generated events were bias towards forward pion angles. A few notable things can be said about the acceptance. It is seen to vary sharply at forward and backward angles as one might expect. The other feature is the sharp dip in acceptance near $\theta_{CM}^{\pi^-} = 90^\circ$ as seen in Figure D.2. This dip is caused by the reproduction of the triggering condition. The trigger in some of the low field g10 data required a hit in the EC bank, and therefore was reproduced in the analysis software (data and simulation). This dips near $\theta_{CM}^{\pi^-} = 90^\circ$ ¹¹, due to the fact that the EC is a forward only detector. If the pion is backward going in the lab (also in center of mass), then the proton was forward going and likely hit the EC and visa versa.

Utilizing the extracted yield and acceptance as discussed above along with the luminosity as determined previously, the differential cross section can be measured. This is shown in Figures D.3-D.5. No quantitative systematic study was performed on this current measurement of $\gamma d \rightarrow \pi^- p(p)$. It is assumed that optimizing the analysis method for this channel would only contribute small systematic effects. Given that different runs in the same data set were used in this calculation versus the previous data, also would result in an added uncertainty in the luminosity. Moreover, an in depth systematic study in this channel may not do any good given that the previous results quoted here are slightly different than found in other locations. Despite these small discrepancies, the overall agreement suggests that the total systematic effect between the two datasets is less than 10% and gives confidence in the data quality. This reaction channel was fit by the BoGa group to help determine the parameters that describe processes on the neutron. If one is to use partial wave analysis on the family of KY cross sections including neutron photoproduction

¹¹ This effect actually varies slightly with energy since the maximum lab angle changes depending on the forward boosting of the proton and π^- .

Figure D.2: Shown is the acceptance of $\gamma d \rightarrow \pi^- p(p)$ at a beam energy of $E_\gamma = 1.15$ GeV.

results, one needs to understand the neutron photocoupling parameters. In other words, this fit was necessary to allow the interpretation of the $\gamma n \rightarrow K^0 \Lambda$ observables.

Figure D.3: Shown is the comparison of the $\gamma d \rightarrow \pi^- p(p)$ cross section using previously measured data (red points) and with the current analysis tools (black points). Also shown is the BnGa fit solution (black solid line) and inverted solution from $\pi^- p \rightarrow \gamma n$ (blue dashed line), where applicable.

Figure D.4: Shown is the comparison of the $\gamma d \rightarrow \pi^- p(p)$ cross section using previously measured data (red points) and with the current analysis tools (black points). Also shown is the BnGa fit solution (black solid line) and inverted solution from $\pi^- p \rightarrow \gamma n$ (blue dashed line), where applicable.

Figure D.5: Shown is the comparison of the $\gamma d \rightarrow \pi^- p(p)$ cross section using previously measured data (red points) and with the current analysis tools (black points). Also shown is the BnGa fit solution (black solid line) and inverted solution from $\pi^- p \rightarrow \gamma n$ (blue dashed line), where applicable.

D.2 Strength of Final State Interactions

Measuring cross sections such as $\gamma d \rightarrow K^0 \Lambda(p)$ are more difficult than similar channels on the proton. This is in part due to the fact that a free neutron target is impossible to construct. To access these channels a deuteron target is often used instead. The reactions measured use conservation laws such as charge and energy conservation to know whether the event was created upon the neutron or proton. This kinematically complete reaction (such as $\gamma d \rightarrow K^0 \Lambda(p)$) can then be approximated as the result for the free neutron. However, this is just an approximation. In reality several factors can affect the reaction to modify certain results. The most obvious factor, is the fact that the neutron is not stationary, it has a Fermi-momentum equal and opposite to that of its proton counter part. This effect is minor as the momentum is typically near 70 MeV, compared to the GeV scale beam energy. Still, this effect can be taken into account by using the detected tracks' momenta to boost into the center of mass frame as well as modeling this momentum distribution in the corresponding simulation. The other effects that make the bound neutron different from the free neutron is referred to as Final State Interactions (FSI). These FSI events originate from the fact that the neighboring proton can be considered to be at the same point in space as the neutron. This could make any final state's tracks, modeled by X in $\gamma n \rightarrow X$, more likely to scatter off the spectator proton.

These hadronic FSI events could do a number of unknown processes:

- The hadrons could scatter elastically. This would give some of the momentum to the spectator proton and/or change the angle of the incident particle. If the proton has enough momentum it could be detected ($>350\text{MeV}$) by CLAS. The incident particle could also be deflected at a different angle, causing an improper measurement. To minimize these effects a cut on the missing momentum ($<300\text{ MeV}$) is placed. This makes the detection the extra proton almost impossible, the low momentum events

are dominated by the quasi-free process making the contribution of the deflection events minimal.

- The FSI could prompt an inelastic hadron collision. This could transfer events out of the channel (i.e. $\gamma d \rightarrow K^0 \Lambda p$ then $\Lambda p \rightarrow n \Sigma^+$), or transfer events into the channel (i.e. $\gamma d \rightarrow pp\pi^-$ then $\pi^- p \rightarrow K^0 \Lambda$). The cross section of $\gamma d \rightarrow pp\pi^-$ is much higher than the cross sections of strange photoproduction and therefore could bias the results. However, the secondary reactions should only be a small portion of events due to the low luminosity. The FSI are much more likely to be dominated by the elastic scattering events.

These FSI effects could influence measurements like the asymmetries or cross sections. To limit these effects a cut is placed on the missing momentum. If the FSI effects are large then the events will be shifted from the pure Fermi momentum distribution. A comparison to the Fermi weighted simulated will show to first order if the momentum shape below a few hundred MeV matches the expected distribution. It is still possible that the events were shifted more than a few hundred MeV, thus losing events entirely. To investigate this effect more closely one can consider measuring proton photoproduction reactions on the deuteron to get a handle on the role of the FSI. This was done considering $\gamma p \rightarrow K^+ \Lambda$ and $\gamma d \rightarrow K^+ \Lambda(n)$.

D.2.1 $\gamma d \rightarrow K^+ \Lambda(n)$

One method to obtain the magnitude of FSI corrections needed to represent the free nucleon target is to compare a photoproduction observable off the deuteron to that of a proton. Although there may be other channels already measured showing the magnitude of these effects, we performed a first order estimate ourselves using a reaction channel consisting of $s\bar{s}$ creation. The channel of interest here being that of $\gamma d \rightarrow K^+ \Lambda(n)$. To perform this study the tracks of a K^+ , p , and π^- were identified using g10 data. When

looking for a K^+ one often get a data sample cluttered with π^+ 's due to the decreased probability of creating a K^+ . This background was reduced significantly using a cut on the invariant mass of the Λ . This reduction can be seen when one looks at the missing mass as in Figure D.6. Although the cut doesn't completely eliminate the events with a misidentified π^+ , the conservation of strangeness, momentum, and energy require that every event with a missing mass of the spectator nucleon must be a $K^+\Lambda$ event. This of course is only the case at the center of the missing mass peak; at the fringes, $K^+\Sigma^0$ and π^+ background starts leaking into the distribution. As with the case of $\gamma d \rightarrow K^0\Lambda(p)$, $\gamma d \rightarrow K^+\Lambda(n)$ can

(a) Shown is the invariant mass of the $p\pi^-$, with the cuts used to isolate the Λ events (Blue vertical lines). (b) Shown is a zoomed in view of Figure D.6a. (c) Shown is the missing mass of $\gamma d \rightarrow K^+ p\pi^- X$, with and without the Λ isolation cut.

Figure D.6: Shown is the reduction of backgrounds due to the Λ isolation cut.

also be cut on missing momentum. The kinematics of the K^+ rather than the $K^0 \rightarrow \pi^-\pi^+$ result in a slightly cleaner momentum distribution as seen from Figure D.7.

(a) Shown is the comparison of the missing momentum versus the missing mass.

(b) Shown is the missing momentum of the event between the black vertical lines in Figure D.7a

Figure D.7: Shown is the missing momentum topology of $\gamma d \rightarrow K^+ p \pi^- X$.

D.2.2 $\gamma p \rightarrow K^+ \Lambda$

The g10 experiment (along with g13) contains some proton target runs. However, the number of files with this target is limited (runs 42309-42330). Even with these limited number of files, some reactions can still be measured with large uncertainties. The cross section of $\gamma p \rightarrow K^+ \Lambda$ was measured with g10 data, to get a first order estimate on the systematic uncertainty of the $\gamma d \rightarrow K^+ \Lambda(n)$ study without an in depth analysis like this thesis topic. The same PID and analysis cuts were used in this calculation. It should be noted that the missing momentum plots will appear to be different, as the proton target did not contain any Fermi momentum. The results of this study are presented along side the $\gamma d \rightarrow K^+ \Lambda(n)$ cross section in Section D.2.3.

D.2.3 Comparison of $K^+ \Lambda$ Differential Cross Sections

A preliminary comparison between g11- $\gamma p \rightarrow K^+ \Lambda$, g1c- $\gamma p \rightarrow K^+ \Lambda$, g10- $\gamma p \rightarrow K^+ \Lambda$, and g10- $\gamma d \rightarrow K^+ \Lambda(n)$ are shown in Figure D.8. Both the g1c and g11

results are shown to provide an estimate of typical systematic uncertainties between two different experiments analyzed by CLAS. The areas of disagreement only exist in areas where both g10 results disagree with g11. This means the disagreement is likely due to K^+ identification problems. Therefore it is concluded that any FSI effects are small, and that the quasi-free events of $\gamma d \rightarrow K^+ \Lambda(n)$ do a reasonable job of approximating the free proton target results. Extrapolating this result, one can imagine that these effects are of similar size on for the $\gamma d \rightarrow K^0 \Lambda(p)$ cross sections.

Figure D.8: Shown is the preliminary comparison between $\gamma p \rightarrow K^+ \Lambda$ ($g10$, $g11$, and $g1c$) and $\gamma d \rightarrow K^+ \Lambda(n)$ ($g10$). The $g11$ and $g1c$ uncertainties are not shown. Only the $g10$ statistical uncertainties are shown.

D.3 Summary

The agreement from with g10 data low field data to the previously measured g10- $\gamma d \rightarrow \pi^- p(p)$ and g11- $\gamma p \rightarrow K^+ \Lambda$ confirm that the g10 data is in good standing, the luminosity is calculated correctly, and the analysis software is viable. Moreover, the discussion and comparison between $\gamma p \rightarrow K^+ \Lambda$ and $\gamma d \rightarrow K^+ \Lambda(n)$ show that corrections for FSI are relatively small for $K^+ \Lambda$ production and therefore likely to be small for the $K^0 \Lambda$ production.

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