Exclusive Analysis of the $\vec{\gamma} \uparrow n \rightarrow K^+ \Sigma^-$ Reaction at $E_\gamma$=0.8-2.3 GeV

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Abstract. Strangeness channels are important in the experimental search for missing resonances. A recent experiment performed at Jefferson Lab (CLAS g13 run period) used a liquid deuterium target with linearly and circularly polarized tagged photon beams covering energies from threshold to 2.5 GeV. It provides high-quality data (about 52 billion triggers) with good kinematic coverage and several experimental observables available for each reaction channel. We have analyzed a few percent of these data to measure strangeness photoproduction on the neutron, in particular, the $\gamma n \rightarrow K^+ \Sigma^-$ reaction. The exclusive analysis of this reaction along with a very preliminary measurement of the photon beam asymmetry is presented.

1. Introduction and motivation

At high energies (asymptotic freedom), experimental measurements are well described by perturbative quantum chromodynamics (pQCD). The confinement of quarks in hadrons is, however, inherently non-perturbative. While lattice QCD has been making rapid progress, at this time the difficulties in solving QCD in this intermediate-energy region makes it necessary for us to resort to phenomenological models. The spectrum of excited states predicted by effective-potential quark models, in which all three nucleons are excited independently, predict a richer resonance spectrum than that measured experimentally [1, 2]. In contrast, quark models with strong quark-quark correlations (diquarks) have fewer degrees of freedom and do not give rise to such a rich spectrum [3]. The set of excited states for the nucleon not yet found experimentally but predicted theoretically by the SU(6) symmetric constituent quark models are known as the “missing resonances”. Finding or ruling out some of these states would thus be important for our understanding of nucleon structure.

Experimentally, most of the known resonances have been measured in channels that include pions either in the initial state or in the final state of the reaction (the other known resonances are related to $\eta$ and $\omega$ production). The question is thus whether the non-observation of the missing states is due to our choice of measurement or really does indicate that they do not exist. Theoretical calculations have shown that some missing resonances could couple weakly to pion channels, but may have significant photocouplings to channels involving strangeness [4].

From a phenomenological point of view, resonances are studied using reaction models that extract resonance parameters, including mass, total width, and branching ratios. These models use Feynman diagrams to include contributions from Born terms, from nucleon resonances, as well as...
non-resonant contributions; the vertices of these diagrams are expressed in terms of parameters to be fitted to the experimental data. In the missing-resonance energy region ($W > 1.7$ GeV), where several channels are opened, it is important to employ a coupled-channels approach [5, 6]. By combining data from various final states, proton and neutron targets, as well as polarization observables, sufficient experimental constraints can be provided for a reliable extraction of the resonance parameters [7].

We are primarily interested in the $\gamma N \rightarrow K\Sigma$ channel, which couples not only to the $I=\frac{1}{2} N^*$, but also to the $I=\frac{3}{2} \Delta^*$ states. Since the $\Sigma$ is an isotriplet, additional constraints can be imposed by measuring all three states. Of these, the $\gamma n \rightarrow K^+\Sigma^-$ requires a neutron target and is the focus of the presented analysis. The current published data for the beam asymmetry of this channel are limited to very forward angles [8]; with this analysis we will be able to extend significantly the angular coverage, which is essential for extraction of $s$-channel resonances.

2. Experimental data

Strangeness photoproduction data have been obtained as part of the g13 run period [9] with the CEBAF Large Acceptance Spectrometer (CLAS) in Hall B at Jefferson Lab. The experiment was performed to collect strangeness data on the neutron with comparable uncertainties to the current existing data on the proton. This translates into data with high statistics, wide kinematic coverage and many polarization observables available for each reaction channel. Thus, g13 data will cause a high impact on the coupled-channels analyses making them suitable to search for missing excited states of the neutron over a wide photon energy range.

The experiment made use of a 40-cm-long liquid deuterium target LD2, the CLAS detector system (which provides nearly $4\pi$ sr coverage) and both circularly (g13a) and linearly (g13b) polarized photon beams with the measurement of kaons or their decay products (pions) and the decay products of the $\Lambda$ and $\Sigma$ (pions and nucleons) in the final state. The first part of the experiment used circularly polarized photons in the photon energy range up to 2.5 GeV, and was run in the Fall of 2006. The second part used linearly polarized photons ranging from 1.1 to 2.3 GeV, and was run in Spring-Summer 2007.

3. Event selection

In the reaction $\gamma D \rightarrow K^+\Sigma^-(p)_s$ the $\Sigma^-$ decays into $n\pi^-$ with a 99.9% branching ratio. In order to perform an exclusive analysis of this reaction it is necessary to detect the $\Sigma^-$ decay products ($n\pi^-$) and the $K^+$ given that the spectator proton ($p)_s$ in the case of the quasi-free reaction is a low-momentum particle making it hard to be detected. The spectator proton and the $\Sigma^-$ are therefore reconstructed from its missing mass $MM(K^+n\pi^-)$ and its invariant mass $M(n\pi^-)$, respectively.

3.1. Particle identification

Charged particles ($K^+, \pi^-$) are identified by imposing momentum-dependent cuts on the difference $\Delta \beta$ between measured and calculated beta. Figure 1 shows the cuts used to select $\pi^-$ and $K^+$ as a function of 100-MeV/c momentum bins.

Neutral particles are identified as a cluster in the electromagnetic calorimeter that is not associated with a track in the drift chambers system. Figure 2 displays the beta distribution for all the neutral hits labeled as neutrons. Neutrons are selected by imposing a cut just below $\beta_{Neutral} < 1.0$. 
Figure 1. (left) $\pi^-$ and (right) $K^+$ identification based on a momentum-dependent $\Delta \beta$ cut. Events within the black lines on each plot correspond to good $\pi^-$ and good $K^+$, respectively.

Figure 2. $\beta$ distribution for detected neutrons.

3.2. Other cuts and corrections
The CLAS regions of non-uniform acceptance were removed from the analysis as well as inefficient scintillator paddles and those events with a vertex time difference $|\Delta T| = T_{K^+} - T_\gamma$ greater than 2.0 ns. Corrections on the energy lost by the charged particles when traveling through the target were also applied.

4. Background
Three main sources of background contamination in the $K^+\Sigma^-$ sample were identified:

- $\pi^+$ mis-identified as $K^+$.
- $\Lambda$ and $\Sigma^0$ production on the proton $\gamma D \rightarrow K^+\Lambda n$ and $\gamma D \rightarrow K^+\Sigma^0 n$.
- Events associated with $\gamma D \rightarrow K^{++}\Sigma^- (p)_s$ and $\gamma D \rightarrow K^+\Sigma^*^- (p)_s$ where $K^{++}$ decays into $K^+\pi^0$ and $\Sigma^*^-$ decays into $\Sigma^-\pi^0$.

The first source can be identified relatively easy by assigning the PDG mass of the $\pi^+$ to the kaon candidate and looking at the correlation $MM(K^+ n \pi^-)$ vs $MM(\text{"}K^+\text{"} n \pi^-)$ where "$K^+$" is the identified kaon given the pion mass. The second source of background is removed by cutting on the momentum of the spectator proton (missing momentum). The fact that we are considering only quasi-free events makes it necessary to restrict the missing momentum to low
values. A 0.2 GeV/c cut was applied. This cut can be justified by looking at Figures 3 and 4 where the missing momentum distribution and the correlation between missing momentum and cosine of missing $\theta$ are displayed, respectively. As can be seen from Figure 3, a 0.2 GeV/c cut removes mainly events with missing momentum in the tail of the Fermi distribution. Figure 4 shows clearly that below 0.2 GeV/c the distribution of low-momentum spectators in the lab frame follows an isotropic behavior which is characteristic of Fermi motion.

![Figure 3. Missing momentum distribution.](image1)

Below 0.2 GeV/c most of the events can be considered to be associated with quasi-free reactions. Above that value, there is a dominance of the final-state interactions.

![Figure 4. Missing momentum vs cosine of missing polar angle.](image2)

Above that threshold, the events are forward-peaked.

The last contribution to background comes from $K^+\Sigma^-$ events with an additional $\pi^0$ in the final state. That contribution can be clearly seen in Figure 5 where the missing mass $MM(K^+n\pi^-)$ is shown. The small bump peaking at around 1.1 GeV/c$^2$ represents such a contamination. In order to isolate those events, we plot the missing mass $MM(n\pi^-)$ as a function of the $K^+$ momentum. From that distribution, shown in Figure 6, it can be observed that $K^+\Sigma^-$ events are clearly separated from $K^+\Sigma^-\pi^0$ events. After slicing the distribution in 100-MeV momentum bins and fitting each piece with two Gaussians + a first order polynomial function (black curves) we obtain the missing mass distribution shown in grey color in Figure 5.

5. Preliminary results

Yields are extracted from the invariant mass distribution $M(n\pi^-)$ by fitting it for each $E_\gamma$ bin with a Breit-Wigner + a first order polynomial function. Figure 7 shows the mass distribution integrated over all angles for $E_\gamma=2.1-2.3$ GeV.

In order to determine the beam asymmetry ($\Sigma$), the linearly polarized data ($g_{13b}$) were taken with two different photon polarization orientations: horizontal and vertical. The beam asymmetry is extracted by taking the flux normalized yields with horizontal ($N_{||}$) and vertical ($N_{\perp}$) orientations. For each $E_\gamma$ and $\cos\theta_{K^+}^*$ bin the asymmetry of $N_{||}$ and $N_{\perp}$, as a function of the kaon azimuthal distribution $\phi$, is fitted by means of a function proportional to $B \cos(2\phi)$ where the fitting parameter $B = \langle P \rangle \Sigma$ with $\langle P \rangle$ corresponding to the average polarization. Hence, by obtaining $B$ from the fit and knowing $\langle P \rangle$, it is possible to extract $\Sigma$. A preliminary beam asymmetry for $E_\gamma=2.1-2.3$ GeV and several $\cos\theta_{K^+}^*$ bins is presented in Figure 8.

The main systematic uncertainties in the extraction of the beam asymmetry come from the calculation of the linear photon polarization. Currently it has been determined with an uncer-
Figure 5. Missing mass of the $K^+n\pi^-$ system. White histogram shows clearly a $K^+\Sigma^-\pi^0$ peak at around 1.1 GeV/c$^2$. Histogram in grey color represents the events remaining after rejecting $K^+\Sigma^-\pi^0$ events. Dashed histogram corresponds to those rejected events.

Figure 6. Missing mass of the $n\pi^-$ system as a function of the $K^+$ momentum. Events above the upper black curve are associated with $K^+\Sigma^-\pi^0$ final states while events within the two black curves are thought to be related to actual $K^+\Sigma^-$ states. Black curves are explained in the text.

Figure 7. Invariant mass distribution $M(n\pi^-)$ fitted with a Breit-Wigner plus a 1st order polynomial. Events within the two black dashed lines corresponds to roughly 99.3% of the total number of events.

tainty of 10% but we expect to have it down to 3%.

6. Summary
We have made a preliminary beam-asymmetry measurement for the $\gamma n \rightarrow K^+\Sigma^-$ quasi-free reaction. Although we have used a few percent of the total data (at the time of this writing, only 15 % of the total linearly polarized data was available to be analyzed) to determine the beam asymmetries, it is noticeable that the obtained asymmetries are all positive and approaching unity at forward angles. This is in contrast with some theoretical models that predict a sign change for the beam asymmetry [10]. Final data will provide a big constraint on coupled-channels analysis involving strangeness photoproduction. Such calculations can be carried out by the Excited Baryon Analysis Center (EBAC) at the Jefferson Lab [7].
Figure 8. Photon beam asymmetry for the reaction $\gamma n \rightarrow K^+ \Sigma^-$ for the 2.1-2.3 GeV photon energy setting as a function of ten different $\cos \theta_{K^+}$ bins. The errors shown are statistical only.

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