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Photoproduction of the doubly-strange Ξ hyperons

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Abstract

We report on the first measurement of exclusive Ξ^- and Ξ^0 photoproduction. The Ξ^- states are produced in the reaction $\gamma p \to K^+K^+\Xi^-$, and the Ξ^0 states in $\gamma p \to K^+K^+\pi^-\Xi^0$. Identification is made by the unique mass measured as the missing mass of the K^+K^+ (or $K^+K^+\pi^-$) system using the CLAS detector at the Thomas Jefferson National Accelerator Facility. A systematic study of the excited Ξ spectrum improves our understanding of the N^* and Δ^* states, since the Ξ^* states are related to them by $SU(3)$ flavor symmetry. At the highest energies available at Jefferson Lab, we begin to find evidence for known excited Ξ^- states in the photoproduction process, and possibly new states at 1770 and 1860 MeV, although we do not have enough statistics to draw a strong conclusion. A search for the $\Xi_5^{--}(1862)$ pentaquark state seen by NA49 is made using the process $\gamma p \to K^+K^+\pi^+X$, but the result is inconclusive for lack of statistics.

1. Introduction

We know very little about the doubly-strange Ξ, or cascade, hyperons. Although $SU(3)_F$ symmetry predicts the existence of a Ξ for every nucleon *and* a Ξ for every Δ, for a total of 44 Ξ states [1], only eleven have been seen to date [2]. Of these eleven,

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only three have been completely identified by their mass, width, spin, and parity. Less still is known about their production mechanisms and decay branching ratios.

The bulk of our knowledge on the cascade spectrum has come from kaon beams, with some information from hyperon beams. It is important to find a new means of producing the Ξ, since there is currently no suitable kaon facility. Ref. [3] first suggested using the photoproduction process $\gamma p \to K^+K^+\Xi^-$ to look for the cascade. The threshold for the production of the ground state $\Xi^-(1321)$ using this process is 2.37 GeV. For the Ξ^0, an extra π^- is detected, and the threshold for the production of the ground state is 2.73 GeV. These processes provide unique event signatures, in which two K^+'s are required. Their exclusive nature results in very little physics background. The Thomas Jefferson National Accelerator Facility (JLab), with its 5.7 GeV tagged photon beam [4] and the CLAS detector [5] is an excellent place for this study.

This study is motivated by the observation that the Ξ states are approximately nine times narrower than the nucleon or Δ states [6]. This was first explained by Riska [7] to be related to the number of light quarks within the baryon. The narrower Ξ states are much easier to detect than the N^* or Δ^* states, and are expected to be visible in a simple missing mass spectrum.

2. Data

There has as yet been no dedicated JLab experiment to search for cascade states. However, there are three existing CLAS data sets (designated g6a, g6b, and g6c) taken for other purposes that are compatible with Ξ photoproduction. The relevant running conditions for each of these data sets are given in Table 1.

3. Results

3.1. Ξ^- photoproduction

Fig. 1 shows the missing mass of the K^+K^+ system for the g6a data set. The missing mass resolution of the CLAS detector was determined by comparisons with the known widths of various hyperon resonances in this analysis, and is approximately 15–20 MeV for each of the data sets used in this measurement. The ground state cascade at 1321 MeV is clearly seen in the spectrum, showing that there is indeed little physics background.

Table 1
The three CLAS data sets used for Ξ photoproduction. The different columns show the tagged photon energy range E_γ, the integrated luminosity $\int \mathcal{L}\, dt$, the position of the target z_{tgt} (0 is at the center of CLAS), and the relative CLAS torus current I_t

Run	E_γ (GeV)	$\int \mathcal{L}\, dt$ (pb^{-1})	z_{tgt} (cm)	I_t
g6a	3.2–3.9	1.1	0	I_0
g6b	3.0–5.2	not well-known	0	I_0
g6c	4.8–5.4	2.7	−100	$0.58I_0$

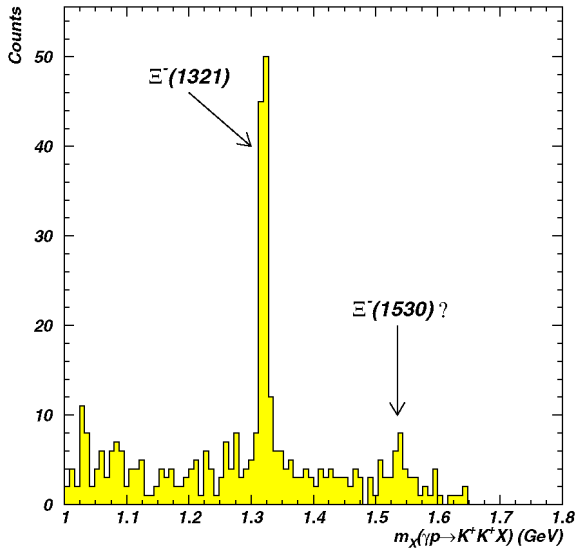

Fig. 1. The K^+K^+ missing mass for the g6a data set with a tight K^+ particle ID. The signal-to-noise ratio for the ground state $\Xi^-(1321)$ is approximately 10 : 1. There is a hint of structure at the position of the first excited cascade state at 1530 MeV.

By using a tight K^+ particle ID, we also see possible structure at the position of the first excited state at 1530 MeV. However, the phase space for the production of the $\Xi^-(1530)$ is too small to show a convincing peak under the g6a running conditions.

Fig. 2 shows the same spectrum from the g6b data set. These data were taken at higher energy; both the ground state and the first excited state of the Ξ^- are clearly seen. The K^+ particle ID is looser than in the g6a data set, which leads to a background due to π/K misidentification. The structure at 1100 MeV in Fig. 2 is due to the process $\gamma p \to K^+\pi^+\Sigma^-$, in which the π^+ is misidentified as a K^+. This can be seen by plotting the K^+K^+ missing mass vs. the missing mass obtained in the $\gamma p \to K^+\pi^+X$ process, by forcing one of the kaon masses to be that of the π^+. Improving the particle ID for this data set is currently under study.

Fig. 3 shows the K^+K^+ missing mass spectrum for the g6c data set. The g6c data set was taken at a much higher photon flux than the g6a and g6b data sets. This led to a large background due to beam accidentals, and increased the background due to π/K misidentification.

The latter can be removed by considering the Ξ^- decay chain $\Xi^- \to \pi^-\Lambda \to \pi^-\pi^- p$ (or $\to \pi^-\pi^0 n$). In the case of a single π/K misidentification, the final state is $K^+\pi^+\Sigma^-$; for double π/K misidentification, it is $\pi^+\pi^+\Delta^-$. Neither of these processes will result in a proton in the final state; both the Σ^- and the Δ^- decay nearly 100% to $\pi^- n$. Consequently, we can remove both of these backgrounds by requiring the presence of a proton in the final state.

Fig. 4 shows the result of this additional requirement. The figure shows the K^+K^+ missing mass for the events in which a proton is also detected. The $\Xi^-(1530)$ is again

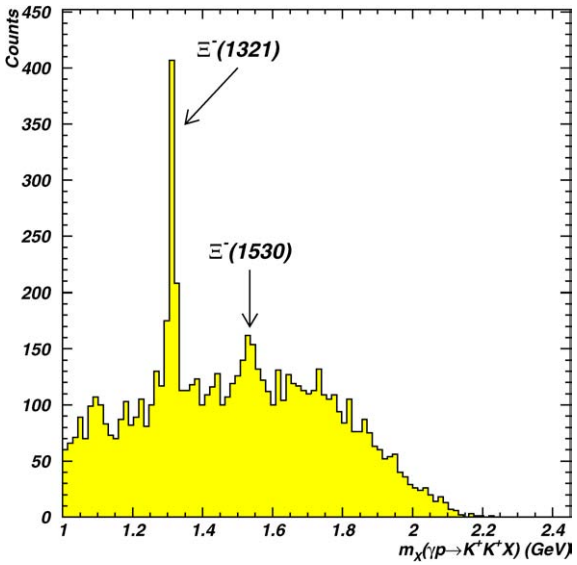

Fig. 2. The K^+K^+ missing mass for the g6b data set, with loose K^+ particle ID. Both the ground state and the first excited state are clearly seen in the data. There is additional structure at 1100 MeV due to the $K^+\pi^+\Sigma^-$ final state in which the π^+ is misidentified as a K^+.

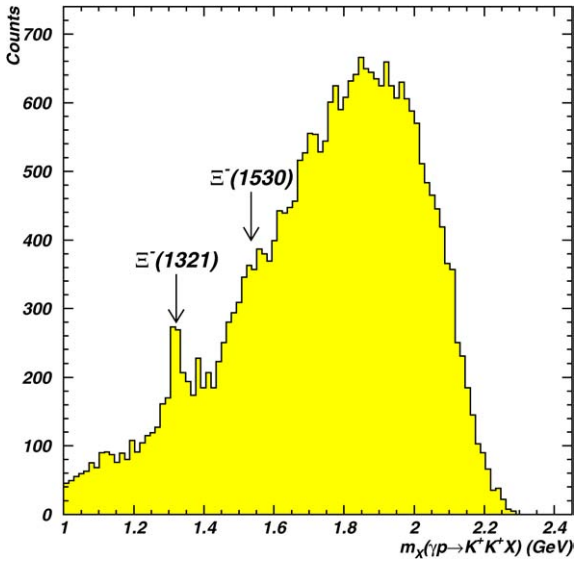

Fig. 3. The K^+K^+ missing mass for the g6c data set. These data were taken with a very high photon flux, which resulted in a large background due to beam accidentals and π/K misidentification. The ground state is still clearly seen, but the $\Xi^-(1530)$ appears only as a shoulder in the plot.

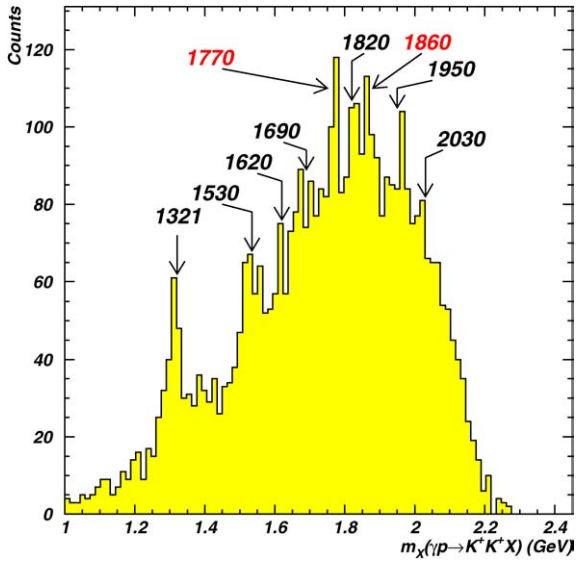

Fig. 4. The same plot as in Fig. 3, with the additional requirement of a proton in the final state. This removes the backgrounds due to π/K misidentification, and reveals a great deal of structure at the higher masses. Arrows on the plot indicate the masses of every cascade hyperon below 2.1 GeV in the Particle Data Book. Two structures appear in this plot that are not listed in the Particle Data Book, at 1770 and 1860 MeV.

clearly seen. This plot reveals a great deal of apparent structure not visible in Fig. 3. To study the significance of the enhancements in Fig. 4, we compare their positions in the plot to known states in the Particle Data Book [2]. These states are shown by arrows in the plot. We find that every state listed in the Particle Data Book up to 2030 MeV is well-matched to an enhancement in Fig. 4 (although the evidence for the $\Xi^-(1620)$ and $\Xi^-(1690)$ in Fig. 4 is weak). Furthermore, we note that Fig. 4 has two additional enhancements that are not in the Particle Data Book, at 1770 and 1860 MeV. In this mass region, these values should be accurate to approximately 15 MeV. Both of these structures are robust, in the sense that they do not appear to be an effect of the histogram binning. We are currently studying the possibility of reducing the background further to enhance the structure.

Information on the production mechanism will be obtained by looking at the energy dependence and angular distribution of cascade photoproduction. These studies are planned for the near future. The preliminary results of this study, which are neither normalized for the photon flux nor corrected for the detector acceptance, are shown in Fig. 5 for the energy dependence, and in Fig. 6 for the angular distribution.

The preliminary nature of Figs. 5 and 6 makes detailed interpretation premature. However, we may already note that the energy dependence appears to have some structure worth investigating, and that the angular dependence of the $\gamma p \to K^+K^+\Xi^-$ reaction is different in the two energy ranges covered by the g6a (3.2–3.9 GeV) and g6b (3.0–5.2 GeV) data sets.

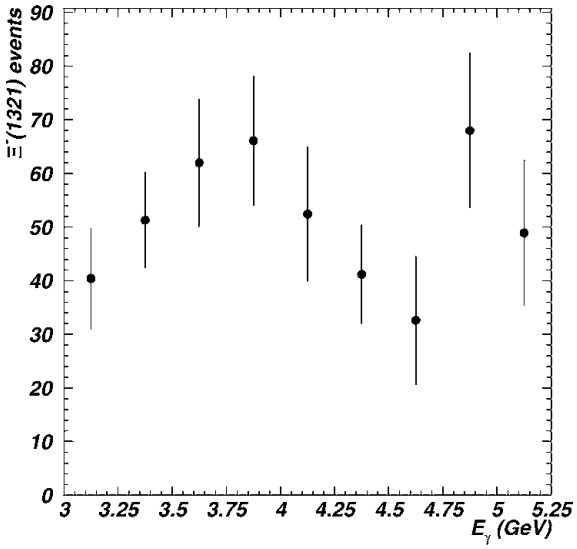

Fig. 5. The total yield for $\gamma p \to K^+K^+\Xi^-$ as a function of the photon energy E_γ for the g6b data set. The points reflect the actual number of detected events in each 250 MeV bin. Neither the photon normalization nor the detector acceptance correction have been applied.

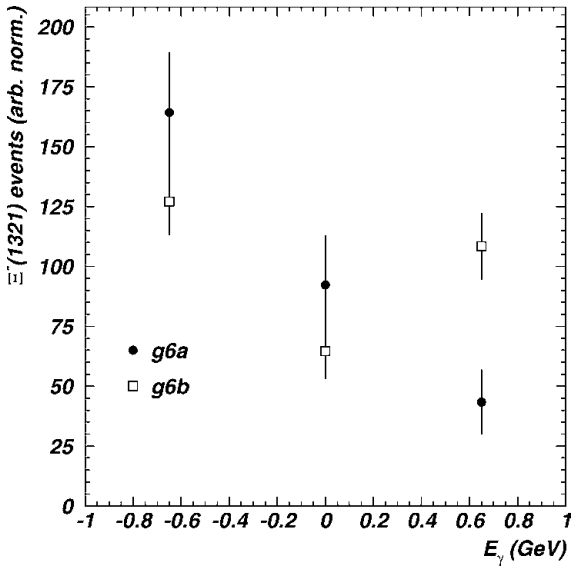

Fig. 6. The angular distribution for the g6a (squares) and g6b (circles) data sets. The event numbers are arbitrarily normalized. Neither the photon normalization nor the detector acceptance correction have been applied.

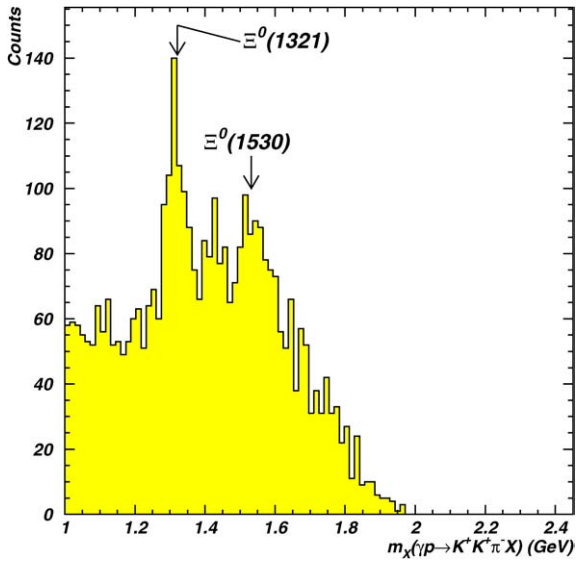

Fig. 7. The $K^+K^+\pi^-$ missing mass in the process $\gamma p \to K^+K^+\pi^-X$ from the g6c data set. There are two peaks in this plot that correspond to the known $\Xi^0(1321)$ ground state and the first excited state at 1530 MeV. The structure between these two peaks is believed to be a π/K misidentification reflection due to the $K^+\pi^+\pi^-\Lambda(1520)$ final state, and is currently under study.

3.2. Ξ^0 photoproduction

We may look for the Ξ^0 in the $K^+K^+\pi^-$ missing mass in the process $\gamma p \to K^+K^+\pi^-X$. Detecting the π^- complicates the analysis; because of the toroidal geometry of CLAS, the acceptance for positive and negative particles is very different. If the K^+ are detected with high acceptance, the π^- acceptance is correspondingly small. The g6c data set was taken with a reduced magnetic field and an upstream target position, both of which improved the acceptance for negatively charged particles. In this data set, we can look for the Ξ^0. Fig. 7 shows our first result for this search. This analysis is still underway. The preliminary result is that we observe the $\Xi^0(1321)$ and the $\Xi^0(1530)$, with a third peak between them at around 1410 MeV. This peak is thought to be a π/K misidentification reflection due to the process $\gamma p \to K^+\pi^+\pi^-\Lambda(1520)$.

3.3. Ξ_5^{--} pentaquark search

The recent discovery of the Θ^+ pentaquark and its confirmation by many groups around the world using different techniques has generated a great deal of excitement in the nuclear physics community. The Θ^+ is predicted to be part of an antidecuplet, of which two other members are also manifestly exotic, in that they cannot be composed of three-quark states. These states are the Ξ_5^{--} and the Ξ_5^{+}. Finding these states is tremendously important to our understanding of the nature of the pentaquarks. Several different models exist to

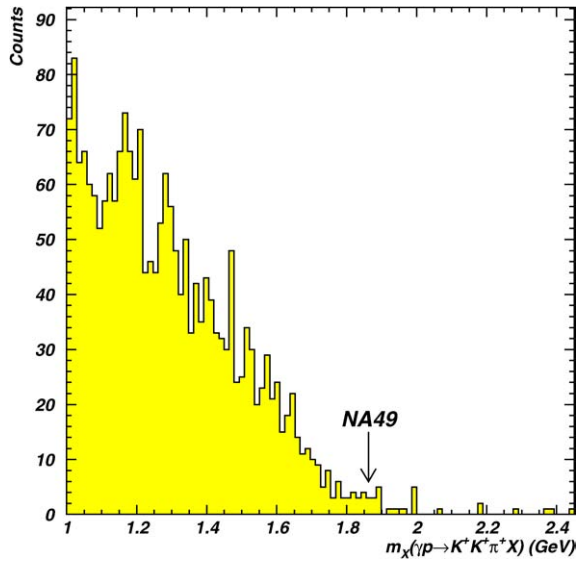

Fig. 8. The $K^+K^+\pi^+$ missing mass for the g6b data set. An arrow marks the position of the NA49 peak at 1860 MeV. The phase space in this plot dies out too early to see any significant structure.

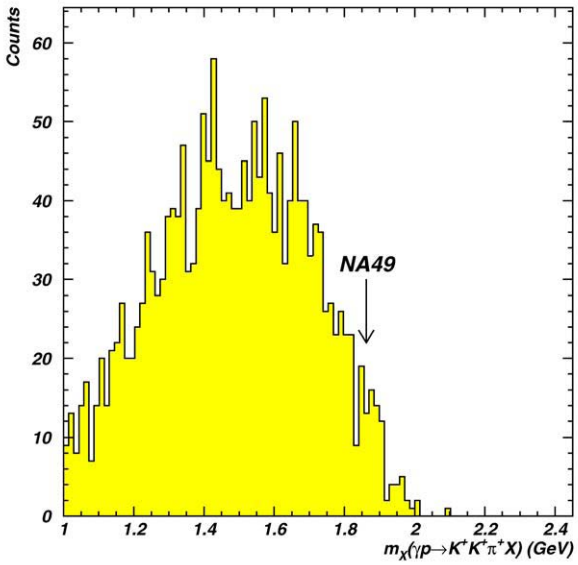

Fig. 9. The $K^+K^+\pi^+$ missing mass plot for the g6c data set. An arrow marks the location of the NA49 peak at 1860 MeV. No significant structure is seen in the plot.

describe their structure, and a determination of even just the mass of these states will help to constrain the models.

The NA49 group has recently claimed to have seen the Ξ_5^{--} in pp collisions at 17.2 GeV [8]. It is vitally important to confirm or refute this discovery as soon as possible. We can look for this state in the g6b and g6c data sets by looking for a peak in the $K^+K^+\pi^+$ missing mass in the process $\gamma p \to K^+K^+\pi^+X$. Fig. 8 shows this missing mass for the g6b data set, and Fig. 9 shows the missing mass plot for the g6c data set. No significant structure is seen in either of the plots. A simple estimate, based on the comparison between the number of ground-state cascades detected in this measurement and in the reported number of ground-state cascades found by the NA49 group indicates that there should only be approximately 5–10 Ξ_5^{--} events in Fig. 9.

4. Conclusions

The interest in cascade physics has increased greatly over the past year. We have data that appears to agree with several states listed in the Particle Data Book, and potentially new structure at 1770 and 1860 MeV. The structure at 1860 MeV is particularly interesting, as it corresponds well to the NA49 discovery of the Ξ_5^{--} pentaquark, a state whose properties must be determined in order to understand the pentaquark structure. The CLAS detector at Jefferson Lab is an excellent facility for the study of these states. The existing cascade physics program at JLab is well-placed to pursue this study. There are currently three separate experimental proposals to search for the Ξ_5^{--}, in an attempt to confirm or refute the NA49 discovery, and Jefferson Lab will produce some of the best new information on Ξ_5 states in the next few years.

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