

Exclusive photoproduction of the cascade ( $\Xi$ ) hyperons

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We report on the first measurement of exclusive  $\Xi^-(1321)$  hyperon photoproduction in  $\gamma p \rightarrow K^+ K^+ \Xi^-$  for  $3.2 < E_\gamma < 3.9$  GeV. The final state is identified by the missing mass in  $p(\gamma, K^+ K^+)X$  measured with the CLAS detector at Jefferson Laboratory. We have detected a significant number of the ground state  $\Xi^-(1321)_{\frac{1}{2}}^{+}$  and have estimated the total cross section for its production. We also have strong evidence for the first excited state  $\Xi^-(1530)_{\frac{3}{2}}^{+}$ . Photoproduction provides a copious source of  $\Xi$ 's. We discuss the possibilities of a search for the recently proposed  $\Xi_5^-$  and  $\Xi_5^+$  pentaquarks.

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Little is known about the doubly strange  $\Xi$  hyperons. According to the *Review of Particle Properties* (RPP),  $J^P$  has been determined for only three states: the  $\Xi(1321)_{\frac{1}{2}}^{+}$ , the  $\Xi(1530)_{\frac{3}{2}}^{+}$ , and the  $\Xi(1820)_{\frac{3}{2}}^{-}$  [1]. Eight more candidates have been reported, but no  $J^P$  determination has been made [1].  $SU(3)_F$  symmetry implies the existence of a  $\Xi$  for every  $N^*$  and also one for every  $\Delta^*$  [2]. The RPP lists 24 well-established (three- or four-star)  $N^*$  and  $\Delta^*$  resonances. There are also 20  $N^*$  and  $\Delta^*$  “candidates” (one- or two-star). We therefore expect to find at least 24  $\Xi^*$  states; another 20 states may also exist.

Because the cascades have strangeness  $S = -2$ , they are difficult to produce. The study of these hyperons has thus far centered on their production in  $K^- p$  reactions; some  $\Xi^*$  states were found using high-energy hyperon beams. It is important to find other means of  $\Xi$  production—there is no suitable  $K^-$  facility for the production of the excited  $\Xi^*$  states available now.

The inclusive photoproduction process  $\gamma p \rightarrow \Xi^- X$  has been studied by two groups. In both cases, the  $\Xi^-$  was reconstructed from the decay products in the chain  $\Xi^- \rightarrow \pi^- \Lambda \rightarrow \pi^- \pi^- p$ . Aston *et al.* [3] used a tagged photon beam in the energy range  $20 < E_\gamma < 70$  GeV at the CERN SPS with the Omega spectrometer, and measured a cross section of  $28 \pm 9$  nb for  $x_F (=2p_{\parallel}^*/\sqrt{s}) > -0.3$ . Abe *et al.* [4] used a 20 GeV laser-backscattered photon beam incident on the SLAC 1-m hydrogen bubble chamber and quote a total cross section of  $117 \pm 17$  nb. They also report a value of  $94 \pm 13$  nb in the same  $x_F$  range as the CERN group, in strong disagreement with Aston *et al.* [3]. This discrepancy has never been addressed.

The availability at the Thomas Jefferson National Accelerator Facility (JLab) of photon and electron beams up to 6 GeV suggests that the prospects for cascade photoproduction should be revisited. All 11 cascade states listed in the RPP are very narrow (9–60 MeV) [1], and there is reason to believe that any missing cascades are also narrow [5]. The  $\Xi^-$  can therefore be observed as a sharp peak in the missing mass spectrum in  $p(\gamma, K^+ K^+)X$ . This method has a great benefit in that it can be used without modification to search for all narrow excited cascade states [6].

In this Brief Report we present the first measurement of exclusive  $\Xi^-$  photoproduction in the process  $\gamma p \rightarrow K^+ K^+ \Xi^-$ . We use the missing mass technique to measure the cross section for the production of the ground state  $\Xi^-$  and establish a signal for the first excited state  $\Xi^-(1530)$ . This method is a viable option for future searches for high-mass  $\Xi^*$  states. The availability of a substantial sample of cascade hyperons, in both the ground state and excited states, will allow the pursuit of several avenues of research [7]. These include the search for the many missing cascade states mentioned above, studies of interesting cascade decays,  $J^P$  measurements of the  $\Xi$  states, the  $s$ - $d$  quark mass difference, and with a long target to allow rescattering,  $\Xi p$  scattering, and double  $\Lambda$  hypernuclear production.

The interest in cascade physics has received a major boost because of the recent evidence for the production of pentaquarks, although their existence is not firmly established [8]. Within the proposed antidecuplet of pentaquark states, three are *manifestly exotic*, in that their quantum numbers preclude them from being three-quark states: the  $\Theta^+(1540)$ ,

the  $\Xi_5^{--}$ , and the  $\Xi_5^+$  (the subscript “5” refers to the pentaquark nature of these objects). Only one experiment, NA49, has claimed a signal for the  $\Xi_5$  [9], although some NA49 members have suggested alternative interpretations of this result [10]. Other experiments with much higher statistics [11–15] have not seen this state. The RPP rates the  $\Xi_5$  as a one-star state [1]. It is urgently necessary to find a complementary approach to investigate the existence of the  $\Xi_5$ .

The photon energy threshold for the production of the ground state  $\Xi^-(1321)\frac{1}{2}^+$  is 2.4 GeV; the first excited state, the  $\Xi^-(1530)\frac{3}{2}^+$ , requires  $E_\gamma > 2.9$  GeV. These energies are available at JLab with the Hall B Photon Tagger [16], whereas the  $K^+$ 's can be detected with the large-acceptance multiparticle spectrometer CLAS [17]. This detector is a six-sector spectrometer with a toroidal magnetic field. Three sets of drift chambers surrounded by a highly segmented scintillation counter system determine the momentum and velocity of the outgoing charged particles at polar angles in the range  $10^\circ$ – $140^\circ$ .

To establish that there are two  $K^+$ 's in the final state, time of flight is used over a  $\sim 5$ -m flight path to the outermost layer of the CLAS detector. This makes the detection efficiency strongly dependent on the kaon momentum. This is partially offset by the toroidal field of the CLAS magnet, which bends positively charged particles away from the beam line.

We have analyzed two existing CLAS data sets for the exclusive photoproduction process  $p(\gamma, K^+K^+)\Xi^-$ . Details of these data sets and the results obtained from them may be found in [18,19]. The first data set, labeled *g6a*, had a photon energy range  $3.2 < E_\gamma < 3.9$  GeV, with a photon flux of  $10^6 \gamma/s$ . For the second data set, *g6b*, the photon energy range was  $3.0 < E_\gamma < 5.2$  GeV, and the photon flux was approximately 5 times higher. The running conditions for the two data sets were otherwise identical. An 18-cm-long liquid-hydrogen target was located at the center of CLAS. The integrated luminosity of the *g6a* data set is  $1.1 \text{ pb}^{-1}$ . The luminosity of the *g6b* set is approximately twice as large, but the absolute normalization uncertainties in this data set prevent us from using it in our evaluation of the cross section. The determination of the photon flux is discussed in Ref. [16].

The identification of a particle as a  $K^+$  is based on the measured momentum and velocity. Figure 1(a) shows the missing mass spectrum for the process  $p(\gamma, K^+K^+)X$  from the *g6a* data set. The spectra in Fig. 1 have not been corrected for acceptance. Figure 1(a) has a large, very narrow peak at 1320 MeV, with a signal-to-background ratio of better than 10:1. The mass is in excellent agreement with the RPP value of  $1321.3 \pm 0.1$  MeV [1]. We estimate the systematic uncertainty in the mass determination of this data set is about 10 MeV. Subtracting a polynomial background, we find that the ground-state peak has  $101 \pm 12$  events. The FWHM is approximately 15 MeV, consistent with the missing mass resolution of the CLAS detector.

The first excited state of the cascade, the  $\Xi^-(1530)\frac{3}{2}^+$ , is not obvious in Fig. 1(a) because of the CLAS detector acceptance for higher mass cascades. At the production threshold for a given cascade, the final-state particles ( $K^+K^+\Xi^-$  in this case) are at rest in the center-of-mass (c.m.) frame and travel along

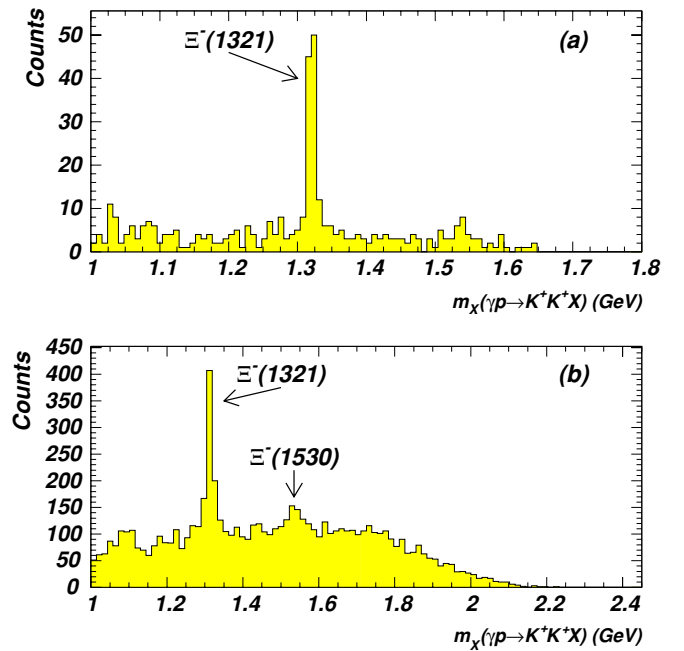


FIG. 1. (Color online) The missing mass  $m_X$  in the process  $p(\gamma, K^+K^+)X$  for (a) the *g6a* data set, and (b) the *g6b* data set. The plots have not been corrected for acceptance. The ground state  $\Xi^-(1321)\frac{1}{2}^+$  is clearly seen in both plots; the signal-to-background ratio for the *g6a* data set exceeds 10:1. The *g6b* data set shows evidence for the first excited state  $\Xi^-(1530)$ .

the beam line in the lab frame. Such events are not detected by CLAS. As the photon energy increases, there is more c.m. energy available to the particles. Only when both kaons have a large enough polar angle can they be detected. The acceptance thus depends not only upon the angular distribution but also on the photon energy. We studied the effect of the production mechanism using a Monte Carlo simulation of the CLAS detector based on GEANT 3.21 and found a difference in the acceptance for the  $K^+K^+\Xi^-(1321)$  and the  $K^+K^+\Xi^-(1530)$  final states of more than a factor of two for the photon-energy range of the *g6a* data set (3.2–3.9 GeV).

To find the  $\Xi^-(1530)$ , we analyzed the *g6b* data set. For the photon-energy range of this data set (3.0–5.2 GeV), a phase-space final-state distribution gives only a 20% difference in the acceptance for the two final states. The missing mass spectrum, shown in Fig. 1(b), clearly shows both the  $\Xi^-(1321)$  and the  $\Xi^-(1530)$ , albeit with a larger background because of the higher photon flux. Subtracting a polynomial background in a similar manner as in Fig. 1(a), we obtain  $470 \pm 30 \Xi^-(1321)$  events and  $150 \pm 40 \Xi^-(1530)$  events. Higher mass states cannot be seen above the background.

One of the advantages of the missing mass technique is that the physics backgrounds are small; if the final state contains two  $K^+$ 's, whatever is left must have the quantum numbers of the  $\Xi^-$ . The first real background that can appear is because of the process  $\gamma p \rightarrow K^+\phi\Lambda$ , where the  $\phi$  decays to  $K^+K^-$ . This background contributes only for missing masses above  $m_{K^-} + m_\Lambda = 1.6$  GeV.

The high photon flux contributes to another background because of  $K/\pi$  misidentification. The analysis procedure

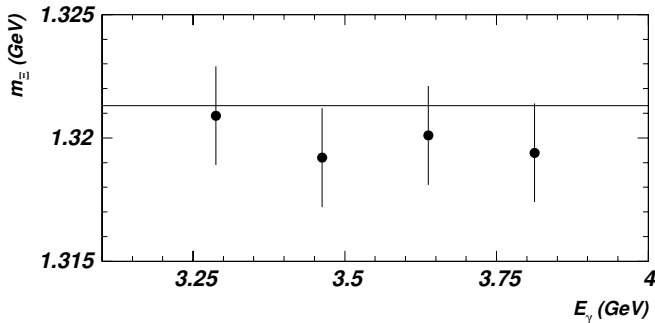


FIG. 2. Consistency of the missing mass of the  $K^+K^+$  system. Shown is the centroid of the peak in the  $K^+K^+$  missing mass for  $\gamma p \rightarrow K^+K^+X$  as a function of the incident photon energy. The vertical error represents one-half the bin width of the plot in Fig. 1(a). The horizontal line is the PDG value of the  $\Xi^-$  mass of 1321.31 MeV.

used for this data matched the timing of each track in CLAS to that of a tagged photon in our photon tagger. The innermost timing detector in CLAS had only three elements, which resulted in a large accidental background from one of two likely final states:  $\pi^+\pi^+\Delta^-$  and  $K^+\pi^+\Sigma^-$ . Both of these can appear to be the  $K^+K^+\Xi^-$  final state if the photon that caused the event was not tagged (if, for instance, it was below the range of the photon tagger), whereas a higher energy photon was tagged nearby in time. This results in the large background in Fig. 1(b).

Even when the photon is tagged correctly, a high-energy pion can masquerade as a high-energy kaon. If this happens in the process  $\gamma p \rightarrow K^+\pi^+\Sigma^-$ , the resulting missing mass will be incorrectly calculated. This results in the enhancement in Fig. 1(b) near 1100 MeV. A similar background, because of the process  $\gamma p \rightarrow K^+\pi^+\Sigma^-(1385)$ , is expected to appear near the mass of the ground-state cascade. Higher mass hyperons are much broader and therefore are not expected to have a sizeable effect.

The large background under the peak in Fig. 1(b), along with the  $g6b$  normalization difficulty mentioned earlier, makes the extraction of a cross section difficult. We therefore do not report cross sections for this data set, as improvements have been made to the CLAS detector to mitigate both of these issues. Future data are expected to be much cleaner.

We can show that a peak is not an artifact of  $K/\pi$  misidentification by investigating the dependence of the position of the peak on the incident photon energy and the cascade production angle. By dividing our data into four  $E_{\gamma}$  bins, we effectively make four independent measurements of the  $\Xi^-$  mass. As seen in Fig. 2, the peak position is stable over a 700-MeV  $E_{\gamma}$  range. A similar test was performed, plotting the peak position as a function of the  $\Xi^-$  c.m. angle, with the same results.

The cascade production mechanism is insufficiently known at present; it likely involves the intermediate production of any of several high-mass  $N^*$  and  $Y^*$  states. This makes the calculation of the acceptance difficult and results in a large systematic uncertainty in the extraction of the cross section. Our estimate of the cross section is based on a uniform  $K^+K^+\Xi^-$  phase-space distribution of the final-state particles. In this special case, we used the simulation described above to

find that the ground-state photoproduction process for the  $g6a$  data set has an acceptance of 2.8%, averaged over the entire  $E_{\gamma}$  range.

The dominant systematic uncertainty is in the acceptance calculation, because of the unknown production mechanism. The limited statistics of this measurement make a detailed study of the production not useful, but we can make an estimate of the effect of different production models by comparing the acceptance based on our phase-space calculation above with a toy model in which the cross section varies as a function of the momentum transfer  $t$  to the  $K^+K^+$  system, with the functional form  $\sigma = Ae^{Bt}$ . For such a model, we obtain a smaller acceptance and a correspondingly higher cross section. By comparing the simulation with the data, we obtain  $B = 1 \pm 1$ , leading to a variation in the calculated acceptance of  $\sim 30\%$ . We use this as our systematic uncertainty and obtain a value for the total cross section, averaged over the photon-energy range for the  $g6a$  data set of  $3.2 < E_{\gamma} < 3.9$  GeV, of  $3.5 \pm 0.5(\text{stat.}) \pm 1.0(\text{syst.})$  nb.

At luminosities attainable with photon experiments with the CLAS detector, our data imply the production of several thousand cascade ground-state hyperons per week. The cross section for the first excited state is roughly 2 to 3 times smaller than for the ground state, but nevertheless provides a reasonable counting rate in a dedicated experiment. We are therefore confident that we will have sufficient counting rates to justify initiating the program of cascade physics outlined in Ref. [7].

With small modifications, the photoproduction method may be used to search for  $\Xi_5$  pentaquarks. In the prediction of [20] and elsewhere, the  $\Xi_5$  has isospin 3/2, with  $-2 \leq Q \leq +1$ . The  $\Xi_5^-$  can be detected using the process  $p(\gamma, K^+K^+)\Xi_5^-$ , similar to the three-quark  $\Xi^-$ . To detect the other three charge states, additional pions of the appropriate charge can be added to the final state. The processes  $p(\gamma, K^+K^+\pi^+)\Xi_5^-$  and  $p(\gamma, K^+K^+\pi^-\pi^-)\Xi_5^+$  would be used to detect the two manifestly exotic cascades. Because these processes have extra particles in the final state, they also have correspondingly higher photon energy thresholds. It is therefore necessary to run at the highest energies available at Jefferson Laboratory (presently 5.7 GeV) for these searches. The identification of the  $\Xi_5^0$  and the  $\Xi_5^+$  as pentaquarks is dependent on also finding the  $\Xi_5^-$  or the  $\Xi_5^+$  at the same mass. If the pentaquarks are found, we may use the process  $p(\gamma, K^+K^+)\Xi_5^-$  to compare the properties of the pentaquark cascades with those of the three-quark cascades, such as mass splittings, widths, decay rates, and decay modes. The ability to look at both of these types of states with the exact same process makes this a powerful approach.

We have shown that JLab has sufficient energy and tagged photon flux to investigate new cascade states. The absolute energy calibration of the Hall B Photon Tagger and CLAS allow the determination of missing masses to  $<1\%$  in the cascade mass region. This method provides a complementary approach to the search for the cascade pentaquark.

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