Study of Ξ^* Photoproduction from Threshold to $W = 3.3$ GeV

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The doubly strange Ξ baryons provide an effective way to study a puzzle called the missing-baryons problem, where both quark models and lattice gauge theory predict more baryon excited states than are seen experimentally. However, few of these excited states have been observed with any certainty. Here, high-mass Ξ^* states have been searched for in photoproduction with the CLAS detector, and upper limits for the total cross sections have been established from threshold to $W = 3.3$ GeV. In addition, the total cross sections of the ground state $\Xi^-(1320)$ and first excited state $\Xi^-(1530)$ are presented, extending significantly the center-of-mass energy range of previous data.

Cascade baryons, also called Ξ states, hold an important place in the development of the quark model, and continue to be useful to the field of baryon spectroscopy [1]. Made from two strange quarks and one light (up or down) quark, the cascade baryons come in only two charge states, Ξ^- and Ξ^0. The Ξ ground state, with $J = 1/2$, completes the octet of ground-state baryons. The first excited state, with $J = 3/2$, is part of the baryon decuplet, which famously led Gell-Mann to predict the mass of the Ω^- [2].

Quark models, both relativistic and non-relativistic [3], along with the chiral-symmetric [4] and algebraic [5] models, all predict many more baryon states than have been observed to date. This so-called "missing-baryons problem" has persisted in light of recent lattice QCD calculations [1], making the measurement of the baryon spectrum a high priority for the understanding of QCD theory. Looking for Ξ^* states experimentally and taking advantage of the known N^* correspondence is the primary motivation for the present study. If the number of Ξ^* states found experimentally is also small, it begs the question why.

Today, there are better calculations than the quark model for the spectrum of excited states of the Cascade baryons, which are done directly using the theory of quantum chromodynamics (QCD). While these lattice calculations [1] are still using a light quark mass greater than the physical mass, the mass spectrum of Cascade baryons can still be extracted and normalized to the Ω^- ground state. The resulting pattern is remarkably similar to that for quark-model calculations, where states with higher spin have systematically higher mass. From lattice methods, seven Ξ^* states have been identified in the first resonance region with negative parity corresponding to $L = 1$, as well as over a dozen excited states at higher mass in the second resonance region with positive parity.

Experimentally, it is appealing to look for the excited cascade states because they are expected to have a narrow width [6]. For example, the ground state Δ resonance has a width of about 120 MeV, whereas the $\Xi(1530)$ and the $\Xi(1690)$ have widths of about 10 MeV [7], which are more easily seen above background. Furthermore, there should be one Ξ^* for each N^* state, and while the N^* states are broad and overlapping, the Ξ^* states are expected to be narrow and easily isolated as a peak in the experimental mass spectrum. However, the cross section for producing cascade baryons is small, especially for photoproduction [8, 9], but this situation is well suited to today's high-rate photon beams and large-acceptance spectrometers.

A new experiment with the CLAS detector with sufficient photon energy and flux to carry out a statistically significant search for Ξ^* states above the $\Xi(1530)$ was carried out. In addition, this is the first time cross sections for the $\Xi(1320)$ and $\Xi(1530)$ have been measured in photoproduction at photon energy $E_\gamma > 4$ GeV with good statistics, where the total cross section is predicted to level off [10]. We report here total cross sections from fits to angular distributions from threshold up to $E_\gamma = 5.4$ GeV.

Theoretical calculations for cascade photoproduction have been carried out by Nakayama, Oh, and Haberzettl [10]. The production mechanism they propose, shown in Fig. 1 for both ground-state and excited cascades, is a two-step process. A high-mass hyperon is made via $\gamma p \to K^+ Y^*$ followed by a decay branch of the Y^* to $K^+\Xi$. Direct production of the Ξ seems unlikely because two $s\bar{s}$ quark pairs would need to be created at the production vertex (a violation of the OZI rule [7]). The hadronic coupling constants in this two-step process are unknown, and so the theoretical calculations have been normalized to data from previous CLAS experiments [9]. No calculations have been published for photoproduction of excited Ξ^* states.

The $\Xi(1690)$ was seen by the WA89 Collaboration [11] with high statistics and more recently by the Belle Collaboration [12] in Λ_c^+ decays. The $\Xi(1820)$ was seen decaying to $\Lambda\overline{K}^0$ and $\Sigma\overline{K}^0$ [15] and also from decays to ΛK^- with 8σ significance [13, 14]. Both states have widths of about 25 MeV [7] (or even less for the $\Xi(1690)$) and should be seen in the present study if the photoproduction cross section is sufficiently high.

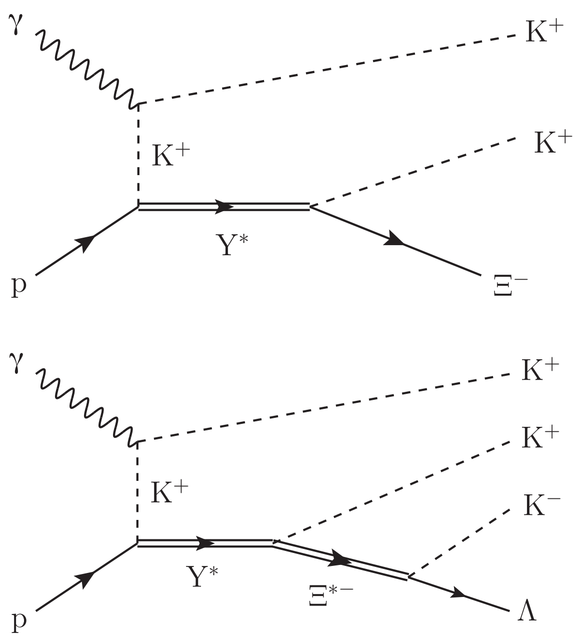

FIG. 1. Diagrams used by Ref. [10] for photoproduction of the Ξ^- ground state (left) and excited states (right) through decay of an intermediate hyperon resonance, Y^*.

Electrons from the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab with beam energy 5.715 GeV were directed onto a thin gold radiator foil to produce bremsstrahlung photons. These were collimated onto a 40 cm long liquid hydrogen target. The CLAS detector [16] was used for this experiment, known as g12, which ran in the second quarter of 2008. The target center was 90 cm upstream from the center of CLAS to provide better acceptance for particles produced at small angles. To allow for high luminosity, with a beam current of 60-65 nA, a 24-segment scintillator start-counter [17] (ST) around the target was used to form a coincidence trigger with the time-of-flight [18] scintillators (TOF) that surrounded the outside of CLAS. Two ST/TOF pairs of hits in separate sectors of CLAS in coincidence with a scattered electron in the bremsstrahlung tagger [19] were required to satisfy the trigger. These conditions, along with several ancillary trigger conditions, resulted in a livetime of the data acquisition system of ~87%. A trigger coincidence window of approximately 100 ns resulted in about 20-30 recorded photons per event.

In this analysis, events were defined as two K^+ particles detected in CLAS within 1.0 ns of the photon's vertex time and the two-particle vertex within the target volume. The K^+K^+ vertex time was calculated using the time at the TOF along with its momentum and path length measured in the drift chambers. In addition, each track was required to have a valid hit in the ST within a ±1.6 ns time window. These timing cuts were rigorously calibrated and studied for their overall efficiency. With these cuts, clean identification of the two charged kaons became possible.

One additional event selection criterion was applied to the data. The mass of each charged particle can be independently calculated from the momentum along with the velocity from the TOF. At high momenta, the above timing cuts alone become less effective at separating kaons from pions. An additional cut on the calculated mass, within 20 MeV of the known kaon mass, was applied to further reduce background from misidentified pions.

In the missing mass off K^+K^+ (Fig. 2), the strong peak at 1.32 GeV corresponds to the Ξ ground state ($J^P = \frac{1}{2}^-$) and the smaller peak at 1.53 GeV is the Ξ^* first excited state ($J^P = \frac{3}{2}^-$). No other statistically significant structures are seen in this mass spectrum.

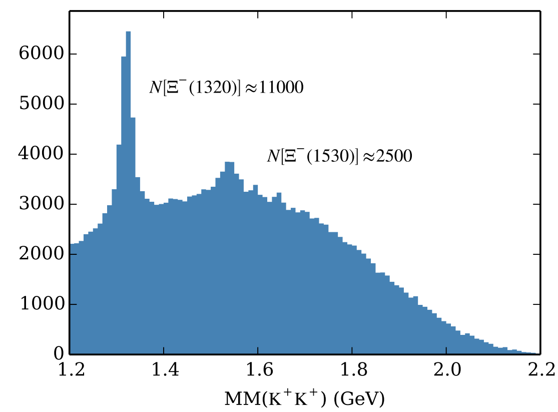

FIG. 2. Missing mass off (K^+K^+) showing the Ξ spectrum above a smooth background, summed over all angles and all E_γ. The two lowest-lying states are shown along with their approximate yields. The missing-mass resolution of the CLAS detector is about 0.01 GeV.

It may be somewhat surprising that no statisically significant peaks are seen corresponding to the known Ξ^* states above the $\Xi(1530)$. The most likely explanation is that the same reaction mechanism that leads to the Ξ and $\Xi(1530)$ do not, for photoproduction, extend to these higher-mass Ξ states, which have different spin and parity. However, theoretical calculations and more precise measurements are needed to test this hypothesis.

The total cross sections are shown in Fig. 3, together with previous CLAS results [9] for the $\Xi(1320)$ ground state and the $\Xi(1535)$ first excited state. This result was obtained by integrating fits to the angular distributions of differential cross sections, which will be shown in a forthcoming paper. These new data, for the first time, show that the total cross section levels off above $W \simeq$

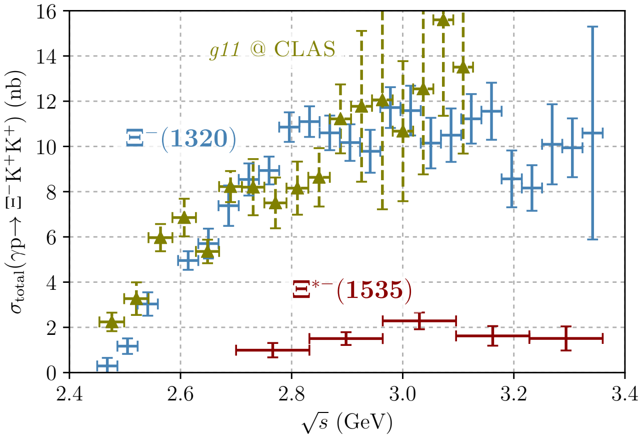

FIG. 3. Total cross section of the $\Xi^-(1320)$ ground state and $\Xi^-(1535)$ first excited state, from photoproduction threshold to $W = 3.3$ GeV. The previous CLAS data (from the g11 dataset) with large uncertainties above 2.9 GeV are shown by the triangle markers.

2.8 GeV, which is only evident now with the new CLAS data. This suggests that the production mechanism is not from an intermediate *s*-channel resonance, in part because it is consistent with the predictions of a two-step reaction mechanism through intermediate N^* and Y^* resonances of Oh *et al.* [10], which becomes flat for $W > 2.9$ GeV.

If the total cross sections maintain reasonably constant values up to higher photon energies, then further studies of the Ξ and Ξ^* states could be done with the future CLAS12 detector [20]. Preliminary estimates [21] show that more than a factor of ten times the statistics on Ξ production could be obtained at CLAS12. In addition, the GlueX experiment at Jefferson Lab is expected to soon have similarly good statistics for Ξ production at higher photon energies [22].

The systematic uncertainties, which are not included in Fig. 3, include 6% due to the normalization (such as photon flux), 5% due to integration of fits to the angular distributions, 3% due to variations of cuts and detector acceptance, and 3% due to other effects such as target length and electronics livetime, giving 8.8% overall.

No evidence is found for higher-mass Ξ states in the missing mass off K^+K^+ of this experiment shown in Fig. 2. Upper limits were calculated on the production total cross sections of the three best-known excited states: the $\Xi(1690)$, the $\Xi(1820)$ and the $\Xi(1950)$ [7] at 0.75 nb, 1.01 nb, and 1.58 nb, respectively, at the 90% confidence limit. Figure 4 shows an expansion of the missing-mass spectrum of Fig. 2. The spectrum is fit to a third-order polynomial along with three Voigtians with fixed means, Lorentzian-widths and Gaussian-widths for the $\Xi(1690)$, $\Xi(1820)$ and $\Xi(1950)$, using their measured widths [7] shown by the filled curve for a 90% confidence level upper limit.

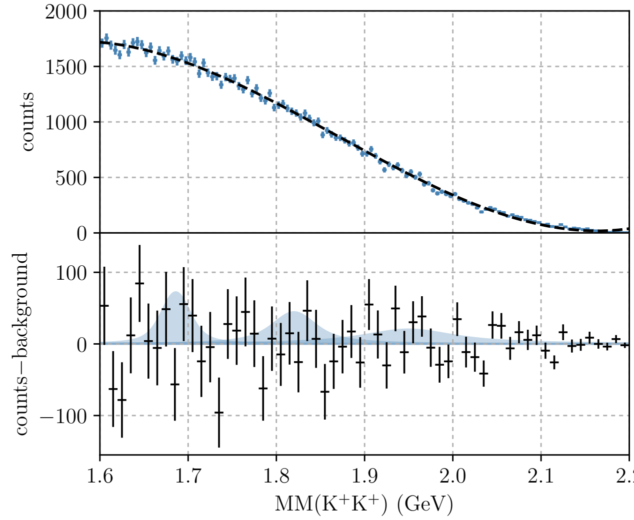

FIG. 4. Missing Mass off K^+K^+ with a fitted 3^{rd}-order polynomial background. The filled curves correspond to the 90% confidence (Feldman-Cousins prescription) yield upper limits of Ξ^{*-} states at 1690, 1820 and 1950 MeV.

The ratio of the $\Xi(1690)$ to $\Xi(1530)$ cross sections in Σ^- production was measured by WA89 [11] to be approximately 2.2%. Of course, the photoproduction mechanism of the CLAS experiment is different from WA89's largely hadronic process, but the upper limit for the $\Xi(1690)$ from the CLAS data is consistent with this hadronic ratio.

In conclusion, we report the first total cross sections for photoproduction of the $\Xi(1320)$ and $\Xi(1530)$ ground states over center-of-mass energies above $W = 2.8$ GeV, where the cross section is found to level off. One of the goals of the present measurements was to explore the spectrum of excited Ξ^* states, but surprisingly these states are much suppressed in photoproduction, and only upper limits could be determined for the total cross sections for three known Ξ^* states (at masses 1690, 1820, and 1950 MeV). The production mechanism that explains such small photoproduction cross sections is not yet known, and begs for an explanation from future theoretical calculations. More measurements at higher photon energies using the upgraded Jefferson Lab accelerator will soon be available to test such calculations.

As mentioned earlier, the spectrum of the Ξ baryons is incomplete, since we expect one Ξ^* resonance for each known N^* resonance. This paper shows that the photoproduction mechanism for $W < 3.3$ GeV does not strongly populate higher-mass Ξ^* resonances, and so one must look to other methods to complete the spectrum of Ξ^* resonances.

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