Cascade physics at CLAS12

Lei Guo

Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract. Cascade spectroscopy offers rich discovering opportunities that are essential to the current JLAB spectroscopy program at both CLAS, CLAS12 and GLUEX. Recent CLAS results have demonstrated the feasibility to study cascade resonances through photoproduction. The cross sections for the ground state cascade is observed to increase as a function of energy in the range of 2.8-5 GeV. With the maximum achievable energy at CLAS12 with the current tagger being 6.3 GeV, cascade resonances up to 2.4 GeV are expected to be produced with reasonable rates. The possible addition of a RICH detector would certainly benefit physics programs requiring the detection of kaons, especially cascade physics.

Keywords: Cascade, hadron spectroscopy, baryon resonances, RICH detector, hyperon photoproduction


INTRODUCTION

Compared with non-strange baryons and $S = -1$ hyperon states, the $\Xi$ resonances are generally under-explored. Only two ground state cascades, the octet member $\Xi$ and the decuplet member $\Xi(1530)$, have four-star status in the PDG [1], with four other three-star candidates. More than 20 $N^*$ and $\Delta^*$ resonances are rated with at least three stars in the PDG [1]. Flavor $SU(3)$ symmetry predicts as many $\Xi$ resonances as $N^*$ and $\Delta^*$ states combined, suggesting that many more cascade resonances remain undiscovered. Of the six $\Xi$ states that have at least three-star ratings in the PDG, only three have spin-parity $(J^P)$ determined: $\Xi(1320)_{\frac{1}{2}^+}$, $\Xi(1530)_{\frac{3}{2}^+}$, $\Xi(1820)_{\frac{3}{2}^-}$.

It is important to map out the missing cascade resonances that are predicted by the Quark-Model [2]. In addition, the narrowness of the cascade resonances compared with the other baryons are generally believed to be the result of the de-coupling of $\Xi^* \rightarrow \Xi \pi$ [2]. The experimental verification thus is necessary, by measuring the decay branching ratios of the excited resonances.

On the other hand, as a whole, hadron spectroscopy is an essential experimental means of accessing fundamental parameters of QCD such as quark masses. The average of the baryon ground state isospin multiplet $(N, \Sigma, \Delta, \Xi, \Sigma_c, \Xi_c)$ mass differences yields a value of $m_d - m_u = + (2.8 \pm 0.3)$ MeV/c$^2$ [3], with the $\Xi$ ground state doublet being the most intriguing. The current global measurement of the mass difference between the $\Xi^0(uss)$ and $\Xi^- (dss)$ is $6.48 \pm 0.24$ MeV/c$^2$ according to the PDG [1], considerably larger than that of the other multiplets. A calculation on the QCD lattice [4] gives a result of $5.68 \pm 0.24$ MeV/c$^2$, while a calculation based on radiative corrections to the quark model [5] gives 6.10 MeV/c$^2$. Experimentally, however, only one measurement of the $\Xi^0$ mass has more than 50 events [6]. It is possible to measure the mass splitting of various $\Xi$ doublet, due to the narrowness of these states. The same measurement would
not be feasible in the excited $S = 0, -1$ sectors, due to the fact they are much wider with much larger uncertainties.

Although the cascade resonances are narrower than their $S = 0, -1$ partners, and easier to identify when produced copiously, they are more difficult to produce. The lack of data is mainly due to smaller $\Xi^{(*)}$ cross sections than the $S = 0$ and $-1$ baryons, and cascade resonances cannot be produced through direct formation. In general, the production mechanisms of the cascade resonances remain unclear. Kaon and hyperon beam experiments conducted to investigate cascade spectroscopy suffer from either low intensity or high combinatorial background. Results from earlier kaon beam experiments indicate that it is possible to produce the $\Xi$ ground state through the decay of high-mass $Y^*$ states [7, 8, 9, 10]. It is therefore possible to produce cascade resonances through $t$-channel photoproduction of hyperon resonances as indicated in Fig. 1.

![Figure 1](image-url)  
**FIGURE 1.** Possible photoproduction mechanisms of $\Xi$ ground states through intermediate hyperon resonances produced in a $t$-channel process. a) $\Xi^-$ production; b) $\Xi^0$ production.

**RECENT CLAS RESULTS OF CASCADE PHOTOPRODUCTION**

Recent results from CLAS [11, 12] have demonstrated the feasibility of investigating cascade physics using photon beam probe. Ground state cascade has been studied in inclusive reaction $\gamma p \rightarrow \Xi^- X$ by reconstructing the $\Xi^-$ from the decay $\Xi^- \rightarrow \Lambda \pi^- \rightarrow p\pi^-\pi^-$ by the CERN-SPS experiment [13] and the SLAC 1-m hydrogen bubble chamber experiment [14]. The new CLAS results [12] represents the first measurements of cascade photoproduction through exclusive reactions such as $\gamma p \rightarrow K^+K^+(X)$ and $\gamma p \rightarrow K^+K^+\pi^- (X)$. The CLAS data set, with an integrated luminosity of 70 pb$^{-1}$, was collected at CLAS [15] from May to July 2004 using a tagged photon beam [16] incident on a proton target. This data set is mostly in the energy range of 1.6-3.85 GeV with the primary electron beam energy ($E_0$) of 4 GeV. About 5% of the data were collected with $E_0 = 5$ GeV. The target consists of a 40-cm-long cylindrical cell containing liquid hydrogen. Momentum information for charged particles was obtained via tracking through three regions of multi-wire drift chambers [17] inside a toroidal magnetic field ($\sim 0.5$ T), generated by six superconducting coils. Time-of-flight (TOF) scintillators were used for charged hadron identification [18]. The interaction time between the incoming photon and the target was measured by the Start Counter [19], consisting of 24 strips of
2.2 mm thick plastic scintillators surrounding the target cell. Coincidences between the photon tagger and two charged particles in the CLAS detector triggered the events.

The \( \Xi^- (1320) \) and \( \Xi^- (1530) \) can be readily observed in the \( K^+ K^+ \) missing mass spectra (Fig. 2). The smooth background are found to be mostly due to pions misidentified as kaons. In fact, the dashed background in Fig. 2 are obtained by studying \( K^+ K^+ \) events with an additional \( K^- \) detected. Possible physics background such as \( \gamma p \rightarrow \phi N^* \) are investigated and found to be insignificant. Therefore, the reduction of this background would be crucial in the future endeavors of searching for missing cascade resonances. The differential cross sections (CM angular distributions, \( K^+ \Xi^- \) invariant mass spectra) are found to be consistent with the production mechanism indicated by Fig. 1 as suggested by Ref. [20].

![Figure 2](image-url)  

**FIGURE 2.** \( MM(K^+K^+) \) distribution for \( E_\gamma > 2.6 \) GeV fitted with two Gaussian functions and an empirical background shape with adjustable normalization (M: mean of the Gaussian peak position, \( \sigma \): width of the Gaussian signal, N: number of events in the peak); Inset: \( MM(K^+K^+) \) distribution enlarged for the 1.36-1.79 GeV/c\(^2\) region, the dashed lines show the empirical background shape from \( K^- \) events normalized to the region of 1.36-1.5 GeV/c\(^2\).

As for the neutral member of the \( \Xi \) (1320) doublet, an additional \( \pi^- \) needs to be detected to conserve the charge, and the reaction \( \gamma p \rightarrow K^+K^+\pi^- (X) \) was studied. The \( \Xi^0 \) was observed in the \( K^+K^+\pi^- \) missing mass spectrum, along with the prominent \( \Lambda \) signal, which is a decay product of \( \Xi^- (1320) \). The background again is mostly due to the events wth pions misidentified as kaons.

The \( \Xi \) doublet mass splitting is measured to be \( 5.4 \pm 1.8 \) MeV/c\(^2\), consistent with the current global value of \( 6.48 \pm 0.24 \) MeV/c\(^2\). Due to the low photon energies, other cascade doublet were not expected and are not observed. However, in the future when higher energy data become available, it is clearly desired, and possible, to measure the mass splitting of the excited cascade doublets.

The \( \Xi^0 \) events are found to be mostly due to the decay of \( \Xi^- (1530) \) with a branching ratio consistent with 100% as expected. Other states, such as \( \Xi^- (1620) \), although plausible, are statistically insignificant [12]. Obviously, the low beam energy represents clear
FIGURE 3. Left: \((K^+K^+\pi^-)\) missing mass spectrum. The dashed background shape is obtained from events with an additional \(\pi^+\) in the same event; Top right: \((K^+K^+\pi^-)\) missing mass with a \(3\sigma\) cut on the \(\Xi^-\) region (in the \((K^+K^+)\) missing mass); Bottom right: \((\Lambda\pi^-)\) invariant mass with a \(3\sigma\) cut on the \(\Lambda\) region (in the \((K^+K^+\pi^-)\) missing mass). Fitting parameter notation is the same as Fig. 2.

FIGURE 4. Total cross section of \(\Xi^-\) results (including both statistical and systematic uncertainties) from the current work compared with model predictions from Ref. [20].

restriction on the cross section of other excited cascade resonances. Recently completed new CLAS g12 experiment, with photon energies up to 5.4 GeV, could potentially provide more insight to the status of \(\Xi(1620)\), and possibly \(\Xi(1690)\) [27]. In particular, Earlier evidence [21, 22, 23] has poor statistics. On the theoretical side, some dynamic models [25, 24] have predicted a possible cascade resonance in the region of 1600 MeV/c². In the framework of a unitary extension of chiral perturbation theory [24], the \(\Xi(1620)\) emerged in the \(\Xi\pi\) invariant mass with a width around 50 MeV/c², and is assigned to an octet together with the \(N^*(1535)\), the \(\Lambda(1670)\), and the \(\Sigma(1620)\). These models clearly contradict the constituent quark model [2]. As for cascade resonances beyond 2 GeV,
the future clearly lies with CLAS12 and GLEUX, where photon energy is expected to reach 8.8 GeV.

**PROSPECTS FOR CASCADE PHYSICS AT CLAS12**

A dedicated cascade physics program at CLAS12 is clearly feasible. At higher photon energies up to 6.3 GeV expected to be available at CLAS 12 with the current tagger system without major upgrade, the cross sections of excited cascade resonances would rise, possibly in a similar manner to that of the ground state (Fig. 4). The current CLAS12 design only include gas cherenkov detectors, which do not provide positive identification of the kaons, essential for the reconstruction of the cascade resonances. As demonstrated in Fig. 2, events with two positive kaons in the final state are dominated by background events with one or two pions being misidentified as kaons. Although tighter cuts on the timing coincidence of various detectors such as TOF and TAGGER could dramatically reduce such background, they can not be totally removed without destroying small signals, which would be the case for the excited cascade resonances, the focus of the program. On the other hand, the possible addition of a RICH detector can veto the pion background without affecting the real signals, thus greatly improve the signal to background ratios, making the data analysis relatively easier.

With the large acceptance and good momentum resolution available at CLAS12, it is expected that new cascade resonances can be identified, and their spin-parity measured. For example, the spin-parity of $\Xi(1820)$ were measured to be $\frac{3}{2}^-$ by the CERN-SPS group using a sample of 50 events [28]. Assuming the cross section of $\Xi^-(1820)$ being around 10 nb at photon energy of 6 GeV, similar to that of the ground state at 4 GeV, then 500 $\Xi^-(1820)$ signals can be collected with 3 months running using a 40cm liquid hydron target, with the complete decay chain ($\Xi^-(1820) \rightarrow \Lambda K^-, \Lambda \rightarrow p\pi^-$) being reconstructed, thus enabling the determination of the spin and parity. Spin-parities of other states, even if produced at smaller rate (1 nb), could also be determined, although bigger uncertainties of course would be expected.

In addition, replacing the hydrogen target with nuclei target such as a thin $^{12}$C target, can also become part of a hypernuclei program, especially the search for the elusive cascade hypernuclei. The $\Xi$-nucleon interaction are widely believed to be binding, similar to, although weaker than, the $\Lambda$-nucleon potential. The precise knowledge of nuclear systems with strangeness is essential to the understanding of dense matter such as the neutron star core [29]. However, the evidence for the existence of $\Xi$-hypernuclei remains unconvincing with very poor statistics [30]. While J-PARC will embark on the search for cascade hypernuclei in the near future using $K^-$ beam, the usage of photon beam as a electromagnetic probe holds the advantage that the incoming beam can interact with the nucleons inside the target, instead of the pion cloud. Experimentally, the identification of $\Xi$-nuclei events at CLAS12 require momentum resolution high enough to separate them from the background continuum, and above all, clean identification of positive kaons. The predicted $\Xi-N$ potential depth of around 15 MeV [31, 32, 33] means that the energies of the tagged photon beam should not exceed much more than 4 GeV at future CLAS12 experiments. Of course, such experiment could be conducted concurrently with the cascade spectroscopy experiments using a simple hydrogen target.
It is important to note that although it has been demonstrated that the ground state, as well as the $\Xi^-$ (1530) can be studied in photoproduction at CLAS without the benefit of RICH detectors, it would be technically more difficult to study other excited resonances as well as cascade nuclei without a RICH detector to reject the misidentified pion background. Equally importantly, the absence of a RICH detector will increase the financial cost of a dedicated cascade program to achieve high statistics.

**SUMMARY**

To summarize, cascade physics offers very rich opportunities in various aspects. It has been demonstrated by recent CLAS results that cascade spectroscopy can be investigated using photon beam as an alternative probe to kaon and hyperon beams that were traditionally used. New resonances can be identified with a dedicated cascade program at CLAS12, as well as GLUEX, at Jefferson Lab. With enough statistics, their properties such as spin-parity, decay branching ratios can be measured. Various Quark-Model and Lattice QCD predictions can be tested, and fundamental parameters such as the mass difference of the u-d quarks could be investigated by measuring the mass splitting of a series of cascade doublets. CLAS12 could also prove to be an excellent spectrometer of cascade nuclei. All these exciting physics would receive a tremendous boost if a RICH detector would become available. A RICH detector will not only greatly improve the data quality for the cascade program at Jefferson Lab, but also vastly reduce the running time necessary to collect enough statistics to be able to achieve these important physics goals.

**ACKNOWLEDGMENTS**

I would like to thank Ben Nefkens, Simon Capstick for their insight and useful discussions, the Jefferson Lab Hall B staff members who have helped me through the years. Jefferson Science Associates (JSA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-060R23177. The author is supported by the Department of Energy office of science for nuclear physics.

**REFERENCES**