2.7 Hyperon Photoproduction at Jefferson Lab

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Abstract

Compared to the many recent experimental progress made in the nucleon resonances, the advances in hyperon spectroscopy have been scarce. The large amount of photoproduction data that have been collected in the past decade by the CLAS collaboration, and the next generation of experiments to be erson Lab, will make it possible to investigate the production mechanisms of all three sectors of hyperon states. It could also become possible to discover the missing hyperon states as expected by various quark model predictions and Lattice QCD calculations.

1. **Introduction**

The strange quark plays an important role in understanding the strong interaction of nucleons. Even though photo- and electroproduction of strangeness has been carried out since the 1950s, there is still no unambiguous and comprehensive model describing the reaction mechanism of baryon and hyperon ($S = -1, -2$ and -3) resonances. This is due, in part, to the difficulties encountered in modeling the strong interaction in the non-perturbative regime. As such, the problem has been approached through the use of effective field theories [1–4], Regge models [5] and hybrid Regge-plus-resonance (RPR) models [6, 7], and more recently, through coupled-channel analyses [8–11]. All of these methods require large and precise data sets in order to constrain fitting parameters. In addition to the crucial study of the strange-quark production mechanism itself, an important part of these efforts is the identification of nucleon and hyperon resonances predicted by various QCD-based models [12–14] but not previously observed. Recent progress in the hyperon sectors in lattice calculations [15] has also made it more urgent to obtain experimental data. Compared with the nucleon resonances sectors, the status of hyperon spectroscopy leaves much to be desired. In the search for missing nucleon resonances, a major difficulty arises from many overlapping broad states. Cascade resonances are typically much narrower and comparatively easier to identify. The status $S = -1$ hyperon states lie somewhere between the nucleon resonances and the cascade sector. In particular, more than 30 excited states are predicted to lie between 2 GeV and 2.3 GeV [13]. Currently, there are only five $S = -1$ states considered to be established, with three or four star rating in the PDG [16] in that region. On the other hand, the $S = -3$ Ω^- state has never been observed in photoproduction. The main issue with the multi-strangeness sector can be attributed to the lack of experimental data as a result of small cross sections. With the existing high statistics data that have been collected in the past decade at Jefferson Lab, and the future experiment at CLAS12 and GlueX, there is a significant opportunity for making progress at all three sectors of the hyperon spectroscopy.

2. **Photoproduction Mechanism for Hyperons**

With a high energy photon beam, it is generally understood that hyperons can be produced via a series of kaon exchanges. Near threshold, the contributions from intermediate nucleon resonances that decay to strange particles, such as $K\Lambda$ and $K\Sigma$, are expected to be significant. In fact, recent CLAS data [17, 18] on the polarization observables for Λ and Σ photoproduction have played an important role in establishing nucleon resonances. However, the non-resonance contributions of hyperon photoproduction remain not entirely understood. For example, a recent study [19] showed that Λ photoproduction on a proton target, seems to be consistent with only K exchanges. Σ^0 photoproduction on a proton target, on the other hand, has comparable contributions from both K and K^* exchanges. Decay angular distributions for excited hyperons such as $\Lambda(1520)$, have been investigated in the past to probe the exchange mechanism in both photoproduction [20] and electroproduction [21]. However, higher statistics was needed. Recent CLAS data on $\Lambda(1520)$, $\Lambda(1405)$ and $\Sigma(1385)$ photoproduction [22] are also suggestive of the contributions of intermediate nucleon resonances. The non-resonance contributions for these states can be further constrained by investigating these states at higher energies, expected to be feasible at both CLAS12 and GlueX.

3. **Beam Helicity Asymmetry in K^+K^- Photoproduction**

Excited $S = -1$ hyperons could be produced in reactions such as $\gamma p \to pK^+K^-$. However, such a reaction also has significant contribution from intermediate meson resonances that decay to $K\bar{K}$. This would be even more complicated in the analogous reaction in the nucleon sector, $\gamma p \to p\pi^+\pi^-$, where the two pion photoproduction is believed to be important for identifying the missing nucleon states. In that reaction, both pions can also resonance with the nucleons, in addition to them being the decay products of intermediate meson states. The K^+K^- photoproduciton, on the hand, does have the advantage due to the lack of NK resonances. In the end, however, the complete understanding of two pesudoscalar meson photoproduction typically still rely on models using effective lagrangian approach. In particular, it is important to point out that polarization observables such as the beam helicity asymmetry $I^\odot$ is expected to be sensitive to the interference of the various competing mechanisms [23], and essential to extract the information of the intermediate resonances.

The beam helicity asymmetry $I^\odot(\tau)$, is defined by

$$I^\odot(\tau) = \frac{1}{P_\gamma(\tau)} \frac{\sigma^+(\tau) - \sigma^-(\tau)}{\sigma^+(\tau) + \sigma^-(\tau)}, \tag{1}$$

where τ is a kinematic bin, and $\sigma^\pm$ is cross sections for photons in a $\pm$ helicity state. $I^\odot$ is typically measured as a function of the angle ϕ between different planes, such as the K^+K^- plane and the production plane in the center-of-momentum frame. Although the beam helicity asymmetries have been measured in reactions such as $\gamma p \to p\pi^+\pi^-$ [24], no data exist for the two-kaon counterparts. The CLAS experiment E04-005 (g12) [25], using a photon beam with energies up to 5.4 GeV, and circular polarization up to 70%, has made it possible to perform these measurements for the two-kaon photoproduction on a proton target [26]. In Fig. 1, the asymmetries between the K^+K^+ and $\pi^-\pi^+$ are shown together, for events with $E_\gamma > 2.8$ GeV, as a function of the angle between the two-meson plane and the production plane. The features of the two reactions are strikingly different, with the two-pion channel showing a dominant $sin(2\phi)$ behavior, while the two-kaon data is mostly changing as a function of $sin(\phi)$. This could be due to the fact of that two-kaon photproduction is not expected to have contributions of pK^+ resonances, while $p\pi^{+/-}$ resonances are certainly

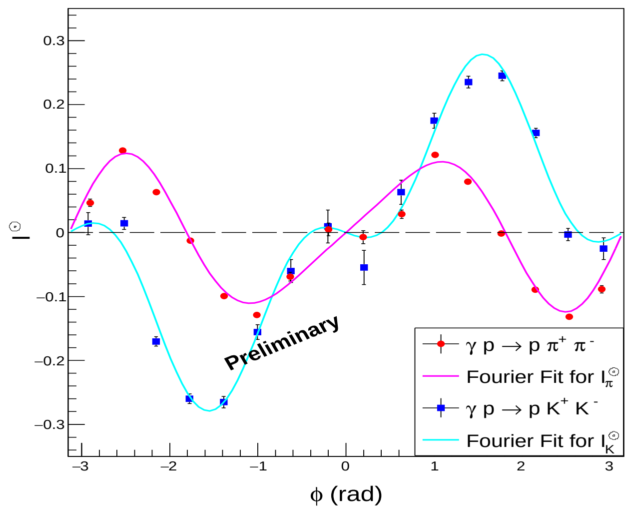

Figure 1: The beam helicity asymmetries, as a function of ϕ, for the reaction of $\gamma p \to p\pi^+\pi^-$(red solid circles), and $\gamma p \to pK^+K^-$ (blue solid squares), from the g12 data set. ϕ is the angle between the production plane and the two-meson plane. The results are integrated over for the E_γ range of $2.8 - 5.4$ GeV and other kinematic variables.

not forbidden. However, in order to further probe the underlying contributions of various intermediate resonances, the beam helicity asymmetry must be measured as a function of various kinematic variables, such as w (Fig. 2) and t.

The angular dependence of the asymmetries, can be fitted to a Fourier series. The sensitivities of these Fourier coefficients to kinematic variables such as pK^- invariant mass (Fig. 3), as well as the definition of the planes, are indicative of the possible contributions of various intermediate hyperon resonances. However, it is important to point out that these results must be combined with cross section measurements, in order to provide meaningful constraints for the production models of two-kaon photoproduction. These efforts are in progress, and could further our understanding of the intermediate $S = -1$ hyperon resonances.

4. **Cascade Polarization in Photoproduction**

Recent CLAS data established that the lowest excited cascades, such as $\Xi(1320)$ and $\Xi(1530)$, can be produced copiously using a photon beam and a thick target for high luminosity [27]. Cascade production is also intimately related to excited hyperons [28, 29]. The $S = -1$ hpyeron states above 2 GeV can be studied in unique channels such as $Y^* \to \Xi^- K^+$, as well as the typical decay mode of $Y^* \to N\bar{K}^{(*)}$. Similar to the important roles of the Λ and Σ polarizations played in extracting the information of the intermediate nucleon resonances, the Ξ^- polarization has also been expected to be essential in constraining the contributions of various intermediate high-mass $S = -1$ hyperons states. Due to the self-analyzing nature of the $\Xi(1320)$ weak decay, its polarization can be measured in various photo-nucleon reactions. In reactions such as $\gamma p \to K^+K^+\Xi^-(1320)$, with two pseudoscalar mesons (K^+) and one $J = \frac{1}{2}$ baryon ($\Xi^-(1320)$) in the final state, the expectation for Ξ^- polarization could be

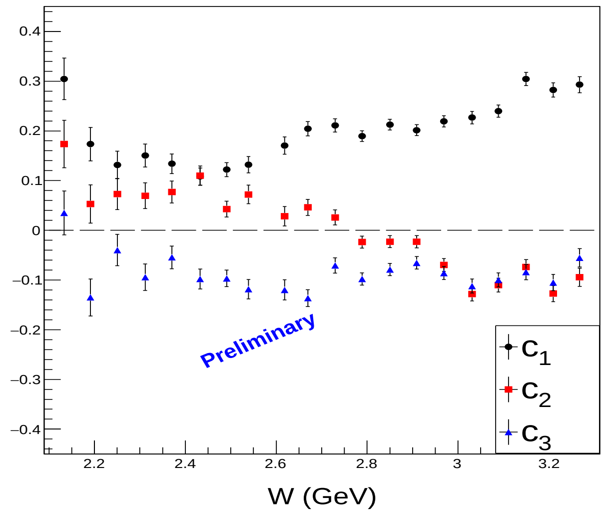

Figure 2: The beam helicity asymmetries as a function of ϕ, are fitted to a Fourier series up to $sin(3\phi)$. The coefficients are plotted as a function of W.

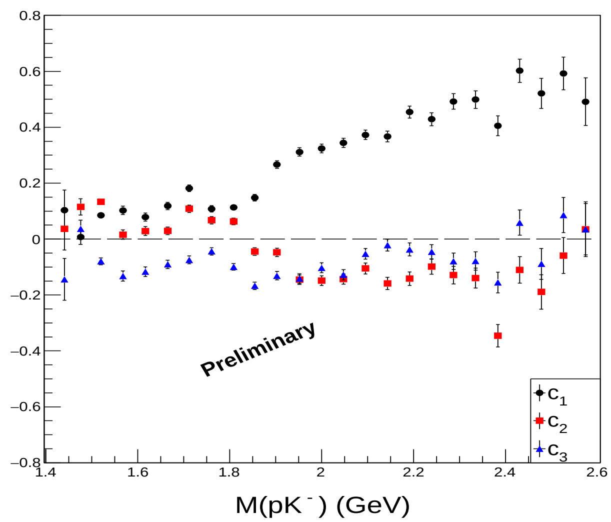

Figure 3: The beam helicity asymmetries as a function of ϕ, are fitted to a Fourier series up to $sin(3\phi)$. The coefficients are plotted as a function of pK^- invariant mass

very different from that of Λ in $\gamma p \to K^+\Lambda$. In fact, recent results on the polarization observables in reactions such as $\gamma p \to \pi\pi N$, using a more realistic three-body framework [30], suggests that the $\Xi^-(1320)$ polarization in all three directions could be non-zero. In addition, quasi-two-body models for Ξ^- photoproduction also suggest non-zero Ξ^- transferred polarization (C_z) [28]. Therefore, the measurement of Ξ^- polarization is an important tool to reveal the production mechanism, for which differential cross section measurements alone are not sufficient.

Recent CLAS data collected by the experiment E04-005 has made the measurement of Ξ^- polarization in photoproduction possible for the first time [31]. In reaction $\gamma p \to K^+K^+\pi^-(\Lambda)$, the Ξ^- was constrained from both the K^+K^+ missing mass and $\pi^-\Lambda$ invariant mass. The Λ is identified using the missing mass technique. The Ξ^- decay is then fully reconstructed. The circular polarization of the beam is a function of the beam energy and the electron beam polarization, allowing the determination of the transferred polarizations C_x and C_z as well. The z-axis is along the beam, and the y-axis is along the norm of the production plane, defined by the beam, target and Ξ^- vectors in the center-of-momentum frame. Preliminary results of the measured polarizations are shown as a function of Ξ^- center-of-momenum angle, in Fig. 4. These results are compared with calculations using parameters from Ref. [28], and Ref. [29], which includes contributions from intermediate hyperons with $J > \frac{3}{2}$. It is important to point out that the lack of statistics in the existing data does not provide any differentiating power for distinguish the models. Furture experiments, discussed in the next section, will certainly be able to take these measurements to the necessary levels.

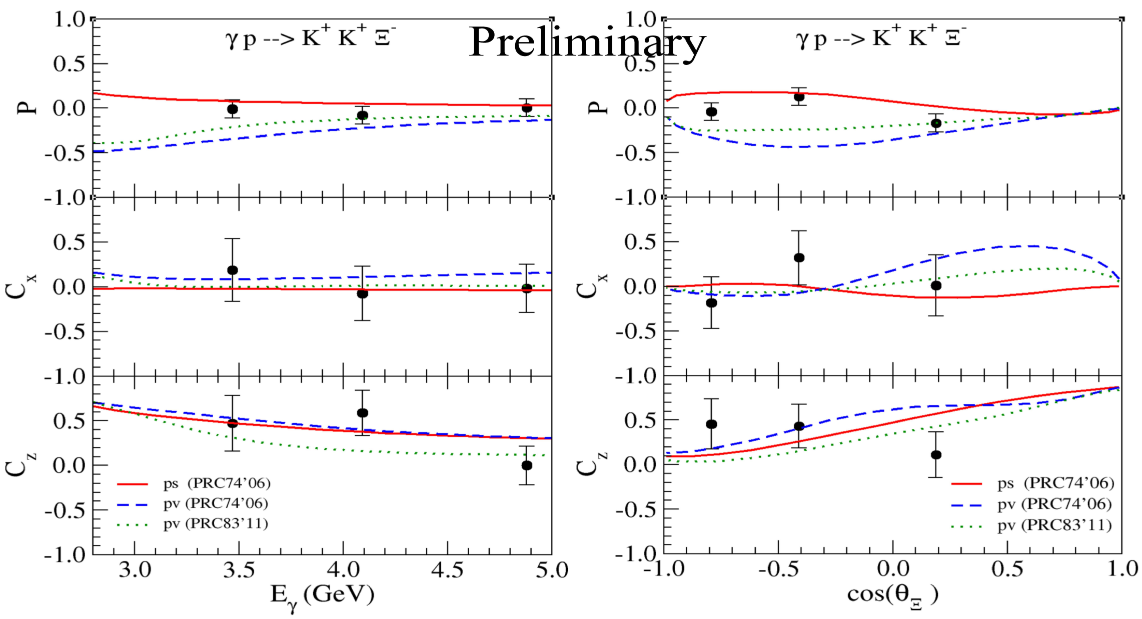

Figure 4: Ξ^- polarization observables (Top: P, Middle: C_x, Bottom: C_z) as a function of E_γ (Left) and Ξ^- angles in the center-of-momentum frame(Right). Only the statistical uncertainties, which are dominant, are shown. The red solid curve is based on the model from Ref. [28], using pseudo-vector coupling. The blue dash-dotted curve uses pseudo-scalar coupling. The green dashed curve includes contributions from intermediate hyperons with $J > \frac{3}{2}$ [29]. The theoretical curves are for $E_\gamma = 4$ GeV.

5. Ω^- **Photoproduction and the Very Strange Experiment at CLAS12**

The prediction and discovery of the Ω^- baryon certainly was one of the great triumphs of the quark model. However, half a century later, there has been little new information about the Ω and Ξ baryons. In fact, only two Ω states and six Ξ states are considered to be well-established, with at least three-star ratings in the PDG [16]. Production of doubly- or triply-strange baryons by means of a photon beam (as with CLAS currently and with CLAS12 and GlueX in the future) is expected to shed light on the genesis of these states which involves the production of multiple $s\bar{s}$ pairs from the vacuum. This significant change in baryon strangeness number from initial ($S = 0$) to final state ($S = -3, -2$) could result from direct production via vector-meson dominance or from a sequence of intermediate transitions. Inference on the production mechanisms of these states in γp collisions can be obtained from precision measurements of the cross section and the invariant mass of these states.

The CLAS12 Very Strange Experiment, E12-11-005a [32], is expected to yield valuable data in the physics of Ω and cascade states. This experiment takes advantage of the large luminosity after the 12 GeV upgrade at the Thomas Jefferson Laboratory. Using the CLAS12 spectrometer and the Forward Tagger (FT) for the quasi-real photon beams, E12-11-005a is expected to yield unprecedented statistics in the production of Cascade and Omega baryons. Excited cascades can be investigated in reactions such as $\gamma p \to K^+K^+\Xi^-(1820), \Xi^-(1820) \to K^-\Lambda$, $\Lambda \to p\pi^-$. This would allow the determination of the spin and parity of the observed excited cascade states [33]. The polarization of ground state Ξ can also be measured with uncertainties sufficiently small to constrain production models that currently can not separate the contributions of various intermediate hyperon resonances. As for the Ω^- photoproduction, detailed differential cross section measurements can be performed, necessary for the understanding the production mechanism, differentiating various models such as vector meson dominance and a sequential decay of intermediate states.

The expected statistics of various reactions for E12-11-005a, is summarized in the Table 1:

	Detected Particles	Measured Decays	Total Detected
Ω^-	$K^+K^+K^0$		$\sim$ 7k
Ω^-	$K^+K^+K^0K^-$	Ω^-	$\sim$ 1k
Ξ^-	$K^+K^+\pi^-$	Ξ^-	$\sim$ 0.9M
$\Xi^-(1530)$	$K^+K^+\pi^-$	$\Xi^-(1530)$	$\sim$ 270k
$\Xi^-(1820)$	$K^+K^+K^-p$	$\Xi^-(1820), \Lambda$	$\sim$ 12k

Table 1: Expected Particle Rate for the CLAS12 Very Strange Experiment (E12-11-005a), based on the simulation including detection efficiency and branching ratios. 80 beam days were assumed.

6. **Summary**

With the effort of the Jefferson Lab 12 GeV upgrade ongoing, and the next generation of high statistics photoproduction experiments expected to yield unprecedented amount of data for hyperon states, it is an exciting time for hyperon spectroscopy. The existing data from the CLAS collaboration have already demonstrated the feasibility and importance of the various polarization observables in hyperon production, and its relation with the intermediate resonances. Future data from both CLAS12 and GlueX will no doubt provide more detailed measurements to understand the production mechanisms of the various hyperon states.

7. **Acknowledgments**

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