Cascade Baryon Production in Photon-Induced Reactions

K. Nakayama\textsuperscript{1,2}, Yongseok Oh\textsuperscript{1}, and H. Haberzettl\textsuperscript{3}

\textsuperscript{1} Department of Physics and Astronomy, University of Georgia, Athens, GA 30602, USA
\textsuperscript{2} Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany
\textsuperscript{3} Center for Nuclear Studies, Department of Physics, George Washington University, Washington DC 20052, USA

E-mail: nakayama@uga.edu

Abstract. The reaction $\gamma N \rightarrow KK\Xi$ is studied within a relativistic meson exchange model of hadronic interactions. This is the first theoretical effort in connection to the cascade baryon spectroscopy program initiated recently at the Thomas Jefferson National Accelerator Facility. The basic features of this reaction and their manifestations in some of the observables are presented.

1. Introduction

In principle, flavor SU(3) symmetry allows for the existence of as many $\Xi$ resonances as the number of $N^*$ and $\Delta^*$ resonances combined. Despite this fact, not much is known about these resonances. Indeed, only a dozen or so $\Xi$ have been identified so far; among them, only two, $\Xi(1318)$ and $\Xi(1530)$, have four-star status [1]. Recently, the CLAS Collaboration at the Thomas Jefferson National Accelerator Facility (JLab) has initiated a cascade-physics program [2]; the collaboration, in particular, has established the feasibility to do cascade baryon spectroscopy via photoproduction reactions like $\gamma p \rightarrow K^+K^0\Xi^-$. A dedicated experiment for these reactions is currently underway; preliminary total cross section data for the first reaction have already been reported [3]. To our knowledge, no theoretical investigation of cascade photoproduction off nucleons exist in connection to the cascade spectroscopy program at JLab. It is extremely timely, therefore, to study this reaction theoretically.

We investigate the $\gamma N \rightarrow KK\Xi$ reaction for incident photon energies up to about 5 GeV which is the energy range covered at JLab. The reaction amplitude is calculated in the tree-level approximation considering the production mechanisms displayed in Fig. 1, which involve excitation of baryon resonances in the intermediate states. The $t$-channel meson-exchange processes with subsequent decay of the emitted meson into two kaons are largely suppressed in this reaction since the produced meson should be exotic having strangeness $S = +2$. This means that, to lowest order, the production of a cascade involves necessarily an excitation of hyperons as shown in Fig. 1. Therefore, cascade photoproduction off nucleons should offer also a possibility to extract information on the hyperons with $S = -1$. Further details of the present approach can be found in Ref. [5].

There are many three- and four-star hyperons which may contribute to the present reaction. Among them, only for the low-mass resonances, i.e., $\Lambda(1116)$, $\Lambda(1405)$, $\Lambda(1520)$, $\Sigma(1190)$, and...
Figure 1. Diagrams contributing to $\gamma N \rightarrow KK\Xi$. The intermediate baryon states are denoted as $N'$ for the nucleon and $\Delta$, $Y, Y'$ for the hyperon $\Lambda$ and $\Sigma$ resonances, and $\Xi'$ for $\Xi(1318)$ and $\Xi(1530)$. The intermediate mesons in the $t$-channel are $K$ [(a) and (b)] and $K^*$ [(h) and (i)]. The diagrams (f) and (g) are the generalized contact currents required to maintain gauge invariance of the total amplitude. The external legs are labeled by the four-momenta of the respective particles in (a). Diagrams corresponding to (a)–(i) with $K(q_1) \leftrightarrow K(q_2)$ are also taken into account in the present calculation.

$\Sigma(1385)$, we have sufficient information to determine the relevant hadronic and electromagnetic coupling constants. In fact, they can be estimated from the experimental data [1] and/or from quark models and SU(3) symmetry considerations. Unfortunately, for higher-mass resonances (those with masses larger than 1.6 GeV), there are not sufficient information to extract the necessary parameters, especially their coupling constants to the cascade baryon. The only available information relevant to the present reaction involving the higher hyperon resonances are the $Y \rightarrow NK$ partial decay widths [1], from which we can extract the magnitude of the corresponding $NYK$ coupling constants. Therefore, for the contribution from these hyperons, we consider only the diagrams (a)–(g) in Fig. 1 with $Y = Y'$ in (d), where the only additional free parameter of the model is the $\Xi Y K$ coupling constant. Also, in the following, we will restrict ourselves to spin-1/2 and -3/2 hyperons. It then happens that, unless the $\Xi Y K$ coupling constants are much larger than the corresponding $NY K$ coupling constants, resonances with $J^P = 1/2^+$ and $3/2^-$ yield much smaller contributions to the reaction amplitude as compared to the $J^P = 1/2^-$ and $3/2^+$ resonance contributions. This can be understood if we consider the limit of the intermediate hyperon resonances being on the mass shell as has been pointed out in Ref. [5].
Figure 2. Total cross sections for $\gamma N \to KK\Xi^-$ according to the mechanisms shown in Fig. 1 as a function of photon incident energy $T_\gamma$ for (a) pseudovector (pv) and (b) pseudoscalar (ps) couplings at the $BYK$ vertices for spin-1/2 baryons $B$ and hyperons $Y$. The dashed curves correspond to the contribution from the diagrams involving only the spin-1/2 hyperons, while the dash-dotted curves correspond to the contribution from the diagrams involving one or more spin-3/2 hyperons. The solid curves represent the total contribution. The (preliminary) data are from Ref. [3], where the open boxes are obtained without the differential cross section measurement.

2. Results

We first discuss the results considering only the low-mass hyperons. The resulting total cross section is shown in Fig. 2. The (two) parameters of the hadronic form factors have been treated as free parameters to be adjusted. The solid curves in Fig. 2 are the sum of all contributions and reproduce the basic features exhibited by the available preliminary data from the CLAS Collaboration [3] quite well. The dashed curves correspond to the contributions from the diagrams in Fig. 1 which involve only the spin-1/2 hyperons in the intermediate state, while the dash-dotted curves correspond to those involving one or more spin-3/2 hyperons.

Although the low-mass intermediate hyperons contribution reproduces the preliminary total cross section data [3], it fails completely in describing the measured angular distributions of $\Xi^-$ and $K^+$. In particular, the model prediction (see Fig. 3, dashed curves) yields a forward (backward) peaked $\Xi^-$ ($K^+$) distribution while the data exhibit backward (forward) peaked $\Xi^-$ ($K^+$) angular distributions [4]. The predicted shapes of the angular distributions are due to the dominance of the hyperon radiative transitions [diagram Fig. 1(d)]. Among the various production mechanisms considered in this work, only the $t$-channel $K$-exchange process [diagram Fig. 1(a)] exhibits the backward- (forward-) peaked angular distribution for $\Xi^-$ ($K^+$).

The most natural way of solving this discrepancy is to consider the higher-mass hyperon resonances. Since they lie close to or above the threshold energy of $\Xi$ production, it is natural to expect them to play a more prominent role than the low-mass hyperons. As discussed previously, we consider the hyperon resonances $\Lambda(1800)1/2^-$ and $\Lambda(1890)3/2^+$. These two $\Lambda$ resonances may be viewed as representatives of the spin-1/2 and -3/2 resonances, respectively, in the region of 1.8–2.0 GeV; they are employed here to indicate what features spin-1/2 and -3/2 resonances may introduce into the present reaction. The additional free parameter in the model is the coupling constant $g_{\Xi Y K}$ involving the two higher-mass hyperons which may be adjusted to reproduce the observed angular distribution data. This leads to a dominance of the $t$-channel $K$-exchange process, Figs. 1(a,b) instead of the radiative transition process due to the low-mass hyperons. It is a simple matter of kinematics that the $t$-channel processes contribute mostly for low $t$
and high incident energies which leads to the forward-peaked $K^+$ angular distribution as the incident photon energy increases. In the c.m. frame this, in turn, leads to the backward-peaked $\Xi^-$ angular distribution as shown by the solid curves in Fig. 3. It is obvious, then, that the angular distributions can tell us about the production mechanism. The total cross sections when the higher-mass hyperons are considered are practically the same as that exhibited in Fig. 2 when the free parameters of the hadronic form factors in the model are readjusted. The use of the $ps$-coupling leads to the results which exhibit the same features as those shown in Fig. 3. This observation also holds for the beam asymmetry discussed below.

Another independent observable that is sensitive to the production mechanism of $\Xi$ in the present reaction is the beam asymmetry. Indeed, our model predicts that this observable, shown in Fig. 4, is small and positive for most $\Xi^-$ emission angles, if only the low-mass hyperons are considered (dashed curves), while it is largely negative at backward angles when the higher-mass hyperons are included (solid curves), a feature that becomes more pronounced as the photon energy increases. The latter is a characteristic feature of the $t$-channel $K$-exchange mechanism. As noted before, $t$-channel processes contribute mostly at small $t$ and higher incident energies. In the c.m. frame, this implies a backward-angle emission of the $\Xi^-$ hyperon. Now, the beam asymmetry due to the $t$-channel $K$-exchange corresponding to Fig. 1(a) alone is identical to $\Sigma_B = -1$, since the three-momentum $q_1$ of the emitted $K^+$ can be chosen to be in the $xz$-plane without loss of generality.

The observables discussed so far are rather insensitive to the choice of the coupling at the $BYK$ vertex for spin-1/2 baryon $B$ and hyperon $Y$, i.e., $pv$- or $ps$-coupling. The right panel of Fig. 4 shows our results for the target asymmetry which exhibits a rather pronounced sensitivity to this choice of the coupling. This sensitivity is due to the $t$-channel $K$-exchange contribution and arises from the fact that the $ps$-coupling involves $\gamma_5$ while the $pv$-coupling involves $\gamma_5 g_\rho \gamma^\mu$. 

**Figure 3.** Predicted angular distributions of the $\Xi^-$ particle in $\gamma p \rightarrow K^+K^+\Xi^-$ in the center-of-mass frame. The dashed lines correspond to the results with only the low-mass hyperon contributions, while the solid lines correspond to those including also the higher-mass hyperons. All the results are obtained using the $pv$-coupling. The number in the right upper corner of each figure indicates the incident photon energy $T_\gamma$ in units of GeV.
Figure 4. Photon asymmetry $\Sigma_B$ (left panel) and target asymmetry $\Sigma_T$ (right panel) as a function of the $\Xi^-$ emission angle in the c.m. frame in $\gamma p \rightarrow K^+K^+\Xi^-$. The dashed curves correspond to the results with the ps-coupling while the solid curves to those with the pv-coupling. Higher-mass hyperon resonances $\Lambda(1800)1/2^-$ and $\Lambda(1890)3/2^+$ are included.

![Figure 4](image)

Figure 5. Predicted $K^+\Xi^-$ invariant-mass distributions in in $\gamma p \rightarrow K^+K^+\Xi^-$. See caption of Fig. 4 for further details.

![Figure 5](image)

at the $BYK$ vertex. The latter coupling leads to an amplitude which contains an extra $\bar{\sigma} \cdot \vec{q}$ factor as compared to the former coupling.

Also, our model calculations of the $K^+\Xi^-$ invariant mass distribution are shown in Fig. 5. The bump at around 1.9 GeV invariant mass is due to the higher-mass hyperon $\Lambda(1890)3/2^+$. The other hyperon considered is $\Lambda(1800)1/2^-$ which is just below the threshold. The other bump close to the maximum invariant mass value is due to the kinematical reflection. The preliminary data [4] indicate that it is not sufficient to consider the two higher-mass resonances, $\Lambda(1800)1/2^-$ and $\Lambda(1890)3/2^+$, in order to reproduce the measured invariant mass distribution. In fact, the data reveal the necessity to consider resonance(s) with mass around 2.05 GeV in order to fill up the valley observed in Fig. 5 in this energy region. There are spin-$5/2$ and $-7/2$ hyperon resonances in this mass region [1] which may potentially contribute to this observable. Work to include these high-spin resonances is in progress.
In summary, the present effort is just a first step toward building a more complete and realistic model for describing cascade baryon photoproduction off nucleons. Our findings should be useful for future investigation of this reaction both experimentally and theoretically.

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[1] Eidelman S et al. 2004 Phys. Lett. B592 1
[2] Price J W et al. 2005 Phys. Rev. C71 058201
[3] Guo L and Weygand D P (for CLAS Collaboration) 2005 Proc. Int. Workshop on the Physics of Excited Nucleons (NSTAR’05) ed S. Capstick, V. Crede, and P. Eugenio, (World Scientific) pp 384-388; hep-ex/0601011
[4] Guo L and Weygand D P, private communication
[5] Nakayama K, Oh Yongseok, and Haberzettl H 2006 Phys. Rev. C 74 035205