2.9 Cascade Production in $\overline{K}$- and Photon-Induced Reactions

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Abstract

The $\bar{K} + N \to K + \Xi$ and $\gamma + N \to K + K + \Xi$ reactions are investigated in a combined analysis within an effective Lagrangian approach to learn about the basic features of these reactions. Such a study should help construct more complete reaction models within a full coupled-channels approach to extract relevant physics information from forthcoming experimental data in the multi-strange particle physics programs at modern experimental facilities including J-PARC and JLab. Among the above-threshold three- and four-star $S = -1$ resonances considered in this work, a minimum of three resonances, namely $\Sigma(2030)7/2^+$, $\Sigma(2265)5/2^-$, and $\Lambda(1890)3/2^+$, are found to be required to reproduce the available data in the considered $\bar{K}$- and photon-induced reactions. Among them, the $\Sigma(2030)7/2^+$ resonance is shown to play a clear and important role in both reactions.

1. **Introduction**

One of the major interests in baryon spectroscopy in the strangeness sector is the possibility to learn about the properties of the so-called multi-strangeness baryons, *i.e.*, baryons with strangeness quantum number $S < -1$. Although the multi-strangeness baryons have played an important role in the development of our understanding of strong interactions, and thus should be an integral part of any baryon spectroscopy program, the current knowledge of these baryons is still extremely limited. In fact, the SU(3) flavor symmetry allows as many $S = -2$ baryon resonances, called Ξ, as there are N and Δ resonances combined (~ 27); however, until now, only eleven Ξ baryons have been discovered [1]. Among them, only three [ground state $\Xi(1318)1/2^+$, $\Xi(1538)3/2^+$, and $\Xi(1820)3/2^-$] have their quantum numbers assigned. This situation is mainly due to the fact that multi-strangeness particle productions have relatively low yields. For example, if there are no strange particles in the initial state, Ξ is produced only indirectly and the yield is only of the order of nb in the photoproduction reaction [2], whereas the yield is of the order of μb [3] in the hadronic $\bar{K}$-induced reaction, where the Ξ is produced directly because of the presence of an $S=-1$ $\bar{K}$ meson in the initial state. The production rates for Ω baryons with $S=-3$ are much lower [4]. The initiative to having a K_L beam at the Thomas Jefferson National Accelerator Facility (JLab) in particular to study, among other things, multi-strangeness baryon spectroscopy is, therefore, extremely valuable.

The study of multi-strangeness baryons has started to attract renewed interests recently. Indeed, the CLAS Collaboration at JLab plans to initiate a Ξ spectroscopy program through the photoproduction reaction using the upgraded 12-GeV machine, and measure exclusive Ω photoproduction for the first time [5]. Some data for the production of the Ξ ground state, obtained from the 6-GeV machine, are already available [2]. J-PARC is going to study the Ξ baryons via the $\bar{K}+N \to K+\Xi$ process (which is the reaction of choice for producing Ξ) [6, 7] in connection to its program proposal for obtaining information on Ξ hypernuclei spectroscopy. It also plans to study the $\pi+N \to K+K+\Xi$ reaction as well as Ω production. At the FAIR facility of GSI, the reaction $\bar{p}+p \to \bar{\Xi}+\Xi$ will be studied by the $\overline{\mathrm{P}}$ANDA Collaboration [8].

In the present work, we concentrate on the production of $S=-2$ Ξ, in particular, on the production reaction processes of the ground state Ξ:

$$\bar{K}+N \quad \to K+\Xi\,, \tag{1}$$

$$\gamma+N \quad \to K+K+\Xi\,. \tag{2}$$

The $\bar{K}$-induced reaction (1) has been studied experimentally mainly throughout the 60's which was followed by several measurements made in the 70's and 80's. The existing data are rather limited and suffer from large uncertainties. There exist only very few early attempts to understand this reaction. Recent calculations are reported by Sharov *et al.* [9] and by Shyam *et al.* [10]. Although the analyses of both works are based on very similar effective Lagrangian approaches, the number of $S=-1$ hyperon resonances included as intermediate states are different. While in Ref. [9] only the $\Sigma(1385)$ and $\Lambda(1520)$ were considered in addition to the above-threshold $\Sigma(2030)$ and $\Sigma(2250)$ resonances, in Ref. [10] eight of the 3- and 4-star Λ and Σ resonances with masses up to 2.0 GeV have been considered. While the authors of Ref. [9] pointed out the significance of the above-threshold resonances, the authors of Ref. [10] have found the dominance of the sub-threshold $\Lambda(1520)$ resonance. Reaction (2) has been also considered by Magas *et al.* [11] within the coupled-channels Unitarized Chiral Perturbation approach when determining the parameters of the next-to-leading-order interactions. The authors of Ref. [11] have added the $\Sigma(2030)$ and $\Sigma(2250)$ resonances into their calculation to improve the fit quality to the total cross section data. Also the Argonne-Osaka group [12, 13] reported applying their Dynamical Coupled Channels (DCC) approach to $\bar{K}$-induced two-body reactions for center-of-momentum energies up to $W=2.1$ GeV. Some of the model-independent aspects of the reaction (1) have been studied recently by the present authors [14, 15].

We note here that the proper identification of resonances and the reliable extraction of their parameters require detailed knowledge of the analytic structures of the scattering amplitude that, to date, can only be obtained through a full coupled-channel treatment, such as that of Refs. [12, 13]. However, because the currently available data in the $K\Xi$ channel are scarce and of low quality, they do not provide sufficient constraints for the model parameters to permit an in-depth analysis of that channel. In this context, we mention that a coupled-channel partial-wave analysis of $\bar{K}$-induced reactions up to $W = 2.1$ GeV has also been performed recently by the Kent State University group [16,17] which includes seven reaction channels, but not the $K\Xi$ channel.

The available experimental data for the photon-induced reaction (2) are also very scarce. In fact, the only data available for this reaction in the resonance energy region are those from JLab [2] using the 6-GeV machine. Specifically, the total cross sections, both the K and Ξ angular distributions and the KK and $K\Xi$ invariant mass distributions are available. Theoretical studies of this reaction are scarce, too. To date, the work of Refs. [18, 19] is the only one that analyzes the JLab data of Ref. [2].

One of the purposes of the present work is to search for a clearer evidence of the $S = -1$ hyperon resonances in reactions (1) and (2). However, we emphasize that our main interest here lies not so much in the accurate extraction of $S = -1$ hyperon resonance parameters, but in an exploratory study to learn about the pertinent reaction mechanisms and, in particular, to identify the resonances that come out to be most relevant for the description of the existing Ξ production data. In fact, with the exception of the $\Sigma(2250)$ resonance, whose mass was adjusted slightly to better reproduce the observed bump structure in the total cross section in the charged Ξ production, the masses and widths of the resonances incorporated here are taken from other sources. Only the product of the coupling constants and the cutoff parameters in the corresponding form factors are adjusted in the present work.

2. Formalism

In the present work, we perform an analysis of the existing data based on a relativistic effective Lagrangian approach that includes a phenomenological contact amplitude which accounts for the rescattering contributions and/or unknown (short-range) dynamics that have not been included explicitly into the model. For photoproduction, local gauge invariance as dictated by the appropriate generalized Ward-Takahashi identity is strictly enforced [20]. Figures 1 and 2 display the Feynman diagrams considered in the present work for the $\bar{K}$- and photon-induced reactions, (1) and (2), respectively. Further details of the model can be found in Ref. [21] for reaction (1) and, in Refs. [18,19], for reaction (2). While the tree-level model used here is not very sophisticated, it captures the essential aspects of the processes in question. As such, the use of a simplified and flexible model is particularly well suited for a situation, such as for the reactions (1) and (2), where scarce and/or poor data prevent a more detailed and complete treatment. The present study is our first step toward building a more complete reaction model capable of reliably extracting the properties of hyperons from the forthcoming experimental data, in addition to providing some guidance for planning future experiments.

3. Results

We now turn to a selected set of results of the present work which treats the reactions (1) and (2) consistent with each other. It should be mentioned that, although similar, the results

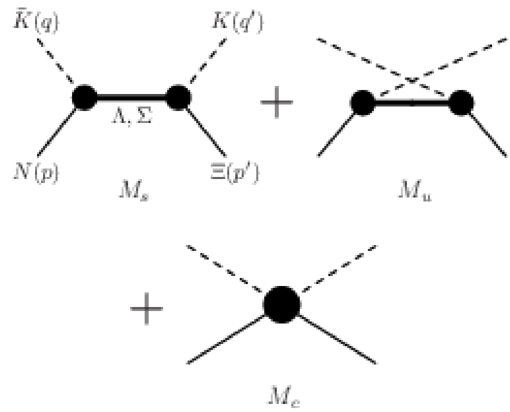

Figure 1: Diagrams describing the amplitude for reaction (1) in the present calculation. The labeling of the external legs of the s-channel diagram, M_s, follows the reaction equation (2); the labels apply correspondingly also to the external legs of the u-channel diagram, M_u, and the contact term M_c. The intermediate hyperon exchanges, Λ and Σ, indicated for M_s also appear in M_u. The details of the formalism, including the contact amplitude, M_c, are given in Ref. [21].

we show here differ from those shown in Refs. [18, 19, 21], for the model parameters have been readjusted to reproduce the available data for both reactions considered simultaneously. As far as the $S = -1$ hyperon contributions are concerned, our analysis reveals that a minimum of three above-the-threshold resonances, namely the $\Sigma(2030)7/2^+$, $\Sigma(2250)5/2^-$ and $\Lambda(1890)3/2^+$ resonances, in addition to the $\Sigma(1385)3/2^+$ and the ground states $\Lambda(1116)$ and $\Sigma(1193)$, suffice to reproduce all the available data in both the $\bar{K} + N \to K + \Xi$ and $\gamma + N \to K + K + \Xi$ reactions.

(a) $\boldsymbol{\bar{K} + N \to K + \Xi}$ **Reaction**

In Fig. 3, we illustrate the amount of the above-threshold resonance contributions of the present model to the total cross sections in reaction (1). We do this by comparing the full results (blue solid curves) to the result found by switching off one resonance at a time. We see in Fig. 3(a) that the largest effect of $\Sigma(2030)$ on the cross sections is in the range of $W \sim 2.0$ to 2.4 GeV. This resonance is clearly needed in our model to reproduce the data. It also affects the recoil polarization as will be discussed later. We note that the present model yields the product of the branching ratios Br$\big(\Sigma(2030) \to KN\big) \times$ Br$\big(\Sigma(2030) \to K\Xi\big) \approx 15.6\%$ which may be contrasted with the corresponding values of $\approx 16.1\%$ (model A) and $\approx 20.4\%$ (model B) extracted in Ref. [13] within a DCC approach. [1] The $\Lambda(1890)$ affects the total cross section in the range of $W \sim 1.9$ to 2.1 GeV, and the $\Sigma(2250)5/2^-$ contributes around $W \sim 2.2$ GeV, where it is needed to reproduce the observed bump structure. A more accurate data set is clearly needed for a more definitive answer about the roles of the $\Lambda(1890)$ and $\Sigma(2250)$ resonances. Figure 3(b), for the neutral Ξ^0 production, also shows a similar feature observed in the Ξ^- case for the $\Sigma(2030)$ resonance. Here, the influence of the

[1] Note that only the product of the KYN and $KY\Xi$ coupling constants ($Y = \Lambda, \Sigma$ resonances) is sensitive to the data in the present model.

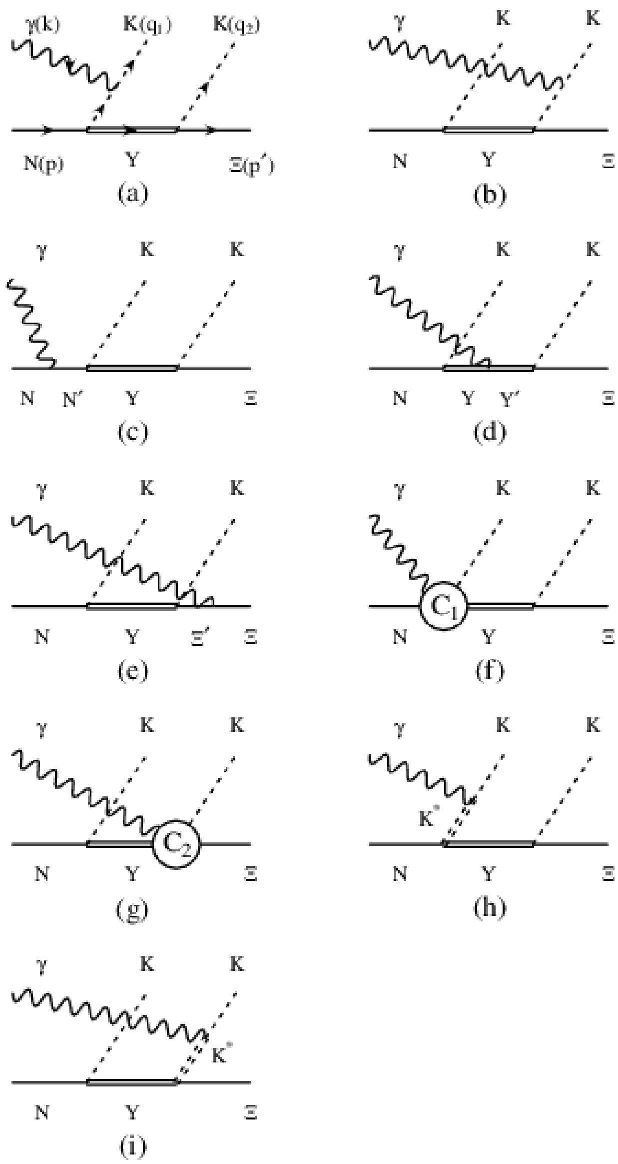

Figure 2: Diagrams contributing to the reaction mechanism of reaction (2). The intermediate baryon states are denoted as N' for the nucleon and Δ resonances, Y, Y' for the Λ and Σ resonances, and Ξ' for $\Xi(1318)$ and $\Xi(1530)$. The intermediate mesons in the t-channel are K [(a) and (b)] and K^* [(h) and (i)]. The diagrams (f) and (g) contain the generalized contact currents that maintain gauge invariance of the total amplitude. Diagrams corresponding to (a)–(i) with $K(q_1) \leftrightarrow K(q_2)$ are also understood. The details of the formalism, including the contact amplitude, M_c, are discussed in Refs. [18, 19].

$\Sigma(2250)5/2^-$ is smaller and that of the $\Lambda(1890)$ is hardly seen. Recall that there is no u-channel Λ contribution in the neutral Ξ^0 production.

A peculiar feature of the $K^- + p \to K^+ + \Xi^-$ process is that it is dominated by the P and D partial-waves (not shown here). In particular, the P-wave dominates the total

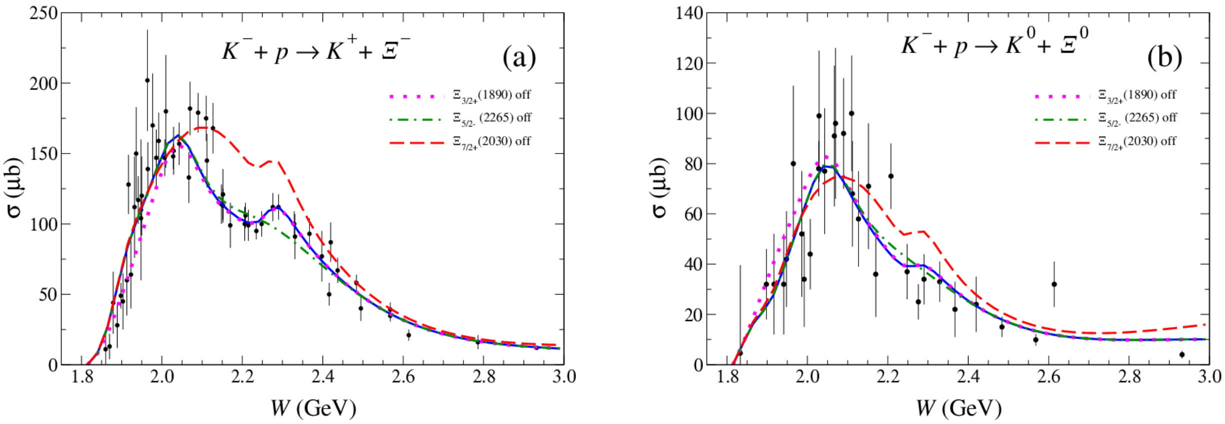

Figure 3: Total cross section results with individual resonances switched off (a) for $K^- + p \to K^+ + \Xi^-$ and (b) for $K^- + p \to K^0 + \Xi^0$. The blue solid lines represent the full result. The red dashed lines, which almost coincide with the blue lines represent the result with $\Lambda(1890)$ switched off. The green dash-dotted lines represent the result with $\Sigma(2030)$ switched off and the magenta dash-dash-dotted lines represent the result with $\Sigma(2250)5/2^-$ switched off. The data are the digitized version from Ref. [9].

cross section even down to energies very close to threshold. This is also corroborated by the DCC calculation of Ref. [12]. The experimental total cross section data (σ) divided by the magnitude of the relative three-momentum in the final state (p'), σ/p', as a function of p'^2, reveal essentially a linear dependence near threshold, a model-independent indication of the P-wave contribution.

The results for the recoil polarization asymmetry multiplied by the cross section are shown in Fig. 4. Overall, we reproduce the data reasonably well. We also find that the results shown at W = 2.11 GeV are still significantly affected by the $\Sigma(2030)$. This corroborates the findings of Ref. [9]. An interesting observation here is that, although small, the measured recoil polarization asymmetry is finite and non-vanishing. This offers an opportunity to measure the parity of the ground state Ξ which has never been measured — its positive parity as assigned by the Particle Data Group stems from quark-model predictions [1]. The reflection symmetry in the reaction plane implies that the target and recoil polarization asymmetries, T and P, respectively, in reaction (1) are related to each other by [14]

$$T = \pi_\Xi P \, , \tag{3}$$

where π_Ξ stands for the parity of the Ξ hyperon.

We also show in Fig. 5 our prediction for the total cross section in the $K_L + p \to K^+ + \Xi^0$ reaction. Unlike the other reaction channels considered above, this channel serves as a total isospin $I = 1$ filter, for no contribution of $I = 0$ is present. However, we note that the isoscalar Λ hyperons still contribute to this reaction via the u-channel process.

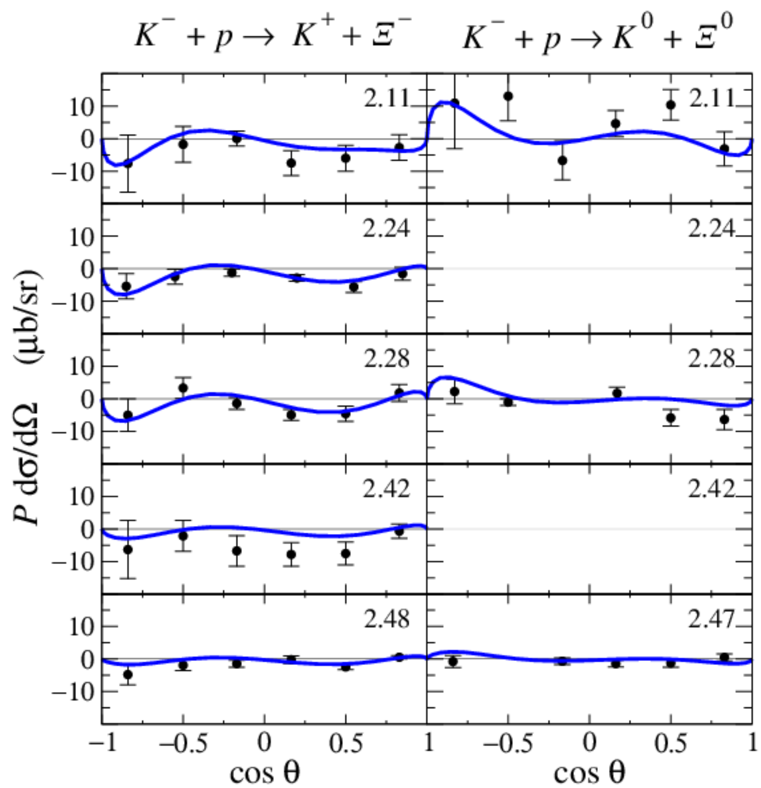

Figure 4: The recoil asymmetry multiplied by the cross section, $P\frac{d\sigma}{d\Omega}$, for both the $K^-+p \to K^+ + \Xi^-$ and $K^-+p \to K^0+\Xi^0$ reactions. The blue solid lines represent the full results of the current model. Data are the digitized version from Ref. [9].

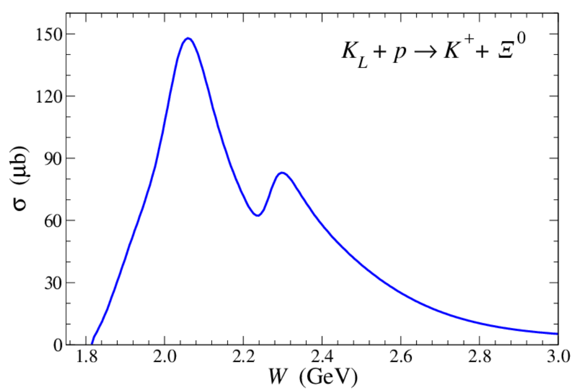

Figure 5: Prediction for the total cross section in the $K_L + p \to K^+ + \Xi^0$ reaction.

(b) $\gamma + N \to K + K + \Xi$ Reaction

Figures 6(a),(b) display the K^+ and Ξ^- angular distributions, respectively, in the center-of-mass frame for the reaction $\gamma+p \to K^+ + K^+ + \Xi^-$. Overall, the data are reproduced very well. The same figures also show the results when the t-channel K-exchange current diagrams [cf. Fig. 2(a),(b)] involving the $S = -1$ hyperon resonances are switched off. We see that they are crucial in providing the observed behavior of the measured angular distributions.

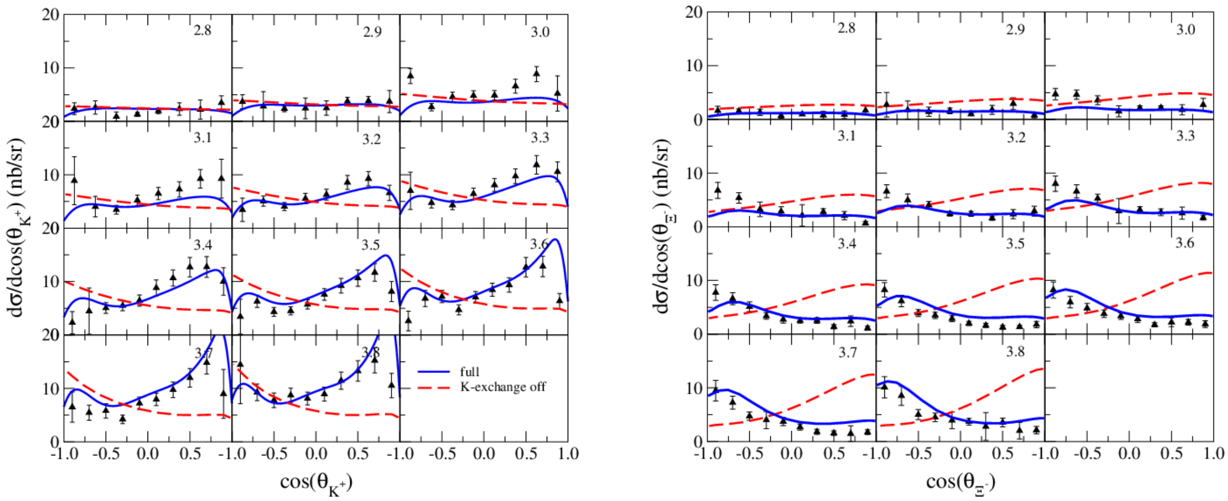

Figure 6: Differential cross sections for the reaction $\gamma + p \to K^+ + K^+ + \Xi^-$ in the center-of-mass frame of the system. Left panel: K^+ angular distribution. Right panel: Ξ^- angular distribution. The blue solid lines represent the full result. The red dashed lines represent the result with the t-channel K-exchange currents [cf. Fig. 2(a) and (b)] switched off. The number in the upper right corner in each graph denotes the incident photon energy in units of GeV in the laboratory frame. The data are from Ref. [2].

The results for the $K^+\Xi^-$ invariant mass distributions are shown in Fig. 7. It reveals the important role of the $\Sigma(2030)$ and $\Lambda(1890)$ resonances in reproducing the experimental data. We found that the $\Sigma(2250)$ resonance has a minor effect here.

4. Conclusion

In this work we have presented a combined analysis of the $\bar{K} + N \to K + \Xi$ and $\gamma + N \to K + K + \Xi$ reactions within an effective Lagrangian approach. All the currently available data, in both the $K^- + p \to K^+ + \Xi^-$ and $K^- + p \to K^0 + \Xi^0$ processes, are well reproduced by the present model overall, and some of the basic features of the ground state Ξ production in these reaction processes have been understood.

The above-threshold resonances $\Lambda(1890)$, $\Sigma(2030)$, and $\Sigma(2250)$ are required to achieve a good fit quality of the K^--induced reaction data. Among them, the $\Sigma(2030)$ resonance is the most critical one. This resonance affects not only the cross sections but also the recoil asymmetry. More accurate data are required before a more definitive answer can be provided for the role of the $\Lambda(1890)$ and $\Sigma(2250)$ resonances. In this regard, the multi-strangeness hyperon production programs using an intense anti-Kaon beam at J-PARC and JLab are of particular relevance in providing the much needed higher-precision data for the $\bar{K}$-induced reaction. While it may perhaps not be entirely clear which role any particular resonance plays for the $K^- + N \to K + \Xi$ reaction, the present and other calculations based on different approaches [9–13] seem to agree that some $S = -1$ hyperon resonances are required to

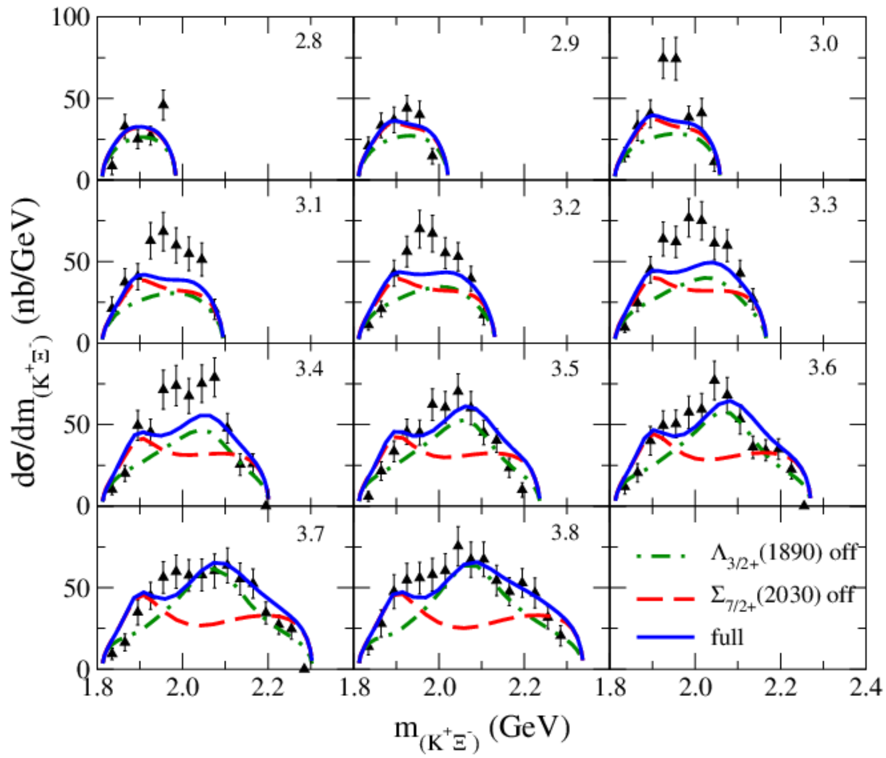

Figure 7: $K^+\Xi^-$ invariant mass distribution for the reaction $\gamma + p \to K^+ + K^+ + \Xi^-$. The blue solid lines represent the full result. The red dashed lines represent the result with $\Sigma(2030)$ switched off. The green dash-dotted lines represent the result with $\Lambda(1890)$ switched off. The number in the upper right corner in each graph denotes the incident photon energy in units of GeV in the laboratory frame. The data are from Ref. [2].

reproduce the existing data. To pin down the role of a particular resonance among them requires more precise and complete data, in addition to more detailed theoretical models such as that of Refs. [12, 13]. In any case, both the $\bar{K}$- and photon-induced reactions studied in the present work are very well suited for studying $S = -1$ hyperon resonances in the ~ 2 GeV region.

We also found that the $\Lambda(1890)$ and $\Sigma(2030)$ resonances play an important role in the photon-induced reaction. In particular, they are required to bring the calculated $K^+\Xi^-$ invariant mass distributions in agreement with the corresponding measurements.

Finally, the present work is our first step toward building a more complete reaction theory to help analyze the data and extract the properties of Ξ resonances in future experimental efforts in Ξ baryon spectroscopy. This is a complementary work to that of a model-independent analysis performed recently in Ref. [15] and will also help in analyzing the data to understand the production mechanisms of Ξ baryons.

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