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# $K^+\Sigma^-$ photoproduction within an isobar model

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**Abstract.** We used an isobar model to study the $K^+\Sigma^-$ photoproduction reaction on a neutron target with focus on the resonance region. In order to achieve a reasonable agreement with the data, we included spin-3/2 and spin-5/2 nucleon resonances in a consistent formalism together with a $\Delta$ resonance and two kaon resonances on top of the Born terms. The free parameters of the model were adjusted to the data from the CLAS and LEPS Collaborations on differential cross sections and photon beam asymmetry. The cornerstone of this analysis was an upgrade of the fitting method. Previously, we used only the plain $\chi^2$ minimization, which could not prevent us from overfitting the data. We, therefore, introduced a regularization method, the least absolute selection shrinkage operator (LASSO), which, together with information criteria, restricts the number of nonzero parameters and prevents us from overfitting the data. In our analysis, we arrived at two models, fit M, whose parameters were fitted with the MINUIT code only, and fit L, where we used the more advanced LASSO. Both models describe the data in a similar way and we observe only slight differences in the $d\sigma/d\Omega$ data description at very forward angles where the fit M is flat whereas the fit L produces two broad peaks, and in the photon beam asymmetries above 2 GeV at backward kaon angles where the fit M produces a bump. Surprisingly, no hyperon resonances are needed for the correct data description in these models. On the other hand, the $N(1720)3/2^+$ nucleon resonance was found to be very important in both models.

## 1 Introduction and methodology

The investigation of kaon-hyperon photo- and electroproduction from nucleons provides us with much needed information on the spectrum of baryon resonances and interactions in the systems of hyperons and nucleons. We can also gather information on the existence and properties of the so-called missing resonances, i.e. states which were predicted in the quark models but have not been seen in the $\pi$ production or $\pi N$ scattering processes. These states may have escaped experimental confirmation due to their stronger decay coupling to strangeness channels rather than to the more well-known pion final states.

Much of the work in the kaon-hyperon production is focused on the $K^+\Lambda$ channel which is most abundant with experimental data. For the time being, the database for the channels using neutron targets is very limited, with available measurements of the differential cross

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section only in the $K^+\Sigma^-$ and $K^0\Lambda$ channels. So far, only two measurements of the photon-beam asymmetry $\Sigma$ were performed: the one by the LEPS Collaboration [1] with a limited kinematical coverage and the other by the CLAS Collaboration [2] which covers a wide range of kinematics. It was this recent analysis which brought our attention to the $K^+\Sigma^-$ channel.

The isobar model we use in our study is based on effective Lagrangians in the tree-level approximation, i.e. we do not take into account any higher-order corrections (such as final-state interaction or rescattering). The nonresonant part of the amplitude includes the Born terms and exchanges of resonances in the $t$ channel ($K^*$ and $K_1$ kaon resonances) and $u$ channel ($\Sigma^*$ hyperon resonances). The resonant part is then modelled by $s$-channel exchanges of nucleon and $\Delta$ resonances whose masses range from the threshold of the process up to approximately 2 GeV. Within the isobar model, we can investigate the kaon-hyperon photoproduction in the energy range from the threshold of 1.609 GeV up to around 2.5 GeV.

Since the kaon photoproduction occurs in the so-called third nucleon resonance region, where there are many nucleon resonances which can contribute and none of them is dominant in this process, we consider around 20 resonances with masses up to around 2 GeV. In the studied energy region, contributions of high-spin resonances play a crucial role. The formalism for baryon fields with a higher spin is problematic because of the presence of non-physical degrees of freedom, which connect to the lower-spin modes of the Rarita-Schwinger field. When this field is off its mass shell, the non physical components of the field can participate in the interaction (we call such interaction inconsistent). Following Refs. [3, 4], we can get rid of these non physical terms in the amplitude: the corresponding vertices are transversal to the momentum of the exchanged particle, which provides only the contributions from the highest-spin components of the propagator (for details, see [5]).

In order to account for the inner structure of hadrons, which is basically neglected in our hadrodynamical approach, and also to fine-tune the behaviour of high-spin resonances, whose contributions can grow strongly due to their high-power momentum dependence, we introduce hadronic form factors. The cutoff parameter of these form factors, which is fitted to experimental data, influences the effectiveness of the hadronic form factor in taming the contributions of high-spin resonances.

The set of considered nucleon resonances was motivated predominantly by analyses which we did in the past on the $K^+\Lambda$ channel [5, 6] and another analysis of the $K\Sigma$ channel [7]. Besides the $N^*$'s included in our studies of $K^+\Lambda$ channel, we had to consider also the $\Delta$ and $\Sigma$ resonances in the $s$ and $u$ channels, respectively. The free model parameters, which are the couplings of individual resonances and cut-off parameters for the hadronic form factors, were adjusted to experimental data and the quality of fit was checked by comparing its prediction with the data. Altogether, we used 674 data points to fit the free parameters of the model. Currently available data in the $K^+\Sigma^-$ channel are only on the differential cross section, photon-beam asymmetry $\Sigma$, and beam-target asymmetry $E$. We did not use the beam-target asymmetry data in the fits, as their errors are much larger than the errors of the other two data sets on other observables.

At the end of the fitting procedure, we selected variants with the smallest values of $\chi^2$/n.d.f. and acceptable values of the parameters. Firstly, we used the plain $\chi^2$ minimization with help of MINUIT library [8] to fit the free parameters of the model. The resulting best fit was dubbed "fit M" (or fit MINUIT). Minimizing $\chi^2$, however, is a good measure to determine underfitting but it may lead to overfitting the data. In the energy region we are concerned with, there are many resonant states with widths at the order of hundreds of MeV, which effectively overlap each other. It is thus of great importance to decrease the number of states which we consider in our analysis. In order to do so, we introduce a penalty term to the standard $\chi^2$ definition, which then restricts the number of nonzero parameters. For more

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details on the fitting method, see Ref. [9]. With this so-called LASSO technique we arrived at a more economical solution which we called "fit L" (or fit LASSO).

## 2 Discussion

As a result of the fitting procedure, there are two different models. The fit M includes 14 resonances and 25 parameters: two kaon resonances, several nucleon resonances, one $\Delta$ resonance and no hyperon resonance, which comes as a surprise since the hyperon resonances contribute significantly in the $K^+\Lambda$ channel. Among the set of included $N^*$'s in the fit M, the most important is the contribution of the $N(1720)3/2^+$ state. Once we omit this state, we underestimate the differential cross sections by a half. A noteworthy effect of this nucleon state was observed also in the $K^0\Sigma^+$ channel [10]. We also point out significant contributions of the $N(1895)1/2^-$ state and the $\Delta(1900)1/2^-$ resonance. All of these states are among the states which were identified as the most important ones in a multi-channel analysis [11].

The fit L includes only 9 resonances and 17 parameters: there is only one kaon resonance ($K^*$) and no $\Delta$ and hyperon resonances. This result further corroborates the result of the fit M that for a reasonable description of the current $K^+\Sigma^-$ data the hyperon resonances are not needed. In the fit L, the most important contributions come from the $K^*$, $N(1720)3/2^+$, and $N(2060)5/2^+$. The role of the kaon resonance lies in capturing the experimental data mainly at forward angles. Without this resonance the cross section drops substantially in this region. The $N(1720)3/2^+$ state creates the first peak in the cross sections and in this region dominates the data description. On the other hand, the second peak in the cross sections is created mainly by the $N(2060)5/2^+$ state. Apart from these states, no other resonance has substantial effect on the cross-section description. In other words, the importance of the other states is more in their mutual interference.

In Fig. 1, we show differential cross sections in dependence on the photon laboratory energy $E_\gamma^{\mathrm{lab}}$ for ten values of $\cos\theta_K^{\mathrm{c.m.}}$. We compare our two results, fits M and L, with the experimental data from the CLAS [2, 12] and LEPS [1] Collaborations. We see that the models are in a satisfactory agreement with the data in all angular bins shown. The fit M diverges at forward kaon angles beyond 2.5 GeV, whereas the fit L tends to underestimate these data. The structures produced by the fit L at forward angles are also notable: While the fit M produces a cross section which is almost flat, the fit L creates two rather broad peaks. The latter behaviour is supported by experiment.

In Fig. 2, we show the photon-beam asymmetry $\Sigma$ as a function of the cosine of the kaon center-of-mass angle $\theta_K^{\mathrm{c.m.}}$. In the threshold region, the two fits produce almost the same beam asymmetry which is large and positive at the central kaon angles and decreases gradually at backward angles; at forward angles the drop is rather sharp. Both models are in a good agreement with experimental data. The only difference is at energies beyond 2 GeV around $\cos\theta_K^{\mathrm{c.m.}} = -0.5$ where the fit L creates a dip while the fit M shows a peak. The former behaviour is more in agreement with experiment as data indicate a dip rather than a peak in this region.

## 3 Conclusion

In this work, we used the isobar model to study the $K^+\Sigma^-$ photoproduction on a neutron target. In the isobar model, we use the tree-level Feynman diagrams with exchanges of particles in their ground and excited states. The main feature of the present analysis is an improvement of the fitting method by adding a penalty function to the definition of $\chi^2$. We arrived at two models that give us good agreement with data. There are only slight differences in the data

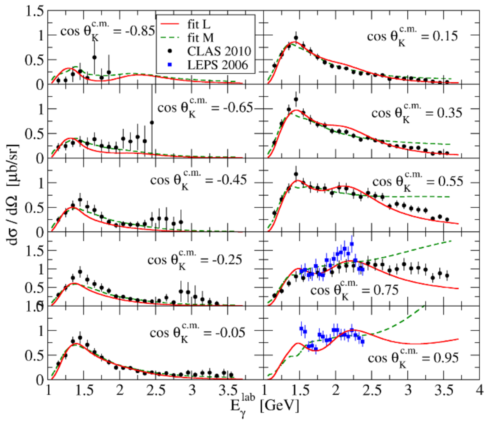


**Figure 1.** The description of the differential cross section as a function of the incident photon energy $E_\gamma^{\mathrm{lab}}$ by fits M (dashed line) and L (solid line). Data are from the CLAS [2, 12] (indicated by circles) and LEPS [1] (squares) Collaborations.

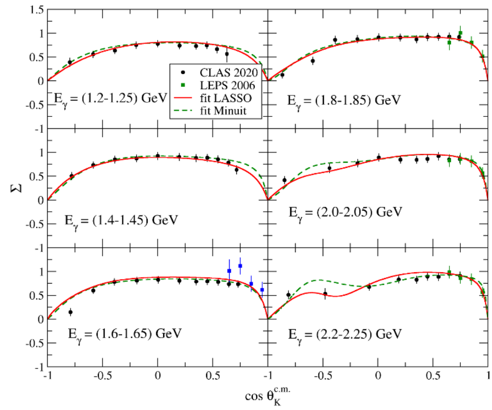


**Figure 2.** The description of the photon-beam asymmetry for six energy bins in dependence on the kaon center-of-mass angle $\theta_K^{\mathrm{c.m.}}$. Notation is the same as in Fig. 1.

description by both models, the most important one being the description of differential cross sections at very forward angles where the fit L produces two broad peaks while the fit M is flat.

Our plans for the future include using the LASSO method to perform a multichannel analysis of the Σ photoproduction channels. In this way, we hope we will be able to arrive at the optimal set of resonances which contribute to the process.

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