Role of the nucleon resonances with different spins in the photoproduction of kaon on the nucleon

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Abstract. We have studied the role of nucleon resonances with different spin numbers in the kaon photoproduction process $\gamma p \rightarrow K^+ \Lambda$ by using an isobar, where the included nucleon resonances have spins up to 9/2. The model was fitted to around 7400 experimental data points. It is found that the most important resonances in the $\gamma p \rightarrow K^+ \Lambda$ reaction are those with spin 3/2, followed by spin 5/2. Contribution of the higher spin resonances is found to be less important in this process.

1. Introduction
The electromagnetic production of meson has been known as a very useful tool to study the nucleon resonances. Most of these resonances decay into the pion-nucleon channels, where theoretical predictions can be made with a high accuracy. However, a number of these resonances have only sizable decay probability to the kaon-hyperon channels, according to the constituent quark models [1]. In fact, the number of nucleon resonances predicted by the constituent quark models [1, 2] is considerably more than what has been observed in the $\pi N \rightarrow \pi N$ scattering experiments. This phenomenon was later known as the “missing resonances” [3]. For instance, the $N(2030)S_{11}$, $N(2145)S_{11}$, and the $N(2195)S_{11}$, were predicted to mostly decay into the $K\Sigma$ channel rather than to the $\pi N$ channels [1]. Therefore, up to now these states have not been observed by the Particle Data Group [4], whose main tool for observing and extracting the properties of resonance states is the $\pi N \rightarrow \pi N$ channels.

To accurately analyze the resonance states in the kaon channels we need a reliable tool. To this end the most often used tool is the isobar model, which is based on the field theoretic or multipoles approach. Basically, the first one is constructed from the suitable Feynman diagrams, where the unknown parameters in the electromagnetic and hadronic vertices can be extracted by fitting the predicted observables to experimental data. Note that the purpose of the present paper is to describe the progress of our work in this approach. The second method, i.e., the multipoles one, can be performed by parameterizing the resonance properties with the help of the Breit-Wigner form (see [5–8] for examples).

2. The isobar model
The isobar model used in the present work is based on our previous report [9]. This model was constructed by using the field theoretic approach and consists of the standard s-, u- and t-channel for the Born terms along with the $K^{*+}(892)$, $K_1(1270)$ vector mesons and the $\Lambda(1600)P_{01}$ and $\Lambda(1810)P_{01}$ hyperon resonances. The two hyperon resonances have been shown to play an
important role in increasing the values of the leading coupling constants as well as the hadronic form factor cutoff [10]. To account for the hadronic structures, hadronic form factors are included in all hadronic interactions. To restore the gauge invariance of the amplitude, which is destroyed by the inclusion of the form factors, we exploit the Haberzettl prescription [11]. The effect of different types of hadronic form factors has been also investigated and the report can be found in [12, 13]. Another issue related to the contribution of the nucleon resonances below the threshold energy has been explained in [14].

The nucleon resonances used in the model are obtained from the list given in the Review of Particle Properties of the Particle Data Group (PDG) [4]. For the best model with the smallest $\chi^2$ we include all resonances with spins up to 9/2, i.e., the $N(1440)F_{11}$, $N(1520)D_{13}$, $N(1535)S_{11}$, $N(1650)S_{11}$, $N(1675)D_{15}$, $N(1680)F_{15}$, $N(1700)D_{13}$, $N(1710)F_{11}$, $N(1720)P_{13}$, $N(1860)F_{15}$, $N(1875)D_{13}$, $N(1880)P_{11}$, $N(1895)S_{11}$, $N(1900)P_{13}$, $N(2000)F_{15}$, $N(2060)D_{13}$, $N(2120)P_{13}$, $N(1990)F_{17}$, $N(2190)G_{17}$, $N(2220)H_{19}$, and $N(2250)G_{19}$.

Since the present analysis relies on the single channel method, it is obvious that the unitarity might be violated. Therefore, a correction at the tree-level is necessary. For this purpose we use the energy-dependent widths with partial branching fractions in the resonance propagators [15].

The model has been fitted to all available experimental data, consisting of about 7400 data points, by minimizing the value of

$$\frac{\chi^2}{N_{\text{dof}}} = \frac{1}{(N_{\text{data}} - N_{\text{par}})} \sum_{i=1}^{N_{\text{data}}} \left( \frac{\sigma_i^{\text{exp}} - \sigma_i^{\text{th}}}{\Delta \sigma_i^{\text{exp}}} \right)^2,$$

where $N_{\text{data}}$ and $N_{\text{par}}$ refer to the numbers of experimental data and fitting parameters, $\sigma_i^{\text{exp}}$ and $\Delta \sigma_i^{\text{exp}}$ denote the $i$-th experimental observable (total cross section, differential cross section, single or double polarization observable) and its error bar, and $\sigma_i^{\text{th}}$ is the corresponding theoretical calculation. Note that the $N_{\text{dof}}$ represents the number of degrees of freedom. A comparison of small part of these data with our best model can be found in our recent report [9].

### 3. Results and discussion

Since the number of coupling constants of the nucleon resonances used in this analysis is very large, we only present the background parameters of the models along with the corresponding $\chi^2/N_{\text{dof}}$ values in table 1, where different models refer to different excluded nucleon resonances. In the second column of table 1 we list the background parameters of the best model, where all nucleon resonances with different spin values are included. In other columns of table 1 the spin number of excluded nucleon resonances is indicated in the header of the table. To have a better view of the role of these resonances the values of $\chi^2/N_{\text{dof}}$ listed in table 1 is plotted in figure 1.

It is obvious that the exclusion of spin-3/2 nucleon resonances leads to the largest $\chi^2$, which indicates that the spin-3/2 nucleon resonances play the most important role in the $\gamma p \rightarrow K^+\Lambda$ process. This finding is consistent with our previous result, which shows that the $N(1720)F_{13}$ and $N(1900)P_{13}$ states are the responsible resonances for explaining the first and second peaks of the $K^+\Lambda$ cross section [16].

The second important resonances are those with spin 5/2. The importance of these resonances has been also highlighted in our recent report [9]. It is quite surprising that the role of spin-1/2 resonances is less important than that of spin-3/2 and -5/2 resonances. Presumably, this originates from the simple form of the spin-1/2 resonance amplitude. Furthermore, the spin-1/2 resonance has only one parameter for the coupling constant. Obviously, the amplitude is less flexible than those of spin-3/2 or -5/2 resonances, where the number of parameters is two, at least, to fit the experimental data. We note, however, that the spin-1/2 state $N(1650)S_{11}$ is
Figure 1. Values of $\chi^2/N_{\text{dof}}$ if the nucleon resonances with certain spin number are excluded from the model. The best model with all nucleon resonances included is indicated by the left bar with $\chi^2/N_{\text{dof}} = 1.25$.

very important in kaon photoproduction [5–7]. Therefore, a more detailed study of the spin-1/2 resonance role is urgently required in the future studies of kaon photoproduction in order to clarify this situation.

The role of higher spin resonances (7/2 and 9/2) is certainly small. This result is as expected, since it requires high energy and momentum to align the spins of quarks to produce baryons with high spin values. Consequently, the probability of finding such resonances is small in our process and their role is also less important.

For completeness, we present the behavior of different models discussed above in figure 2 in term of the calculated total cross sections as a function of the total center of momentum energy

Table 1. List of the background parameters, the hadronic form factor cutoffs, and the $\chi^2/N_{\text{dof}}$ obtained by including all resonances (Best) and excluding nucleon resonances with a specific spin number. Notation of the parameters is as in our previous studies [3,9].

| Parameters | Best | Spin-1/2 | Spin-3/2 | Spin-5/2 | Spin-7/2 | Spin-9/2 |
|------------|------|----------|----------|----------|----------|----------|
| $g_{K\Lambda N}/\sqrt{4\pi}$ | $-3.00$ | $-3.00$ | $-4.40$ | $-4.40$ | $-3.00$ | $-3.00$ |
| $g_{K\Sigma N}/\sqrt{4\pi}$ | $0.90$ | $0.90$ | $1.30$ | $1.30$ | $1.30$ | $0.90$ |
| $G^V_{K^+}/4\pi$ | $-0.18$ | $-0.50$ | $-0.00$ | $-0.09$ | $0.05$ | $-0.23$ |
| $G^V_{\Lambda^*}/4\pi$ | $0.72$ | $0.83$ | $0.11$ | $0.01$ | $0.18$ | $0.72$ |
| $G^V_{\Lambda_0}/4\pi$ | $-0.63$ | $0.12$ | $-0.02$ | $0.01$ | $0.49$ | $-0.70$ |
| $G^V_{\Lambda_1}/4\pi$ | $-2.94$ | $-2.84$ | $-0.43$ | $-0.49$ | $0.26$ | $-2.80$ |
| $G^V_{\Lambda(1600)}/4\pi$ | $-7.19$ | $-10.00$ | $-9.23$ | $-6.63$ | $7.62$ | $-7.78$ |
| $G^V_{\Lambda(1810)}/4\pi$ | $10.0$ | $3.49$ | $-10.0$ | $10.0$ | $-10.0$ | $10.0$ |
| $\Lambda_B(\text{GeV})$ | $0.70$ | $0.70$ | $1.11$ | $0.79$ | $0.86$ | $0.70$ |
| $\Lambda_R(\text{GeV})$ | $1.18$ | $1.17$ | $0.98$ | $1.12$ | $1.25$ | $1.17$ |
| $\theta_{\text{had}}(\text{deg})$ | $90.0$ | $115$ | $125$ | $90.0$ | $111$ | $90.0$ |
| $\phi_{\text{had}}(\text{deg})$ | $0.01$ | $90.0$ | $159$ | $0.00$ | $141$ | $0.08$ |
| $\chi^2/N_{\text{dof}}$ | $1.25$ | $2.21$ | $3.26$ | $2.60$ | $1.45$ | $1.36$ |
Figure 2. Total cross section calculated by using all resonances (Best Model) compared with those obtained by excluding nucleon resonance with a specific spin. Experimental data obtained from the CLAS Collaboration (solid squares [17]) and prediction of Kaon-Maid [3] are also shown for comparison. Note that the experimental data shown in this figure are only for comparison and were not included in the fitting process.

$\sigma_{\text{tot}}$ where the corresponding experimental data are also shown for comparison. Figure 2 clearly reveals that the role of the spin-1/2 resonances is very decisive in the low energy region. Without the spin-1/2 resonances it is impossible to explain the first peak of the cross section, as we have previously discussed. On the other hand, figure 2 also displays that without spin-3/2 resonances the calculated cross section deviates significantly from the experimental data.

4. Summary and conclusion
We have investigated the role of nucleon resonances with different spin values in the kaon photoproduction process $\gamma p \rightarrow K^+ \Lambda$. We have found that the nucleon resonances with spin 3/2 play the most important role in this process, followed by the spin-5/2 and spin-1/2 resonances. The higher spin resonances are found to be less important for this process.

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