**K⁺Λ and K⁰Λ photoproduction with High-Spin Nucleon Resonances**

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**Abstract.** A new model for photoproduction of KΛ, i.e. γ + p → K⁺Λ and γ + n → K⁰Λ has been constructed by using the Feynman diagrammatic approach. By using this approach, we have calculated the scattering amplitude analytically. In addition, we have also included a number of very-high-spin nucleon resonances, i.e. those with spins 11/2 and 13/2, which are listed by the Particle Data Group (PDG). The unknown parameters in the model, i.e., the hadronic coupling constants, were extracted by fitting the calculated observables to nearly 9000 experimental data points. The result of the model calculations is compared with those of previous investigations and experimental data. From the comparison we may conclude that the constructed model can nicely reproduce the experimental data.

1. Introduction

Kaon photoproduction is one of the well-studied reaction that includes the production of strange quark anti-quark pair. Theoretical studies have been conducted to better explain the results of experimental data to enrich our understanding of baryon structure. Based on the conservation of isospin, there are six possible channels of kaon photoproduction. Out of these possible channels, the γ + p → K⁺Λ process has the most abundant data points from multiple experimental collaborations and has been studied meticulously. However, the γ + n → K⁰Λ process has not been as well understood, due to the fact that the target in this reaction is neutron, instead of proton. The unstable nature of free neutron and its short lifetime, as well as the difficulty in detecting neutral kaons, contribute to the lack of experimental data for this process. In 2017, CLAS collaboration reported the first measurement for the K⁰Λ process through a deuteron target [1]. The measurement resulted in 361 data points of differential cross section with the energy ranging from 0.8 to 3.6 GeV. In addition, the A2 collaboration at MAMI also successfully measured the reaction in 2018, albeit with drastic difference in the energy range, only up to 1.85 GeV [2].

Theoretical models to investigate kaon photoproduction processes with Λ hyperon in the final state have been constructed and improved throughout the years. Our previous study has successfully constructed a theoretical model to simultaneously calculate the K⁺Λ and K⁰Λ processes and has included the recent CLAS and MAMI data. An isobar model was constructed in this study, with the inclusion of spin-7/2 and spin-9/2 nucleon resonances. The recent study comprised of three models, the first model (M1) was constructed with only the CLAS collaboration data, whereas the second model (M2) was constructed with only the MAMI data,
and the third model (M3) was constructed by including both the CLAS and MAMI data. The best result was obtained from the first model (M1) albeit the difference in the error of the three models was only by a small factor. This current isobar model has not yet considered the inclusion of spin-11/2 and spin-13/2 nucleon resonances, despite the fact that there are two established particles as tabulated by the Particle Data Group [3], and it is concluded in the previous works that the addition of spin-7/2 and spin-9/2 improved the model accuracy. In this paper, we shall extend the constructed isobar model for simultaneous calculation of the $K^+\Lambda$ and $K^0\Lambda$ processes to include nucleon resonances with higher spins.

2. Isobar Model

Over the years, there have been several theoretical models to explain kaon photoproduction. The most notable one is the isobar model, where the appropriate Feynman diagrams are used to derive the reaction scattering amplitude. Our present study follows our previous work [4] where $K^+\Lambda$ and $K^0\Lambda$ reactions have been calculated simultaneously with the covariant isobar model. In this study, we extend our model to include spin-11/2 and spin-13/2 nucleon resonances. The model consists of background terms, that is comprised of intermediate resonance particles on the t-channel and the u-channel, as well as non-resonance intermediate particles. In addition to the background terms, the resonance term includes all nucleon resonances with spins up to spin-13/2. The resonance properties are given in Table 1. The analytical calculation for high-spin resonances are considerably complicated in the isobar model in comparison with other models, such as the multipole approach. Furthermore, the inclusion of high-spin resonances leads to the inconsistent interaction problem. This problem has been overcome by Pascalutsa [5] and Vrancx [6], and we were able to adapt the prescription and construct the formalism for high-spin resonances in our previous work [7]. In this work, we investigate the improvement of the model with the inclusion of the spin-11/2 and spin-13/2 nucleon resonances. The model is fitted to around 9300 experimental data points, from which we were able to extract the background and resonance parameters. In the fitting process of the model, a numerical program is used to minimize the value of $\chi^2/N$, formulated as:

$$\frac{\chi^2}{N} = \frac{1}{N_{\text{data}} - N_{\text{par}}} \sum_{i=1}^{N_{\text{data}}} \left[ \frac{\sigma_i(\text{exp}) - \sigma_i(\text{theory})}{\delta\sigma_i} \right]^2.$$  (1)

Where $\sigma$ denotes an observable, $\delta\sigma$ denotes the corresponding error bar, $N_{\text{data}}$ denotes the total number of data, and $N_{\text{par}}$ is the number of parameters used in our analysis.

Table 1. Properties of nucleon resonances with spins-11/2 and 13/2 as tabulated by PDG [3].

| Resonance  | $J^P$  | Status | Mass (MeV) | Width (MeV) |
|------------|--------|--------|------------|-------------|
| $N(2600)$  | 11/2−  | ***    | 2600 ± 50  | 650 ± 150   |
| $N(2700)$  | 13/2+  | **     | 2612 ± 45  | 350 ± 50    |

3. Results and Discussion

The result of the fitting process is used to calculate observables which will be compared with our previous work and experimental data. The current model will be referred to as Model A, whereas our previous work is dubbed as Model B. The fitted parameters from both models are compared and displayed in Table 2. As seen from the comparison, the value of $\chi^2/N$ decreases slightly, meaning the inclusion of high-spin nucleon resonances improves the agreement of experimental
Table 2. Extracted coupling constants and parameters of the background terms, total number of data, and $\chi^2/N$ obtained from models A and B.

| Parameters | Model A | Model B |
|------------|---------|---------|
| $g_{KA}/\sqrt{4\pi}$ | -4.40 | -3.40 |
| $g_{K\Sigma N}/\sqrt{4\pi}$ | 0.90 | 1.30 |
| $G_{K^+}/4\pi$ | 0.22 | 0.18 |
| $G_{K^+}/4\pi$ | 0.45 | 0.17 |
| $G_{K^0}/4\pi$ | 0.54 | -0.16 |
| $\Lambda_B$(GeV) | 0.70 | 0.70 |
| $\Lambda_R$(GeV) | 1.17 | 1.10 |
| $\theta_{\text{had}}$(deg) | 68 | 90 |
| $\phi_{\text{had}}$(deg) | 90 | 8.0 |

- $\chi^2$ | 13784 | 14068 |
- $N_{\text{par}}$ | 264 | 247 |
- $N_{\text{data}}$ | 9424 | 9424 |
- $\chi^2/N$ | 1.50 | 1.53 |

data with the constructed model. We can infer from this result that the contributions of added nucleon resonances (i.e. spin-11/2 and spin-13/2) to the studied channel are not significant, but still need to be considered as it improves theoretical model with respect to experimental data.

In addition to the extracted parameters, the comparison of the two models can also be seen from the plot of the observables. The result from our current and previous analyses are shown in the following figures. As shown in Fig.1, Kaon-Maid cannot reproduce experimental data in the $W \geq 1.7$ GeV region. Both our previous works, Model B and PRD 96 [8] can nicely reproduce the experimental data. However, there are significant difference in the results of our current work, and the previous work in the second peak of the curve. At $W \approx 1.85$ GeV Model A displays the second peak, whereas in Model B the second peak is apparent in the energy region $W \approx 1.95$ GeV. The results from our current analysis shows more agreement with the results from PRD 96, where the $K^0\Lambda$ reaction was not included in the calculation, particularly in the second peak.

![Figure 1](image-url)
However, as apparent in Fig. 2, the agreement of our current work is slightly better in the backward region (cos $\theta = -0.70$), particularly in the energy region of $W \geq 2.1$ GeV. Higher-spin resonances have higher energy level, therefore it makes sense if the improvement in the model is found in higher energy region. We can confirm this with Fig.3, where we see at $W = 2.415$ GeV the constructed model is able to reproduce experimental data, in comparison with the lower energy level shown ($W = 1.635$ GeV), there is only slight improvement in Model A, and the agreement between models and experimental data are not satisfying.

![Figure 2](image1.png)

**Figure 2.** Energy distribution of the differential cross sections for the $\gamma p \rightarrow K^+ \Lambda$ process. Red solid curve denotes the results of current work, black dashed curve are results from previous work. Experimental data points shown are from CLAS 2006 (solid squares) [9], CLAS 2010 (open squares) [10], Crystal Ball 2014 (open circles) [11] and LEPS 2006 (solid triangles) [12].

![Figure 3](image2.png)

**Figure 3.** Angular distribution of the differential cross sections for the $\gamma p \rightarrow K^+ \Lambda$ process. Red solid curve denotes the results of current work, black dashed curve are results from previous work. Experimental data points shown are from CLAS 2006 (solid squares) [9], CLAS 2010 (open squares) [10], Crystal Ball 2014 (open circles) [11] and LEPS 2006 (solid triangles) [12].

For the $K^0 \Lambda$ reaction, Fig.4 shows that the agreement between data and the constructed models is rather poor. This is due to the fact that there are hardly any experimental data on this channel compared to the $K^+ \Lambda$ channel. Furthermore, as we can see from Fig.4, the data from MAMI collaboration are scattered compared to the data from CLAS g10 and CLAS g13 and ultimately will effect the quality of the model. Figure 4 displays the calculated total cross section of the $K^0 \Lambda$ reaction. As shown in the figure, the total cross section of model A is bigger than model B and experimental data. Model A, Model B and Kaon-Maid have significant difference of total cross section at $W \approx 1.6$ GeV energy region. However, it should be considered that at $W > 1.8$ GeV energy region, both Model A and B have similar trends. The experimental data included in the figure are from CLAS g10, CLAS g13 and MAMI 2018.

The energy distribution of the $K^0 \Lambda$ differential cross section are displayed in Figure 5, there are significant differences between models A and B in the energy level above 1.6 GeV. However,
Figure 4. Calculated cross section for the $\gamma n \to K^0\Lambda$ process.

Figure 5. Energy distribution of the differential cross sections for the $\gamma n \to K^0\Lambda$ process. Red solid curve denotes the results of current work, black dashed curve are results from previous work. Experimental data points shown are from CLAS g13 (solid squares) [1], CLAS g10 (solid circles)[1], MAMI 2018 (open circles)[2].

Figure 6. Angular distribution of the differential cross sections for the $\gamma n \to K^0\Lambda$ process. Red solid curve denotes the results of current work, black dashed curve are results from previous work. Experimental data points shown are from CLAS g13 (solid squares) [1], CLAS g10 (solid circles)[1], MAMI 2018 (open circles)[2].

in the energy level of $W \gtrsim 1.9$ GeV, the agreement between models A and B with experimental data appears to be improving. We can also observe this in Fig. 6, where close to $W = 2.342$ GeV both models A and B have significantly higher agreement with the experiment data whereas for the $W = 1.824$ GeV, the agreement of models A and B calculation and experimental data points is somewhat disappointing. This confirms that since the high-spin resonances have higher masses, the reactions that involve them will only occur at higher energies.
4. Conclusion
We have extended the isobar model for kaon photoproduction that includes spin-11/2 and spin-13/2 nucleon resonances which reproduces the $K^+\Lambda$ and $K^0\Lambda$ photoproduction data. We found that the inclusion of these high-spin resonances improve the agreement between the constructed model calculation with experimental data, as seen from the reduced value of $\chi^2/N$. In general, for both channels of the reaction, the addition of the nucleon resonances improves the model substantially at higher energies.

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