Nucleon Resonances in the Photoproduction $\gamma p \rightarrow K^{*+} \Lambda$

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The differential cross-section data from the CLAS Collaboration for $\gamma p \rightarrow K^{*+} \Lambda$ have been analyzed based on an effective Lagrangian approach. The t -channel K , κ , K^* exchanges, the s -channel N and near-threshold N^* 's exchanges, the u -channel Λ , Σ , $\Sigma^*(1385)$ exchanges, and the generalized contact term are considered in constructing the reaction amplitude. It is found that by including the $N(2060)5/2^-$ resonance, which is responsible for the shape of the angular distribution of $\gamma p \rightarrow K^{*+} \Lambda$ near the $K^* \Lambda$ threshold, and one of the $N(2000)5/2^+$, $N(2040)3/2^+$, $N(2100)1/2^+$, $N(2120)3/2^-$ and $N(2190)7/2^-$ resonances, one can describe the cross-section data for this reaction reasonably well. More experimental data on spin observables are needed to further pin down the resonance contents and associated resonance parameters in this reaction.

Keywords: ΛK^* photoproduction; effective Lagrangian approach; nucleon resonances.

1. Introduction

The study of excited nucleon states (N^* 's) is imperative to learn about the non-perturbative properties of QCD. Our current knowledge of most of the N^* 's is mainly coming from the analyses of πN scattering and π photoproduction off the nucleon. One of the problems with this situation is the so-called *missing resonance problem*¹ — the quark models predict many more resonances than those found in experiments.^{2,3,4} One possible explanation of this problem is that some N^* 's may couple weakly to πN but strongly to other channels. This motivates us to study N^* 's in channels other than πN .

In the present work⁵ we are interested in the $K^* \Lambda$ photoproduction reaction, as the $K^* \Lambda$ channel has the following advantages in investigating N^* 's: (1) it has a better chance than the πN channel to reveal resonances with sizable hidden $s\bar{s}$ content, (2) it is more suited than the π production reactions for investigating the high mass N^* 's, as the threshold of

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$K^*\Lambda$ is much higher than that of πN , and (3) it acts as an “isospin filter” isolating the N^* 's with isospin $I = 1/2$.

Experimentally, the first high-statistics cross section data for $\gamma p \rightarrow K^{*+}\Lambda$ were reported in 2013 by the CLAS Collaboration⁶. The differential cross section data clearly show some structures near the $K^{*+}\Lambda$ threshold which indicates some possible contribution from nucleon resonance(s).

Theoretically, the work of Ref. 7 presents a detailed theoretical analysis of the high-statistics differential cross section data reported by the CLAS Collaboration⁶. It describes the differential cross section data qualitatively well. Nevertheless, there is still some room for improvement near the $K^{*+}\Lambda$ threshold, where the nucleon resonances are relevant. Figure 1 illustrates this issue; there, a comparison of the differential cross sections from the calculation of Ref. 7 (blue dashed lines) with the CLAS data⁶ (scattered symbols) at some selected energies in the near-threshold region is shown. It is clearly seen from Fig. 1 that there is still some room for improvement in the differential cross section results of Ref. 7.

In this work⁵, we investigate the $\gamma p \rightarrow K^{*+}\Lambda$ reaction based on an effective Lagrangian approach in the tree-level approximation. We expect that a better description of the data for this reaction will allow for a more reliable extraction of the resonance content and their associated parameters.

2. Formalism

The full reaction amplitude for $\gamma N \rightarrow K^*\Lambda$ is expressed as

$$M^{\nu\mu} = M_s^{\nu\mu} + M_t^{\nu\mu} + M_u^{\nu\mu} + M_{\text{int}}^{\nu\mu}, \quad (1)$$

Fig. 1. (Color online) Status of theoretical description of the differential cross sections for $\gamma p \rightarrow K^{*+}\Lambda$ at selected energies in the near threshold region. The numbers in parentheses denote the photon laboratory incident energy (left number) and the total center-of-mass energy of the system (right number). The blue dashed lines represent the results from Ref. 7, and the black solid lines denote the results from model I of our present work which will be discussed later. The scattered symbols are the most recent data from CLAS Collaboration⁶.

with ν and μ being the Lorentz indices of K^* and γ , respectively. The terms $M_s^{\nu\mu}$, $M_t^{\nu\mu}$, and $M_u^{\nu\mu}$ stand for the s -, t -, and u -channel pole diagrams, respectively, and the term $M_{\text{int}}^{\nu\mu}$ stands for the interaction current which arises from the photon attaching to the internal structure of the $\Lambda N K^*$ interaction vertex. All four terms on the right-hand side of Eq. (1) are diagrammatically depicted in Fig. 2. The s -, t - and u -channel amplitudes, $M_s^{\nu\mu}$, $M_t^{\nu\mu}$, and $M_u^{\nu\mu}$, respectively, can be calculated straightforward by using an effective Lagrangian approach. The interaction current $M_{\text{int}}^{\nu\mu}$ is modeled by a generalized contact current following Refs. 8, 9, 10,

$$M_{\text{int}}^{\nu\mu} = \Gamma_{\Lambda N K^*}^{\nu}(q) C^{\mu} + M_{\text{KR}}^{\nu\mu} f_t. \quad (2)$$

Here $\Gamma_{\Lambda N K^*}^{\nu}(q)$ is the vertex function of $\Lambda N K^*$ coupling and $M_{\text{KR}}^{\nu\mu}$ is the Kroll-Ruderman term,

$$M_{\text{KR}}^{\nu\mu} = g_{\Lambda N K^*} \frac{\kappa_{\Lambda N K^*}}{2M_N} \sigma^{\nu\mu} Q_{K^*}, \quad (3)$$

with Q_{K^*} being the electric charge of K^* ; f_t in Eq. (2) is the phenomenological form factor attached to the amplitude of t -channel K^* -exchange; C^{μ} is an auxiliary current introduced to ensure that the full photoproduction amplitude of Eq. (1) satisfies the generalized WTI and thus is fully gauge invariant. Following Refs. ^{9,10}, we choose C^{μ} for $\gamma p \rightarrow K^{*+} \Lambda$ as

$$C^{\mu} = -Q_{K^*} \frac{f_t - \hat{F}}{t - q^2} (2q - k)^{\mu} - Q_N \frac{f_s - \hat{F}}{s - p^2} (2p + k)^{\mu}, \quad (4)$$

with

$$\hat{F} = 1 - \hat{h} (1 - f_s) (1 - f_t). \quad (5)$$

Here p , q , and k are 4-momenta of the incoming N , outgoing K^* and the incoming photon, respectively; Q_N is the electric charge of N ; f_s is the phenomenological form factor for s -channel N -exchange. $\hat{h}$ is taken to be 1 for the sake of simplicity.

The explicit expressions of the Lagrangians, propagators and form factors employed in this work can be found in Ref. 5.

Fig. 2. Generic structure of the K^* photoproduction amplitude for $\gamma N \rightarrow K^* \Lambda$. Time proceeds from left to right.

3. Results and discussion

The near threshold structures shown in the CLAS high statistic differential cross section data (cf. Fig. 1) for $\gamma p \rightarrow K^* \Lambda$ indicate there are contributions from possible N^* 's in this energy region. In the Particle Data Group (PDG) review¹¹, there are six N^* 's advocated near the $K^* \Lambda$ threshold, namely, $N(2000)5/2^+$, $N(2040)3/2^+$, $N(2060)5/2^-$, $N(2100)1/2^+$, $N(2120)3/2^-$, and $N(2190)7/2^-$. In our present work⁵, we introduce the nucleon resonances as few as possible to fit the data. We find that apart from the t -channel K , κ , K^* exchanges, the s -channel N exchange, the u -channel Λ , Σ , $\Sigma^*(1385)$ exchanges, and the generalized contact current, at least two N^* 's near the $K^* \Lambda$ threshold should be included in the s -channel in order to obtain a satisfactory description of the CLAS high-statistics differential cross section data. One is the $N(2060)5/2^-$ which is responsible for the shape of the angular distribution near the $K^* \Lambda$ threshold, and the other one could be one of the $N(2000)5/2^+$, $N(2040)3/2^+$, $N(2100)1/2^+$, $N(2120)3/2^-$ and $N(2190)7/2^-$ resonances. This results in five different fits which describes the CLAS high statistic differential and total cross section data quite well with similar fit qualities. The corresponding model parameters are listed in Table 1 and the resulted differential cross sections for $\gamma p \rightarrow K^* \Lambda$ are shown in Fig. 3.

It is seen from Table 1 that the fitted values of Λ_K , the cutoff parameter in the K -meson exchange contribution, are very close to each other in models I-V — they are all around 1.0 GeV. This value is determined mainly by the data in the high energy region, where the K

Table 1. Model parameters in five different fits. Here $\beta_{\Lambda K^*}$ is the branching ratio for resonance decay to ΛK^* , and $A_{1/2}$, $A_{3/2}$ (in $10^{-3} \text{ GeV}^{-1/2}$) are helicity amplitudes for resonance radiative decay to γp . For the definition of other parameters, see Ref. 5. The stars below resonance names denote the overall status of these resonances evaluated by PDG¹¹. The numbers in brackets below the resonance masses and widths represent the corresponding values estimated by PDG¹¹.

Model	I	II	III	IV	V
χ^2/N	1.35	1.79	1.85	2.09	2.18
$g_{\Sigma^* \Lambda \gamma}^{(1)}$	0.74 ± 0.16	-0.90 ± 0.17	-0.87 ± 0.14	-0.60 ± 0.18	-0.22 ± 0.16
Λ_K [MeV]	1000 ± 6	1019 ± 4	993 ± 7	1030 ± 3	1018 ± 4
N^* Name	$N(2060)5/2^-$ **	$N(2060)5/2^-$ **	$N(2060)5/2^-$ **	$N(2060)5/2^-$ **	$N(2060)5/2^-$ **
M_R [MeV]	2033 ± 2	2009 ± 5	2032 ± 3	2043 ± 4	2038 ± 3
Γ_R [MeV]	65 ± 4	213 ± 20	81 ± 8	202 ± 16	77 ± 8
Λ_R [MeV]	1188 ± 20	965 ± 16	1126 ± 12	889 ± 13	981 ± 22
$\sqrt{\beta_{\Lambda K^*}} A_{1/2}$	0.69 ± 0.06	0.03 ± 0.01	0.33 ± 0.03	0.60 ± 0.06	-0.21 ± 0.02
$\sqrt{\beta_{\Lambda K^*}} A_{3/2}$	-1.39 ± 0.13	-0.10 ± 0.01	-1.10 ± 0.10	-1.94 ± 0.19	-1.56 ± 0.15
N^* Name	$N(2000)5/2^+$ **	$N(2040)3/2^+$ *	$N(2120)3/2^-$ **	$N(2190)7/2^-$ ****	$N(2100)1/2^+$ *
M_R [MeV]	2115 ± 22	2200 ± 62	2203 ± 9 [≈ 2120]	2243 ± 6 [2100 ~ 2200]	2100 ± 15 [≈ 2100]
Γ_R [MeV]	450 ± 10	540 ± 7	433 ± 33	450 ± 33 [300 ~ 700]	450 ± 9
Λ_R [MeV]	1644 ± 21	1564 ± 36	1726 ± 58	936 ± 13	1431 ± 31
$\sqrt{\beta_{\Lambda K^*}} A_{1/2}$	-2.87 ± 0.81	3.12 ± 0.85	4.53 ± 0.38	5.21 ± 0.33	-7.22 ± 1.40
$\sqrt{\beta_{\Lambda K^*}} A_{3/2}$	-1.04 ± 0.29	7.87 ± 2.13	7.84 ± 0.65	3.71 ± 0.24	

meson exchange dominates the whole amplitude of this reaction. The fitted values of the mass of $N(2060)5/2^-$ from various models are also very close to each other, while those of its decay width are not. In each of the models I-V, the value of the fitted mass of the other resonance is compatible with that quoted in PDG¹¹.

It is seen from Fig. 3 that the overall description of the CLAS high-statistics angular distribution data is fairly satisfactory in all of the five models. In particular, the angular dependence of the differential cross sections near the ΛK^* threshold is qualitatively in good agreement with the data, much better than the description of Ref. 7 (cf. Fig. 1). This is because in all our models I-V, there is a significant contribution from the $N(2060)5/2^-$ resonance in the low energy region that is responsible for reproducing the observed shape of the angular distribution through an interference with the large K -meson exchange contribution near the ΛK^* threshold. In contrast, Ref. 7 has a rather small contribution of $N(2060)5/2^-$

Fig. 3. (Color online) Differential cross sections for $\gamma p \rightarrow K^{*+} \Lambda$ as a function of $\cos \theta$ in the center-of-mass frame from models I (black solid lines), II (green dash-double-dotted lines), III (black solid lines), IV (red dash-dotted lines) and V (cyan dotted lines). The scattered symbols denote the CLAS data⁶. The numbers in parentheses denote the centroid value of the photon laboratory incident energy (left number) and the corresponding total center-of-mass energy of the system (right number), in MeV.

and clear discrepancies are seen in its description of the near threshold differential cross section data (cf. Fig. 1). This consideration explains why the mass of $N(2060)5/2^-$ is fairly well constrained as can be seen from the resulting values in Table 1 for models I-V. For further detailed discussions about the individual contributions from various interaction dynamics in models I-V and the results of total cross sections, see Ref. 5.

4. Summary

The most recent data⁶ for $\gamma p \rightarrow K^{*+} \Lambda$ have been analyzed based on an effective Lagrangian approach. It is found that to obtain a satisfactory description of the data, *at least* two N^{*} 's should be included in the s -channel interaction diagrams, among which one is the $N(2060)5/2^-$ that is responsible for the shape of the angular distribution near $K^{*} \Lambda$ threshold via its interference with the t -channel K exchange, and the other one could be one of the $N(2000)5/2^+$, $N(2040)3/2^+$, $N(2100)1/2^+$, $N(2120)3/2^-$ and $N(2190)7/2^-$, respectively. More data on spin observables are needed to further pin down the resonance contents and the associated resonance parameters in this reaction.

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