The role of $N^*(2120)$ nucleon resonance in $K\Lambda(1520)$ photon and hadronic productions

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The associate $K\Lambda(1520)$ photon and hadronic production in the $\gamma p \to K^+\Lambda(1520)$, $pp \to pK^+\Lambda(1520)$ and $\pi^-p \to K^0\Lambda(1520)$ reactions are investigated within the effective Lagrangian approach and the isobar model. We are interested in the contribution from the $N^*(2120)$ (previously called $N^*(2080)$) resonance, which has a significant coupling to the $K\Lambda(1520)$ channel. The theoretical results show that the current experimental data for the $\gamma p \to K^+\Lambda(1520)$ reaction favor the existence of the $N^*(2120)$ resonance, and that these measurements can be used to further constrain its properties. We present results, including the $N^*(2120)$ contribution, for total cross sections of the $\gamma p \to K^+\Lambda(1520)$, $\pi^-p \to K^0\Lambda(1520)$, and $pp \to pK^+\Lambda(1520)$ reactions. For this latter one, we also calculate invariant mass and Dalitz plot distributions.

Keywords: $\Lambda(1520)$ production, Nucleon resonance $N^*(2120)$, Isobar model.

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1. Introduction

The investigation of the baryon spectrum and the baryon couplings from experimental data are two of the most important issues in hadronic physics and they are attracting much attention. Both on the experimental and theoretical sides, the nucleon excited states below 2.0 GeV have been extensively studied. However, the current information for the properties of states around or above 2.0 GeV is scarce. On the other hand in this region of energies, many theoretical approaches (constituent quark and chiral unitary) predict predicted missing $N^*$ states, which have not been so far observed. Hence, the study of the possible role played by the 2.0 GeV region nucleon resonances in the available accurate data is timely and could shed light into the complicated dynamics that governs the high excited nucleon spectrum.

The associate $K\Lambda(1520)$ photon and hadronic production reactions might be adequate to study the $N^*$ resonances around 2.0 GeV, as long as they have sig-
significant couplings to the $K\Lambda(1520)$ pair. This is because the $K\Lambda(1520)$ is a pure isospin 1/2 channel and the threshold is about 2.0 GeV. Besides, these reactions require the creation of an $ss$ quark pair. Thus, a thorough and dedicated study of the strangeness production mechanism in these reactions has the potential to gain a deeper understanding of the interaction among strange hadrons and also on the nature of the nucleon resonances.

Recently, there have been several measurements for the $\gamma p \to K^+\Lambda(1520)$ reaction \cite{8,9,10,11}. These data suggest that there is a sizeable contribution of total and differential cross sections from the nucleon resonances with masses around 2.0 GeV. On the theoretical side, in addition to the contributions from $K$ and $K^*$ exchange in the $t$–channel and the contact term, the contributions from the nucleon states, including the $N^*(2120)$, in the $s$–channel \cite{12,13,14,15,16} and the $\Lambda(1115)$ pole in the $u$–channel have been studied \cite{16}. The theoretical results show that when the contributions from the $N^*(2120)$ resonance and the $\Lambda(1115)$ are taken into account, the current experimental data \cite{8,9,11} can be well described. Thus, it is becoming clear that the current experimental data for $\Lambda(1520)$ photoproduction favor the existence of the $N^*(2120)$ resonance, and that these measurements can be used to further constrain its properties. On the other hand, based on the results of $\gamma p \to K^+\Lambda(1520)$ reaction, the $K\Lambda(1520)$ production in the $pp \to pK^+\Lambda(1520)$ and $\pi^-p \to K^0\Lambda(1520)$ hadronic processes are also studied, paying an special attention to the contributions from the $N^*(2120)$ resonance \cite{17}. In the present work, we will review the main results from these theoretical studies.

\section*{2. Study on $\gamma p \to K^+\Lambda(1520)$ reaction}

For the $\gamma p \to K^+\Lambda(1520)$ reaction, the differential cross section, in the center of mass frame (c.m.), and for unpolarized photon beam reads,

$$
\frac{d\sigma}{d(cos \theta_{c.m.})} = \frac{K_1^{c.m.} |p_1^{c.m.}|}{4\pi} \frac{M_N M_{\Lambda^*}}{(W^2 - M_N^2)^2} \sum_{s_p, s_{\Lambda^*}, \lambda} |T|^2,
$$

with $W$ the invariant mass of the $\gamma p$ pair. Besides, $K_1^{c.m.}$ and $p_1^{c.m.}$ are the photon and $K^+$ meson c.m. three-momenta, and $\theta_{c.m.}$ is the $K^+$ polar scattering angle.

The invariant scattering amplitudes are defined as

$$
-iT_i = \bar{u}_\mu(p_2, s_{\Lambda^*}) A_i^{\mu\nu} u(k_2, s_p) \epsilon_\nu(k_1, \lambda),
$$

where $u_\mu$ and $u$ are dimensionless Rarita-Schwinger and Dirac spinors for final $\Lambda(1520)$ and the initial proton, respectively, while $\epsilon_\nu(k_1, \lambda)$ is the photon polarization vector. Besides, $s_p$ and $s_{\Lambda^*}$ are the baryon polarization variables. The sub-index $i$ stands for the contact, $t$–channel $K^-$ exchange, contact, $s$–channel nucleon pole and $N^*$ resonance terms (depicted in Fig. 1 of Ref. \cite{13}) and the $u$–channel $\Lambda(1115)$ contribution (see Fig. 2 of Ref. \cite{16}).

In Fig. \ref{fig:1} the theoretical calculations of the differential cross section $d\sigma/d(cos \theta_{c.m.})$ as a function of the photon beam energy $E_\gamma$ are shown. These predic-
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Fig. 1. The $\gamma p \rightarrow K^+\Lambda(1520)$ differential $d\sigma/d(\cos \theta_{c.m.})$ cross sections at forward $K^+$ angles compared with the LEPS data. Dashed and dotted lines show the contributions from the background ($t-$channel $K^-$ exchange, $s-$channel nucleon pole, and contact term) and $N^*(2120)$ resonance terms, respectively, while the solid line displays the full result. For this latter curve we also show the statistical 68% confidence level (CL) band.

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Fig. 2. The $\gamma p \rightarrow K^+\Lambda(1520)$ differential cross section (left panel) and total cross section (right panel) as a function of the photon beam energy $E_\gamma$. Left panel: black-dash-dotted curves show the $u-$channel $\Lambda(1115)$ contribution, while the red-solid lines show the full contributions. Right panel: blue-dashed and green-dotted lines show the contributions from the background and $N^*(2120)$ resonance terms, respectively, while the red-solid line displays the results from the full model. In both panels, we display the 68% CL bands.

3. Study on $\pi^- p \rightarrow K^0\Lambda(1520)$ and $pp \rightarrow pK^+\Lambda(1520)$ reactions

Since the $N^*(2120)$ resonance played an important role in the $\gamma p \rightarrow K^+\Lambda(1520)$ reaction as discussed above, it may also have important contributions to the $\pi^- p \rightarrow K^0\Lambda(1520)$ and $pp \rightarrow pK^+\Lambda(1520)$ reactions, which has also been studied in Ref. [17].

For the $\pi^- p \rightarrow K^0\Lambda(1520)$ reaction, the differential cross section in the c.m. frame can be expressed as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s} \frac{|p^3_{\text{c.m.}}|}{|p_1^1_{\text{c.m.}}|} \left( \frac{1}{2} \sum_{s_{A^-} \neq p} |T|^2 \right).$$

In the equation above $\theta$ denotes the angle of the outgoing $K^0$ relative to beam direction in the c.m. frame, while $p^3_{\text{c.m.}}$ and $p_1^1_{\text{c.m.}}$ are the three-momenta of the initial $\pi^-$ and final $K^0$ mesons, respectively. The total invariant scattering amplitude $T$ is given by,

$$T = T_s + T_t + T_u + T_R,$$

(1)

where the contributions from the $s-$channel nucleon pole, $t-$channel $K^*$ exchange, $u-$channel $\Sigma^+$ and $s-$channel $N^*(2120)$ terms are considered.

With the parameters for the $N^*(2120)KA(1520)$ strong couplings that were obtained from the $\gamma p \rightarrow K^+\Lambda(1520)$ reaction, the role of the $N^*(2120)$ resonance in the $\pi^- p \rightarrow K^0\Lambda(1520)$ reaction has been investigated. Theoretical results for the total $\pi^- p \rightarrow K^0\Lambda(1520)$ cross section are shown in Fig. 3 and compared with the data taken from Ref. [18]. The solid lines represent the full results, while the contributions from the $s-$channel nucleon pole, $t-$channel $K^*$ exchange, $u-$channel
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$\Sigma^+$ and $s$–channel $N^*(2120)$ terms are shown by the dashed, dotted, dot-dashed, and dash-dot-dotted lines, respectively. We see that we can describe the experimental data of total cross sections quite well, while the $s$–channel nucleon pole and $N^*(2120)$ resonance and also the $u$–channel $\Sigma^+$ exchange give the dominant contributions below $\sqrt{s} = 2.4$ GeV. The $t$–channel $K^*$ exchange diagram gives a minor contribution.

For the $pp \to pK^+\Lambda(1520)$ reaction, the total cross section versus the beam momentum ($p_{\text{lab}}$) of the proton is calculated by using a Monte Carlo multi-particle phase space integration program. The results for beam momentum $p_{\text{lab}}$ from just above the production threshold 3.59 GeV to 5.0 GeV are shown in Fig. 4. The dashed, dotted, and dash-dotted lines stand for contributions from nucleon pole, $\Sigma^+$ pole and $N^*(2120)$ resonance, respectively. The total contribution is shown by the solid line. From Fig. 4 we mechanisms see that the contribution from the $u$–channel $\Sigma^+$ exchange is dominant very close to threshold, but, when the beam energy increases, the contributions from the $s$–channel nucleon pole and the $N^*(2120)$ resonance turn to be very important.

It is worth to note that our predictions for the total $pp \to pK^+\Lambda(1520)$ cross section, at $p_{\text{lab}} = 3.65$ GeV, is $0.01\mu$b, which is 20 times smaller than the experimental upper limit of $0.2\mu$b as measured by the COSY-ANKE Collaboration. This shows that our model predictions are consistent with the experimental results.
Moreover, the total cross section of the $pp \to pK^+\Lambda(1520)$ reaction has been also measured with HADES\cite{20} at GSI for a kinetic energy $T_p = 3.5$ GeV (corresponding to $p_{lab} = 4.34$ GeV). The result is $5.6 \pm 1.1 \pm 0.4_{-1.6}^{+1.1} \mu b$, as shown in Fig. 5, this is to be compared with our theoretical result, $11.5 \mu b$. However, if we modify the cut off parameters $\Lambda_\pi$ and $\Lambda_\pi^*$ from 1.3 GeV to 1.0 GeV, we get $\sigma = 5.45 \mu b$, which would be in agreement with the experimental data. However, it does not make sense to fit only one data point. So we still keep $\Lambda_\pi = \Lambda_\pi^* = 1.3$ GeV as used in many previous works\cite{21}. We should also mention that, in the present calculation, we did not include the $\Lambda(1520)p$ final-state-interaction (FSI), which can increase the results even by a factor of 10 at the very near threshold region, similarly to the important role played by $\Lambda p$ FSI in the $pp \to pK^+\Lambda$ reaction\cite{22}. We ignore this effect because there are no experimental data on this reaction and also very scarce information about the $\Lambda(1520)p$ FSI.

Furthermore, the corresponding momentum distributions of the final proton and $K^+$ meson, the $K\Lambda(1520)$ invariant mass spectrum, and also the Dalitz Plot for the $pp \to pK^+\Lambda(1520)$ reaction at beam momentum $p_{lab} = 3.67$ GeV, which is accessible for DISTO Collaboration\cite{24} are calculated and shown in Fig. 5(a), Fig. 5(b), Fig. 5(c), and Fig. 5(d), respectively. The dashed lines are just phase space distributions, while, the solid lines are full results from our model. From Fig. 5 we see that even at $p_{lab} = 3.67$ GeV, there is a clear bump in the $K\Lambda(1520)$ invariant mass distribution, which is produced by the contribution of the $N^*(2120)$ resonance.

Fig. 4. Total cross section vs proton beam momentum $p_{lab}$ for the $pp \to pK^+\Lambda(1520)$ reaction. The dashed, dotted, and dash-dotted lines stand for contributions from nucleon pole, $\Sigma^+$ pole and $N^*(2080)$ resonance, respectively. The total contribution is shown by the solid line.
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4. Summary

We have reviewed the role of $N^*(2120)$ resonance in the associate $K\Lambda(1520)$ photon and hadronic productions at low energies within an effective Lagrangian approach and the isobar model. In addition to the contact, $t$–channel $\bar{K}$ exchange, and $s$–channel nucleon pole contributions, the contributions from the $u$–channel $\Lambda(1115)$ hyperon pole term and $N^*(2120)$ resonance are also considered. The results show that when the contributions from the $N^*(2120)$ resonance and the $\Lambda(1115)$ are taken into account, both the new CLAS [11] and the previous LEPS data [8,9] for the $\gamma p \rightarrow K^+\Lambda(1520)$ reaction can be simultaneously described.

Actually, we find an overall good description of the data, both at forward and
backward $K^+$ angles, and for the whole range of measured $\gamma p$ invariant masses. The contribution of the $u -$channel $\Lambda(1115)$ pole term produces an enhancement at backward angles, and it becomes more and more relevant as the photon energy increases, becoming essential above $W \geq 2.35$ GeV and $\cos \theta_{c.m.} \leq -0.5$. On the other hand, the CLAS data, clearly support the existence of a spin-parity $J^P = 3/2^-$ nucleon resonance with a mass around 2.1 GeV, a width of at least 200 MeV and a large partial decay width into $\Lambda(1520) K$. These characteristics could be easily accommodated within the constituent quark model results of Simon Capstick and W. Roberts of Ref. 23. Such resonance might be identified with the two stars PDG $N^*(2120)$ state, which would confirm previous claims from the analysis of the bump structure in the LEPS differential cross section at forward $K^+$ angles discussed in Fig. 1.

On the other hand, motivated by the study of the $\gamma p \rightarrow K^+\Lambda(1520)$ reaction, the role of $N^*(2120)$ has also been investigated in the $\pi^- p \rightarrow K^+\Lambda(1520)$ and $pp \rightarrow pK^+\Lambda(1520)$ reactions. The results show that the contribution from the $u -$channel $\Sigma^+$ exchange is dominant in the very near threshold region, but, when the beam energy increases, the contributions from $s -$channel nucleon pole and $N^*(2120)$ resonance turn to be very important. Furthermore, the invariant mass distribution and the Dalitz Plot are also predicted which can be tested by the future experiments.

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