Role of the $N^*(2080)$ in $pp \rightarrow pK^+\Lambda(1520)$ and $\pi^-p \rightarrow K^0\Lambda(1520)$ reactions

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We investigate the $\Lambda(1520)$ hadronic production in the $pp \rightarrow pK^+\Lambda(1520)$ and $\pi^-p \rightarrow K^0\Lambda(1520)$ reactions within the effective Lagrangian method. For $\pi^-p \rightarrow K^0\Lambda(1520)$ reaction, in addition to the "background" contributions from $t$-channel $K^*$ exchange, $u$-channel $\Sigma^+$ exchange, and $s$-channel nucleon pole terms, we also consider the contribution from the nucleon resonance $N^*(2080)$ (spin-parity $J^P = 3/2^-$), which has significant coupling to $K\Lambda(1520)$ channel. We show that the inclusion of the $N^*(2080)$ leads to a fairly good description of the low energy experimental total cross section data of $\pi^-p \rightarrow K^0\Lambda(1520)$ reaction. From fitting to the experimental data, we get the $N^*(2080)N\pi$ coupling constant $g_{N^*(2080)N\pi} = 0.14 \pm 0.04$. By using this value and with the assumption that the excitation of $N^*(2080)$ is due to the $\pi^0$-meson exchanges, we calculate the total and differential cross sections of $pp \rightarrow pK^+\Lambda(1520)$ reaction. We also demonstrate that the invariant mass distribution and the Dalitz Plot provide direct information of the $\Lambda(1520)$ production, which can be tested by future experiments.

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I. INTRODUCTION

The study of hadron structure and the spectrum of hadron resonance is one of the most important issues in hadronic physics and is attracting much attention (see Ref. \textsuperscript{1} for a general review). In past decades, many excited states of baryon were observed and their properties have been measured \textsuperscript{2}. For those nucleon resonances with mass below 2 GeV, most of their parameters, such as mass, total decay width, decay modes, etc., have been more or less studied both on experimental and theoretical sides. However, for the states around or above 2 GeV, our present knowledge on them is still in its infancy \textsuperscript{2}. Moreover there are still many theoretical predictions of "missing $N^*$ states" around 2 GeV, which have not so far been observed \textsuperscript{3}. Since more number of effective degree of freedoms will induce more predicted number of excited states, the "missing $N^*$ states" problem is in favor of the diquark configuration which has less degree of freedom and predicts less $N^*$ states \textsuperscript{4}. So, studying the nucleon resonances around or above 2 GeV, not only on experimental side but also on theoretical side, is interesting and needed.

The associated strangeness production reaction, $pp \rightarrow pK^+\Lambda(1520)$, is interesting. Firstly, this reaction requires the creation of an $s\bar{s}$ quark pair. Thus, a thorough and dedicated study of strangeness production mechanism in this reaction has the potential to gain a deeper understanding of the interaction among strange hadrons and also on the nature of baryon resonances. Secondly, it is a good channel to study the $N^*$ resonances around 2.0 GeV which have significant couplings to $K\Lambda(1520)$ channel, because the $K\Lambda(1520)$ is a pure isospin 1/2 channel and the production threshold of $K\Lambda(1520)$ is about 2.0 GeV ($m_K + m_{\Lambda(1520)} \approx 2.0$ GeV). Thirdly, the near threshold differential and total cross sections for kaon pair production in the $pp \rightarrow pK^+K^-$ reaction have been measured by DISTO Collaboration \textsuperscript{5}, COSY-11 Collaboration \textsuperscript{6,7}, and COSY-ANKE Collaboration \textsuperscript{8–10}. These results show clear evidence for the excitation and decay of $\phi$ meson sitting on a smooth $K^+K^-$ background. For the non-$\phi$ kaon pair production, the role of the low energy $\Lambda$ excited state, $\Lambda(1405)$, have been studied in Refs. \textsuperscript{11–13} by using chiral unitary theory and in Ref. \textsuperscript{12} within an unified approach using an effective Lagrangian model. Since the $\Lambda(1405)$ state lies below $K^-p$ threshold, it is expected to give significant contribution at the energies near the reaction threshold. However, at higher energies, the next $\Lambda$ excited state, $\Lambda(1520)$, could be important for the non-$\phi$ kaon pair production in the $pp \rightarrow pK^+\Lambda(1520)$ reaction. Furthermore, the $pp \rightarrow pK^+\Lambda(1520)$ reaction is also the basic input for the $\Lambda(1520)$ production in the proton-nucleus reactions \textsuperscript{14}.

In Refs. \textsuperscript{15–17}, the contribution from a nucleon resonance with spin-parity $3/2^-$ and mass around 2.1 GeV was studied in the $\Lambda(1520)$ ($\equiv \Lambda^*$) photo- or electro-production processes. They all found that this nucleon resonance has a significant coupling to $K\Lambda(1520)$ channel and plays an important role in these reactions. Before the year of 2012, this nucleon resonance was filed for the year of 2012, this nucleon resonance was filed as $N^*(2120)$ \textsuperscript{2}. Even though, in order for convenience, here after, we still call it as $N^*(2080)$.

In the present work, we study the role of $N^*(2080)$ resonance ($\equiv N^*$) in the $pp \rightarrow pK^+\Lambda(1520)$ and $\pi^-p \rightarrow K^0\Lambda(1520)$ reactions.
method. Since the information about $N^*(2080)$ resonance is scarce \[2\] and the knowledge of its properties, like mass, total decay width, branch ratios, are poor, we take its mass and total decay width as 2115 MeV and 254 MeV, respectively, which are obtained by fitting them to the experimental data on the $\gamma p \to K^+\Lambda(1520)$ reaction in Ref. \[13\]. For the $N^*(2080)\Lambda\Lambda(1520)$ coupling constant, we also take the value that was obtained in our previous work \[15\]. Finally, from fitting to the experimental data of $\pi^- p \to K^0\Lambda(1520)$ reaction, we can get the $N^*(2080)N\pi$ coupling constant, then we study the role of $N^*(2080)$ resonance in the $pp \to pK^+\Lambda(1520)$ reaction with the assumption that the production mechanism is due to the $n^0$-meson exchange.

It will be helpful to mention that though the effective Lagrangian method is a convenient tool to catch the qualitative features of the reaction processes, it is not consistent with the unitary requirements, which in principle are important for extracting the parameters of the nucleon resonances from the analysis of the experimental data \[15\, 19\], especially for those reactions involving many intermediate coupled channels and three-particle final states \[20\, 21\]. In the present work, basing on phenomenological Lagrangians, we only consider the tree-diagram contributions, in which the unitarity condition is not ensured and coupled channel effects are not taken into account. However, our model can give a reasonable description of the experimental data in the considered energy region. Meanwhile, our calculation offers some important clues for the mechanisms of the $\pi^- p \to K^0\Lambda(1520)$ reaction and make a first effort to study the role of $N^*(2080)$ resonance in relevant reactions.

In the next section, we will give the formalism and ingredients in our calculation, then numerical results and discussions are given in Sect. III. A short summary is given in the last section.

II. FORMALISM AND INGREDIENTS

The combination of effective Lagrangian method and isobar model is an important theoretical approach in describing the various processes in resonance production region. In this section, we introduce the theoretical formalism and ingredients to calculate the $\Lambda(1520)$ hadronic production in $\pi^- p \to K^0\Lambda(1520)$ and $pp \to pK^+\Lambda(1520)$ reactions within the effective Lagrangian method.

A. Feynman diagrams and interaction Lagrangian densities

The basic tree level Feynman diagrams for the $\pi^- p \to K^0\Lambda(1520)$ and $pp \to pK^+\Lambda(1520)$ reactions are depicted in Fig. 1 and Fig. 2 respectively. For the $\pi^- p \to K^0\Lambda(1520)$ reaction, in addition to the "background" diagrams, such as $t$-channel $K^*$ exchange (Fig. 1(b)), $u$-channel $\Sigma^+$ exchange (Fig. 1(c)), and $s$-channel nucleon pole diagrams (Fig. 1(a)), we also consider the $s$-channel $N^*(2080)$ resonance excitation process (Fig. 1(a)). While for the $pp \to pK^+\Lambda(1520)$ reaction, the $t$-channel $K^*$ exchange process is neglected since its contribution is small, which will be discussed below. In Fig. 2 we show the tree-level Feynman diagrams for $pp \to pK^+\Lambda(1520)$ reaction. The diagram Fig. 2(a) and Fig. 2(c) show the direct processes, while Fig. 2(b) and Fig. 2(d) show the exchange processes.

\[\begin{align*}
\mathcal{L}_{\pi NN} &= ig_{\pi NN}\bar{N}\gamma_5\vec{\tau}\cdot \vec{n}N, \\
\mathcal{L}_{K\Lambda\Sigma^+} &= \frac{g_{K\Lambda\Sigma^+}}{m_K}\bar{\Lambda}\gamma_\mu(\partial_\mu K)\gamma_5 N + h.c., \\
\mathcal{L}_{\pi NN^*} &= \frac{g_{\pi NN^*}}{m_\pi}\bar{N}^s\gamma_5(\partial_\mu \vec{\tau}\cdot \vec{\pi})N + h.c., \\
\mathcal{L}_{K\Lambda^*\Sigma^+} &= \frac{g_{1}}{m_K}\bar{\Lambda}\gamma_5\gamma_\mu(\partial^\nu K)N^{s\nu} + \frac{ig_\omega}{m_K}\bar{\Lambda}\gamma_5(\partial^{\mu}\partial_\nu K)N^{s\nu} + h.c.,
\end{align*}\]

For the $\pi^- p \to K^0\Lambda(1520)$ reaction, to compute the contributions of those terms shown in Fig. 1 we use the interaction Lagrangian densities as in Refs. \[17\, 22\, 30\],

\[\begin{align*}
\mathcal{L}_{K^*\Lambda N^*} &= ig_{K^*\Lambda N^*}\bar{\Lambda}^s\mu K^*_\mu N + h.c., \\
\mathcal{L}_{K^*\Lambda\Sigma^+} &= g_{K^*\Lambda\Sigma^+}[\bar{K}(\partial^\mu \vec{\tau}\cdot \vec{n})\partial_\mu \bar{\Sigma} + (\partial^\mu K)\vec{\tau}\cdot \vec{\Sigma}K^*_\mu] + h.c.,
\end{align*}\]

for the $t$-channel $K^*$ exchange process, while

\[\begin{align*}
\mathcal{L}_{K\Lambda\Sigma} &= -ig_{K\Lambda\Sigma}\bar{N}\gamma_5 K\vec{\tau}\cdot \vec{\Sigma} + h.c., \\
\mathcal{L}_{2\Sigma\Lambda^*} &= \frac{g_{2\Sigma\Lambda^*}}{m_\pi}\bar{\Lambda}\gamma_5(\partial^{\mu}\partial_\nu \Sigma)N^{s\nu} + h.c.,
\end{align*}\]

for the $u$-channel $\Sigma^+$ exchange diagram. The above Lagrangian densities are also used to study the contributions of the terms shown in Fig. 2 for $pp \to pK^+\Lambda(1520)$ reaction.
It is worth to note that we use the Rarita-Schwinger formalism [31, 32] to describe the spin $J = \frac{3}{2}$ $\Lambda(1520)$ and $N^*(2080)$ resonances, while the $\Lambda(1520)$ and $N^*(2080)$ hadronic couplings will be discussed in the following section.

**B. Coupling constants and form factors**

Firstly, the coupling constant for $\pi NN$ vertex is taken to be $g_{\pi NN} = 13.45$, and the coupling constant $g_{KN\Sigma}$ is taken as 2.69 from SU(3) symmetry. While the $N^*(2080)|\Lambda(1520)$ coupling constants $g_{1,2}$ are taken as the values that we have obtained in Ref. [17], with the values $g_1 = 1.4$ and $g_2 = 5.5$. The $\Lambda^*NK^*$ vertex shown in Eq. (6) is predominantly $s$-wave, and the value of its coupling constant, $g_{K^*NK^*}$, is 0.5, which was obtained and used in Ref. [22] (see more details about the $\Lambda^*NK^*$ couplings in that reference).

Secondly, the coupling constants, $g_{\Lambda^*KN}, g_{K^*Kn},$ and $g_{\Lambda^*\pi\Sigma},$ are determined from the experimentally observed partial decay widths of the $K^* \rightarrow K\pi$, $\Lambda(1520) \rightarrow KN$, and $\Lambda(1520) \rightarrow \pi\Sigma$, respectively. With the effective interaction Lagrangians described by Eq. (2), Eq. (6), and Eq. (5), the partial decay widths $\Gamma_{\Lambda(1520) \rightarrow KN}$, $\Gamma_{K^* \rightarrow K\pi}$, and $\Gamma_{\Lambda(1520) \rightarrow \pi\Sigma}$, can be easily calculated. The coupling constants are related to the partial decay widths as,

\[
\Gamma_{\Lambda(1520) \rightarrow KN} = \frac{g_{\Lambda^*KN}^2 |\vec{p}_{KN}\rangle^2 m_N^3 (E_N - m_N)}{6\pi m_K^2 M_{\Lambda^*}}, \tag{9}
\]

\[
\Gamma_{K^* \rightarrow K\pi} = \frac{g_{K^*Kn}^2 |\vec{p}_{K\pi}\rangle^2 m_K^3}{2\pi m_{K^*}^2}, \tag{10}
\]

\[
\Gamma_{\Lambda(1520) \rightarrow \pi\Sigma} = \frac{g_{\Lambda^*\pi\Sigma}^2 |\vec{p}_{\pi\Sigma}\rangle^2 m_{\pi\Sigma}^3 (E_{\pi\Sigma} - m_{\pi\Sigma})}{4\pi m_{\Lambda^*}^2}, \tag{11}
\]

where

\[
E_{N/\Sigma} = \frac{M_{\Lambda^*}^2 + m_{N/\Sigma}^2 - m_{K/\pi}^2}{2M_{\Lambda^*}}, \tag{12}
\]

and

\[
|\vec{p}_{KN}\rangle = \sqrt{E_N^2 - m_N^2}, \quad |\vec{p}_{K\pi}\rangle = \sqrt{E_K^2 - m_K^2}, \tag{13}
\]

\[
|\vec{p}_{\pi\Sigma}\rangle = \sqrt{m_{K^*}^2 - (m_K + m_{K^*})^2,} \quad |\vec{p}_{\Lambda^*}\rangle = \frac{m_{\Lambda^*}^2 - m_{K^*}^2}{2m_K}. \tag{14}
\]

With mass ($M_{\Lambda^*} = 1519.5$ MeV, $m_{K^*} = 893.1$ MeV), total decay width ($\Gamma_{\Lambda^*} = 15.6$ MeV, $\Gamma_{K^*} = 49.3$ MeV), and decay branching ratios of $\Lambda(1520)$ [$\text{Br}(\Lambda^* \rightarrow K\pi) = 0.45 \pm 0.01$, $\text{Br}(\Lambda^* \rightarrow \pi\Sigma) = 0.42 \pm 0.01$] and $K^*$ [$\text{Br}(K^* \rightarrow K\pi) \sim 1$], we obtain these coupling constants as listed in Table I.

| Decays modes Adopted branching ratios $g_s^2/4\pi$ $^a$ |
|---------------|----------|----------|
| $\Lambda^* \rightarrow KN$ | 0.45 | 8.77 |
| $\Lambda^* \rightarrow \pi\Sigma$ | 0.42 | 0.02 |
| $K^* \rightarrow K\pi$ | 1.00 | 0.84 |

$^a$It should be stressed that the partial decay width determine only the square of the corresponding coupling constants as shown in Eqs. (6) (10) (14), thus their signs remain uncertain. Predictions from quark model can be used to constrain these signs. Unfortunately, quark model calculations for these vertices are still sparse. So, in the present calculation, we choose a positive sign for these results.

Finally, the strong coupling constant $g_{N^*N\pi}$ is a free parameter, which will be obtained by fitting it to the total cross sections of $\pi^- p \rightarrow K^0\Lambda(1520)$ and $pp \rightarrow pK^+\Lambda(1520)$ reactions. These have been estimated from the decay branching ratios quoted in the PDG book [2], though it should be noted that these are for all final charged states.

\[
f_i = \frac{\Lambda_{1s}^4}{\Lambda_{s}^4 + (q_i^2 - M_i^2)^2} \quad s = t, u, R \tag{15},
\]

with

\[
\begin{cases}
q_s = q_R = s, q_t = t, q_u = u, \\
M_s = m_N, M_R = M_{N^*}, \\
M_t = m_{\Sigma^+}, \\
M_u = m_{K^*}.
\end{cases} \tag{16}
\]

where $s$, $t$, and $u$ are the Lorentz-invariant Mandelstam variables. In the present calculation, $q_s = q_R = p_1 + p_2$, $q_t = p_1 - p_3$, and $q_u = p_4 - p_1$ are the 4-momentum of intermediate nucleon pole and $N^*(2080)$ in the $s$–channel, exchanged $K^*$ meson in the $t$–channel, and exchanged $\Sigma^+$ in the $u$–channel, respectively. While $p_1$, $p_2$, $p_3$ and $p_4$ are the 4-momenta for $\pi$, $p$, $K^0$ and $\Lambda(1520)$, respectively. Besides, we will consider different cut-off values.
for the background and resonant terms, i.e. \( \Lambda_s = \Lambda_t = \Lambda_u \neq \Lambda_R \).

For \( pp \rightarrow pK^+\Lambda(1520) \) reaction, we also need the relevant off-shell form factors for \( \pi NN \) and \( \pi NN^* \) vertexes. We take them as

\[
F^{NN}_\pi(k_\pi^2) = \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - k_\pi^2}, \tag{17}
\]

\[
F^{NN^*}_\pi(k_\pi^2) = \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - k_\pi^2}, \tag{18}
\]

with \( k_\pi \) the 4-momentum of the exchanged \( \pi \) meson. The cutoff parameters are taken as \( \Lambda_\pi = \Lambda_\pi^* = 1.3 \text{ GeV} \) as used in Ref. \[34\].

C. Scattering amplitudes

For the \( \pi^- p \rightarrow K^0\Lambda(1520) \) reaction, with the effective interaction Lagrangian densities given above, we can easily construct the invariant scattering amplitudes,

\[
-\imath T_i = \bar{u}_\mu(p_4, s_{A'}) A^\mu_i(p_2, s_p), \tag{19}
\]

where \( u_\mu \) and \( u \) are dimensionless Rarita-Schwinger and Dirac spinors, respectively, while \( s_{A'} \) and \( s_p \) are the spin polarization variables for final \( \Lambda(1520) \) resonance and initial proton, respectively. To get the scattering amplitude, we also need the propagators for nucleon and \( N^*(2080) \), \( K^+ \) meson, and \( \Sigma^+ \) baryon,

\[
G_N(q_s) = \frac{\imath}{q_s + m_N}, \tag{20}
\]

\[
G^{\mu\nu}_K(q_t) = \frac{-g^{\mu\nu} + q_t^\mu q_t^\nu}{t - m_K^2}, \tag{21}
\]

\[
G_\Sigma(q_u) = \frac{\imath}{q_u + m_\Sigma}, \tag{22}
\]

\[
G^{\mu\nu}_N(q_R) = \frac{\imath}{q_R + M_N^*} \frac{s - M_N^*}{s - M_N^* + iM_N^* - \Gamma_N}, p^{\mu\nu}, \tag{23}
\]

and

\[
P^{\mu\nu} = -g^{\mu\nu} + \frac{1}{3} \gamma^\mu \gamma^\nu + \frac{2}{3M_N^*} q_R^{\mu} q_R^{\nu} + \frac{1}{3M_N^*} (\gamma^\mu q_R^{\nu} - \gamma^\nu q_R^{\mu}), \tag{24}
\]

where \( M_{N^*} \) and \( \Gamma_N \) are the mass and the total decay width of the \( N^* \) resonance.

Then, the reduced \( A^\mu_i \) amplitudes in Eq. (19) can be easily obtained,

\[
A^\mu_s = -\imath \sqrt[2]{g_{\pi NN^*} g_{NN^*}} \left( \frac{q_s - m_n}{m_K^2 - m_n^2} \right) \gamma_5 p_S^\mu f_s, \tag{25}
\]

\[
A^\mu_t = -\imath \sqrt[2]{g_{\pi NN^*} g_{NN^*}} \left( \frac{p_t^\mu + p_S^\mu}{t - m_K^2} \right) - \frac{m_\pi^2 - m_n^2}{m_K^2} q_t^\mu f_t, \tag{26}
\]

\[
A^\mu_u = -\imath \sqrt[2]{g_{\pi NN^*} g_{NN^*}} \left( \frac{q_u - m_{\Sigma^*}^+}{u - m_{\Sigma^*}^+} \right) p_u^\mu f_u, \tag{27}
\]

\[
A^\mu_R = \imath \sqrt[2]{g_{\pi NN^*} g_{NN^*}} \left( \frac{q_R - m_{\Sigma^*}}{m_K m_{NN^*}^0} \right) \left[ g_1 \gamma_5 (q_R - m_{NN^*}) \left( p_t^\mu - \frac{1}{3} \gamma^\mu p_1 + \frac{1}{3M_{NN^*}} (\gamma^\mu q_R \cdot p_1 - q_R^\mu p_1) + \frac{g_2}{m_K} (q_R - m_{NN^*}) p_5^\mu (p_1 \cdot p_3 - \frac{1}{3} p_3^\mu p_1 + \frac{1}{3} (p_3 q_R \cdot p_1 - q_R \cdot p_3 p_1) - \frac{2}{3M_{NN^*}} q_R \cdot p_S q_R \cdot p_1 \right) f_R, \tag{28}
\]

with the sub-indices \( s, t, u \) and \( R \) stand for the \( s \)-channel nucleon pole, \( t \)-channel \( K^+ \) exchange, \( u \)-channel \( \Sigma^+ \) exchange, and resonance \( N^*(2080) \) terms.

For the \( pp \rightarrow pK^+\Lambda \) reaction, the full invariant amplitude in our calculation is composed of four parts corresponding to the \( s \)-channel nucleon pole and \( N^*(2080) \) resonance, \( t \)-channel \( K^+ \), and \( u \)-channel \( \Sigma^+ \), which are produced by the \( \pi^0 \)-meson exchanges, respectively,

\[
\mathcal{M} = \sum_{i=s, t, u, R} \mathcal{M}_i. \tag{29}
\]

Each of the above amplitudes can be obtained straightforwardly with the effective couplings and following the Feynman rules. Here we give explicitly the amplitude \( \mathcal{M}_s \), as an example,

\[
\mathcal{M}_s = \sqrt[2]{g_{\pi NN^*} g_{NN^*}} \mathcal{F}^{NN}_\pi(\mu)^* \mathcal{F}^{NN^*}_\pi(\nu) \mathcal{F}^{NN^*}_\pi(q_s^2) G_N(k_{\pi}^2) \times
\]

\[
\bar{u}_\mu(p_4, s_{A'}) p_5^\mu \gamma_5 G_N(q_N) u(p_1, s_1) \bar{u}(p_3, s_3) \gamma_5 u(p_2, s_2) + \text{exchange term with } p_1 \leftrightarrow p_2, \tag{30}
\]

where \( s_i \) (\( i = 1, 2, 3 \)) and \( p_i \) (\( i = 1, 2, 3 \)) represent the spin projection and 4-momenta of the two initial and one final protons, respectively. While \( p_4 \) and \( p_5 \) are the 4-momenta of the final \( \Lambda(1520) \) and \( K^+ \) meson, respectively. And \( s_4 \) stands the spin projection of \( \Lambda(1520) \). In Eq. (30), \( k_{\pi} = p_2 - p_3 \) and \( q_N = p_1 + p_3 \) stand for the 4-momenta of the exchanged \( \pi \) meson and intermediate nucleon. And \( G_{s}(k_{\pi}) \) is the pion meson propagator,

\[
G_s(k_{\pi}) = \frac{i}{k_{\pi}^2 - m_{\pi}^2}. \tag{31}
\]
D. Cross sections for $\pi^- p \to K^0 \Lambda(1520)$ reaction

The differential cross section for $\pi^- p \to K^0 \Lambda(1520)$ reaction at center of mass (c.m.) frame can be expressed as

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s} \left| \frac{\vec{p}_3^{c.m.}}{\vec{p}_1^{c.m.}} \right| \left( \frac{1}{2} \sum_{s_{\Lambda^*}, s_p} |T|^2 \right), \quad (32)$$

where $\theta$ denotes the angle of the outgoing $K^0$ relative to beam direction in the (c.m.) frame, while $\vec{p}_{1,3}^{c.m.}$ are the 3-momentum of the initial $\pi^-$ and final $K^0$ mesons. The total invariant scattering amplitude $T$ is given by,

$$T = T_s + T_t + T_u + T_R. \quad (33)$$

From the amplitude, we can easily obtain the total cross sections of the $\pi^- p \to K^0 \Lambda(1520)$ reaction as functions of the invariant mass of $\pi^- p$ system. We perform three parameter $(g_{N^* N\pi}, \Lambda_s = \Lambda_t = \Lambda_u$ and $\Lambda_R)$ $\chi^2$-fits to the experimental data [37] on total cross sections for $\pi^- p \to K^0 \Lambda(1520)$ reaction. There is a total of 12 data points below $\sqrt{s} = 3.1$ GeV.

![Figure 3](image_url)

**FIG. 3:** Total cross sections vs the invariant mass $s^{1/2}$ for $\pi^- p \to K^0 \Lambda(1520)$ reaction. The experimental data are from Ref. [37]. The curves are the contributions from $s-$channel nucleon pole term (dashed), $t-$channel $K^*$ term (dotted), $u-$channel $\Sigma^*$ term (dash-dotted), $s-$channel $N^*(2080)$ term (dash-dot-dotted) and the total contributions of them (solid).

The fitted parameters are: $g_{N^* N\pi} = 0.14 \pm 0.04, \Lambda_s = \Lambda_t = \Lambda_u = 0.89 \pm 0.05$ and $\Lambda_R = 0.91 \pm 0.03$. The resultant $\chi^2$/dof is 1.1. The best fitting results for the total cross sections are shown in Fig. 3 comparing with the data. The solid lines represent the full results, while the contributions from the $s-$channel nucleon pole, $t-$channel $K^*$ exchange, $u-$channel $\Sigma^*$ and $s-$channel $N^*(2080)$ terms are shown by the dashed, dotted, dot-dashed, and dash-dot-dotted lines, respectively. From Fig. 3 one can see that we can describe the experimental data of total cross sections quite well, while the $s-$channel nucleon pole and $N^*(2080)$ 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 the minor contribution.

![Figure 4](image_url)

**FIG. 4:** Differential cross sections for $\pi^- p \to K^0 \Lambda(1520)$ reaction. The curves are the contributions from $s-$channel nucleon pole term (dashed), $t-$channel $K^*$ term (dotted), $u-$channel $\Sigma^*$ term (dash-dotted), $s-$channel $N^*(2080)$ term (dash-dot-dotted) and the total contributions of them (solid).
With the above fitted parameters, the corresponding calculation results for the differential cross sections for the reaction $\pi^- p \rightarrow K^0 \Lambda(1520)$ at the energy around the central mass of $N^*(2080)$ resonance, $\sqrt{s} = 2.05$ GeV, $\sqrt{s} = 2.10$ GeV, and $\sqrt{s} = 2.15$ GeV, are shown in Fig. 4(a), Fig. 4(b), and Fig. 4(c), respectively. These predictions can be checked by the future experiments.

Besides, with the strong coupling constant, $g_{N\pi}$, which was obtained from the $\chi^2$-fits, we have evaluated the $N^*(2080)$ resonance to $N\pi$ partial decay width,

$$\Gamma_{N^* \rightarrow N\pi} = \frac{g_{N\pi}^2}{4\pi} \frac{|\vec{p}_{N\pi}^c|}{m_{N^*}^2 M_{N^*}} (E_N - m_N),$$

(34)

as deduced from the Lagrangian density of Eq. (3). In the above expression,

$$E_N = \frac{M_{N^*}^2 + m_{N^*}^2 - m_N^2}{2M_{N^*}},$$

(35)

$$|\vec{p}_{N\pi}^c| = \sqrt{E_N^2 - m_N^2}.$$  

(36)

With the values of $M_{N^*} = 2115$ MeV, $\Gamma_{N^*} = 254$ MeV, and also $g_{N\pi N} = 0.14 \pm 0.04$, we can get

$$\text{Br}(N^* \rightarrow N\pi) = \frac{\Gamma_{N^* \rightarrow N\pi}}{\Gamma_{N^*}} = (2.9 \pm 1.6)\%,$$

(37)

with the error from the uncertainty of the coupling constant $g_{N\pi N}$. The above value is consistent with the result ($6 \pm 2)\%$ that was obtained from the multichannel analysis [38].

### III. NUMERICAL RESULTS FOR $pp \rightarrow pK^+\Lambda(1520)$ REACTION AND DISCUSSIONS

With the formalism and ingredients given above, the calculations of the differential and total cross sections for $pp \rightarrow pK^+\Lambda(1520)$ are straightforward,

$$d\sigma(pp \rightarrow pK^+\Lambda(1520)) = \frac{1}{4} \frac{m_p^4}{E_3} \sum_{s_1,s_2} \sum_{s_3,s_4} |\mathcal{M}|^2 \times$$

$$m_p d^3p_3 m_{\Lambda(1520)} d^3p_4 d^3p_5 \frac{1}{2E_5} \delta^4(p_1 + p_2 - p_3 - p_4 - p_5),$$

(38)

with the flux factor

$$F = (2\pi)^5 \sqrt{(p_1 \cdot p_2)^2 - m_p^4}.$$  

(39)

The total cross section versus the beam energy $(p_{\text{lab}})$ of the proton for the $pp \rightarrow pK^+\Lambda(1520)$ reaction is calculated by using a Monte Carlo multi-particle phase space integration program. The results for beam energies $p_{\text{lab}}$ from just above the production threshold $3.59$ GeV to $5.0$ GeV are shown in Fig. 5. The dashed, dotted, and dash-dotted lines stand for contributions from nucleon pole, $\Sigma^+$ pole and $N^*(2080)$ resonance, respectively. Their total contributions are shown by the solid line. The one experimental data point is taken from Ref. [40].

**FIG. 5:** Total cross sections vs beam energy $p_{\text{lab}}$ of proton for the $pp \rightarrow pK^+\Lambda(1520)$ reaction from present calculation. The dashed, dotted, and dash-dotted lines stand for contributions from nucleon pole, $\Sigma^+$ pole and $N^*(2080)$ resonance, respectively. Their total contribution are shown by the solid line. The one experimental data point is taken from Ref. [40].

It is important to note that our predictions for the total cross section of $pp \rightarrow pK^+\Lambda(1520)$ reaction, at $p_{\text{lab}} = 3.65$ GeV, is $0.01 \mu b$, which is the upper limit, $0.2 \mu b$ as measured by the COSY-ANKE Collaboration [39]. This shows that our model predictions are consistent with the experimental results. Moreover, the total cross section of $pp \rightarrow pK^+\Lambda(1520)$ reaction is measured with HADES [40] at GSI at kinetic beam energy $T_p = 3.5$ GeV, in agreement with our theoretical result, $11.5 \mu b$. 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 is in agreement with the experimental data well. However, it does not make sense to fit the only one data point. So we still keep $\Lambda_\pi = \Lambda_\pi^* = 1.3$ GeV as used in many previous works [39]. We should also mention that, in the present calculation, we did not include the $t$-channel $K^*$ meson exchange gives very small contribution to the $\pi^- p \rightarrow K^0\Lambda(1520)$ reaction, especially for the invariant mass of $\Lambda(1520)$ below $2.4$ GeV, so in the calculation for $pp \rightarrow pK^+\Lambda(1520)$ reaction, we ignore its contribution.

1. Since the $t$-channel $K^*$ meson exchange gives very small contribution to the $\pi^- p \rightarrow K^0\Lambda(1520)$ reaction, especially for the invariant mass of $\Lambda(1520)$ below $2.4$ GeV, so in the calculation for $pp \rightarrow pK^+\Lambda(1520)$ reaction, we ignore its contribution.

2. $p_{\text{lab}} = \sqrt{E_{\text{lab}}^2 - m_p^2} = \sqrt{(T_p + m_p)^2 - m_p^2}$. 


\(\Lambda(1520)p\) final-state-interaction (FSI), which can increase the results even by a factor of 10 at the very near threshold region, such as the important role played by \(\Lambda p\) FSI in the \(pp \rightarrow pK^+\Lambda(1520)\) reaction \(\text{[39]}\). This is because there are no experimental data on this reaction and also very scarce information about the \(\Lambda(1520)p\) FSI.

Furthermore, the corresponding momentum distribution of the final proton and \(K^+\) meson, the \(K\Lambda(1520)\) invariant mass spectrum, and also the Dalitz Plot for the \(pp \rightarrow pK^+\Lambda(1520)\) reaction at beam momentum \(p_{\text{lab}} = 3.67\) GeV, which is accessible for DISTO Collaboration \(\text{[5]}\), are calculated and shown in Fig. 6(a), Fig. 6(b), Fig. 6(c), and Fig. 6(d), respectively. The dashed lines are pure phase space distributions, while, the solid lines are full results from our model. From Fig. 6, we can see that even at \(p_{\text{lab}} = 3.67\) GeV, there is a clear bump in the \(K\Lambda(1520)\) invariant mass distribution, which is produced by including the contribution from \(N^*(2080)\) resonance.

At the energy point of beam momentum \(p_{\text{lab}} = 3.67\) GeV, the contribution from \(u\)-channel \(\Sigma^+\) exchange is still dominant, so, for comparing, we also present our calculated differential distributions at \(p_{\text{lab}} = 4.34\) GeV where the contribution from the \(s\)-channel nucleon pole and \(N^*(2080)\) resonance is dominant. Our results are shown in Fig. 7. We can see that our model results for the momentum distribution of final proton are much different from the phase space distribution.

The momentum distribution, invariant mass spectra

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\(^3\) It is worth to note that our results are calculated in the reaction laboratory frame, in which the target proton is at rest.
and the Dalitz plots in Figs. 6 and 7 show direct information about the \( pp \rightarrow pK^+\Lambda(1520) \) reaction mechanism and may be tested by the future experiments.

**IV. SUMMARY**

In this paper, the \( \Lambda(1520) \) hadronic production in proton-proton and \( \pi^- p \) collisions are studied within the combination of the effective Lagrangian approach and the isobar model. For \( \pi^- p \rightarrow K^0\Lambda(1520) \) reaction, in addition to the "background" contributions from \( t^- \)–channel \( K^* \) exchange, \( u^- \)–channel \( \Sigma^+ \) exchange, and \( s^- \)–channel nucleon pole terms, we also considered the contribution from the nucleon resonance \( N^*(2080) \) (spin-parity \( J^P = 3/2^- \)), which has significant coupling to \( K\Lambda(1520) \) channel. We show that the inclusion of the nucleon resonance \( N^*(2080) \) leads to a fairly good description of the low energy experimental total cross section data of \( \pi^- p \rightarrow K^0\Lambda(1520) \) reaction. The \( s^- \)–channel nucleon pole and \( N^*(2080) \) resonance and also the \( u^- \)–channel \( \Sigma^+ \) exchange give the dominant contributions below invariant mass \( \sqrt{s} = 2.4 \) GeV, while the \( t^- \)–channel \( K^* \) exchange diagram gives the minor contribution.

From \( \chi^2 \)–fits to the available experimental data for the \( \pi^- p \rightarrow K^0\Lambda(1520) \) reaction, we get the \( g_{N^*(2080)N\pi} = 0.14 \pm 0.04 \), which gives the branching ration of \( N^*(2080) \) resonance to \( N\pi \) as \( (2.9 \pm 1.6)\% \). Our result is consistent with the previous work. Besides, the corresponding predictions for the differential cross sections of \( \pi^- p \rightarrow K^0\Lambda(1520) \) are also shown, by which the future experiments can check our model.

Basing on the study of \( \pi^- p \rightarrow pK^+\Lambda(1520) \) reaction, we study the \( pp \rightarrow pK^+\Lambda(1520) \) reaction with the assumption that the production mechanism is due to the \( \pi^0 \)–meson exchanges. We give our predictions about total cross sections of this reaction. Our results show that the contribution from the \( u^- \)–channel \( \Sigma^+ \) exchange is predominant at the very near threshold region, but,
when the beam energy goes up, the contributions from \(s\)-channel nucleon pole and \(N^*(2080)\) resonance turn to be very important. Furthermore, we also demonstrate that the invariant mass distribution and the Dalitz Plot provide direct information of the \(pp \to pK^+\Lambda(1520)\) reaction mechanisms and may be tested by the future experiments.

Finally, we would like to stress that due to the important role played by the resonant contribution in the \(\pi^- p \to K^0\Lambda(1520)\) and \(pp \to pK^+\Lambda(1520)\) reactions, accurate data for these reactions can be used to improve our knowledge on the \(N^*(2080)\) properties, which are at present poorly known. This work constitutes a first step in this direction.

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