\( \Xi(1690)^- \) resonance production via \( K^- p \to K^+ K^- \Lambda \)

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In this talk, we investigate \( \Xi(1690)^- \) production from the \( K^- p \to K^+ K^- \Lambda \) reaction with the effective Lagrangian method and consider the \( s \)- and \( u \)-channel \( \Sigma/\Lambda \) ground states and resonances for the \( \Xi \)-pole contributions, in addition to the \( s \)-channel \( \Lambda \), \( u \)-channel nucleon pole, and \( t \)-channel \( K^- \) exchange for the \( \phi \)-pole contributions. The \( \Xi \)-pole includes \( \Xi(1320), \Xi(1535), \Xi(1690)(J^P = 1/2^-) \), and \( \Xi(1820)(J^P = 3/2^-) \). We compute the Dalitz plot density of \( \frac{d^2\sigma}{dM_{K^-}dM_{K^-}} \) at 4.2 GeV/c and the total cross sections for the \( K^- p \to K^+ K^- \Lambda \). Employing the parameters from the fit, we present the cross sections for the two-body \( K^- p \to K^+ \Xi(1690)^- \) reaction near the threshold. We also demonstrate that the Dalitz plot analysis for \( p_K^- = 1.915 \sim 2.065 \text{ GeV/c} \) makes us to explore direct information for \( \Xi(1690)^- \) production, which can be done by future \( K^- \) beam experiments.

**KEYWORDS:** Strangeness \( S = -2 \), \( \Xi(1690) \), kaon beam, Dalitz process.

1. Introduction

\( S = -2 \) three-star baryon states include \( \Xi(1690)^- \), \( \Xi(1820)(J^P = 3/2^-) \), \( \Xi(1500) \), and \( \Xi(2030) \). The third state of \( \Xi \) has not yet been confirmed between \( \Xi(1620) \) and \( \Xi(1690)^- \) \([2–8]\). \( \Xi(1690)^- \) is near the \( \Sigma K \) threshold, and its existence has been firmly established by several experiments \([9–12]\). Recently, the Babar Collaboration \([13]\) reported that \( J = 1/2 \) assignment was favored for \( \Xi(1690)^- \) from its decay angular distribution. The \( \Xi(1690)^0 \) was reconstructed from \( \Lambda K^0_S \) in the \( \Lambda^+_c \to \Lambda K^0_S K^+ \) decay. Nevertheless, its spin and parity have not yet been clearly determined.

Experimentally, \( \Lambda^+_c \to \Lambda K^0_S K^+ \) is particularly attractive, as high-statistics data are available from Belle/Belle-II and LHCb Collaborations. Nonetheless, the interference between \( \Xi(1690)^- \) and \( a_0(980) \) appears with a fixed crossing location in the phase space. The phase in the interference between the two resonances could change the spin analysis result. Hence, it is necessary to carry out an \( \Xi(1690)^- \) production experiment using the \( (K^-, K^+) \) reaction near the threshold. \( \Xi(1690)^- \) is produced in the \( (K^-, K^+) \) reaction and decays to \( \Lambda K^- \). In the \( K^- p \to K^+ K^- \Lambda \) reaction, the \( \phi(1020) \to K^+ K^- \) amplitude could interfere with the \( \Xi(1690)^- \) production amplitude. However, the \( \phi(1020) \) resonance is very narrow, so it can readily be isolated from the \( \Xi(1690)^- \) resonance. Moreover, the relative location of the interference region can change with the \( K^- \) beam momentum.

In this talk, we provide numerical calculation results for the production of \( \Xi(1690)^- \) from the \( K^- p \to K^+ K^- \Lambda \) reaction within the effective Lagrangian approach. We calculate the total and differential cross sections for the \( K^- p \to \Xi(1690)^- K^+ \) reaction in a beam momentum range from 2.1 GeV/c to 2.3 GeV/c. We also demonstrate that the Dalitz plot analysis of the \( K^- p \to K^+ K^- \Lambda \) reaction enables us to access direct information concerning the \( \Xi(1690)^- \) production. The details of the present talk can be found in Ref. \([14]\).
2. Theoretical framework

For the $K^- p \to K^+ K^- \Lambda$ reaction, the $s$- and $u$-channel diagrams are taken into account for the $\Xi$ production. Four $\Lambda$ states ($\Lambda(1116)(J^P = 1/2^+)$, $\Lambda(1405)(J^P = 1/2^-)$, $\Lambda(1520)(J^P = 3/2^-)$, and $\Lambda(1670)(J^P = 1/2^-)$) and two $\Sigma$ states ($\Sigma(1192)(J^P = 1/2^+)$ and $\Sigma(1385)(J^P = 3/2^+)$) are included in the present calculation for $s$- and $u$-channel contributions. For the $\Xi$ production, four $\Xi$ states ($\Xi(1322)(J^P = 1/2^+)$, $\Xi(1532)(J^P = 3/2^+)$, $\Xi(1690)(J^P = 1/2^-)$, and $\Xi(1820)(J^P = 3/2^-)$) are considered for the $\Lambda K^-$ decay channel. The relevant Feynman diagrams are depicted in Fig. 1.

Here, we assume that the $\Xi(1690)^-$ has a spin-parity of $J^P = 1/2^-$, as suggested by theoretical works [5, 8] and reported by the BaBar Collaboration [13]. To compute the invariant amplitudes for the $K^- p \to K^+ K^- \Lambda$ reaction, we use the effective Lagrangian densities for the interaction vertices as follows:

\[
\mathcal{L}_{\text{KBB}} = -ig_{\text{MBB}}(\overline{B}\Gamma)(\gamma_5 K)(\Gamma B),
\]

\[
\mathcal{L}_{\text{KKB}} = \frac{g_{\text{KBB}}}{M_K}(\overline{B}_\mu \Gamma \gamma_5 \gamma_\mu K)(\Gamma B),
\]

\[
\mathcal{L}_{\phi KK} = -ig_{\phi KK}\phi \phi^\mu \left[\partial_\mu K^\dagger K - (\partial_\mu K)K^\dagger\right] + \text{h.c.},
\]

\[
\mathcal{L}_{\phi BB} = -g_{\phi BB}\overline{B} \gamma^\mu \left[\gamma^\mu - \frac{\kappa_{\phi BB}}{2M_B} \sigma_{\mu\nu} \partial^\nu\right] \phi B + \text{h.c.},
\]

where $B$ and $\overline{B}$ stand for baryons with spin-$1/2$ and spin-$3/2$, respectively. We should mention that, in the present calculation, we did not consider the $K\overline{B}B$ vertex for brevity, as there are no experimental data available for this reaction.

The coupling constants for the ground-state hadron vertices, such as $g_{K N \Lambda(1116)}$, are taken from the prediction of the Nijmegen soft-core potential model (NSC97a) [15]. The coupling constants for the $s$-wave resonances, $\Lambda(1405)$ and $\Lambda(1670)$, are obtained from the chiral unitary model [16], where the resonances are generated dynamically by the coupled-channel method with the Weinberg–Tomozawa (WT) chiral interaction. The couplings for $\Xi(1690)$ and $\Xi(1820)$ are estimated by ChUM [8] and the SU(6) relativistic quark model [5], respectively.

![Feynman diagrams for the $K^- p \to K^+ K^- \Lambda$ reaction at the tree-level Born approximation. Diagrams (a) and (b) contributed to the $\Xi$-pole, whereas (c), (d), and (e) contributed to the $\phi$-pole. The intermediate $\Lambda/\Sigma^0/\Xi^-$ denote the ground-states as well as the resonances.](image-url)
Fig. 2. (Color online) (Left) Calculated Dalitz plot density \((d^2\sigma/dM_{KK}-dM_{K\Lambda})\) for the \(K^-p \rightarrow K^+K^-\Lambda\) reaction at \(p_{K^-} = 4.2\) GeV. (Right) Differential cross section \(d\sigma/dM_{K\Lambda}\) as a function of the invariant mass squared \(M^2_{K\Lambda}\) at \(p_{K^-} = 4.2\) GeV. The green and blue areas indicate the results with and without the \(\phi(1020)\) contribution, respectively. The experimental data [17] are overlaid as a histogram.

Regarding the coupling constants with two hyperon resonances, such as \(g_{KK^*\Xi^-}\) and \(g_{K\Sigma^*\Xi^-}\), there is no experimental nor theoretical information available. Furthermore, it is also difficult and uncertain to simply employ the flavor SU(3)-symmetry relation, which is used to obtain \(g_{KK^*\Xi^-}\) and \(g_{K\Sigma^*\Xi^-}\) as in Ref. [18]. Hence, we set those coupling constants to be zero for simplicity, although in practice their unknown contributions can be absorbed into the cutoff parameters of the form factors.

We choose the phenomenological phase factors, \(e^{i\pi/2}\) and \(e^{i\pi/2}\) for the amplitudes with the spin-1/2 and spin-3/2 \(\Xi\) hyperons, respectively, as follows:

\[
iM_{\text{total}} = ie^{i\pi/2}M_{\Xi_1/2} + ie^{i3\pi/2}M_{\Xi_3/2} + iM_{\phi}. \tag{5}\]

Note that these phase factors are determined to reproduce the experimental data [17].

3. Numerical results

In this Section, we discuss the numerical results for the \(\Xi(1690)\) production. We first show the numerical results for the \(K^-p \rightarrow K^+K^-\Lambda\) reaction. The calculated Dalitz plot for the double differential cross section \(d^2\sigma/dM_{KK}-dM_{K\Lambda}\) at \(p_{K^-} = 4.2\) GeV (\(E_{cm} = 3.01\) GeV) is represented in the left panel of Fig. 2, where the \(\Xi'(1690)\) and \(\Xi(1820)\) resonances appear as vertical bands, while \(\phi(1020)\) appears as a horizontal band in the bottom side. At this energy, there is no interference effect between \(\Xi\)'s and \(\phi(1020)\). The Dalitz plot was projected on the \(K^-\Lambda\) mass axis, as shown in the right panel of Fig. 2. The experimental data are taken from Ref. [17], which is the only data set available so far for the \(K^-p \rightarrow K^+K^-\Lambda\) reaction. The experiment was performed using the \(K^-\) beam at 4.2 GeV/c to study \(\Xi(1820)\) and higher resonances. We then fit the data with the line shape of our calculation result in the low-mass region below \(M^2_{K\Lambda} = 3.3\) GeV²/c⁴.

After fixing the model parameters by fitting with the three-body experimental data, the total cross sections for \(K^-p \rightarrow K^+\Xi(1690)^-\) are computed and represented as a function of \(K^-\) beam momentum \((p_{K^-})\) from threshold to 4 GeV/c in the left panel of Fig. 3. It increases rapidly from the threshold and peaks at \(p_{K^-} = 2.6\) GeV/c (\(E_{cm} = 2.47\) GeV) with 1.5 \(\mu b\), after which it decreases smoothly. As shown in the right panel of Fig. 3, the \(u\)-channel contribution is much larger than the \(s\)-channel contribution. In our present calculation, we set the coupling constant \((g_{KY\Xi})\) to zero to avoid further theoretical uncertainty. Shyam et al. [18] assumed that \(g_{KY\Xi} = g_{KY\Lambda}\) for the \(K^-p \rightarrow K^+\Xi^-\) reaction.
However, there is no firmly established theoretical basis for the coupling constants \(g_{K^+\Xi^-}\).

4. Summary

In this talk, we present our recent work on the \(\Xi(1690)^-\) production in the \(K^- p \rightarrow K^+ \Xi(1690)^-\) reaction within the effective Lagrangian approach. We consider the \(s\)- and \(u\)-channel \(\Sigma/\Lambda\) ground states and resonances for the \(\Xi\)-pole contributions, in addition to the \(s\)-channel \(\Lambda\), \(u\)-channel nucleon pole, and \(t\)-channel \(K^-\)-exchange for the \(\phi\)-pole contributions. The \(\Xi\)-pole includes \(\Xi(1320), \Xi(1535), \Xi(1690)(J^P = 1/2^-),\) and \(\Xi(1820)(J^P = 3/2^-)\). We calculate the Dalitz plot density of \(d^2\sigma/dM_K^+ dM_K^-\) at 4.2 GeV/c and the total cross sections for the \(K^- p \rightarrow K^+ K^-\Lambda\) reaction near the threshold to determine the coupling constants and the form factors for the two-body \(K^- p \rightarrow K^+ \Xi(1690)^-\) reaction. The calculated differential cross sections for the \(K^- p \rightarrow K^+ \Xi(1690)^-\) reaction near the threshold show a strong enhancement at backward \(K^+\) angles, caused by the dominant \(u\)-channel contribution.

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