$\Xi(2030)$ and $\Xi(2120)$ as $K^*\Sigma$ molecular states

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In this work, the molecular states from the $K^*\Sigma$ interaction are studied in a quasipotential Bethe-Salpeter equation approach with the one-boson-exchange potentials. We consider the exchanges of vector ($\rho$, $\omega$, and $\phi$) mesons and pseudoscalar ($\pi$ and $\eta$) mesons to describe the $K^*\Sigma$ interaction with the coupling constants determined by the SU(3) symmetry. The poles of the scattering amplitude are searched for to find the molecular states dynamically generated from the $K^*\Sigma$ interaction. A bound state with quantum number $I(J^P) = 1/2(5/2^+)$ is produced, which can be associated to the $\Xi(2030)$ baryon. Other bound states with $J \leq 5/2$ are also searched for and it is found that there exist bound states with quantum numbers $I(J^P) = 1/2(1/2^+)$, $1/2(3/2^-)$, and $1/2(3/2^+)$. The $\Xi(2120)$ may be a candidate for one of these three bound states. In addition, we also find two bound states with isospin $3/2$ and spin parities $1/2^-$ and $1/2^+$.

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I. INTRODUCTION

The observation of the hidden-charmed pentaquark states, $P_c(4450)$ and $P_c(4380)$, by the LHCb collaboration has reignited interests in exotic baryons both theoretically and experimentally [1]. Many explicit models have been proposed to understand these exotic baryons [2]. Considering the progress in the heavy flavor sector, it is interesting to study possible exotic baryons in the light flavor sector.

In fact, even before the quark model was proposed by Gell-Mann and Zweig, the $\Lambda(1405)$ had been suggested as a bound state from the $\bar{K}N$ interaction, i.e., a hadronic molecular state in modern terminology [3]. After its introduction, the quark model has been remarkably successful in explaining most of the known hadrons as either quark- or diquark-antidiquark states. Recent reviews of the constituent quark model and its coupled channel [4–7] molecules, two nucleon resonances with a mass about 2.0 GeV, the $N(1875)$ and the $N(2100)$, were also interpreted as hadronic molecular states from the $\Sigma K$ and $\Sigma K^*$ interactions, respectively [8]. Such an assignment is also supported by a recent calculation in the constituent quark model [28]. The $\Sigma^{(*)}K^{(*)}$ system has strangeness zero and behaves as a nucleon resonance. If we change the $K^{(*)}$ to a $\bar{K}^{(*)}$, the system becomes double-strange, and can be related to a $\Xi$ baryon. Different from the very recent observation of the double-charmed baryon $\Xi_{cc}$, several double-strange $\Xi$ baryons have been listed in the recent re-referendum of particle data group (PDG) [9]. Considering the interpretations of the $\Lambda(1405)$ as a $\bar{K}N$ bound state and the $N(1875)$ and $N(2100)$ as $\Sigma K$ and $\Sigma K^*$ molecular states, it is interesting to study whether $\Sigma^{(*)}$ and $\bar{K}^{(*)}$ can be bound together to form a hadronic molecular state corresponding to a $\Xi$ baryon.

At present, there are eleven $\Xi$ baryons listed in the review of PDG [10]. The ground-state octet and decuplet baryons, the $\Xi(1320)$ and the $\Xi(1530)$, are well established with four-star ratings and can be easily fitted into the conventional quark model. For the states $\Xi(1690)$, $\Xi(1820)$, $\Xi(2030)$ and $\Xi(2120)$, there exist many different interpretations, such as $qqq$ states, molecular systems, etc [29–34]. In this work, we study the $K^*\Sigma$ interaction and try to understand the double-strange baryons, the $\Xi(2030)$ and the $\Xi(2120)$, which have...
masses close to the $\bar{K}\Sigma$ threshold.

The $\Xi(2030)$ is a three-star state and has a mass of $2025 \pm 5$ MeV and a width of $20^{+15}_{-10}$ MeV [16]. An early experimental analysis [35] suggested that the spin of the $\Xi(2030)$ should be $J \geq 5/2$. Before the experimental observation of the $\Xi(2030)$, Samios et al. predicted that according to the SU(3) flavor symmetry the $\Xi(2030)$ is most likely the partner of the $N(1680)$, $\Lambda(1820)$ and $\Sigma(1915)$ with $J^P = 5/2^+$ [36]. The constituent quark model calculations in Refs. [32, 33] indicated that the $\Xi(2030)$ might be a candidate for the second $J^P = 5/2^+$ state or $J^P = 7/2^+$ state. However, the strong decay analysis based on the experimental measurements disfavors the assignment of the $\Xi(2030)$ as a member of the $5/2^+$ octet [37]. Also, the strong decay analysis in the chiral quark model [34] concludes that the $\Xi(2030)$ could not be assigned as any spin-parity $J^P = 7/2^+$ states or pure $J^P = 5/2^+$ states. It seems to favor the $J^P = 3/2^+$ assignment. However, this conflicts with the analysis of the data [35]. Generally speaking, the $\Xi(2030)$ can not easily be understood as a conventional $qqq$ state.

Compared with the $\Xi(2030)$, the experimental information on the one-star state $\Xi(2120)$ is scarce [16]: both the spin parity and the width is not known experimentally. The $\Xi(2120)$ was first observed in the $K\Lambda$ invariant mass spectrum by the Amsterdam-CERN-Nijmegen-Oxford Collaboration [38], and later confirmed by the French-Soviet and CERN-Soviet Collaboration [39] in the 1970’s, where a mass of about 2120 MeV and a width of about 20 MeV were suggested by those observations with poor statistics. There exist a few theoretical studies about the nature of the $\Xi(2120)$. A study in the chiral unitary approach suggested that a pole around 2100 MeV can be produced from the interaction between pseudoscalar/vector mesons and baryons with $J^P = 1/2^+$ and $3/2^+$, which can be associated to the $\Xi(2120)$ [40, 41]. In Ref. [42] the $I(J^P) = 1/2(3/2^+)$ state located at 2046 $- i 8.2$ MeV is identified as a meson-baryon molecule that can be associated to the $\Xi(2120)$. Meanwhile, it is claimed that the $\Xi(2120)$ have a big $K^\ast\Sigma$ component.

From the above discussion, it is clear that the $\Xi(2030)$ can not be easily understood as a $qqq$ state. The mass of the $\Xi(2030)$ is close to the $K^\ast\Sigma$ threshold, which encourages us to interpret $\Xi(2030)$ as a bound state of $K^\ast\Sigma$. The $\Xi(2120)$ was also interpreted as a molecular state in the literature [40–42]. It is natural to interpret the $\Xi(2030)$ and $\Xi(2120)$ baryons as two bound states from the $K^\ast\Sigma$ interaction with different quantum numbers. It is analogous to the interpretations of the LHCb pentaquark states, $P_c(4450)$ and $P_c(4380)$, as bound states of $D^0\Sigma$ with spin parities $5/2^+$ and $3/2^+$ [23]. With such an assumption, the $\Xi(2030)$ is at least a $P$-wave bound state. According to Ref. [23], a molecular state in $P$ wave can still be produced and observed in experiment. In this work, the $K^\ast\Sigma$ interaction will be studied in a quasipotential Bethe-Salpeter equation and the bound states, especially those relevant to the $\Xi(2030)$ and $\Xi(2120)$ will be searched for to investigate the possibility of interpreting both $\Xi(2030)$ and $\Xi(2120)$ as hadronic molecular states.

This paper is organized as follows. The theoretical formalism is explained in Sec. II. In Sec. III, the molecular states of $K^\ast\Sigma$ are searched for by looking for poles of the scattering amplitude on the complex plane. In the last section, we provide a short summary and outlook.

II. THEORETICAL FRAMEWORK

In this section, we construct the potential kernel of the $K^\ast\Sigma$ interaction described by the one-meson-exchange model [43]. For the system studied here, the pseudoscalar $\pi$ and $\eta$ mesons and vector $\rho$, $\omega$ and $\phi$ mesons are considered. The tree level Feynman diagram is illustrated in Fig. 1.

![FIG. 1: Feynman diagram for the $K^\ast\Sigma \to K^\ast\Sigma$ interaction. We also show the definition of the kinematics $(k_1, k_1', k_2, k_2')$ that we use to calculate the potential kernel.](image)

The effective Lagrangian terms required for the relevant interaction vertices have the following form [26]:

$$L_{K^\ast K^\ast V} = \frac{g_{K^\ast K^\ast V}}{2}(K^\ast\mu\nu\chi K^\ast\nu + K^\ast\mu\nu\chi K^\ast\nu + K^\ast\mu\nu\chi K^\ast\nu)$$

$$L_{K^\ast K^\ast P} = g_{K^\ast K^\ast P} e^{\nu\alpha\beta}  \partial_\mu K^\ast_\mu \partial_\nu P^\ast_\nu$$

$$L_{\Sigma\Sigma V} = -g_{\Sigma\Sigma V} [\gamma^\nu - \frac{k\Sigma\Sigma\gamma\nu}{2m_\Sigma}] V, \Sigma$$

$$L_{\Sigma\Sigma P} = \frac{g_{\Sigma\Sigma P}}{m_\pi} \Sigma^\nu \gamma^\nu \partial_\mu P, \Sigma$$

where $V$ denotes $\rho$, $\omega$, $\phi$ and $P$ denotes $\pi, \eta$. For an isovector $V$ and $P$, $V \to \bar{V} \cdot \tau$ and $P \to \bar{P} \cdot \tau$ if the vertices are $K^\ast V$ and $K^\ast P$, respectively. If the vertices are $\Sigma V$ and $\Sigma P$ instead, then $V \to \bar{V} \cdot \hat{T}$ and $P \to \bar{P} \cdot \hat{T}$, where $\hat{T}$ is the isospin transition operator [44]. The $m_\pi$ and $m_\Sigma$ are the mass of $\pi$ and the nucleon, respectively. The $K^\ast$ isodoublets are defined as

$$K^\ast = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \sigma^+ \\ \sigma^0 \\ \Sigma^- \end{pmatrix}$$

The $\bar{\rho}$ and $\bar{\Sigma}$ represents the $\pi, \rho$ and $\Sigma$ triplets

$$\bar{\rho} = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix}$$

The field-strength tensor are defined as $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$ and $K^\ast_{\mu\nu} = \partial_\mu K^\ast_\nu - \partial_\nu K^\ast_\mu$. The $\tau$ is the Pauli matrix, while $\sigma_{\mu\nu}$ is the Levi-Civita tensor. In the above Lagrangian terms, $\sigma_{\mu\nu} = \frac{1}{2}(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$. 
According to the SU(3) symmetry, the coupling constants have the following relation [45],

\[ g_{k^+ k^0} = \frac{g_{k^+ k^+}}{\sqrt{2}} = \frac{g_{pp}}{2}, \quad (7) \]

\[ g_{\Sigma^+ p} = g_{\Sigma^+ N} = 2 \alpha_{NNp} g_{NNp}, \quad (8) \]

\[ g_{\Sigma^0} = -\frac{g_{k^+ k^-}}{\sqrt{2}} = \frac{g_{\pi^0 \pi^0}}{2}, \quad (9) \]

\[ g_{k^+ k^-} = \frac{g_{k^+ k^0}}{\sqrt{3}} = \frac{g_{\pi^+ \pi^0}}{2}, \quad (10) \]

\[ g_{\Sigma^0} = \frac{2 \alpha_{NN\pi} g_{NN\pi}}, \quad (11) \]

\[ g_{\Sigma^0} = \frac{2}{3} (1 - \alpha_{NN\pi}) g_{NN\pi}. \quad (12) \]

The explicit values are tabulated in Table I. They can be determined from \( \alpha_{NNp} = 1.15 \) [46], \( \alpha_{NN\pi} = 0.4 \) [46],

\[ g_{pp} = g_{\pi^+ \pi^-} = 6.1994 [44, 47, 48], \quad g_{NNp} = g_{NN\pi}/2[44, 46], \]

\[ g_{\pi^+ \pi^0} = 11.2 [44], \quad g_{NN\pi} = 1.0. \quad [46]. \]

The magnetic couplings \( k_{\Sigma^+ \pi^-}, k_{\Sigma^0 \pi^-} \), and \( \kappa_{\Sigma^0 \pi^-} \) can also be obtained from Ref. [46] as

\[ \kappa_{\Sigma^+ \pi^-} = 1.33, \quad \kappa_{\Sigma^0 \pi^-} = -2.35. \]

| V | P |
|---|---|
| \( \alpha \) | \( \rho \) | \( \omega \) | \( \phi \) | \( \pi \) | \( \eta \) |
| 3.10 | 3.10 | 4.38 | 5.60 | 9.70 |
| 7.13 | 7.13 | -5.70 | 0.80 | 0.69 |

With the above Lagrangian terms and coupling constants, the potential for the \( \bar{K}^* \Sigma \) interaction via the exchange of vector mesons and pseudoscalar mesons are

\[ iM_{\bar{K}^* \Sigma}(p, p') = \hat{r}V_{\bar{K}^* \Sigma}(p, p) + \sum_{x \neq 0} \frac{g_{\pi^0 \pi^0}}{2(2\pi)^3} \times \hat{r}V_{\bar{K}^* \Sigma}(p, p')G_0(p')iM_{\bar{K}^* \Sigma}(p, p). \quad (15) \]

In order to get the one-dimensional Bethe-Salpeter equation, the covariant spectator theory is applied by putting the \( \Sigma \) on shell \([52-55]\). For details, see Ref. [49].

The partial wave potential \( \hat{r}V_{\bar{K}^* \Sigma} \) can be calculated as

\[ \hat{r}V_{\bar{K}^* \Sigma}(p, p') = 2\pi \int d\cos \theta [d_{\bar{K}^* \Sigma}(\theta) \hat{r}V_{\bar{K}^* \Sigma}(p, p) + \beta d_{\bar{J} \Sigma}(\theta) \hat{r}V_{\bar{K}^* \Sigma}(p, p)]. \quad (16) \]

where \( p' = |p| \), and the \( d_{\bar{K}^* \Sigma}(\theta) \) is the Wigner d-matrix. The \( \beta = FP_1 P_{12}^{-1} \) and \( S_{12} \) being the parity and \( J \) and \( J_{12} \) being the angular momenta for the system and particle 1 or 2. In this work we adopt an exponential regularization in the propagator as \( G_0(p) \rightarrow G_0(p)e^{-(q^2 - m^2)/A^2} \) with \( k_1 \) and \( m_1 \) being the momentum and the mass of \( K^* \), respectively. The form factor of \( \Sigma \) is not necessary due to its on-shell-ness. In our model, there exists only one free parameter, the cutoff \( \Lambda \). And we expect it not far from 1 GeV, here in a range from 0.6 to 5.0 GeV.

III. RESULTS AND DISCUSSIONS

Possible bound state from the \( \bar{K}^* \Sigma \) interaction can be studied by searching for poles of the scattering amplitude \( M = V/(1 - VG) \). By analytic continuation into the complex plane \( W \rightarrow z \), poles will be searched for by varying \( z \) in the complex plane to have \( |1 - V(z)G(z)| = 0 [49] \).

Since \( \bar{K}^* \) and \( \Sigma \) carries spin parities \( 1^- \) and \( 1^+ \), respectively, an S-wave bound state should have spin parity \( 1^- \) or \( 3/2^- \). An early experimental analysis [35] suggested that the \( \Xi(3030) \) should carry a spin \( J \geq 5/2 \). It requires that the \( \Xi(3030) \) is at least a \( P \)-wave state if it is a \( \bar{K}^* \Sigma \) molecular state. We would like to note that in our formalism the partial wave decomposition is only on \( J^p \) because we work in a relativistic framework. Here we do not distinguish the explicit contributions from \( S \) (\( P \)) and \( D \) (\( G \)) waves. Generally, the contributions with smaller \( L \) is more important for a certain spin parity close to threshold. In this work, we will consider the spin parities where at least \( P \) wave is involved. Since a system with \( J \geq 7/2 \) will be a \( D \)- (\( G \))- wave state, only the isospin 1/2 systems with \( J \leq 5/2 \) will be considered in this work. Given such constraints, possible bound state produced from the \( \bar{K}^* \Sigma \) interaction are listed in Table II with the variation of the cutoff \( \Lambda \).

In the six cases considered, four bound states with isospin 1/2 can be found in the \( \bar{K}^* \Sigma \) system with spin parities \( 1^- \), \( 3/2^- \), \( 3/2^+ \), and \( 5/2^+ \). As in other systems [22, 23, 49, 51], the binding energies of the bound states produced from the \( \bar{K}^* \Sigma \) interaction increase with the cutoff \( \Lambda \). Among these four
bound states, the 1/2(1/2−) and 1/2(3/2−) states are from S and/or D wave while the 1/2(3/2+) and 1/2(5/2+) states from P and/or G wave. Since the contributions with smaller L is more important for a certain spin parity close to threshold, one can say that there exist two P-wave bound states and two S-wave bound states from the K∗Σ interaction. The two negative-parity states in S wave appear with cutoffs about 1 GeV and two positive-parity states in P wave appear with cutoffs about 1.2 GeV. It shows that near threshold a larger cutoff is needed to enhance the attraction for the P-wave system than for the S-wave system. Such a phenomenon is also found in the case of the DΣ interaction [23].

The experimental analysis [35] favors a spin not less than 5/2 for the Ξ(2030), which is also suggested by PDG [16]. As discussed above, the system with a spin parity 5/2− and spin J ≥ 7/2 is at least a D-wave state, whose contribution should be small. The study in Ref. [23] suggested that P-wave contributions are still considerable and may be observed in experiment. The only possible spin parity to interpret the Ξ(2030) in our molecular picture is 5/2+. Fortunately, a bound state can be found at a cutoff about 1.3 GeV in our model as expected, and with the increase of the cutoff its mass can reach 2030 MeV. The pole with \( I(J^P) = 1/2(5/2)^+ \) is illustrated in Fig. 2.

For the Ξ(2120), the experimental information is scarce, which makes its assignment to a certain state difficult. In our study, two states with 1/2(1/2−) and 1/2(3/2−) are produced from the K∗Σ interactions, which is consistent with the results of the chiral unitary approach [40–42]. In Ref. [42] a bound state with 3/2− arises at 2046 − i8.2, which is consistent with our results. In addition to these two S-wave negative-parity states, a P-wave positive-parity state with 1/2(3/2+) is also produced from the K∗Σ interaction. Because of the lack of experimental information on the spin parity of the Ξ(2120), any of the three bound states can be a candidate for the Ξ(2120).

Table I lists the results of the isospin 1/2 channel, which corresponds to the Ξ baryon. In the qqg picture, the isospin of a Ξ baryon is 1/2 because there is only one u/d quark. However, in the K∗Σ system, there exist two u/d quarks and a u/̅d antiquark. Hence, an isospin 3/2 is allowed for a molecular state, which is analogous to the existence of a charged charmonium-like state. In Table II, we list the bound states with isospin 3/2 from the K∗Σ interaction. Only two bound states with \( J^P = 1/2^- \) and \( J^P = 1/2^+ \) can be produced with cutoffs about 1 GeV.

### Table II: Masses of the bound states with \( I = 1/2 \) from the K∗Σ interaction with different cutoffs \( \Lambda \). Both the cutoff \( \Lambda \) and energy \( W \) are in units of GeV.

| \( J^P \) | \( \Lambda \) | \( W \) | \( J^P \) | \( \Lambda \) | \( W \) |
|---|---|---|---|---|---|
| \( 1^- \) | 0.90 | 2.084 | \( 3^- \) | 1.28 | 2.073 |
| | 0.95 | 2.078 | | 1.30 | 2.063 |
| | 1.00 | 2.071 | | 1.32 | 2.051 |
| | 1.10 | 2.048 | | 1.34 | 2.036 |
| \( 3^- \) | 1.00 | 2.082 | \( 3^- \) | 1.24 | 2.067 |
| | 1.10 | 2.077 | | 1.26 | 2.058 |
| | 1.20 | 2.070 | | 1.28 | 2.046 |
| | 1.40 | 2.050 | | 1.30 | 2.031 |

### Table III: Masses of the bound states with \( I = 3/2 \) from the K∗Σ interaction with different cutoffs \( \Lambda \). Both the cutoff \( \Lambda \) and energy \( W \) are in units of GeV.

| \( J^P \) | \( \Lambda \) | \( W \) | \( J^P \) | \( \Lambda \) | \( W \) |
|---|---|---|---|---|---|
| \( 1^- \) | 1.10 | 2.082 | \( 1^- \) | 0.94 | 2.082 |
| | 1.15 | 2.073 | | 0.97 | 2.071 |
| | 1.20 | 2.058 | | 1.00 | 2.056 |
| | 1.25 | 2.038 | | 1.03 | 2.036 |

### IV. SUMMARY

Inspired by the LHCb observation of the pentaquark states and their molecular interpretations, we have studied possible bound states from the K∗Σ interaction by solving a quasipotential Bethe-Salpeter equation within the one-boson exchange model. A bound state with the quantum number \( I(J^P) = 1/2(5/2)^+ \) from the K∗Σ interaction is produced at \( \Lambda = 1.3 \) GeV. This bound state can be associated to the Ξ(2030) as a P-wave molecular state. Three other bound states with quantum numbers \( J^P = 1/2(1/2)^- \), \( 1/2(3/2)^- \) and 1/2(3/2+) are also produced from the K∗Σ interaction.

For the Ξ(2030), our study showed that it could be a P-wave K∗Σ bound state with spin parity 5/2+, consistent with the available experimental information. On the other hand, we do not have enough experimental information to determine which bound state produced from the K∗Σ interaction is the Ξ(2120). If we follow the assignment in Ref. [42], that the...
ξ(2120) is a molecular bound state with \(1/2(3/2^-)\), it is interesting to see that the \(\Xi(2120)\) and \(\Xi(2030)\) exhibit a pattern analogous to the \(P_s(4380)\) and \(P_s(4450)\) in Ref. [23], where it was found that the \(P_s(4450)\) and \(P_s(4380)\) can be produced from the \(\bar{D}^*\Sigma\) interaction as a \(P\)-wave and \(S\)-wave state with \(5/2^+\) and \(3/2^-\), respectively.

Clearly, more experimental efforts are needed to better understand the nature of the \(\Xi(2120)\) and test the scenario proposed in the present study. There exist plans to study double-strangeness baryons at facilities such as JLab, J-PARC, and PANDA. We strongly recommend our experimental colleagues to study the \(\Xi(2030)\), \(\Xi(2120)\) and the double-strangeness baryons with isospin 3/2. These studies can also help improve our understanding of the LHCb pentaquark states.

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