$\bar{K}\Lambda$ molecular explanation to the newly observed $\Xi(1620)^0$

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The newly observed $\Xi(1620)^0$ by the Belle Collaboration inspires our interest in performing a systematic study on the interaction of an antistrange meson ($\bar{K}^{(*)}$) with a strange or doubly strange ground octet baryon B (Λ , Σ , and Ξ), where the spin-orbit force and the recoil correction are considered in the adopted one-boson-exchange model. Our results indicate that $\Xi(1620)^0$ can be explained as a $\bar{K}\Lambda$ molecular state with $I(J^P) = 1/2(1/2^-)$ and the intermediate force from σ exchange plays an important role. Additionally, we also predict several other possible molecular candidates, i.e., the $\bar{K}\Sigma$ molecular state with $I(J^P) = 1/2(1/2^-)$ and the triply strange $\bar{K}\Xi$ molecular state with $I(J^P) = 0(1/2^-)$.

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I. INTRODUCTION

Recently, the Belle Collaboration [1] announced the observation of $\Xi(1620)^0$ in the $\Xi_c^- \pi^+$ invariant mass spectrum of the $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ process, which confirmed early experimental evidence of $\Xi(1620)$ existing in the $K^- p$ reaction in the 1970s [2–4]. The measured mass and width are

$$M = 1610.4 \pm 6.0(\text{stat})_{-3.5}^{+5.9}(\text{syst}) \text{ MeV},$$

$$\Gamma = 59.9 \pm 4.8(\text{stat})_{-3.0}^{+2.8}(\text{syst}) \text{ MeV},$$

respectively. Besides observing the $\Xi(1620)^0$ signal, Belle also first reported the evidence of $\Xi(1690)^0$ in the $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ process [1].

Focusing on $\Xi(1620)^0$, we must mention the similarities between $\Xi(1620)^0$ and the famous $\Lambda(1405)$. As shown in Fig. 1, we list the mass gaps of several typical states and the corresponding thresholds. We notice that the mass gap between $\Xi(1620)$ and $\Xi(1315)$ is similar to that of $\Lambda(1405)$ and $\Lambda(1115)$, where $\Lambda(1115)$ and $\Xi(1315)$ are ground

states with $J^P = 1/2^+$ in the corresponding Λ and Ξ baryon families. And, these two mass gaps around 300 MeV are two times smaller than the mass gap between the $N(1535)$ and the nucleon. These phenomena show that $\Lambda(1405)$ and $\Xi(1620)^0$ are not consistent with the predicted masses of $\Lambda(1/2^-)$ and $\Xi(1/2^-)$ from quark model [5]. What is more special is that $\Xi(1620)^0$ and $\Lambda(1405)$ are just below the $\bar{K}N$ and the $\bar{K}\Lambda$ thresholds, respectively.

Since M. Gell-Mann [6] and G. Zweig [7] first proposed the existence of the exotic states in their pioneer work on the quark model, great theoretical and experimental efforts were made on searching for exotic hadronic matter. The studies of exotic hadronic matter can deepen our understanding of the nonperturbative behavior of QCD. As an important configuration of exotic hadronic matter, hadronic molecules have received extensive attentions in the past

FIG. 1. A comparison between the masses of the molecular candidates and the mass thresholds of a pair of antimeson and baryon systems.

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decade [8–10]. In particular, the updated analysis from the LHCb Collaboration indicated the observation of three near threshold hidden-charm pentaquarks, $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ [11], which provides a strong evidence for the existence of hidden-charm meson-baryon configuration molecular states [12–19].

In fact, there is a long-term discussion on the meson-baryon molecules in the light flavor sector. $\Lambda(1405)$ is a typical example which was assigned as a $\bar{K}N$ molecular candidate with $I(J^P) = 0(1/2^-)$, since its mass is close to the $\bar{K}N$ threshold but far away from the prediction in quark model (see the review articles [20,21] for details).

Due to these similarities between $\Xi(1620)$ and $\Lambda(1405)$, it is interesting to study whether the $\Xi(1620)$ can be the doubly strange molecular partner of the $\Lambda(1405)$. In Refs. [22,23], the $\Xi(1620)$ was interpreted as a $J^P = 1/2^-$ resonance dynamically generated in chiral unitary approach. By introducing the vector exchange interaction, the Bethe-Salpeter equation approach [24] was applied to identify the $\Xi(1620)$ as a $\bar{K}\Lambda$ or a $\bar{K}\Sigma$ molecular state.

In this work, we will discuss the $\Xi(1620)$ as a molecular state in the framework of the one-boson-exchange (OBE) model. In general, the spin-orbit force and the recoil correction are very important for hadron-hadron interactions in the light flavor sector, which will be also included in the following calculations. As a byproduct, the $\bar{K}^{(*)}\mathcal{B}$ ($\mathcal{B} = \Lambda/\Sigma/\Xi$) systems will also be investigated.

This paper is organized as follows. In Sec. II, we present the deduction of the OBE effective potentials. In Sec. III, the corresponding numerical results and discussion for $\bar{K}^{(*)}\mathcal{B}$ systems are given. This paper will end with a summary in Sec. IV.

II. INTERACTIONS

In the local hidden gauge approach [25,26], the effective Lagrangians depicting the interaction of vector mesons, vector meson with pseudoscalar mesons can be constructed as

$$\mathcal{L}_{VVV} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle, \quad (2.1)$$

$$\mathcal{L}_{PPV} = -ig\langle[P, \partial_\mu P]V^\mu\rangle, \quad (2.2)$$

$$\mathcal{L}_{VVP} = \frac{G}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\langle\partial_\mu V_\nu\partial_\alpha V_\beta P\rangle. \quad (2.3)$$

In the above Lagrangians, $g = \frac{12}{2\sqrt{2}}$ and $G = \frac{3g^2}{4\pi^2 f_\pi}$ with $f_\pi = 93$ MeV were given in Ref. [25]. In Ref. [26], the lowest order baryon meson Lagrangians are expressed as

$$\begin{aligned} \mathcal{L}_{BBP} &= -\frac{D+F}{\sqrt{2}f_\pi}\langle\bar{B}\gamma_\mu\gamma_5\partial^\mu PB\rangle - \frac{D-F}{\sqrt{2}f_\pi}\langle\bar{B}\gamma_\mu\gamma_5 B\partial^\mu P\rangle, \\ \mathcal{L}_{BBV} &= g(\langle\bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle), \end{aligned} \quad (2.4)$$

where $D = 0.75$ and $F = 0.51$ [26]. Here, matrixes for vector mesons, pseudoscalar mesons, and light baryons in SU(3) octet are respectively written as

$$\begin{aligned} V &= \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}, \\ P &= \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}, \\ B &= \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}. \end{aligned}$$

In the framework of the OBE model, the intermediate-range interaction is provided by the σ exchange process. This scalar meson exchange contribution has been widely introduced to study various other multiquark molecular bound states [13,14,27–34]. The corresponding Lagrangians are

$$\mathcal{L}_{PP\sigma} = g_\sigma m_P \langle PP\sigma\rangle, \quad (2.5)$$

$$\mathcal{L}_{VV\sigma} = g_\sigma m_V \langle VV\sigma\rangle, \quad (2.6)$$

$$\mathcal{L}_{BB\sigma} = g'_\sigma \langle \bar{B}\sigma B\rangle. \quad (2.7)$$

Here, m_V and m_P denote the masses of vector and pseudoscalar mesons, respectively. In quark model, the coupling constants in Eqs. (2.5)–(2.7) have the relation of $g'_\sigma = g_{\sigma NN} = \frac{3}{2}g_\sigma$. In Ref. [28], $\frac{g_{\sigma NN}^2}{4\pi} = 5.69$ was determined.

With the Lagrangians given in Eqs. (2.1)–(2.7), we can derive the scattering amplitude for the $\bar{K}^{(*)}\mathcal{B} \rightarrow \bar{K}^{(*)}\mathcal{B}$ process in t -channel. In Fig. 2, we present the corresponding Feynman diagram and the four momentum for the initial and the final states. The OBE effective potential

FIG. 2. Feynman diagram for the $\bar{K}^{(*)}\mathcal{B} \rightarrow \bar{K}^{(*)}\mathcal{B}$ process.

$\mathcal{V}_E^{h_1 h_2 \rightarrow h_3 h_4}(\vec{q})$ can be related to the scattering amplitude for the process $h_1 h_2 \rightarrow h_3 h_4$ via the Breit approximation, i.e.,

$$\mathcal{V}_E^{h_1 h_2 \rightarrow h_3 h_4}(\vec{q}) = -\frac{\mathcal{M}(h_1 h_2 \rightarrow h_3 h_4)}{\sqrt{\prod_i 2M_i \prod_f 2M_f}}, \quad (2.8)$$

where $\mathcal{M}(h_1 h_2 \rightarrow h_3 h_4)$ is the scattering amplitude. M_i and M_f denote the masses of initial and final states, respectively.

And then, we get the OBE effective potentials for the $\bar{K}\mathcal{B}^{(*)}$ systems

$$V_\sigma = \frac{-g_\sigma g'_\sigma}{\vec{q}^2 + m_\sigma^2} \left[1 - \frac{\vec{k}^2}{2m_B^2} - \frac{1}{4m_B^2} i\vec{\sigma} \cdot (\vec{q} \times \vec{k}) \right], \quad (2.9)$$

$$V_V = -\frac{g^2}{\vec{q}^2 + m_V^2} \left[1 - \frac{\vec{q}^2}{8m_B^2} + \frac{\vec{k}^2}{m_K m_B} + \frac{m_K + 2m_B}{4m_B^2 m_K} i\vec{\sigma} \cdot (\vec{q} \times \vec{k}) \right], \quad (2.10)$$

$$V'_\sigma = -\frac{g_\sigma g'_\sigma}{\vec{q}^2 + m_\sigma^2} (\vec{\epsilon}_4^{\dagger'} \cdot \vec{\epsilon}_2) \left[1 - \frac{\vec{k}^2}{2m_B^2} - \frac{i\vec{\sigma} \cdot (\vec{q} \times \vec{k})}{4m_B^2} \right], \quad (2.11)$$

$$V'_V = -\frac{g^2}{\vec{q}^2 + m_V^2} \left\{ (\vec{\epsilon}_4^{\dagger'} \cdot \vec{\epsilon}_2) \left[1 - \frac{\vec{q}^2}{m_B^2} + \frac{\vec{k}^2}{m_{K^*} m_B} \right] - \frac{(\vec{\epsilon}_4^{\dagger'} \cdot \vec{q})(\vec{\epsilon}_2 \cdot \vec{q})}{2m_{K^*}^2} + \frac{m_{K^*} + 2m_B}{4m_B^2 m_{K^*}} (\vec{\epsilon}_4^{\dagger'} \cdot \vec{\epsilon}_2) [i\vec{\sigma} \cdot (\vec{q} \times \vec{k})] + \frac{i[(\vec{\epsilon}_4^{\dagger'} \times \vec{\epsilon}_2) \times \vec{q}] \cdot (\vec{\sigma} \times \vec{q})}{2m_{K^*} m_B} + \frac{m_B + 2m_{K^*}}{2m_B m_{K^*}^2} (\vec{\epsilon}_4^{\dagger'} \times \vec{\epsilon}_2) \cdot (\vec{q} \times \vec{k}) \right\}, \quad (2.12)$$

$$V_P = -\frac{\sqrt{2}G}{4(\vec{q}^2 + m_P^2)} i[(\vec{\epsilon}_4^{\dagger'} \times \vec{\epsilon}_2) \cdot \vec{q}](\vec{\sigma} \cdot \vec{q}). \quad (2.13)$$

Here, V_σ and V_V are σ exchange and vector exchange potentials for the $\bar{K}\mathcal{B} \rightarrow \bar{K}\mathcal{B}$ processes, respectively. While in the $\bar{K}^*\mathcal{B} \rightarrow \bar{K}^*\mathcal{B}$ processes, σ exchange, vector exchange, and pseudoscalar exchange potentials are respectively denoted by V'_σ , V'_V , and V_P . $\vec{q} = \vec{p}' - \vec{p}$ and $\vec{k} = 1/2(\vec{p} + \vec{p}')$. Additionally, m_σ , m_P , and m_V denote the masses of exchanged scalar meson (σ), pseudoscalar mesons (π, η) and vector mesons (ρ, ω, ϕ), respectively. After performing the Fourier transformation, we may extract the effective potentials in the coordinate space, i.e.,

$$\mathcal{V} = \int \frac{d^3\vec{q}}{(2\pi^3)} e^{i\vec{q} \cdot \vec{r}} \mathcal{V}_E^{h_1 h_2 \rightarrow h_3 h_4}(\vec{q}) \mathcal{F}^2(q^2, m_E^2). \quad (2.14)$$

Here, the form factor $\mathcal{F}(q^2, m_E^2) = (\Lambda^2 - m_E^2)/(\Lambda^2 - q^2)$ is introduced in every interactive vertex, which can reflect the finite size effect of the discussed hadrons and compensate the off-shell effects of the exchanged mesons. Λ , m_E , and q are the cutoff, mass and four momentum of the exchanged mesons, respectively. According to the experience from deuteron [27], the cutoff Λ is taken around 1.0 GeV, which is often regarded as a typical cutoff value for a loosely bound hadronic molecular state.

Since the $S - D$ wave mixing effect is considered, the spin-orbital wave functions for the $\bar{K}^{(*)}\mathcal{B}$ systems with quantum numbers J^P can be written as

$$\begin{aligned} \bar{K}\mathcal{B} \left(\frac{1^-}{2} \right) &: |^2S_{\frac{1}{2}}\rangle, \\ \bar{K}^*\mathcal{B} \left(\frac{1^-}{2} \right) &: |^2S_{\frac{1}{2}}\rangle, \quad |^4D_{\frac{1}{2}}\rangle, \\ \bar{K}^*\mathcal{B} \left(\frac{3^-}{2} \right) &: |^4S_{\frac{3}{2}}\rangle, \quad |^4D_{\frac{3}{2}}\rangle, \quad |^4D_{\frac{5}{2}}\rangle. \end{aligned}$$

The expansions of the spin-orbital wave functions $|\bar{K}^{(*)}\mathcal{B}^{(2S+1)L_J}\rangle$ are

$$\begin{aligned} |\bar{K}\mathcal{B}^{(2S+1)L_J}\rangle &= \sum_{m,m'} C_{Sm_S, Lm_L}^{J,M} \chi_{\frac{1}{2}m} |Y_{L,m_L}\rangle, \\ |\bar{K}^*\mathcal{B}^{(2S+1)L_J}\rangle &= \sum_{\lambda, \lambda', m_S, m_L} C_{\frac{1}{2}\lambda, 1\lambda'}^{S, m_S} C_{Sm_S, Lm_L}^{J,M} \chi_{\frac{1}{2}\lambda} \epsilon_{\lambda'} |Y_{L,m_L}\rangle. \end{aligned}$$

Here, $C_{Sm_S, Lm_L}^{J,M}$ and $C_{\frac{1}{2}\lambda, 1\lambda'}^{S, m_S}$ are the Clebsch-Gordan coefficients. $\chi_{\frac{1}{2}\lambda}$ and Y_{L,m_L} denote the spin wave function and the spherical harmonic function, respectively. $\epsilon_{\lambda'}$ is the polarization vector of a vector meson in the laboratory frame [35], with the explicit expression

$$\epsilon_{\lambda'} = \left(\frac{\vec{p} \cdot \vec{\epsilon}_{\lambda'}}{m}, \vec{\epsilon}_{\lambda'} + \frac{(\vec{p} \cdot \vec{\epsilon}_{\lambda'})\vec{p}}{m(p_0 + m)} \right), \quad (2.15)$$

where $p = (p_0, \vec{p})$ is the four-momentum in the laboratory frame and m denotes the mass of vector meson.

The detailed Fourier transformations for different types of effective potentials are expressed as [36]

$$FT \left\{ \frac{1}{\vec{q}^2 + m^2} \left(\frac{\Lambda^2 - m^2}{\Lambda^2 + \vec{q}^2} \right)^2 \right\} = Y(\Lambda, m, r), \quad (2.16)$$

$$FT \left\{ \frac{\vec{q}^2}{\vec{q}^2 + m^2} \left(\frac{\Lambda^2 - m^2}{\Lambda^2 + \vec{q}^2} \right)^2 \right\} = -\nabla^2 Y(\Lambda, m, r), \quad (2.17)$$

$$FT \left\{ \frac{\vec{k}^2}{\vec{q}^2 + m^2} \left(\frac{\Lambda^2 - m^2}{\Lambda^2 + \vec{q}^2} \right)^2 \right\} = \frac{1}{4} \nabla^2 Y(\Lambda, m, r) - \frac{1}{2} \{ \nabla^2, Y(\Lambda, m, r) \}. \quad (2.18)$$

TABLE I. The matrix elements for all the operators.

J^P	$\langle \mathcal{D}_1 \rangle$	$\langle \mathcal{D}_2 \rangle$	$\langle \mathcal{E}_1 \rangle$
$\frac{1}{2}^-$	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 2 & 0 \\ 0 & -1 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 \\ 0 & 3 \end{pmatrix}$
$\frac{3}{2}^-$	$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & -1 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 2 & -1 \\ 0 & -1 & -2 \end{pmatrix}$
J^P	$\langle \mathcal{E}_3 \rangle$	$\langle \mathcal{F}_1 \rangle$	$\langle \mathcal{F}_2 \rangle$
$\frac{1}{2}^-$	$\begin{pmatrix} 0 & 0 \\ 0 & -3 \end{pmatrix}$	$\begin{pmatrix} 0 & -2\sqrt{2} \\ -2\sqrt{2} & 2 \end{pmatrix}$	$\begin{pmatrix} 0 & \sqrt{2} \\ \sqrt{2} & 2 \end{pmatrix}$
$\frac{3}{2}^-$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -2 \\ 0 & -2 & -2 \end{pmatrix}$	$\begin{pmatrix} 0 & 2 & -2 \\ 2 & 0 & -2 \\ -2 & -2 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 & -2 \\ -1 & 0 & 1 \\ -2 & 1 & 0 \end{pmatrix}$

Here, the $\vec{k}^2$ term in Eq. (2.18) is named as the recoil correction term, and the function $Y(\Lambda, m, r)$ is defined as

$$Y(\Lambda, m, r) = \frac{1}{4\pi r} (e^{-mr} - e^{-\Lambda r}) - \frac{\Lambda^2 - m^2}{8\pi\Lambda} e^{-\Lambda r}. \quad (2.19)$$

In the above effective potentials, we also introduce several spin-spin interaction operators $\mathcal{D}_1$, $\mathcal{D}_2$, spin-orbital operators $\mathcal{E}_1$, $\mathcal{E}_2$, $\mathcal{E}_3$, and tensor operators $\mathcal{F}_1$, $\mathcal{F}_2$. The explicit forms of these operators are

$$\begin{aligned} \mathcal{D}_1 &= \chi_3^\dagger \vec{e}_4^\dagger \cdot \vec{e}_2 \chi_1, & \mathcal{D}_2 &= \chi_3^\dagger i(\vec{e}_4^\dagger \times \vec{e}_2) \cdot \vec{\sigma} \chi_1, \\ \mathcal{E}_1 &= \chi_3^\dagger i(\vec{e}_4^\dagger \times \vec{e}_2) \cdot \vec{L} \chi_1, & \mathcal{E}_2 &= \chi_3^\dagger \vec{\sigma} \cdot \vec{L} \chi_1, \\ \mathcal{E}_3 &= \chi_3^\dagger (\vec{e}_4^\dagger \cdot \vec{e}_2) (\vec{\sigma} \cdot \vec{L}) \chi_1, & \mathcal{F}_1 &= \chi_3^\dagger S(\vec{r}, \vec{e}_4^\dagger, \vec{e}_2) \chi_1, \\ \mathcal{F}_2 &= \chi_3^\dagger S(\vec{r}, i(\vec{e}_4^\dagger \times \vec{e}_2), \vec{\sigma}) \chi_1, \end{aligned}$$

where $S(\vec{r}, \vec{x}, \vec{y})$ is the tensor force operator $S(\vec{r}, \vec{x}, \vec{y}) = 3(\vec{r} \cdot \vec{x})(\vec{r} \cdot \vec{y}) - \vec{x} \cdot \vec{y}$, with $\vec{r} = \vec{r}/|\vec{r}|$. In Table I, we present the numerical matrices for these operators.

With the above preparation, we obtain the total effective potentials for the $\bar{K}^{(*)}\mathcal{B}$ systems

$$V_{\bar{K}N}^I = V_\sigma + \mathcal{G}(I)V_\rho + \frac{3}{2}V_\omega, \quad (2.20)$$

$$V_{\bar{K}\Lambda} = V_\sigma + V_\omega - V_\phi, \quad (2.21)$$

$$V_{\bar{K}^*\Lambda} = V'_\sigma + V'_\omega - V'_\phi, \quad (2.22)$$

$$V_{\bar{K}\Sigma}^I = V_\sigma + \mathcal{H}(I)V_\rho + V_\omega - V_\phi, \quad (2.23)$$

$$\begin{aligned} V_{\bar{K}^*\Sigma}^I &= V'_\sigma + \mathcal{H}(I)V'_\rho + V'_\omega - V'_\phi + \mathcal{H}(I)\frac{g_1 - g_2}{2}V_\pi \\ &\quad - \frac{1}{6}(g_1 + g_2)V_\eta, \end{aligned} \quad (2.24)$$

TABLE II. The flavor wave functions for the discussed $\bar{K}^{(*)}\mathcal{B}$ systems, where $\mathcal{B}$ denotes strange or doubly strange ground octet baryons (Λ , Σ , and Ξ).

Systems	$ I, I_3\rangle$	Flavor wave functions
$\bar{K}N$	$ 0, 0\rangle$	$\frac{1}{\sqrt{2}}(\bar{K}^0 n + K^- p)$
$\bar{K}^{(*)}\Lambda$	$ \frac{1}{2}, \frac{1}{2}\rangle$	$\bar{K}^{(*)0}\Lambda$
	$ \frac{1}{2}, -\frac{1}{2}\rangle$	$K^{(*)-}\Lambda$
$\bar{K}^{(*)}\Sigma$	$ \frac{3}{2}, \frac{3}{2}\rangle$	$\bar{K}^{(*)0}\Sigma^+$
	$ \frac{3}{2}, \frac{1}{2}\rangle$	$\sqrt{\frac{1}{3}}\bar{K}^{(*)-}\Sigma^+ - \sqrt{\frac{2}{3}}\bar{K}^{(*)0}\Sigma^0$
	$ \frac{3}{2}, -\frac{1}{2}\rangle$	$\sqrt{\frac{2}{3}}\bar{K}^{(*)-}\Sigma^0 - \sqrt{\frac{1}{3}}\bar{K}^{(*)0}\Sigma^-$
	$ \frac{3}{2}, -\frac{3}{2}\rangle$	$K^{(*)-}\Sigma^-$
	$ \frac{1}{2}, \frac{1}{2}\rangle$	$\sqrt{\frac{2}{3}}\bar{K}^{(*)-}\Sigma^+ + \sqrt{\frac{1}{3}}\bar{K}^{(*)0}\Sigma^0$
	$ \frac{1}{2}, -\frac{1}{2}\rangle$	$\sqrt{\frac{2}{3}}\bar{K}^{(*)0}\Sigma^- + \sqrt{\frac{1}{3}}K^-\Sigma^0$
$\bar{K}^{(*)}\Xi$	$ 1, 1\rangle$	$\bar{K}^{(*)0}\Xi^0$
	$ 1, 0\rangle$	$\frac{1}{\sqrt{2}}(K^{(*)-}\Xi^0 - \bar{K}^{(*)0}\Xi^-)$
	$ 1, -1\rangle$	$K^{(*)-}\Xi^-$
	$ 0, 0\rangle$	$\frac{1}{\sqrt{2}}(\bar{K}^{(*)0}\Xi^- + K^{(*)-}\Xi^0)$

$$V_{\bar{K}\Xi}^I = V_\sigma + \mathcal{G}(I)V_\rho + \frac{1}{2}V_\omega - 2V_\phi, \quad (2.25)$$

$$\begin{aligned} V_{\bar{K}^*\Xi}^I &= V'_\sigma + \mathcal{G}(I)V'_\rho + \frac{1}{2}V'_\omega - 2V'_\phi + \mathcal{G}(I)(-g_2)V_\pi \\ &\quad + \frac{1}{6}(2g_1 - g_2)V_\eta, \end{aligned} \quad (2.26)$$

where $g_1 = -\frac{D_1+F_1}{\sqrt{2}f_\pi}$ and $g_2 = -\frac{D_1-F_1}{\sqrt{2}f_\pi}$. $\mathcal{H}(I)$ and $\mathcal{G}(I)$ are the isospin factors

$$\begin{aligned} \mathcal{H}(I=1/2) &= 2, & \mathcal{H}(I=3/2) &= -1, \\ \mathcal{G}(I=0) &= 3/2, & \mathcal{G}(I=1) &= -1/2. \end{aligned}$$

The flavor wave functions for the $\bar{K}^{(*)}\mathcal{B}$ systems are collected in Table II.

III. NUMERICAL RESULTS

After obtaining the effective potentials and solving the Schrödinger equations, we first study whether the newly observed $\Xi(1620)$ can be assigned as a $\bar{K}\Lambda$ molecular state with $I(J^P) = 1/2(1/2^-)$. In addition, other possible doubly strange and triply strange $\bar{K}^{(*)}\mathcal{B}$ molecular candidates will be predicted.

A. $\bar{K}\mathcal{B}$ molecules and the $\Xi(1620)$

For the $\bar{K}\Lambda$ system, there does not exist the $\pi/\eta/\rho$ exchange process due to the spin-parity conservation. As shown in Fig. 3(a), we present the OBE potentials for the

$\bar{K}\Lambda$ system with $I(J^P) = 1/2(1/2^-)$ which depends on r . We need to emphasize that we ignore the contribution from the recoil correction. We can see that the dominant σ exchange and ω exchange interactions are both attractive, while the ϕ exchange is weakly repulsive.

From Fig. 3(b) we can see that the recoil correction only has obvious contribution in the short distance. Since the second term proportional to $\{\nabla^2, Y(\Lambda, m, r)\}$ in Eq. (2.8) should be calculated by acting on the wave functions, we plot the potentials neglecting the corresponding terms in Fig. 3(b). Comparing Fig. 3(b) with Fig. 3(a), we may see that the recoil correction significantly changes the line shape of ϕ and ω exchange potentials at $r \leq 0.5$ fm.

As shown in Fig. 4, when the cutoff is taken as 1.26 GeV, we obtain a $\bar{K}N[0(1/2^-)]$ molecular state with the binding energy $E = -30.9$ MeV and the root-mean-square radius $r_{rms} = 1.31$ fm. This molecular state can correspond to the observed $\Lambda(1405)$.

FIG. 3. The r dependence of the OBE effective potentials for the $\bar{K}\Lambda$ system with quantum number $I(J^P) = 1/2(1/2^-)$. Diagrams (a) and (b) present the OBE effective potentials without and with the recoil correction effect, respectively.

FIG. 4. The Λ dependence of the bound state masses and the root-mean-square (RMS) radius r_{RMS} for the $\bar{K}N$ and the $\bar{K}\Lambda$ systems with quantum numbers $I(J^P) = 0(1/2^-)$ and $I(J^P) = 1/2(1/2^-)$, respectively. E is the binding energy. The vertical dotted line and the horizontal solid lines correspond to the cutoff Λ value and the thresholds of meson-baryon systems, respectively.

With the same cutoff, we predict that the $\bar{K}\Lambda$ system with $I(J^P) = 1/2(1/2^-)$ has the binding energy -2.9 MeV, corresponding to the $\Xi(1620)$ observed by the Belle Collaboration [11]. Besides, the binding energy of the $\Lambda(1405)$ is much deeper than that of the $\Xi(1620)$, which can be understood from the obtained potentials. First, from Eqs. (2.20)–(2.21), we can know that the σ exchange process provides comparable attractive contributions for both $\bar{K}N[0(1/2^-)]$ and $\bar{K}\Lambda[1/2(1/2^-)]$ systems. Besides, for the $\bar{K}N[0(1/2^-)]$ system, ρ and ω exchange provide attractive forces. However, for the $\bar{K}\Lambda[1/2(1/2^-)]$ system, the allowed exchanged vector mesons include ω and ϕ , which provide an attractive and a very weakly repulsive force, respectively. Thus, the interaction of the $\bar{K}N[0(1/2^-)]$ system must be more attractive than that of the $\bar{K}\Lambda[1/2(1/2^-)]$ system.

Taking the same cutoff $\Lambda = 1.26$ GeV, we further study the $\bar{K}\Sigma$ and the $\bar{K}\Xi$ systems. As presented in Fig. 5, the doubly strange $\bar{K}\Sigma[1/2(1/2^-)]$ state and the triply strange $\bar{K}\Xi[0(1/2^-)]$ state have the binding energies -37.7 MeV and -10.2 MeV, respectively. Here, in this work, these two predicted states are labeled as $\Xi(1650)$ and $\Omega(1800)$, respectively. We expect that further experiment can confirm our prediction to the existence of $\Xi(1650)$ and $\Omega(1800)$.

Since we study the interactions of the systems composed of a light meson and a baryon, the recoil corrections may have considerable contributions when forming the molecular bound states. In Table III, we present the binding energy with and without considering the recoil corrections for the $\bar{K}N[0(1/2^-)]$, the $\bar{K}\Lambda[1/2(1/2^-)]$, the $\bar{K}\Sigma[1/2(1/2^-)]$, and the $\bar{K}\Xi[0(1/2^-)]$ systems. The cutoff is fixed at $\Lambda = 1.26$ GeV.

Meanwhile, we show the binding energies and RMS radii for the isospin partners of the $\bar{K}B$ systems in Table IV.

FIG. 5. The Λ dependence of the bound state masses and the root-mean-square (RMS) radius r_{RMS} for the $\bar{K}\Sigma$ and the $\bar{K}\Xi$ systems with quantum numbers $I(J^P) = 1/2(1/2^-)$ and $I(J^P) = 0(1/2^-)$, respectively. E is the binding energy. The vertical dotted line and the horizontal solid lines correspond to the cutoff Λ value and the thresholds of meson-baryon systems, respectively.

TABLE III. The contributions of the recoil effect when forming the $\bar{K}N[0(1/2)^-]$, the $\bar{K}\Lambda[1/2(1/2)^-]$, the $\bar{K}\Sigma[1/2(1/2)^-]$, and the $\bar{K}\Xi[0(1/2)^-]$ molecular states. The cutoff is fixed at $\Lambda = 1.26$ GeV. Here, E_{nor} and E denotes the binding energy without and with including the recoil correction terms. All the binding energy are in units of MeV.

	E_{nor}	E
$\bar{K}N[0(1/2)^-]$	-20.4	-30.9
$\bar{K}\Lambda[1/2(1/2)^-]$	-3.3	-2.9
$\bar{K}\Sigma[1/2(1/2)^-]$	-27.4	-37.7
$\bar{K}\Xi[0(1/2)^-]$	-9.1	-10.2

TABLE IV. Bound state solutions for the $\bar{K}\mathcal{B}$ systems. E_{nor} and E denotes the binding energy without and with including the recoil correction terms. Here, the cutoff Λ , the binding energy, and the root-mean-square radius r_{RMS} are in units of GeV, MeV, and fm, respectively.

$\bar{K}\Sigma[3/2(1/2)^-]$				$\bar{K}\Xi[1(1/2)^-]$			
Λ	E_{nor}	E	r_{RMS}	Λ	E_{nor}	E	r_{RMS}
1.5	-6.3	-3.0	3.38	1.6	-5.8	-2.1	3.84
1.6	-10.8	-5.4	2.53	1.9	-13.0	-4.5	2.80
1.7	-16.1	-8.0	2.20	2.2	-19.8	-6.2	2.40

The binding energy without including recoil corrections E_{nor} are also presented. From Table IV, we find that the recoil corrections still have considerable contributions in forming the $\bar{K}\Sigma[3/2(1/2)^-]$ and the $\bar{K}\Xi[1(1/2)^-]$ molecular states. In addition, for the $\bar{K}\Sigma$ state with $I(J^P) = 3/2(1/2)^-$ and the $\bar{K}\Xi$ state with $I(J^P) = 1(1/2)^-$, the binding energies are around several MeV and their RMS radii are around several fm. When the cutoff Λ is around 1.6 GeV, we find that $E(\bar{K}\Sigma[1/2(1/2)^-]) < E(\bar{K}\Sigma[3/2(1/2)^-])$ and $E(\bar{K}\Xi[0(1/2)^-]) < E(\bar{K}\Xi[1(1/2)^-])$, which are reflected by that the interaction of $\bar{K}\Sigma[1/2(1/2)^-](\bar{K}\Xi[0(1/2)^-])$ is much stronger attractive than that of $\bar{K}\Sigma[3/2(1/2)^-] \times (\bar{K}\Xi[1(1/2)^-])$.

B. The $\bar{K}^*\mathcal{B}$ systems

For the $\bar{K}^*\mathcal{B}$ systems, the $S-D$ wave mixing effect is also considered, and the pseudoscalar exchange process is allowed. We list the bound state solutions in Table V. Here, the obtained conclusions include

- (1) The recoil corrections still have considerable contributions on bounding the $\bar{K}^*\mathcal{B}$ systems.
- (2) The $\bar{K}^*\Lambda$ systems with $I(J^P) = 1/2(1/2)^-, 1/2(3/2)^-$ can be good candidates of doubly strange molecular states.
- (3) For the $\bar{K}^*\Sigma$ systems, the states with $I(J^P) = 1/2(1/2)^-, 1/2(3/2)^-,$ and $3/2(3/2)^-$ are promising molecular candidates. And $\bar{K}^*\Sigma[3/2(1/2)^-]$ as a molecular state is also possible.

TABLE V. Bound solutions for $\bar{K}^*\mathcal{B}$ systems. E_{nor} and E denotes the binding energy without and with including the recoil correction terms. Here, the cutoff Λ , the binding energy and the root-mean-square radius r_{RMS} are in units of GeV, MeV, and fm, respectively.

$I(J^P)$	Λ	E_{nor}	E	r_{RMS}	$I(J^P)$	Λ	E_{nor}	E	r_{RMS}
$\bar{K}^*\Lambda$									
$\frac{1}{2}(\frac{1}{2}^-)$	1.1	-6.0	-4.9	2.36	$\frac{1}{2}(\frac{3}{2}^-)$	1.1	-4.7	-3.8	2.67
	1.2	-20.2	-16.8	2.36		1.2	-16.3	-13.6	1.58
	1.3	-39.7	-33.0	1.16		1.3	-32.2	-27.0	1.21
$\bar{K}^*\Sigma$									
$\frac{3}{2}(\frac{1}{2}^-)$	1.4	-5.3	-3.5	2.67	$\frac{3}{2}(\frac{3}{2}^-)$	1.05	-8.6	-3.9	2.56
	1.5	-9.5	-6.2	2.18		1.15	-22.3	-14.7	1.50
	1.6	-14.3	-9.2	1.87		1.25	-39.5	-29.4	1.15
$\frac{1}{2}(\frac{1}{2}^-)$	0.88	-2.2	-1.8	3.36	$\frac{1}{2}(\frac{3}{2}^-)$	1.05	-2.9	-2.9	2.81
	0.93	-14.6	-13.6	1.51		1.15	-16.9	-17.3	1.47
	0.98	-36.3	-35.2	1.05		1.25	-39.0	-40.8	1.09
$\bar{K}^*\Xi$									
$1(\frac{1}{2}^-)$	1.05	-7.0	-3.1	2.64	$1(\frac{3}{2}^-)$	1.15	-3.7	-2.9	2.89
	1.15	-18.7	-11.8	1.60		1.25	-9.8	-7.4	1.96
	1.25	-30.8	-21.7	1.26		1.35	-17.4	-12.4	1.60
$0(\frac{1}{2}^-)$	1.05	-2.6	-2.6	2.81	$0(\frac{3}{2}^-)$	1.0	-3.5	-2.9	2.87
	1.15	-17.1	-16.8	1.41		1.1	-18.8	-18.0	1.37
	1.25	-40.0	-38.8	1.02		1.2	-41.0	-40.0	1.02

- (4) Several possible triply strange molecular states can be predicted, i.e., the $\bar{K}^*\Xi$ states with $1(1/2)^-, 3/2(1/2)^-$ and $0(1/2)^-, 3/2(1/2)^-$.

Further, we also check the results when only considering S -wave contribution in the potentials. And we find that the above conclusions keep the same, as the D -wave contribution is negligible compared with the S -wave contribution.

IV. SUMMARY

Searching for exotic hadronic matter is an interesting research issue for hadron physics. Especially, with more and more observations of charmoniumlike XYZ states and P_c states in the past years, the candidates of hidden-charm tetraquark and pentaquark have been provided, which also stimulated extensive discussions of different hadronic configurations [8–10,37–43]. Among them, hadronic molecular state is very popular to apply to explain these novel phenomena. Recently, the LHCb's observation of three P_c states again gave strong evidence of hadronic molecular states composed of an anticharmed meson and a charmed baryon.

Besides the heavy flavor sector, theorists and experimentalists also paid more attentions to the light flavor sector. For example, the $\Lambda(1405)$ as a $\bar{K}N$ molecule with $I(J^P) = 0(1/2)^-$ have been proposed [20,21]. Recently, Belle reported the observation of $\Xi(1620)$ [1] in the $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ process. If comparing the properties of

the $\Xi(1620)$ and the $\Lambda(1405)$, we may find their similarities, which inspires our interest to exam the possibility of the newly observed $\Xi(1620)$ as the $\bar{K}\Lambda$ molecular state.

In this work, we perform a systematical study on the $\bar{K}^{(*)}\mathcal{B}$ interactions within the framework of the one-boson-exchange model, where $\mathcal{B}$ stands for the strange or doubly strange ground octet baryons. Here, the $S - D$ wave mixing effect, the spin-orbit potential, and the recoil correction are taken into account. The analysis of recoil effect is explicitly performed. From our numerical results, we conclude that the recoil correction will provide considerable contributions for light-light $\bar{K}^{(*)}\mathcal{B}$ systems. By reproducing the mass of $\Lambda(1405)$ under the $\bar{K}N[0(1/2)^-]$ molecular picture, the parameter $\Lambda = 1.26$ GeV can be fixed, which is directly applied to obtain the corresponding bound state solution for the $\bar{K}\Lambda$ molecular state. Our result shows that the newly observed $\Xi(1620)$ as the $\bar{K}\Lambda$ molecular state with $I(J^P) = 1/2(1/2^-)$ can be supported in our theoretical framework.

Testing the scenario of the $\bar{K}\Lambda$ molecular assignment to the $\Xi(1620)$ is the main task of this work. In addition, we also give more theoretical predictions, i.e., there may exist the $\bar{K}\Sigma$ molecule with $I(J^P) = 1/2(1/2^-)$ and the $\bar{K}\Xi$

molecule with $I(J^P) = 0(1/2^-)$, which are labeled as $\Xi(1650)$ and $\Omega(1800)$, respectively. Besides, the $\bar{K}^*\mathcal{B}$ systems are also investigated and some possible molecules composed of $\bar{K}^*\Lambda$, $\bar{K}^*\Sigma$, and $\bar{K}^*\Xi$ are also predicted.

Experimental search for these predicted states will be an interesting research topic. More theoretical efforts should be paid in the near future. With the running of Belle II at Super KEKB, we have reason to believe that more evidence of light flavor molecular states will be revealed, which will provide more abundant information of exotic hadronic matter. It will be an effective way to deepen our understanding to the nonperturbative behavior of QCD.

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