Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon*

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Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

Key words: exotic hidden-charm baryons, the one-boson-exchange model, molecular state

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1 Introduction

In the past eight years, more and more experimental observations of new hadron states have been announced, which has inspired extensive interest in revealing the underlying structure of these newly observed states. Besides making the effort to categorize them under the framework of the conventional $q\bar{q}$ or qqq states, theorists have also tried to explain some of these newly observed hadrons as exotic states due to their peculiarities, which are different from the conventional $q\bar{q}$ or qqq states.

Among different schemes to explain the structures of these newly observed hadrons, molecular states composed of a hadron pair became very popular due to the fact that the corresponding observations are often near the threshold of a pair of hadrons, as shown in in Table 1. In order to explore whether these newly observed hadrons can be accommodated in the molecular framework, there are many theoretical calculations of various molecular states [12–40].

Table 1. The thresholds near the corresponding newly observed hadron states.

observation	threshold	observation	threshold
X(1860) [1]	$p\bar{p}$	$D_s(2317)$ [2]	DK
$D_s(2460)$ [3]	D^*K	X(3872) [4]	D^*D
Y(3940) [5]	D^*D^*	Y(4140) [6]	$D_s^*D_s^*$
Y(4274) [7]	$D_s(2317)D$	Y(4630) [8]	$\Lambda_c\Lambda_c$
$Z^+(4430)$	$D_1D^*/D_1'D^*$	$Z^+(4250)$ [9]	D_1D/D_0D^*
$\Lambda_c(2940)$ [10]	D^*N	$\Sigma_c(2800)$ [11]	DN

Generally speaking, conventional hadrons with a charm quark can be grouped into three families, i.e. charmonium, charmed meson and charmed baryon, with the configurations [$c\bar{c}$], [$c\bar{q}$] and [cqq], respectively, where q or $\bar{q}$ denotes the light quark or antiquark with different flavors. In principle, we may

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extend these configurations by adding the $q\bar{q}$ pair, which is allowed by quantum chromodynamics. Such extension results in three new exotic configurations, $[c\bar{c}q\bar{q}]$, $[c\bar{q}q\bar{q}]$ and $[cqqq\bar{q}]$, which can be named molecular charmonium, molecular charmed meson and molecular charmed baryon, respectively, if the corresponding constituents in these configurations are color singlet. Inspired by the recent experimental observations, many theoretical investigations focusing on molecular charmonium, molecular charmed meson and molecular charmed baryon have been performed [13–40].

Apart from the above exotic molecular systems, which have been discussed extensively in the literature, new configurations of the exotic molecular state may also exist if adding qqq into $[c\bar{c}]$ and [cqq], which correspond to the exotic molecular states with components $[c\bar{c}qqq]$ and [cqqqqq]. These states may be accessible by future experiments such as PANDA, Belle II and SuperB, since the masses of the lightest exotic molecular states with components [cqqqqq] and $[c\bar{c}qqq]$ are about 3.3 and 4.1 GeV, respectively.

At present, carrying out a dynamical study of these exotic molecular systems is especially important, and will provide experimentalists with valuable information such as their mass spectrums and decay behaviors. There has been lots of theoretical work performed recently. In Ref. [41], Liu and Oka discussed whether the $\Lambda_c N$ molecular states exist. Narrow N^* and Λ^* resonances with hidden charm were proposed as the meson-baryon dynamically generated states [42]. Later, the authors in Ref. [43] calculated the S-wave $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states with isospin $I=1/2$ and spin $S=1/2$ using the chiral constituent quark model and the resonating group method.

In this work, we will investigate the hidden-charm molecular baryons which are composed of an S-wave anti-charmed meson and an S-wave charmed baryon. The S-wave charmed baryons can be assigned as either the symmetric 6_F or antisymmetric $\bar{3}_F$ flavor representations, as illustrated in Fig. 1. Thus, the spin-parity of the S-wave charmed baryons is $J^P=1/2^+$ or $3/2^+$ for 6_F and $J^P=1/2^+$ for $\bar{3}_F$. The pseudoscalar and vector anti-charmed mesons constitute S-wave anti-charmed mesons. In the following, we mainly focus on the hidden-charm molecular states composed of the charmed baryons and anti-charmed mesons existing in the green range.

We apply the one-boson-exchange (OBE) model to study the hidden-charm molecular states, which is an effective approach for calculating the hadron-hadron interaction [17, 24–29]. The interactions between S-wave anti-charmed mesons and S-wave charmed baryons with $J^P=1/2^+$ are described in terms of the meson exchange with phenomenologically determined parameters. In our former work [30], we studied the interaction between the vector charmed meson D^* and the nucleon N, which could be related to $\Lambda_c(2940)$ [10]. To some extent, the framework in this work is similar to that in Ref. [30].

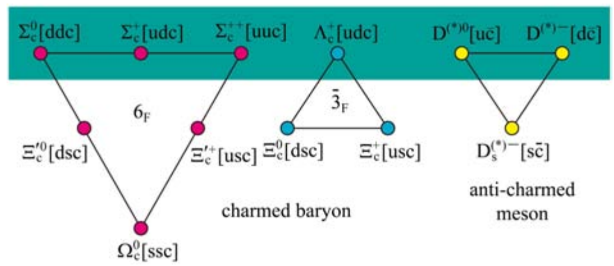

Fig. 1. (Color online). The S-wave charmed baryons with $J^P=1/2^+$ and the S-wave anti-charmed pseudoscalar/vector mesons contributing to the double-charm molecular baryons.

This paper is organized as follows. After the introduction, we present the calculation of the interactions between S-wave anti-charmed mesons and S-wave charmed baryons with $J^P=1/2^+$. Then, the numerical results are presented, and the last section contains the discussion and conclusion.

2 The interaction of hidden-charm molecular baryons

2.1 Flavor wave functions

In this work, we mainly focus on the systems composed of an S-wave anti-charmed meson and an S-wave charmed baryon with $J^P=1/2^+$. These systems are of negative parity. Furthermore, the states composed of an S-wave charmed baryon with $J^P=1/2^+$ and an anti-charmed meson with spin zero include the $\bar{D}\Lambda_c$ and $\bar{D}\Sigma_c$ systems, which are of $I(J^P)=0\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$. Such a system contains one state only

$$\left|I\left(\frac{1}{2}^-\right)\right\rangle_0 : \quad \left|{}^2\mathbb{S}_{\frac{1}{2}}\right\rangle. \tag{1}$$

For comparison, $\bar{D}^*\Lambda_c$ and $\bar{D}^*\Sigma_c$ are the systems with an S-wave charmed baryon with $J^P=1/2^+$ and an anti-charmed meson with spin one, which are of $I(J^P)=\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{3}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$.

Thus, several states may contribute to such systems

$$\left|I\left(\frac{1}{2}^-\right)\right\rangle_1: \quad \left|^2\mathbb{S}_{\frac{1}{2}}\right\rangle, \quad \left|^4\mathbb{D}_{\frac{1}{2}}\right\rangle. \tag{2}$$

$$\left|I\left(\frac{3}{2}^-\right)\right\rangle_1: \quad \left|^4\mathbb{S}_{\frac{3}{2}}\right\rangle, \quad \left|^2\mathbb{D}_{\frac{3}{2}}\right\rangle, \quad \left|^4\mathbb{D}_{\frac{3}{2}}\right\rangle. \tag{3}$$

In Eqs. (1)–(3), we use notation $^{2S+1}L_J$ to distinguish different states, where S, L and J denote the total spin, angular momentum and total angular momentum, respectively. Indices $\mathbb{S}$ and $\mathbb{D}$ show that the couplings between anti-charmed mesons and charmed baryons occur via the S-wave and D-wave interactions, respectively.

The general expressions of states in Eq. (1) and Eqs. (2)–(3) can be explicitly written as

$$\left|^{2S+1}L_J\right\rangle_0 = \chi_{\frac{1}{2}M}Y_{00}, \tag{4}$$

$$\left|^{2S+1}L_J\right\rangle_1 = \sum_{m,m',m_L,m_S} C^{JM}_{Sm_S,Lm_L}C^{Sm_S}_{\frac{1}{2}m,1m'} \times\epsilon^{m'}_n\chi_{\frac{1}{2}m}Y_{Lm_L}, \tag{5}$$

where $C^{JM}_{\frac{1}{2}m,Lm_L}$, $C^{JM}_{Sm_S,Lm_L}$ and $C^{Sm_S}_{\frac{1}{2}m,1m'}$ are Clebsch-Gordan coefficients, Y_{Lm_L} is the spherical harmonics function, $\chi_{\frac{1}{2}m}$ denotes the spin wave function and the polarization vector for $\bar{\mathrm{D}}^*$ is defined as $\epsilon^m_\pm = \mp\frac{1}{\sqrt{2}}\left(\epsilon^m_x \pm \mathrm{i}\epsilon^m_y\right)$ and $\epsilon^m_0 = \epsilon^m_z$.

2.2 Effective Lagrangian

When adopting the OBE model to calculate the effective potential of the hidden-charm molecular baryons, we need to construct the effective Lagrangian describing the interactions of the charmed or anti-charmed baryons/mesons with the light mesons (π, η, ρ, ω, σ, ⋯). According to the chiral symmetry and heavy quark limit, the Lagrangian for the S-wave heavy mesons interacting with light pseudoscalar, vector and vector mesons reads [44–48]

$$\mathcal{L}_{HH\mathbb{P}} = \mathrm{i}g_1\langle \bar{H}^{\bar{\mathrm{Q}}}_a\gamma_\mu A^\mu_{ba}\gamma_5 H^{\bar{\mathrm{Q}}}_b\rangle, \tag{6}$$

$$\mathcal{L}_{HH\mathbb{V}} = -\mathrm{i}\beta\langle \bar{H}^{\bar{\mathrm{Q}}}_a v_\mu\left(\mathcal{V}^\mu_{ab} - \rho^\mu_{ab}\right)H^{\bar{\mathrm{Q}}}_b\rangle + \mathrm{i}\lambda\langle \bar{H}^{\bar{\mathrm{Q}}}_b\sigma_{\mu\nu}F^{\mu\nu}(\rho)\bar{H}^{\bar{\mathrm{Q}}}_a\rangle, \tag{7}$$

$$\mathcal{L}_{HH\sigma} = g_{\mathrm{s}}\langle \bar{H}^{\bar{\mathrm{Q}}}_a\sigma\bar{H}^{\bar{\mathrm{Q}}}_a\rangle, \tag{8}$$

which satisfies Lorentz and C, P, T invariance, where $\langle\cdots\rangle$ denotes the trace over the the 3×3 matrices. The multiplet field H composed of the pseudoscalar $\mathcal{P}$ and vector $\mathcal{P}^*$ with $\mathcal{P}^{(*)\mathrm{T}} = (\mathrm{D}^{(*)0}, \mathrm{D}^{(*)+}, \mathrm{D}^{(*)+}_{\mathrm{s}})$ or $(\mathrm{B}^{(*)-}, \bar{\mathrm{B}}^{(*)0}, \bar{\mathrm{B}}^{(*)0}_{\mathrm{s}})$ is defined as $H^{\bar{Q}}_a = [\tilde{\mathcal{P}}^{*\mu}_a\gamma_\mu - \tilde{\mathcal{P}}_a\gamma_5]\frac{1-\not{v}}{2}$ and $\bar{H} = \gamma_0 H^\dagger\gamma_0$ with $v = (1, \mathbf{0})$. The $\tilde{\mathcal{P}}$ and $\tilde{\mathcal{P}}^*$ satisfy the normalization relations $\langle 0|\tilde{\mathcal{P}}|\bar{Q}q(0^-)\rangle = \sqrt{M_{\mathcal{P}}}$ and $\langle 0|\tilde{\mathcal{P}}^*_\mu|\bar{Q}q(1^-)\rangle = \epsilon_\mu\sqrt{M_{\mathcal{P}^*}}$. In the above expressions, the axial current is $A^\mu = \frac{1}{2}(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger) = \frac{\mathrm{i}}{f_\pi}\partial_\mu\mathbb{P} + \cdots$ with $\xi = \exp(\mathrm{i}\mathbb{P}/f_\pi)$ and $f_\pi = 132$ MeV. $\rho^\mu_{ba} = \mathrm{i}g_V\mathbb{V}^\mu_{ba}/\sqrt{2}$, $F_{\mu\nu}(\rho) = \partial_\mu\rho_\nu - \partial_\nu\rho_\mu + [\rho_\mu,\ \rho_\nu]$, and $g_V = m_\rho/f_\pi$. Here, $\mathbb{P}$ and $\mathbb{V}$ are the pseudoscalar and vector matrices

$$\mathbb{P} = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}, \tag{9}$$

$$\mathbb{V} = \begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}. \tag{10}$$

Thus, Eqs. (6)–(8) can be further expanded as follows:

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{P}} = \mathrm{i}\frac{2g}{f_\pi}\varepsilon_{\alpha\mu\nu\lambda}v^\alpha\tilde{\mathcal{P}}^{*\mu\dagger}_a\tilde{\mathcal{P}}^{*\lambda}_b\partial^\nu\mathbb{P}_{ab}, \tag{11}$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}\mathbb{P}} = \frac{2g}{f_\pi}\left(\tilde{\mathcal{P}}^{*\dagger}_{a\lambda}\tilde{\mathcal{P}}_b + \tilde{\mathcal{P}}^\dagger_a\tilde{\mathcal{P}}^*_{b\lambda}\right)\partial^\lambda\mathbb{P}_{ab}, \tag{12}$$

$$\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\mathbb{V}} = \sqrt{2}\beta g_V\tilde{\mathcal{P}}^\dagger_a\tilde{\mathcal{P}}_b v\cdot\mathbb{V}_{ab}, \tag{13}$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}\mathbb{V}} = -2\sqrt{2}\lambda g_V v^\lambda\varepsilon_{\lambda\mu\alpha\beta}(\tilde{\mathcal{P}}^{*\mu\dagger}_a\tilde{\mathcal{P}}_b + \tilde{\mathcal{P}}^\dagger_a\tilde{\mathcal{P}}^{*\mu}_b)\left(\partial^\alpha\mathbb{V}^\beta\right)_{ab}, \tag{14}$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{V}} = -\sqrt{2}\beta g_V\tilde{\mathcal{P}}^{*\dagger}_a\cdot\tilde{\mathcal{P}}^*_b v\cdot\mathbb{V}_{ab} - \mathrm{i}2\sqrt{2}\lambda g_V\tilde{\mathcal{P}}^{*\mu\dagger}_a\tilde{\mathcal{P}}^{*\nu}_b\left(\partial_\mu\mathbb{V}_\nu - \partial_\nu\mathbb{V}_\mu\right)_{ab}, \tag{15}$$

$$\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\sigma} = -2g_{\mathrm{s}}\tilde{\mathcal{P}}_b\tilde{\mathcal{P}}^\dagger_b\sigma, \tag{16}$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\sigma} = 2g_{\mathrm{s}}\tilde{\mathcal{P}}^*_b\cdot\tilde{\mathcal{P}}^{*\dagger}_b\sigma. \tag{17}$$

The effective Lagrangians depicting the S-wave heavy flavor baryons with the light mesons with chiral symmetry, heavy quark limit and hidden local symmetry are [41]

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}} = \frac{1}{2}\langle\bar{\mathcal{B}}_{\bar{3}}(\mathrm{i}v\cdot D)\mathcal{B}_{\bar{3}}\rangle+\mathrm{i}\beta_{\mathrm{B}}\langle\bar{\mathcal{B}}_{\bar{3}}v^{\mu}(\mathcal{V}_{\mu}-\rho_{\mu})B_{\bar{3}}\rangle +\ell_{\mathrm{B}}\langle\bar{\mathcal{B}}_{\bar{3}}\sigma\mathcal{B}_{\bar{3}}\rangle, \quad (18)$$

$$\begin{aligned}\mathcal{L}_{\mathrm{S}} = &-\langle\bar{\mathcal{S}}^{\alpha}(\mathrm{i}v\cdot D-\Delta_{\mathrm{B}})\mathcal{S}_{\alpha}\rangle \\ &-\frac{3}{2}g_1\epsilon^{\mu\nu\lambda\kappa}v_{\kappa}\langle\bar{\mathcal{S}}_{\mu}A_{\nu}\mathcal{S}_{\lambda}\rangle \\ &+\mathrm{i}\beta_{\mathrm{S}}\langle\bar{\mathcal{S}}_{\mu}v_{\alpha}(\mathcal{V}^{\alpha}-\rho^{\alpha})\mathcal{S}^{\mu}\rangle \\ &+\lambda_{\mathrm{S}}\langle\bar{\mathcal{S}}_{\mu}F^{\mu\nu}(\rho)\mathcal{S}_{\nu}\rangle+\ell_{\mathrm{S}}\langle\bar{\mathcal{S}}_{\mu}\sigma\mathcal{S}^{\mu}\rangle.\end{aligned} \quad (19)$$

Here, $\mathcal{S}_{\mu}^{ab}$ is composed of Dirac spinor operators

$$\mathcal{S}_{\mu}^{ab} = -\sqrt{\frac{1}{3}}(\gamma_{\mu}+v_{\mu})\gamma^5\mathcal{B}_6^{ab}+\mathcal{B}_{6\mu}^{*ab}, \quad (20)$$

$$\bar{\mathcal{S}}_{\mu}^{ab} = \sqrt{\frac{1}{3}}\bar{\mathcal{B}}_6^{ab}\gamma^5(\gamma_{\mu}+v_{\mu})+\bar{\mathcal{B}}_{6\mu}^{*ab}. \quad (21)$$

$\mathcal{V}_{\mu}=\frac{1}{2}(\xi^{\dagger}\partial_{\mu}\xi+\xi\partial_{\mu}\xi^{\dagger})=\frac{\mathrm{i}}{2f_{\pi}^2}[\mathbb{P},\partial_{\mu}\mathbb{P}]+\cdots$. In the above expressions, $\mathcal{B}_{\bar{3}}$ and $\mathcal{B}_6$ denote the multiplets with $J^P=1/2^+$ in $\bar{3}_{\mathrm{F}}$ and 6_{F} flavor representations, respectively, while $\mathcal{B}_{6^*}$ is the multiplet with $J^P=3/2^+$ in 6_{F} flavor representation. Here, the $\mathcal{B}_{\bar{3}}$ and $\mathcal{B}_6$ matrices are

$$\mathcal{B}_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_{\mathrm{c}}^{+} & \Xi_{\mathrm{c}}^{+} \\ -\Lambda_{\mathrm{c}}^{+} & 0 & \Xi_{\mathrm{c}}^{0} \\ -\Xi_{\mathrm{c}}^{+} & -\Xi_{\mathrm{c}}^{0} & 0 \end{pmatrix}, \quad (22)$$

$$\mathcal{B}_6 = \begin{pmatrix} \Sigma_{\mathrm{c}}^{++} & \frac{1}{\sqrt{2}}\Sigma_{\mathrm{c}}^{+} & \frac{1}{\sqrt{2}}\Xi_{\mathrm{c}}^{\prime+} \\ \frac{1}{\sqrt{2}}\Sigma_{\mathrm{c}}^{+} & \Sigma_{\mathrm{c}}^{0} & \frac{1}{\sqrt{2}}\Xi_{\mathrm{c}}^{\prime0} \\ \frac{1}{\sqrt{2}}\Xi_{\mathrm{c}}^{\prime+} & \frac{1}{\sqrt{2}}\Xi_{\mathrm{c}}^{\prime0} & \Omega_{\mathrm{c}}^{0} \end{pmatrix}. \quad (23)$$

Additionally, $D_{\mu}\mathcal{B}_{\bar{3}}=\partial_{\mu}\mathcal{B}_{\bar{3}}+\mathcal{V}_{\mu}\mathcal{B}_{\bar{3}}+\mathcal{B}_{\bar{3}}\mathcal{V}_{\mu}^{\mathrm{T}}$ and $D_{\mu}\mathcal{S}_{\nu}=\partial_{\mu}\mathcal{S}_{\nu}+\mathcal{V}_{\mu}\mathcal{S}_{\nu}+\mathcal{S}_{\nu}\mathcal{V}_{\mu}^{\mathrm{T}}$.

With Eqs. (18)–(19), we obtain the explicit effective Lagrangians

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}\mathbb{V}} = \frac{\beta_{\mathrm{B}}g_V}{\sqrt{2}}\langle\bar{\mathcal{B}}_{\bar{3}}\ v\cdot\mathbb{V}\ \mathcal{B}_{\bar{3}}\rangle, \quad (24)$$

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}\sigma} = \ell_{\mathrm{B}}\langle\bar{\mathcal{B}}_{\bar{3}}\ \sigma\ \mathcal{B}_{\bar{3}}\rangle, \quad (25)$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = \frac{\mathrm{i}g_1}{2f_{\pi}}\epsilon^{\mu\nu\lambda\kappa}v_{\kappa}\langle\bar{\mathcal{B}}_6\ \gamma_{\mu}\gamma_{\lambda}\partial_{\nu}\mathbb{P}\ \mathcal{B}_6\rangle, \quad (26)$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{V}} = -\frac{\beta_{\mathrm{S}}g_V}{\sqrt{2}}\langle\bar{\mathcal{B}}_6\ v\cdot\mathbb{V}\ \mathcal{B}_6\rangle -\frac{\mathrm{i}\lambda_{\mathrm{S}}g_V}{3\sqrt{2}}\langle\bar{\mathcal{B}}_6\gamma_{\mu}\gamma_{\nu}(\partial^{\mu}\mathbb{V}^{\nu}-\partial^{\nu}\mathbb{V}^{\mu})\mathcal{B}_6\rangle, \quad (27)$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\sigma} = -\ell_{\mathrm{S}}\langle\bar{\mathcal{B}}_6\ \sigma\ \mathcal{B}_6\rangle. \quad (28)$$

We list the values of the coupling constants in Eqs. (11)–(17) and (24)–(28) in Table 2, which are given in literature [41, 49, 50].

2.3 The OBE potential

We apply the constructed effective Lagrangians to deduce the OBE potential of the hidden-charm molecular baryons. When calculating the OBE potential, we first need to relate the scattering amplitude with the OBE potential in the momentum space, which is from the Breit approximation

$$V(\boldsymbol{q})=-\frac{1}{\sqrt{\prod_{\mathrm{i}}2M_{\mathrm{i}}\prod_{\mathrm{f}}2M_{\mathrm{f}}}}M(J,J_Z), \quad (29)$$

where M_{i} and M_{f} are the masses of the initial and final states, respectively. Here, when deducing scattering amplitude, the monopole form factor $F(\boldsymbol{q}^2)=(\Lambda^2-m_{\mathrm{i}}^2)/(\Lambda^2-q^2)$ is introduced for compensating the off shell effect of the exchanged meson and describing the structure effect of every interaction vertex. After performing the Fourier transformation, we finally obtain the effective potential in the coordinate space.

In terms of the method presented in Eq. (29), we obtain the effective potentials for $\Lambda_{\mathrm{c}}\bar{\mathrm{D}}\to\Lambda_{\mathrm{c}}\bar{\mathrm{D}}$, $\Lambda_{\mathrm{c}}\bar{\mathrm{D}}^*\to\Lambda_{\mathrm{c}}\bar{\mathrm{D}}^*$, $\Sigma_{\mathrm{c}}\bar{\mathrm{D}}\to\Sigma_{\mathrm{c}}\bar{\mathrm{D}}$, $\Sigma_{\mathrm{c}}\bar{\mathrm{D}}^*\to\Sigma_{\mathrm{c}}\bar{\mathrm{D}}^*$ scattering processes by exchanging {ω, σ}, {ω, σ}, {ρ, ω, σ} and {π, η, ρ, ω, σ}, respectively. The corresponding expressions of the effective potential are

$$\mathcal{V}_{\Lambda_{\mathrm{c}}\bar{\mathrm{D}}}^{I=\frac{1}{2}}(r) = -2g_{\mathrm{S}}l_{\mathrm{B}}Y(\Lambda,m_{\sigma},r) -\frac{1}{2}\beta\beta_{\mathrm{B}}g_V^2Y(\Lambda,m_{\omega},r), \quad (30)$$

$$\mathcal{V}_{\Lambda_{\mathrm{c}}\bar{\mathrm{D}}^*}^{I=\frac{1}{2}}(r) = -2g_{\mathrm{S}}l_{\mathrm{B}}\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^{\dagger}Y(\Lambda,m_{\sigma},r) -\frac{1}{2}\beta\beta_{\mathrm{B}}g_V^2\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^{\dagger}Y(\Lambda,m_{\omega},r), \quad (31)$$

Table 2. The parameters and coupling constants adopted in our calculation [15, 41, 49, 50].

β	g	g_V	λ/GeV^{-1}	g_{S}	β_{B}	β_{S}	ℓ_{B}	ℓ_{S}	g_1	λ_{S}/GeV^{-1}
0.9	0.59	5.8	0.56	0.76	−0.87	1.74	-3.1	6.2	0.94	3.31

$$\mathcal{V}^{I=\frac{3}{2}}_{\Sigma_c\bar{D}}(r) = -l_S g_S Y(\Lambda,m_\sigma,r)+\left[-\frac{1}{4}\beta\beta_S g_V^2 Y(\Lambda,m_\rho,r)-\frac{1}{4}\beta\beta_S g_V^2 Y(\Lambda,m_\omega,r)\right], \tag{32}$$

$$\mathcal{V}^{I=\frac{1}{2}}_{\Sigma_c\bar{D}}(r) = -l_S g_S Y(\Lambda,m_\sigma,r)+\left[\frac{1}{2}\beta\beta_S g_V^2 Y(\Lambda,m_\rho,r)-\frac{1}{4}\beta\beta_S g_V^2 Y(\Lambda,m_\omega,r)\right], \tag{33}$$

$$\begin{aligned}\mathcal{V}^{I=\frac{1}{2}}_{\Sigma_c\bar{D}^*}(r) =& -g_S l_S \boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger Y(\Lambda,m_\sigma,r)+\Bigg\{-\Bigg[\frac{1}{2}\beta\beta_S g_V^2\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger Y(\Lambda,m_\rho,r)-\frac{2\lambda\lambda_S g_V^2}{3}\Bigg(-\frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\rho,r)\\ &+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\rho,r)\Bigg)\Bigg]+\frac{1}{2}\Bigg[\frac{1}{2}\beta\beta_S g_V^2\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger Y(\Lambda,m_\omega,r)-\frac{2\lambda\lambda_S g_V^2}{3}\Big(-\frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\omega,r)\\ &+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\omega,r)\Big)\Bigg]\Bigg\}+\Bigg\{\frac{gg_1}{f_\pi^2}\Bigg[\frac{1}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\pi,r)+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\pi,r)\Bigg]\\ &-\frac{gg_1}{6f_\pi^2}\Bigg[\frac{1}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\eta,r)+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\eta,r)\Bigg]\Bigg\},\end{aligned} \tag{34}$$

$$\begin{aligned}\mathcal{V}^{I=\frac{3}{2}}_{\Sigma_c\bar{D}^*}(r) =& -g_S l_S \boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger Y(\Lambda,m_\sigma,r)+\Bigg\{\frac{1}{2}\Bigg[\frac{1}{2}\beta\beta_S g_V^2\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger Y(\Lambda,m_\rho,r)-\frac{2\lambda\lambda_S g_V^2}{3}\Bigg(-\frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\rho,r)\\ &+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\rho,r)\Bigg)\Bigg]+\frac{1}{2}\Bigg[\frac{1}{2}\beta\beta_S g_V^2\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger Y(\Lambda,m_\omega,r)-\frac{2\lambda\lambda_s g_V^2}{3}\Big(-\frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\omega,r)\\ &+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\omega,r)\Big)\Bigg]\Bigg\}+\Bigg\{-\frac{gg_1}{2f_\pi^2}\Bigg[\frac{1}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\pi,r)+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\pi,r)\Bigg]\\ &-\frac{gg_1}{6f_\pi^2}\Bigg[\frac{1}{3}\boldsymbol{\sigma}\cdot\boldsymbol{T}Z(\Lambda,m_\eta,r)+\frac{1}{3}S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})T(\Lambda,m_\eta,r)\Bigg]\Bigg\},\end{aligned} \tag{35}$$

with

$$Y(\Lambda,m_E,r) = \frac{1}{4\pi r}\left(e^{-m_E r}-e^{-\Lambda r}\right)-\frac{\Lambda^2-m_E^2}{8\pi\Lambda}e^{-\Lambda r}, \tag{36}$$

$$Z(\Lambda,m_E,r) = \nabla^2 Y(\Lambda,m_E,r), \tag{37}$$

$$T(\Lambda,m_E,r) = r\frac{\partial}{\partial r}\frac{1}{r}\frac{\partial}{\partial r}Y(\Lambda,m_E,r). \tag{38}$$

Here, in the above expressions we define $S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T}) = 3\hat{\boldsymbol{r}}\cdot\boldsymbol{\sigma}\ \hat{\boldsymbol{r}}\cdot\boldsymbol{T} - \boldsymbol{\sigma}\cdot\boldsymbol{T}$ and $\boldsymbol{T}=i\boldsymbol{\epsilon}_4^\dagger\times\boldsymbol{\epsilon}_2$.

With effective potentials shown in Eqs. (30)–(35), we finally obtain the total effective potentials of the hidden-charm systems composed of anti-charmed mesons and charmed baryons. The effective potentials shown in Eqs. (30)–(35) should be sandwiched between the states in Eqs. (4)–(5). We take the $\Sigma_c\bar{D}^*$ system with $I\left(\frac{3}{2}^-\right)$ as an example. Its total effective potential can be expressed as

$$V^{\rm total}(r) = {}_1\left\langle I\left(\frac{3}{2}^-\right)\middle|\mathcal{V}^{I=\frac{3}{2}}_{\Sigma_c\bar{D}^*}(r)\middle|I\left(\frac{3}{2}^-\right)\right\rangle_1, \tag{39}$$

which is a three-by-three matrix. Using the same approach, we can obtain the total effective potential of the other systems with definite $I(J^P)$ quantum number. In Table 3, we list the matrixes corresponding to operators $\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger$, $\boldsymbol{\sigma}\cdot\boldsymbol{T}$ and $S(\hat{\boldsymbol{r}},\ \boldsymbol{\sigma},\ \boldsymbol{T})$ in Eqs. (30)–(35) when transferring the potentials in Eqs. (30)–(35) into the total effective potentials of the hidden-charm systems composed of the anti-charmed mesons and charmed baryons.

The kinetic terms are

$$K_{|I(\frac{1}{2}^-)\rangle_0} = -\frac{\Delta}{2\tilde{m}}, \tag{40}$$

$$K_{|I(\frac{1}{2}^-)\rangle_1} = {\rm diag}\left(-\frac{\Delta}{2\tilde{m}},\ -\frac{\Delta_2}{2\tilde{m}}\right), \tag{41}$$

$$K_{|I(\frac{3}{2}^-)\rangle_1} = {\rm diag}\left(-\frac{\Delta}{2\tilde{m}},\ -\frac{\Delta_2}{2\tilde{m}},\ -\frac{\Delta_2}{2\tilde{m}}\right), \tag{42}$$

corresponding to the systems in Eqs. (1)–(3), respectively, where $\Delta = \frac{1}{r^2}\frac{\partial}{\partial r}r^2\ \frac{\partial}{\partial r}$, $\Delta_2 = \Delta-\frac{6}{r^2}$. $\tilde{m}=m_B m_{P^{(*)}}/(m_B+m_{P^{(*)}})$ is the reduced mass of

Table 3. The matrixes corresponding to $_1\left\langle I\left(\frac{1}{2}^-\right)\middle|\mathcal{O}_i\middle|I\left(\frac{1}{2}^-\right)\right\rangle_1$ and $_1\left\langle I\left(\frac{3}{2}^-\right)\middle|\mathcal{O}_i\middle|I\left(\frac{3}{2}^-\right)\right\rangle_1$, where $\mathcal{O}_i$ denotes operators $\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger$, $\boldsymbol{\sigma}\cdot\boldsymbol{T}$ and $S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})$ in Eqs. (30)–(35). Here, $\left|I\left(\frac{1}{2}^-\right)\right\rangle_1$ and $\left|I(\frac{3}{2}^-)\right\rangle_1$ are defined in Eqs. (2)–(3).

	$\boldsymbol{\epsilon}_2\cdot\boldsymbol{\epsilon}_4^\dagger$	$\boldsymbol{\sigma}\cdot\boldsymbol{T}$	$S(\hat{\boldsymbol{r}},\boldsymbol{\sigma},\boldsymbol{T})$
$_1\left\langle I\left(\frac{1}{2}^-\right)\middle|\mathcal{O}_i\middle|I\left(\frac{1}{2}^-\right)\right\rangle_1$	$\begin{pmatrix}1&0\\0&1\end{pmatrix}$	$\begin{pmatrix}2&0\\0&-1\end{pmatrix}$	$\begin{pmatrix}0&-\sqrt{2}\\-\sqrt{2}&2\end{pmatrix}$
$_1\left\langle I\left(\frac{3}{2}^-\right)\middle|\mathcal{O}_i\middle|I\left(\frac{3}{2}^-\right)\right\rangle_1$	$\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$	$\begin{pmatrix}-1&0&0\\0&2&0\\0&0&-1\end{pmatrix}$	$\begin{pmatrix}0&1&-2\\1&0&-1\\-2&-1&0\end{pmatrix}$

the system, where $m_{\rm B}$ and $m_{{\rm P}^{(*)}}$ are the masses of charmed baryon and pseudoscalar (vector) anti-charmed meson, respectively.

3 Numerical results

In this work, we mainly investigate the hidden-charm systems $\Lambda_{\rm c}\bar{\rm D}$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\Lambda_{\rm c}\bar{\rm D}^*$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{3}{2}^-\right)$, $\Sigma_{\rm c}\bar{\rm D}$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$, $\Sigma_{\rm c}\bar{\rm D}^*$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$, $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$. If we replace $\bar{\rm D}^{(*)}$ and the charmed baryon by the corresponding ${\rm B}^{(*)}$ and bottom baryon, we can extend the same formalism listed to discuss the hidden-bottom molecular baryons composed of a bottom meson and a bottom baryon, which include $\Lambda_{\rm b}{\rm B}$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\Lambda_{\rm b}{\rm B}^*$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{3}{2}^-\right)$, $\Sigma_{\rm b}{\rm B}$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$, $\Sigma_{\rm b}{\rm B}^*$ with $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$, $\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$.

Using the potential obtained above, the binding energy can be obtained by solving the coupled-channel Schrödinger equation. We use the FESSDE program [51] to produce the numerical results for the binding energy and the corresponding root-mean-square radius r with the variation of the cutoff Λ in the region of $0.8 \leqslant \Lambda \leqslant 2.2$ GeV, as shown in Fig. 2. Here, we only show the bound state solution with binding energy less than 50 MeV since the OBE model is only valid for dealing with the loosely bound hadronic molecular system.

One notices that $\Lambda_{\rm c}$ does not combine with $\bar{\rm D}^{(*)}$ to form a hidden-charm molecular state. There does exist a hidden-bottom molecular state composed of $\Lambda_{\rm b}$ and ${\rm B}^{(*)}$. As shown in Fig. 2, we find bound state solutions for only five hidden-charm states, i.e. $\Sigma_{\rm c}\bar{\rm D}^*$ states with $I(J^P)=\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{3}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$ and $\Sigma_{\rm c}\bar{\rm D}$ states with $\frac{3}{2}\left(\frac{1}{2}^-\right)$. We also find the bound state solutions for the hidden-bottom molecular baryons, which are $\Sigma_{\rm b}{\rm B}^*$ states with $I(J^P)=\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{3}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$ and $\Sigma_{\rm b}{\rm B}$ with $\frac{3}{2}\left(\frac{1}{2}^-\right)$.

For the heavy baryon sector, we adopt the values of coupling constants, including the signs as given in

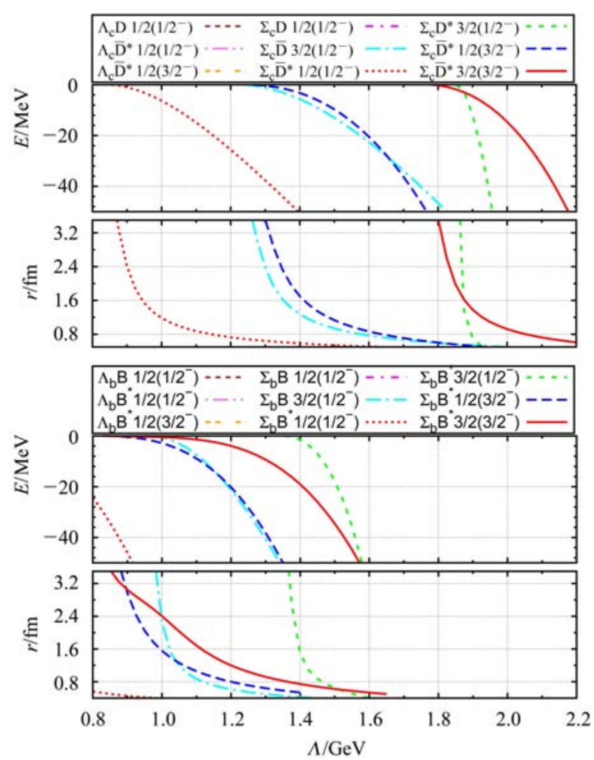

Fig. 2. (Color online). The Λ dependence of the binding energy and the obtained root-mean-square radius r of the hidden-charm or hidden-bottom system.

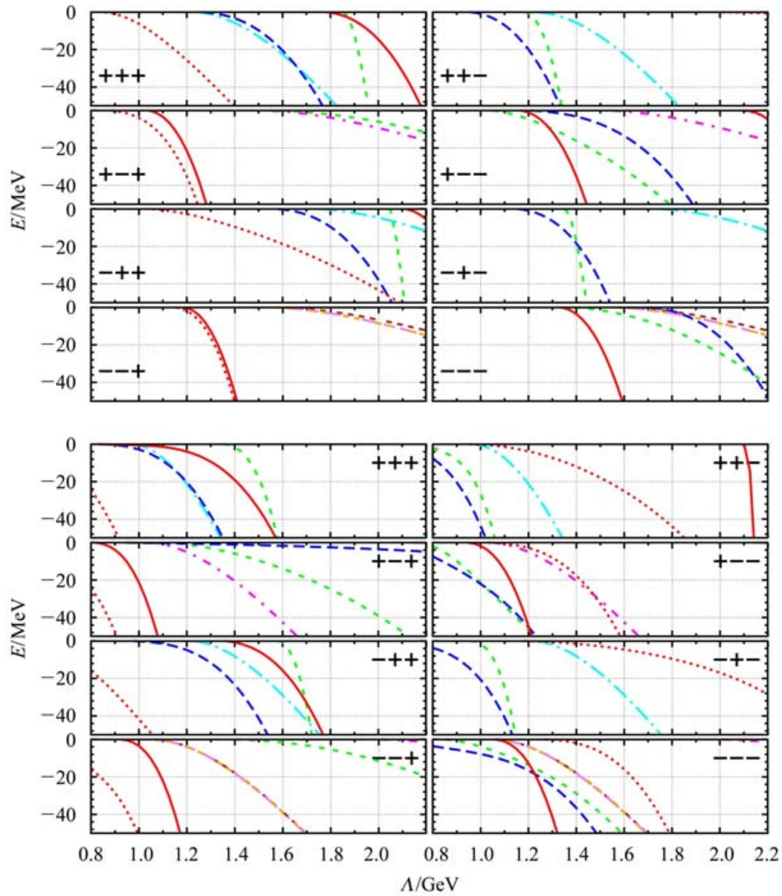

Fig. 3. (color online). The binding energy of the hidden-charm state (top) or hidden-bottom state (bottom). Here, +/− in "$\pm1\pm1\pm1$" denotes that we need to multiply the corresponding sigma, vector and pion exchange potentials by an extra factor, $+1/-1$, which comes from the changes of the signs of the coupling constants. The other conventions are the same as in Fig. 2.

Ref. [41]. However, for the heavy meson sector, the signs of the coupling constants g, β/λ, g_S, cannot be well constrained by the available experimental data or theoretical considerations, which results in uncertainty of the signs of the corresponding sigma, vector and pion exchange potentials. For the sake of completeness, we present the dependence of the binding energy on Λ under eight combinations of the signs of g, β/λ, g_S, as shown in Fig. 3. The notation +/− denotes an extra factor $+1/-1$, which changes the signs of g, β/λ, g_S in the corresponding pion, vector and sigma exchange potentials. Generally speaking, the sigma exchange contribution is negligible, while the π and ρ/ω meson exchanges play a very important role.

4 Discussion and conclusion

In this work we employed the OBE model to study whether the loosely bound hidden-charm molecular states composed of an S-wave anti-charmed meson and an S-wave charmed baryon do exist. Our numerical results indicate that $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not exist, due to the absence of bound state solution, which is an interesting observation in this work. Additionally, we only notice the bound state solutions for five hidden-charm states, i.e. $\Sigma_c\bar{D}^*$ states with $I(J^P)=\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{3}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$ and $\Sigma_c\bar{D}$ states with $\frac{3}{2}\left(\frac{1}{2}^-\right)$. We also extend the same formulism to study a hidden-bottom system with an S-wave bottom meson and an S-wave bottom baryon. The mass of the component in the hidden-bottom system is heavier than that in the hidden-charm system, which leads to reduced kinetic energy and is helpful in the formation of the loosely bound states. Our numerical results confirmed this point. The $\Sigma_b B^*$ molecular states with $I(J^P)=\frac{1}{2}\left(\frac{1}{2}^-\right)$, $\frac{1}{2}\left(\frac{3}{2}^-\right)$, $\frac{3}{2}\left(\frac{1}{2}^-\right)$, $\frac{3}{2}\left(\frac{3}{2}^-\right)$ and the $\Sigma_b B$ state with $\frac{3}{2}\left(\frac{1}{2}^-\right)$ do exist. The above conclusion is from Fig. 2. If the signs of the coupling constants are changed, the results of the bound state solution can be found in Fig. 3.

Hidden-charm systems, composed of an S-wave anti-charmed meson and an S-wave charmed baryon, are very interesting. Since the masses of such exotic systems are around 4 GeV, they may be accessible to the forthcoming PANDA, Belle-II and SuperB experiments. These exotic hidden-bottom baryons might also be searched for at J-PARC or LHCb. The exploration of these states may shed some light on the mechanism of forming molecular states and help reveal the underlying structures of some of these newly observed near-threshold hadrons.

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