Possible molecular states from interactions of charmed baryons

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In this work, we perform a systematic study of possible molecular states composed of two charmed baryons including hidden-charm systems ΛcΛc, Σc+Σc−, and ΛcΣc, and corresponding double-charm systems ΛcΛc, Σc+Σc−, and ΛcΣc. With the help of the heavy quark chiral effective Lagrangians, the interactions are described with π, ρ, η, ω, φ, and σ exchanges. The potential kernels are constructed, and inserted into the quasipotential Bethe-Salpeter equation. The bound states from the interactions considered is studied by searching for the poles of the scattering amplitude. The results suggest that strong attractions exist in both hidden-charm and double-charm systems considered in the current work, and bound states can be produced in most of the systems. More experimental studies about these molecular states are suggested though the nucleon-nucleon collision at LHC and nucleon-antinucleon collision at PANDA.

I. INTRODUCTION

With the development of the experimental technology, a large amount of data accumulated in experiment provide opportunity to the study of the hadron spectrum. In the recent years, more and more hadrons have been observed in experiment [1]. Many of these new observed hadrons cannot be put into the conventional quark model, which is the basic frame to understand the hadron spectrum [2, 3]. A growing number of efforts have been paid to explain their origin and internal structure. An obvious observation is that many newly observed particles are close to the threshold of two hadrons, so a popular picture to understand these exotic hadrons is the molecular state, which is a loosely bound state of hadrons. The XYZ particles, such as X(3872), Zc(3900) and Zc(10610) and Zc(10650), were widely assigned as molecular states in the literature [4–8]. Particularly, the observed hidden-charm pentaquarks provide a wonderful spectrum of molecular states composed of an anticharmed meson and a charmed baryon [9–15]. Such picture is enhanced by the recent observed strange hidden-charm pentaquarks [16–19]. However, though the well-known deuteron and the dibaryon with nucleon, Λ, and Λ baryon were predicted and studied in both theory and experiment very far before the XYZ particle and pentaquarks, few predicted molecular states of two baryons are observed in experiment [1, 20]. Some theoretical studies have been performed to discuss the possibility of existence of molecular states composed of two baryons beyond nucleon, Λ, and Λ baryon [21–26].

Most of the molecular state candidates observed in the past two decades are in the hidden-charm sector. Hence, it is natural to expect the molecular state composed of a charmed baryon and an anticharmed baryon. In recent years, the structures near the ΛcΛc threshold has attracted much attention. A charmoniumlike Y(4630) with quantum numbers JPC = 1−− was observed at Belle [27]. After the experimental discovery of Y(4630), many theoretical works have performed to understand its origin, such as conventional charmonium state [28, 29] and compact multiquark state [30–33]. Due to the closeness of the mass of Y(4630) and the ΛcΛc threshold, the relation between Y(4630) and the threshold effect was studies in Ref. [24]. In Ref. [35], the mechanism of Y(4630) enhancement in ΛcΛc electroproduction was also studied. The ΛcΛc molecular state also attracts much attention [21, 33–35]. Theoretical calculations suggest strong attraction between a Λc baryon and an Λc baryon by σ and ω exchanges, which favors the existence of a ΛcΛc molecular state [21, 35]. In our previous work, the ΛcΛc molecular state can be produced from the interaction, but it is difficult to be used to interpret the Y(4630) [25]. The studies of more molecular states with a charmed baryon and an anticharmed baryon are also helpful to understand this exotic structure. In the current work, the interactions ΛcΛc, Σc+Σc−, and ΛcΣc will be studied in a quasipotential Bethe-Salpeter equation (qBSE) approach.

In our model, the double-charm molecular states can be obtained by replacing the anticharmed hadron by a charmed hadron [36–38]. The recent experimental observation exhibits the ability to observe double-charm hadrons in experiment. The LHCb Collaboration reported a state ΣcΣc [39], which indicates the possibility of experimental observation of double-heavy molecular state. Very recently, the LHCb Collaboration observed an open charm tetraquark state Tc+c below the D0D∗++ mass threshold [40], which has already been predicted by a lot of theoretical works in the diquark and antiquark picture [41–48], also in the molecular picture [49–55]. The doubly charm dibaryon attracts some attentions from the hadron physics community [56–61]. Hence, in the current work, the double-charm systems ΛcΛc, Σc+Σc−, and ΛcΣc will be also calculated.

This article is organized as follows. After the Introduction, Section II shows the details of dynamics of the charmed baryons interactions, reduction of potential kernel and a brief introduction of the qBSE. In Section III, the numerical results are given. Finally, summary and discussion are given in Section IV.

II. THEORETICAL FRAME

To study the interactions of charmed baryons, we need to construct the potential kernel, which is performed by introducing the exchanges of pseudoscalar P, vector V and
scalar $\sigma$ mesons. The Lagrangians depicting the couplings of light mesons and baryons are required and will be presented below.

A. Relevant Lagrangians

The Lagrangians for the couplings between charmed baryon and light mesons are constructed under the heavy quark limit and chiral symmetry as [26, 62, 63],

\[
L_S = -\frac{3}{2} g_1 (\nu_m) e^{\mu \nu \lambda} \epsilon^{i j k} \left[ \tilde{S}_\mu \epsilon_{i j k} (\nu^\rho - \rho^\sigma) S^\rho \right] + \lambda_3 \tilde{S}_\mu F^\mu \epsilon_{i j k} \epsilon^{i j k} + \lambda_5 \tilde{S}_\mu \sigma S^\rho \epsilon_{i j k} \epsilon^{i j k},
\]

\[
L_{B_3} = i g_\ell [\tilde{B}_3 \sigma_c (\nu^\rho - \rho^\sigma) B_3] + \ell_B [\tilde{B}_3 \sigma B_3],
\]

\[
L_{int} = i g_\ell [\tilde{S}_\mu \epsilon_{i j k} \epsilon^{i j k} (\nu^\rho + \rho^\sigma) \tilde{S}_\nu F_{\epsilon \lambda} B_3] + H.c.,
\]

where $S_{\mu}^{ab}$ is composed of the Dirac spinor operators,

\[
S_{\mu}^{ab} = - \sqrt{\frac{3}{2}} (g_{\mu} + \nu_{\mu}) \gamma^5 B_{\mu}^{ab} + B_{\mu}^{ab} \equiv B_{\mu}^{ab} + B_{\mu}^{ab},
\]

and the bottomed baryon matrices are defined as

\[
B_3 = \begin{pmatrix}
0 & \Lambda_+^{+} & \Xi_0^{+} \\
- \Lambda^{+} & 0 & \Xi_0^{+} \\
\Xi_0^{+} & - \Xi_0^{+} & 0
\end{pmatrix}, \quad B = \begin{pmatrix}
\Sigma_+^{++} & \frac{1}{\sqrt{2}} \Sigma_0^{++} & \frac{1}{\sqrt{2}} \Xi_0^{++} \\
\frac{1}{\sqrt{2}} \Sigma_+^{++} & \Sigma_0^{++} & \Xi_0^{++} \\
\frac{1}{\sqrt{2}} \Xi_0^{++} & \frac{1}{\sqrt{2}} \Xi_0^{++} & \Omega_0^{++}
\end{pmatrix}.
\]

The explicit forms of the Lagrangians can be written as,

\[
L_{BBV} = -i \frac{3 g_1}{4 F} \epsilon^{\mu \nu \lambda} \gamma_5 P \sum_{i=0,1} \tilde{B}_i \gamma_5 \partial_\mu B_{ji},
\]

\[
L_{BBV} = - \frac{g_\ell \gamma_v}{\sqrt{2} m_B m_B} \gamma_5 P \sum_{i=0,1} \tilde{B}_i \gamma_5 \partial_\mu B_{ji},
\]

\[
L_{BB,B_{ji}} = \frac{g_\ell \gamma_B}{\sqrt{2} m_B m_B} \gamma_5 P \sum_{i=0,1} \tilde{B}_i \gamma_5 \partial_\mu B_{ji},
\]

\[
L_{BB,B_{ji}} = - \frac{g_\ell \gamma_B}{\sqrt{2} m_B m_B} \gamma_5 P \sum_{i=0,1} \tilde{B}_i \gamma_5 \partial_\mu B_{ji},
\]

\[
L_{BB,\gamma_5} = \frac{g_\ell \gamma_B}{\sqrt{2} m_B m_B} \gamma_5 P \sum_{i=0,1} \tilde{B}_i \gamma_5 \partial_\mu B_{ji} + H.c.,
\]

\[
L_{BB,\gamma_5} = \frac{g_\ell \gamma_B}{\sqrt{2} m_B m_B} \gamma_5 P \sum_{i=0,1} \tilde{B}_i \gamma_5 \partial_\mu B_{ji} + H.c.,
\]

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L_{BB,\gamma_5} = \frac{g_\ell \gamma_B}{\sqrt{2} m_B m_B} \gamma_5 P \sum_{i=0,1} \tilde{B}_i \gamma_5 \partial_\mu B_{ji} + H.c.,
\]

The $\mathbb{V}$ and $\mathbb{P}$ are the vector and pseudoscalar matrices as

\[
\mathbb{P} = \begin{pmatrix}
\frac{\sqrt{2} \rho^{+}}{\sqrt{3}} & \pi^{+} & K^{+} \\
\pi^{-} & \frac{\sqrt{2} \rho^{-}}{\sqrt{3}} & K^{0} \\
K^{-} & K^{0} & \frac{2}{\sqrt{3}}
\end{pmatrix}, \quad \mathbb{V} = \begin{pmatrix}
\frac{\rho^{+}}{\sqrt{2}} & \frac{\rho^{-}}{\sqrt{2}} & K^{+} \\
K^{-} & K^{0} & \frac{2}{\sqrt{3}}
\end{pmatrix}.
\]

The masses of particles involved in the calculation are chosen as suggested central values in the Review of Particle Physics (PDG) [1]. The mass of broad $\sigma$ meson is chosen as 500 MeV. The coupling constants involved are listed in Table I.

**TABLE I**: The coupling constants adopted in the calculation, which are cited from the literature [19, 26, 62–65]. The $\lambda$ and $\lambda_b$, are in the units of GeV$^{-1}$. Others are in the units of 1.

| $\beta$ | $g$ | $g_v$ | $\lambda$ | $g_s$ |
|--------|----|-------|-----------|------|
| $\beta_s$ | $g_s$ | $g_v$ | $\lambda$ | $g_s$ |
| 0.9 | 0.59 | 5.9 | 0.56 | 0.76 |

First, we should construct flavor wave functions with definite isospin under $SU(3)$ symmetry. In this paper, we take the following charge conjugation conventions for two-baryon system as [23],

\[
|B_1 B_2\rangle_c = \frac{1}{\sqrt{2}} |B_1 B_2\rangle - (-1)^{J_1 - J_2} C_{c_{12}} |B_2 B_1\rangle,
\]

where $J$ and $J_i$ are the spins of system $|B_1 B_2\rangle$ and $|B_i\rangle$, respectively, and $c_i$ is defined by $C(B_i) = c_i B_i$. For the isovector state, the $C$ parity cannot be defined, so we will use the $G$ parity instead as $G = (-1)^J C$ with $C = c$. Following the method in Ref. [66], we input vertices $\Gamma$ and propagators $P$ into the code directly. The potential can be written as

\[
\mathcal{V}_{\mathbb{V},\sigma} = \ell_{\mathbb{V},\sigma} \Gamma_2 \mathbb{P} \mathbb{P} f(q^2), \quad \mathcal{V}_{\mathbb{V}} = \ell_{\mathbb{V}} \Gamma_{1\mathbb{V}} \Gamma_{2\mathbb{V}} \mathbb{P} \mathbb{P} f(q^2).
\]

In this work, both hidden-charm and double-charm systems will be considered in the calculation. The well-known $G$-parity rule will be adopted to write the interaction of a charmed and an anticharmed baryon from the interaction of two charmed baryons. By inserting the $G$-parity $G$ operator into the potential, the $G$-parity rule can be obtained easily as [21, 22, 67, 68],

\[
V = \sum_i \zeta_i \mathcal{V}_{i\mathbb{V} h},
\]

The $G$ parity of the exchanged meson is left as a $\zeta_i$ factor for $i$ meson.

The propagators are defined as usual as

\[
P_{\mathbb{V},\sigma} = \frac{i}{q^2 - m_{\mathbb{V},\sigma}^2}, \quad P_{\mathbb{V}} = \frac{i}{q^2 - m_{\mathbb{V}}^2}.
\]
where the form factor $f(q^2)$ is adopted to compensate the off-shell effect of exchanged meson as $f(q^2) = e^{-m^2_{\pi}/q^2}$ with $m_{\pi}$ and $q$ being the $m_{\pi}$, $q$ and the momentum of the exchanged meson. The $I_i$ is the flavor factor for certain meson exchange $i$ of certain interaction, and the explicit values are listed in Table II.

**Table II: The flavor factors $I_i$ and $(-1)^{I_{i+1}} I_i$ of exchange $i$ for direct diagram and cross diagram, respectively. The values in bracket are for the heavy-heavy baryons if the values are different from those of heavy-antibaryons.**

| $I_i$ | $I$ | $\pi$ | $\eta$ | $\rho$ | $\omega$ | $\sigma$ |
|------|-----|-------|-------|-------|-------|-------|
| $\Lambda, \bar{\Lambda}$, $[\Lambda, \bar{\Lambda}]$ | 0 | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ |
| $\Sigma^i, \bar{\Sigma}^i$, $[\Sigma^i, \bar{\Sigma}^i]$ | 0 | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ |
| $\Lambda, \Xi, [\Lambda, \Xi]$ | 1 | $-1$ | $\frac{1}{2}$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ |
| $(-1)^{I_{i+1}} I_i$ | $I$ | $\pi$ | $\eta$ | $\rho$ | $\omega$ |
| $\Lambda, \bar{\Lambda}$, $[\Lambda, \bar{\Lambda}]$ | 1 | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ |
| $\Lambda, \Xi, [\Lambda, \Xi]$ | 1 | $-1$ | $\frac{1}{2}$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ |
| $\Sigma, \bar{\Sigma}$, $[\Sigma, \bar{\Sigma}]$ | 0 | 1 | $\frac{1}{2}$ | $\frac{1}{2}$ | $-\frac{1}{2}$ | $\frac{1}{2}$ |

With the potential kernel obtained, the qBSE is adopted to solve the scattering amplitude [7, 19, 36, 38, 69–72]. The 4-dimensional Bethe-Salpeter equation in the Minkowski space can be reduced to a 1-dimensional equation with fixed spin-parity $J^P$ as [71], after partial-wave decomposition and spectator quasipotential approximation,

$$i M^{\prime}_{x,I}(p', p) = r V^{\prime}_{x,I}(p', p) + \sum_{J''} \int \frac{p''^2 dp''}{(2\pi)^3} \cdot r V^{\prime}_{x,J''}(p', p'') G_0(p'') i M^{\prime}_{x,J''}(p'', p),$$

where the sum extends only over non-negative helicity $J''$. The $G_0(p'')$ is reduced from the 4-dimensional propagator $G(p')$ under quasipotential approximation with one of two baryons on-shell as

$$G(p') = \frac{\delta^2(p_h^2 - m_h^2)}{P_{l'}^2 - m_l^2}$$

$$\rightarrow G_0(p'') = \frac{1}{2E_0(p'')(W - E_0(p''))^2 - E_l^2(p'')}.$$
interaction, the $\omega$ exchange is repulsive, which reduces the attraction.

**FIG. 1:** The binding energies of the bound states from $\Lambda_c \bar{\Lambda}_c$ (left) and $\Lambda_c \Lambda_c$ (right) interactions with the variation of parameter $\alpha$.

**B. Interactions $\Sigma^c(\Sigma^c)^*$ and $\Sigma^c(\Sigma^c)^*$**

Different from the isoscalar $\Lambda_c$ baryon, the $\Sigma^c$ baryon is an isovector particle. Hence, more channels will be involved in certain interaction. In Fig. 2, the bound states from the $\Sigma_c \bar{\Sigma}_c$ interaction and their double-charm partners are presented. Here, the isospin $I$ can be 0, 1, or 2, and the spin $S=0$ or 1, which leads to six channels for each interaction.

**FIG. 2:** The binding energies of the bound states from $\Sigma_c \bar{\Sigma}_c$ (left) and $\Sigma_c \Sigma_c$ (right) interactions with the variation of parameter $\alpha$.

As shown in Fig. 2, bound states are produced in all channels, but with different behaviors with the variation of parameter $\alpha$. For the isoscalar hidden-charm $\Sigma_c \bar{\Sigma}_c$ system, the bound states are produced at an $\alpha$ value below 0, and the binding energies increase rapidly with the increase of $\alpha$ value. As shown in Table II, the strong attraction is from the $\rho$ exchange with a large flavor factor $-1$. The corresponding double-charm partners appear at larger $\alpha$ value, which means that it is less attractive than the hidden-charm case due to the different signs for $\pi$ and $\omega$ exchanges. The binding energies for states with different spins are almost the same. For the states with $I=1$, the binding energies at an $\alpha$ value of 0 are smaller than those with $I=0$. As shown in Table II, the flavor factors for $\rho$ and $\pi$ exchanges are half of those for $I=0$, which leads to less attraction. For the states with $I=2$, the attraction becomes weaker due to reversing the signs of the $\rho$ and $\pi$ exchanges. The hidden-charm states are produced at a small $\alpha$ value, and binding energies increase to a value larger than 30 GeV very quickly at an $\alpha$ value of about 0.7. However, the binding energies of their double-charm partners appear at $\alpha$ value of about 0.2, and increase relatively slowly.

The binding energies of the states produced from the $\Sigma^c \bar{\Sigma}_c^*$ interaction are shown in Fig. 3. Except that there are four spins $S=0, 1, 2, \text{ and } 3$, due to the flavor factors are the same as those for the $\Sigma_c \bar{\Sigma}_c$ system, the results are similar to the results in Fig. 2. For the hidden-charm system with $I=0$, there are three states with spins $J=1, 2, \text{ and } 3$ producing at an $\alpha$ value of about 0. As in the case of $\Sigma_c \bar{\Sigma}_c$, the attractions for
the corresponding double-charm systems are weaker than the hidden-charm systems. The hidden-charm bound states with \( I = 1 \) appear at an \( \alpha \) value of about 0, and the binding energies increase to 30 MeV at \( \alpha \) value about 0.7. The hidden-charm states with \( I = 2 \) appear at an \( \alpha \) value little larger than 0 while their double-charm partners appear at \( \alpha \) value of 0.5 or larger. Generally speaking, the attractions of \( \Sigma^c_1 \Sigma^*_c \) interaction are a little weaker than the case of \( \Sigma_c \Sigma_c \) interaction.

The results for the \( \Sigma_c \Sigma^*_c \) and \( \Sigma_c \Sigma^*_c \) interactions are presented in Fig. 4. For the hidden-charm states, there are two \( G \) parities, \( G = \pm 1 \), which do not involve in the double-charm sector. For the hidden-charm systems with \( I=0 \), the bound states appear at \( \alpha \) value a little below 0, and increase with the increase of the parameter \( \alpha \) to 30 MeV at \( \alpha \) value about 1. For their double-charm partners, the bound states appear at an \( \alpha \) value about 0, and the binding energies increase more slowly than the hidden-charm states. In the case with \( I=1 \), the states appear at an \( \alpha \) value of about 0, and increase to 30 MeV at an \( \alpha \) value about 1.2. The hidden-charm states with \( I = 2 \) appear at \( \alpha \) value of about 0, which is smaller than these for the double-charm states, about 0.5.

The results of the double-charm systems with \( I = 1 \) appear at an \( \alpha \) value of about 0, and the binding energies increase to 30 MeV at \( \alpha \) value about 0.7. The hidden-charm states with \( I = 2 \) appear at an \( \alpha \) value little larger than 0 while their double-charm partners appear at \( \alpha \) value of 0.5 or larger. Generally speaking, the attractions of \( \Sigma^c_1 \Sigma^*_c \) interaction are a little weaker than the case of \( \Sigma_c \Sigma_c \) interaction.

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![FIG. 4: The binding energies of the bound states from \( \Sigma_c \Sigma^*_c \) (left) and \( \Sigma_c \Sigma^*_c \) (right) interactions with the variation of parameter \( \alpha \).](image)

### IV. SUMMARY

In the current work, the study of the molecular states from interactions of charmed baryons is performed. The hidden-charm systems \( \Lambda_c \bar{\Lambda}_c \), \( \Sigma^c_1 \Sigma^*_c \), and \( \Lambda_c \Sigma^c_1 \), as well as their double-charm partners, are considered in the calculation. With the help of the Lagrangians in heavy quark limit and with chiral symmetry, the potential kernels are constructed in a one-boson-exchange model, and inserted into the qBSE to search the bound states.

The calculation suggests that the attractions widely exist in the systems of two charmed baryons. For the \( \Lambda_c \bar{\Lambda}_c \) interaction, the bound states are produced with spin parities \( J^P = 0^- \) and \( 1^- \), and their double-charm partner can be produced with a binding energies smaller than 30 MeV in a larger range of the parameter \( \alpha \). Due to the same flavor factors for the \( \Sigma_c \Sigma_c \), \( \Sigma^*_c \Sigma^*_c \) and \( \Sigma^*_c \Sigma^*_c \) interactions, the binding energies for these three interactions behave in a similar manner. The most strong attraction can be found in the case with \( I = 0 \) for both hidden-charm and doubly-charm cases due to the large \( \rho \) exchange as suggested by its flavor factor, which is consistent with the results in Ref. [23, 61]. For the interactions \( \Lambda_c \Sigma^c_1 \) and \( \Lambda_c \Sigma^c_1 \), all bound states produced are relatively stable, has a binding energy below 30 MeV in a large range of \( \alpha \) value. Generally

![FIG. 5: The binding energies of the bound states from \( \Lambda_c \Sigma^c_1 \) (upper left) and \( \Lambda_c \Sigma^c_1 \) (upper right) \( \Lambda_c \Sigma^c_1 \) (bottom left) and \( \Lambda_c \Sigma^c_1 \) (bottom right) interactions with the variation of parameter \( \alpha \).](image)
speak, the interactions of two charmed baryons are attractive, and many bound states are produced. However, only a few candidates, such as $Y(4630)$, were reported in experiment. More experiment studies about these states are suggested though the processes including the nucleon- nucleon collision at LHC and nucleon-antinucleon collision at PANDA.

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[1] R.L. Workman et al. [Particle Data Group], “Review of Particle Physics,” Prog. Theor. Exp. Phys. 2022, 083C01 (2022)
[2] S. Godfrey and N. Isgur, “Mesons in a Relativized Quark Model with Chromodynamics,” Phys. Rev. D 32, 189-231 (1985)
[3] S. Capstick and N. Isgur, “Baryons in a relativized quark model with chromodynamics,” Phys. Rev. D 34, no.9, 2809-2835 (1986)
[4] H. X. Chen, W. Chen, X. Liu and S. L. Zhu, “The hidden-charm pentaquark and tetraquark states,” Phys. Rept. 639, 1-121 (2016)
[5] F. K. Guo, C. Hanhart, U. G. Meißer, Q. Wang, Q. Zhao and B. S. Zou, “Hadronic molecules,” Rev. Mod. Phys. 90, no.1, 015004 (2018) [erratum: Rev. Mod. Phys. 94, no.2, 029901 (2022)]
[6] N. A. Tornqvist, “From the deuteron to deusons, an analysis of deuteron - like meson meson bound states,” Z. Phys. C 61, 525-537 (1994)
[7] J. He, “Study of the $B^0/B^0$ bound states in a Bethe-Salpeter approach,” Phys. Rev. D 90, no.7, 076008 (2014)
[8] Z. F. Sun, J. He, X. Liu, Z. G. Luo and S. L. Zhu, $Z_0(1061)^+$ and $Z_0(1065)^+$ as the $B^0 \bar{B}$ and $B^+ \bar{B}^-$ molecular states,” Phys. Rev. D 84, 054002 (2011)
[9] J. J. Wu, R. Molina, E. Oset and B. S. Zou, “Prediction of narrow $N'$ and $A'$ resonances with hidden charm above 4 GeV,” Phys. Rev. Lett. 105, 232001 (2010)
[10] Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, “The possible hidden-charm molecular baryons composed of anti-charmed meson and charmed baryon,” Chin. Phys. C 36, 6-13 (2012)
[11] C. W. Xiao, J. Nieves and E. Oset, “Combining heavy quark spin and local hidden gauge symmetries in the dynamical generation of hidden charm baryons,” Phys. Rev. D 88, 056012 (2013)
[12] R. Chen, X. Liu, X. Q. Li and S. L. Zhu, “Identifying exotic hidden-charm pentaquarks,” Phys. Rev. Lett. 115, no.13, 132002 (2015)
[13] J. He, “$D^{(*)}\bar{D}^{(*)}$ and $D^*\bar{D}^*$ interactions and the LHCb hidden-charmed pentaquarks,” Phys. Lett. B 753, 547 (2016)
[14] M. Z. Liu, Y. W. Fan, F. Z. Peng, M. Sánchez Sánchez, L. S. Geng, A. Hosaka and M. Pavon Valderrama, “Emergence of a complete heavy-quark spin symmetry multiplet: seven molecular pentaquarks in light of the latest LHCb analysis,” Phys. Rev. Lett. 122, no.24, 242001 (2019)
[15] J. He, “Study of $P_c(4457)$, $P_c(4440)$, and $P_c(4312)$ in a quasipotential Bethe-Salpeter equation approach,” Eur. Phys. J. C 79, no.5, 393 (2019)
[16] F. Z. Peng, M. J. Yan, M. Sánchez Sánchez and M. P. Valderrama, “The $P_c(4459)$ pentaquark from a combined effective field theory and phenomenological perspective,” Eur. Phys. J. C 81, no.7, 666 (2021)
[17] Z. G. Wang, “Analysis of the $P_c(4459)$ as the hidden-charm pentaquark state with QCD sum rules,” Int. J. Mod. Phys. A 36, no.10, 2150071 (2021)
[18] R. Chen, J. He and X. Liu, “Possible strange hidden-charm pentaquarks from $\Sigma^{(*)}\bar{D}^*$ and $\Xi^{(*)}\bar{D}^*$ interactions,” Chin. Phys. C 41, no.10, 103105 (2017)
[19] J. T. Zhu, L. Q. Song and J. He, “$P_c(4459)$ and other possible molecular states from $\Xi^{(*)}\bar{D}^*$ and $\Xi^{(*)}\bar{D}^*$ interactions,” Phys. Rev. D 103, no.7, 074007 (2021)
[20] H. Clement, “On the History of Dibaryons and their Final Observation,” Prog. Part. Nucl. Phys. 93, 195 (2017)
[21] N. Lee, Z. G. Luo, X. L. Chen and S. L. Zhu, “Possible Deuteron-like Molecular States Composed of Heavy Baryons,” Phys. Rev. D 84 (2011), 014031
[22] J. T. Zhu, Y. Liu, D. Y. Chen, L. Jiang and J. He, “$X(2239)$ and $\eta(2225)$ as hidden-strange molecular states from $\Lambda \bar{\Lambda}$ interaction,” Chin. Phys. C 44 (2020) no.12, 123103
[23] X. K. Dong, F. K. Guo and B. S. Zou, “A survey of heavy-antihadronic molecules,” Progr. Phys. 41 (2021), 65-93
[24] E. van Beveren, X. Liu, R. Coimbra and G. Rupp, “Possible ps(5S), psi(4D), psi(6S) and psi(6D) signals in Lambda(c) anti-Lambda(c)”, EPL 85 (2009) no.6, 61002
[25] L. Q. Song, D. Song, J. T. Zhu and J. He, “Possible $\Lambda\bar{\Lambda}$ molecular states and their productions in nucleon-antinucleon collision,” [arXiv:2207.13957 [hep-ph]].
[26] Y. R. Liu and M. Oka, “$A\bar{N}$ bound states revisited,” Phys. Rev. D 85, 014015 (2012)
[27] G. Pakhlova et al. [Belle], “Observation of a near-threshold enhancement in the $e^+e^- \rightarrow \Lambda(1520)_c^*\Lambda(1520)_c$ cross section using initial-state radiation,” Phys. Rev. Lett. 101, 172001 (2008)
[28] A. M. Badalian, B. L. G. Bakker and I. V. Danilkin, “The $S$ - $D$ mixing and di-electron widths of higher charmonium 1−, states,” Phys. Atom. Nucl. 72 (2009), 638-646
[29] J. Segovia, D. R. Entem and F. Fernandez, “Charm spectroscopy beyond the constituent quark model,” [arXiv:0810.2875 [hep-ph]].
[30] L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, “The $Z(4430)$ and a New Paradigm for Spin Interactions in Tetraquarks,” Phys. Rev. D 89 (2014), 114010
[31] S. J. Brodsky, D. S. Hwang and R. F. Lebed, “Dynamical Picture for the Formation and Decay of the Exotic XYZ Mesons,” Phys. Rev. Lett. 113 (2014) no.11, 112001
[32] G. Cotugno, R. Faccini, A. D. Polosa and C. Sabelli, “Charmed Baryonium,” Phys. Rev. Lett. 104 (2010), 132005
[33] X. W. Wang, Z. G. Wang and G. I. Yu, “Study of $\Lambda\bar{\Lambda}$ dibaryon and $\Lambda\bar{\Lambda}$ baryonium states via QCD sum rules,” Eur. Phys. J. A 57, no.9, 275 (2021)
[34] Y. D. Chen and C. F. Qiao, “Baryonium Study in Heavy Baryon Chiral Perturbation Theory,” Phys. Rev. D 85 (2012), 034034
[35] Y. A. Simonov, “Theory of hadron decay into baryon-antibaryon final state,” Phys. Rev. D 85 (2012), 105025
[36] Z. M. Ding, H. Y. Jiang and J. He, “Molecular states from $D_s^{(*)}\bar{D}^{(*)}/B^{(*)}\bar{B}^{(*)}$ and $D^{(*)}\bar{D}^{(*)}/B^{(*)}\bar{B}^{(*)}$ interactions,” Eur. Phys. J. C 80 (2020) no.12, 1179
[37] Z. M. Ding, H. Y. Jiang, D. Song and J. He, “Hidden and doubly heavy molecular states from interactions $D_s^{(*)}\bar{D}^{(*)}/B^{(*)}\bar{B}^{(*)}$ and $D_s^{(*)}\bar{D}^{(*)}/B^{(*)}\bar{B}^{(*)}$,” Eur. Phys. J. C 81, no.8, 732 (2021)
[38] S. Y. Kong, J. T. Zhu, D. Song and J. He, “Heavy-strange meson
[39] R. Aaij et al. [LHCb], “Observation of the doubly charmed baryon Ξ_c^+,” Phys. Rev. Lett. 119 (2017) no.11, 112001

[40] R. Aaij et al. [LHCb], “Observation of an exotic narrow doubly charmed tetraquark,” [arXiv:2109.01038 [hep-ex]].

[41] J. P. Ader, J. M. Richard and P. Taxil, “Do Narrow Heavy Multiquark States exist?,” Phys. Rev. D 25 (1982), 2370

[42] S. Zouzou, B. Silvestre-Brac, C. Gignoux and J. M. Richard, “Four Quark Bound States,” Z. Phys. C 30 (1986), 457

[43] H. J. Lipkin, “A Model Independent Approach to Multi-quark Bound States,” Phys. Lett. B 172 (1986), 242-247

[44] L. Heller and J. A. Tjon, “On the Existence of Stable Dimesons,” Phys. Rev. D 35 (1987), 969

[45] J. Carlson, L. Heller and J. A. Tjon, “Stability of Dimesons,” Phys. Rev. D 37 (1988), 744

[46] B. Silvestre-Brac and C. Semay, “Systematics of L = 0 q-2 anti-q-2 systems,” Z. Phys. C 57 (1993), 273-282

[47] C. Semay and B. Silvestre-Brac, “Diquonia and potential models,” Z. Phys. C 61 (1994), 271-275

[48] B. A. Gelman and S. Nussinov, “Does a narrow tetraquark cc anti-u anti-d state exist?,” Phys. Lett. B 551 (2003), 296-304

[49] A. V. Manohar and M. B. Wise, “Exotic Q Q anti-q anti-q states in QCD,” Nucl. Phys. B 399 (1993), 17-33

[50] S. Pepin, F. Stancu, M. Genovese and J. M. Richard, “Tetraquarks with color blind forces in chiral quark models,” Phys. Lett. B 393 (1997), 119-123

[51] R. Molina, T. Branz and E. Oset, “A new interpretation for the D_s^+ (2573) and the prediction of novel exotic charmed mesons,” Phys. Rev. D 82 (2010), 014010

[52] N. Li, Z. F. Sun, X. Liu and S. L. Zhu, “Coupled-channel analysis of the possible D_s^+D_s^-\bar{B}^0\bar{B}^0 and D_s^+\bar{B}^0\bar{B}^0 molecular states,” Phys. Rev. D 88 (2013) no.11, 114008

[53] Z. G. Wang, “Analysis of the axialvector doubly heavy tetraquark states with QCD sum rules,” Acta Phys. Polon. B 49 (2018), 1781

[54] L. Maiani, A. D. Polosa and V. Riquer, “Hydrogen bond of QCD in doubly heavy baryons and tetraquarks,” Phys. Rev. D 100 (2019) no.7, 074002

[55] M. Z. Liu, T. W. Wu, M. Pavon Valderrama, J. J. Xie and L. S. Geng, “Heavy-quark spin and flavor symmetry partners of the X(3872) revisited: What can we learn from the one boson exchange model?,” Phys. Rev. D 99 (2019) no.9, 094018

[56] N. Li and S. L. Zhu, “Hadronic Molecular States Composed of Heavy Flavor Baryons,” Phys. Rev. D 86, 014020 (2012)

[57] H. Garcilazo and A. Valcarce, “Doubly charmed multibaryon systems,” Eur. Phys. J. C 80, no.8, 720 (2020)

[58] T. F. Carames and A. Valcarce, “Heavy flavor dibaryons,” Phys. Rev. D 92, no.3, 034015 (2015)

[59] K. Chen, R. Chen, L. Meng, B. Wang and S. L. Zhu, “Systematics of the heavy flavor hadronic molecules,” Eur. Phys. J. C 82, no.7, 581 (2022)

[60] X. Z. Ling, M. Z. Liu and L. S. Geng, “Masses and strong decays of open charm hexaquark states \Sigma_c^{(-)}\Sigma_c^{(+)},” Eur. Phys. J. C 81 (2021) no.12, 1090

[61] X. K. Dong, F. K. Guo and B. S. Zou, “A survey of heavy–heavy hadronic molecules,” Commun. Theor. Phys. 73, no.12, 125201 (2021)

[62] C. Isola, M. Ladisa, G. Nardulli and P. Santorelli, “Charming penguins in B \to K^*\pi, K(\rho, \omega, \phi) decays,” Phys. Rev. D 68, 114001 (2003)

[63] A. F. Falk and M. E. Luke, “Strong decays of excited heavy mesons in chiral perturbation theory,” Phys. Lett. B 292, 119 (1992)

[64] R. Chen, Z. F. Sun, X. Liu and S. L. Zhu, “Strong LHCb evidence supporting the existence of the hidden-charm molecular pentaquarks,” Phys. Rev. D 100, no.1, 011502 (2019)

[65] J. T. Zhu, S. Y. Kong, L. Q. Song and J. He, Phys. Rev. D 105 (2022) no.9, 094036 doi:10.1103/PhysRevD.105.094036 [arXiv:2205.07586 [hep-ph]].

[66] J. He and D. Y. Chen, “Molecular states from \Sigma_c^{(-)}D_s^{(*)} – \Lambda_cD^{(*)} interaction,” Eur. Phys. J. C 79 no.11, 887 (2019)

[67] R. J. N. Phillips, “Antinuclear Forces,” Rev. Mod. Phys. 39, 681 (1967).

[68] E. Klepft, F. Bradamante, A. Martin and J. M. Richard, “Antinucleon nucleon interaction at low energy: Scattering and protonium,” Phys. Rept. 368, 119 (2002).

[69] J. He, “Internal structures of the nucleon resonances N(1875) and N(2120),” Phys. Rev. C 91, no.1, 018201 (2015)

[70] J. He, “Nucleon resonances N(1875) and N(2100) as strange partners of LHCb pentaquarks,” Phys. Rev. D 95, no.7, 074031 (2017)

[71] J. He, “The Z_c(3900) as a resonance from the D\bar{D}^* interaction,” Phys. Rev. D 92, no.3, 034004 (2015)

[72] J. He, D. Y. Chen and X. Liu, “New Structure Around 3250 MeV in the Baryonic B Decay and the D^*_s(2400)/N Molecular Hadron,” Eur. Phys. J. C 72, 2121 (2012)

[73] M. Z. Liu, T. W. Wu, M. Sánchez Sánchez, M. P. Valderrama, L. S. Geng and J. Xie, “Spin-parities of the P_s(4440) and P_s(4457) in the one-boson-exchange model,” Phys. Rev. D 103, no.5, 054004 (2021)