The DD̄* interaction with isospin zero in an extended hidden gauge symmetry approach

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Abstract: The $D\bar{D}^*$ interaction via a ρ or ω exchange is constructed within an extended hidden gauge symmetry approach, where the strange quark is replaced by the charm quark in the $SU(3)$ flavor space. With this $D\bar{D}^*$ interaction, a bound state slightly lower than the $D\bar{D}^*$ threshold is generated dynamically in the isospin zero sector by solving the Bethe-Salpeter equation in the coupled-channel approximation, which might correspond to the $X(3872)$ particle announced by many collaborations. This formulism is also used to study the $B\bar{B}^*$ interaction, and a $B\bar{B}^*$ bound state with isospin zero is generated dynamically, which has no counterpart listed in the review of the Particle Data Group. Furthermore, the one-pion exchange between the D meson and the $\bar{D}^*$ is analyzed precisely, and we do not think the one-pion exchange potential need be considered when the Bethe-Salpeter equation is solved.

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1   Introduction

The hidden gauge symmetry approach has been shown to be a successful method to include the vector meson in the Lagrangian [1–4]. Along these lines, the pseudoscalar meson and vector meson interaction [5], the vector meson and vector meson interaction [6, 7], the vector meson and baryon octet interaction [8, 9], and the vector meson and baryon decuplet interaction [10, 11] in $SU(3)$ flavor space have been studied in the coupled-channel unitary approximation. This method is extended to $SU(4)$ space when the components related to c and c̄ quarks are taken into account [12–14]. In the past few years, more and more XYZ states have been discovered, and it has become necessary to include the c and b quark components in the effective Lagrangian when the interaction of hadrons is investigated. However, since mesons composed of c and b quarks are much heavier than mesons composed of light quarks, the exchange of heavier mesons is extremely suppressed, and the mesons which consist completely of light quarks, such as pions, and ρ and ω mesons, play a dominant role in the interactions of hadrons.

The c and b quarks usually act as spectators in the interactions of hadrons. Thus, strange quarks can be replaced by c or b quarks in the process of strangeness zero, and then the interactions of hadrons composed of heavier flavor quarks can be discussed in the $SU(3)$ subspace of u, d and c(b) quark components. Many studies have been done on this topic [15–17], and it should especially be stressed that this replacement is used in the study of the generation of charm-beauty bound states of B(B*)D(D*) and B(B*)D̄(D̄*) interactions [18]. It is clear that the model becomes much simpler than those used in Refs. [12–14], where the $SU(4)$ hidden gauge symmetry approach is discussed in detail.

The $X(3872)$ state was first observed by the Belle Collaboration in 2003 [19], and then confirmed by many experimental collaborations. Finally, a mass of 3871.69± 0.17 MeV [20] and a decay width <1.2 MeV [21] are given by fitting the experimental data, which is extremely close to the $D\bar{D}^*$ threshold. A lot of theoretical research work has been done on the properties of $X(3872)$. Some people suppose $X(3872)$ to be a $D\bar{D}^*/\bar{D}D^*$ bound state since its mass is very close to the $D\bar{D}^*$ threshold [22–25]. $X(3872)$ is also described as a virtual state of $D\bar{D}^*/\bar{D}D^*$ [26, 27], a tetraquark [28–30], a hybrid state [31] or a mixture of a charmonium $\chi_{c1}(2P)$ with a $D\bar{D}^*/\bar{D}D^*$ component [32, 33]. Moreover, the $X(3872)$ state is studied by using the pole counting rule method [34, 35], and it is found that two nearby poles are necessary to describe the experimental data [36, 37].

In the present work, we will replace the strange quark by the charm quark in the $SU(3)$ hidden gauge symmetry approach, and then study the D$\bar{\text{D}}^*$ interaction in the coupled-channel unitary approximation by solving the Bethe-Salpeter equation. Consequently, the $X(3872)$ state is generated dynamically when the ρ and ω exchanges between D and $\bar{\text{D}}^*$ mesons are taken into account.

One-pion exchange between D and $\bar{\text{D}}^*$ mesons at the D$\bar{\text{D}}^*$ threshold is addressed specially. Since the mass of the $\bar{\text{D}}^*$ meson is about one pion mass larger than the mass of the D meson, the intermediate pion might be regarded as a real particle at the D$\bar{\text{D}}^*$ threshold, therefore the behavior of the DD* interaction through one-pion exchange is interesting. However, although it is divergent at the D$\bar{\text{D}}^*$ threshold, the one-pion exchange potential of D$\bar{\text{D}}^*$ becomes weaker when the total energy of the system departs from the D$\bar{\text{D}}^*$ threshold. When the hidden gauge symmetry approach is considered, the ρ and ω meson exchange between D and $\bar{\text{D}}^*$ mesons is dominant, and thus the one-pion exchange potential is neglected in the present work.

In addition, this model is extended to study the B$\bar{\text{B}}^*$ interaction in the isospin zero sector by replacing the c quark with a b quark, and a new bound state is predicted, which is not listed in the review of the Particle Data Group (PDG) [20].

This article is organized as follows. The formulism is described in Section 2, and then the implementation of unitarity is discussed in Section 3, where the contribution from the longitudinal part of the vector meson propagator in the loop function of the Bethe-Salpeter equation is taken into account. The one-pion exchange potential of D$\bar{\text{D}}^*$ is analyzed in Section 4. The calculation results on the D$\bar{\text{D}}^*$ and B$\bar{\text{B}}^*$ interactions are presented in Section 5. Finally, a summary is given in Section 6.

2   Formalism

The hidden gauge symmetry approach is successful when vector mesons are involved in the Lagrangian, where vector mesons are treated as gauge bosons of the $SU(3)$ local gauge symmetry breaking spontaneously [1–5]. This formalism can be extended to study the interaction of the D meson and the $\bar{\text{D}}^*$ meson by replacing the s and $\bar{\text{s}}$ quarks with c and $\bar{\text{c}}$ quarks, respectively.

In the hidden gauge symmetry approach, the D$\bar{\text{D}}^*$ interaction would proceed through the exchange of a vector meson, as depicted in Fig. 1(a). Since the vector propagator contributes a factor of $1/M_V^2$ if the momentum transfer between the D meson and the $\bar{\text{D}}^*$ meson can be neglected, the exchange of ρ and ω mesons is dominant, while the possible exchange of heavier vector mesons is suppressed.
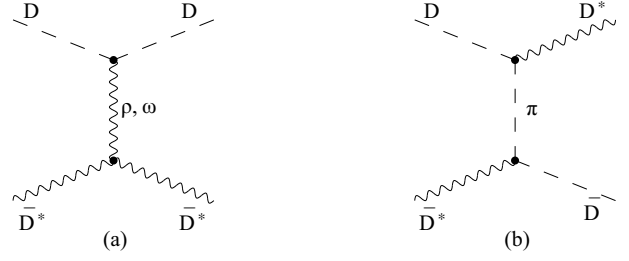

Fig. 1.   The interactions of the D and $\bar{\text{D}}^*$ mesons. (a) Vector meson exchange, (b) One-pion exchange.

The DDρ and DDω couplings can be obtained with the Lagrangian

$$\mathcal{L} = -\mathrm{i}g\langle V_\mu [P, \partial^\mu P]\rangle, \tag{1}$$

where

$$g = \frac{M_V}{2f_\pi}, \tag{2}$$

with $f_\pi = 93$ MeV the pion decay constant and M_V the mass of the ρ meson.

The matrices of vector mesons and pseudoscalar mesons take the form of

$$V_\mu = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & \bar{D}^{*0} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & D^{*-} \\ D^{*0} & D^{*+} & 0 \end{pmatrix}, \tag{3}$$

and

$$P = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} & \pi^+ & \bar{D}^0 \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} & D^- \\ D^0 & D^+ & 0 \end{pmatrix}, \tag{4}$$

respectively, where only the relevant mesons are enumerated.

The Lagrangian density of vector mesons can be written as

$$\mathcal{L}_V = -\frac{1}{4}\langle V_{\mu\nu} V^{\mu\nu}\rangle, \tag{5}$$

with

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - \mathrm{i}g[V_\mu, V_\nu]. \tag{6}$$

According to Eq. (5), we can derive the D*D*ρ and D*D*ω couplings from the interaction Lagrangian

$$\mathcal{L}_{VVV} = \mathrm{i}g\langle (\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle. \tag{7}$$

Since the mass of the ω meson $m_\omega = 782$ MeV is similar to that of the ρ meson $m_\rho = 770$ MeV, we suppose $M_V \approx m_\rho \approx m_\omega$, then the potential of the D meson and $\bar{\text{D}}^*$ meson is simplified as

$$V_{ij} = C_{ij}\frac{1}{f_\pi^2}[(k_1 + k_2)\cdot(p_1 + p_2)]\varepsilon\cdot\varepsilon^*, \tag{8}$$

with ε and ε^* the polarization vectors of the initial and final vector mesons, and $k_1(p_1)$ and $k_2(p_2)$ the momenta of the initial and final $D(\bar{D}^*)$ mesons, respectively. The coefficients C_{ij} in the different channels are shown in Table 1.

Table 1.   The coefficients C_{ij} in the D and $\bar{D}^*$ interaction, $C_{ji}=C_{ij}$.

C_{ij}	D^+D^{*-}	$D^0\bar{D}^{*0}$	$\bar{D}^0D^{*0}$	D^-D^{*+}
D^+D^{*-}	$\frac{1}{4}$	$\frac{1}{4}$	0	0
$D^0\bar{D}^{*0}$	$\frac{1}{4}$	$\frac{1}{4}$	0	0
$\bar{D}^0D^{*0}$	0	0	$\frac{1}{4}$	$\frac{1}{4}$
D^-D^{*+}	0	0	$\frac{1}{4}$	$\frac{1}{4}$

The $D\bar{D}^*$ pair with isospin $I=0$ takes the form of

$$|D\bar{D}^*,I=0\rangle$$
$$= \frac{1}{\sqrt{4}}\left(|D^+D^{*-}\rangle+|D^0\bar{D}^{*0}\rangle-|\bar{D}^0D^{*0}\rangle-|D^-D^{*+}\rangle\right), \quad (9)$$

where the C-parity of the $D\bar{D}^*$ pair is assumed to be positive.

According to Eqs. (8) and (9), the potential of $D\bar{D}^*$ with isospin $I=0$ can be written as

$$V^t_{D\bar{D}^*\to D\bar{D}^*}=\frac{1}{2}\frac{1}{f_\pi^2}[(k_1+k_2)\cdot(p_1+p_2)]\varepsilon\cdot\varepsilon^*. \quad (10)$$

According to Ref. [38], the kernel $\tilde{V}^t_{D\bar{D}^*\to D\bar{D}^*}$ can be obtained from the potential form in Eq. (10) when the Bethe-Salpeter equation is solved, i.e.,

$$\tilde{V}^t_{D\bar{D}^*\to D\bar{D}^*}=\frac{1}{2}\frac{1}{f_\pi^2}[(k_1+k_2)\cdot(p_1+p_2)], \quad (11)$$

where the $\varepsilon\cdot\varepsilon^*$ structure has been eliminated.

Actually, the kernel in Eq. (11) can be written as

$$\tilde{V}^t_{D\bar{D}^*\to D\bar{D}^*} = \frac{1}{2}\frac{1}{f_\pi^2}(s-u)$$
$$= \frac{1}{2}\frac{1}{f_\pi^2}(2s+t-2(M_D^2+M_{D^*}^2)), \quad (12)$$

where the Mandelstam variables $s=(p_1+k_1)^2$, $t=(k_2-k_1)^2$ and $u=(p_2-k_1)^2$. In the derivation of Eq. (11), we have neglected the momentum transfer $q=k_2-k_1$ compared to the mass of the vector meson M_V, which would be a good approximation for the interaction relatively close to threshold where bound states or resonances are searched for, i.e., $t=(k_2-k_1)^2=0$ is assumed in the approximation. Thus the kernel in Eq. (12) is only a function of the Mandelstam variables s, which is the square of the total energy in the center of mass frame.

$$\tilde{V}^t_{D\bar{D}^*\to D\bar{D}^*} = \frac{1}{f_\pi^2}(s-M_D^2-M_{D^*}^2). \quad (13)$$

3   Implementation of unitarity

In the coupled-channel unitary approach, the unitarity can be implemented into the $D\bar{D}^*$ interaction by solving the Bethe-Salpeter equation:

$$\tilde{T} = [I-\tilde{V}\tilde{G}]^{-1}\tilde{V}, \quad (14)$$

where $\tilde{V}$ is the kernel of the $D\bar{D}^*$ interaction provided by Eq. (11), and $\tilde{G}$ is the $D\bar{D}^*$ loop function. The loop function is logarithmically divergent and thus is calculated with a three-momentum cutoff [39, 40], or by means of dimensional regularization [41]. Recently, a loop function of a pseudoscalar meson and a vector meson is derived in the dimensional regularization scheme, where the contribution of the longitudinal part of the vector meson propagator is taken into account in Ref. [38]. In the present work, this formula of the loop function will be applied to the $D\bar{D}^*$ interaction in the hidden gauge symmetry approach.

The loop function can be written as

$$\tilde{G}(s)=-\left(G_{D^*D}(s)+\frac{1}{M_{D^*}^2}H^{00}_{D^*D}(s)+\frac{s}{4M_{D^*}^2}H^{11}_{D^*D}(s)\right), \quad (15)$$

where $G_{D^*D}(s)$ is the original form of the loop function in Ref. [41], while the terms related to $H^{00}_{D^*D}(s)$ and $H^{11}_{D^*D}(s)$ stem from the longitudinal part of the vector meson propagator, and their analytical forms can be found in the appendix of Ref. [38].

4   One-pion exchange

From the Lagrangian in Eq. (1), we can obtain the interaction Lagrangian for the $D^*D\pi$ coupling, which can be written as

$$\begin{aligned}
\mathcal{L}_{D^*D\pi} = -\frac{ig}{\sqrt{2}}[&\bar{D}^{*0}_\mu(D^0\partial^\mu\pi^0-\partial^\mu D^0\pi^0)\\
&+\sqrt{2}\bar{D}^{*0}_\mu(D^+\partial^\mu\pi^--\partial^\mu D^+\pi^-)\\
&+\sqrt{2}D^{*0}_\mu(\pi^+\partial^\mu D^--\partial^\mu\pi^+D^-)\\
&+D^{*0}_\mu(\pi^0\partial^\mu\bar{D}^0-\partial^\mu\pi^0\bar{D}^0)\\
&+\sqrt{2}D^{*-}_\mu(D^0\partial^\mu\pi^+-\partial^\mu D^0\pi^+)\\
&-D^{*-}_\mu(D^+\partial^\mu\pi^0-\partial^\mu D^+\pi^0)\\
&+\sqrt{2}D^{*+}_\mu(\pi^-\partial^\mu\bar{D}^0-\partial^\mu\pi^-\bar{D}^0)\\
&-D^{*+}_\mu(\pi^0\partial^\mu D^--\partial^\mu\pi^0D^-)].
\end{aligned} \quad (16)$$

Therefore, the one-pion exchange potential of the D and $\bar{D}^*$ mesons is obtained as

$$V^u_{ij}=D_{ij}g^2(q-k_1)\cdot\varepsilon^*\frac{1}{q^2-m_\pi^2}(q-k_2)\cdot\varepsilon, \quad (17)$$

as shown in Fig. 1(b). The coefficients D_{ij} in Eq. (17) for different channels are listed in Table 2. According to Eq. (9), the one-pion exchange potential of the D and $\bar{D}^*$ mesons in the sector of isospin $I=0$ can be written as

$$V^u_{D\bar{D}^*\to D\bar{D}^*} = 6g^2q\cdot\varepsilon^*\frac{1}{q^2-m_\pi^2}q\cdot\varepsilon, \quad (18)$$

where $q = p_2 - k_1 = p_1 - k_2$, $p_1 \cdot \varepsilon = 0$ and $p_2 \cdot \varepsilon^* = 0$ are used in the derivation.

Table 2. The coefficients D_{ij} in the one-pion exchange potential of the D and $\bar{\mathrm{D}}^*$ interaction, $D_{ji} = D_{ij}$.

D_{ij}	$\mathrm{D}^+\mathrm{D}^{*-}$	$\mathrm{D}^0\bar{\mathrm{D}}^{*0}$	$\bar{\mathrm{D}}^0\mathrm{D}^{*0}$	$\mathrm{D}^-\mathrm{D}^{*+}$
$\mathrm{D}^+\mathrm{D}^{*-}$	0	0	-1	$-\frac{1}{2}$
$\mathrm{D}^0\bar{\mathrm{D}}^{*0}$	0	0	$-\frac{1}{2}$	-1
$\bar{\mathrm{D}}^0\mathrm{D}^{*0}$	-1	$-\frac{1}{2}$	0	0
$\mathrm{D}^-\mathrm{D}^{*+}$	$-\frac{1}{2}$	-1	0	0

Since the $\bar{\mathrm{D}}^*$ meson mass is about one pion mass larger than that of the D meson, $M_{\mathrm{D}*} - M_{\mathrm{D}} \approx m_\pi$, the intermediate pion can be regarded as a real particle approximately at the threshold of $\mathrm{D}\bar{\mathrm{D}}^*$, i.e., $q_0^2 \approx \vec{q}^2 + m_\pi^2$. The denominator in the one-pion exchange potential of the D and $\bar{\mathrm{D}}^*$ mesons in Eq. (18) can be written as

$$
\begin{aligned}
q^2 - m_\pi^2 &= q_0^2 - \vec{q}^2 - m_\pi^2 = [\sqrt{\vec{q}^2 + m_\pi^2}]^2 - \vec{q}^2 - m_\pi^2 \\
&= \left[m_\pi \sqrt{1 + \frac{\vec{q}^2}{m_\pi^2}} \right]^2 - \vec{q}^2 - m_\pi^2 \\
&\sim \left[m_\pi \left(1 + \frac{\vec{q}^2}{2m_\pi^2} \right) \right]^2 - \vec{q}^2 - m_\pi^2 \sim \frac{|\vec{q}|^4}{(2m_\pi)^2}, \quad (19)
\end{aligned}
$$

approximately. However, the zero component of the polarization vector of the $\bar{\mathrm{D}}^*$ meson is in inverse proportion to the $\bar{\mathrm{D}}^*$ meson mass, and thus can be neglected in the calculation, so we have

$$
q \cdot \varepsilon^* \sim |\vec{q}|, \quad (20)
$$

and

$$
q \cdot \varepsilon \sim |\vec{q}|. \quad (21)
$$

According to Eqs. (19), (20) and (21), although the one-pion exchange potential of the D and $\bar{\mathrm{D}}^*$ mesons is divergent at the $\mathrm{D}\bar{\mathrm{D}}^*$ threshold,

$$
V^u_{\mathrm{D}\bar{\mathrm{D}}^* \to \mathrm{D}\bar{\mathrm{D}}^*} \sim \frac{1}{|\vec{q}|^2}, \quad (22)
$$

it can be neglected when the total energy of the system is far away from the $\mathrm{D}\bar{\mathrm{D}}^*$ threshold.

In Ref. [22], the one-pion exchange potential of the D and $\bar{\mathrm{D}}^*$ mesons is assumed to be dominant in the generation of the $X(3872)$ state. The formula of the one-pion exchange potential is given explicitly in the second term in Eq. (11) of Ref. [22], which is relevant to the external three-momentum in the center-of-mass frame. The potentials of the D and $\bar{\mathrm{D}}^*$ mesons as functions of the total energy of the system $\sqrt{s}$ are depicted in Fig. 2, and it can be found that the vector meson exchange potential is more important than the one-pion exchange potential of the D and $\bar{\mathrm{D}}^*$ mesons if the hidden gauge symmetry is taken into account. Therefore, the one-pion exchange potential of the D and $\bar{\mathrm{D}}^*$ mesons is neglected in the present work.
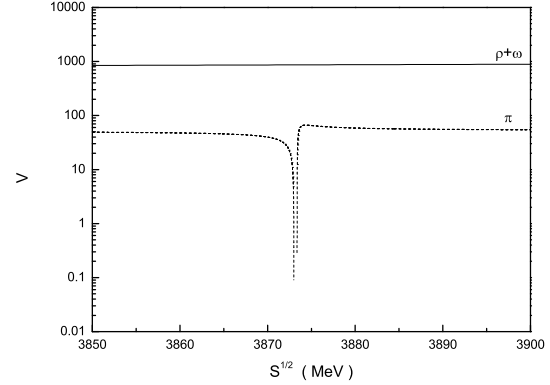

Fig. 2. The vector meson exchange potential of $\mathrm{D}\bar{\mathrm{D}}^*$ in Eq. (13) (solid line) and the one-pion exchange potential of $\mathrm{D}\bar{\mathrm{D}}^*$ in Eq. (11) of Ref. [22] (dashed line) as functions of the total energy of the system $\sqrt{s}$.

5   Results

In Ref. [42], the $\mathrm{D}\bar{\mathrm{D}}^*$ interaction is studied in the $SU(4)$ flavor space, and an intermediate J/ψ exchange in the kernel is taken into account besides the ρ and ω exchanges. Actually, the J/ψ particle is heavier than the ρ and ω mesons, and the $\mathrm{D}\bar{\mathrm{D}}^*$ interaction via a J/ψ exchange can be neglected in the calculation. Moreover, we suppose that the pion decay constant $f_\pi = 93$ MeV in the $\mathrm{D}\bar{\mathrm{D}}^*$ potential in Eq. (8). However, the f_π^2 is replaced with $f_i f_j$ in the potential in Eq. (4) of Ref. [42], related to the initial and final particles, respectively. In the $\mathrm{D}\bar{\mathrm{D}}^* \to \mathrm{D}\bar{\mathrm{D}}^*$ process, both f_i and f_j take the value of the decay constant of the D meson, i.e., $f_i = f_j = f_D = 165$ MeV.

Five channels of $\frac{1}{\sqrt{2}}(\bar{\mathrm{K}}^{*-}\mathrm{K}^+ - \mathrm{c.c.})$, $\frac{1}{\sqrt{2}}(\bar{\mathrm{K}}^{*0}\mathrm{K}^0 - \mathrm{c.c.})$, $\frac{1}{\sqrt{2}}(\mathrm{D}^{*+}\mathrm{D}^- - \mathrm{c.c.})$, $\frac{1}{\sqrt{2}}(\mathrm{D}^{*0}\bar{\mathrm{D}}^0 - \mathrm{c.c.})$ and $\frac{1}{\sqrt{2}}(\mathrm{D}^{*+}_\mathrm{s}\mathrm{D}^-_\mathrm{s} - \mathrm{c.c.})$ are discussed in Ref. [42]. A potential is given by

$$
V_{ij}(s,t,u) = \frac{\xi_{ij}}{4 f_i f_j}(s - u)\vec{\epsilon} \cdot \vec{\epsilon}^*, \quad (23)
$$

where ξ_{ij} denotes the coefficient between these channels, and $\vec{\epsilon}$ and $\vec{\epsilon}^*$ are 3-dimensional polarization vectors of the initial and final vector mesons, respectively. When the J/ψ exchange is neglected, the coefficients ξ_{ij} for the $\frac{1}{\sqrt{2}}(\mathrm{D}^{*+}\mathrm{D}^- - \mathrm{c.c.})$ and $\frac{1}{\sqrt{2}}(\mathrm{D}^{*0}\bar{\mathrm{D}}^0 - \mathrm{c.c.})$ channels can be obtained from the values listed in Table 1. It is apparent that $\vec{\epsilon} \cdot \vec{\epsilon}^*$ is supposed to be -1 in Ref. [42], and thus the coefficients in these two channels take negative values in Eq. (5) of Ref. [42].

The $\bar{\mathrm{K}}^*\mathrm{K}$ threshold is far lower than the energy region where the $X(3872)$ is detected. Thus the $\frac{1}{\sqrt{2}}(\bar{\mathrm{K}}^{*-}\mathrm{K}^+ - \mathrm{c.c.})$ and $\frac{1}{\sqrt{2}}(\bar{\mathrm{K}}^{*0}\mathrm{K}^0 - \mathrm{c.c.})$ channels can be excluded when the generation of the $X(3872)$ particle is discussed. Moreover, it should be emphasized that the $\frac{1}{\sqrt{2}}(\mathrm{D}^{*+}_\mathrm{s}\mathrm{D}^-_\mathrm{s} - \mathrm{c.c.})$ channel only contributes about 0.016

of the probability in the wave function of the $X(3872)$ particle, as discussed in Ref. [42], so the $\frac{1}{\sqrt{2}}(\mathrm{D}^{*+}\mathrm{D}^- - \mathrm{c.c.})$ and $\frac{1}{\sqrt{2}}(\mathrm{D}^{*0}\bar{\mathrm{D}}^0 - \mathrm{c.c.})$ channels play an important role in the generation of the $X(3872)$ particle. Therefore, it is reasonable that only the $\mathrm{D}\bar{\mathrm{D}}^*$ interaction is taken into account in the present work.

The resonance state of $\mathrm{D}\bar{\mathrm{D}}^*$ corresponds to the condition

$$\det(I - \tilde{V}\tilde{G}) = 0. \qquad (24)$$

In a single channel, Eq. (24) leads to poles in the $\tilde{T}$ amplitude when $\tilde{V}^{-1} = \tilde{G}$. Figure 3 shows the real parts of the loop function $\tilde{G}$ of $\mathrm{D}\bar{\mathrm{D}}^*$ with different values of the regularization scale μ in Eq. (15) as functions of the total energy of the system $\sqrt{s}$ in the center-of-mass frame. The inverse of the kernel $\tilde{V}$ in Eq. (13) is also shown. The real part of the loop function $\tilde{G}$ is less than the value of $\tilde{V}^{-1}$ when the regularization scale $\nu < 750$ MeV with $a = -2$ fixed. Therefore, no resonance state is generated dynamically in the $\mathrm{D}\bar{\mathrm{D}}^*$ channel with isospin zero even if a peak of the $\tilde{T}$ amplitude is detected on the complex energy plane of $\sqrt{s}$. A pole of the $\tilde{T}$ amplitude appears at $3872.62 + i0.00$ MeV in the complex energy plane of $\sqrt{s}$ if the value of the regularization scale is set to be $\mu = 800$ MeV with the subtraction constant $a = -2$ fixed, which is consistent with the experimental data for the $X(3872)$ particle. The real part of the pole position is about $1 \sim 2$ MeV lower than the $\mathrm{D}\bar{\mathrm{D}}^*$ threshold, and thus the $X(3872)$ particle can be regarded as a $\mathrm{D}\bar{\mathrm{D}}^*$ bound state.
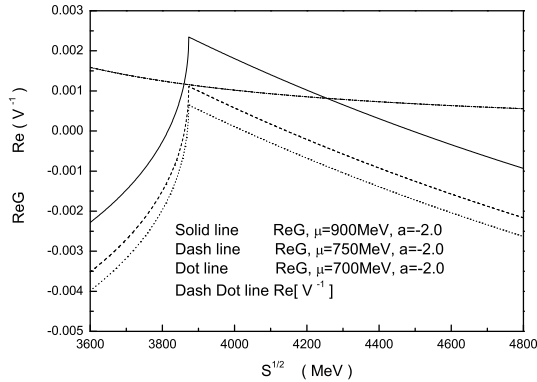

Fig. 3.   The inverse of the $\mathrm{D}\bar{\mathrm{D}}^*$ potential in Eq. (13) and the real part of the loop function in Eq. (15) with different values of the regularization scale μ as functions of the total energy of the system $\sqrt{s}$, where the subtraction constant $a = -2$ is fixed. The solid, dashed and dotted lines stand for the real part of the loop function with $\mu = 900$ MeV, $\mu = 750$ MeV and $\mu = 700$ MeV, respectively, while the dash-dotted line denotes the inverse of the $\mathrm{D}\bar{\mathrm{D}}^*$ potential.

If the longitudinal part of the vector propagator in the loop function $\tilde{G}$ is excluded, a bound state can also

be generated in the corresponding energy region by adjusting values of the regularization scale μ and the subtraction constant a. In this case, a pole of the $\tilde{T}$ amplitude is detected at $3871.69 + i0.00$ MeV on the complex energy plane of $\sqrt{s}$ with $\mu = 813$ MeV and $a = -2$.

The real and imaginary parts of the loop function $\tilde{G}$ as functions of the total energy of the system $\sqrt{s}$ in the center of mass frame are depicted in Fig. 4. The solid lines denote the case where the longitudinal part of the intermediate vector meson propagator is taken into account, and the parameters are set to be $\mu = 800$ MeV and $a = -2$. The dashed lines show the case where only the transverse part of the intermediate vector meson propagator in the loop function $\tilde{G}$ is considered, and the regularization scale is set to be $\mu = 813$ MeV with the subtraction constant $a = -2$.
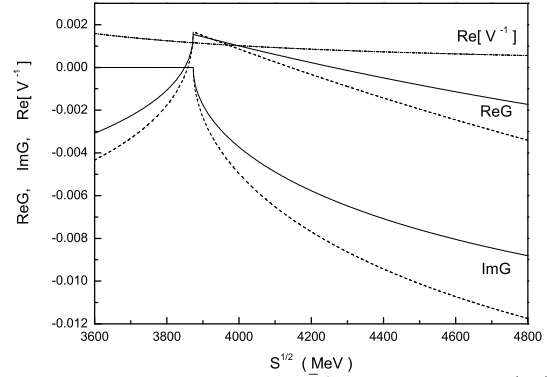

Fig. 4.   The inverse of the $\mathrm{D}\bar{\mathrm{D}}^*$ potential in Eq. (13) and the real and imaginary parts of the loop function as functions of the total energy of the system $\sqrt{s}$. The solid lines show the case where both the transverse and longitudinal parts of the vector meson propagator in the loop function with $\mu = 800$ MeV are taken into account, and the dashed lines show the case where only the transverse part of the vector meson propagator in the loop function with $\mu = 813$ MeV is considered. The dash-dotted line denotes the inverse of the $\mathrm{D}\bar{\mathrm{D}}^*$ potential.

The formalism in Section 2 can be extended to study the interaction of the B meson and $\bar{\mathrm{B}}^*$ meson by replacing the c and $\bar{\mathrm{c}}$ quarks with b and $\bar{\mathrm{b}}$ quarks, respectively. When the longitudinal part of the vector meson propagator in the loop function is taken into account, the amplitude satisfies the pole condition in Eq. (24) only in the case of $\mu > 1700$ MeV with $a = -2$ fixed. When the regularization scale μ takes the value of 1800 MeV, the pole of the amplitude is detected at $10600.97 + i0$ MeV on the complex energy plane of $\sqrt{s}$, which is about 3 MeV lower than the $\mathrm{B}\bar{\mathrm{B}}^*$ threshold, and can be regarded as a bound state of the $\mathrm{B}\bar{\mathrm{B}}^*$ system. If the longitudinal part of the vector meson propagator in the loop function is excluded in the calculation, the pole of the amplitude appears when $\mu > 1974$ MeV with $a = -2$. If

the regularization scale $\mu = 2000$ MeV, the pole lies at $10603.64 + i0$ MeV, which is below the $B\bar{B}^*$ threshold. Moreover, it is worth stressing that the bound state of the $B\bar{B}^*$ interaction has no counterpart in the Particle Data Group review.

6   Summary

The $D\bar{D}^*$ interaction is investigated in the hidden gauge symmetry approach of the $SU(3)$ flavor subspace of the u, d and c quark components. The one-pion exchange between the D meson and the $\bar{D}^*$ meson is analyzed precisely. Since the mass of the $\bar{D}^*$ meson is just one pion mass larger than that of the D meson, the intermediate pion can be treated as a real particle at the $D\bar{D}^*$ threshold. Thus the diagram of the one-pion exchange between the D meson and the $\bar{D}^*$ meson is divergent and supplies a singularity at the $D\bar{D}^*$ threshold. However, this one-pion exchange potential becomes trivial when the total energy of the $D\bar{D}^*$ system is far away from the threshold, so it is neglected in this work.

A kernel of the $D\bar{D}^*$ interaction by exchanging a ρ or ω meson is derived, and then this kernel is used to solving the Bethe-Salpeter equation in the coupled-channel unitary approximation. In the isospin $I = 0$ sector, a $D\bar{D}^*$ bound state with a mass about 3872 MeV is produced, which is slightly lower than the $D\bar{D}^*$ threshold and can be regarded as a counterpart of the $X(3872)$ particle. This method is also extended to study the $B\bar{B}^*$ interaction by replacing the corresponding c quarks with b quarks, respectively, and a bound state is produced in the isospin $I = 0$ sector, which has no counterpart in the PDG data. It should be emphasized that the regularization scale takes different values from the $D\bar{D}^*$ case when the subtraction constant is fixed. The heavy quark flavor symmetry should be considered in our future work.

Although a $D\bar{D}^*$ bound state can be generated dynamically in the isospin $I = 0$ sector, which stems from the ρ and ω meson exchange due to the hidden gauge symmetry approach, the $D\bar{D}^*$ interaction in the isospin $I = 1$ sector is unfortunately zero, and thus no bound state can be generated dynamically. This implies that other mechanisms need to be considered besides the hidden gauge symmetry approach.

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