

X(3872) and the bound state problem of $D^0\bar{D}^{*0}(\bar{D}^0D^{*0})$ in a chiral quark model

Yan-Rui Liu (刘言锐)^{1,*} and Zong-Ye Zhang (张宗烨)^{1,2,†}

¹*Institute of High Energy Physics, CAS, P. O. Box 918-4, Beijing 100049, People's Republic of China*

²*Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, People's Republic of China*

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The bound state problem of $D^0\bar{D}^{*0}(\bar{D}^0D^{*0})$ is relevant to the molecular interpretation of the X(3872). We investigated this problem in a chiral quark model by solving the resonating group method equation. We found the system is unbound through S -wave π and σ interactions. The inclusion of ρ and ω meson exchanges is helpful to the formation of a molecule. Because the binding energy relies on the coupling constants, we cannot draw a definite conclusion as to whether a molecular state exists in the $D^0\bar{D}^{*0}(\bar{D}^0D^{*0})$ system. When moving on to the bottom counterpart, we obtained an S -wave $B\bar{B}^*$ state.

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I. INTRODUCTION

In recent years, a number of new charmonium-like states have been observed [1–4]. One of the most interesting states is the X(3872). The Belle Collaboration first discovered this state in the $\pi^+\pi^-J/\psi$ channel of B decay in 2003 [5]. Thereafter, CDF [6], D0 [7], and BaBar [8] Collaborations have confirmed its existence. The X(3872) is almost on the threshold of $D^0\bar{D}^{*0}$. Its width is very narrow ($\Gamma < 2.3$ MeV from the Particle Data Group [9]). The measurements from Belle [10] and CDF [11] favor the quantum numbers $J^{PC} = 1^{++}$, but 2^{-+} have not been ruled out yet. In the search for a charged X state, BaBar excluded the isovector hypothesis [12].

Experiments have accumulated much information about the decay of the X(3872). The analysis from CDF [13] supports that the two pions in the channel $X(3872) \rightarrow \pi^+\pi^-J/\psi$ come from the ρ meson. In addition, Belle observed the 3π decay $\pi^+\pi^-\pi^0J/\psi$ and the radiative decay $\gamma J/\psi$ [14]. BaBar also reported evidence of the latter mode [15]. The measured ratios include [14]

$$\frac{\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-\pi^0J/\psi)}{\mathcal{B}(X(3872) \rightarrow \pi^+\pi^-J/\psi)} = 1.0 \pm 0.4 \pm 0.3, \quad (1)$$

$$\frac{\mathcal{B}[X(3872) \rightarrow \gamma J/\psi]}{\mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]} = 0.14 \pm 0.05, \quad (2)$$

and [8,15,16]

$$\frac{\mathcal{B}[X(3872) \rightarrow \gamma J/\psi]}{\mathcal{B}[X(3872) \rightarrow J/\psi\pi^+\pi^-]} \approx 0.3. \quad (3)$$

One notes that the ratio between the 3π mode and the dipion mode in Eq. (1) indicates the large isospin violation when the X(3872) decays.

Recently, Belle announced a new near-threshold enhancement with $M = 3875.4 \pm 0.7^{+1.2}_{-2.0}$ MeV in the channel $B \rightarrow X(3875)K \rightarrow D^0\bar{D}^0\pi^0K$ [17]. This state has been confirmed by BaBar [18]. It is unclear whether or not these two X states

are the same one. If the X(3875) is identical to the X(3872), there are two more ratios [17],

$$\frac{\mathcal{B}[X \rightarrow D^0\bar{D}^0\pi^0]}{\mathcal{B}[X \rightarrow \pi^+\pi^-J/\psi]} = 8.8^{+3.1}_{-3.6} \quad (4)$$

and

$$\frac{\mathcal{B}[B^0 \rightarrow XK^0]}{\mathcal{B}[B^+ \rightarrow XK^+]} \approx 1.6. \quad (5)$$

The exotic properties of the X(3872) have triggered heated discussions about its nature. The low mass, the extremely narrow width, and the large isospin violation decay are difficult to understand in the conventional $c\bar{c}$ assignment [19]. Up to now, there exist many interpretations: a molecular state [20–24], a cusp [25], an S -wave threshold effect [26], a hybrid charmonium [27], a four-quark state [28,29], a vector glueball mixed with some charmonium components [30], and a dynamically generated resonance [31]. In addition, there are discussions that the puzzles for the X(3872) may possibly be resolved in the scheme of mixing [32–36].

The molecular interpretation is the most popular one in understanding the structure of the X(3872). In fact, the existence of a loosely bound molecule (deuson) of two heavy mesons has been proposed long ago [37–39]. In such systems, the contribution from the kinetic term is lowered because of the presence of the heavy quarks. Since the attraction from the light quarks is unaffected by the mass of the heavy quark, the formation of the heavy deuson is possible. According to the calculation in Ref. [39], several deusons of two bottom mesons should exist while the predicted deusons of two charmed mesons are close to the thresholds.

The proximity of the mass of the X(3872) to the threshold of $D^0\bar{D}^{*0}(\bar{D}^0D^{*0})$ motivated its molecular interpretation. Numerous discussions have taken place within this picture [40–48]. The mass, the quantum numbers J^{PC} , the isospin violating decay, and the 3π decay appear to be naturally understood.

However, the ratios in Eq. (2) and Eq. (3) challenged the molecular interpretation. Both are inconsistent with the molecular picture's prediction, which is around 7×10^{-3} . If the X(3875) and the X(3872) are the same state, the values in Eq. (4) and Eq. (5) are also much larger than the theoretical

* yrliu@ihep.ac.cn

† zhangzy@ihep.ac.cn

predictions. $\frac{B[X \rightarrow D^0 \bar{D}^0 \pi^0]}{B[X \rightarrow \pi^+ \pi^- J/\psi]}$ from the molecular assumption is 0.05 and $\frac{B[B^0 \rightarrow X K^0]}{B[B^0 \rightarrow X K^+]}$ is less than 0.1 [42].

Therefore, whether the molecular picture is correct or not remains inconclusive. This question is relevant to whether $D^0 \bar{D}^{*0} (\bar{D}^0 D^{*0})$ can form a molecule. Up till now, dynamical studies of this system are still scarce. In the calculation of Swanson [23] and Wong [22], binding is possible when the short-range quark-gluon force is considered. However, the purely molecular assumption of the X(3872) was questioned in Ref. [33].

To further understand the nature of the X(3872), it is worthwhile to study dynamically the molecular assumption for the X(3872) with various methods. In a previous work [49], we have investigated at hadronic level whether the formation of a bound state of D^0 and \bar{D}^{*0} is possible. We found that one-pion and one-sigma exchange interactions could not bind the system to an S -wave molecule. The same framework was also applied to the newly observed $Z^+(4430)$ [50].

In this paper, we reanalyze whether the X(3872) could be an S -wave $D^0 \bar{D}^{*0}$ molecule in a different approach. We will study this system in a chiral constituent quark model and calculate the binding energy by solving the resonating group method (RGM) equation [51,52].

The chiral quark model [53] is a useful tool in connecting QCD theory and experimental observables, especially for light quark systems. This phenomenological model has been quite successful in reproducing the energies of the baryon ground states, the binding energy of the deuteron, the nucleon-nucleon (NN) scattering phases, and the hyperon-nucleon (YN) cross sections. In this model, the interacting potentials between the two constituent quarks include the confinement, the one-gluon exchange (OGE) part, and the pseudoscalar- and scalar-meson exchange part. It has been controversial whether OGE or vector-meson exchange dominates the short-range quark-quark interaction in the low-lying baryon states. Thus the vector-meson exchange part has been included in Ref. [54]. The model was named as the extended chiral SU(3) quark model. It was found that the OGE is nearly replaced by the vector-meson exchanges. By solving the RGM equation, the experimental observables were well reproduced.

Recently, the chiral quark model has been extended to study bound state problems for the baryon-meson system [55] and the baryon-antibaryon system [56] by solving the RGM equation. In this work, we will study a similar problem for the $D^0 \bar{D}^{*0}$ system within this approach.

This paper is organized as follows. In Sec. II, we present the formalism for the calculation. In Sec. III, we give the methods to determine the parameters and their values. Then in Sec. IV we show the numerical results, and the last section gives a summary and discussion.

II. FORMALISM

A. The molecular picture

The heavy molecular state bound by the one-meson exchange interaction in the chiral quark model can be depicted in Fig 1, where A and B are two heavy mesons. The OGE

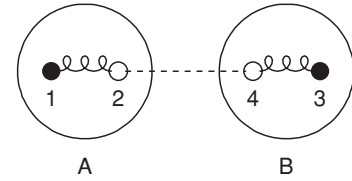


FIG. 1. The molecule bound by a one-meson exchange interaction in the chiral quark model. The solid (empty) dot is the heavy (light) quark or antiquark.

and the confinement interactions occur inside the color-singlet mesons only. The interactions between the two clusters are induced by the one-meson exchange potential between light quarks.

If the X(3872) is really a molecule, the wave function in flavor space should be [2,49]

$$X(3872) = \frac{a_0}{\sqrt{2}} [D^0 \bar{D}^{*0} - D^{*0} \bar{D}^0] + \frac{a_1}{\sqrt{2}} [D^+ D^{*-} - D^{*+} D^-] + \dots, \quad (6)$$

where the ellipses denote other hadronic components. Because of the large isospin violation in the decay, one expects the first part to dominate with $a_0 \gg a_1$. In the following calculation, we study whether D^0 and \bar{D}^{*0} may form an S -wave molecule with the flavor wave function [49]

$$|X_D\rangle = \frac{1}{\sqrt{2}} [|D^0 \bar{D}^{*0}\rangle - |D^{*0} \bar{D}^0\rangle]. \quad (7)$$

If the answer is yes, this molecular state should lie below the threshold and identifying the X(3872) as an X_D -dominated molecule is favored. Otherwise, the pure molecular interpretation of the X(3872) is problematic. We search for an answer by calculating the binding energy of the system $D^0 \bar{D}^{*0}$. Besides the pion and sigma exchange interactions, the ρ and the ω exchange effects are also considered and discussed.

B. Hamiltonian

The details of the chiral SU(3) quark model can be found in Refs. [53,54]. Here we just present essential constituents for the calculation. The Hamiltonian has the form

$$H = \sum_{i=1}^4 T_i - T_G + V^{\text{OGE}} + V^{\text{conf}} + \sum_M V^M, \quad (8)$$

where T_i is the kinetic term of the i th quark or antiquark and T_G is the kinetic energy operator of the center-of-mass motion.

The potential of the OGE part reads

$$V_{\bar{q}Q}^{\text{OGE}} = g_q g_Q \mathbf{F}_{\bar{q}}^c \cdot \mathbf{F}_Q^c \left\{ \frac{1}{r} - \frac{\pi}{2} \delta^3(\mathbf{r}) \left[\frac{1}{m_q^2} + \frac{1}{m_Q^2} + \frac{4}{3} \frac{1}{m_q m_Q} (\boldsymbol{\sigma}_q \cdot \boldsymbol{\sigma}_Q) \right] \right\}, \quad (9)$$

where $\mathbf{F}_Q^c = \frac{\lambda}{2}$ for quarks and $\mathbf{F}_{\bar{q}}^c = -\frac{\lambda^*}{2}$ for antiquarks and m_q (m_Q) is the light (heavy) quark mass. The linear confinement

potential is

$$V_{\bar{q}Q}^{\text{conf}} = -4\mathbf{F}_{\bar{q}}^c \cdot \mathbf{F}_Q^c (a_{aQ}^c r + a_{qQ}^c).$$

There are similar expressions for $V_{q\bar{Q}}^{\text{OGE}}$ and $V_{q\bar{Q}}^{\text{conf}}$.

From Refs. [53,54], one gets

$$V_{uu}^\sigma(\mathbf{r}_{ij}) = -C(g_{\text{ch}}, m_\sigma, \Lambda) X_1(m_\sigma, \Lambda, r_{ij}), \quad (10)$$

$$V^{\pi_a}(\mathbf{r}_{ij}) = C(g_{\text{ch}}, m_{\pi_a}, \Lambda) \frac{m_{\pi_a}^2}{12m_{q_i}m_{q_j}} X_2(m_{\pi_a}, \Lambda, r_{ij}) \\ \times [\boldsymbol{\sigma}(i) \cdot \boldsymbol{\sigma}(j)] [\tau_a(i)\tau_a(j)], \quad (11)$$

$$V^{\rho_a}(\mathbf{r}_{ij}) = C(g_{\text{chv}}, m_{\rho_a}, \Lambda) \left\{ X_1(m_{\rho_a}, \Lambda, r_{ij}) + \frac{m_{\rho_a}^2}{6m_{q_i}m_{q_j}} \right. \\ \times \left[1 + \frac{f_{\text{chv}}}{g_{\text{chv}}} \frac{m_{q_i} + m_{q_j}}{M_N} + \left(\frac{f_{\text{chv}}}{g_{\text{chv}}} \right)^2 \frac{m_{q_i}m_{q_j}}{M_N^2} \right] \\ \left. \times X_2(m_{\rho_a}, \Lambda, r_{ij}) [\boldsymbol{\sigma}(i) \cdot \boldsymbol{\sigma}(j)] \right\} [\tau_a(i)\tau_a(j)], \quad (12)$$

$$V_{uu}^\omega(\mathbf{r}_{ij}) = C(g_{\text{chv}}, m_\omega, \Lambda) \left\{ X_1(m_\omega, \Lambda, r_{ij}) + \frac{m_\omega^2}{6m_u^2} \right. \\ \times \left(1 + \frac{f_{\text{chv}}}{g_{\text{chv}}} \frac{2m_u}{M_N} + \left(\frac{f_{\text{chv}}}{g_{\text{chv}}} \right)^2 \frac{m_u^2}{M_N^2} \right) \\ \left. \times X_2(m_\omega, \Lambda, r_{ij}) [\boldsymbol{\sigma}(i) \cdot \boldsymbol{\sigma}(j)] \right\}, \quad (13)$$

$$V_{u\bar{u}}^M = G_M V_{uu}^M. \quad (14)$$

Where G_M is the G -parity of the exchanged meson and

$$C(g_{\text{ch}}, m, \Lambda) = \frac{g_{\text{ch}}^2}{4\pi} \frac{\Lambda^2 m}{\Lambda^2 - m^2}, \quad (15)$$

$$X_1(m, \Lambda, r) = Y(mr) - \frac{\Lambda}{m} Y(\Lambda r), \quad (16)$$

$$X_2(m, \Lambda, r) = Y(mr) - \left(\frac{\Lambda}{m} \right)^3 Y(\Lambda r), \quad (17)$$

$$Y(x) = \frac{e^{-x}}{x}. \quad (18)$$

The tensor term and the spin-orbital term have been omitted in the potentials since we consider only S -wave interactions. We use the same cutoff Λ for various mesons. Its value is around the scale of chiral symmetry breaking (~ 1 GeV).

C. Bound state problem

According to the quark cluster model, the wave function of the two mesons system in coordinate space reads

$$\Psi = \psi_A(\boldsymbol{\xi}_A) \psi_B(\boldsymbol{\xi}_B) \chi(\mathbf{R}_{AB}) Z(\mathbf{R}_{\text{cm}}), \quad (19)$$

where $\boldsymbol{\xi}_A = \mathbf{r}_2 - \mathbf{r}_1$ and $\boldsymbol{\xi}_B = \mathbf{r}_4 - \mathbf{r}_3$ are the internal coordinates of clusters A and B , respectively, \mathbf{R}_{AB} is the relative coordinate between the two clusters, and \mathbf{R}_{cm} is the center-of-mass coordinate of the system. $\psi_A(\boldsymbol{\xi}_A)$ and $\psi_B(\boldsymbol{\xi}_B)$ are the wave functions of A and B and $Z(\mathbf{R}_{\text{cm}})$ represents

the center-of-mass motion wave function of the system in coordinate space. All of them are treated as Gaussian functions:

$$\psi_A(\boldsymbol{\xi}_A) = \left(\frac{m_A \omega}{\pi} \right)^{3/4} e^{-\frac{1}{2} m_A \omega \boldsymbol{\xi}_A^2}, \\ \psi_B(\boldsymbol{\xi}_B) = \left(\frac{m_B \omega}{\pi} \right)^{3/4} e^{-\frac{1}{2} m_B \omega \boldsymbol{\xi}_B^2}, \quad (20) \\ Z(\mathbf{R}_{\text{cm}}) = \left(\frac{M_{AB} \omega}{\pi} \right)^{3/4} e^{-\frac{1}{2} M_{AB} \omega \mathbf{R}_{\text{cm}}^2},$$

where $m_A = m_B = \frac{m_q m_Q}{m_q + m_Q}$ is the reduced mass for the cluster A or B and $M_{AB} = M_A + M_B = 2(m_q + m_Q)$ is the total mass of the two clusters. The universal oscillator frequency ω is associated with the width parameter b_u of the up quark through

$$\frac{1}{b_u^2} = m_u \omega. \quad (21)$$

The unknown relative orbital wave function $\chi(\mathbf{R}_{AB})$ is expanded to partial waves as

$$\chi(\mathbf{R}_{AB}) = \sum_{L=0}^{\infty} \frac{1}{R_{AB}} \chi^L(R_{AB}) Y_{LM}(\hat{\mathbf{R}}_{AB}), \quad (22)$$

$$\chi^L(R_{AB}) = \sum_{i=1}^N c_i 4\pi R_{AB} \left(\frac{\mu_{AB} \omega}{\pi} \right)^{3/4} e^{-\frac{1}{2} \mu_{AB} \omega (R_{AB}^2 + S_i^2)} \\ \times i_L(\mu_{AB} \omega R_{AB} S_i), \quad (23)$$

where $S_i (i = 1, 2, \dots, N)$ are the generator coordinates, $\mu_{AB} = \frac{1}{2}(m_q + m_Q)$ is the reduced mass of the two clusters, and $i_L(x)$ is the modified spherical Bessel function of L order. The coefficients c_i are to be obtained by solving the Schrödinger equation.

The RGM equation for the bound state problem reads

$$\sum_{j=1}^N [H_{ij}^L - E N_{ij}^L] c_j = 0 \quad (i = 1, \dots, N), \quad (24)$$

where

$$\left\{ \begin{matrix} H_{ij}^L \\ N_{ij}^L \end{matrix} \right\} = \int Y_{LM}^*(\hat{S}_i) \left\{ \begin{matrix} H_{ij} \\ N_{ij} \end{matrix} \right\} Y_{LM}(\hat{S}_j) d\hat{S}_i d\hat{S}_j, \quad (25) \\ \left\{ \begin{matrix} H_{ij} \\ N_{ij} \end{matrix} \right\} = \int \Psi(S_i) \left\{ \begin{matrix} H \\ 1 \end{matrix} \right\} \Psi(S_j) \prod_{k=1}^4 dr_k,$$

with

$$\Psi(S_i) = \phi_A(\boldsymbol{\xi}_A) \phi_B(\boldsymbol{\xi}_B) \chi(\mathbf{R}_{AB}, S_i) Z(\mathbf{R}_{\text{cm}}), \quad (26)$$

$$\chi(\mathbf{R}_{AB}, S_i) = \left(\frac{\mu_{AB} \omega}{\pi} \right)^{3/4} e^{-\frac{1}{2} \mu_{AB} \omega (\mathbf{R}_{AB} - S_i)^2}. \quad (27)$$

Here $\phi_A(\phi_B)$ denotes the total wave function of the cluster $A(B)$, which includes the radial and spin parts.

By solving Eq. (24), the energy E and the corresponding relative motion wave function of the system (c_i) are obtained. From the energy E , it is easy to derive the binding energy $E_0 = M_{D^0} + M_{D^{*0}} - M_{X_D}$. If E_0 is negative, the system would be unbound.

III. DETERMINING THE PARAMETERS

There are numerous parameters in the Hamiltonian and the wave functions: $g_q, g_Q, a_{qQ}^c, a_{qQ}^{c0}, m_Q, m_u, \omega, g_{\text{ch}}, g_{\text{chv}}, f_{\text{chv}}$, and Λ . The mass of the phenomenological σ meson is also treated as an adjustable parameter.

One should note that $M_{D^0}, M_{D^{*0}}$, and M_{X_D} are all calculated with the Gaussian functions presented in Sec. II. The binding energy will be irrelevant to the internal potentials of the color-singlet mesons because of the cancellation. That is, the form of the confinement and the values of g_q, g_Q, a_{qQ}^c , and a_{qQ}^{c0} will not affect the numerical result of E_0 . This feature can be understood with the effective potential between the clusters A and B in the generator coordinate method:

$$V^L(S_i, S_j) = \frac{V_{ij}^L}{N_{ij}^L} - V_{D^0} - V_{D^{*0}}. \quad (28)$$

One can examine that the parts due to V^{OGE} and V^{conf} of Eq. (8) are exactly zero. Therefore, we may take any values, in principle, for these four parameters. In the following calculation, we deduce g_Q, a_{qQ}^c , and a_{qQ}^{c0} by fitting the masses of the ground-state mesons $D, D^*, D_s, D_s^*, J/\psi$, and η_c using a least-squares fit with the assumption $a_{cu}^c = a_{cs}^c = a_{cc}^c$.

In the determination, we treat m_u, m_s, ω (or b_u), m_Q, g_u , and g_s as inputs. For the up and strange quark masses, we use the values given in the previous work [53–56], $m_u = 313$ MeV and $m_s = 470$ MeV. The width parameter $b_u = 0.5$ fm in the chiral SU(3) quark model and $b_u = 0.45$ fm in the extended chiral SU(3) quark model. These values have been fitted to reproduce the masses of the ground-state baryons, the binding energy of the deuteron, and the NN and YN scattering observables. To see the effects of this parameter, we also use a larger value for the width parameter, $b_u = 0.6$ fm. To investigate the heavy quark mass dependence, we take several typical values: $m_c = 1430$ MeV [57], $m_c = 1550$ MeV [58], and $m_c = 1870$ MeV [59]. For the coupling constants, we can use $(g_u, g_s) = (0.886, 0.917), (0.886, 0.755), (0.875, 0.920), (0.237, 0.451)$, or $(0.363, 0.500)$ [55,60]. With these inputs, one gets sets of fitted values. Selected results are presented in Table I.

Actually, in the two-meson-molecule picture (see Fig. 1), the meson exchanges play the dominant role in the energy of the system. The parameters of this part include the quark-meson coupling constants and the meson masses. In the

TABLE I. Fitted parameters for the calculation in the hidden charm case.

m_c (MeV)	b_u (fm)	g_u	g_c	a_{uc}^c (MeV ²)	a_{uc}^{c0} (MeV)
1430	0.45	0.237	0.718	45548	-166.07
	0.5	0.886	0.774	51320	-143.36
	0.6	0.886	1.086	54343	-150.96
1550	0.45	0.886	0.642	43129	-150.08
	0.5	0.886	0.772	47360	-152.71
	0.6	0.875	1.097	51600	-161.86
1870	0.45	0.363	0.771	27296	-187.07
	0.5	0.886	0.858	35445	-168.59
	0.6	0.886	1.165	42579	-180.69

chiral quark model, the π and σ exchanges have the same coupling constant, named g_{ch} , because of the chiral symmetry requirement. The coupling constant g_{ch} is fixed through

$$\frac{g_{\text{ch}}^2}{4\pi} = \frac{9}{25} \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{m_N^2}, \quad (29)$$

with $g_{NN\pi}^2/(4\pi) = 13.67$ determined experimentally, from which one has $g_{\text{ch}} = 2.621$. Thus, when the vector-meson exchanges are not included, the mass of σ and the cutoff mass Λ are the only adjustable parameters that can be fixed in the light quark systems. For the coupling constants of the vector-meson exchange, one can use $(g_{\text{chv}}, f_{\text{chv}}) = (3.0, 0.0)$ [61], (2.09, 5.26), (2.351, 0.0), and (1.972, 1.315) [54].

To study the effects of the uncertainty of the mass of the σ , we use $m_\sigma = 595, 535$, and 547 MeV [54,55]. For other mesons, we take the masses from the Particle Data Group [9]: $m_{\pi^0} = 134.98$ MeV, $m_{\rho^0} = 775.8$ MeV, and $m_\omega = 782.59$ MeV. In the calculation, we adopt cutoff values of $\Lambda = 1000, 1100$, and 1500 MeV.

In this work, we also calculated the binding energy for the case of the bottom analog where the flavor wave function is

$$|X_B\rangle = \frac{1}{\sqrt{2}}[|B^+ B^{*-}\rangle - |B^{*+} B^-\rangle]. \quad (30)$$

The procedure to determine the parameters is very similar. Now the ground-state mesons $B, B^*, B_s, B_s^*, \Upsilon(1S)$, and η_b are used. As an input, we chose $m_b = 4720$ MeV, which is close to the value in Ref. [62], $m_b = 5100$ MeV [63], and $m_b = 5259$ MeV [59]. By repeating the fitting procedure, one gets sets of parameters. We present the selected results in Table II.

IV. NUMERICAL RESULTS

Before the numerical evaluation, we first take a look at the effective potential

$$V(S) = V^{L=0}(S, S), \quad (31)$$

where the generator coordinate S can qualitatively describe the distance between the two clusters. These potentials rely on the meson exchange part in Eq. (8). We illustrate the potentials corresponding to various considerations in Fig. 2.

TABLE II. Fitted parameters for the calculation in the hidden bottom case.

m_b (MeV)	b_u (fm)	g_u	g_b	a_{ub}^c (MeV ²)	a_{ub}^{c0} (MeV)
4720	0.45	0.886	0.897	63452	-149.44
	0.5	0.875	1.100	68609	-153.70
	0.6	0.237	1.567	66134	-207.04
5100	0.45	0.875	0.931	46250	-177.68
	0.5	0.363	1.208	47881	-200.74
	0.6	0.875	1.551	61739	-194.71
5259	0.45	0.886	0.943	39073	-183.09
	0.5	0.363	1.218	41301	-210.85
	0.6	0.886	1.565	56580	-204.13

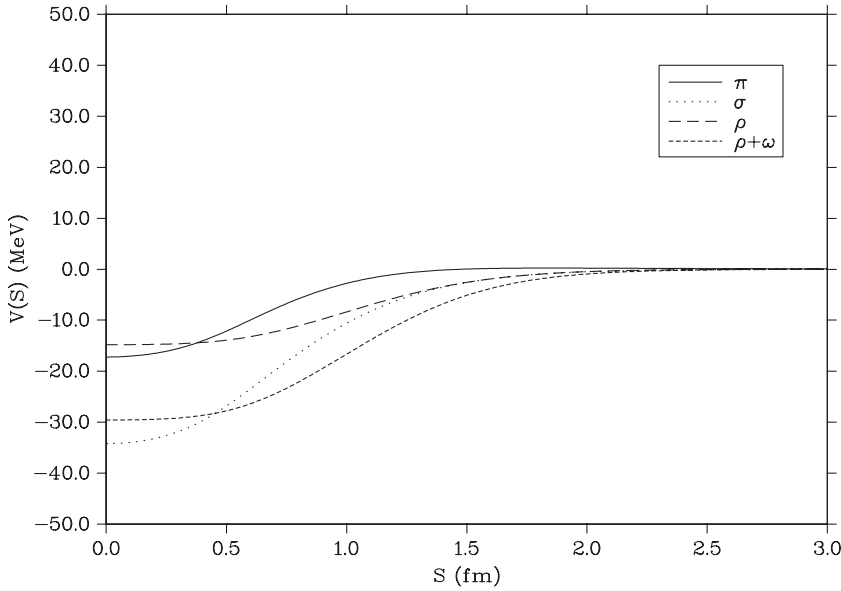


FIG. 2. The effective potential $V(S)$ for different meson exchanges. The parameters used are $b_u = 0.5$ fm, $m_u = 313$ MeV, $m_c = 1870$ MeV, $g_{ch} = 2.621$, $g_{chv} = 3.0$, $f_{chv} = 0.0$, $m_\sigma = 595$ MeV, $m_\pi = 134.98$ MeV, $m_\rho = 775.8$ MeV, $m_\omega = 782.59$ MeV, and $\Lambda = 1100$ MeV. Here the line for π corresponds to $V^\pi(S)$, the line for σ corresponds to $V^\sigma(S)$, and so on.

From Fig. 2, one sees that the interactions from π , σ , ρ , and ω are all attractive.¹ The amplitudes for ρ and ω exchanges are comparable and their contributions should not be ignored arbitrarily. We will consider π and σ interactions for the moment and then include the vector-meson contributions.

Now we calculate the binding energy for the system $D^0 \bar{D}^{*0}$ through solving Eq. (24). Here we do not constrain the sets of the parameters with the experimental data as was done in the studies of Refs. [54,55]. After exploring all possible combinations of the parameters in the former section, we fail to get a bound state solution. Thus the $D^0 \bar{D}^{*0}$ system is unbound when we consider only S -wave π and σ exchange interactions in this framework. This conclusion agrees with that of Ref. [49].

Since the bottom quark is much heavier, the possibility of getting a bound state in B meson systems is increased. Our former dynamical calculation is in favor of the existence of an S -wave X_B molecule. We also study this case in the present framework. When applying the evaluation to the bottom analog $B \bar{B}^*$, we get positive binding energies with the parameters in Sec. III. The results are given in Table III. From that table, one finds that a larger binding energy can be obtained with a larger m_b , a smaller m_σ , a smaller b_u , or a bigger cutoff Λ . A deeper bound state should have a smaller root-mean-square radius r_{rms} , which is also illustrated in Table III.

¹The qualitative properties for meson exchange potentials in different frameworks should be consistent. When comparing the present result with the potentials at the hadron level, we found inconsistencies. In fact, we missed a minus sign when deriving the σ exchange potential in Eq. (13) of Ref. [49]. Therefore that potential should also be attractive (see also Ref. [64]). The σ exchange terms in Eqs. (15), (18), and (22) also change sign. Fortunately, the total potential and the numerical results change little and the final conclusion is not affected. For the vector-meson exchange potentials for the $D \bar{D}^*$ system, we obtained attractive forces at the hadron level in Ref. [64]. After carefully checking the calculation in the present framework, we confirmed those signs for ρ and ω exchange potentials.

To explore additional effects, we move on to include the vector-meson exchanges. We use the parameters to reproduce experimental data for light quark systems [54]. The parameters and the results for $D^0 \bar{D}^{*0}$ and $B^+ \bar{B}^{*0}$ are presented in

TABLE III. Numerical results for the hidden bottom case when π and σ exchange potentials are considered. The first, second, and third values for E_0 and r_{rms} correspond to cutoffs $\Lambda = 1000, 1100,$ and 1500 MeV, respectively.

m_b (MeV)	b_u (fm)	m_σ (MeV)	E_0 (MeV)	r_{rms} (fm)	
4720	0.45	595	3.3/3.7/5.0	1.1/1.1/1.1	
		547	5.0/5.5/7.0	1.1/1.1/1.0	
		535	5.4/6.0/7.5	1.1/1.1/1.0	
	0.5	595	2.0/2.3/3.1	1.3/1.3/1.2	
		547	3.4/3.8/4.7	1.2/1.2/1.2	
		535	3.8/4.2/5.2	1.2/1.2/1.2	
	0.6	595	0.5/0.7/1.0	1.6/1.6/1.5	
		547	1.5/1.7/2.1	1.5/1.5/1.5	
		535	1.8/1.9/2.4	1.5/1.5/1.4	
	5100	0.45	595	4.2/4.7/6.1	1.1/1.1/1.0
			547	6.0/6.6/8.2	1.0/1.0/1.0
			535	6.5/7.1/8.8	1.0/1.0/1.0
0.5		595	2.8/3.1/4.0	1.2/1.2/1.2	
		547	4.2/4.6/5.7	1.2/1.2/1.1	
		535	4.6/5.1/6.2	1.2/1.1/1.1	
0.6		595	1.0/1.2/1.6	1.5/1.5/1.4	
		547	2.0/2.2/2.7	1.4/1.4/1.4	
		535	2.3/2.5/3.0	1.4/1.4/1.4	
5259		0.45	595	4.6/5.1/6.6	1.1/1.0/1.0
			547	6.4/7.0/8.7	1.0/1.0/1.0
			535	6.9/7.6/9.3	1.0/1.0/1.0
	0.5	595	3.1/3.4/4.4	1.2/1.2/1.1	
		547	4.6/5.0/6.1	1.1/1.1/1.1	
		535	5.0/5.4/6.5	1.1/1.1/1.1	
	0.6	595	1.2/1.4/1.8	1.5/1.5/1.4	
		547	2.2/2.4/2.9	1.4/1.4/1.3	
		535	2.5/2.7/3.3	1.4/1.4/1.3	

TABLE IV. Numerical results for the hidden charm case when the vector-meson exchange interactions are also included. Here $m_u = 313$ MeV and $g_{\text{ch}} = 2.621$ are used. The three values for E_0 and r_{rms} correspond to $m_c = 1430, 1550,$ and 1870 MeV in order. The first and second sets of E_0 and r_{rms} values correspond to $\Lambda = 1100$ and 1500 MeV, respectively. The \times symbol indicates that the system is unbound.

	χ QM	Ex. χ QM	
		$f_{\text{chv}}/g_{\text{chv}} = 0$	$f_{\text{chv}}/g_{\text{chv}} = 2/3$
b_u (fm)	0.5	0.45	0.45
m_σ (MeV)	595	535	547
g_{chv}		2.351	1.972
E_0 (MeV)	\times	$\times / \times / 1.7$	\times
r_{rms} (fm)	\times	$\times / \times / 1.7$	\times
E_0 (MeV)	\times	$\times / 0.5 / 3.0$	\times
r_{rms} (fm)	\times	$\times / 1.8 / 1.6$	\times

Table IV and V, respectively. For comparison, the solutions without considering vector mesons are also given. Now a bound state seems to be possible in the $D^0\bar{D}^{*0}$ system. For its bottom analogy, the vector-meson exchange interactions increase the binding energy about 10–20 MeV.

Up till now, we considered only neutral components of the system. In Refs. [64] and [65], the authors studied the symmetric wave function case [i.e., $a_0 = a_1 = \frac{1}{\sqrt{2}}$ in Eq. (6)] and they found that the coupling to charged components is important. We also present the numerical results for this case in Table VI and VII, which support the result that channel coupling should be considered in studying the X(3872).

V. DISCUSSION AND SUMMARY

In this work we have studied whether $D^0\bar{D}^{*0}(\bar{D}^0D^{*0})$ may form an S -wave molecule bound by the $\pi, \sigma, \rho,$ and ω exchange interactions in a chiral quark model. These potentials are all attractive. By solving the RGM equation, we failed to get a binding solution in this system if we consider only π and σ contributions. When the vector-meson contributions

TABLE V. Numerical results for the hidden bottom case when the vector-meson exchange interactions are also included. Here $m_u = 313$ MeV and $g_{\text{ch}} = 2.621$ are used. The three values for E_0 and r_{rms} correspond to $m_b = 4720, 5100,$ and 5259 MeV in order. The first and second sets of E_0 and r_{rms} values correspond to $\Lambda = 1100$ and 1500 MeV, respectively.

	χ QM	Ex. χ QM	
		$f_{\text{chv}}/g_{\text{chv}} = 0$	$f_{\text{chv}}/g_{\text{chv}} = 2/3$
b_u (fm)	0.5	0.45	0.45
m_σ (MeV)	595	535	547
g_{chv}		2.351	1.972
E_0 (MeV)	2.3/3.1/3.4	17.2/18.7/19.3	11.1/12.3/12.8
r_{rms} (fm)	1.3/1.2/1.2	0.9/0.9/0.9	1.1/1.0/0.9
E_0 (MeV)	3.1/4.0/4.4	20.7/22.4/23.1	13.6/15.0/15.6
r_{rms} (fm)	1.2/1.2/1.1	0.9/0.8/0.8	1.0/0.9/0.9

TABLE VI. Numerical results for the hidden charm case with the symmetric wave function. Here $m_u = 313$ MeV and $g_{\text{ch}} = 2.621$ are used. The three values for E_0 and r_{rms} correspond to $m_c = 1430, 1550,$ and 1870 MeV in order. The first and second sets of E_0 and r_{rms} values corresponds to $\Lambda = 1100$ and 1500 MeV, respectively. The \times symbol indicates that the system is unbound.

	χ QM	Ex. χ QM	
		$f_{\text{chv}}/g_{\text{chv}} = 0$	$f_{\text{chv}}/g_{\text{chv}} = 2/3$
b_u (fm)	0.5	0.45	0.45
m_σ (MeV)	595	535	547
g_{chv}		2.351	1.972
E_0 (MeV)	\times	12.1/14.2/19.3	4.5/6.0/9.7
r_{rms} (fm)	\times	1.3/1.3/1.1	1.6/1.5/1.3
E_0 (MeV)	\times	16.3/18.6/24.5	6.9/8.6/13.0
r_{rms} (fm)	\times	1.2/1.2/1.0	1.5/1.4/1.2

are included, the existence of the $D^0\bar{D}^{*0}$ molecule seems to be possible. The coupling to charged components is also important for a bound state.

When moving on to the heavier B meson system, we obtain binding state solutions. Our calculation favors the existence of an S -wave $B\bar{B}^*(\bar{B}B^*)$ molecular state, which agrees with the conclusion from Ref. [49]. It will be very interesting to search for such a bound state in the radiative decay channel $X_B \rightarrow B^+B^-\gamma$ and the strong decay channel $X_B \rightarrow \pi^+\pi^-\Upsilon$ in the future. Finding it may be possible at the Tevatron or with the Large Hadron Collider beauty (LHCb) experiment [66].

In the study of the deuteron, it was found that the tensor force that mixes the S -wave and D -wave interactions is crucial in binding the proton and the neutron. In an earlier calculation it was also concluded that the tensor potential is very important in the mesonic case [39]. In the present work, we did not consider effects from the D wave. Further study using the current approach will be helpful to clarify whether this part can lead to a loosely bound $D^0\bar{D}^{*0}(\bar{D}^0D^{*0})$ state.

From the numerical values, we observe that vector-meson contributions are important in binding two color-singlet mesons. However, the results rely on the vector coupling constants g_{chv} and f_{chv} . In our calculation the parameters

TABLE VII. Numerical results for the hidden bottom case with the symmetric wave function. Here $m_u = 313$ MeV and $g_{\text{ch}} = 2.621$ are used. The three values for E_0 and r_{rms} correspond to $m_b = 4720, 5100,$ and 5259 MeV in order. The first and second sets of E_0 and r_{rms} values correspond to $\Lambda = 1100$ and 1500 MeV, respectively.

	χ QM	Ex. χ QM	
		$f_{\text{chv}}/g_{\text{chv}} = 0$	$f_{\text{chv}}/g_{\text{chv}} = 2/3$
b_u (fm)	0.5	0.45	0.45
m_σ (MeV)	595	535	547
g_{chv}		2.351	1.972
E_0 (MeV)	12.4/13.8/14.4	47.6/50.0/50.9	32.0/34.0/34.8
r_{rms} (fm)	0.9/0.9/0.9	0.7/0.7/0.7	0.8/0.8/0.8
E_0 (MeV)	14.6/16.2/16.8	56.4/59.0/60.0	38.3/40.5/41.4
r_{rms} (fm)	0.9/0.9/0.8	0.7/0.6/0.6	0.7/0.7/0.7

of the light quark part are taken from Ref. [54], in which the calculated NN scattering phase shifts and the binding energy of the deuteron are consistent with the experimental data. But since the mechanism of the short-range quark-quark interaction is still an open problem, whether OGE or vector-meson exchange is dominant, or whether both of them are needed, one should be cautious when making conclusions from these results.

In short summary, we have performed a dynamical calculation to investigate whether the $D^0\bar{D}^{*0}(\bar{D}^0D^{*0})$ may form a molecule by considering the π, σ, ρ , and ω exchange interactions. We could not find an S -wave molecular state in this system in the chiral quark model but its existence is not excluded in the extended chiral quark model. More details

of the dynamics should be considered in further study of the X(3872). If it is really not a molecule, the scheme of mixing a charmonium and a molecular state is probably a way to solve the puzzles of the X(3872).

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- [1] E. S. Swanson, *Phys. Rep.* **429**, 243 (2006).
 [2] M. B. Voloshin, *Prog. Part. Nucl. Phys.* **61**, 455 (2008); arXiv:0711.4556 [hep-ph].
 [3] S. Godfrey and S. L. Olsen, *Annu. Rev. Nucl. Part. Sci.* **58**, 51 (2008); arXiv:0801.3867 [hep-ph].
 [4] S. L. Zhu, *Int. J. Mod. Phys. E* **17**, 283 (2008); *Nucl. Phys.* **A805**, 221c (2008).
 [5] S. K. Choi *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **91**, 262001 (2003).
 [6] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **93**, 072001 (2004).
 [7] V. M. Abazov *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **93**, 162002 (2003).
 [8] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **71**, 071103 (2005).
 [9] W. M. Yao *et al.* (Particle Data Group), *J. Phys. G* **33**, 1 (2006).
 [10] K. Abe *et al.* (Belle Collaboration), arXiv:hep-ex/0505038.
 [11] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **98**, 132002 (2007).
 [12] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **71**, 031501 (2005).
 [13] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **96**, 102002 (2006).
 [14] K. Abe *et al.* (Belle Collaboration), arXiv:hep-ex/0505037.
 [15] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **74**, 071101(R) (2006).
 [16] B. Aubert *et al.* (BaBar Collaboration), *Phys. Rev. D* **73**, 011101(R) (2006).
 [17] G. Gokhroo *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **97**, 162002 (2006).
 [18] (BaBar Collaboration), talk given by P. Grenier in Moriond QCD 17–24 March 2007, <http://moriond.in2p3.fr/QCD/2007/SundayAfternoon/Grenier.pdf>.
 [19] T. Barnes and S. Godfrey, *Phys. Rev. D* **69**, 054008 (2004).
 [20] F. E. Close and P. R. Page, *Phys. Lett.* **B578**, 119 (2004).
 [21] M. B. Voloshin, *Phys. Lett.* **B579**, 316 (2004); **B604**, 69 (2004).
 [22] C. Y. Wong, *Phys. Rev. C* **69**, 055202 (2004).
 [23] E. S. Swanson, *Phys. Lett.* **B588**, 189 (2004); **B598**, 197 (2004).
 [24] N. A. Törnqvist, *Phys. Lett.* **B590**, 209 (2004).
 [25] D. V. Bugg, *Phys. Lett.* **B598**, 8 (2004).
 [26] J. L. Rosner, *Phys. Rev. D* **74**, 076006 (2006).
 [27] B. A. Li, *Phys. Lett.* **B605**, 306 (2005).
 [28] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, *Phys. Rev. D* **71**, 014028 (2005); L. Maiani, A. D. Polosa, and V. Riquer, *Phys. Rev. Lett.* **99**, 182003 (2007).
 [29] H. Hogaasen, J. M. Richard, and P. Sorba, *Phys. Rev. D* **73**, 054013 (2006); D. Ebert, R. N. Faustov, and V. O. Galkin, *Phys. Lett.* **B634**, 214 (2006); N. Barnea, J. Vijande, and A. Valcarce, *Phys. Rev. D* **73**, 054004 (2006); J. Vijande, E. Weissman, N. Barnea, and A. Valcarce, *ibid.* **76**, 094022 (2007); Y. Cui, X. L. Chen, W. Z. Deng, and S. L. Zhu, *High Energy Phys. Nucl. Phys.* **31**, 7 (2007); R. D. Matheus, S. Narison, M. Nielsen, and J. M. Richard, *Phys. Rev. D* **75**, 014005 (2007); T. W. Chiu and T. H. Hsieh, *Phys. Lett.* **B646**, 95 (2007); K. Terasaki, *Prog. Theor. Phys.* **118**, 821 (2007).
 [30] K. K. Seth, *Phys. Lett.* **B612**, 1 (2005).
 [31] D. Gamermann and E. Oset, *Eur. Phys. J. A* **33**, 119 (2007); **36**, 189 (2008).
 [32] E. J. Eichten, K. Lane, and C. Quigg, *Phys. Rev. D* **69**, 094019 (2004).
 [33] M. Suzuki, *Phys. Rev. D* **72**, 114013 (2005).
 [34] C. Meng, Y. J. Gao, and K. T. Chao, arXiv:hep-ph/0506222; C. Meng and K. T. Chao, *Phys. Rev. D* **75**, 114002 (2007).
 [35] Y. S. Kalashnikova, *Phys. Rev. D* **72**, 034010 (2005).
 [36] M. R. Pennington and D. J. Wilson, *Phys. Rev. D* **76**, 077502 (2007).
 [37] M. B. Voloshin and L. B. Okun, *JETP Lett.* **23**, 333 (1976).
 [38] A. De Rujula, H. Georgi, and S. L. Glashow, *Phys. Rev. Lett.* **38**, 317 (1977).
 [39] N. A. Törnqvist, *Phys. Rev. Lett.* **67**, 556 (1991); *Z. Phys. C* **61**, 525 (1994).
 [40] M. T. AlFiky, F. Gabbiani, and A. A. Petrov, *Phys. Lett.* **B640**, 238 (2006).
 [41] P. Colangelo, F. De Fazio, and S. Nicotri, *Phys. Lett.* **B650**, 166 (2007).
 [42] E. Braaten and M. Kusunoki, *Phys. Rev. D* **71**, 074005 (2005).
 [43] E. Braaten, M. Kusunoki, and S. Nussinov, *Phys. Rev. Lett.* **93**, 162001 (2004); E. Braaten and M. Kusunoki, *Phys. Rev. D* **69**, 074005 (2004); **69**, 114012 (2004); **72**, 014012 (2005); **72**, 054022 (2005); E. Braaten, *ibid.* **73**, 011501(R) (2006); **77**, 034019 (2008); E. Braaten and M. Lu, *ibid.* **74**, 054020 (2006); **76**, 094028 (2007); E. Braaten, M. Lu, and J. Lee, *ibid.* **76**, 054010 (2007).
 [44] S. Dubynskiy and M. B. Voloshin, *Phys. Rev. D* **74**, 094017 (2006); M. B. Voloshin, *ibid.* **76**, 014007 (2007).

- [45] S. Fleming, M. Kusunoki, T. Mehen, and U. van Kolck, Phys. Rev. D **76**, 034006 (2007).
- [46] C. Hanhart, Y. S. Kalashnikova, A. E. Kudryavtsev, and A. V. Nefediev, Phys. Rev. D **76**, 034007 (2007).
- [47] G. Y. Chen and J. P. Ma, Phys. Rev. D **77**, 097501 (2008).
- [48] Y. Dong, A. Faessler, T. Gutsche, and V. E. Lyubovitskij, Phys. Rev. D **77**, 094013 (2008).
- [49] Y. R. Liu, X. Liu, W. Z. Deng, and S. L. Zhu, Eur. Phys. J. C **56**, 63 (2008).
- [50] X. Liu, Y. R. Liu, W. Z. Deng, and S. L. Zhu, Phys. Rev. D **77**, 034003 (2008); **77**, 094015 (2008); X. Liu, Y. R. Liu, and W. Z. Deng, AIP Conf. Proc. **1030**, 346 (2008).
- [51] M. Kamimura, Suppl. Prog. Theor. Phys. **62**, 236 (1977).
- [52] M. Oka and K. Yazaki, Prog. Theor. Phys. **66**, 556 (1981).
- [53] Z. Y. Zhang, Y. W. Yu, P. N. Shen, L. R. Dai, A. Faessler, and U. Straub, Nucl. Phys. **A625**, 59 (1997).
- [54] L. R. Dai, Z. Y. Zhang, Y. W. Yu, and P. Wang, Nucl. Phys. **A727**, 321 (2003).
- [55] F. Huang, Z. Y. Zhang, and Y. W. Yu, Phys. Rev. C **70**, 044004 (2004); **72**, 065208 (2005); **73**, 025207 (2006); High Energy Phys. Nucl. Phys. **29**, 948 (2005); Commun. Theor. Phys. **44**, 665 (2005); F. Huang and Z. Y. Zhang, Phys. Rev. C **70**, 064004 (2004); **72**, 024003 (2005); **72**, 068201 (2005); F. Huang, D. Zhang, Z. Y. Zhang, and Y. W. Yu, *ibid.* **71**, 064001 (2005); F. Huang, W. L. Wang, Z. Y. Zhang, and Y. W. Yu, *ibid.* **76**, 018201 (2007); W. L. Wang, F. Huang, Z. Y. Zhang, Y. W. Yu, and F. Liu, Eur. Phys. J. A **32**, 293 (2007).
- [56] D. Zhang, F. Huang, L. R. Dai, Y. W. Yu, and Z. Y. Zhang, Phys. Rev. C **75**, 024001 (2007); H. R. Pang, J. L. Ping, and F. Wang, Chin. Phys. Lett. **25**, 3192 (2008).
- [57] H. X. Zhang, W. L. Wang, Y. B. Dai, and Z. Y. Zhang, Commun. Theor. Phys. **49**, 414 (2008).
- [58] J. Vijande, H. Garcilazo, A. Valcarce, and F. Fernandez, Phys. Rev. D **70**, 054022 (2004).
- [59] B. Silvestre-Brac and C. Semay, Z. Phys. C **57**, 273 (1993).
- [60] D. Zhang, F. Huang, Z. Y. Zhang, and Y. W. Yu, Nucl. Phys. **A756**, 215 (2005).
- [61] D. O. Riska and G. E. Brown, Nucl. Phys. **A679**, 577 (2001).
- [62] H. X. Zhang, M. Zhang, and Z. Y. Zhang, Chin. Phys. Lett. **24**, 2533 (2007); M. Zhang, H. X. Zhang, and Z. Y. Zhang, Commun. Theor. Phys. **50**, 437 (2008).
- [63] J. Vijande, F. Fernandez, and A. Valcarce, J. Phys. G **31**, 481 (2005).
- [64] X. Liu, Z.-G. Luo, Y.-R. Liu, and S.-L. Zhu, arXiv:0808.0073 [hep-ph].
- [65] C. E. Thomas and F. E. Close, Phys. Rev. D **78**, 034007 (2008).
- [66] W. S. Hou, Phys. Rev. D **74**, 017504 (2006).