Possible *H*-like dibaryon states with heavy quarks

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Possible H-like dibaryon states $\Lambda_c\Lambda_c$ and $\Lambda_b\Lambda_b$ are investigated within the framework of the quark delocalization color screening model. The results show that the interaction between two Λ_c's is repulsive, so it cannot be a bound state by itself. However, the strong attraction in $\Sigma_c\Sigma_c$ and $\Sigma_c^*\Sigma_c^*$ channels and the strong channel coupling, due to the central interaction of one-gluon exchange and one-pion exchange, among $\Lambda_c\Lambda_c$, $\Sigma_c\Sigma_c$ and $\Sigma_c^*\Sigma_c^*$ push the energy of system below the threshold of $\Lambda_c\Lambda_c$ by 3-20 MeV. The $\Lambda_b\Lambda_b$ system has properties similar to those of the $\Lambda_c\Lambda_c$ system, and a bound state is also possible in the $\Lambda_b\Lambda_b$ system.

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I. INTRODUCTION

The H dibaryon, a six quark ($uuddss$) state corresponding asymptotically to a bound $\Lambda\Lambda$ system, was first proposed by Jaffe in 1977 [1]. This hypothesis initiated worldwide activity of theoretical studies and experimental searches for dibaryon states [2]. In 1987, M. Oka *et al*. claimed that a sharp resonance appears in $^1S_0\Lambda\Lambda$ scattering at $E_{\rm c.m.} = 26.3$ MeV, which might correspond to the H dibaryon state [3]. Moreover, M. Oka also proposed several $J^P = 2^+$ dibaryons in the quark cluster model without meson exchange [4]. Despite numerous claims, no dibaryon candidate has been confirmed experimentally so far. Recently, interest in the H dibaryon has been revived by lattice QCD calculations of different collaborations, NPLQCD [5] and HALQCD [6]. These two groups reported that the H particle is indeed a bound state at pion masses larger than the physical ones. Then, Carames and Valcarce examined the H dibaryon within a chiral constituent quark model and obtained a bound H dibaryon with binding energy $B_H = 7$ MeV [7].

Understanding the hadron-hadron interactions and searching for exotic quark states are important topics in temporary hadron physics. Recently many near-threshold charmonium-like states were observed, such as $X(3872)$, $Y(3940)$, and $Z^+(4430)$, triggering lots of studies on the molecule-like bound states containing heavy quark hadrons. Such studies will give further information on the hadron-hadron interactions. In the heavy-quark sector, the large masses of the heavy baryons reduce the kinetic energy of the system, which makes them easier to form bound states. One may wonder whether or not an H-like dibaryon state $\Lambda_c\Lambda_c$ exists.

In particular, the deuteron is a loosely bound state of a proton and a neutron, which may be regarded as a hadronic molecular state. The possibility of existing deuteron-like states, such as $N\Sigma_c$, $N\Xi_c^{'}$, $N\Xi_{cc}$, $\Xi\Xi_{cc}$, and so on, were investigated by several realistic phenomenological nucleon-nucleon interaction models [8,9]. The $N\Lambda_c$ system and relevant coupled channel effects were both studied on the hadron level [10] and on the quark level [11]. However, differences were found for these two approaches. On the hadron level [10], it is found that molecular bound states of $N\Lambda_c$ are plausible in both the one-pion-exchange potential model and the one-boson-exchange potential model. On the quark level [11], our group found the attraction between N and Λ_c is not strong enough to form any $N\Lambda_c$ bound state within our quark delocalization color screening model (QDCSM). Whereas the attraction between N and Σ_c is strong enough to form a bound state $N\Sigma_c(^3S_1)$, it becomes a resonance state by coupling to the open $N\Lambda_c$ D-wave channels. We also explored the corresponding states $N\Lambda_b$, $N\Sigma_b$ and properties similar to those of states $N\Lambda_c$, $N\Sigma_c$ were found. Recently, the possible $\Lambda_c\Lambda_c$ molecular state was studied in the one-boson-exchange potential model [12] and in the one-pion-exchange potential model [13] on the hadron level. Different results were obtained by these two models. The $\Lambda_c\Lambda_c$ does not exist in the former model, whereas the molecular bound state of $\Lambda_c\Lambda_c$ is possible in the latter model. So the quark level study of the $\Lambda_c\Lambda_c$ system is interesting and necessary.

The quark delocalization color screening model (QDCSM) was developed in the 1990s with the aim of explaining the similarities between nuclear and molecular forces [14]. The model gives a good description of NN and YN interactions and the properties of deuteron [15]. It is also employed to calculate the baryon-baryon scattering phase shifts in the framework of the resonating group method (RGM), and the dibaryon candidates are also studied with this model [16,17]. Recent studies also show that the NN intermediate-range attraction mechanism in the QDCSM, quark delocalization and color screening, is an alternative mechanism for the σ-meson exchange in the most common quark model, the chiral quark model, and the color screening is an effective description of the hidden color channel coupling [16,17]. In the frame of QDCSM, the H dibaryon mass is around the $\Lambda\Lambda$ threshold [18]. Therefore, it is very interesting to investigate whether an H-like dibaryon state $\Lambda_c\Lambda_c$ exists or not in QDCSM.

In present work, QDCSM is employed to study the properties of $\Lambda_c\Lambda_c$ systems. the channel-coupling effects of $\Sigma_c\Sigma_c$, $\Sigma_c\Sigma_c^*$, $\Sigma_c^*\Sigma_c^*$, and $N\Xi_{cc}$ are included. Our purpose is to understand the interaction properties of the $\Lambda_c\Lambda_c$ system and to see whether an H-like dibaryon state $\Lambda_c\Lambda_c$ exists or not. Extension of the study to the bottom case is also interesting

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and is performed too. The structure of this paper is as follows. After the introduction, we present a brief description of the quark models used in Sec. II. Section III is devoted to the numerical results and discussions. The summary is given in the last section.

II. THE QUARK DELOCALIZATION COLOR SCREENING MODEL (QDCSM)

The detail of QDCSM used in the present work can be found in Refs. [14–17]. Here, we just present the salient features of the model. The model Hamiltonian is

$$
\begin{aligned}
H &= \sum_{i=1}^{6}\left(m_i+\frac{p_i^2}{2m_i}\right)-T_c+\sum_{i<j}[V^G(r_{ij})+V^{\chi}(r_{ij})+V^C(r_{ij})],\\
V^G(r_{ij}) &= \frac{1}{4}\alpha_s\boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j\left[\frac{1}{r_{ij}}-\frac{\pi}{2}\left(\frac{1}{m_i^2}+\frac{1}{m_j^2}+\frac{4\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j}{3m_im_j}\right)\delta(r_{ij})-\frac{3}{4m_im_jr_{ij}^3}S_{ij}\right],\\
V^{\chi}(r_{ij}) &= \frac{1}{3}\alpha_{ch}\frac{\Lambda^2}{\Lambda^2-m_\chi^2}m_\chi\left\{\left[Y(m_\chi r_{ij})-\frac{\Lambda^3}{m_\chi^3}Y(\Lambda r_{ij})\right]\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j+\left[H(m_\chi r_{ij})-\frac{\Lambda^3}{m_\chi^3}H(\Lambda r_{ij})\right]S_{ij}\right\}\mathbf{F}_i\cdot\mathbf{F}_j,\ \chi=\pi,K,\eta,\\
V^C(r_{ij}) &= -a_c\boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j[f(r_{ij})+V_0],\\
f(r_{ij}) &= \begin{cases} r_{ij}^2 & \text{if } i,j \text{ occur in the same baryon orbit},\\ \frac{1-e^{-\mu_{ij}r_{ij}^2}}{\mu_{ij}} & \text{if } i,j \text{ occur in different baryon orbits},\end{cases}\\
S_{ij} &= \frac{(\boldsymbol{\sigma}_i\cdot\mathbf{r}_{ij})(\boldsymbol{\sigma}_j\cdot\mathbf{r}_{ij})}{r_{ij}^2}-\frac{1}{3}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j,
\end{aligned}
\tag{1}
$$

where S_{ij} is the quark tensor operator; $Y(x)$ and $H(x)$ are standard Yukawa functions [19]; T_c is the kinetic energy of the center of mass; α_{ch} is the chiral coupling constant determined as usual from the π-nucleon coupling constant; and α_s is the quark-gluon coupling constant. In order to cover the wide energy range from light, strange, to heavy quarks one introduces an effective scale-dependent quark-gluon coupling $\alpha_s(u)$ [20]:

$$\alpha_s(u)=\frac{\alpha_0}{\ln\left(\frac{u^2+u_0^2}{\Lambda_0^2}\right)}. \tag{2}$$

All other symbols have their usual meanings. Here, a phenomenological color screening confinement potential is used, and μ_{ij} is the color screening parameter. For the light-flavor quark system, it is determined by fitting the deuteron properties, NN scattering phase shifts, $N\Lambda$ and $N\Sigma$ scattering phase shifts, respectively, with $\mu_{uu}=1.2$ fm^{-2}, $\mu_{us}=0.3$ fm^{-2}, $\mu_{ss}=0.08$ fm^{-2}, satisfying the relation $\mu_{us}^2=\mu_{uu}*\mu_{ss}$ [17]. When extending to the heavy quark case, there is no experimental data available, so we take it as a common parameter. In the present work, we take $\mu_{cc}=0.001$ fm^{-2} and $\mu_{uc}=0.0346$ fm^{-2}, also satisfying the relation $\mu_{uc}^2=\mu_{uu}*\mu_{cc}$. All other parameters are also taken from our previous work [17], except for the charm and bottom quark masses m_c and m_b, which are fixed by a fitting to the masses of the charmed and bottom baryons. The values of those parameters are listed in Table I. In order to test the sensitivity of the QDCSM to model parameters, two sets of parameters (QDCSM1 and QDCSM2) are used in the calculations. The corresponding masses of the charmed and bottom baryons are shown in Table II.

TABLE I. Two sets of model parameters discussed in this paper; $m_\pi=0.7$ fm^{-1}, $m_k=2.51$ fm^{-1}, $m_\eta=2.77$ fm^{-1}, $\Lambda_\pi=4.2$ fm^{-1}, $\Lambda_k=5.2$ fm^{-1}, $\Lambda_\eta=5.2$ fm^{-1}, $\alpha_{ch}=0.027$.

	QDCSM1	QDCSM2
b (fm)	0.518	0.60
m_s (MeV)	573	539
m_c (MeV)	1788	1732
m_b (MeV)	5141	5070
a_c (MeV fm^{-2})	58.03	18.52
V_0 (fm^2)	−1.2883	−0.3333
α_0	0.5101	0.7089
Λ_0 (fm^{-1})	1.5250.2	1.7225
u_0 (MeV)	445.8080	445.8512

TABLE II. The Masses (in MeV) of the charmed and bottom baryons obtained from QDCSM1 and QDCSM2. Experimental values are taken from the Particle Data Group (PDG) [21].

	Σ_c	Σ_c^*	Λ_c	Ξ_c^*	Ξ_c	$\Xi_c^{'}$	Ω_c	Ω_c^*
Expt.	2455	2520	2286	2645	2467	2575	2695	2770
QDCSM1	2465	2489	2286	2638	2551	2621	2785	2796
QDCSM2	2462	2492	2286	2653	2557	2632	2816	2829
	Σ_b	Σ_b^*	Λ_b	Ξ_b	Ω_b			
Expt.	5811	5832	5619	5791	6071			
QDCSM1	5809	5817	5619	5888	6131			
QDCSM2	5809	5818	5619	5895	6165			

TABLE III. The $\Lambda_c\Lambda_c$ and $\Lambda_b\Lambda_b$ states and the channels coupled to them.

Channels	1	2	3	4	5	6	7
$J^P = 0^+$	$\Sigma_c\Sigma_c(^1S_0)$	$N\Xi_{cc}(^1S_0)$	$\Lambda_c\Lambda_c(^1S_0)$	$\Sigma_c^*\Sigma_c^*(^1S_0)$	$N\Xi_{cc}^*(^5D_0)$	$\Sigma_c\Sigma_c^*(^5D_0)$	$\Sigma_c^*\Sigma_c^*(^5D_0)$
$J^P = 0^+$	$\Sigma_b\Sigma_b(^1S_0)$	$N\Xi_{bb}(^1S_0)$	$\Lambda_b\Lambda_b(^1S_0)$	$\Sigma_b^*\Sigma_b^*(^1S_0)$	$N\Xi_{bb}^*(^5D_0)$	$\Sigma_b\Sigma_b^*(^5D_0)$	$\Sigma_b^*\Sigma_b^*(^5D_0)$

The quark delocalization in QDCSM is realized by specifying the single-particle orbital wave function of QDCSM as a linear combination of left and right Gaussians, the single-particle orbital wave functions used in the ordinary quark cluster model,

$$\psi_\alpha(\mathbf{s}_i,\epsilon) = (\phi_\alpha(\mathbf{s}_i) + \epsilon\phi_\alpha(-\mathbf{s}_i))\,/N(\epsilon),$$
$$\psi_\beta(-\mathbf{s}_i,\epsilon) = (\phi_\beta(-\mathbf{s}_i) + \epsilon\phi_\beta(\mathbf{s}_i))/N(\epsilon),$$
$$N(\epsilon) = \sqrt{1+\epsilon^2+2\epsilon e^{-s_i^2/4b^2}}, \qquad (3)$$
$$\phi_\alpha(\mathbf{s}_i) = \left(\frac{1}{\pi b^2}\right)^{3/4} e^{-\frac{1}{2b^2}(\mathbf{r}_\alpha-\mathbf{s}_i/2)^2},$$
$$\phi_\beta(-\mathbf{s}_i) = \left(\frac{1}{\pi b^2}\right)^{3/4} e^{-\frac{1}{2b^2}(\mathbf{r}_\beta+\mathbf{s}_i/2)^2}.$$

Here $\mathbf{s}_i$, $i = 1,2,\ldots,n$ are the generating coordinates, which are introduced to expand the relative motion wave function [15]. The mixing parameter $\epsilon(\mathbf{s}_i)$ is not an adjusted one but determined variationally by the dynamics of the multiquark system itself. This assumption allows the multiquark system to choose its favorable configuration in the interacting process. It has been used to explain the crossover transition between the hadron phase and the quark-gluon plasma phase [22].

III. RESULTS AND DISCUSSIONS

Here, we perform a dynamical calculation of the $\Lambda_c\Lambda_c$ system with $IJ^P = 00^+$ in QDCSM1 and QDCSM2. The channel coupling effects are also considered. The labels of all coupled channels are listed in Table III.

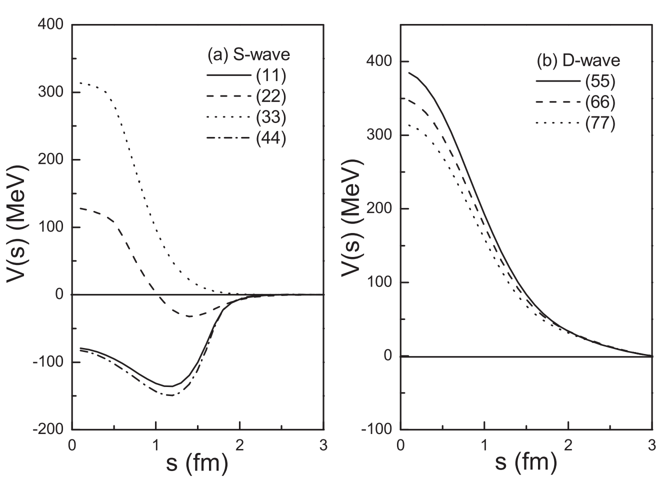

FIG. 1. The potentials of different channels for the $J^P = 0^+$ case of the $\Lambda_c\Lambda_c$ system.

Because an attractive potential is necessary for forming a bound state or resonance, we first calculate the effective potentials of all the channels listed in Table III. The effective potential between two colorless clusters is defined as $V(s) = E(s) - E(\infty)$, where $E(s)$ is the diagonal matrix element of the Hamiltonian of the system in the generating coordinate. The results of QDCSM1 and QDCSM2 are similar, so we only give the effective potentials of QDCSM2 here. The effective potentials of the S-wave and D-wave channels are shown in Figs. 1(a) and 1(b) respectively. From Fig. 1(a), we can see that the potentials are attractive for the $^1S_0$ channels $\Sigma_c\Sigma_c$, $N\Xi_{cc}$, and $\Sigma_c^*\Sigma_c^*$, while for the channel $\Lambda_c\Lambda_c$ the potential is repulsive and so no bound state can be formed in this single channel. However, because the attractions of the $\Sigma_c\Sigma_c$ channel and the $\Sigma_c^*\Sigma_c^*$ channel are very large, the channel coupling effects of $\Sigma_c\Sigma_c$ and $\Sigma_c^*\Sigma_c^*$ to $\Lambda_c\Lambda_c$ will push the energy of $\Lambda_c\Lambda_c$ downward, so it is possible to from a bound state. For the $^5D_0$ channels shown in Fig. 1(b), the potentials are all repulsive.

In order to see whether or not there is any bound state, a dynamic calculation is needed. Here the RGM equation is employed. Expanding the relative motion wave function between two clusters in the RGM equation by Gaussians, the integrodifferential equation of RGM can be reduced to an algebraic equation, the generalized eigenequation. The energy of the system can be obtained by solving the eigenequation. In the calculation, the baryon-baryon separation ($|\mathbf{s}_n|$) is taken to be less than 6 fm (to keep the matrix dimension manageably small).

The single-channel calculation shows that the energy of $\Lambda_c\Lambda_c$ is above its threshold, the sum of masses of two Λ_c's. This is reasonable, because the interaction between the two Λ_c's is repulsive as mentioned above. For the $N\Xi_{cc}$ channel, the attraction is too weak to tie the two particles together, so it is also unbound. At the same time, due to the stronger attraction, the energies of $\Sigma_c\Sigma_c$ and $\Sigma_c^*\Sigma_c^*$ are below their corresponding thresholds. The binding energies of $\Sigma_c\Sigma_c$ and $\Sigma_c^*\Sigma_c^*$ states are listed in Table IV, in which "ub" means unbound. For the $^5D_0$ channels, they are all unbound since the potentials are all repulsive, so we leave them out of Table IV. We also do a channel-coupling calculation, and a bound state, whose energy is below the threshold of $\Lambda_c\Lambda_c$, is obtained. The binding energy is also shown in Table IV under the head

TABLE IV. The binding energy B.E. (MeV) of every $^1S_0$ channel of the $\Lambda_c\Lambda_c$ system, and channel coupling (c.c.).

Channels	$\Sigma_c\Sigma_c$	$N\Xi_{cc}$	$\Lambda_c\Lambda_c$	$\Sigma_c^*\Sigma_c^*$	c.c.
QDCSM1	−35.4	ub	ub	−30.4	−3.3
QDCSM2	−75.4	ub	ub	−87.0	−19.4

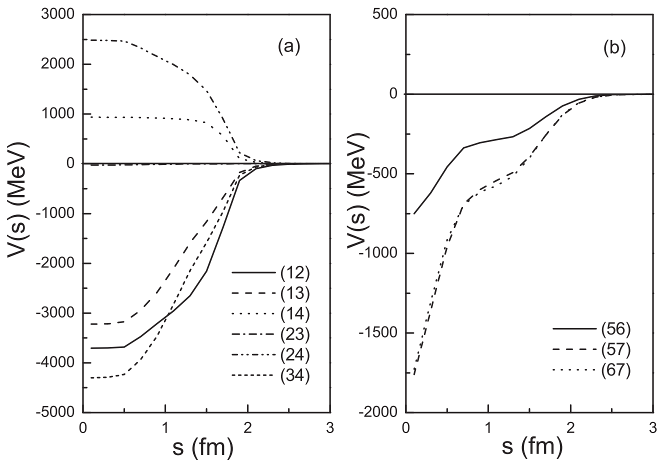

FIG. 2. The transition potentials of (a) S-wave channels and (b) D-wave channels for the $J^P = 0^+$ case of the $\Lambda_c\Lambda_c$ system.

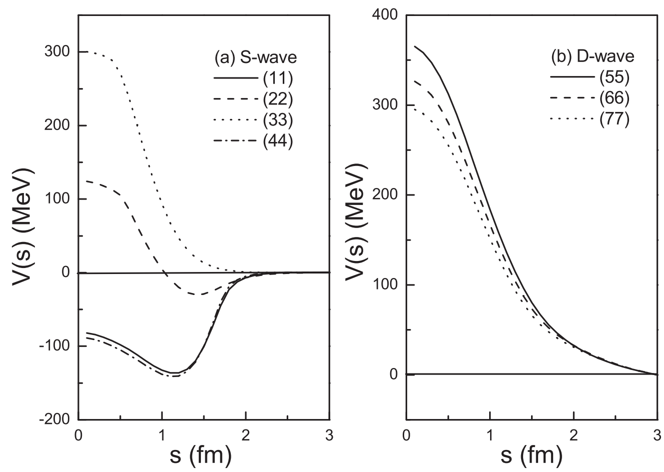

FIG. 4. The potentials of different channels for the $J^P = 0^+$ case of the $\Lambda_b\Lambda_b$ system.

"c.c.". From Table IV, we also find the results of QDCSM1 and QDCSM2 are similar. There are several features which are discussed below.

First, the individual S-wave $\Lambda_c\Lambda_c$ channel is unbound in our quark level calculation, which is consistent with the conclusion on the hadron level [12,13]. For other individual channels, there are some different results. In Ref. [13], the calculation shows all the individual channels are unbound and in Ref. [12], $\Sigma_c\Sigma_c$ is bound. In our quark level calculation, the individual $\Sigma_c\Sigma_c$ and $\Sigma_c^*\Sigma_c^*$ are deeply bound.

Second, by taking into account the channel-coupling effect, a bound state is obtained for the $\Lambda_c\Lambda_c$ system, which is also consistent with the conclusion on the hadron level [13]. However, the channel-coupling effect is different between our quark level calculation and their hadron level calculation. In Ref. [13], the coupling of $\Lambda_c\Lambda_c$ to the D-wave channels $\Sigma_c\Sigma_c^*$ and $\Sigma_c^*\Sigma_c^*$ are crucial in binding two Λ_c's. This indicates the importance of the tensor force. This conclusion is the same as their calculation of the $N\Lambda_c$ system [10]. In our quark level calculation, the coupling between $\Lambda_c\Lambda_c$, $N\Xi_{cc}$, $\Sigma_c\Sigma_c$, and $\Sigma_c^*\Sigma_c^*$ channels is through the central force. The transition potentials of these four channels of QDCSM2 are shown in Fig. 2(a). It is the strong coupling among these channels that makes $\Lambda_c\Lambda_c(^1S_0)$ the bound state. The transition potentials of three D-wave channels of QDCSM2 are shown in Fig. 2(b). To see the effects of the tensor force, the transition potentials for S- and D-wave channels of QDCSM2 are shown in Figs. 3(a) and 3(b). From this, one can see that the effects of the tensor force are much smaller compared with that of the central force. Thus the S- and D-wave channel-coupling effect is small in our quark model calculation. This conclusion is consistent with our calculation of the $N\Lambda_c$ system [11], in which the effect of the $N\Sigma_c^*(^5D_0)$ channel coupling to $N\Lambda_c(^1S_0)$ is very small.

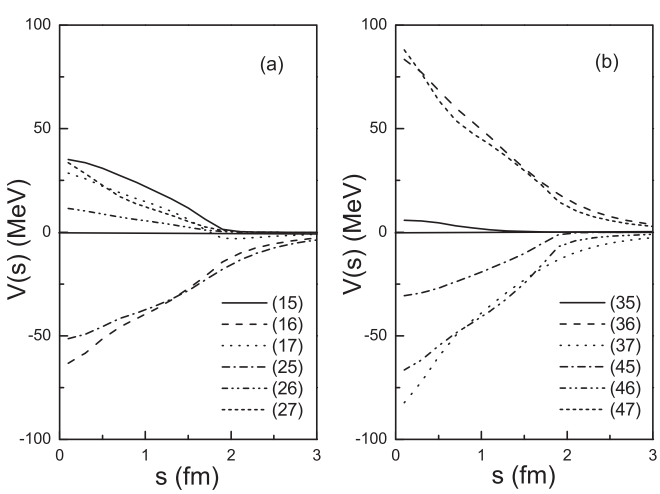

FIG. 3. The transition potentials of S-D wave channels for the $J^P = 0^+$ case of the $\Lambda_c\Lambda_c$ system.

Third, the properties of the $\Lambda_c\Lambda_c$ system in our quark model are similar to those of the $\Lambda\Lambda$ system. Our group has calculated the H dibaryon before [18], in which the single channel $\Lambda\Lambda$ is unbound, but when coupled to the channels $N\Xi$ and $\Sigma\Sigma$, it becomes a weakly bound state. Here, we extend our model to study the heavy flavor dibaryons, and we find it is possible to form a bound state in the $\Lambda_c\Lambda_c$ system, with a binding energy of 3.0–20 MeV, which is an H-like dibaryon state.

In the previous discussion, the $\Lambda_c\Lambda_c$ system was investigated and an H-like dibaryon state was found. Because of the heavy flavor symmetry, we also extend the study to the bottom case of $\Lambda_b\Lambda_b$ system. The numerical results for the $N\Lambda_b$ system are listed in Fig. 4 and Table V. The results are similar to those of the $\Lambda_c\Lambda_c$ system. From Table V, we find there is also an H-like dibaryon state in the $\Lambda_b\Lambda_b$ system with a binding energy of 3.0–20 MeV in our quark model.

TABLE V. The binding energy B.E. (MeV) of every $^1S_0$ channel of the $\Lambda_b\Lambda_b$ system, and channel coupling (c.c.).

Channels	$\Sigma_b\Sigma_b$	$N\Xi_{bb}$	$\Lambda_b\Lambda_b$	$\Sigma_b^*\Sigma_b^*$	c.c
QDCSM1	−36.0	ub	ub	−28.2	−3.6
QDCSM2	−78.8	ub	ub	−83.0	−19.7

IV. SUMMARY

In this work, we perform a dynamical calculation of the $\Lambda_c\Lambda_c$ system with $IJ^P = 00^+$ in the framework of QDCSM. Our results show that the interaction between two Λ_c's is repulsive, so it cannot be a bound state by itself. The attractions of $\Sigma_c\Sigma_c$ and $\Sigma_c^*\Sigma_c^*$ channels are strong enough to bind two Σ_c's and two Σ_c^*'s together. It is possible to form an H-like dibaryon state in the $\Lambda_c\Lambda_c$ system with the binding energy 3-20 MeV in our quark model by including the channel-coupling effect. This result is consistent with the result of the calculation on the hadron level [13]. However, the effect of the channel coupling is different between these two approaches. The role of the central force is much more important than the tensor force in our quark level calculation, while, in the calculation on the hadron level [13], the tensor force is shown to be important and the D-wave channels are crucial in binding two Λ_c's. Further investigation should be done to understand the difference between the approaches on the hadron level and the quark level. It will help us to understand whether the quark-hadron description is equivalent or not.

Extension of the study to the bottom case has also been done. The results of the $\Lambda_b\Lambda_b$ system are similar to those of the $\Lambda_c\Lambda_c$ system, and there exits an H-like dibaryon state in the $\Lambda_b\Lambda_b$ system with a binding energy of 3-20 MeV in our quark model. On the experimental side, finding the H-like dibaryon states $\Lambda_c\Lambda_c$ and $\Lambda_b\Lambda_b$ will be an exciting and challenging subject.

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