Possible heavy dibaryons*

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Abstract In the framework of the constituent quark model, the possible S-wave heavy dibaryon states with the c flavor are investigated. The factors which are responsible for the binding behavior of the dibaryon system are analyzed. It is shown that both the symmetry character of the system and the energy of interactions between interacting quarks are important for the binding behavior of the two-baryon system with the heavy flavor. As a result, seven possible candidates of heavy dibaryons with c flavor are predicted.

Key words constituent quark model, heavy baryon, dibaryon

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1 Introduction

In recent years, the experimental progress on hadron physics has been re-stimulating physicist's interest in heavy baryons. Particularly in the sector with c flavor, all the S-wave ground states and some lower excited states have been identified experimentally [1]. According to the flavor $SU(4)$ quark model, heavy baryons belong to either a $SU(3)$ $\bar{3}_{\rm F}$ anti-symmetric representation or a $SU(3)$ $6_{\rm F}$ symmetric representation [2]. The baryons in the enlarged flavor space together with the corresponding data observed recently [2] provides an opportunity to study the hadron structure and the basic interaction intensively from a newly opened window.

In a strong interactive system, the short- and medium-range interactions between quarks are very important. They dominate the basic properties of hadrons and hadronic systems as well. A typical strong interactive system besides baryons and mesons is the multi-quark system. The dibaryon as a six-quark system is one of these systems and has smaller size. By carefully studying such a system, one can extract more information about the short- and medium-range behaviors of QCD and may obtain the direct evidence of the quark-gluon degrees of freedom in the hadronic system. Therefore, the dibaryon could be another suitable place to study the strong interaction, in particular, the nonperturbative effect of QCD. In fact, since Jaffe proposed the H-particle as a candidate in 1977 [3], many dibaryons were predicted by various models. But experimentally, up to now, none of these predicted dibaryons has affirmatively been observed. Among the theoretical predictions, the investigation of the possible candidates of S-wave dibaryons with u, d and s quarks by using a chiral $SU(3)$ constituent quark model [4] should be paid attention. In that paper the authors proposed that a two baryon system with heavier flavor might have a larger binding energy so that it might form a deeply bound six-quark system, namely the dibaryon.

The heavy baryon contains at least one quark with heavy flavor. The mass of the c quark is much larger than that of the light quarks, including the u, d and

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s quarks. Introducing the c quark will change the number of possible meson exchanges. Thus, a baryon-baryon system containing c quarks might have a larger binding energy to form a dibaryon. In this paper, in the framework of the Resonating Group Method (RGM), we apply the chiral constituent quark model to the flavor $SU(4)$ baryon-baryon system to study its binding behavior. We briefly introduce the chiral constituent quark model in the next section and give the numerical results in section 3. In section 4, we draw the conclusions.

2 Model and parameters

We start from the $SU(3)$ constituent quark model established in Ref. [4]. The foundational ideas and details of the model can be referred in Ref. [4]. Because the considered heavy baryon has c flavor, an interaction mediated by a boson with c flavor might be necessary. This interaction can phenomenologically be taken into account by extrapolating the form of the quark-boson interaction in the $SU(3)$ case. Then, the Σ boson field can be written in the following form

$$\Sigma = \frac{2}{N}\sigma_0 + 2\sum_{a=1}^{15} T_a\sigma_a + \frac{2}{N}\mathrm{i}\gamma_5\pi_0 + 2\mathrm{i}\sum_{a=1}^{15}\gamma_5 T_a\pi_a, \qquad (1)$$

where π_a $(a=0,\cdots,15)$ are the pseudo-scalar singlet and 15-plet fields, respectively, and σ_a $(a=0,\cdots,15)$ denote the scalar singlet and 15-plet fields, respectively. The T_a's are the generators of the flavor $SU(4)$ group. With this assumption we can derive boson-field-induced flavor $SU(4)$ quark-quark potentials

$$V^{\mathrm{OBE}} = V^{\mathrm{ps}} + V^{\mathrm{s}}, \qquad (2)$$

with V^{ps} and V^{s} being the pseudoscalar- and scalar-field induced quark-quark potentials, respectively. The detailed forms of these potentials are the same as those shown in Ref. [4], except of a constant factor and the generators of the $SU(4)$ group. By fitting the observed masses of the ground states of the flavor $SU(4)$ baryons and satisfying the stability conditions for these baryons, we can fix all the model parameters. The resulting model parameters are tabulated in Table 1. The fitted masses of the ground states of flavor $SU(4)$ baryons are shown in Table 2. In this table, the left part shows the spin-1/2 baryons (20_M-plets) and the right part presents the spin-3/2 baryons (20_S-plets). The question mark means that the mass of the corresponding baryon has not yet been fixed by experiment.

Table 1. The model parameters.

m_{u}/MeV	313.00
m_{s}/MeV	450.00
m_{c}/MeV	1600.00
ω	442.87
g_{u}	0.98
g_{s}	0.97
g_{c}	0.79
$a^{\mathrm{c}}_{\mathrm{uu}}/(\mathrm{MeV\cdot fm^{-2}})$, $a^{\mathrm{c0}}_{\mathrm{uu}}$/MeV	36.18/−24.09
$a^{\mathrm{c}}_{\mathrm{us}}/(\mathrm{MeV\cdot fm^{-2}})$, $a^{\mathrm{c0}}_{\mathrm{us}}$/MeV	43.66/−15.43
$a^{\mathrm{c}}_{\mathrm{uc}}/(\mathrm{MeV\cdot fm^{-2}})$, $a^{\mathrm{c0}}_{\mathrm{uc}}$/MeV	71.09/−18.84
$a^{\mathrm{c}}_{\mathrm{ss}}/(\mathrm{MeV\cdot fm^{-2}})$, $a^{\mathrm{c0}}_{\mathrm{ss}}$/MeV	111.19/−31.19
$a^{\mathrm{c}}_{\mathrm{sc}}/(\mathrm{MeV\cdot fm^{-2}})$, $a^{\mathrm{c0}}_{\mathrm{sc}}$/MeV	117.91/−19.50
$a^{\mathrm{c}}_{\mathrm{cc}}/(\mathrm{MeV\cdot fm^{-2}})$, $a^{\mathrm{c0}}_{\mathrm{cc}}$/MeV	322.35/−46.96
$m^{(\mathrm{ps})}_0/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{ps})}_0/\mathrm{fm}^{-1}$	4.79/5.50
$m^{(\mathrm{ps})}_{1-3}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{ps})}_{1-3}/\mathrm{fm}^{-1}$	0.70/5.00
$m^{(\mathrm{ps})}_{4-7}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{ps})}_{4-7}/\mathrm{fm}^{-1}$	2.50/4.20
$m^{(\mathrm{ps})}_8/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{ps})}_8/\mathrm{fm}^{-1}$	2.89/5.00
$m^{(\mathrm{ps})}_{9-12}/\mathrm{fm}^{-1}$,$\Lambda^{(\mathrm{ps})}_{9-12}/\mathrm{fm}^{-1}$	9.47/11.50
$m^{(\mathrm{ps})}_{13-14}/\mathrm{fm}^{-1}$,$\Lambda^{(\mathrm{ps})}_{13-14}/\mathrm{fm}^{-1}$	9.97/13.00
$m^{(\mathrm{ps})}_{15}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{ps})}_{15}/\mathrm{fm}^{-1}$	15.10/16.50
$m^{(\mathrm{s})}_0/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{s})}_0/\mathrm{fm}^{-1}$	2.89/4.20
$m^{(\mathrm{s})}_{1-3}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{s})}_{1-3}/\mathrm{fm}^{-1}$	4.85/5.00
$m^{(\mathrm{s})}_{4-7}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{s})}_{4-7}/\mathrm{fm}^{-1}$	4.85/5.00
$m^{(\mathrm{s})}_8/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{s})}_8/\mathrm{fm}^{-1}$	4.85/5.00
$m^{(\mathrm{s})}_{9-12}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{s})}_{9-12}/\mathrm{fm}^{-1}$	11.50/15.10
$m^{(\mathrm{s})}_{13-14}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{s})}_{13-14}/\mathrm{fm}^{-1}$	13.00/16.50
$m^{(\mathrm{s})}_{15}/\mathrm{fm}^{-1}$, $\Lambda^{(\mathrm{s})}_{15}/\mathrm{fm}^{-1}$	16.50/17.50

Table 2. The masses of ground state baryons.

baryon	theory	Exp't	baryon	theory	Exp't
p	939.00	938.27	Δ^{++}	1232.00	1231.88
n	939.00	939.57	Δ^{+}	1232.00	1231.60
Σ^{+}	1193.15	1189.37	Δ^{0}	1232.00	1234.35
Σ^{0}	1193.15	1192.64	Δ^{-}	1232.00	?
Σ^{-}	1193.15	1197.45	Σ^{*+}	1369.95	1382.80
Λ	1115.68	1115.68	Σ^{*0}	1369.95	1383.70
Ξ^{0}	1339.96	1314.83	Σ^{*-}	1369.95	1387.20
Ξ^{-}	1339.96	1321.31	Ξ^{*0}	1516.76	1531.80
Σ_{c}^{++}	2526.97	2454.02	Ξ^{*-}	1516.76	1535.00
Σ_{c}^{+}	2526.97	2452.90	Ω^{-}	1672.43	1672.45
Σ_{c}^{0}	2526.97	2453.76	Σ_{c}^{++}	2569.76	2518.40
$\Xi_{\mathrm{c}}^{\prime+}$	2673.07	2575.70	Σ_{c}^{+}	2569.76	2517.50
$\Xi_{\mathrm{c}}^{\prime0}$	2673.07	2578.00	Σ_{c}^{0}	2569.76	2518.00
Ω_{c}^{0}	2828.04	2697.50	Ξ_{c}^{*+}	2713.57	2646.60
Λ_{c}^{+}	2360.16	2286.46	Ξ_{c}^{*0}	2713.57	2646.10
Ξ_{c}^{+}	2582.20	2467.90	Ω_{c}^{*0}	2866.23	?
Ξ_{c}^{0}	2582.20	2471.00	Ξ_{cc}^{*++}	3706.76	?
Ξ_{cc}^{++}	3663.98	?	Ξ_{cc}^{*+}	3706.76	?
Ξ_{cc}^{+}	3663.98	3518.90	$\Omega_{\mathrm{cc}}^{*+}$	3856.43	?
Ω_{cc}^{+}	3818.23	?	$\Omega_{\mathrm{ccc}}^{++}$	4643.01	?

3 Numerical calculations and results

The binding energy of a two-baryon system can dynamically be solved in the framework of the Resonating Group Method (RGM) [5]. Under the assumption of a two-cluster structure, the trial wave function of the six quark system can be written as

$$\Psi=\mathcal{A}_{\rm rel}[\hat{\phi}_A(\vec{\xi}_1,\vec{\xi}_2)\hat{\phi}_B(\vec{\xi}_4,\vec{\xi}_5)\chi_{\rm rel}(\vec{R})\chi_{\rm CM}(\vec{R}_{\rm CM})]_{\rm ST}, \tag{3}$$

where $\hat{\phi}_{A(B)}$ denotes the anti-symmetrized wave function of the baryon cluster $A(B)$ with $A(B)$ being the aggregate of the quantum numbers of the cluster, $\chi_{\rm rel}(\vec{R})$ is the trial wave function of the relative motion between the interacting clusters A and B, $\chi_{\rm CM}(\vec{R}_{\rm CM})$ the wave function of the total center of mass (CM) motion of the system, and $\vec{\xi}_i$ are the Jacobi coordinates with $i=1$ and 2 for cluster A and $i=4$ and 5 for cluster B, respectively. The symbol $\mathcal{A}_{\rm rel}$ describes the operation of the anti-symmetrization between quarks which are located in different clusters. S and T denote the total spin and isospin of the system. The operator $\mathcal{A}_{\rm rel}$ is defined as

$$\mathcal{A}_{\rm rel}=N\sum_P \epsilon_P P, \tag{4}$$

where P is an exchange operator which permutes the quark of cluster A with that of cluster B, $\epsilon_P=1(-1)$ for even (odd) permutations P and N is a normalization factor. Considering the permutation symmetry, $\mathcal{A}_{\rm rel}$ can also be written as

$$\mathcal{A}_{\rm rel}=N'\left(1-\sum_{i\in A,j\in B}P_{ij}^{\rm osfc}\right), \tag{5}$$

where $P_{i,j}^{\rm osfc}$ denotes the exchange operation between the i-th quark in cluster A and the j-th quark in cluster B in the orbital, spin and color spaces simultaneously, and N' is a normalization factor.

Substituting Ψ into the projection equation

$$\langle\, \delta\Psi \mid (H-E) \mid \Psi\, \rangle=0\ , \tag{6}$$

where

$$E\ =\ E_A\ +\ E_B\ +\ E_{\rm rel}, \tag{7}$$

with E, $E_{A(B)}$ and $E_{\rm rel}$ being the total energy, the energy of the cluster $A(B)$ and the relative energy between the clusters A and B, respectively. From Eq. (6), we obtain a RGM equation [5]

$$\int[\mathcal{H}(\vec{R}',\vec{R}'')-E\mathcal{N}(\vec{R}',\vec{R}'')]\chi_{\rm rel}(\vec{R}'')\mathrm{d}\vec{R}''=0, \tag{8}$$

where $\mathcal{H}$ and $\mathcal{N}$ denote the non-local Hamiltonian and normalization kernels, respectively.

We solve Eq. (8) by using a variational method, in which the unknown $\chi_{\rm rel}$ is expanded by a set of well-established basis functions

$$\chi_{\rm rel}(\vec{R})=\sum_{i=1}^{n}c_i u(\vec{R},\vec{S}_i) \tag{9}$$

and the expansion coefficients c_i are left to be solved. The details of the method can be found in Ref. [4] and the references therein.

As already stated in Ref. [4], we also find that two crucial physical factors affect the binding behavior of the two-baryon system with heavy flavor. One is the symmetry property of the system, namely the structure feature, and the other is the contribution provided by the interactions between the quarks located in different baryon clusters.

Similar to the results in Ref. [4], the symmetry property of the system is characterized by the matrix element of the operator $P_{36}^{\rm sfc}$. For $\langle P_{36}^{\rm sfc}\rangle\sim 1/9$ (corresponding to $\langle\mathcal{A}\rangle\sim 0$), the Pauli blocking effect between the baryons becomes so strong that a two-baryon S-wave state is almost forbidden. If $\langle P_{36}^{\rm sfc}\rangle\sim 0$ (corresponding to $\langle\mathcal{A}\rangle\sim 1$), the Pauli blocking effect between the baryons is very small, so that the exchange effect between the quarks located in different baryons becomes negligible and these two baryons are relative independent from each other. Moreover, in a two-baryon system, if $\langle P_{36}^{\rm sfc}\rangle\sim -1/9$ (corresponding to $\langle\mathcal{A}\rangle\sim 2$), the Pauli blocking effect between baryons would be extremely beneficial for binding these two baryons together, i.e. to form a bound state. Therefor, from the symmetry point of view, it is possible to form a weakly bound state in the second case and possibly to form a deeply bound state in the third case. We will mainly discuss the binding behavior of the system for the third case.

On the other hand, the effect of the interaction between quarks located in different baryons is also not negligible. In the second case, because $\langle P_{36}^{\rm sfc}\rangle\sim 0$, this interaction effect becomes dominant. However, due to the symmetry feature, although the overall effect of the interaction shows an attractive feature, it would not be very strong. The formed bound state usually is weakly bound. In the third case, besides the fact that the symmetry feature of the system ($\langle P_{36}^{\rm sfc}\rangle\sim -1/9$) is beneficial for binding, this feature also makes the overall effect of the interaction stronger. It would be strongly responsible for the binding behavior of the system. If the overall effect of the interaction provides a strong enough attraction, it is possible to form a bound state, even a deeply bound state, namely a dibaryon with a relative smaller size.

By solving Eq. (8), we find that in the third case, in addition to the seven possible candidates of light S-wave dibaryon states, there are seven possible candidates of S-wave heavy dibaryon states whose contents include one or two charmed baryons. We tabulate them together with their binding energies in Table 3.

Table 3. Possible S-wave dibaryon states containing chamed baryons.

	(I,S)	$\mathcal{A}$	OGE	OBE/ps	E/MeV
$\Sigma_c^*\Delta$	$(\frac{5}{2},0)$	2	−80	−18	217.1
$\Sigma_c^*\Delta$	$(\frac{1}{2},3)$	2	−16	−10	323.6
$\Sigma_c^*\Sigma^*$	$(0,3)$	2	−16	−10	337.3
$\Xi_{cc}^*\Omega_{ccc}$	$(\frac{1}{2},0)$	2	−80	−18	100.0
$\Omega_c\Omega$	(0, 0)	2	−80	−18	346.7
$\Omega_{cc}\Omega_{ccc}$	(0, 0)	2	−80	−18	94.7
$\Omega_{ccc}\Omega_{ccc}$	(0, 0)	2	−80	−18	81.7

4 Conclusion

In terms of the $SU(4)$ constituent quark model we systematically study the possibility of forming a S-wave heavy dibaryon state with charmed baryons. We phenomenologically extrapolate the form of the boson-quark interaction proposed in Ref. [4] to the form of the $SU(4)$ boson-quark interaction. As in Ref. [4], we also find that both the symmetry property of the system, characterized by the expectation value of the antisymmetrizer, and the overall effect of the interaction are major factors in affecting the binding behavior of the system. If $\langle P_{36}^{\rm sfc}\rangle \sim -1/9$, the symmetry of the system favors binding. It also makes the overall effect of the interaction more attractive. Both effects would lead to seven additional possible candidates of dibaryons with charmed baryon contents in addition to the possible candidates of the normal light dibaryons. These preliminary results are very interesting and significant for the future experiments to study heavy baryons and dibaryons. To confirm this finding, further theoretical and experimental efforts are required.

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