Possible dibaryons with strangeness $s=-5$

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In the framework of the resonating group method, the binding energy of the six-quark system with strangeness $s=-5$ is systematically investigated under the SU(3) chiral constituent quark model. The single $\Xi^*\Omega$ channel calculation with spins $S=0$ and 3 and the coupled $\Xi\Omega$ and $\Xi^*\Omega$ channel calculation with spins $S=1$ and 2 are considered, respectively. The results show the following observations. In the spin=0 case, $\Xi^*\Omega$ may be a bound dibaryon with the binding energy being 80.0~92.4 MeV. In the $S=1$ case, $\Xi\Omega$ may also be a bound dibaryon. Its binding energy ranges from 26.2 to 32.9 MeV. In the $S=2$ and $S=3$ cases, no evidence of bound dibaryons is found. The scattering lengths in the $S=0$ and $S=1$ cases are also given.

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Since Jaffe predicted the H particle in 1977 [1], the dibaryon has been an important object to be investigated both theoretically and experimentally. Because this object is supposed to be a color singlet multiquark system within a sufficiently smaller volume, the quark-gluon degrees of freedom become dominant. There is no doubt that studying this object can enrich our knowledge of the strong interaction in the short-range and can further prove and complete the basic theory of strong interaction, quantum chromodynamics (QCD). In the past 20 years, many dibaryons were proposed. Among them, some are strangenessless such as d^* [2,3], d' [4], etc., and the others carry strangeness [2,5]. Moreover, as is well known, introducing strangeness and even heavier flavor opens a new area to study strong interaction. It enables us to further understand and deal with the effect of the nonperturbative QCD (NPQCD) and to refine our knowledge of the strong interaction and, consequently, the hadronic structure by employing new model theories in the quark-gluon degrees of freedom via a variety of new experimental data. Investigating a dibaryon with strangeness is just one of the most interesting subjects in this aspect. Recently, Yu *et al.* reported that in a system with higher strangeness, it would be highly possible to find bound dibaryons [5]. They predicted the existence of the $\Omega\Omega$ ($S=0$, $T=0$, $L=0$) and $\Xi\Omega$ ($S=1$, $T=1/2$, $L=0$) dibaryons, where S, T, and L denote the spin, isospin, and angular momentum, respectively. In this Brief Report, we will systematically study the possible existence of bound dibaryons in the system with strangeness $s=-5$. However, because of the lack of experimental data for strange systems, there is no well or definitely confirmed baryon-baryon interaction up to now. In order to study a multistrangeness system, one needs a reliable baryon-baryon interaction. The best way to study this interaction is to investigate it in the quark-gluon degrees of freedom with a more reliable model theory of strong interaction.

As is well known, the basic theory for studying the dibaryon should be QCD theory. However, because of the complexity of NPQCD effect at the lower energy region, for practice, one has to develop QCD-inspired models. To study the dibaryon, the model has to meet the twofold requirement: it cannot only explain the relevant existing experimental data well but also can be applied to the new physics study without additional parameters. The SU(3) chiral-quark model is just such a model [6]. By employing this model, one can explain not only the single baryon properties [7] but also the scattering data of the N-N and Y-N processes [6]. Moreover, the resultant binding energy of H [8] is consistent with the experimental data available [8,9]. Thus, it is reasonable to study the bound state problem in the case with $s=-5$ by using this model.

In the SU(3) chiral quark model, the potential between the ith and jth constituent quarks can be written as

$$V_{ij}=\sum_{i<j}(V_{ij}^{\rm conf}+V_{ij}^{\rm ch}+V_{ij}^{\rm OGE}). \quad (1)$$

In Eq. (1), the confinement potential $V_{ij}^{\rm conf}$ describes the long range effect of NPQCD, the one-gluon exchange potential (OGE) basically depicts the short-range perturbation QCD (PQCD) effect. The potential induced by the chiral-quark-field coupling is in the form of

$$V_{ij}^{\rm ch}=\sum_a V_{\pi_a}(\mathbf{r}_{ij})+\sum_a V_{\sigma_a}(\mathbf{r}_{ij}) \quad (2)$$

and mainly signifies the medium-range NPQCD effect. In this expression, the subscripts π_a and σ_a represent pseudoscalar mesons π, k, η, and η' and scalar mesons σ, σ', κ, and ϵ, respectively. The explicit forms of these potentials can be found in Ref. [6]. It should be emphasized that the chiral field induced interaction $V^{\rm ch}$ is derived from an interactive Lagrangian $\mathcal{L}_I$ which is invariant under the chiral transformation [6]. Because with this model one can explain most existing experimental data as mentioned above, it seems that $V^{\rm ch}$ derived in this way can depict as much NPQCD effect in the short and medium range as possible. Then the residual NPQCD effect (or even the partial PQCD effect from the higher order diagram) can be absorbed into the values of model parameters such as the strong coupling constants, confinement strength, etc. In particular, we introduce a form

TABLE I. Model parameters. (By employing either set 1 or set 2, the experimental NN and NY scattering data as well as some properties of single baryons can be well reproduced.)

	Set 1	Set 2		Set 1	Set 2
m_u (MeV)	313	313			
m_s (MeV)	470	430			
b_u (fm)	0.505	0.53			
m_π (fm^{-1})	0.7	0.7	Λ_π (fm^{-1})	4.2	4.2
m_k (fm^{-1})	2.51	2.51	Λ_k (fm^{-1})	4.2	4.2
m_η (fm^{-1})	2.78	2.78	Λ_η (fm^{-1})	5.0	5.0
$m_{\eta'}$ (fm^{-1})	4.85	4.85	$\Lambda_{\eta'}$ (fm^{-1})	5.0	5.0
m_σ (fm^{-1})	3.17	3.04	Λ_σ (fm^{-1})	4.2	7.0
$m_{\sigma'}$ (fm^{-1})	4.85	4.85	$\Lambda_{\sigma'}$ (fm^{-1})	5.0	5.0
m_κ (fm^{-1})	4.85	4.85	Λ_κ (fm^{-1})	5.0	7.0
m_ϵ (fm^{-1})	4.85	4.85	Λ_ϵ (fm^{-1})	5.0	7.0
g_u	0.936	1.010			
g_s	0.924	0.965			
a_{uu} (MeV/fm^2)	54.34	34.37	a^0_{uu} (MeV)	−47.69	−19.76
a_{us} (MeV/fm^2)	65.75	39.59	a^0_{us} (MeV)	−41.73	−7.73
a_{ss} (MeV/fm^2)	102.97	69.91	a^0_{ss} (MeV)	−45.04	−11.54

factor $F(q^2)=[\Lambda^2_{\rm CSB}/(\Lambda^2_{\rm CSB}+q^2)]^{1/2}$ to compensate the residual instanton effect that has been mentioned in Ref. [12].

The wave function of the dibaryon can be written in the framework of the resonating group method (RGM) as

$$\Psi_{6q}=\mathcal{A}[\Phi_{\rm A}\Phi_{\rm B}\chi(\mathbf{R}_{\rm AB})Z(\mathbf{R}_{\rm c.m.})], \tag{3}$$

where $\chi(\mathbf{R}_{\rm AB})$ is the trial relative wave function between clusters A and B, $Z(\mathbf{R}_{\rm c.m.})$ represents the c.m. wave function of the six-quark system and $\mathcal{A}$ denotes the antisymmetrizer. Expanding unknown $\chi(\mathbf{R}_{\rm AB})$ by employing well-defined basis wave functions, such as Gaussian functions, one can solve the RGM bound state equation to obtain eigenvalues and corresponding wave functions, simultaneously. The details of solving the RGM bound-state problem can be found in Refs. [10,11].

All the model parameters employed in this Brief Report are those used in our previous papers [5–8]. These parameters can be determined by the mass splittings among N, Δ, Λ, Σ, and Ξ, respectively, and the stability conditions of the octet ($S=1/2$) and decuplet ($S=3/2$) baryons, respectively. The values of the parameters are tabulated in Table I.

It should be emphasized that a very important factor for forming a bound dibaryon is the symmetry structure of the six-quark system, which is characterized by the expectation value of antisymmetrizer in the *spin-flavor-color* (sfc) space, $\langle\mathcal{A}^{\rm sfc}\rangle$. In the $\Xi^*\Omega$ case, $\langle\mathcal{A}^{\rm sfc}\rangle=2$, which indicates that the system is the mostly antisymmetric in the sfc space and the mostly symmetric in the orbital space. Thus, it is possible to form a bound $\Xi^*\Omega$. If the chiral field can further provide attraction, the system would be deeply bound. On the other hand, in the $\Xi\Omega$ case, $\langle\mathcal{A}^{\rm sfc}\rangle=1$, namely the quark exchange effect can almost be ignored. Whether this system can be bound depends on the overall contributions from chiral fields.

TABLE II. Binding energy $B_{\rm AB}$ and rms of $\Xi^*\Omega(S=0)$ and $\Xi\Omega(S=1)$. ($B_{\rm AB}$ denotes the binding energy between clusters A and B.)

Channel	One channel $\Xi^*\Omega(S=0)$		One channel $\Xi\Omega(S=1)$		Coupled channel $\Xi\Omega-\Xi^*\Omega(S=1)$	
	$B_{\Xi^*\Omega}$ (MeV)	rms (fm)	$B_{\Xi\Omega}$ (MeV)	rms (fm)	$B_{\Xi\Omega}$ (MeV)	rms (fm)
Set 1	92.4	0.71	9.6	1.02	32.9	0.78
Set 2	80.0	0.76	6.3	1.12	26.2	0.85

The six-quark system with strangeness $s=-5$, isospin $T=1/2$, and spin $S=0$ is studied first. This is a single channel calculation. The model parameters used in the first step are set 1 in Table I, which is frequently used in our previous investigations [6–8]. The resultant binding energy ($B_{\Xi^*\Omega}$) and corresponding root-mean-square (rms) radius are tabulated in Table II, respectively. It is shown that the binding energy is 92.4 MeV and the corresponding rms is 0.71 fm. It indicates that this is a bound dibaryon. However, Ξ^* is not a stable particle and easily subjects the strong decay $\Xi^*\to\Xi+\pi$. To detect the $\Xi^*\Omega$ dibaryon in the experiment easily, it is better to have the mass of the $\Xi^*\Omega$ dibaryon lower than the threshold of the $\Xi+\Omega+\pi$ channel, or the binding energy of $\Xi^*\Omega$

$$B_{\Xi^*\Omega}>-(M_\Xi+M_\pi-M_{\Xi^*})=76\ \ \text{MeV}.$$

In fact, the predicted mass of the $\Xi^*\Omega$ dibaryon is about 16.4 MeV below the $\Xi\Omega\pi$ threshold, namely, this dibaryon is stable against the strong decay $\Xi^*\to\Xi+\pi$.

The model parameter dependence of the binding energy of $\Xi^*\Omega$ is then examined. The calculated result shows that the binding energy increases if the masses of the s quark and κ meson and the cutoff masses of the σ, σ', and ϵ mesons increase and the masses of the σ, σ', and ϵ mesons and the cutoff mass of the κ meson decrease. In particular, in a six-quark system with a higher strangeness number, increasing b_u would make the binding energy smaller. Therefore, another set of parameters in limits, set 2, which can fit all mentioned empirical data, is also employed to estimate the binding energy. The results are shown in Table II. The lower limit of the binding energy of $\Xi^*\Omega$ is 80.0 MeV and the corresponding rms is 0.76 fm. Further considering the strong decay of Ξ^* into $\Xi\pi$, the mass of $\Xi^*\Omega$ is 4.0 MeV lower than the $\Xi\Omega\pi$ threshold. Anyway, the $\Xi^*\Omega$ dibaryon is a stable particle against the strong decay $\Xi^*\to\Xi+\pi$, and its mass is 4.0–16.4 MeV below the $\Xi\Omega\pi$ threshold.

Next, the six-quark system with $s=-5$, $T=1/2$, and $S=1$ is studied. $\Xi\Omega(S=1,\ T=1/2,\ L=0)$ was predicted in the single channel RGM calculation [5]. As is well known, there exists another possible channel $\Xi^*\Omega$ having same quantum numbers. Although the threshold of the $\Xi^*\Omega$ channel is about 200 MeV higher than that of the $\Xi\Omega$ channel, because the cross-channel interaction matrix element might not be small, it is necessary to check whether the additional

TABLE III. The scattering length a.

	One channel $\Xi^*\Omega$ ($S=0$)	Coupled channel $\Xi\Omega-\Xi^*\Omega$ ($S=1$)
Set 1	1.18 (fm)	1.55 (fm)
Set 2	1.31 (fm)	1.73 (fm)

$\Xi^*\Omega$ channel exerts a substantial effect on the single channel prediction. In the calculation, the $L=0$ and $L=2$ states for each channel are considered. The results with set 1 and set 2 are collected in Table II. From these data, one sees that the additional $\Xi^*\Omega$ channel indeed gives a sizable contribution and cannot be ignored. The resultant binding energy of $\Xi\Omega$ is ranged from 26.2 MeV to 32.9 MeV. and the corresponding rms of $\Xi\Omega$ is in the region of 0.85–0.78 fm. Again, $\Xi\Omega$ is a stable dibaryon.

Finally, the six-quark system with $s=-5$, $T=1/2$, and $S=2$ and 3 is studied. In the $S=2$ case, it is a coupled $\Xi\Omega-\Xi^*\Omega$ channel calculation and in the $S=3$ case, it is just a single $\Xi^*\Omega$ channel calculation. With either parameter set 1 or set 2, no evidence of the bound dibaryon is found.

To crosscheck dibaryons' binding behaviors, we further calculated the scattering length a of the one channel $\Xi^*\Omega(S=0)$ and the coupled channel $\Xi\Omega-\Xi^*\Omega(S=1)$ with parameter sets 1 and 2. The results are presented in Table III. With the convention in nuclear physics that a positive scattering length of two scattering particles is corresponding to the bound state, we see that the scattering lengths are consistent with our above findings.

In conclusion, we announce that in the $s=-5$ sector of the six-quark system, there may exist two bound states or bound dibaryons. One of them is $\Xi^*\Omega$ with $S=0$, $T=1/2$ and $L=0$. The binding energy of this system ranges from 80.0 MeV to 92.4 MeV. Because the mass of the $\Xi^*\Omega$ particle is 4.0–16.4 MeV below the $\Xi\Omega\pi$ threshold, this particle should be a stable dibaryon against the strong decay $\Xi^*\rightarrow\Xi+\pi$, but it still can weakly decay into $\Lambda\Omega\pi\pi$, $\Xi\Lambda k\pi$, etc. The width of $\Xi^*\Omega$ can roughly be estimated in the following. It might be narrower than that of single Ξ^* which decays through the strong mode $\Xi^*\rightarrow\Xi\pi$ and comparable to that of Ξ or Ω which decay through weak modes $\Xi\rightarrow\Lambda\pi$, $\Omega\rightarrow\Lambda k$, etc. Another possible stable dibaryon is $\Xi\Omega$ $(S=1,T=1/2,L=0)$. In the coupled $\Xi\Omega-\Xi^*\Omega$ (with $L=0$ and 2) channel approximation, its binding energy is in the region of 26.2–32.9 MeV. Since Ξ^*, Ξ, and Ω are secondary particles, $\Xi^*\Omega$ $(S=0,\ T=1/2)$ and $\Xi\Omega$ $(S=1,\ T=1/2)$ dibaryons might be experimentally studied in the heavy ion collision. Whether they can be searched in the heavy ion collision should be further investigated.

Of course, the investigation of possible dibaryons in other strange sectors is also of interest and significance. These investigations would be the project in the next step.

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