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NΩ and ΔΩ dibaryons in a SU(3) chiral quark model

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Abstract. The binding energy of the six-quark system with strangeness $s = -3$ is investigated under the chiral $SU(3)$ constituent quark model in the framework of RGM. The calculations of the single NΩ channel with spin $S = 2$ and the single $\Delta\Omega$ channel with spin $S = 3$ are performed. The results show that both systems could be dibaryons and the interaction induced by the chiral field plays a very important role on forming bound states in the systems considered. The phase shifts and scattering lengths in corresponding channels are also given.

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1 Introduction

Dibaryon, which contains six quarks, has been an important object to be investigated both theoretically and experimentally since Jaffe predicted the H particle in 1977 [1]. Different from the deuteron, whose property can be well explained by the meson exchange mechanism on the baryon level, this object is supposed to be a color-singlet multi-quark system with a sufficiently smaller size, and the quark-gluon degrees of freedom could be dominant degrees. No doubt, the dibaryon should be a perspective field to study the phenomenology of the strong interaction. Through study, we can enrich our knowledge of the strong interaction between quarks in the short-range region and further understand the basic theory of the strong interaction, Quantum Chromodynamics (QCD), especially its nonperturbative effect.

In past twenty years, various kinds of dibaryons were proposed. Among these particles, some of them are strangenessless such as d* [2,3], d$'$ [4] and etc., and the others carry strangeness [2,5]. The H particle is just the one that has most intensively been investigated in both theoretical and experimental studies. The advantage of investigating dibaryon with strangeness is that one can study the strong interaction from a variety of sides by using the new data involving strangeness and proposing new model theories and learn how to properly deal with the nonperturbative QCD (NPQCD) effect and further the hadronic structure. Recently, it was reported that in the system with multi-strangeness, the dibaryon state is highly possible to show up [5]. Yu *et al.* predicted the possible existences of $\Omega\Omega(S = 0, L = 0)$ and $\Xi\Omega(S = 1, L = 0)$ (single-channel calculation) dibaryons [5], where S and L denote the spin and angular momentum, respectively. Li and Shen announced the possible existences of $\Xi^*\Omega(S = 0)$ and $\Xi\Omega$-$\Xi^*\Omega(S = 1, L = 0)$ (coupled-channel calculation) [6,7]. In this paper, we would study the possible S-wave dibaryons in the system with $s = -3$, namely, the N$\Omega(S = 2, T = 1/2, L = 0)$ and $\Delta\Omega(S = 3, T = 3/2, L = 0)$ dibaryons. Because of the available nucleon beam and the only weak decay modes of Ω, it would be easier to find the NΩ dibaryon than the others such as H and d*. Experimentally searching NΩ would be an especially interesting investigation.

In the next section, the model employed for this study is briefly given. In section 3, the results are presented and discussed. And the conclusion is drawn in section 4.

2 Model

Nowadays, more evidences show that QCD is the underlying theory of the strong interaction. However, because of the complexity of the nonperturbative effect of QCD at the lower-energy region, one has to develop QCD-inspired models. In early 1980's, the constituent quark model showed its power in studying nucleon-nucleon (NN) interactions [8]. By considering the coupling between the constituent quark and chiral fields, that model was modified to the chiral quark model [9], and later, was fur-

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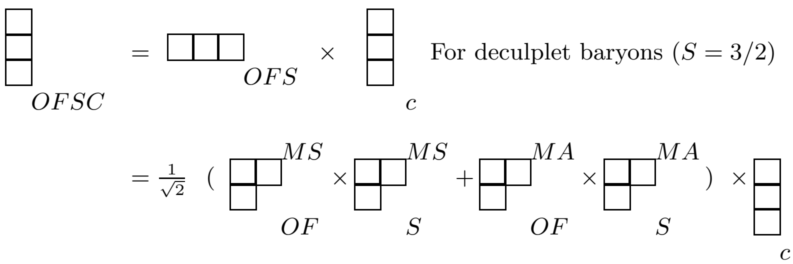

For octet baryons ($S = 1/2$). (5)

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ther extended to the $SU(3)$ chiral quark model [10]. In the $SU(3)$ chiral quark model, both pseudoscalar nonet mesons π, K, η and η' and the scalar nonet mesons σ, σ', κ and ϵ are involved in the interaction between quarks. With such model, not only the single-baryon properties can be basically explained [11], but also the scattering data of the NN and the nucleon-hyperon (YN) processes can be well-reproduced [10]. Applying this model to the system with two strangeness without further introducing additional parameters, the resultant binding energy of the H particle is consistent with the experimental data available [12,13]. These are just the basic requirements for a model which would be employed to study the nuclear systems where no experimental data are available and to predict their properties. In this paper, we would use the chiral $SU(3)$ quark model to study the bound state problem in the systems with $s = -3$ and believe that the results would be reasonable and reliable.

In the chiral quark model, the dynamics of the dibaryon, the six-quark system, is governed by the Hamiltonian

$$H = \sum_i T_i - T_G + \sum_{i<j} V_{ij}, \tag{1}$$

where the first and second terms are the total kinetic energy operator of the system and the kinetic energy operator of the center-of-mass motion (CM) of the system, respectively. V_{ij} represents the interaction between the i-th and j-th constituent quarks and can be written as

$$V_{ij} = \sum_{i<j} \left(V_{ij}^{\mathrm{conf}} + V_{ij}^{\mathrm{ch}} + V_{ij}^{\mathrm{OGE}}\right). \tag{2}$$

In this equation, the confinement potential V_{ij}^{conf} describes the long-range effect of NPQCD, which has the form of

$$V_{ij}^{\mathrm{conf}} = -\lambda_i^{\mathrm{c}} \cdot \lambda_j^{\mathrm{c}} \left(a_{ij} r_{ij}^2 + a_{ij}^0\right) \tag{3}$$

with a_{ij} and a_{ij}^0 being the confinement strength and the corresponding zero-point energy between the i-th and j-th constituent quarks, respectively, and $\lambda_{i(j)}^{\mathrm{c}}$ being the generator of the color $SU(3)$ group. The introduction of a_{ij}^0 is to fit the masses of octet and deculplet baryons to the empirical data. The one-gluon exchange (OGE) potential V_{ij}^{OGE} mainly depicts the short-range perturbation QCD (PQCD) effect. The forms of these potentials can be found in ref. [10]. V_{ij}^{ch} denotes the chiral-quark field coupling induced potential

$$V_{ij}^{\mathrm{ch}} = \sum_a V_{\pi_a}(\mathbf{r}_{ij}) + \sum_a V_{\sigma_a}(\mathbf{r}_{ij}), \tag{4}$$

where subscripts π_a and σ_a can be pseudoscalar mesons π, K, η and η' and scalar mesons σ, σ', κ and ϵ, respectively. The explicit forms of these potentials can also be found in ref. [10]. The wave function of the single baryon can be expressed as

see equation (5) *above.*

It should be mentioned that due to the flavor symmetry breaking, the wave functions in the orbit and flavor spaces are always associated. The quark wave function of specific type i (i=up, down or strange) in a baryon, can be written as

$$\Phi_i(\mathbf{r}_i) = (1/\pi b_i^2)^{3/4} \exp\left[\frac{-(\mathbf{r}_i - \mathbf{R})^2}{2b_i^2}\right], \tag{6}$$

where $\mathbf{R}$ is the coordinate vector of the center-of-mass motion of the baryon. The width parameter b_i is associated with the oscillator frequency ω by the constituent quark mass m_i

$$\frac{1}{b_i^2} = m_i \omega. \tag{7}$$

Then the wave function of the dibaryon with quantum numbers S and T, which should be totally antisymmetric, can be written in the framework of the Resonating Group Method (RGM) as

$$\Psi_{6q} = \mathcal{A}\left[\Phi_{\mathrm{A}} \Phi_{\mathrm{B}} \chi(\mathbf{R}_{\mathrm{AB}}) Z(\mathbf{R}_{\mathrm{CM}})\right], \tag{8}$$

where $\chi(\mathbf{R})$ is the trial relative wave function between the clusters A and B, respectively, $Z(\mathbf{R}_{\mathrm{CM}})$ represents the CM wave function of the six-quark system and $\mathcal{A}$ denotes the antisymmetrizer. Expanding the unknown $\chi(\mathbf{R})$ by 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. [14,15].

All the model parameters employed in the calculation are fixed by the mass splittings among N, Δ, Λ, Σ and

Table 1. Model parameters under $SU(3)$ chiral quark model.

	Set1	Set2		Set1	Set2
$m_{\rm u}$(MeV)	313	313			
$m_{\rm s}$(MeV)	470	470			
$b_{\rm u}$ (fm)	0.505	0.505			
m_π(fm^{-1})	0.7	0.7	Λ_π(fm^{-1})	4.2	4.2
$m_{\rm K}$(fm^{-1})	2.51	2.51	$\Lambda_{\rm K}$(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	3.17	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	7.09	Λ_κ(fm^{-1})	5.0	7.61
m_ϵ(fm^{-1})	4.85	7.09	Λ_ϵ(fm^{-1})	5.0	7.61
$g_{\rm u}$	0.936	0.936			
$g_{\rm s}$	0.924	0.781			
$a_{\rm uu}$(MeV/fm^2)	54.34	57.71	$a^0_{\rm uu}$(MeV)	-47.69	-48.89
$a_{\rm us}$(MeV/fm^2)	65.75	66.51	$a^0_{\rm us}$(MeV)	-41.73	-50.57
$a_{\rm ss}$(MeV/fm^2)	102.97	115.39	$a^0_{\rm ss}$(MeV)	-45.04	-68.11

Ξ, respectively, and the stability conditions of the octet ($S = 1/2$) and decuplet ($S = 3/2$) baryons, respectively.

We used two sets of parameters to calculate the binding energy of the N$\Omega(S = 2, T = 1/2)$ and $\Delta\Omega(S = 3, T = 3/2)$ systems in the $SU(3)$ chiral quark model. The first set of parameters has widely been used in our previous investigations [10,11,5]. Because the strange clouds around baryons may be influential for a system with $s = -3$, in Set 2, we further choose the masses of κ and ϵ mesons to be those which have the same quantum numbers in the Particle Data Table (PDT) [16]. The values of these parameters are tabulated in table 1.

In this table, $m_{\rm A}$ denotes the mass of particle A which can be either the valence quark or the meson involved, $\Lambda_{\rm A}$ represents the corresponding cut-off mass of the particle, $g_{\rm q}$ is the coupling constant between gluon and valence quark q. It should be mentioned that by using these two sets of parameters, we can meet the above-mentioned requirement, namely, the mentioned empirical data can be well reproduced. A typical example can be seen in fig. 1, where the solid and dashed curves represent the total Λp elastic scattering cross-section as a function of the Λ lab energy by using Sets 1 and 2, respectively.

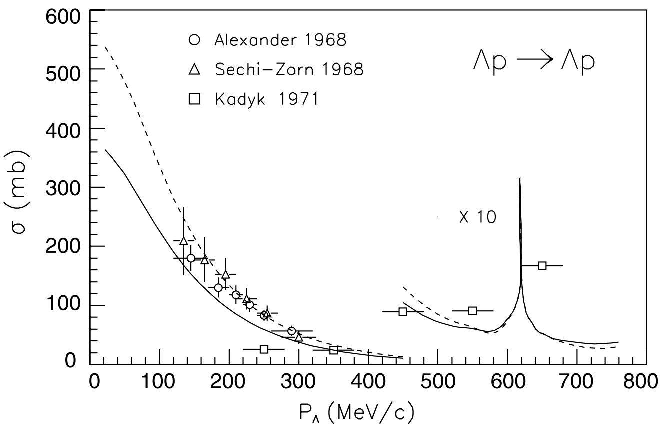

Fig. 1. The total cross-section of Λp elastic scattering.

Table 2. Binding energy $B_{\rm AB}$ and RMS of N$\Omega(S = 2, T = 1/2)$ and $\Delta\Omega(S = 3, T = 3/2)$ *.

Channel	One channel N$\Omega(S = 2, T = 1/2)$		One channel $\Delta\Omega(S = 3, T = 3/2)$	
	$B_{{\rm N}\Omega}$ (MeV)	RMS (fm)	$B_{\Delta\Omega}$ (MeV)	RMS (fm)
$SU(3)$ Set1	3.5	1.18	4.4	1.15
$SU(3)$ Set2	12.7	0.98	14.2	0.96
ext. $SU(2)$	31.8	0.81	34.3	0.80
$SU(2)$	49.5	0.74	49.5	0.74

$^*B_{\rm AB}$ denotes the binding energy between A and B baryons and RMS represents the corresponding root-mean-square radius.

3 Results and discussions

The resultant binding energies and corresponding root-mean-square radii (RMS) of the systems concerned are tabulated in table 2. It is shown that with Set 1 the binding energies of the N$\Omega(S = 2, T = 1/2)$ and $\Delta\Omega(S = 3, T = 3/2)$ systems are 3.5 MeV and 4.4 MeV, respectively, and the corresponding RMS are 1.18 fm and 1.15 fm, respectively. With Set 2, the corresponding binding energies are 12.7 MeV and 14.2 MeV for NΩ and $\Delta\Omega$, respectively, and the corresponding RMS are 0.98 fm and 0.96 fm, respectively. Our calculation shows that the chiral-field–induced interaction would be very important for the binding behavior, especially the interaction caused by σ is the dominant piece. The larger binding energy in Set 2 indicates that due to the larger m_κ, m_ϵ, Λ_κ and Λ_ϵ, chiral-field–induced interactions, in particular from the σ field, increase the dibaryon binding energy in the

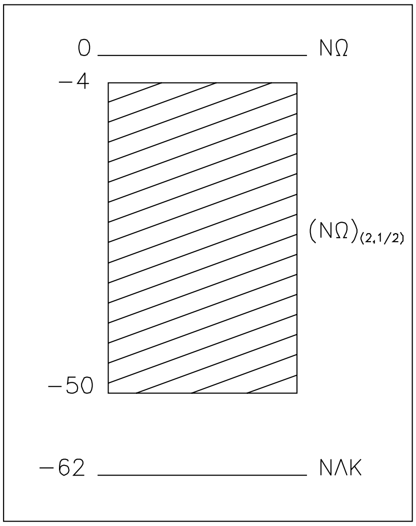

Fig. 2. Energy level sketch for $(\mathrm{N}\Omega)_{(2,1/2)}$ system.

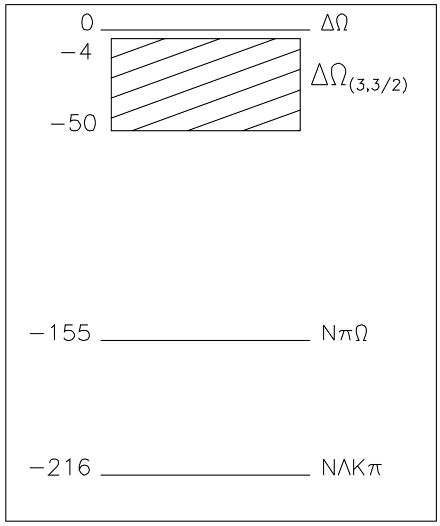

Fig. 3. Energy level sketch for $(\Delta\Omega)_{(3,3/2)}$ system.

$\mathrm{N}\Omega(S=2, T=1/2)$ and $\Delta\Omega(S=3, T=3/2)$ systems in the chiral $SU(3)$ quark model.

It should be emphasized that in these two systems, the expectation values of the antisymmetrizer in the spin-flavor-color space is equal to 1. It means that there is no quark exchange effect, and whether the system is bound merely depends on the characteristics of the interaction induced by the chiral-quark field coupling. To further demonstrate the effects of chiral clouds, we study the $\mathrm{N}\Omega(S=2, T=1/2)$ and $\Delta\Omega(S=3, T=3/2)$ systems by employing other two chiral quark models, the extended $SU(2)$ model and the $SU(2)$ model. $SU(3)$ contains the exchange of all mesons listed in table one. The extended $SU(2)$ includes the following meson exchanges: π, K, η, η', and σ; while $SU(2)$ includes only the exchange of the following mesons between the quarks: π and σ. The results are also tabulated in table 2. It shows that the binding energies of these two systems in the extended $SU(2)$ chiral quark model and $SU(2)$ chiral quark model are larger than those in the $SU(3)$ chiral quark model and these systems are even bounder in the $SU(2)$ chiral quark model. The reason is clear. Because ignoring the repulsive-natured ϵ, the relative wave function would distribute more inward. As a consequence, the expectation value of the σ-meson–induced interaction would pick up more strength from the σ-induced potential so that more attractive character presents. For further reference, we give the energy level sketches of these systems in figs. 2 and 3. The shaded areas are our predictions.

To cross-check our predictions, we demonstrate the S-wave phase shifts of the $\mathrm{N}\Omega(S=2, T=1/2)$ and the $\Delta\Omega(S=3, T=3/2)$ systems in the $SU(3)$ chiral quark model with parameter Sets 1 and 2 in figs. 4 and 5, respectively. In these figures, solid curves are the results with Set 1 and the dashed curves represent the results with Set 2. According to the phase shifts, one can estimate the scattering length a. The results are presented in table 3.

Both phase shifts and scattering lengths are consistent with our findings.

Table 3. The Scattering length a of the dibaryons.

	One channel $\mathrm{N}\Omega$ $(S=2)$	One channel $\Delta\Omega$ $(S=3)$
Set 1	−3.68 (fm)	−3.40 (fm)
Set 2	−2.32 (fm)	−2.22 (fm)

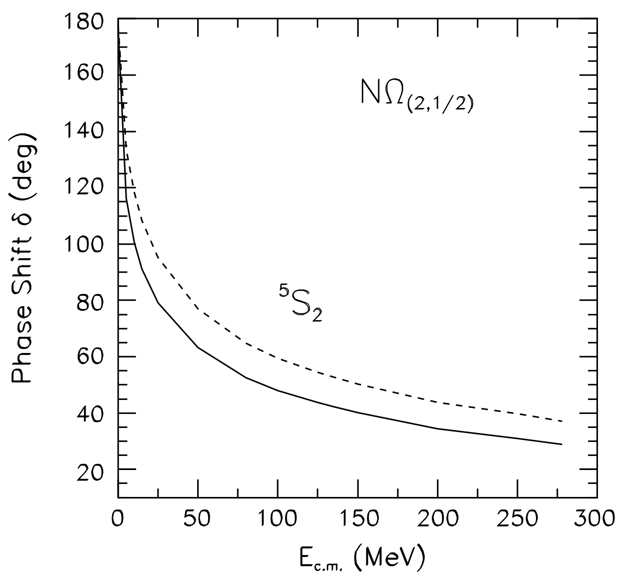

Fig. 4. S-wave scattering phase shifts for $(\mathrm{N}\Omega)_{(2,1/2)}$ system.

It should be mentioned that there are still other channels such as $\Lambda\Xi^*$, $\Sigma\Xi^*$, $\Xi\Sigma^*$ and etc. that may mix with $\mathrm{N}\Omega_{(2,1/2)}$, and $\Sigma^*\Xi^*$ and etc. that may mix with $\Delta\Omega_{(3,3/2)}$. The influence of these possible channels on the corresponding one-channel results depend on both the interactive matrix element and channel threshold differences. No doubt, taking coupled channels into consideration would deepen the binding energy. If one-channel calculation has given the binding behavior already, just like those in our case, introducing additional channels into the

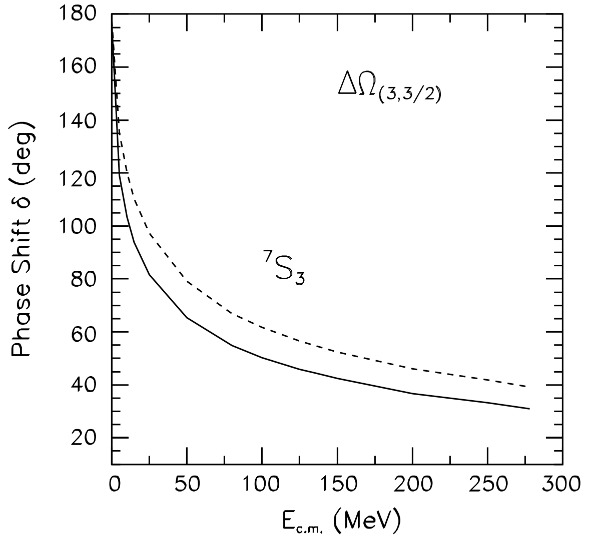

Fig. 5. S-wave scattering phase shifts for $(\Delta\Omega)_{(3,3/2)}$ system.

calculation would only quantitatively deepen the binding and would not qualitatively change the binding behavior. Because coupled-channel calculation is much more complicated than that in the single channel case, we will carry out the coupled-channel calculation in the next step of this project.

4 Conclusion

In the framework of the $SU(3)$ chiral quark model, we investigated the possible S-wave baryon-baryon bound states in the $s = -3$ sector of the six-quark system. By employing either the $SU(3)$ or extended $SU(2)$ or $SU(2)$ chiral quark models, we would report that there may exist two bound states, N$\Omega(S = 2, T = 1/2, L = 0)$ and $\Delta\Omega(S = 3, T = 3/2, L = 0)$. The results show that these systems are more bound in the $SU(2)$ and less bound in the $SU(3)$ chiral quark model. If we believe that the $SU(3)$ chiral quark model is more correct, the resultant binding energies of N$\Omega(S = 2, T = 1/2, L = 0)$ and $\Delta\Omega(S = 3, T = 3/2, L = 0)$ should be ranged from 3.5 to 12.7 MeV and from 4.4 to 14.2 MeV, respectively, and their RMS are $1.18 \sim 0.98$ fm and $1.15 \sim 0.96$ fm, accordingly. The predictions in the extended $SU(2)$ and $SU(2)$ chiral quark model can serve as alternative references for searching NΩ and $\Delta\Omega$. Because binding energy of the $\Delta\Omega$ system in any model is above the threshold of the N$\Omega\pi$ channel which is coupled to the $\Delta\Omega$ state due to the strong decay mode $\Delta \rightarrow$ Nπ, the $\Delta\Omega$ would have a broad width and might not be easy to detect in the experiment. However, the Ω-baryon can only decay through the weak mode, NΩ would have a narrow width. Considering the possible nucleon beam, it would especially be interesting to search N$\Omega(S = 2, T = 1/2, L = 0)$ in the experiment, especially in the heavy-ion collision.

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