第24卷第9期 高能物理与核物理 Vol.24, No.9
2000年9月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Sep., 2000

Is Any $s=-3$ Dibaryon Possible?*

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Abstract We investigate the binding energy of six-quark systems with strangeness $s=-3$ under the constituent quark model in the framework of RGM. The single NΩ channel with spin $S=2$ and the single ΔΩ channel with spin $S=3$ are considered, respectively. The results show that both two systems can form loosely bound states: the binding energies are ranged from 3.5—12.7 MeV for NΩ and 4.4—14.2 MeV for ΔΩ system, respectively.

Key words RGM, constitutent quark model, binding energy

Although H particle was predicted by Jaffe in 1977[1], none of the dibaryons has been found experimentally. This is not only because of experimental difficulty, but also due to lack of accurate prediction which is caused by the unsolvable complexity of nonperturbative quantum chromodynamics (NPQCD) effects at low energy region. It has been known that dibaryon is a color singlet multi-quark system with a sufficiently smaller size and is believed to be a prospective field to study the strong interaction phenomenology because the effect of the quark-gluon degrees of freedom may show up. Through study, the knowledge of the strong interaction between quarks in particular in the short- and medium- regions can be enriched and the basic theory of the strong interaction, Quantum Chromodynamics (QCD) can further be proven and refined. That is why dibaryon has received intensive attention from both theorists and experimentalists.

In past twenty years, the dibaryon has theoretically been studied in two directions. One is to investigate the structure, the accurate binding energy, the decay property, and etc., and the other is to reveal possible dibaryons of various kinds. Among these particles, some of them are strangenessless such as d^*[2,3], d'[4] and etc., and the others carry strangeness[2], for instance, H particle[10,11] and recently predicted $\Omega\Omega(S=0,L=0)$, and $\Xi^*\Omega(S=0,L=0)$ dibaryons[5,6]。

The present paper studies the possibility of forming dibaryons in the systems with strangeness $s=-3$, for instance NΩ $(S=2,L=0)$ and ΔΩ $(S=3,L=0)$. The proposed work is based on two reasons: 1) As is well known, introducing strangeness and even heavier flavor allows us to learn strong interaction from another sight. By using various kinds of new experimental data, the new degrees of freedom and new model theories, one may find an efficient way to handle NPQCD effect and obtain a more reliable basic interaction and structure model. 2) Because the nucleon beams are available and Ω decays only through weak modes, if N and Ω can form a bound state, such state should have narrow width and should

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Received 16 February 2000

* Supported by National Natural Science Foundation of China and Science Foundation of The Chinese Academy of Sciences

be highly possible to be detected.

The chiral $SU(3)$ quark model is employed to carry out the investigation. This model was originated from the constituent quark model (CQM). The major accomplishment of CQM was to provide the basic explanations of the baryon spectrum and the repulsive core of the nuclear force.[7] However, due to lack of medium-and short-range attractions, namely the NPQCD effect at the lower energy region, the experimental data, in particular the nucleon – nucleon scattering data, could not be well reproduced. Thus one had to develop QCD-inspired models to properly describe the nonperturbative effect of QCD. In early 90's, by considering the symmetry property in the strong interaction, the chiral symmetry, the chiral $SU(2)$ quark model was proposed, and later was extended to the chiral $SU(3)$ quark model[8]. The advantage of the presently used model is that by using the same set of parameters, not only the single baryon properties can basically be explained[9], but also the scattering data of the N – N and N – Y processes can better be reproduced[8]. Extrapolating that model to the system with two strangeness, the resultant binding energy of H-dibaryon ($S=0, T=0$) is consistent with the experimental data available[10,11]. When this model is employed to study a multi – strange – quark system, no additional parameters are requested. Thus the chiral $SU(3)$ model is a reasonable, reliable and prospective model to study the bound state problem where the number of strange quark is greater than two.

In the chiral $SU(3)$ quark model, the interaction between the ith and jth constituent quarks is written as

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

The confinement potential V_{ij}^{conf} describes the long – range effect of NPQCD, the one – gluon exchange potential (OGE) mainly depicts the short – range perturbation QCD (pQCD) effect. V_{ij}^{ch} denotes the chiral – quark field coupling induced potential

$$V_{ij}^{\mathrm{ch}} = \sum_a V_{\pi_a}(\boldsymbol{r}_{ij}) + \sum_a V_{\sigma_a}(\boldsymbol{r}_{ij}), \tag{2}$$

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, basically represents the short-and medium-range NPQCD effects. The explicit forms of these potentials can also be found in Ref.[8].

The Resonating Group Method (RGM) is employed to study the bound state problem of the six – quark system. The much larger model space in this method enables us to obtain a reliable result in a more effcient way. In this framework, the wave function of the system can be written as

$$\Psi_{6q} = \mathcal{A}[\Phi_A\Phi_B\chi(\boldsymbol{R}_{AB})Z(\boldsymbol{R}_{CM})] \tag{3}$$

where $\chi(\boldsymbol{R}_{AB})$ is the trial relative wave function between clusters A and B, respectively, $Z(\boldsymbol{R}_{CM})$ represents the wave function of the center of mass of the system and $\mathcal{A}$ denotes the antisymmetrizer. Expanding unknown $\chi(\boldsymbol{R}_{AB})$ by well-defined basis wave functions, such as Gaussian functions, one can solve the RGM bound state equation and obtain eigenvalues and corresponding wave functions, simultaneously. The details of solving RGM bound state problem can be found in Refs.[12,13].

All the model parameters employed in the calculation are determined by 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 resultant binding energy and corresponding root – mean – square radius (*RMS*) of the systems are tabulated in Table 1. In the table, the Model Ⅰ Set 1 means the chiral $SU(3)$quark model with the parameters set which is frequently used in our previous investigations,[7,8,14]. It is shown that both NΩ($S=2$) and ΔΩ($S=3$) are bound. Their binding energies are 3.5 MeV and 4.4 MeV, respectively, and the corresponding *RMS* are 1.18 fm and 1.15 fm, respectively.

Table 1. Binding energy B_{AB} and RMS of NΩ ($S=2$) and ΔΩ ($S=3$)*

Channel	one channel NΩ($S=2$)		one channel ΔΩ($S=3$)	
	$B_{N\Omega}$(MeV)	*RMS*(fm)	$B_{\Delta\Omega}$(MeV)	*RMS*(fm)
Model Ⅰ Set1	3.5	1.18	4.4	1.15
Model Ⅰ Set2	12.7	0.98	14.2	0.96
Model Ⅱ	31.8	0.81	34.3	0.80
Model Ⅲ	49.5	0.74	49.5	0.74

* B_{AB} denotes the binding energy between A and B dibaryons and RMS represents the corresponding root - mean - square radius.

It should particularly be noticed that the symmetry property of the system shows $\langle \mathscr{A}^{sfc} \rangle = 1$. This means that the quark exchange effect is less important and the contribution from the kinetic energy terms would be repulsive in nature. Asa consequence, two interacting baryons would be further apart. In order to make the system bound, the chiral-quark filed interaction must play an important role, namely strong attraction. Therefore, in the rest of the paper, we would focus our attention on the contributions provided by chiral fields.

Firstly, we presume that the chiral field carrying strangeness must be important medium for a system with multi-strang-quarks. To see this effect, we increase the mass and cut-off of scalar mesons κ and ε to 1.4 GeV and 1.5 GeV, respectively, which are close to the real masses of particles with the same quantum numbers of κ and ε. By using the same procedure, we obtain the values of parameters in Model Ⅰ Set 2. With this set of parameter, the above mentioned data can also be well described. The result in table 1 shows that with Set 2 the binding energies of NΩ and ΔΩ are increased to 12.7 MeV and 14.2 MeV, respectively, and the corresponding *RMS* are reduced to 0.98 fm and 0.96 fm, respectively. It seems that the strange clouds κ and ε would offer visible effect which is positive for forming bound NΩ ($S=2$) and ΔΩ ($s=3$).

Secondly, we investigate the roles of other chiral fields using Models Ⅱ and Ⅲ, respectively. The Model Ⅱ is the extended chiral $SU(2)$ quark model where scalar field σ and pseudoscalars π, K, η and η′are involved, while Model Ⅲ is the chiral $SU(2)$ quark model where only pseudoscalar meson π and scalar meson σ are remained.

The corresponding binding energies and *RMS* of NΩ ($S=2$) and ΔΩ ($S=3$) in these two models are also tabulated in Table 1, respectively. It is shown that the binding energies of two systems in Model Ⅱ is much larger than those in Model Ⅰ and smaller than those in Model Ⅲ. The reason is the following. The inter-cluster interaction induced by the σ field for both systems are dominantly attractive in all models, which plays the most important role in forming bound states. The interaction induced by the π field has no contributions to binding, because the π meson cannot be exchanged between the u(d) quark in N (or Δ) and the s quark in Ω. The interactions induced by the chiral fields other than σ and π basically paly a negative role in binding namely, the contributions provided by scalar meson ε, and pseudoscalar mesons K and η are repulsive.

As the conclusion, in the framework of RGM, we employ the chiral $SU(3)$ quark model, which is one of the most prospective model and can give a unified description for as much experimental data as possible, to investigate possible dibaryons in $s=-3$ systems. We announce that in the $s=-3$ sector of the six-quark system, there may exist two bound states, NΩ ($S=2$, $L=0$) with the binding energy of 3.5—12.7 MeV and corresponding RMS of 1.18—0.98 fm, and ΔΩ ($S=3$, $L=0$) with the binding energy of 4.4—14.2 MeV and corresponding of RMS 1.15—0.96 fm. By comparing the results in Models Ⅰ, Ⅱ, and Ⅲ, one sees that the chiral fields, especially the σ field, play important roles in binding. The results also show that the binding energies in the extended chiral $SU(2)$ quark model and the chiral $SU(2)$ quark model are much larger than those in the chiral $SU(3)$ quark model where the repulsive nature of the scalar meson ϵ and pseudoscalar mesons K and η are taken into account. Because the energy level of ΔΩ ($S=3$) in any particular model is higher than the threshold of the ΩNπ channel which is caused by Δ strong decay mode $\Delta \rightarrow N\pi$, ΔΩ($S=3$) would have a broad width. While due to no strong decay mode for Ω, NΩ ($S=2$) would be a narrow width bound state.

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论是否存在 $s=-3$ 的双重子*

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摘要 在共振群框架下用组分夸克模型研究了奇异数为 $s=-3$ 的六夸克系统的束缚能．分别考虑了自旋 $S=2$ 的单道 NΩ 和自旋 $S=3$ 的单道 ΔΩ．结果显示两个系统都可以形成松散的束缚态：NΩ 的束缚能为3.5到12.7MeV，而 ΔΩ 的束缚能为4.4到14.2MeV．

关键词 共振群 组分夸克模型 束缚能

2000-02-16收稿

* 国家自然科学基金和中国科学院基金资助