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Dibaryons without Strangeness

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Abstract: In the present work we discuss three dibaryons without strangeness in the chiral $SU(3)$ quark model by solving the resonating group method (RGM) equation. In the calculation, the model parameters are taken from our previous work in which the nucleon-nucleon (NN) scattering phase shifts are fitted quite well. Firstly, the structure of deuteron is discussed, which is very important since it is the first dibaryon confirmed by experiment in the past many years. Deuteron belongs to NN system with spin $S=1$ and isospin $T=0$, the binding energy, scattering length and the relative wave functions of deuteron are discussed. The results show that the chiral $SU(3)$ quark model describes the properties of deuteron quite well and tensor interaction is important in forming the deuteron loosely bound. Secondly, the predicted results of $\Delta\Delta$ dibaryon with $S=3$ and $T=0$ are shown, the resultant binding energy and size of root-mean-square (RMS) of six quarks are calculated by including the L coupling and hidden color channel (CC) coupling. The results show that the CC coupling effect is much larger than the L mixing effect, which means that CC coupling plays an important role in forming the spin $S=3$ $\Delta\Delta$ dibayon state. Our predicted binding energy is several tens MeV, it is lower than the threshold of the $\Delta\Delta$ channel and higher than the mass of $\mathrm{N}\Delta\pi$. Unexpectedly, our predicted mass is quite close to the recent confirmation by WASA experiments in 2014. Thirdly, we present our new results of $\Delta\Delta$ dibaryon with $S=0$ and $T=3$, obtained recently by extending the single-channel calculation to including the CC coupling. It is seen that the CC coupling also has a relatively large effect on $(\Delta\Delta)_{ST=03}$ state. However, its mass is still lower than the threshold of the $\Delta\Delta$ channel and higher than the mass of $\mathrm{N}\Delta\pi$, similar as that of $(\Delta\Delta)_{ST=30}$ state. Finally, we further make some comparisons between $S=3$ and $S=0$ $\Delta\Delta$ states to show the difference of the two dibaryons. The results show that the attractive interactions from σ' meson and OGE exchanges are dominantly important for $S=0$ and $S=3$ states, respectively, so their binding energies all become larger in coupled-channel calculation.

Key words: deuteron; tensor force; dibaryon; hidden color channel

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1 Introduction

Exploring dibaryon will deepen our understanding of strong interaction, since it is a good place to see the short-distance behavior and non-perturbative effect of quantum chromodynamics (QCD) which is believed to be the fundamental theory of the strong interaction.

Recently, the very exciting news is the experimental confirmation of the exotic $\Delta\Delta$ dibaryon with spin $S=3$ and isospin $T=0$[1–4], denoting as $(\Delta\Delta)_{ST=30}$ or d* dibaryon state. It is bringing us new attention to study other possible and interesting dibaryons. Actually, there are two kinds of dibaryon, one is loosely bound state, and the other is tightly bound state. The new $(\Delta\Delta)_{ST=30}$ state belongs to a tightly bound state, and the deuteron is a loosely bound state. The deuteron is nucleon-nucleon (NN) system with spin $S=1$ and isospin $T=0$, denoting as $(\mathrm{NN})_{ST=10}$ dibaryon, which was the only confirmed experimentally dibaryon state before the confirmation of $(\Delta\Delta)_{ST=30}$ in the past many years. Now the new $(\Delta\Delta)_{ST=30}$ state has stimulated the experimental interest of other interesting dibaryons, for instance, the dibaryon candidate with its mirrored quantum numbers $S=0$ and $T=0$, we call it $(\Delta\Delta)_{ST=03}$ state, was recently reported by the WASA experiment[5]. Accordingly, this has stimulated theoretical interest on the study related to $(\Delta\Delta)_{ST=03}$ state.

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Theoretically, the possibility of the existence of $\Delta\Delta$ dibaryon states was first proposed in 1964 by Dyson[6] and Xuong from a simple group classification based on $SU(6)$ symmetry with no dynamical effects being taken into account. Since then, a lot of theoretical work has been devoted to explore the possible $\Delta\Delta$ dibaryon, such as dynamical chiral quark models[7, 8], the chiral $SU(3)$ quark model[9] and three-body hadronic model[10]. In fact, the existence of $(\Delta\Delta)_{ST=30}$ dibaryon had been predicted by many models before the recent WASA experiments. Among these models, one of the most successful models is the chiral $SU(3)$ quark model[11]. In this model, by including the interaction between the quark field and chiral field into the constituent quark model, one successfully reproduced the data of nucleon-nucleon (NN) scattering phase shifts and hyperon-nucleon (YN) cross sections. Hence, if we further predict the dibaryon, this model would provide a much reliable platform to study the structure of dibaryon. In 1999, this model was firstly applied to study the $(\Delta\Delta)_{ST=30}$ dibaryon, in which the hidden color channel (CC) being properly taken into account[12]. Unexpectedly, the predicted mass is quite close to the recent new experimental data, hence it is very reasonable and interesting to investigate other possible dibaryons within the same framework of the chiral $SU(3)$ quark model. Thus, we extend the single-channel calculation[13, 14] of $(\Delta\Delta)_{ST=03}$ state to include the CC coupling effect[15]. In this work, we present the calculated results of three dibaryons without strangeness in the chiral $SU(3)$ quark model.

2 Formulation

2.1 Model

In our chiral $SU(3)$ quark model[11], the Hamiltonian of the induced interaction between quark and chiral field

$$H_{\rm ch} = g_{\rm ch} F(\boldsymbol{q}^2)\bar{\psi}\left(\sum_{a=0}^{8}\sigma_a\lambda_a + i\sum_{a=0}^{8}\pi_a\lambda_a\gamma_5\right)\psi \ . \quad (1)$$

Here we insert a form factor $F(\boldsymbol{q}^2)$ to describe the chiral-field structure as

$$F(\boldsymbol{q}^2) = \left(\frac{\Lambda^2}{\Lambda^2+\boldsymbol{q}^2}\right)^{1/2} , \quad (2)$$

where Λ is the cutoff mass corresponding to the chiral symmetry breaking scale. In Eq. (1) the σ_a and π_a represnt the basic chiral fields. Here we call $\sigma, \sigma', \kappa, \epsilon$ for the scalar σ_a mesons and π, K, η, η' for the pseudoscalar π_a mesons, respectively.

The total Hamiltonian is written as

$$H = \sum_{i=1}^{6} T_i - T_G + \sum_{j>i=1}^{6}\left(V_{ij}^{\rm OGE} + V_{ij}^{\rm conf} + V_{ij}^{\rm ch}\right) , \quad (3)$$

with T_i being the kinetic energy operator for the i-th quark, T_G is the kinetic energy operator for the center of mass motion of the whole six-quark system, and the one-gluon-exchange (OGE) interaction is expressed as

$$V_{ij}^{\rm OGE} = \frac{1}{4} g_i g_j \left(\boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c\right)\left\{\left[\frac{1}{r_{ij}} - \frac{\pi}{m_q^2}\delta(\boldsymbol{r}_{ij})\times \right.\right. \quad (4)$$

$$\left.\left.\left(1+\frac{2}{3}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\right) - \frac{1}{4m_q^2}\frac{1}{r_{ij}^3}S_{ij}\right]\right\} , \quad (5)$$

where r_{ij} denotes the relative distance between two quarks, m_q being the quark mass. The quadratic confinement potential is taken as

$$V_{ij}^{\rm conf} = -\left(\boldsymbol{\lambda}_i^c\cdot\boldsymbol{\lambda}_j^c\right)\left(a_{ij}^c r_{ij}^2 - a_{ij}^{c0}\right) \ . \quad (6)$$

The chiral fields induced effective interaction between the i-th quark and the j-th quark is written as,

$$V_{ij}^{\rm ch} = \sum_{a=0}^{8} V_{ij}^{\sigma_a} + \sum_{a=0}^{8} V_{ij}^{\pi_a} \ , \quad (7)$$

with

$$V_{ij}^{\sigma_a} = -C(g_{\rm ch}, m_{\sigma_a}, \Lambda) Y_1(m_{\sigma_a}, \Lambda, r_{ij})\left(\lambda_a^i\lambda_a^j\right) , \quad (8)$$

$$V_{ij}^{\pi_a} = C(g_{\rm ch}, m_{\pi_a}, \Lambda)\Big[Y_3(m_{\pi_a}, \Lambda, r_{ij})(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j) + \quad (9)$$

$$H_3(m_{\pi_a}, \Lambda, r_{ij}) S_{ij}\Big]\left(\lambda_a^i\lambda_a^j\right)\frac{m_{\pi_a}^2}{12 m_q^2} , \quad (10)$$

and

$$C(g_{\rm ch}, m, \Lambda) = \frac{g_{\rm ch}^2}{4\pi}\frac{\Lambda^2}{\Lambda^2 - m^2} m , \quad (11)$$

$$Y_1(m, \Lambda, r) = Y(mr) - \frac{\Lambda}{m} Y(\Lambda r) , \quad (12)$$

$$Y_3(m, \Lambda, r) = Y(mr) - \left(\frac{\Lambda}{m}\right)^3 Y(\Lambda r) , \quad (13)$$

$$H_3(m, \Lambda, r) = H(mr) - \left(\frac{\Lambda}{m}\right)^3 H(\Lambda r) , \quad (14)$$

$$Y(x) = \frac{1}{x}{\rm e}^{-x} , \quad (15)$$

$$H(x) = \left(1 + \frac{3}{x} + \frac{3}{x^2}\right) Y(x) , \quad (16)$$

$$S_{ij} = 3\boldsymbol{\sigma}_i\cdot\hat{\boldsymbol{r}}_{ij}\,\boldsymbol{\sigma}_j\cdot\hat{\boldsymbol{r}}_{ij} - \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j \ . \quad (17)$$

2.2 Hidden-color channel

In our calculation, the CC coupling is included to study the structure of ΔΔ dibaryon. The Δ and C are described as states with the following symmetries and quantum numbers

Δ: $(0s)^3[3]_{\rm orb}; S=3/2; T=3/2; {\rm C}=(00)$,

C: $(0s)^3[3]_{\rm orb}; S=3/2; T=3/2; {\rm C}=(11)$,

where $(0s)^3$ is the harmonic-oscillator shell wave function, $[3]_{\rm orb}$ represents the symmetry in orbit space for each cluster, and S, T and C are quantum numbers of spin, isospin and color for each cluster, respectively.

The final CC for both $(\Delta\Delta)_{ST=30}$ and $(\Delta\Delta)_{ST=03}$ cases can be constructed as

$$|{\rm CC}\rangle=-\frac{1}{2}|\Delta\Delta\rangle+\frac{5}{2}\mathcal{A}^{\rm sfc}|\Delta\Delta\rangle\ , \tag{18}$$

where the symbol $\mathcal{A}^{\rm sfc}$ denotes the antisymmetrizer in spin-flavor-color (sfc) space, the definition is

$$\mathcal{A}^{\rm sfc}=\frac{1}{10}\left(1-\sum_{i=1,2,3;j=4,5,6}P_{ij}^{\rm sfc}\right),$$

with $P_{ij}^{\rm sfc}$ is the permutation operator in sfc space for the i-th quark and j-th quark inside clusters A and B, respectively.

2.3 The model parameters

In our calculation, the model parameters are listed in Table 1, which are properly fixed in fitting NN scattering phase shifts[16].

Table 1 Model parameters. The meson masses and the cutoff mass are $m_\pi=138$ MeV, $m_\eta=549$ MeV, $m_{\eta'}=957$ MeV, $m_{\sigma'}=m_\epsilon=980$ MeV, $\Lambda=1100$ MeV.

$b_{\rm u}$=0.5 fm	m_σ =595 MeV
$m_{\rm u}$=313 MeV	$g_{\rm u}^2=0.785$
$g_{\rm ch}=2.62$	$a_{\rm uu}^{\rm c0}$= -43.6 MeV
$a_{\rm uu}^{\rm c}=48.1$ MeV fm^{-2}	

We briefly discuss how to determine the model parameters in our chiral $SU(3)$ quark model: the harmonic-oscillator width parameter is taken to be $b_{\rm u}=0.5$ fm and the u or d quark mass is taken to be $m_{\rm u(d)}=313$ MeV as usual. The coupling constant $g_{\rm ch}$, which represents the coupling between the quark field and the scalar and pseudoscalar chiral fields, is determined according to the relation

$$\frac{g_{\rm ch}^2}{4\pi}=\left(\frac{3}{5}\right)^2\frac{g_{\rm NN\pi}^2}{4\pi}\frac{m_{\rm u}^2}{M_{\rm N}^2}\ , \tag{19}$$

where $g_{\rm NN\pi}^2/4\pi=13.67$ is taken from the empirical value, σ meson mass is fixed by fitting the NN scattering data, and the masses of other mesons are taken to be the experimental values. The cutoff mass Λ is taken from the chiral symmetry breaking scale[17–19]. The OGE coupling constant $g_{\rm u}$ is then determined by the mass split of N-Δ. The confinement strength $a_{\rm uu}^{\rm c}$ and the zero-point energies $a_{\rm uu}^{\rm c0}$ are fixed by the stability condition and the mass of nucleon, respectively.

3 Results and discussion

By taking the model parameters in Table 1, we dynamically investigate the properties of three dibaryons without strangeness. The standard method is used to study the bound state problem of dibaryon or six-quark system in the chiral $SU(3)$ quark model by solving the resonating group method (RGM) equation[20] to get the binding energy and the corresponding wave function. As usual, the generator coordinate method (GCM) will be used to solve the two cluster problem, similar with our previous work in Refs. [12–16, 21–23].

3.1 Deuteron

Firstly, we study the structure of deuteron, it is $L=0$, $S=1$, $J=1$, $T=0$ state of NN system with L, S, J and T being the orbital, spin, total angular momentum and isospin, respectively. It is an interesting state, since for the past many years it was the only confirmed dibaryon state before the recent WASA experiments.

The resultant binding energy and scattering length and corresponding experimental data[24] are listed in Table 2, where the minus sign indicates the system is bound state. One can see that for $L=0$ case,

Table 2 The calculated binding energy and scattering length of the deuteron, and corresponding experimental data[24].

L-coupling and experiment value	Binding energy /MeV	Scattering length/fm
$L=0$	6.04	−4.96
$L=0+2$	−2.13	5.532
Exp.	−2.2	5.424

the binding energy is about 6.04 MeV (unbound) and scattering length is −4.96 fm, in this case only central interaction is considered, which means that there is no tensor interaction from OGE and and pseudoscalar field exchanges; and for $L=0+2$ case, the coupling of $L=0$ and $L=2$ is further considered, then the binding energy becomes into −2.13 MeV and scattering length is 5.532 fm, which is consistent with the experimental data very well. In this case, we not only consider central interaction but also include tensor interaction from OGE and pseudoscalar field exchanges. Hence one can see that in the study of deuteron structure, the tensor interaction is important and can not be ignored. In Fig. 1 we further show the relative wave functions of deuteron in the chiral $SU(3)$ quark model, where the solid curve and dashed curves denote the S and D-wave, respectively. One can see that the deuteron has a considerable D-wave contribution due to tensor interaction, which is actually crucial in making the deuteron loosely bound. It is clear to see that the chiral $SU(3)$ quark model not only describe reasonably the NN phase shifts, but also the properties of deuteron, in which tensor interaction is important in forming the deuteron loosely bound.

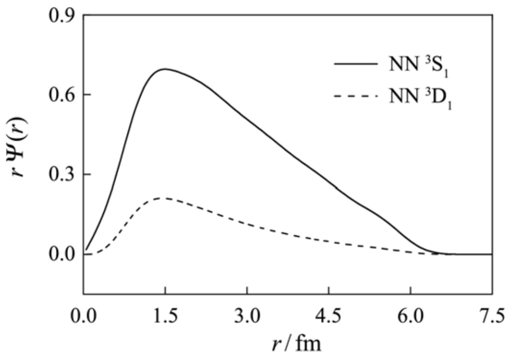

Fig. 1 Relative wave functions of deuteron in the chiral $SU(3)$ quark model.

3.2 $(\Delta\Delta)_{ST=30}$ dibaryon

Secondly, our results of $(\Delta\Delta)_{ST=30}$ dibaryons are presented here in the chiral $SU(3)$ quark model[12, 21].

In fact, in 1999 and later in 2005 we predicted the possible $(\Delta\Delta)_{ST=30}$ dibaryon candidate in the chiral $SU(3)$ quark model[12, 21]. This state belongs to $\Delta\Delta$ system with $L = 0$, $S = 3$, $J = 3$, $T = 0$. The resultant binding energy and root-mean-square (RMS) radius of six quarks are shown in Table 3, in which the minus sign indicates the system is bound state. Both L coupling and CC coupling are included in our calculation. It is seen that the binding energy is about -23.0 MeV for $L=0$ case of single-channel calculation, and the binding energy becomes -40.5 MeV after including the CC, which means that the coupling to the CC results in an increment of about -17.5 MeV to the binding energy of $(\Delta\Delta)_{ST=30}$ state. It is also seen that the binding energy is about -29.1 MeV for $L=0+2$ case of single-channel calculation, which means that the coupling to the $L = 2$ results in an increment of about -6.1 MeV to the binding energy of $(\Delta\Delta)_{ST=30}$ state. Hence one can see that the CC coupling effect is much larger than the L mixing effect, the coupling to the CC plays an important role in forming the spin $S=3$ dibayon of $\Delta\Delta$ system. From Table 3, we can see that the predicted binding energy is always several tens MeV, it is lower than the threshold of the $\Delta\Delta$ channel and higher than the mass of N$\Delta\pi$. Unexpectedly, we find that our predicted mass is quite close to the recent WASA experiments, hence it is very interesting to investigate other possible dibaryon candidates within the same framework of chiral $SU(3)$ quark model.

Table 3 Binding energy and root-mean-square (RMS) of six quarks for $(\Delta\Delta)_{ST=30}$ state.

L-coupling and channel coupling	Binding energy /MeV	RMS of six quarks/fm
$\Delta\Delta(L=0)$	-23.0	0.98
$\Delta\Delta$+CC$(L=0)$	-40.5	0.89
$\Delta\Delta(L=0+2)$	-29.1	0.96
$\Delta\Delta$+CC$(L=0+2)$	-48.3	0.88

3.3 $(\Delta\Delta)_{ST=03}$ dibaryon

Thirdly, we present our newly predicted results for another interesting dibaryon, $(\Delta\Delta)_{ST=03}$, it is with the mirrored quantum numbers of above state, which belongs to $L=0$, $S=0$, $J=0$, $T=3$ of $\Delta\Delta$ system.

Actually this state was predicted in the previous works of our group[13, 14], however, all those results were obtained in single-channel calculation. Recently we investigate this interesting dibaryon by further including the CC coupling in the chiral $SU(3)$ quark model[15]. The resultant binding energy and RMS of six quarks for $(\Delta\Delta)_{ST=03}$ state are shown in Table 4. One can see that the binding energy is about -22.3 MeV for single-channel calculation, and the binding energy becomes -31.3 MeV after including the CC. It means that the coupling to the CC results in an increment of about -9 MeV to the binding energy of $(\Delta\Delta)_{ST=03}$ state. Hence, it can be seen that the coupling to the CC also plays an important role in forming the spin $S=0$ state of $\Delta\Delta$ system. It also tell us that the mass of this predicted $(\Delta\Delta)_{ST=03}$ state is lower than the threshold of the $\Delta\Delta$ channel and higher than the mass of $N\Delta\pi$.

Table 4 The same as Table. 3 but for $(\Delta\Delta)_{ST=03}$ state.

Channel coupling	Binding energy /MeV	RMS of six quarks /fm
$\Delta\Delta(L=0)$	-22.3	1.03
$\Delta\Delta$+CC$(L=0)$	-31.3	0.97

3.4 Comparisons between $(\Delta\Delta)_{ST=30}$ and $(\Delta\Delta)_{ST=03}$ dibaryons

In this section, we present the comparisons between $S=3$ and $S=0$ states of $\Delta\Delta$ system. In Fig. 2, the GCM matrix elements are shown in single-channel calculation, s is the generator coordinate which can qualitatively describe the distance between the two clusters. It should be mentioned that we only draw the different parts and neglect the same parts of the GCM matrix elements for $(\Delta\Delta)_{ST=03}$ (a) and $(\Delta\Delta)_{ST=30}$ (b) states, respectively. For $S=0$ state, the OGE provides strong repulsion, and η, η' also contribute some repulsive interactions, but the σ' contribute strongly attractive interaction; for $S = 3$ state, the contributions are all opposite, it means that the OGE, η and η' contribute attractive interactions, but σ' contribute strongly repulsive interaction. In Fig. 3, the GCM transition matrix elements of $\Delta\Delta$-CC are shown, in which also only the different parts are given and the same parts are neglected. The results show that $S=0$ can mainly obtain strong attractive interaction from σ' scalar meson exchange. However, the $S = 3$ state obtains much more attractive interaction dominantly from OGE. In a word, in coupled-channel calculation, we find that the attractive interactions from σ' meson and OGE exchanges are dominantly important for $S=0$ and $S=3$ states, respectively, so their binding energies all become larger.

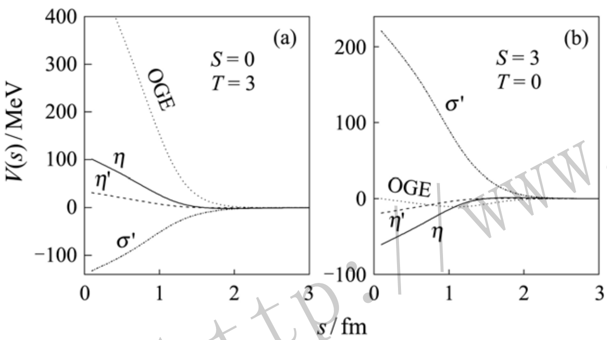

Fig. 2 The GCM matrix elements for $S = 0$ (a) and $S = 3$ (b) states are shown in single-channel calculation.

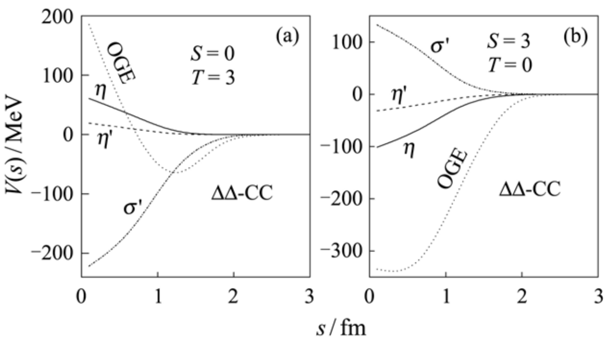

Fig. 3 The GCM transition matrix elements of $\Delta\Delta$-CC for $S = 0$ (a) and $S = 3$ (b) states are shown in coupled-channel calculation.

4 Conclusions

In summary, we systematically investigate the dibaryons without strangeness by using the chiral $SU(3)$ quark model that describe the NN scattering data satisfactorily, in which a dynamical RGM equation is solved. Firstly, the properties of deuteron are well reproduced and find that the tensor interaction is important in forming the deuteron loosely bound. Secondly and thirdly, by including the CC coupling, we study both $S = 3$ and $S = 0$ states of $\Delta\Delta$ system. The results tell us the effect from CC has large effect both on $S = 3$ state and $S = 0$ state, respectively. Finally, we present the detailed comparison of these two states due to different spin structures. In a word, one can see that both in single-channel calculation and coupled-channel calculation, the masses of both $(\Delta\Delta)_{ST=30}$ and $(\Delta\Delta)_{ST=03}$ are always lower than the threshold of the $\Delta\Delta$ channel and higher than the mass of $\mathrm{N}\Delta\pi$.

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不带奇异数的双重子态

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摘要： 在手征 $SU(3)$ 夸克模型下应用共振群方法讨论了三个非奇异的双重子态的性质。计算中的模型参数取自我们以前的工作，拟合核子-核子相互作用散射相移确定下来的。首先，研究了氘核的性质，这是非常重要的，因为氘核是多年来实验上唯一发现的双重子态。氘核属于核子-核子系统，它是自旋为 $S=1$ 和同位旋为 $T=0$ 的双重子态。我们计算了氘核的结合能、散射长度以及氘核的相对运动波函数，结果表明手征 $SU(3)$ 夸克模型可以合理描述氘核的性质并且发现张量力对形成松散束缚态的氘核是重要的。然后，给出了 $S=3$ 和 $T=0$ 的 $\Delta\Delta$ 双重子态的理论预言结果，这里考虑了分波耦合和隐色道耦合效应，计算了结合能和均方根半径。结果表明，隐色道耦合效应比分波耦合效应大，也就是说隐色道耦合效应在形成 $(\Delta\Delta)_{ST=30}$ 双重子态中是重要的。我们的理论预言结果在几十个 MeV 左右，低于 $\Delta\Delta$ 道的阈值但是高于 $\mathrm{N}\Delta\pi$ 的阈值. 出乎意料地，我们的预言结果很接近最近 2014 年 WASA 的实验结果。接着，给出了对 $S=0$ 和 $T=3$ 的 $\Delta\Delta$ 双重子态性质的最新研究结果，这里在以前的单道计算基础上考虑了隐色道耦合效应。结果表明，隐色道耦合对$(\Delta\Delta)_{ST=03}$的结合能也有较大的影响。但是，和 $(\Delta\Delta)_{ST=30}$ 一样，它的质量低于 $\Delta\Delta$ 道的阈值但是高于 $\mathrm{N}\Delta\pi$ 的阈值。最后，对 $S=3$ 以及 $S=0$ 两个不同 $\Delta\Delta$ 自旋态，详细比较了两者结构之间的差异。结果表明，σ' 介子交换和 OGE 交换对自旋 $S=0$ 和 $S=1$ 态提供的吸引作用分别是主要的，从而导致耦合道计算中系统的结合能变大。

关键词： 氘核；张量力；双重子；隐色道

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