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# Study of $\Sigma^*$-$\Delta$ Interactions*

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**Abstract**: We study the $\Sigma^*$-$\Delta$ interaction in the chiral $SU(3)$ quark model and in the extended chiral $SU(3)$ quark model. In these two models, the short-range interaction mechanism are totally different, one is from the one-gluon exchange and another is from the vector meson exchange. The possible reasons of forming strangeness －1 bound states are given. Comparisons between the cases with and without quark exchange effect are made. The results show the quark exchange effect does give attractions to $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ and $(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$ systems, which means the special symmetry is important. Also, we make some analysis on chiral field effect, our results show that the $\sigma$ exchange dominantly provides the attractive interaction for these two states.

**Key words**: dibaryon; symmetry; chiral field
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## 1 Introduction

Searching dibaryons both theoretically and experimentally has attracted worldwide attention since Jaffe's first prediction of H dibaryon in 1977[1]. Various quark models were proposed to study their possible existence of dibaryons.

In order to explain the nucleon-nucleon (NN) experimental data, the $\sigma$ meson exchange must be introduced to get the intermediate-range attraction[2−6] from quark model calculation in the past 15 years. Recently the existence of $\sigma$ meson is confirmed by experiments[7].

Among these models, one of most successful model is the chiral $SU(3)$ quark model[8], in which the energies of the baryon ground states, the binding energy of the deuteron, the nucleon-nucleon (NN) scattering phase shifts, and the hyperon-nucleon (YN) cross sections can be reasonably reproduced by solving a resonating group method (RGM) equation[9]. In this model, from chiral symmetry requirement, the coupling between quarks and nonet scalar meson fields and nonet pseudo-scalar meson fields is introduced to describe the medium and long range interactions, and we use one gluon exchange (OGE) to describe the short range interaction. Then, using the same set of parameters, many possible dibaryon states have been predicted[10−13] in this chiral $SU(3)$ quark model.

In the study of NN interactions on quark level, the short-range feature can be explained by OGE interaction and the quark exchange effect. As we know, in the traditional one boson exchange (OBE) model on baryon level, the short-range NN

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interaction comes from vector meson ($\rho$, $\omega$, $K^*$ and $\phi$) exchanges. In order to study vector-meson exchange effect on quark level, the extended chiral $SU(3)$ quark model was proposed[14], in which the coupling of the quark with vector chiral fields was included. The OGE that acts an important role in the short-range quark-quark interaction in the chiral $SU(3)$ quark model is now nearly replaced by the vector meson exchanges in the extended chiral $SU(3)$ quark model. The energies of the baryon ground states, the binding energy of the deuteron, and the NN scattering phase shifts[14] can be also reasonably reproduced in this extended model, also some interesting results for meson-baryon systems were obtained, which are quite similar to those given by the chiral unitary approach study[15].

Since geometric size of a dibaryon is small, the short range feature of the interactions must be important for form possible dibaryon. The strangeness −1 dibaryon $\Sigma^*\Delta$ has been studied in Refs. [12, 16], and some interesting results were shown. In this work, we further study the $\Sigma^*$-$\Delta$ interaction with spin 0 and spin 3 systems in this extended chiral $SU(3)$ quark model. We mainly make some analysis from special symmetry and $\sigma$ meson exchange interaction both in the chiral $SU(3)$ quark model and in the extended chiral $SU(3)$ quark model, since the short-range mechanisms are totally different in these two models.

## 2 Model

The chiral $SU(3)$ quark model[8] and the extended chiral $SU(3)$ quark model[14] have been widely described in the literature and we refer the reader to those works for details. Here we just give the salient feature of these two models.

In these two models, the total Hamiltonian of baryon-baryon systems can be written as

$$H=\sum_{i=1}^{6}T_i-T_G+\sum_{i<j=1}^{6}V_{ij}, \tag{1}$$

where $\sum_i T_i - T_G$ is the kinetic energy of the system, and $V_{ij}$ is the quark-quark interactions,

$$V_{ij}=V_{ij}^{\rm OGE}+V_{ij}^{\rm conf}+V_{ij}^{\rm ch}, \tag{2}$$

where $V_{ij}^{\rm OGE}$ is the OGE interaction, and $V_{ij}^{\rm conf}$ is the confinement potential. $V_{ij}^{\rm ch}$ as the chiral fields induced effective quark-quark potential. In the chiral $SU(3)$ quark model, $V_{ij}^{\rm ch}$ includes the scalar boson exchanges and the pseudoscalar exchanges,

$$V_{ij}^{\rm ch}=\sum_{a=0}^{8}V_{\sigma_a}(\boldsymbol{r}_{ij})+\sum_{a=0}^{8}V_{\pi_a}(\boldsymbol{r}_{ij}) \tag{3}$$

and in the extended chiral $SU(3)$ quark model, the vector boson exchanges are also included,

$$V_{ij}^{\rm ch}=\sum_{a=0}^{8}V_{\sigma_a}(\boldsymbol{r}_{ij})+\sum_{a=0}^{8}V_{\pi_a}(\boldsymbol{r}_{ij})+\sum_{a=0}^{8}V_{\rho_a}(\boldsymbol{r}_{ij}) \tag{4}$$

Here $\sigma_0,\cdots,\sigma_8$ are the scalar nonet fields, $\pi_0,\cdots,\pi_8$ are the pseudoscalar nonet fields and $\rho_0,\cdots,\rho_8$ are the vector nonet fields. The expressions of these potentials can be found in the Ref. [14].

All the model parameters are taken from our previous work, which gave a satisfactory description of the energies of the baryon ground states, the binding energy of the deuteron, the NN scattering phase shifts. Here we briefly give the procedure for the parameter determination. The three initial input parameters, i. e., the harmonic oscillator width parameter $b_u$, the up (down) quark mass $m_{u(d)}$ and the strange quark mass $m_s$, are taken to be the usual values: $b_u=0.5$ fm for the chiral $SU(3)$ quark model and 0.45 fm for the extended chiral $SU(3)$ quark model $m_{u(d)}=313$ MeV, and $m_s=470$ MeV. The coupling constant for scalar and pseudoscalar chiral field coupling, $g_{ch}$, is fixed by the relation:

$$\frac{g_{\rm NN\pi}^2}{4\pi}=\frac{9}{25}\frac{m_u^2}{M_N^2}\frac{g_{\rm ch}^2}{4\pi}, \tag{5}$$

with the experimental value $g_{\rm NN\pi}^2/4\pi=13.67$. The coupling constants for vector coupling $g_{\rm chv}$ and tensor coupling $f_{\rm chv}$ of the vector-meson field are taken to be the same as used in the NN case[14]. The masses of the mesons are taken to be the experimental values, except for the $\sigma$ meson. The $m_\sigma$ is adjusted to fit the binding energy of the deuteron. The OGE coupling constants $g_u$ and $g_s$ are for exchange of u(d) and s quark, respectively, and the strengths of the confinement potential are fitted by baryon masses and their stability conditions.

Here, for the chiral $SU(3)$ quark model, we call Model A, for the extended $SU(3)$ model without and with tensor coupling of vector-meson field, we call Model B and Model C, respectively.

# 3 Results and Discussion

In order to study the binding energy of two-baryon system on quark level dynamically, we solve the Resonating Group Method (RGM) equation of the Hamiltonian. In RGM calculation, the trial wave function is taken to be

$$\Psi_{ST} = \sum_i c_i \Psi^i_{ST}(\boldsymbol{s}_i) \quad (6)$$

with

$$\Psi^i_{ST}(\boldsymbol{s}_i) = \mathscr{A}(\phi_A(\xi_1, \xi_2)\phi_B(\xi_1, \xi_2) \times \chi(\boldsymbol{R}_{AB} - \boldsymbol{s}_i)\mathscr{R}_{CM}(R_{CM}), \quad (7)$$

where A and B shows two clusters, and $\phi$, $\chi$, and $\mathscr{R}$ represent internal, relative and center of mass motion wave function, respectively. $\boldsymbol{s}_i$ is the generator coordinates and $\mathscr{A}$ is the antisymmetrizing operator defined as

$$\mathscr{A} = 1 - \sum_{i\in A,\ j\in B} P_{ij}, \quad (8)$$

where $P_{ij}$ is the permutation operator of i-th and j-th quarks.

Expanding unknown $\chi(\boldsymbol{R}_{AB} - \boldsymbol{s}_i)$ by employing well-defined basis wave functions, such as Gaussian functions, one can solve the RGM equation for a bound-state problem to obtain the binding energy for the two-cluster system.

In Table 1, the parameters of Model A and the corresponding binding energies of deuteron, $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ and $(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$ are listed. The results show these two systems are bound states in the chiral $SU(3)$ quark model. In order to study the special symmetry of these two states, we omit the quark exchange effect ($P_{ij}=0$), and found the binding energies of these two states are reduced a lot. For $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ system, the binding energy changes from 35.6 to 23.0 MeV, while for $(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$ system, the binding energy changes from 34.7 to 15.7 MeV. The results tell us that quark exchange effect can make these two states more bound. Fig. 1 shows the diagonal matrix elements of the OGE and $\sigma$ meson exchange in the chiral $SU(3)$ quark model for the $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ system in the generator coordinate method (GCM) calculation, which is regarded as the effective in interaction of two clusters $\Sigma^*$ and $\Delta$ qualitatively. $s$ denotes the generator coordinate which can qualitatively describe the distance between the two clusters. From Fig. 1, one see that OGE contribute repulsive interaction, while $\sigma$ exchange provides the strong attractive interaction for this system. From our analysis, the $\sigma'$ meson and $\varepsilon$ meson exchange

**Table 1 For Model A, the parameters and binding energies (MeV). Here $m_\pi$=138 MeV, $m_K$=495 MeV, $m_\eta$=549 MeV, $m_{\eta'}$=957 MeV, $m_{\sigma'}=m_\varepsilon=m_\kappa$= 980 MeV, and $\Lambda$=1 100 MeV**

| | with quark exchange $P_{ij}\neq 0$ | without quark exchange $P_{ij}=0$ |
|---|---|---|
| $m_u$/MeV | 313 | 313 |
| $m_s$/MeV | 470 | 470 |
| $b_u$/fm | 0.5 | 0.5 |
| $m_\sigma$/MeV | 595 | 595 |
| $g_{ch}$ | 2.73 | 2.73 |
| $g_u^2$/OGE | 0.77 | 0.77 |
| $g_s^2$/OGE | 0.85 | 0.85 |
| $a^c_{uu}$/MeV | 46.6 | 46.6 |
| $a^c_{us}$/MeV | 58.7 | 58.7 |
| $a^{c0}_{us}$/MeV | −42.4 | −42.4 |
| $a^{c0}_{us}$/MeV | −36.2 | −36.2 |
| deuteron | 2.13 | 9.65 |
| $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ | 35.6 | 23.0 |
| $(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$ | 34.7 | 15.7 |

also provides the attractive interaction, but relatively weaker than $\sigma$ exchange contribution.

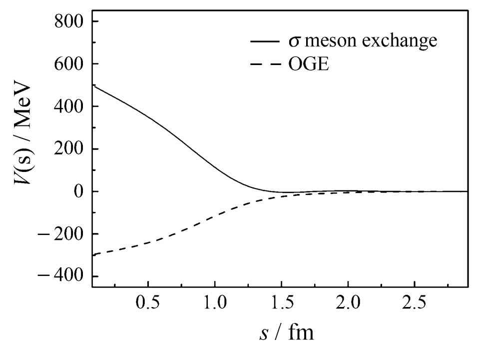


Fig. 1 The GCM matrix elements of Model A for $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ system.

In Table 2, the parameters of Model B and the corresponding binding energies of deuteron, $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ and $(\Sigma^*\Delta)_{ST=3\,\frac{1}{2}}$ are listed. The results show these two systems are bound states in the extended chiral $SU(3)$ quark model without tensor coupling of the vector-meson field. Again, when we omit the quark exchange effect, we also found the binding energies of these two states are reduced a lot. For $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ system, the binding energy changes from 21.7 to 14.4 MeV, while for $(\Sigma^*\Delta)_{ST=3\,\frac{1}{2}}$ system, the binding energy changes from 76.7 to 47.7 MeV. The results tells us that quark exchange effect is important, especially for $(\Sigma^*\Delta)_{ST=3\,\frac{1}{2}}$ system. Fig. 2 shows the diagonal matrix elements of the vector meson, OGE and $\sigma$

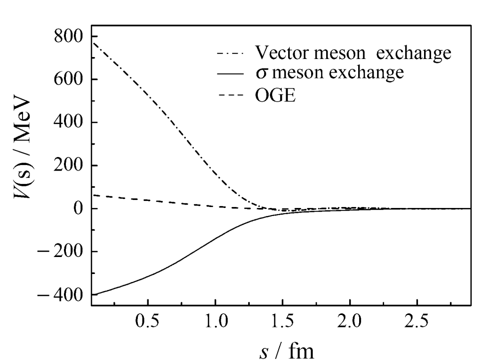


Fig. 2 The GCM matrix elements of Model B for $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ system.

meson exchange in the extended chiral $SU(3)$ quark model for the $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ system in the GCM calculation. From Fig. 2, one can see that vector meson contribute repulsive interaction, while $\sigma$ exchange provides the strong attractive interaction, OGE contribution almost can be omitted. Also $\sigma'$ meson and $\varepsilon$ meson exchange provides relatively weaker attractive interaction than $\sigma$ meson.

**Table 2 For Model B, the parameters and binding energies (MeV). Here $m_\rho=770$ MeV, $m_{K^*}=892$ MeV, $m_\omega=782$ MeV, $m_\phi=1\,020$ MeV**

| | with quark exchange $P_{ij}\neq 0$ | without quark exchange $P_{ij}=0$ |
|---|---|---|
| $m_u$/MeV | 313 | 313 |
| $m_s$/MeV | 470 | 470 |
| $b_u$/fm | 0.45 | 0.45 |
| $m_\sigma$/MeV | 535 | 535 |
| $g_{ch}$ | 2.73 | 2.73 |
| $g_{chv}$ | 2.35 | 2.35 |
| $g_u^2$/OGE | 0.06 | 0.06 |
| $g_s^2$/OGE | 0.20 | 0.20 |
| $a_{uu}^c$/MeV | 44.5 | 44.5 |
| $a_{us}^c$/MeV | 79.6 | 79.6 |
| $a_{us}^{c0}$/MeV | −72.3 | −72.3 |
| $a_{us}^{c0}$/MeV | −87.6 | −87.6 |
| deuteron | 2.19 | 9.3 |
| $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ | 21.7 | 14.4 |
| $(\Sigma^*\Delta)_{ST=3\,\frac{1}{2}}$ | 76.7 | 47.7 |

In Table 3, the parameters of Model C and the corresponding binding energies of deuteron, $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ and $(\Sigma^*\Delta)_{ST=3\,\frac{1}{2}}$ are presented. The results show these two systems are still bound states in the extended chiral $SU(3)$ quark model with tensor coupling of the vector-meson field. When we omit the quark exchange effect, the binding energy changes from 30.0 to 21.1 MeV for $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ system, while the binding energy changes from 59.5 to 32.6 MeV for $(\Sigma^*\Delta)_{ST=3\,\frac{1}{2}}$ system.

In summary, we studied the special symmetry and vector meson exchange effect on two dibaryon systems $(\Sigma^*\Delta)_{ST=0\,\frac{5}{2}}$ and $(\Sigma^*\Delta)_{ST=3\,\frac{1}{2}}$ on quark level. In the chiral $SU(3)$ quark model, the short range mechanism is from OGE. In the extended chiral $SU(3)$ quark model, the vector meson exchanges played a dominate role in the short range interactions. The results show that these two systems can be bound states both in the chiral $SU(3)$

**Table 3 For Model C, the parameters and binding energies (MeV)**

| | with quark exchange $P_{ij}\neq 0$ | without quark exchange $P_{ij}=0$ |
|---|---|---|
| $m_u$/MeV | 313 | 313 |
| $m_s$/MeV | 470 | 470 |
| $b_u$/fm | 0.45 | 0.45 |
| $m_\sigma$/MeV | 547 | 547 |
| $g_{ch}$ | 2.73 | 2.73 |
| $g_{chv}$ | 1.973 | 1.973 |
| $f_{chv}$ | 1.315 | 1.315 |
| $g_u^2$/OGE | 0.13 | 0.13 |
| $g_s^2$/OGE | 0.25 | 0.25 |
| $a_{uu}^c$/MeV | 39.1 | 39.1 |
| $a_{us}^c$/MeV | 69.2 | 69.2 |
| $a_{us}^{c0}$/MeV | −62.9 | −62.9 |
| $a_{us}^{c0}$/MeV | −74.6 | −74.6 |
| deuteron | 2.14 | 8.64 |
| $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ | 30.0 | 21.1 |
| $(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$ | 59.5 | 32.6 |

quark model and in the extended chiral $SU(3)$ quark model. A comparison between the cases with and without quark exchange effect is made. When the quark exchange effect is omitted, the binding energy of deuteron is increased by ~6 MeV, while $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ system is reduced by 7—12 MeV and $(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$ system is reduced by 19—29 MeV. That means the quark exchange effect is not important for deuteron, it gives repulsion to deuteron. However, the quark exchange effect does give attractions to $(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$ and $(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$ systems. In our work, the $\sigma$ meson is introduced by chiral symmetry breaking and treated as a basic filed, and its mass is an adjustablet parameter which is used to fit the deuteron binding energy. In our calculation, its value is located in a reasonable region of 550—650 MeV. Our analysis shows that the $\sigma$ exchange dominantly provides the attractive interaction for these two states. This work could be helpful to understand the coupling between quark and $\sigma$ chiral field.

We should emphasize that we only made some qualitative analysis in this work, more quantitative calculations will be done in the near future.

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