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Mixing of scalar meson and baryon-baryon interaction*

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Abstract At quark level, we study the effect of ideal mixing of singlet σ_0 and octet σ_8 scalar mesons on baryon-baryon interaction in the chiral $SU(3)$ quark model. We solve the resonating group method equation for scattering process and bound state. The results show that the binding energy of deuteron and nucleon-nucleon and hyperon-nucleon scattering data can be reasonably described for ideal mixing. Taking the same parameters we used in the scattering calculation, we further investigate the possible dibaryons and find the binding energy of $(\Omega\Omega)_{ST=00}$ and $(\Xi^*\Omega)_{ST=0\frac{1}{2}}$ can be reduced a lot for ideal mixing.

Key words quark model, chiral symmetry, ideal mixing

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1 Introduction

In Ref. [1], they failed to describe the kaon-nucleon (K-N) scattering data using the resonating group method (RGM)[2, 3] calculation. In their model, the short-range interaction from one-gluon exchange (OGE) and long-range interaction from confinement potential are included, also parameterized π and σ field exchanges between quarks are included. Their results show that the attractive force from σ meson exchange is too strong to describe the K-N data. Therefore, it seems that a reasonable and effective model is needed.

The chiral $SU(3)$ quark model [4] has been quite successful in reproducing the energies of the baryon ground states, the binding energy of deuteron, the nucleon-nucleon(N-N) scattering phase shifts of different partial waves, and the hyperon-nucleon(Y-N) cross sections by the RGM calculation. In the chiral $SU(3)$ quark model, the nonet pseudoscalar meson exchanges and the nonet scalar meson exchanges are considered, and also includes the OGE and confinement potential. In this model, Huang [5] et al. further introduced the mixing of scalar meson to study the K-N scattering data by solving the RGM equation. The experimental K-N data can be described quite well in this model. Compared with Ref. [1], the mixing between singlet σ_0 and octet σ_8 scalar meson can be introduced in Ref. [5], which is the main reason to successfully describe K-N interaction. When the mixing of scalar meson is considered, the attraction force of scalar meson between K and N can be reduced a lot, so the K-N scattering can be reasonably described.

Inspired by this, now the mixing of scalar meson is further considered to study baryon-baryon interaction and some interesting dibaryons in the chiral $SU(3)$ quark model. Actually, in previous works, N-N and Y-N scattering process [4] and some dibaryons [6–10] have been investigated in this model. However, we never consider the mixing of scalar meson in all previous works. The present paper is organized as follows. In the next section, the framework of the chiral $SU(3)$ quark model are briefly introduced. The calculated results and some discussions are shown in Sec. 3 and the summary is given in Sec. 4.

2 Formulation

2.1 Model

The chiral $SU(3)$ quark model has been described in the literature [4] and we refer the reader to the work for details. Here we just give the salient feature of this model.

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In the chiral $SU(3)$ quark model, the coupling between chiral field and quark is introduced to describe nonperturbative QCD effect. The interacting Lagrangian can be written as:

$$\mathcal{L}_{\rm I}=-g_{\rm ch}\overline{\psi}\left(\sum_{a=0}^{8}\sigma_a\lambda_a+{\rm i}\sum_{a=0}^{8}\pi_a\lambda_a\gamma_5\right)\psi, \quad (1)$$

where λ_0 is a unitary matrix, σ_0,..., σ_8 are the scalar nonet fields, and π_0,...,π_8 the pseudoscalar nonet fields. We can prove that $L_{\rm I}$ is invariant under the infinitesimal chiral $SU(3)_{\rm L}\times SU(3)_{\rm R}$ transformation. We should mention here that only one coupling constant $g_{\rm ch}$ is needed by chiral symmetry requirement.

In this model, the total Hamiltonian of baryon-baryon systems can be written as

$$H=\sum_{i=1}^{6}T_i-T_{\rm G}+\sum_{i<j=1}^{6}V_{ij}, \quad (2)$$

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

$$V_{ij}=V_{ij}^{\rm OGE}+V_{ij}^{\rm Conf}+V_{ij}^{\rm ch}, \quad (3)$$

where $V_{ij}^{\rm OGE}$ is the OGE interaction, and $V_{ij}^{\rm Conf}$ is the confinement potential. $V_{ij}^{\rm ch}$ represents the chiral fields induced effective quark-quark potential, which includes the scalar boson exchanges and the pseudoscalar boson exchange,

$$V_{ij}^{\rm ch}=\sum_{a=0}^{8}V_{ij}^{\sigma_a}+\sum_{a=0}^{8}V_{ij}^{\pi_a}. \quad (4)$$

More details can be found in Ref. [4].

2.2 Determination of the parameters

We briefly give the procedure for the parameter determination. The three initial input parameters, i.e, the harmonic-oscillator width parameter $b_{\rm u}$, the up (down) quark mass $m_{\rm u(d)}$ and the strange quark mass $m_{\rm s}$, are taken to be the usual values: $b_{\rm u}$=0.5 fm, $m_{\rm u(d)}$=313 MeV, and $m_{\rm s}$=470 MeV. the coupling constant for scalar and pseudoscalar chiral field coupling, $g_{\rm ch}$, is fixed by the relation

$$\frac{g_{\rm ch}^2}{4\pi}=\frac{9}{25}\frac{m_{\rm u}^2}{M_{\rm N}^2}\frac{g_{\rm NN\pi}^2}{4\pi}, \quad (5)$$

with the experimental value $g_{\rm NN\pi}^2/4\pi$=13.67. The mass of the pseudoscalar mesons are taken to be experimental values. The mass of σ meson is a adjustable parameter, which can be decided by fitting the experimental binding energy of deuteron. The OGE coupling constants $g_{\rm u}$ and $g_{\rm s}$ and the strengths of the confinement potential are fitted by baryon masses and their stability conditions. For mixing of scalar meson, the definition is as follow:

$$\sigma=\sigma_8\sin\theta^S+\sigma_0\cos\theta^S,$$
$$\epsilon=\sigma_8\cos\theta^S-\sigma_0\sin\theta^S, \quad (6)$$

For no mixing, the $\theta^S=0°$. For ideally mixing, the $\theta^S=35.3°$, which means that σ meson only acts on the u(d) quark, and ϵ meson on the s quark. In this work, the ideal mixing will be considered. The model parameters are listed in Table 1. We firstly use these parameters to calculate the binding energy of deuteron, the result is 2.21 MeV which is reasonably consistent with the experimental data.

Table 1. Model parameters for ideal mixing.

$b_{\rm u}$	$m_{\rm u}$	$m_{\rm s}$	$g_{\rm ch}$	θ^S
0.5 fm	313 MeV	470 MeV	2.62	35.3°
m_σ	m_κ	$m_{\sigma'}$	m_ϵ	Λ
560 MeV	780 MeV	980 MeV	980 MeV	1100 MeV

3 Results

With all the parameters determined, we investigate the N-N and Y-N scattering and bound process in chiral $SU(3)$ quark model by solving the corresponding RGM equation. The trial wave function is taken to be

$$\Psi_{ST}=\sum_i c_i\Psi_{ST}^{(i)}(\overrightarrow{s_i}), \quad (7)$$

$$\Psi_{ST}^{i}(\overrightarrow{s_i})=\mathcal{A}(\phi_A(\overrightarrow{\xi_1},\overrightarrow{\xi_2})\phi_B(\overrightarrow{\xi_3},\overrightarrow{\xi_4})\chi(\overrightarrow{R}_{AB}-\overrightarrow{s_i})Z(\overrightarrow{R}_{CM})), \quad (8)$$

where A and B show two clusters, and ϕ, χ and Z represent internal, relative and center of mass motion wave function, respectively. $\overrightarrow{s_i}$ is the generator coordinate, and $\mathcal{A}$ is the anti-symmetrization operator

$$\mathcal{A}=1-\sum_{i\in A,j\in B}P_{ij}, \quad (9)$$

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

3.1 N-N and Y-N scattering

For ideal mixing, the theoretical results of N-N S-wave phase shifts and Y-N scattering $\Sigma^-{\rm P}\rightarrow\Lambda$ n differential and total cross sections are given in Fig. 1 and Fig. 2, experimental data from [11, 12]. We can see the theoretical results are consistent with the experiments.

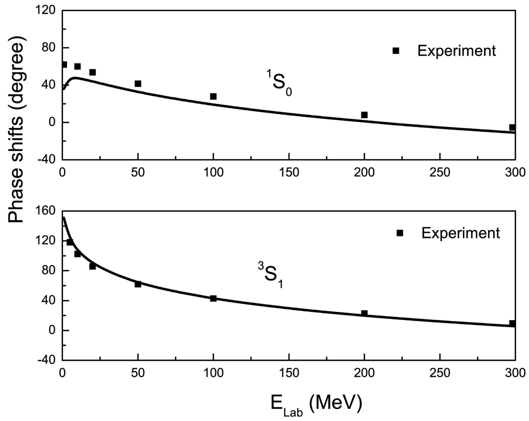

Fig. 1. N-N S-wave phase shifts.

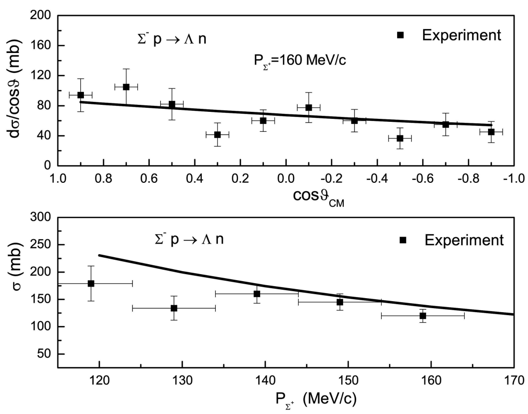

Fig. 2. Y-N differential and total cross sections.

3.2 dibaryon

Using the same parameters for ideal mixing as in the scattering calculation, now we discuss the bound states. Table 2 list the binding energies for different dibaryons. Compared with no mixing [6–10], we find two changes: one is that the binding energies of $(\Omega\Omega)_{ST=00}$ and $(\Xi^*\Omega)_{ST=0\frac{1}{2}}$ states are reduced a lot. For no mixing, they have been predicted deeply bound states. In this case, σ meson and ϵ all contribute attractive forces. For ideal mixing, i.e. there is no σ meson exchange between s quarks, the binding energies for these two states are reduced to about 20 MeV. Another change is that for $(\mathrm{N}\Omega)_{ST=2\frac{1}{2}}$ and $(\Delta\Omega)_{ST=3\frac{3}{2}}$ states. For no mixing, these two states are very weakly bound states. In this case, σ meson exchange provide attractive force, the ϵ meson exchange provide relatively larger repulsive force. However, for ideal mixing, they becomes unbound states, where the attraction force from σ meson exchange disappear. We also find that no matter what kind of mixing is taken, other dibayons are very stable. It means the binding energy doesn't change much.

Table 2. For ideal mixing, binding energy for some interesting dibaryons.

strangeness	dibaryon	binding energy
0	$(\Delta\Delta)_{ST=30}$	45 MeV
0	$(\Delta\Delta)_{ST=03}$	22 MeV
−6	$(\Omega\Omega)_{ST=00}$	26 MeV
−5	$(\Xi^*\Omega)_{ST=0\frac{1}{2}}$	29 MeV
−1	$(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$	25 MeV
−1	$(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$	15 MeV
−3	$(\mathrm{N}\Omega)_{\mathrm{ST}=2\frac{1}{2}}$	unbound
−3	$(\Delta\Omega)_{ST=3\frac{3}{2}}$	unbound

4 Summary

To conclude, we are finding that in the case of ideal mixing, the N-N and Y-N scattering data can be reasonably described in the chiral $SU(3)$ quark model, where the σ meson only acts on the u(d) quark, and ϵ meson on the s quark. Using the same parameters as in the scattering calculation, we find the binding energies of $(\Omega\Omega)_{ST=00}$ and $(\Xi^*\Omega)_{ST=0\frac{1}{2}}$ states are around 20 MeV, and $(\mathrm{N}\Omega)_{ST=2\frac{1}{2}}$ and $(\Delta\Omega)_{ST=3\frac{3}{2}}$ become unbound states.

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