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Study of $N\bar{\Omega}$ systems in a chiral quark model

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The $N\bar{\Omega}$ systems with spin $S = 1$ and $S = 2$ are dynamically investigated in the chiral SU(3) quark model and the extended chiral SU(3) quark model by solving the equation in the framework of the resonating group method (RGM). The model parameters are taken from our previous work, which gave a good description of the energies of the baryon ground states, the binding energy of deuteron, and the experimental data of the nucleon-nucleon (NN) and nucleon-hyperon (NY) scattering processes. The results show that $N\bar{\Omega}$ states with spin $S = 1$ and $S = 2$ can be bound in both the chiral SU(3) and the extended chiral SU(3) quark models, and the binding energies are about 28–59 MeV. When the s-channel interaction is considered, the binding energies increase to about 37–130 MeV, which indicates that the effect of s-channel interaction plays a relatively important role in forming a $N\bar{\Omega}$ bound state. At the same time, the $N\bar{\Omega}$ elastic scattering processes are also studied, and the S, P, D partial wave phase shifts and the total cross sections of $S = 1$ and $S = 2$ channels are obtained.

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I. INTRODUCTION

The baryon-antibaryon ($B\bar{B}$) system is believed to be a good field to explore the quality of strong interactions, especially short-range ones. Whether $N\bar{N}$ bound states or resonances exist has been widely studied by many theoretical and experimental scientists for the past few decades, but it is still an open question. The main reason is that the annihilation effect at short distances is very important in the $N\bar{N}$ system, which enhances its complexity. Since the 1980s, processes of $N\bar{N}$ annihilation into two and three mesons have been investigated on the quark level and some interesting results have been obtained [1–4]. The models used in those studies assessed three kinds of annihilation mechanisms: (1) the quark-antiquark ($q\bar{q}$) pair was destroyed and created with vacuum quantum numbers; (2) quarks in N and antiquarks in $\bar{N}$ rearrangement led to the annihilation into mesons; and (3) the $q\bar{q}$ pair was annihilated with the quantum number of gluon. Those analyses indicated that in the $N\bar{N}$ system, the first mechanism is the dominant one of the three, and the models using that mechanism could give a reasonable description of $N\bar{N}$ annihilation data [3,4].

Even though some progress has been made in the study of the annihilation effect, there are still some uncertainties regarding the $N\bar{N}$ systems, because there are three different annihilation modes and it is difficult to distinguish the contribution and characteristic of each mechanism. Thus, it is hard to give a convincing theoretical prediction of $N\bar{N}$ bound states or resonances. It seems more appropriate to study some special systems that have only one kind of annihilation mechanism. We think the $N\bar{\Omega}$ system is an interesting one. Since $\bar{\Omega}$ is composed of three $\bar{s}$ quarks and N of three $u(d)$ quarks, $u\bar{s}$ and $d\bar{s}$ cannot annihilate to the vacuum, nor can they annihilate to the gluon because the gluon is flavorless. Therefore, the $N\bar{\Omega}$ system can only annihilate into three mesons with strangeness by rearrangement, so this system provides an optimal place for studying the rearrangement mechanism of the annihilation processes. Moreover, for the t-channel interactions, there is no one-gluon-exchange interaction, and the meson exchanges play important roles in this system, so the $N\bar{\Omega}$ system is also an ideal place for examining the chiral field coupling.

As is well known, QCD is the underlying theory of the strong interaction. At the high-energy region, the perturbative treatment of QCD is quite successful, while it fails at low and intermediate energy domains. However, the nonperturbative QCD (NPQCD) effect is very important in light quark systems, but to date there is no serious approach to solving the NPQCD problem. To help study the baryon physics, people still need QCD-inspired models. Among these models, the chiral SU(3) quark model has been quite successful in reproducing the energies of the baryon ground states, binding energy of the deuteron, nucleon-nucleon (NN) scattering phase shifts, and hyperon-nucleon (YN) cross sections [5]. In this model, the quark-quark interaction contains confinement, one gluon exchange (OGE), and boson exchanges stemming from chiral-quark coupling. In the study of NN interactions on the quark level, the short-range feature can be explained by the OGE interaction and the quark exchange effect. As we know, in the traditional one boson exchange (OBE) model on the baryon level, the short-range NN interaction comes from vector-meson (ρ, ω, K^*, and ϕ) exchanges. To study the vector-meson exchange effect on the quark level, the extended chiral SU(3) quark model was proposed [6]. In this extended model, we further include the coupling of the quark and vector chiral fields. The OGE that plays 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

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in the extended chiral SU(3) quark model. This extended chiral quark model can also reasonably explain the energies of the baryon ground states, the binding energy of the deuteron, and the NN scattering phase shifts [6]. Recently, both the chiral SU(3) quark model and the extended chiral SU(3) quark model were extended to systems with antiquarks to study baryon-meson interactions by solving a resonating group method (RGM) equation [7]. Some interesting results were obtained, which are quite similar to those given by the chiral unitary approach study [8]. Inspired by all these achievements, we extended our study to the baryon-antibaryon systems in the framework of these two models.

In the present work, we dynamically investigate the characteristics of the $N\bar{\Omega}$ systems with spin $S=1$ and $S=2$ in the chiral SU(3) quark model and the extended SU(3) quark model. The model parameters are taken from our previous work [5,6]. As a primary study, only one-channel $N\bar{\Omega}$ calculations are performed, i.e., the coupling between the $N\bar{\Omega}$ channel and the three-meson channel coming from the rearrangement is not included. First, the binding energies of the $N\bar{\Omega}$ states as well as the effect of s-channel interaction are studied. The results show that $N\bar{\Omega}$ states with spin $S=1$ and $S=2$ can be bound states in both the chiral SU(3) and the extended chiral SU(3) quark models, and the binding energies range from 28 to 59 MeV. When the effect of the s-channel interaction is considered, the binding energies increase to around 37–130 MeV. Second, to get more information on the $N\bar{\Omega}$ structure, the $N\bar{\Omega}$ elastic scattering processes are also calculated, and the phase shifts of S, P, and D partial waves and the total cross sections are acquired.

The paper is organized as follows. In the next section, the framework of the chiral SU(3) quark model and the extended model are briefly introduced. The calculated results of the $N\bar{\Omega}$ states are shown and discussed in Sec. III. Finally, the summary is given in Sec. IV.

II. FORMULATION

A. Model

The chiral SU(3) quark model and the extended chiral SU(3) quark model have been widely described in the literature [5–7], and we refer the reader to those works for details. Here, we just give the salient features of these two models.

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

$$H=\sum_{i=1}^{6}T_i-T_G+\sum_{i<j=1}^{3}V_{qq}(ij)+\sum_{i<j=4}^{6}V_{\bar{q}\bar{q}}(ij)+\sum_{\substack{i=1,3\\ j=4,6}}V_{q\bar{q}}(ij), \tag{1}$$

where T_G is the kinetic energy operator for the center-of-mass motion, and $V_{qq}(ij)$ represents the interaction between two quarks qq within the nucleon,

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

where $V_{qq}^{\rm OGE}(ij)$ is the OGE interaction

$$V_{qq}^{\rm OGE}(ij)=\frac{1}{4}g_i g_j\left(\lambda_i^c\cdot\lambda_j^c\right)\times\left\{\frac{1}{r_{ij}}-\frac{\pi}{2}\delta(\boldsymbol{r}_{ij})\left(\frac{1}{m_{q_i}^2}+\frac{1}{m_{q_j}^2}+\frac{4}{3}\frac{1}{m_{q_i}m_{q_j}}(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\right)\right\}+V_{\rm OGE}^{\boldsymbol{l}\cdot\boldsymbol{s}}++V_{\rm OGE}^{\rm ten}, \tag{3}$$

$V_{qq}^{\rm conf}(ij)$ is the confinement potential taken as the quadratic form

$$V_{qq}^{\rm conf}(ij)=-a_{ij}^c\left(\lambda_i^c\cdot\lambda_j^c\right)r_{ij}^2-a_{ij}^{c0}\left(\lambda_i^c\cdot\lambda_j^c\right), \tag{4}$$

and $V_{qq}^{\rm ch}(ij)$ represents 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 boson exchanges,

$$V_{qq}^{\rm ch}(ij)=\sum_{a=0}^{8}V_{\sigma_a}(\boldsymbol{r}_{ij})+\sum_{a=0}^{8}V_{\pi_a}(\boldsymbol{r}_{ij}); \tag{5}$$

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

$$V_{qq}^{\rm ch}(ij)=\sum_{a=0}^{8}V_{\sigma_a}(\boldsymbol{r}_{ij})+\sum_{a=0}^{8}V_{\pi_a}(\boldsymbol{r}_{ij})+\sum_{a=0}^{8}V_{\rho_a}(\boldsymbol{r}_{ij}). \tag{6}$$

Here $\sigma_0,\ldots,\sigma_8$ are the scalar nonet fields; $\pi_0,\ldots,\pi_8$ the pseudoscalar nonet fields; and $\rho_0,\ldots,\rho_8$ the vector nonet fields. The expressions of these potentials are

$$V_{\sigma_a}(\boldsymbol{r}_{ij})=-C\left(g_{\rm ch},m_{\sigma_a},\Lambda\right)X_1\left(m_{\sigma_a},\Lambda,r_{ij}\right)[\lambda_a(i)\lambda_a(j)]+V_{\sigma_a}^{\boldsymbol{l}\cdot\boldsymbol{s}}(\boldsymbol{r}_{ij}), \tag{7}$$

$$V_{\pi_a}(\boldsymbol{r}_{ij})=C\left(g_{\rm ch},m_{\pi_a},\Lambda\right)\frac{m_{\pi_a}^2}{12m_{q_i}m_{q_j}}X_2\left(m_{\pi_a},\Lambda,r_{ij}\right)(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\times[\lambda_a(i)\lambda_a(j)]+V_{\pi_a}^{\rm ten}(\boldsymbol{r}_{ij}), \tag{8}$$

$$V_{\rho_a}(\boldsymbol{r}_{ij})=C\left(g_{\rm chv},m_{\rho_a},\Lambda\right)\left\{X_1\left(m_{\rho_a},\Lambda,r_{ij}\right)+\frac{m_{\rho_a}^2}{6m_{q_i}m_{q_j}}\left(1+\frac{f_{\rm chv}}{g_{\rm chv}}\frac{m_{q_i}+m_{q_j}}{M_P}+\frac{f_{\rm chv}^2}{g_{\rm chv}^2}\frac{m_{q_i}m_{q_j}}{M_P^2}\right)\times X_2\left(m_{\rho_a},\Lambda,r_{ij}\right)(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\right\}[\lambda_a(i)\lambda_a(j)]+V_{\rho_a}^{\boldsymbol{l}\cdot\boldsymbol{s}}(\boldsymbol{r}_{ij})+V_{\rho_a}^{\rm ten}(\boldsymbol{r}_{ij}), \tag{9}$$

where

$$C(g_{\rm ch},m,\Lambda)=\frac{g_{\rm ch}^2}{4\pi}\frac{\Lambda^2}{\Lambda^2-m^2}m, \tag{10}$$

$$X_1(m,\Lambda,r)=Y(mr)-\frac{\Lambda}{m}Y(\Lambda r), \tag{11}$$

$$X_2(m,\Lambda,r)=Y(mr)-\left(\frac{\Lambda}{m}\right)^3Y(\Lambda r), \tag{12}$$

$$Y(x)=\frac{1}{x}e^{-x}, \tag{13}$$

and M_P is a mass scale, taken as proton mass. m_{σ_a} is the mass of the scalar meson; m_{π_a} the mass of the pseudoscalar meson; and m_{ρ_a} the mass of the vector meson.

$V_{\bar{q}\bar{q}}(ij)$ in Eq. (1) is the antiquark-antiquark ($\bar{q}\bar{q}$) interaction within the $\bar{\Omega}$,

$$V_{\bar{q}\bar{q}} = V_{\bar{q}\bar{q}}^{\mathrm{conf}} + V_{\bar{q}\bar{q}}^{\mathrm{OGE}} + V_{\bar{q}\bar{q}}^{\mathrm{ch}}. \tag{14}$$

Replacing the $\lambda_i^c \cdot \lambda_j^c$ in Eqs. (3) and (4) by $\lambda_i^{c*} \cdot \lambda_j^{c*}$, we can obtain the forms of $V_{\bar{q}\bar{q}}^{\mathrm{OGE}}$ and $V_{\bar{q}\bar{q}}^{\mathrm{conf}}$. And $V_{\bar{q}\bar{q}}^{\mathrm{ch}}$ has the same form as V_{qq}^{ch}.

$V_{q\bar{q}}(ij)$ in Eq. (1) represents the interaction between one q in N and one $\bar{q}$ in $\bar{\Omega}$, which includes the s-channel K and K^* exchanges besides the t-channel interactions. Thus $V_{q\bar{q}}(ij)$ is written as

$$V_{q\bar{q}} = V_{q\bar{q}}^{t} + V_{q\bar{q}}^{s}. \tag{15}$$

Since N and $\bar{\Omega}$, are two color-singlet clusters with no common flavor quarks, there is no OGE interaction between them. In Eq. (15),

$$V_{q\bar{q}}^{t} = V_{q\bar{q}}^{\mathrm{conf}} + V_{q\bar{q}}^{\mathrm{ch}}, \tag{16}$$

with

$$V_{q\bar{q}}^{\mathrm{conf}}(ij) = -a_{ij}^{c}\left(-\lambda_i^c \cdot \lambda_j^{c*}\right) r_{ij}^2 - a_{ij}^{c0}\left(-\lambda_i^c \cdot \lambda_j^{c*}\right), \tag{17}$$

$$V_{q\bar{q}}^{\mathrm{ch}} = \sum_j (-1)^{G_j} V_{qq}^{\mathrm{ch},j}, \tag{18}$$

where the vector mesons ω and ϕ consist of $\sqrt{1/2}(u\bar{u} + d\bar{d})$ and $(s\bar{s})$, respectively; i.e., they are ideally mixed by the λ_0 field (ω_0) and λ_8 field (ω_8). Consequently, the ω and ϕ mesons contribute nothing to the special $N\bar{\Omega}$ systems. In Eq. (18), $(-1)^{G_j}$ represents the G parity of the jth meson. Also, in Eq. (15),

$$V_{q\bar{q}}^{s} = V_s^{K} + V_s^{K^*}, \tag{19}$$

with

$$V_s^{K} = C^{K}\left(\frac{1 - \boldsymbol{\sigma}_q \cdot \boldsymbol{\sigma}_{\bar{q}}}{2}\right)_s \left(\frac{2 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{6}\right)_c (2)_f \delta(\boldsymbol{r}), \tag{20}$$

and

$$V_s^{K^*} = C^{K^*}\left(\frac{3 + \boldsymbol{\sigma}_q \cdot \boldsymbol{\sigma}_{\bar{q}}}{2}\right)_s \left(\frac{2 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{6}\right)_c (2)_f \delta(\boldsymbol{r}), \tag{21}$$

where C^K and C^{K^*} are treated as parameters, and we adjust them to fit the masses of K and K^* mesons.

B. Determination of parameters

All the model parameters are taken from our previous work [5,6], which can give a satisfactory description of the energies of the baryon ground states, the binding energy of deuteron, the NN scattering phase shifts. The harmonic-oscillator width parameter b_u is taken with different values for the two models: $b_u = 0.50$ fm in the chiral SU(3) quark model and $b_u = 0.45$ fm in the extended chiral SU(3) quark model. This means that the bare radius of baryon becomes smaller when more meson clouds are included in the model, which sounds reasonable in the sense of the physical picture. The up (down) quark mass $m_{u(d)}$ and the strange quark mass m_s are taken to be the usual values: $m_{u(d)} = 313$ and $m_s = 470$ MeV. The coupling constant for scalar and pseudoscalar chiral field coupling, g_{ch}, is determined according to the relation

$$\frac{g_{\mathrm{ch}}^2}{4\pi} = \left(\frac{3}{5}\right)^2 \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{M_N^2}, \tag{22}$$

with the empirical value $g_{NN\pi}^2/4\pi = 13.67$. The coupling constant for vector coupling of the vector-meson field is taken to be $g_{\mathrm{chv}} = 2.351$, the same as used in the NN case [6]. The masses of the mesons are taken to be the experimental values, except for the σ meson. The m_σ is adjusted to fit the binding energy of the deuteron. The cutoff radius Λ^{-1} is taken to be the value close to the chiral symmetry breaking scale [9]. The OGE coupling constants, g_u and g_s, can be determined by the mass splits between N, Δ and Σ, Λ, respectively. The confinement strengths a_{uu}^c, a_{us}^c, and a_{ss}^c are fixed by the stability conditions of N, Λ, and Ξ, and the zero-point energies a_{uu}^{c0}, a_{us}^{c0}, and a_{ss}^{c0} by fitting the masses of N, Σ, and $\overline{\Xi + \Omega}$, respectively. Three sets of parameters are tabulated in Table I: set I is for the chiral SU(3) quark model and sets II and III are for the extended model by taking $f_{\mathrm{chv}}/g_{\mathrm{chv}}$ as 0 and 2/3, respectively. Here, g_{chv} and f_{chv} are the coupling constants for vector coupling and tensor coupling of the vector meson fields, respectively. σ' is the isovector scalar meson and ϵ is the isoscalar scalar meson, and the mixing between σ and ϵ is not introduced.

C. The framework of resonating group method

With all the parameters determined, the $N\bar{\Omega}$ system can be dynamically studied within the framework of the RGM,

TABLE I. Model parameters. Meson masses and cutoff masses (in MeV): $m_{\sigma'} = 980$, $m_\kappa = 980$, $m_\epsilon = 980$, $m_\pi = 138$, $m_K = 495$, $m_\eta = 549$, $m_{\eta'} = 957$, $m_\rho = 770$, $m_{K^*} = 892$, $m_\omega = 782$, $m_\phi = 1020$, and $\Lambda = 1100$ MeV for all mesons.

	χ-SU(3) QM	Ex. χ-SU(3) QM	
	I	II	III
		$f_{\mathrm{chv}}/g_{\mathrm{chv}} = 0$	$f_{\mathrm{chv}}/g_{\mathrm{chv}} = 2/3$
b_u (fm)	0.5	0.45	0.45
m_u (MeV)	313	313	313
m_s (MeV)	470	470	470
g_u^2	0.766	0.056	0.132
g_s^2	0.846	0.203	0.250
g_{ch}	2.621	2.621	2.621
g_{chv}		2.351	1.973
m_σ (MeV)	595	535	547
a_{uu}^c (MeV/fm^2)	46.6	44.5	39.1
a_{us}^c (MeV/fm^2)	58.7	79.6	69.2
a_{ss}^c (MeV/fm^2)	99.2	163.7	142.5
a_{uu}^{c0} (MeV)	−42.4	−72.3	−62.9
a_{us}^{c0} (MeV)	−36.2	−87.6	−74.6
a_{ss}^{c0} (MeV)	−33.8	−108.0	−91.0

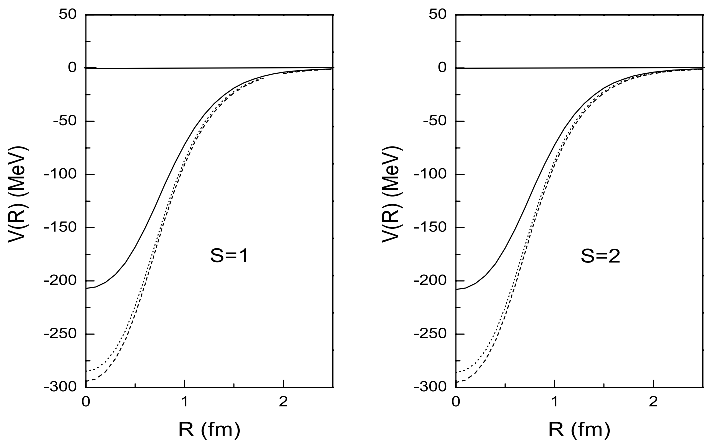

FIG. 1. S-wave $N\bar{\Omega}$ effective potential as a function of the relative coordinate, where the s-channel interaction is not included. The solid line represents the results obtained in chiral SU(3) quark model with set I, and the dashed and dotted lines represent the results in extended chiral SU(3) quark model with set II and set III, respectively.

a well-established method for detecting the interaction between two clusters. The cases for the $N\bar{\Omega}$ states are much simpler, since there are three quarks in N and three antiquarks in $\bar{\Omega}$, and antisymmetrization between N and $\bar{\Omega}$ is not necessary. Thus, the wave function of this six-quark system is taken as

$$\Psi = \hat{\phi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\phi}_{\bar{\Omega}}(\boldsymbol{\xi}_3, \boldsymbol{\xi}_4)\chi(\boldsymbol{R}_{N\bar{\Omega}}), \tag{23}$$

where $\boldsymbol{\xi}_1, \boldsymbol{\xi}_2$ are the internal coordinates for the cluster N, and $\boldsymbol{\xi}_3, \boldsymbol{\xi}_4$ the internal coordinates for the cluster $\bar{\Omega}$. $\boldsymbol{R}_{N\bar{\Omega}} \equiv \boldsymbol{R}_N - \boldsymbol{R}_{\bar{\Omega}}$ is the relative coordinate between the two clusters, N and $\bar{\Omega}$. The $\hat{\phi}_N$ ($\hat{\phi}_{\bar{\Omega}}$) is the antisymmetrized internal cluster wave function of $N(\bar{\Omega})$, and $\chi(\boldsymbol{R}_{N\bar{\Omega}})$ the relative wave function of the two clusters. For a bound-state problem or a scattering one, by solving the equation

$$\langle \delta\Psi|(H - E)|\Psi\rangle = 0, \tag{24}$$

we can obtain binding energies or scattering phase shifts for the two-cluster systems. The details of solving the equation in the RGM framework can be found in Refs. [7,10,11].

III. RESULTS AND DISCUSSIONS

The bound-state case of S-wave $N\bar{\Omega}$ systems with spin $S = 1$ and $S = 2$ is investigated in both the chiral SU(3) quark model and the extended chiral SU(3) quark model. As the first step, we will not consider the s-channel interactions. Figure 1 shows the interaction potentials for the $N\bar{\Omega}$ systems with $S = 1$ and $S = 2$. There, $V(R)$ denotes the effective potential between N and $\bar{\Omega}$, and R denotes the relative coordinate which describes the distance between the two clusters. From Fig. 1, we can see that for both $S = 1$ and $S = 2$ states, effective potentials are attractive, and the attractions in the extended model are greater than those in the chiral SU(3) quark model. Since the $N\bar{\Omega}$ system is quite special, in both the chiral SU(3) quark model and the extended quark model, there is no OGE and no $\sigma', \kappa, \pi, K, \rho, K^*, \omega, \phi$ exchanges between N and $\bar{\Omega}$, thus the attractive force between them is mainly from σ exchange. In our calculation, the model parameters are fitted by the NN scattering phase shifts, and the mass of σ is adjusted by fitting the deuteron binding energy, so the value of m_σ is somewhat different for these three cases. In sets II and III, the mass of the σ meson is smaller than that of set I, so the $N\bar{\Omega}$ states can have greater attraction in the extended chiral SU(3) quark model. Meanwhile, the results of $N\bar{\Omega}$ with spin $S = 1$ and $S = 2$ are quite similar. This is easy to understand, because as presented above, in the S-wave calculation, the σ exchange plays the dominant role, which is spin independent.

The calculated binding energies and corresponding rms radii are tabulated in Table II. One can see that such attractive potentials can cause the bound states of the $N\bar{\Omega}$ systems. Here, the binding energy $B_{N\bar{\Omega}}$ and rms radius $\overline{R}$ are defined as

$$B_{N\bar{\Omega}} = -[E_{N\bar{\Omega}} - (M_N + M_{\bar{\Omega}})], \tag{25}$$

$$\overline{R} = \sqrt{\frac{1}{6}\sum_{i=1}^{6}\langle(\boldsymbol{r}_i - \boldsymbol{R}_{\text{c.m.}})^2\rangle}. \tag{26}$$

From Table II, we see that for both $S = 1$ and $S = 2$ channels, the binding energies of $N\bar{\Omega}$ bound states are about 28 MeV in set I, i.e., in the chiral SU(3) quark model, and about 59 MeV in set II, i.e., in the extended chiral SU(3) quark model with $f_{\text{chv}}/g_{\text{chv}} = 0$, and about 54 MeV in set III, i.e., in the extended model with $f_{\text{chv}}/g_{\text{chv}} = 2/3$. As we have seen in Fig. 1, the $N\bar{\Omega}$ interactions for both $S = 1$ and $S = 2$ are more attractive in the extended chiral SU(3) quark model than those in the chiral SU(3) quark model, and thus sets II and III get bigger binding energies than those of set I.

Compared with the results of $(N\Omega)_{S=2}$ system [12], in which the predicted binding energies are 3.0 in set I, 20.4 in set II, and 12.1 MeV in set III, the binding energies of $(N\bar{\Omega})_{S=2}$ are larger for all of these three cases. This is because the K and κ meson exchanges provide repulsive interactions in the $(N\Omega)_{S=2}$ system, while they make no contribution in the $(N\bar{\Omega})_{S=2}$ case, thus $(N\bar{\Omega})_{S=2}$ can get greater binding energies.

TABLE II. Binding energy $B_{N\bar{\Omega}}$ and corresponding rms radius $\overline{R}$ of $N\bar{\Omega}$ without the s-channel interaction.

Model	$S = 1$		$S = 2$	
	$B_{N\bar{\Omega}}$ (MeV)	$\overline{R}$ (fm)	$B_{N\bar{\Omega}}$ (MeV)	$\overline{R}$ (fm)
I	28.3	0.8	28.8	0.8
II	58.8	0.7	59.5	0.7
III	53.7	0.7	54.4	0.7

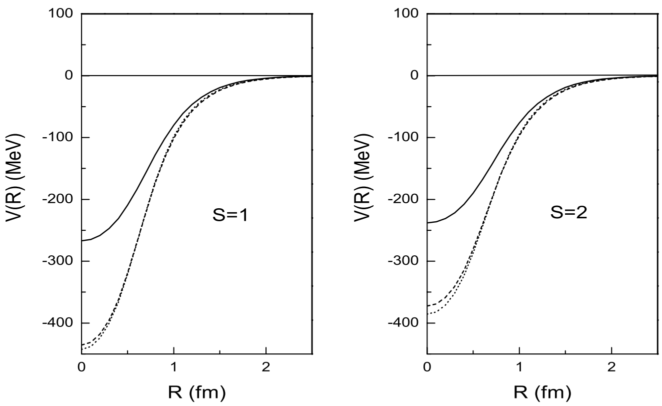

FIG. 2. S-wave $N\bar{\Omega}$ effective potential as a function of the relative coordinate, where the s-channel interaction is included. Same notation as in Fig. 1.

The rms radii for the states of $(N\bar{\Omega})_{S=1}$ and $(N\bar{\Omega})_{S=2}$ were also calculated. In Table II, the rms radii we obtained are relatively small ($\sim 0.7 - 0.8$ fm); it seems that the effect of the s-channel interaction should be considered in our calculation for these two states. In the following calculations, we will consider the s-channel interactions by using Eqs. (19)–(21), and the parameters C^K and C^{K^*} in Eqs. (20) and (21) are fitted by the masses of K and K^* mesons.

After including the s-channel interactions, the effective potentials for both $S = 1$ and $S = 2$ $N\bar{\Omega}$ states were obtained and are illustrated in Fig. 2, and the numerical results of the binding energies and corresponding rms radii with the effect of the s-channel interaction involved are shown in Table III. Obviously, for both $S = 1$ and $S = 2$, the effective potential becomes more attractive and the binding energies increase after considering the s-channel effect. In set I, the energy shift is about 18 for $S = 1$ and 8 MeV for $S = 2$. In set II, it is about 70 for $S = 1$ and 42 MeV for $S = 2$, and in set III, about 78 for $S = 1$ and 54 MeV for $S = 2$. It seems that after the s-channel interactions are included in the $N\bar{\Omega}$ systems, the $N\bar{\Omega}$ systems can be regarded as deeply bound states, especially in the extended chiral SU(3) quark model.

Additionally, the binding energies of P-wave $N\bar{\Omega}$ systems were studied. The results indicate that regardless of whether the s-channel interactions are taken into account, P-wave $N\bar{\Omega}$ systems are always unbound in both the chiral SU(3) quark and extended models.

To get more information about the systems of $N\bar{\Omega}$, we further studied the $N\bar{\Omega}$ elastic scattering processes. The phase shifts of S, P, and D partial waves of $(N\bar{\Omega})_{S=2}$ and $(N\bar{\Omega})_{S=1}$ were calculated. As a primary study, the spin-orbit and tensor forces were not considered for the P and D waves, i.e., only the central force was considered. The phase shifts of $(N\bar{\Omega})_{S=2}$ and $(N\bar{\Omega})_{S=1}$ for the S, P, and D partial waves are illustrated in Figs. 3, 4, and 5, respectively. We see that the signs of the phase shifts in these two models are the same, and the magnitudes of the phase shifts in the extended model are higher, especially for set II. This indicates that the $N\bar{\Omega}$ systems have more attractive interactions in the extended chiral SU(3) quark model, consistent with the results of the binding energy calculation.

Furthermore, the cross sections of the $N\bar{\Omega}$ elastic scattering were studied as well. The contributions of different partial waves and the total cross sections are shown in Figs. 6 and 7, respectively. Here, the total cross sections are the averages of $S = 1$ and $S = 2$ as usual. From these figures, one can see some differences between the results in the chiral SU(3) quark model and those in the extended model. In the very low energy region, S partial waves are dominantly important, and the contribution in set I is the largest. However, with energy enhancement, P-wave cross sections increase, and those in sets II and III are larger than that in set I and even larger than those of S partial waves at the higher energy region. Moreover, there are nearly no contributions from D partial waves. Therefore, trends of curves in the extended model are different from those in the chiral SU(3) quark model. The greatest difference in the cross sections between set I and set II is about 170 mb in the very low energy region. However, in the medium energy region

TABLE III. Binding energy $B_{N\bar{\Omega}}$ and corresponding rms radius $\overline{R}$ of $N\bar{\Omega}$ with the s-channel interaction.

Model	$S = 1$		$S = 2$	
	$B_{N\bar{\Omega}}$ (MeV)	$\overline{R}$ (fm)	$B_{N\bar{\Omega}}$ (MeV)	$\overline{R}$ (fm)
I	46.2	0.8	37.2	0.8
II	129.5	0.6	102.0	0.6
III	132.2	0.6	107.3	0.6

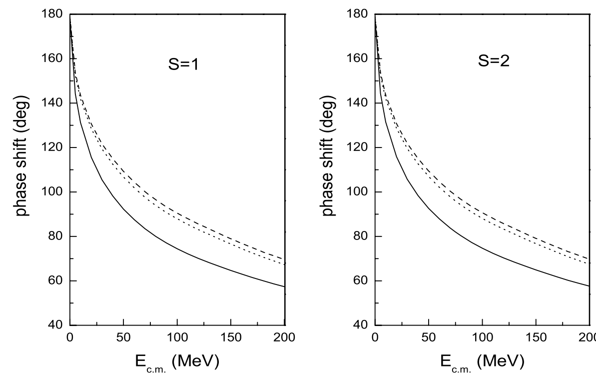

FIG. 3. $N\bar{\Omega}$ S-wave phase shifts as a function of the energy of the center of mass motion. Same notation as in Fig. 1.

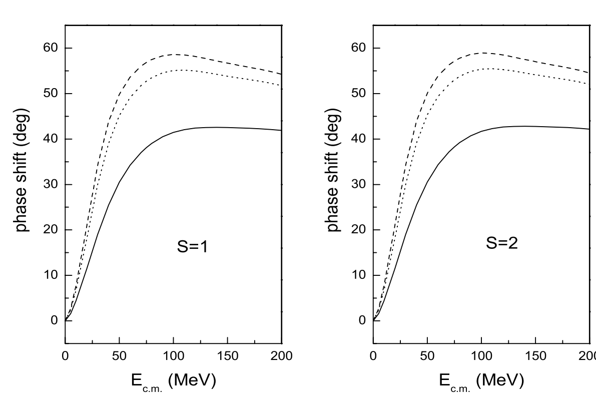

FIG. 4. Same as Fig. 3, but for P-wave phase shifts.

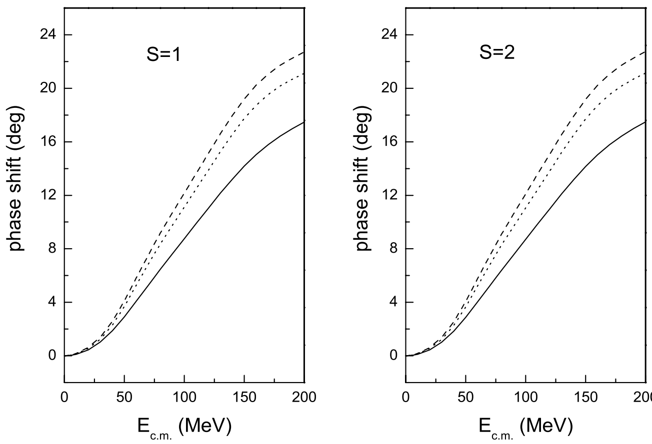

FIG. 5. Same as Fig. 3, but for D-wave phase shifts.

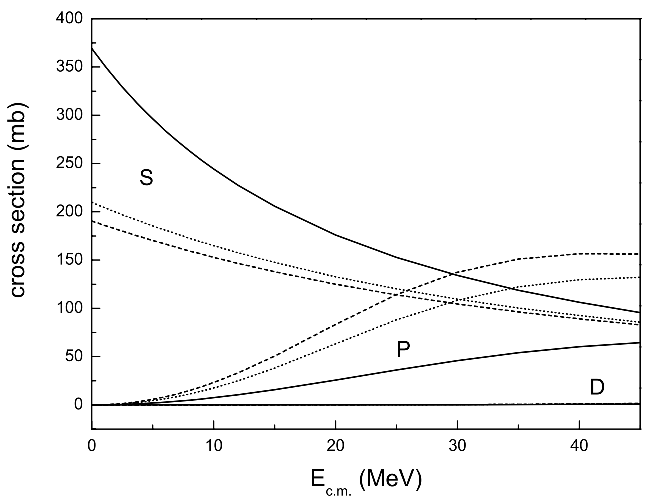

FIG. 6. Contributions of S, P, and D partial waves to $N\bar{\Omega}$ total cross sections as a function of the energy of the center of mass motion. Same notation as in Fig. 1.

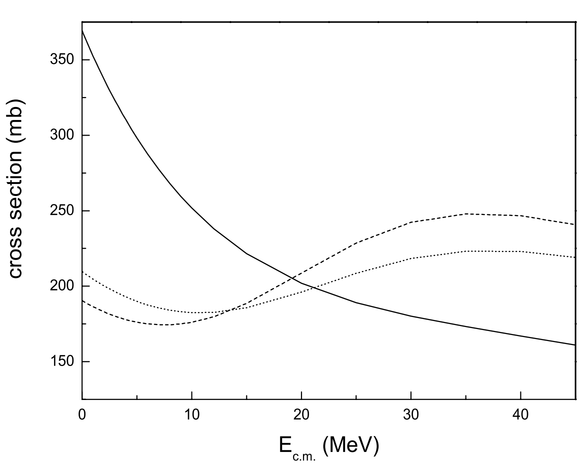

FIG. 7. $N\bar{\Omega}$ total cross sections as a function of the energy of the center of mass motion. Same notation as in Fig. 1.

($E_{\mathrm{c.m.}} \approx$ 10–30 MeV), the cross sections are around 175–250 mb for sets I, II, and III. It is expected that the experimental data on $N\bar{\Omega}$ elastic scattering processes in the future will be useful to check our two chiral quark models.

The figures of scattering processes given above are the results obtained without considering the s-channel interactions. When the effect of the s-channel interaction is included, all the amplitudes in the phase shifts are a little higher, but the tendencies of all curves remain invariant. In addition, for $(N\bar{\Omega})_{S=1}$ and $(N\bar{\Omega})_{S=2}$, the results of phase shifts are very similar, because our calculations neglected the spin-orbit and tensor forces. When we only consider the central force, the σ meson exchange still plays the dominant role, and we know it is spin independent. Moreover, η meson exchange includes the tensor force, but it contributes little to the $N\bar{\Omega}$ system. The spin-orbit interaction exists in the σ exchange, and whether it can affect the properties of P or D waves deserves further study.

IV. SUMMARY

We performed a dynamical study of $N\bar{\Omega}$ states with spin $S=1$ and $S=2$ within the chiral SU(3) quark model and the extended chiral SU(3) quark model by solving the equation in the RGM framework. All the model parameters were taken to be the values we used before, which can reasonably explain the energies of the baryon ground states, the binding energy of deuteron, the NN scattering phase shifts, and the YN cross sections [5,6]. The numerical results show that the $N\bar{\Omega}$ systems with both $S=1$ and $S=2$ are bound in both chiral quark models. When the effect of the s-channel interaction is considered, the $N\bar{\Omega}$ system becomes more bound. This means that the s-channel interaction plays a non-negligible role in the $N\bar{\Omega}$ systems. At the same time, the $N\bar{\Omega}$ elastic scattering phase shifts and total cross sections were also investigated. The calculated phase shifts are qualitatively similar in the chiral SU(3) and extended chiral SU(3) quark models. For either the bound-state problem or the elastic scattering processes, the results of $(N\bar{\Omega})_{S=1}$ and $(N\bar{\Omega})_{S=2}$ are quite alike.

It is noteworthy that the properties of the $\bar{N}\Omega$ system are the same as those of the $N\bar{\Omega}$ one. Although some characteristics need further study—such as decay width, branching ratio, and spin-orbit coupling effect for higher partial wave phase shifts—we would still like to emphasize that if the qualitative features of the $N\bar{\Omega}$ system we obtained are correct and its annihilation width is not very large, then the $N\bar{\Omega}$ system should be a very interesting one to investigate. Since the abundance of N is larger than that of $\bar{N}$, and the abundance of $\bar{\Omega}$ is almost the same as that of Ω, which is not very small, the production rate of $N\bar{\Omega}$ will be higher than that of $\bar{N}\Omega$ in heavy ion collision experiments. More accurate study of the structure and properties of $N\bar{\Omega}$ systems is worth doing in future work.

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