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

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Abstract

The $N\bar{\Omega}$ systems with spin $S = 1$ and $S = 2$ are dynamically investigated within the framework of the chiral SU(3) quark model and the extended chiral SU(3) quark model by solving the resonating group method (RGM) equation. 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 both in the chiral SU(3) and extended chiral SU(3) quark models, and the binding energies are about $28 - 59$ MeV. When the annihilation effect is considered, the binding energies increase to about $37 - 130$ MeV, which indicates the annihilation effect plays a relatively important role in forming an $N\bar{\Omega}$ bound state. At the same time, the $N\bar{\Omega}$ elastic scattering processes are also studied. The $S, P, D$ partial wave phase shifts and the total cross sections of $S = 1$ and $S = 2$ channels have been calculated by solving the RGM equation for scattering problems.

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I. INTRODUCTION

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 a great deal of theoretical and experimental scientists for a few decades, but up to now it is still an open question. The main reason is that the annihilation effect at short distance is very important in the $N\bar{N}$ system, which enhances its complexity. From 1980s’ processes of $N\bar{N}$ annihilation into two and three mesons were investigated on quark level and obtained some interesting results [1, 2, 3, 4]. In their models, there were three kinds of annihilation mechanisms:

1) the quark-antiquark ($q\bar{q}$) pair could be destroyed and created with vacuum quantum numbers;

2) quarks in $N$ and antiquarks in $\bar{N}$ rearrangement led to the annihilation into mesons;

3) the $q\bar{q}$ pair annihilated with the quantum number of gluon.

And their analysis indicated that the first one is the dominant among the three annihilation mechanisms in the $N\bar{N}$ system, which can give a reasonable description of $N\bar{N}$ annihilation data [3, 4].

Despite that some progresses have been made in the study of the annihilation effect, there are still some uncertainties in the $N\bar{N}$ systems, because in which 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 convinced theoretical prediction for $N\bar{N}$ bound states or resonances. It seems more appropriate to choose some special systems which 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, $u\bar{s}$ or $d\bar{s}$ is impossible to annihilate to the vacuum, and also impossible to annihilate to gluon because gluon is flavorless. Therefore, the $N\bar{\Omega}$ system can only annihilate into three mesons with strangeness by rearrangement, and it provides an optimal place to study 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 it is also an ideal place for examining the chiral field coupling.

As is well known, the quantum chromodynamics (QCD) is the underlying theory of the strong interaction. At high-energy region, the perturbative treatment of QCD is quit successful, while it fails at low and intermediate energy domain. However, nonperturbative QCD (NPQCD) effect is very important for light quark systems and till now there is no serious approach to solve the NPQCD problem. To study the baryon physics, people still need QCD-inspired models to help. Among these models, the chiral SU(3) quark model has been quite successful in reproducing 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. In this model, the quark-quark interaction containing confinement, one gluon exchange (OGE) and boson exchanges stemming from chiral-quark coupling. 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 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. In this extended model, we further include the coupling of the quark and vector chiral fields. 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. 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. Recently both the chiral SU(3) quark model and the extended chiral SU(3) quark model have been extended to the systems with antiquarks to study the baryon-meson interactions by solving a resonating group method (RGM) equation. Some interesting results were obtained, which are quite similar to those given by the chiral unitary approach study. Inspired by all these achievements, we try to extend our study to the baryon-antibaryon systems in the framework of these two models.

In the present work, we dynamically investigate the characteristic 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. Firstly, the binding energies of the N$\bar{\Omega}$ states are studied, and the annihilation effect is discussed as well. The results show that N$\bar{\Omega}$ states with spin $S = 1$ and $S = 2$ can be bound states both in the chiral SU(3) and extended chiral SU(3) quark models, and the binding energies range from 28 MeV to 59 MeV. When the annihilation effect is considered, the binding energies increase to around 37 – 130 MeV. Secondly, in order to get more information of the N$\bar{\Omega}$ structure, the N$\bar{\Omega}$ elastic scattering processes are also studied and the phase shifts of $S$, $P$ and $D$ partial waves and the total cross sections are obtained.

The paper is organized as follows. In the next section the framework of the chiral SU(3) quark model and the extended chiral SU(3) quark model are briefly introduced. The calculated results of the N$\bar{\Omega}$ states are shown in Sec. III, where some discussions are made as well. 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\cite{5,6} 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-antibaryon systems can be written as

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

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

$$V_{qq}(ij) = V_{qq}^{OGE}(ij) + V_{qq}^{conf}(ij) + V_{qq}^{ch}(ij),$$

where $V_{qq}^{OGE}(ij)$ is the one-gluon-exchange interaction,

$$V_{qq}^{OGE}(ij) = \frac{1}{4} g_i g_j (\lambda_i^c \cdot \lambda_j^c) \times \left\{ \frac{1}{r_{ij}} - \frac{\pi}{2} \delta(r_{ij}) \left( \frac{1}{m_{q_i}^2} + \frac{1}{m_{q_j}^2} + \frac{4}{3 m_{q_i} m_{q_j}} (\sigma_i \cdot \sigma_j) \right) \right\} + V_{OGE}^{L_s} + + V_{OGE}^{ten},$$

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

$$V_{qq}^{conf}(ij) = \frac{a_c}{r_{ij}^2} - \frac{a_0}{r_{ij}^4} (\lambda_i^c \cdot \lambda_j^c).$$

$V_{qq}^{ch}(ij)$ represents the chiral fields induced effective quark-quark potential. In the chiral SU(3) quark model, $V_{ij}^{ch}$ includes the scalar boson exchanges and the pseudoscalar boson exchanges,

$$V_{qq}^{ch}(ij) = \sum_{a=0}^{8} V_{\sigma_a}(r_{ij}) + \sum_{a=0}^{8} V_{\pi_a}(r_{ij}),$$

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

$$V_{qq}^{ch}(ij) = \sum_{a=0}^{8} V_{\sigma_a}(r_{ij}) + \sum_{a=0}^{8} V_{\pi_a}(r_{ij}) + \sum_{a=0}^{8} V_{\rho_a}(r_{ij}).$$

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

$$V_{\sigma_a}(r_{ij}) = -C(g_{ch}, m_{\sigma_a}, \Lambda) X_1(m_{\sigma_a}, \Lambda, r_{ij}) \lambda_a(i) \lambda_a(j) + V_{\sigma_a}^{L_s}(r_{ij}),$$
\[ V_{\pi a}(r_{ij}) = C(g_{ch}, m_{\pi a}, \Lambda) \frac{m_{\pi a}^2}{12m_{q_i}m_{q_j}} X_2(m_{\pi a}, \Lambda, r_{ij})(\sigma_i \cdot \sigma_j)[\lambda_a(i)\lambda_a(j)] + V_{\pi a}^{ten}(r_{ij}), \] (8)

\[ V_{\rho a}(r_{ij}) = C(g_{chv}, m_{\rho a}, \Lambda) \left\{ X_1(m_{\rho a}, \Lambda, r_{ij}) + \frac{m_{\rho a}^2}{6m_{q_i}m_{q_j}} \left( 1 + \frac{f_{chv} m_{q_i} + m_{q_j}}{g_{chv} M_P} + \frac{f_{chv}^2}{g_{chv}} \right) \right\} X_2(m_{\rho a}, \Lambda, r_{ij})(\sigma_i \cdot \sigma_j)[\lambda_a(i)\lambda_a(j)] + V_{\rho a}^{K*(r_{ij})} + V_{\rho a}^{ten}(r_{ij}), \] (9)

where

\[ C(g_{ch}, m, \Lambda) = \frac{g_{ch}^2 \Lambda^2}{4\pi \Lambda^2 - m^2 m}, \] (10)

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

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

\[ Y(x) = \frac{1}{x} e^{-x}, \] (13)

and \( M_P \) being a mass scale, taken as proton mass. \( m_{\sigma a} \) is the mass of the scalar meson, \( m_{\pi a} \) the mass of the pseudoscalar meson, and \( m_{\rho a} \) the mass of the vector meson.

\( V_{\bar{q}q}(ij) \) in Eq.11 is the antiquark-antiquark (\( \bar{q} \bar{q} \)) interaction,

\[ V_{\bar{q}q} = V_{\bar{q}q}^{conf} + V_{\bar{q}q}^{OGE} + V_{\bar{q}q}^{ch}, \] (14)

Replacing the \( \lambda^c_i \cdot \lambda^c_j \) in Eq.11 and Eq.14 by \( \lambda^{c *} i \cdot \lambda^{c *} j \), we can obtain the forms of \( V_{\bar{q}q}^{OGE} \) and \( V_{\bar{q}q}^{confl} \). \( V_{\bar{q}q}^{ch} \) has the same form as \( V_{\bar{q}q}^{ch} \).

\( V_{qq}(ij) \) in Eq.14 represents the interaction between quark and antiquark (\( qq \)). Between \( N \) and \( \bar{Q} \), there is no one-gluon-exchange interaction and the confinement potential scarcely contributes any interactions, so \( V_{qq} \) only includes two parts: the meson fields induced effective potential and annihilation parts,

\[ V_{qq} = V_{qq}^{ch} + V_{qq}^{ann}, \] (15)

where

\[ V_{qq}^{ch} = \sum_j (-1)^{G_j} V_{qq}^{ch,j}. \] (16)
Here \((-1)^{G_j}\) represents the G parity of the \(j\)th meson. As mentioned above, for the \(N\bar{\Omega}\) systems \(u(d)\bar{s}\) can only annihilate into \(K\) and \(K^*\) mesons by rearrangement mechanism—i.e.,

\[
V_{q\bar{q}}^{\text{ann}} = V_{q\bar{q}}^{K} + V_{q\bar{q}}^{K^*},
\]

with

\[
V_{q\bar{q}}^{K} = C^K \left( \frac{1 - \sigma_q \cdot \sigma_{\bar{q}}}{2} \right) \left( \frac{2 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{6} \right) \frac{38 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{18} \delta(r),
\]

and

\[
V_{q\bar{q}}^{K^*} = C^{K^*} \left( \frac{3 + \sigma_q \cdot \sigma_{\bar{q}}}{2} \right) \left( \frac{2 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{6} \right) \frac{38 + 3\lambda_q \cdot \lambda_{\bar{q}}^*}{18} \delta(r),
\]

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 the 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: \(m_{u(d)} = 313\) MeV and \(m_s = 470\) MeV. The coupling constant for scalar and pseudoscalar chiral field coupling, \(g_{\text{ch}}\), is determined according to the relation

\[
g_{\text{ch}}^2 = \left( \frac{3}{5} \right) \frac{g_{NN\pi}^2 m_u^2}{4\pi M_N^2},
\]

with 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 \(g_{\text{chv}} = 2.351\), the same as used in the \(NN\) case [4]. 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 cutoff radius \(\Lambda^{-1}\) is taken to be the value close to the chiral symmetry breaking scale [6]. The OGE coupling constants, \(g_u\) and \(g_s\), can be determined by the mass splits between \(N, \Delta\) and \(\Sigma, \Lambda\), respectively. The confinement strengths \(a_{uu}^c, a_{us}^c,\) and \(a_{ss}^c\) are fixed by the stability conditions of \(N, \Lambda,\) and \(\Xi\) and the zero-point energies \(a_{uu}^{0}, a_{us}^{0},\) and
TABLE I: Model parameters. The meson masses and the cutoff masses: $m_\sigma = 980$ MeV, $m_\pi = 980$ MeV, $m_\epsilon = 980$ MeV, $m_\pi = 138$ MeV, $m_K = 495$ MeV, $m_\eta = 549$ MeV, $m_\eta' = 957$ MeV, $m_\rho = 770$ MeV, $m_{K^*} = 892$ MeV, $m_\omega = 782$ MeV, $m_\phi = 1020$ MeV, and $\Lambda = 1100$ MeV for all mesons.

| Parameter          | Chiral SU(3) quark model | Extended chiral SU(3) quark model |
|--------------------|--------------------------|----------------------------------|
|                    | I                        | II, $f_{chv}/g_{chv} = 0$ | III, $f_{chv}/g_{chv} = 2/3$ |
| $b_u$ (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                           |
| $m_\sigma$ (MeV)   | 595                      | 535                             | 547                             |
| $a_{uu}^{c0}$ (MeV/fm$^2$) | 46.6                   | 44.5                           | 39.1                             |
| $a_{us}^{c0}$ (MeV/fm$^2$) | 58.7                   | 79.6                           | 69.2                             |
| $a_{ss}^{c0}$ (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                            |

$a_{ss}^{c0}$ by fitting the masses of $N$, $\Sigma$, and $\Xi + \Omega$, respectively. All the parameters are tabulated in Table I where the first set is for the chiral SU(3) quark model (I), the second and third sets are for the extended chiral SU(3) quark model by taking $f_{chv}/g_{chv}$ as 0 (II) and 2/3 (III), respectively. Here $g_{chv}$ and $f_{chv}$ are the coupling constants for vector coupling and tensor coupling of the vector meson fields, respectively.

C. Resonating group method (RGM)

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

$$\Psi = \hat{\phi}_N(\xi_1, \xi_2)\hat{\phi}_\Omega(\xi_3, \xi_4)\chi(R_{N\Omega}),$$  

(21)

where $\xi_1, \xi_2$ are the internal coordinates for the cluster $N$, and $\xi_3, \xi_4$ the internal coordinate for the cluster $\Omega$. $R_{N\Omega} \equiv R_N - R_{\Omega}$ is the relative coordinate between the two clusters, $N$ and $\Omega$. The $\hat{\phi}_N$ ($\hat{\phi}_\Omega$) is the antisymmetrized internal cluster wave function of $N$ ($\Omega$), and $\chi(R_{N\Omega})$ the relative wave function of the two clusters. For a bound-state problem or a scattering one, by solving the equation

$$\langle \delta\Psi | (H - E) | \Psi \rangle = 0,$$  

(22)

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

III. RESULTS AND DISCUSSIONS

FIG. 1: The GCM matrix elements of the $S$-wave $N\Omega$ effective potential as a function of the generator coordinate, where the annihilation effect 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.

The bound-state case of $S$-wave $N\Omega$ 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
TABLE II: Binding energy $B_{N\bar{\Omega}}$ and corresponding RMS radius $\bar{R}$ of $N\bar{\Omega}$ without the annihilation effect.

| Model | S=1 |       | S=2 |       |
|-------|-----|-------|-----|-------|
|       | $B_{N\bar{\Omega}}$ (MeV) | $\bar{R}$ (fm) | $B_{N\bar{\Omega}}$ (MeV) | $\bar{R}$ (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   |

not consider the annihilation effect. Fig. I shows the diagonal matrix elements of the interaction potentials for the $N\bar{\Omega}$ systems with $S = 1$ and $S = 2$ in the generator coordinate method (GCM) calculations, which can be regarded as the effective potential of two clusters $N$ and $\bar{\Omega}$. In Fig. II $V(s)$ denotes the effective potential between $N$ and $\bar{\Omega}$, and $s$ denotes the generator coordinate which can qualitatively describe the distance between the two clusters. From Fig. I we can see that for both $S = 1$ and $S = 2$ states, effective potentials are attractive, and the attractions in the extended chiral SU(3) quark 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 chiral SU(3) 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 $\sigma$ exchange. In our calculation, the model parameters are fitted by the $NN$ scattering phase shifts and the mass of $\sigma$ is adjusted by fitting the deuteron’s binding energy, so the value of $m_\sigma$ is somewhat different for these three cases. In sets II and III, the mass of $\sigma$ meson is smaller than that of sets I, so the $N\bar{\Omega}$ states can get more attractions 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 be understood, because as presented above, in the $S$-wave calculation, the $\sigma$ exchange plays the dominant role, which is spin independent.

By solving bound-state RGM equation, the calculated binding energies and corresponding root-mean-squared (RMS) radii are obtained and tabulated in Table III. One can see that such attractive potentials can make for bound states of the $N\bar{\Omega}$ systems. Here, the binding energy ($B_{N\bar{\Omega}}$) and RMS radius ($\bar{R}$) are defined as

$$B_{N\bar{\Omega}} = -[E_{N\bar{\Omega}} - (M_N + M_{\bar{\Omega}})]$$  (23)

$$\bar{R} = \sqrt{\frac{1}{6} \sum_{i=1}^{6} (r_i - R_{cm})^2}$$  (24)
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 $f_{chv}/g_{chv} = 0$, and about 54 MeV in set III, i.e., in the extended chiral SU(3) quark model with $f_{chv}/g_{chv} = 2/3$. As have seen in Fig. I 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 the sets II and III get bigger binding energies than those of set I.

![Figure 2](image-url)  
**FIG. 2:** The GCM matrix elements of the $S$-wave $N\bar{\Omega}$ effective potential as a function of the generator coordinate, where the annihilation effect is included. Same notation as in Fig. I

**TABLE III: Binding energy $B_{N\bar{\Omega}}$ and corresponding RMS radius $\bar{R}$ of $N\bar{\Omega}$ with the annihilation effect.**

| Model | $S=1$ | $S=2$ |
|-------|-------|-------|
|       | $B_{N\bar{\Omega}}$ (MeV) | $\bar{R}$ (fm) | $B_{N\bar{\Omega}}$ (MeV) | $\bar{R}$ (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   |

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

The root-mean-squared radius for the states of \((N\bar{\Omega})_{S=1}\) and \((N\bar{\Omega})_{S=2}\) are also calculated. In Table II, the RMS radii we acquired are relatively small (~0.7-0.8 fm), it seems that the annihilation effect should be considered in our calculation for these two states. As pointed out above, for the \(N\bar{\Omega}\) system, the annihilations to vacuum and gluon are forbidden and the \(u\bar{s}(d\bar{s})\) can only annihilate to \(K\) and \(K^*\) mesons. Therefore, in the following calculations, we will consider the annihilation to \(K\) and \(K^*\) mesons by using the Eqs. (17)-(19), and the parameters \(C^K\) and \(C^{K^*}\) in Eqs. (18) and (19) are fitted by the masses of \(K\) and \(K^*\) mesons.

After including the annihilation effect, the diagonal GCM matrix elements of the effective potentials for both \(S = 1\) and \(S = 2\) \(N\bar{\Omega}\) states are illustrated in Fig. 2 and the numerical results of the binding energies and corresponding RMS radii with the annihilation effect involved are shown in Table III. Obviously for both \(S = 1\) and \(S = 2\), the effective potential become more attractive and the binding energies increase after considering the annihilation effect. In set I, the energy shift is about 18 MeV for \(S = 1\) and 8 MeV for \(S = 2\). In set II, it is about 70 MeV for \(S = 1\) and 42 MeV for \(S = 2\), and in set III, about 78 MeV for \(S = 1\) and 54 MeV for \(S = 2\). It seems that, after the annihilation effect is 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 \(N\bar{\Omega}\) system are also studied. The results manifest that no matter whether the annihilation effect is taken into account, \(P\)-wave \(N\bar{\Omega}\) systems are always unbound in both the chiral SU(3) quark model and the extended chiral SU(3) quark model.

To get more information about the systems of \(N\bar{\Omega}\), we further study the \(N\bar{\Omega}\) elastic scattering processes. The phase shifts of \(S, P\) and \(D\) partial waves of \((N\bar{\Omega})_{S=2}\) and \((N\bar{\Omega})_{S=1}\) are calculated. As a primary study, the spin-orbit and tensor forces are not considered for the \(P\) and \(D\) waves, i.e. only central force is 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 Fig. 4, Fig. 5 and Fig. 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 chiral SU(3) quark model are higher, especially for set II. This indicates that the \(N\bar{\Omega}\) systems get more attractive interactions in the extended chiral SU(3) quark model, consisted with the results of the binding energy calculation.

Furthermore, the cross sections of the \(N\bar{\Omega}\) elastic scattering are studied as well. The contributions of different partial waves and the total cross sections are shown in Fig. 6 and Fig. 7 respectively. From these figures, one can see that there are some differences between the results
in the chiral SU(3) quark model and those in the extended chiral SU(3) quark model. In the very low energy region $S$ partial waves are dominantly important, and the contribution in set I is the largest. However, with the energy enhancing, $P$-wave cross sections increase and those in sets II and III are larger than that in set I, even larger than those of $S$ partial waves at higher energy region. And there are nearly no contributions of $D$ partial waves. Thereby trends of curves in the
FIG. 5: $N\bar{\Omega}$ D-wave phase shifts as a function of the energy of the center of mass motion. Same notation as in Fig. 1.

FIG. 6: The 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.

extended chiral SU(3) quark model are different from those in the chiral SU(3) quark model. The greatest difference of 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 ($E_{cm} \approx 10 - 30$ MeV), the cross sections are around 200-250 mb for set I, set II and set III. It is expected that the experimental data about $N\bar{\Omega}$ elastic scattering processes in the future will check our two chiral quark models.
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.

The figures of scattering processes given above are the results without considering the annihilation effect. When the effect of the annihilation interaction is included, all the amplitudes in both phase shifts and the total cross sections 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 and cross sections are very similar. Because in our calculation, the spin-orbit and tensor forces are neglected. When we only consider the central force, the $\sigma$ meson exchange still plays the dominant role, and we know it is spin independent. Moreover, $\eta$ meson exchange includes tensor force, but it contributes little in the $N\bar{\Omega}$ system. The spin-orbit interaction exists in the $\sigma$ exchange, and whether it can affect the properties of $P$ or $D$ wave deserves further study.

IV. SUMMARY

In summary, we perform a dynamical study of $N\bar{\Omega}$ states with spin $S = 1$ and $S = 2$ in the framework of the chiral SU(3) quark model and the extended chiral SU(3) quark model by solving the RGM equation. All the model parameters are 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 states in these two chiral quark models. When the annihilation effect is considered, the $N\bar{\Omega}$ system will become more bound. This
means that the annihilation effect plays an un-negligible role in the \( N\bar{\Omega} \) systems. At the same time, the \( N\bar{\Omega} \) elastic scattering phase shifts, as well as the total cross sections are 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 worthy of notice that the properties of the \( \bar{N}\Omega \) system are the same as those of the \( N\bar{\Omega} \) one. Although there are some problems to be further studied, such as detailed annihilation mechanism (e.g. annihilation width or branching ratios, etc.), the spin-orbit coupling effect for higher partial wave phase shifts and so on, yet we still would like to emphasize that if the qualitative feature of the \( \bar{N}\Omega \) system we obtained is right and its annihilation width is not very large, the \( N\bar{\Omega} \) system should be a very interesting one. It can be easier to be searched in the heavy ion collision experiments, because the abundance of \( \bar{N} \) is large and that of \( \bar{\Omega} \), same as \( \Omega \), is not very small. More accurate study of the structure and the properties of \( N\bar{\Omega} \) system is worth doing in the future work.

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