$N\phi$ states in a chiral quark model

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The structures of $N\phi$ states with spin-parity $J^p = 3/2^-$ and $J^p = 1/2^-$ are dynamically studied in both the chiral SU(3) quark model and the extended chiral SU(3) quark model by solving a resonating group method (RGM) equation. 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 nucleon-nucleon (NN) scattering phase shifts, and the hyperon-nucleon (YN) cross sections. The channel coupling of $N\phi$ and ΛK^* is considered, and the effect of the tensor force which results in the mixing of S and D waves is also investigated. The results show that the $N\phi$ state has an attractive interaction, and in the extended chiral SU(3) quark model such an attraction plus the channel coupling effect can consequently make for an $N\phi$ quasi-bound state with several MeV binding energy.

I. INTRODUCTION

The $N\phi$ state has first been studied in Ref. [1], where the authors followed the idea of Ref. [2] and estimated the QCD van der Waals attractive force of the $N\phi$ system. They claimed that the QCD van der Waals attractive force, mediated by multigluon exchanges, can be strong enough to form a bound $N\phi$ state with a binding energy of about 1.8 MeV. At the same time they pointed out that it is possible to search for such a bound state using the ϕ meson below threshold quasifree photoproduction kinematics experimentally. Using a simple model, the authors calculated the rate for such subthreshold quasifree production process using a realistic Jefferson Laboratory luminosity and a large acceptance detection system. They concluded that such an experiment is feasible. To our way of thinking, it is necessary and desirable to study the possibility of the $N\phi$ bound state via different theoretical approaches. The $N\phi$ is a light quark system and the study based on the constituent quark model seems to be significant and indispensable. Furthermore, since the N and ϕ are two color singlet hadrons with no common flavor quarks, there is no one gluon exchange (OGE) interaction between these two clusters, thus the $N\phi$ system is really a special case to examine the quark-quark interactions and further the interactions between these two hadrons.

It is a general consensus that the quantum chromodynamics (QCD) is the underlying theory of the strong interaction. However, as the nonperturbative QCD (NPQCD) effect is very important for light quark systems in the low energy region and it is difficult to be seriously solved, people still need QCD-inspired models to be a bridge connecting the QCD fundamental theory and the experimental observables. Among these phenomenological 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 [3]. In this model, the quark-quark interaction containing confinement, OGE and boson exchanges stemming from scalar and pseudoscalar nonets, and the short range quark-quark interaction is provided by OGE and quark exchange effects.

Actually it is still a controversial problem for low-energy hadron physics whether gluon or Goldstone boson is the proper effective degree of freedom besides the constituent quark. Glozman and Riska proposed that the Goldstone boson is the only other proper effective degree of freedom [4,5]. But Isgur gave a critique of the boson exchange model and insisted that the OGE governs the baryon structure [6,7]. Anyway, it is still a challenging problem in the low-energy hadron physics whether OGE or vector-meson exchange is the right mechanism or both of them are important for describing the short-range quark-quark interaction. Thus the chiral SU(3) quark model has been extended to 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 original chiral SU(3) quark model is now nearly replaced by the vector meson exchanges. This model, named the extended chiral SU(3) quark model, has also been successful in reproducing the the energies of the baryon ground states, the binding energy of the deuteron, and the nucleon-nucleon (NN) scattering phase shifts [8].

Recently, we have extended both the chiral SU(3) quark model and the extended chiral SU(3) quark model from the study of baryon-baryon scattering processes to the baryon-meson systems by solving a resonating group method (RGM) equation [9–14]. We found that some results are similar to those given by the chiral unitary approach study, such as that both the ΔK system with isospin $I = 1$ and the ΣK system with $I = 1/2$ have quite strong attractions [11–13]. In the study of the KN scattering [9–11], we get a considerable improvement not only on the signs but also on the magnitudes of the theoretical phase shifts comparing with other's previous work. We also studied the phase shifts of πK [15], and got

reasonable fit with the experiments in the low energy region. All these achievements encourage us to investigate more baryon-meson systems by using the same group of parameters.

In this work, we dynamically study the $N\phi$ interaction in both the chiral SU(3) quark model and the extended chiral SU(3) quark model by using the RGM. All the model parameters are taken from our previous work. The channel coupling of $N\phi$ and ΛK^* is considered, and the effect of the tensor force which makes for the mixing of S and D waves is also investigated. 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 results for the $N\phi$ state are shown in Sec. III, where some discussion is presented as well. Finally, the summary is given in Sec. IV.

II. FORMULATION

The chiral SU(3) quark model and the extended chiral SU(3) quark model has been widely described in the literature [9–13], 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-meson systems can be written as

$$H = \sum_{i=1}^{5} T_i - T_G + \sum_{i<j=1}^{4} V_{ij} + \sum_{i=1}^{4} V_{i\bar{5}}, \qquad (1)$$

where T_G is the kinetic energy operator for the center-of-mass motion, and V_{ij} and $V_{i\bar{5}}$ represent the quark-quark and quark-antiquark interactions, respectively,

$$V_{ij} = V_{ij}^{\mathrm{OGE}} + V_{ij}^{\mathrm{conf}} + V_{ij}^{\mathrm{ch}}, \qquad (2)$$

where V_{ij}^{OGE} is the OGE interaction, and V_{ij}^{conf} is the confinement potential. V_{ij}^{ch} 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,

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

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

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

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 can be found in the literature [9–13].

$V_{i\bar{5}}$ in Eq. (1) includes two parts: direct interaction and annihilation parts,

$$V_{i\bar{5}} = V_{i\bar{5}}^{\mathrm{dir}} + V_{i\bar{5}}^{\mathrm{ann}}, \qquad (5)$$

with

$$V_{i\bar{5}}^{\mathrm{dir}} = V_{i\bar{5}}^{\mathrm{conf}} + V_{i\bar{5}}^{\mathrm{OGE}} + V_{i\bar{5}}^{\mathrm{ch}}, \qquad (6)$$

and

$$V_{i\bar{5}}^{\mathrm{ch}} = \sum_{j} (-1)^{G_j} V_{i\bar{5}}^{\mathrm{ch},j}. \qquad (7)$$

Here $(-1)^{G_j}$ represents the G parity of the jth meson. The $q\bar{q}$ annihilation interactions, $V_{i\bar{5}}^{\mathrm{ann}}$, are not included in this work because they are assumed not to contribute significantly to a molecular state or a scattering process which is the subject of our present study.

All the model parameters are taken from our previous work [12,13], which gave a satisfactory description of the energies of the baryon ground states, the binding energy of the deuteron, and 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

$$\frac{g_{\mathrm{ch}}^2}{4\pi} = \left(\frac{3}{5}\right)^2 \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{M_N^2}, \qquad (8)$$

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 [8]. 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 OGE coupling constants and the strengths of the confinement potential are fitted by baryon masses and their stability conditions. All the parameters are tabulated in Table I, where the first set is for the original chiral SU(3) quark model, the second and third sets are for the

TABLE I. Model parameters. The meson masses and the cutoff masses: $m_{\sigma'} = 980$ MeV, $m_\kappa = 980$ 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.

	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
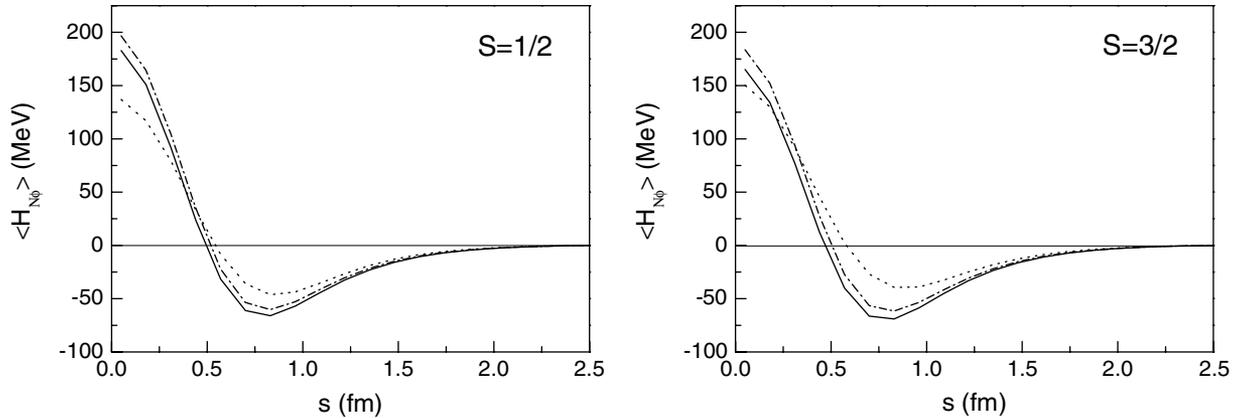
FIG. 1. The GCM matrix elements of the Hamiltonian. The dotted, solid and dash-dotted lines represent the results obtained in model I, II, and III, respectively.

extended chiral SU(3) quark model by taking $f_{\mathrm{chv}}/g_{\mathrm{chv}}$ as 0 and 2/3, respectively. Here f_{chv} is the coupling constant for tensor coupling of the vector meson fields.

From Table I one can see that for both set II and set III, g_u^2 and g_s^2 are much smaller than the values of set I. This means that in the extended chiral SU(3) quark model, the coupling constants of OGE are greatly reduced when the coupling of quarks and vector-meson field is considered. Thus the OGE that plays an important role of the quark-quark short-range interaction in the original chiral SU(3) quark model is now nearly replaced by the vector-meson exchange. In other words, the mechanisms of the quark-quark short-range interactions in these two models are quite different.

With all parameters determined, the $N\phi$ state can be dynamically studied in the framework of the RGM, a well established method for studying the interaction between two composite particles. The wave function of the $N\phi$ system is of the form

$$\Psi = \mathcal{A}[\hat{\psi}_N(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\hat{\psi}_\phi(\boldsymbol{\xi}_3)\chi(\boldsymbol{R}_{N\phi})], \qquad (9)$$

where $\boldsymbol{\xi}_1$ and $\boldsymbol{\xi}_2$ are the internal coordinates for the cluster N, and $\boldsymbol{\xi}_3$ the internal coordinate for the cluster ϕ. $\boldsymbol{R}_{N\phi} \equiv \boldsymbol{R}_N - \boldsymbol{R}_\phi$ is the relative coordinate between the two clusters, N and ϕ. The $\hat{\psi}_N$ and $\hat{\psi}_\phi$ are the antisymmetrized internal cluster wave functions of N and ϕ, and $\chi(\boldsymbol{R}_{N\phi})$ the relative wave function of the two clusters. The symbol $\mathcal{A}$ is the antisymmetrizing operator defined as

$$\mathcal{A} \equiv 1 - \sum_{i \in N} P_{i4} \equiv 1 - 3P_{34}. \qquad (10)$$

Expanding unknown $\chi(\boldsymbol{R}_{N\phi})$ by employing well-defined basis wave functions, such as Gaussian functions, one can solve the RGM equation for a bound-state problem or a scattering one to obtain the binding energy or scattering phase shifts for the two-cluster systems. The details of solving the RGM equation can be found in Refs. [16–18].

III. RESULTS AND DISCUSSIONS

As mentioned above, the $N\phi$ system is a very special two-hadron state since these two color singlet clusters have no common flavor quarks. Although the structure of the $N\phi$ state has already been studied by using the QCD van der Waals attractive potential in Ref. [1], a dynamical investigation of this light quark system in the framework of the constituent quark model including the coupling of the quark and chiral fields is still essential. Here we study the $N\phi$ state in our chiral quark model by treating N and ϕ as two clusters and solving the corresponding RGM equation. Figure 1 shows the diagonal matrix elements of the Hamiltonian for the $N\phi$ system in the generator coordinate method (GCM) [16] calculation, which can be regarded as the effective Hamiltonian of two clusters N and ϕ qualitatively. In Fig. 1, $\langle H_{N\phi} \rangle$ includes the kinetic energy of the relative motion and the effective potential between N and ϕ, and s denotes the generator coordinate which can qualitatively describe the distance between the two clusters. From Fig. 1, one sees that the $N\phi$ interaction is attractive in the medium range for both spin $S = 1/2$ and $S = 3/2$ cases, this is because this attraction dominantly comes from the σ field coupling and σ field is spin and flavor independent. To study if such an attraction can make for a quasi-bound state of the $N\phi$ system, we solve the RGM equation for the bound state problem. The results show that in model I, i.e., the original chiral SU(3) quark model, and model III, i.e., the extended chiral SU(3) quark model with $f_{\mathrm{chv}}/g_{\mathrm{chv}} = 2/3$, the $N\phi$ states are unbound for both spin $S = 1/2$ and $S = 3/2$, though the $N\phi$ interaction is attractive. However in model II, i.e., the extended chiral SU(3) quark model with $f_{\mathrm{chv}}/g_{\mathrm{chv}} = 0$, we get a weakly bound state of $N\phi$ with about 1 and 3 MeV binding energy for $S = 1/2$ and $S = 3/2$, respectively. Actually, as can be seen in Fig. 1, the $N\phi$ interaction in model II is more attractive than those in models I and III, thus in model II we can get a weakly $N\phi$ bound state while in model I and III the $N\phi$ is unbound.

Since the threshold of ΛK^* is only 49 MeV higher than that of $N\phi$, the channel coupling effect of these two channels would be uneglegible. This effect is considered by solving a coupled-channel RGM equation for the bound state problem,

TABLE II. The binding energy of $N\phi$ (in MeV).

Model	One-channel		Coupled-channel	
	$S = 1/2$	$S = 3/2$	$S = 1/2$	$S = 3/2$
I	–	–	–	–
II	1	3	3	9
III	–	–	1	6

and the calculated binding energies are shown in Table II. One sees that in model I, the $N\phi$ states are yet unbound for both spin $S = 1/2$ and $S = 3/2$ channels, while in models II and III, the $N\phi$ states are weakly bound with the binding energies of about 3 and 1 MeV for $S = 1/2$ and 9 and 6 MeV for $S = 3/2$, respectively. These results tell us that the effect of the channel coupling between $N\phi$ and ΛK^* is considerable and it can make the $N\phi$ binding energies a little bit larger.

We also study the effect of the tensor force from OGE, pseudoscalar and vector field coupling, which results in the mixing of S and D waves. Our results show that the tensor force in the $N\phi$ system is very small and its effect can be neglected. This can be understood easily because in the $N\phi$ system the tensor force from OGE and π and ρ exchanges are absent and only K, η, η', and K^* exchanges with the quark exchange can offer tiny tensor force.

As mentioned in Ref. [1], in the $N\phi$ system, the OGE is not allowed since the two color-singlet clusters have no common flavor quarks, and the attraction between N and ϕ comes from the QCD van der Waals interaction mediated by multigluon exchanges. In the chiral SU(3) quark model, there is also no contributions from OGE, while the σ exchange dominantly provides the $N\phi$ attractive interaction. As regards in the extended chiral SU(3) quark model, there is no contribution from ρ, ω and ϕ exchanges, and the attraction in this special system also dominantly comes 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's binding energy, thus the value of m_σ is somewhat different for the cases I, II, and III. In model II the mass of the σ meson is smaller than those in models I and III,

which means that in model II $N\phi$ gets more attraction than those in models I and III, thus much more binding energy of $N\phi$ is obtained in model II than in models I and III.

Actually, all of the results including the estimation from color van der Waals force in Ref. [1] are model and parameter dependent. However while the results obtained from different theoretical approaches are qualitatively similar, then it would make sense and this special system becomes more interesting. At the same time, an experimental measurement of the $N\phi$ binding energy to examine whether the $N\phi$ system can be bound would be very important for getting more knowledge of the coupling between quark and σ chiral field.

IV. SUMMARY

In this work, we dynamically study the $N\phi$ state in the chiral SU(3) quark model as well as in the extended chiral SU(3) quark model by solving the RGM equation. All the model parameters are taken from our previous work, which can give a satisfactory description of the energies of the baryon ground states, the binding energy of the deuteron, and the NN scattering phase shifts. The channel coupling of $N\phi$ and ΛK^* is considered and the effect of the tensor force is also studied. The calculated results show that the $N\phi$ state has an attractive interaction, dominantly provided by the σ exchange, for both spin $S = 1/2$ and $S = 3/2$ channels. The effect of the channel coupling of $N\phi$ and ΛK^* is shown to be considerable, while the tensor force is displayed to be so small that can be neglected. In the extended chiral SU(3) quark model, the $N\phi$ attractive interaction plus the coupling to the ΛK^* channel can make for an $N\phi$ quasi-bound state with several MeV binding energy. Experimentally whether their is an $N\phi$ quasi-bound state or resonance state can help us to test the strength of the coupling of the quark and σ chiral field.

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