Investigation of the pentaquark resonance in the *NK* system

Xuejie Liu,* Hongxia Huang,† and Jialun Ping‡

Department of Physics and Jiangsu Key Laboratory for Numerical Simulation of Large Scale Complex Systems, Nanjing Normal University, Nanjing 210023, People's Republic of China

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A dynamical calculation of pentaquark systems with quark contents $uudd\bar{s}$ is performed in the framework of a quark delocalization color screening model with the help of the resonating group method. The effective potentials between baryon and meson clusters are given, and the possible bound states or resonances are investigated. The single calculations show that the NK^* with $I=0, J^P=\frac{1}{2}^-$, ΔK^* with $I=1, J^P=\frac{1}{2}^-$, and ΔK^* with $I=2, J^P=\frac{3}{2}^-$ are all bound, but they all turn into scattering states by coupling with the corresponding open channels. A possible resonance state ΔK^* with $I=1, J^P=\frac{5}{2}^-$ is proposed. The mass is around 2110.5 MeV, and the decay modes are NK in D wave and $NK\pi\pi$ in P waves.

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I. INTRODUCTION

After decades of experimental and theoretical studies of hadrons, many multiquark candidates have been proposed for the hadrons beyond the ordinary quark-antiquark and three-quark structures. On one hand, the underlying theory of the strong interaction, quantum chromodynamics (QCD) does not forbid the existence of the exotic hadronic states such as glueballs (without quarks and antiquarks), hybrids (gluons mixed with quarks and/or antiquarks), compact multiquark states, and hadronic molecules. On the other hand, dozens of nontraditional charmonium- and bottomonium-like states, the so-called XYZ mesons, have been observed in recent decades by experimental collaborations [1–13].

The intriguing pentaquark states were also searched for in various colliders. In 2003, the LEPS Collaboration announced the observation of pentaquark $\Theta^+(1540)$ [14], an exotic K^+n or K^0p resonance, which inspired many theoretical and experimental work to search for pentaquarks. The pentaquark $\Theta^+(1540)$ with quantum numbers $I=0$ and $Y=2$ as a K^*N resonance had been predicted as the member of an antidecuplet in 1987 [15], and a narrow pentaquark had also been predicted in the chiral soliton models in 1997 [16]. After the experiment happened, there were many theoretical analysis devoted to the $\Theta^+(1540)$ pentaquarks which address various aspects of pentaquarks, including the Skyrme model [17,18], the constituent quark model [19–22], the diquark-diquark-$\bar{q}$ approach [23], QCD sum rules [24], large N_c QCD [25], lattice QCD [26], and many others [27]. However, the existence of $\Theta^+(1540)$ has not been confirmed by other experimental collaborations [28] and it is still a controversial issue [29]. Studies on pentaquarks were scarce to some extent until the observation of two candidates of hidden-charm pentaquarks, $P_c^+(4380)$ and $P_c^+(4450)$, in the decay $\Lambda_b^0 \to J/\psi K^- p$ by the LHCb Collaboration [30–32]. Very recently, the LHCb Collaboration reported three other pentaquarks, $P_c^+(4312)$, $P_c^+(4440)$, and $P_c^+(4457)$, by the same decay mode [33]. A lot of theoretical calculations have been performed to investigate these exotic states [34–46]. In 2017, CERN announced an exceptional discovery by the LHCb, which unveiled five states all at one time [47]. These five states were also interpreted as exotic baryons [48–50].

Now that the hidden charm pentaquarks have been observed in the charmed sector, possible pentaquarks should also be considered in the hidden strange sector, in which the $c\bar{c}$ is replaced by $s\bar{s}$. In fact, the $N\phi$ bound state was proposed by Gao *et al.* in 2001 [51]. In Ref. [52], the $N\phi$ resonance state was obtained in the quark delocalization color screening model (QDCSM), where the channel coupling played an important role. Researchers [53] showed that a bound state could be produced from the $N\phi$ interaction with spin parity $\frac{3}{2}^-$ after introducing a van der Waals force between the nucleon and ϕ meson. In Ref. [54], the authors also studied possible strange molecular pentaquarks composed of Σ (or Σ^*) and K (or K^*), and the results showed that the ΣK, ΣK^*, and $\Sigma^* K^*$ with $IJ^P = \frac{1}{2}\frac{1}{2}^-$ and ΣK^*, $\Sigma^* K$, and $\Sigma^* K^*$ with $IJ^P=\frac{1}{2}\frac{3}{2}^-$ were resonance states by coupling the open channels. Besides, He interpreted the $N^*(1875)$ as a hadronic molecular state from the $\Sigma^* K$ interaction [55].

In addition to the hidden strange pentaquark, many theorists have also studied other possible pentaquarks. For instance, $\Lambda_c(2940)$ was reported by the BaBar Collaboration by analyzing the D^0p invariant mass spectrum [56], and it

*1830592517@qq.com

†Corresponding author: hxhuang@njnu.edu.cn

‡Corresponding author: jlping@njnu.edu.cn

was confirmed as resonant structure in the final state of $\Sigma_c(2455)\pi \to \Lambda_c\pi\pi$ by the Belle Collaboration [57]. Since $\Lambda_c(2940)$ are near the threshold of ND, many works treat them as candidates of molecular states, so there are a lot of work on the ND system. For example, Zhao *et al.* did a bound-state calculation of the ND system in QDCSM and interpreted $\Lambda_c(2940)$ as an ND^* molecular state [58]. He *et al.* also proposed that $\Lambda_c(2940)$ may be a D^*p molecular state with $J^P = \frac{1}{2}^-$ [59]. Extending the study to the strange sector, we can also study the NK system, where the D meson is replaced by the K meson. In fact, many theoretical studies have been devoted to the NK system. In Ref. [60], the authors use the standard nonrelativistic quark model of Isgur-Karl to investigate the NK scattering problem, and the NK scattering phase shift showed no resonance in the energy region 0–500 MeV above the NK threshold. In Ref. [61], Barnes and Swanson used the quark-Born-diagram method to derive the NK scattering amplitudes and obtained reasonable results for the NK phase shifts, but they were limited to the S wave. In Ref. [62], the NK interaction was studied in the constituent quark model and the numerical results of different partial waves were in good agreement with the experimental data. Hence, it is worthwhile to make a systematical study of the NK system by using different methods, which will deepen our understanding of possible pentaquarks.

It is the general consensus that it is difficult to directly study complicated systems in the low-energy region by QCD because of the nonperturbative nature of QCD, so one has to rely on effective theories or QCD-inspired models to tackle the problem of the multiquark. One of the common approaches to study the multiquark system is the quark model. There are various kinds of quark models, such as the one-boson-exchange model, the chiral quark model, the QDCSM, and so on. In particular, the QDCSM was developed in the 1990s with the aim of explaining the similarities between nuclear (hadronic clusters of quarks) and molecular forces [63–65]. In this model, quarks confined in one cluster are allowed to escape to another cluster; this means that quark distribution in two clusters is not fixed, which is determined by the dynamics of the interacting quark system, and thus it allows the quark system to choose the most favorable configuration through its own dynamics in a larger Hilbert space. The confinement interaction between quarks in different clusters is modified to include a color screening factor. The latter is a model description of the hidden-color channel-coupling effect [66]. This model is successful in describing nucleon-nucleon and hyperon-nucleon interactions and the properties of the deuteron [67–69]. It is also employed to study the pentaquark system in hidden-strange, hidden-charm, and hidden-bottom sectors [35,54]. In the present work, QDCSM is employed to study the nature of NK systems, and the channel-coupling effect is considered. Besides, we also investigate the scattering processes of the NK systems to see if any bound or resonance state exists.

This paper is organized as follows. In the next section, the framework of the QDCSM is briefly introduced. The results for the NK systems are shown in Sec. III, where some discussion is presented as well. Finally, the summary is given in Sec. IV.

II. THE QUARK DELOCALIZATION COLOR SCREENING MODEL (QDCSM)

The quark delocalization color screening model (QDCSM) is an extension of the native quark cluster model [70] and was developed with aim of addressing multiquark systems. The details of QDCSM can be found in Refs. [63–66,68,69]. Here, we just present the salient features of the model. The model Hamiltonian is

$$H = \sum_{i=1}^{5}\left(m_i + \frac{\boldsymbol{p}_i^2}{2m_i}\right) - T_{\text{c.m.}} + \sum_{j>i=1}^{5}[V^C(r_{ij}) + V^G(r_{ij}) + V^B(r_{ij})], \tag{1}$$

$$V^G(r_{ij}) = \frac{1}{4}\alpha_s \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c \left[\frac{1}{r_{ij}} - \frac{\pi}{2}\delta(\boldsymbol{r}_{ij})\left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{3m_im_j}\right) - \frac{3}{4m_im_jr_{ij}^3}S_{ij}\right] \tag{2}$$

$$V^B(r_{ij}) = V_\pi(\boldsymbol{r}_{ij})\sum_{a=1}^{3}\lambda_i^a\lambda_j^a + V_K(\boldsymbol{r}_{ij})\sum_{a=4}^{7}\lambda_i^a\lambda_j^a + V_\eta(\boldsymbol{r}_{ij})\left[\left(\lambda_i^8\lambda_j^8\right)\cos\theta_P - \left(\lambda_i^0\lambda_j^0\right)\sin\theta_P\right] \tag{3}$$

$$\begin{aligned} V_\chi(\boldsymbol{r}_{ij}) = {} & \frac{g_{ch}^2}{4\pi}\frac{m_\chi^2}{12m_im_j}\frac{\Lambda_\chi^2}{\Lambda_\chi^2 - m_\chi^2}m_\chi\left\{(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j)\left[Y(m_\chi r_{ij}) - \frac{\Lambda_\chi^3}{m_\chi^3}Y(\Lambda_\chi r_{ij})\right]\right. \\ & \left. + \left[H(m_\chi r_{ij}) - \frac{\Lambda_\chi^3}{m_\chi^3}H(\Lambda_\chi r_{ij})\right]S_{ij}\right\}, \qquad \chi = \pi, K, \eta, \end{aligned} \tag{4}$$

$$V^C(r_{ij}) = -a_c\boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c[f(r_{ij}) + V_0], \tag{5}$$

$$f(r_{ij}) = \begin{cases} r_{ij}^2 & \text{if } i, j \text{ occur in the same baryon orbit} \\ \frac{1-e^{-\mu_{ij} r_{ij}^2}}{\mu_{ij}} & \text{if } i, j \text{ occur in different baryon orbits} \end{cases},$$

$$S_{ij} = \left\{ \frac{(\boldsymbol{\sigma}_i \cdot \boldsymbol{r}_{ij})(\boldsymbol{\sigma}_j \cdot \boldsymbol{r}_{ij})}{r_{ij}^2} - \frac{1}{3}\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \right\}, \tag{6}$$

$$H(x) = (1 + 3/x + 3/x^2)Y(x), \qquad Y(x) = e^{-x}/x. \tag{7}$$

where $T_{\mathrm{c.m.}}$ is the kinetic energy of the center-of-mass motion, and $\boldsymbol{\sigma}, \boldsymbol{\lambda}^c, \boldsymbol{\lambda}^a$ are the SU(2) Pauli, SU(3) color, and SU(3) flavor Gell-Mann matrices, respectively. S_{ij} is the quark tensor operator. The subscripts i, j denote the quark index in the system. $Y(x)$ and $H(x)$ are the standard Yukawa functions [71], Λ_χ is the chiral symmetry-breaking scale, and α_s is the effective scale-dependent running quark-gluon coupling constant [72]. $\frac{g_{ch}^2}{4\pi}$ is the chiral coupling constant for scalar and pseudoscalar chiral field coupling, determined from π-nucleon-nucleon coupling constant through

$$\frac{g_{ch}^2}{4\pi} = \left(\frac{3}{5}\right)^2 \frac{g_{\pi NN}^2}{4\pi} \frac{m_{u,d}^2}{m_N^2}. \tag{8}$$

In the phenomenological confinement potential V^C, the color screening parameter μ_{ij} is determined by fitting the deuteron properties, NN scattering phase shifts, and $N\Lambda$ and $N\Sigma$ scattering cross sections, respectively, with $\mu_{qq} = 0.45$, $\mu_{qs} = 0.19$, and $\mu_{ss} = 0.08$, satisfying the relation $\mu_{qs}^2 = \mu_{qq}\mu_{ss}$, where q represents u or d.

The quark delocalization effect is realized by specifying the single-particle orbital wave function in QDCSM as a linear combination of left and right Gaussians; the single-particle orbital wave functions used in the ordinary quark cluster model are

$$\psi_r(\boldsymbol{r}, \boldsymbol{s}_i, \epsilon) = [\phi_R(\boldsymbol{r}, \boldsymbol{s}_i) + \epsilon\phi_L(\boldsymbol{r}, \boldsymbol{s}_i)]/N(\epsilon), \tag{9}$$

$$\psi_l(\boldsymbol{r}, \boldsymbol{s}_i, \epsilon) = [\phi_L(\boldsymbol{r}, \boldsymbol{s}_i) + \epsilon\phi_R(\boldsymbol{r}, \boldsymbol{s}_i)]/N(\epsilon), \tag{10}$$

$$N(\epsilon) = \sqrt{1 + \epsilon^2 + 2\epsilon e^{-s_i^2/4b^2}}, \tag{11}$$

$$\phi_R(\boldsymbol{r}, \boldsymbol{s}_i) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{1}{2b^2}(\boldsymbol{r}-\frac{2}{5}\boldsymbol{s}_i)^2}, \tag{12}$$

$$\phi_L(\boldsymbol{r}, \boldsymbol{s}_i) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{1}{2b^2}(\boldsymbol{r}+\frac{3}{5}\boldsymbol{s}_i)^2}. \tag{13}$$

The $\boldsymbol{s}_i$, $i = 1, 2, \ldots, n$, are the generating coordinates, which are introduced to expand the relative motion wave function [64,65,67]. The mixing parameter $\epsilon(s_i)$ is not an adjusted one but determined variationally by the dynamics of the multiquark system itself. It is this assumption that allows the multiquark system to choose its favorable configuration in the interacting process. It has been used to explain the crossover transition between the hadron phase and the quark-gluon plasma phase [73]. From the expressions (9) and (10), we can see that the property of $\psi_r(\boldsymbol{r}, \boldsymbol{s}_i, \epsilon)$ and $\psi_l(\boldsymbol{r}, \boldsymbol{s}_i, \epsilon)$ under the space inversion is same as that of $\phi_R(\boldsymbol{r}, \boldsymbol{s}_i)$ and $\phi_L(\boldsymbol{r}, \boldsymbol{s}_i)$, which is independent of ϵ. So, the parity of the system with delocalized single-particle wave functions is the same as that of system with Gaussian as the single-particle wave functions, $P = (-1)^{L+1}$, where L is the orbital angular momentum between two subclusters if the subclusters are in the ground states. In fact, Stancu and Wilets showed this property in their Fig. 2 of Ref. [74]. All the other symbols in the above expressions have their usual meanings. All the parameters of the Hamiltonian are given in Table I, which is from our previous work of hidden strange pentaquark [54]. The calculated masses of baryons and mesons in comparison with experimental values are shown in Table II.

III. THE RESULTS AND DISCUSSIONS

In this work, we investigate the NK systems with $I = 0, 1, 2$, $J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$ in the QDCSM. For negative parity, the orbital angular momentum L between two clusters is set to 0. All the channels involved are listed in Table III. To investigate the properties of the NK systems and to see if any bound or resonance state exists or not, a three-step procedure is invoked.

A. The effective potential calculation

Because the attractive potential is necessary for forming a bound state or a resonance, for the first step, the effective potentials of all the channels listed in the Table III are calculated. The effective potential between two colorless clusters is defined as

$$V(s) = E(s) - E(\infty),$$

where $E(s)$ is the energy of the state at the separation s between two clusters. The effective potentials of the S-wave NK systems with $I = 0, 1, 2$ are shown in Figs. 1–3, respectively. For the $IJ^P = 0\frac{1}{2}^-$ system [Fig. 1(a)], one see that the potential of the NK state is almost repulsive, which means that it is difficult for the NK to form a bound state, whereas the

TABLE I. Model parameters: $m_\pi = 0.7$ fm^{-1}, $m_k = 2.51$ fm^{-1}, $m_\eta = 2.77$ fm^{-1}, $\Lambda_\pi = 4.2$ fm^{-1}, $\Lambda_K = 5.2$ fm^{-1}, $\Lambda_\eta = 5.2$ fm^{-1}, $g_{ch}^2/(4\pi) = 0.54$, and $\theta_p = -15^o$.

b (fm)	m_u (MeV)	m_s (MeV)	a_c (MeV fm^{-2})
0.518	313	573	58.03
V_0^{qq} (fm^2)	$V_0^{q\bar{q}}$ (fm^2)	a_s^{uu}	a_s^{us}
−1.2883	−0.2012	0.5652	0.5239
a_s^{ss}	$a_s^{u\bar{u}}$	$a_s^{u\bar{s}}$	$a_s^{s\bar{s}}$
0.4506	1.7930	1.7829	1.5114

TABLE II. The masses of ground-state baryons and mesons (in MeV).

	N	Δ	Λ	Σ	Σ^*	Ξ	Ξ^*	Ω
QDCSM	939	1232	1124	1238	1360	1374	1496	1642
Expt. [75]	939	1232	1116	1193	1385	1318	1533	1672
	η'		ϕ		K		K	
QDCSM	852		1020		495		892	
Expt. [75]	958		1020		495		892	

potential of the NK^* channel is attractive in the short range and therefore a bound state or a resonance NK^* is possible. From Fig. 1(b), one can see that the NK^* channel is weakly attractive, so this channel may be a bound state, and a dynamic calculation about the NK system would be needed. For the $I = 1$ system, Fig. 2(a) shows the potential of the NK system with $J^P = \frac{1}{2}^-$, in which the potential of the channel NK shows repulsive property, while other two channels are attractive. The attraction between Δ and K^* is much larger than that of the NK^* channel, which indicates that it is possible for ΔK^* to form a bound or resonance state. In Fig. 2(b), the potentials of both the $J^P = \frac{3}{2}^-$ channels ΔK and ΔK^* are weakly attractive and the potential of the channel NK^* is repulsive. From Fig. 2(c), it is obvious that the potential of the $J^P = \frac{5}{2}^-$ channel ΔK^* has a strong attraction, and it is interesting to explore the possibility of formation of bound or resonance state. For the $I = 2$ system, the potential of both the $J^P = \frac{1}{2}^-$ and $\frac{3}{2}^-$ ΔK^* channels are attractive, and a dynamic calculation is needed here to check for the existence of bound or resonance states. The potentials of ΔK with $J^P = \frac{3}{2}^-$ and ΔK^* with $J^P = \frac{5}{2}^-$ are repulsive, so a bound or resonance state is impossible here.

B. The bound-state calculation

In order to check whether the possible bound or resonance states can be realized, a dynamic calculation is needed. Here, the resonating group method (RGM) equation, which is a successful method in nuclear physics for studying a bound-state problem or scattering one, is employed. After expanding the relative motion wave function between two clusters by Gaussians, the integrodifferential equation of the

TABLE III. The coupling channels of each quantum number.

$I = 0$	$s = \frac{1}{2}$	NK, NK^*
$I = 0$	$s = \frac{3}{2}$	NK^*
$I = 1$	$s = \frac{1}{2}$	$NK, NK^*, \Delta K^*$
$I = 1$	$s = \frac{3}{2}$	$NK^*, \Delta K, \Delta K^*$
$I = 1$	$s = \frac{5}{2}$	ΔK^*
$I = 2$	$s = \frac{1}{2}$	ΔK^*
$I = 2$	$s = \frac{3}{2}$	$\Delta K, \Delta K^*$
$I = 2$	$s = \frac{5}{2}$	ΔK^*

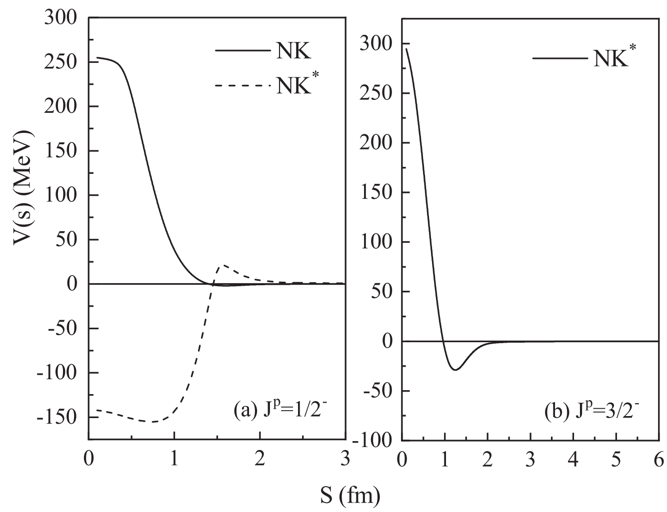

FIG. 1. The effective potential of different channels for the NK system with $I = 0$.

RGM can be reduced to a algebraic equation, the generalized eigenequation. The energy of the system can be obtained by solving the eigenequation. The details of solving the RGM equation can be found in Refs. [76,77]. In the calculation, the baryon-meson separation is taken to be less than 6 fm (to

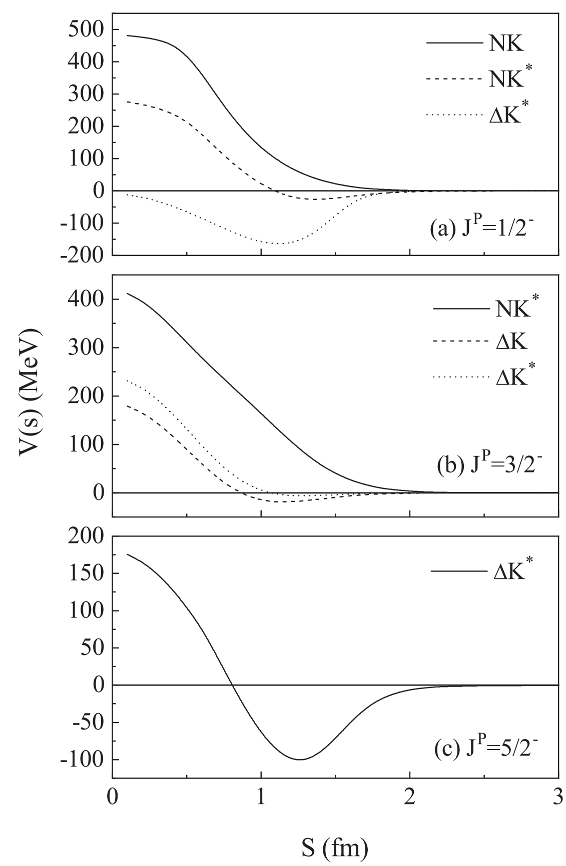

FIG. 2. The effective potential of different channels for the NK system with $I = 1$.

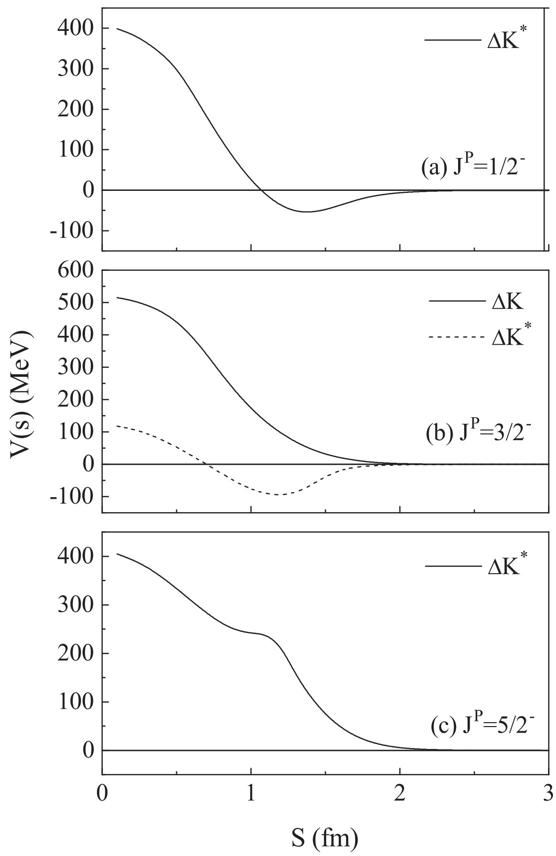

FIG. 3. The effective potential of different channels for the NK system with $I = 2$.

keep the matrix dimension manageably small). The binding energies and the masses of every single channel and those with channel coupling are listed in Table IV.

For the $I = 0, J^P = \frac{1}{2}^-$ system, the single-channel calculation shows that the energy of the NK channel is above the threshold because the attraction between N and K is too weak to tie the two particles together, which means that there is no bound state in this channel. However, for the NK^* state, the strong attractive interaction between N and K^* leads to the energy of the NK^* state below the threshold of the two particles, so the NK^* state is bound in the single-channel calculation. By coupling two channels of NK and NK^*, the lowest energy is still above the threshold of the NK channel, which indicates that no bound state for $I = 0, J^P = \frac{1}{2}^-$ system. However, we should check if the NK^* is a resonance state in the channel coupling calculation, which is presented in the next subsection. For the $I = 0, J^P = \frac{3}{2}^-$ system, the only channel is NK^* state. From Table IV, the result shows that the NK^* state is unbound, because the attraction between N and K^* is not large enough to form a bound state.

For the $I = 1$ system, the state with $J^P = \frac{1}{2}^-$ has three channels: NK, NK^*, and ΔK^*. The NK and NK^* are all unbound. It is reasonable. As shown in Fig. 2(a), the effective potential between N and K is repulsive and the one between N and K^* is weakly attractive, so neither NK nor NK^* is bound here. However, the attraction between Δ and K^* is strong enough to bind Δ and K^*, so the ΔK^* is a bound state with the binding energy of -68.1 MeV in the single calculation. Then, the channel coupling is also considered. The lowest energy is still is above the threshold of the NK channel and it means that there is no bound state for $I = 1,\ J^P = \frac{1}{2}^-$ system. The ΔK^* may turn out to be a resonance state by coupling to the open channels, NK and NK^*, which should be investigated in the scattering process of the open channels. The state with $J^P = \frac{3}{2}^-$ includes three channels: NK^*, ΔK, and ΔK^*. The effective potential of NK^* is repulsive, which make the state unbound. Both ΔK and ΔK^* are also unbound due to the weakly attractive potentials between Δ and K or K^*, as shown in Fig. 2(b). The coupling of all channels also cannot make any state bound. For the $J^P = \frac{5}{2}^-$ system, there is only one channel: ΔK^*. The attraction between Δ and K^* is large enough to form a bound state and the binding energy is -13.5 MeV.

For the $I = 2$ system, both ΔK^* with $J^P = \frac{1}{2}^-$ and $J^P = \frac{5}{2}^-$ are unbound. For the $J^P = \frac{3}{2}^-$ system, the ΔK is unbound while the ΔK^* is bound with the binding energy of -10.2 MeV in the single-channel calculation. However, the channel coupling cannot push the lowest energy under the threshold of the ΔK channel, so no bound state is obtained by channel coupling. We will check if ΔK^* is a resonance state by coupling the open channel.

It is worth mentioning that a subtraction procedure is used here to obtain the mass of a bound state here. Because the quark model cannot reproduce the experimental masses of all baryons and mesons, the theoretical threshold and the experimental threshold for a given channel is different (the threshold is the sum of the masses of the baryon and the meson in the given channel). However, the binding energy, the difference between the calculated energy of the state and the theoretical threshold, can minimize the deviation. So, we define the mass of a bound state as $M = M^{\mathrm{cal}}(5q) -$

TABLE IV. The binding energies and the masses of every single channel and those of channel coupling for the pentaquarks. The values are provided in units of MeV. "ub" denotes unbound. Empty cells indicate the channel does not exist.

Channel	$IJ^P = 0\frac{1}{2}^-$	$IJ^P = 0\frac{3}{2}^-$	$IJ^P = 1\frac{1}{2}^-$	$IJ^P = 1\frac{3}{2}^-$	$IJ^P = 1\frac{5}{2}^-$	$IJ^P = 2\frac{1}{2}^-$	$IJ^P = 2\frac{3}{2}^-$	$IJ^P = 2\frac{5}{2}^-$
NK	ub		ub					–
NK^*	$-62.3/1768.7$	ub	ub	ub				–
ΔK				ub			ub	–
ΔK^*			$-68.1/2055.9$	ub	$-13.5/2110.5$	ub	$-10.2/2113.8$	ub
E_{cc}	ub	ub	ub	ub	bound	ub	ub	ub

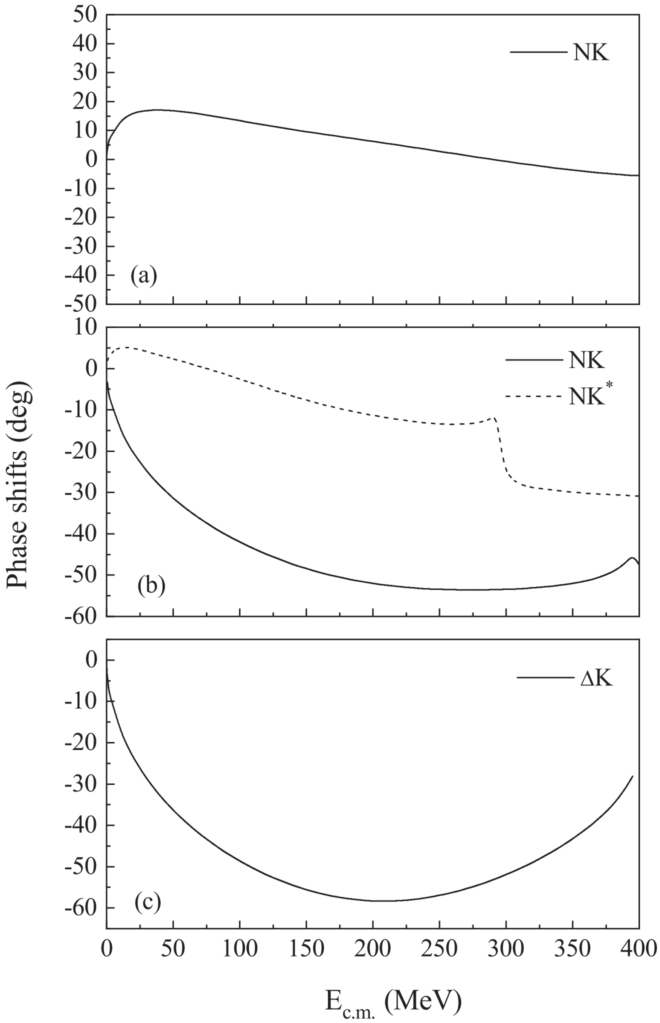

FIG. 4. The phase shift of (a) $I = 0, J^P = \frac{1}{2}^-$, (b) $I = 1, J^P = \frac{1}{2}^-$, and (c) $I = 2, J^P = \frac{3}{2}^-$.

$M^{\mathrm{cal}}(B) - M^{\mathrm{cal}}(M) + M^{\mathrm{exp}}(B) + M^{\mathrm{exp}}(M)$, where $M(B)$ and $M(M)$ denote the baryon mass and the meson mass, respectively, and the superscripts cal, exp stand for calculated and experimental, respectively.

C. The resonance state calculation

Resonances are unstable particles usually observed in the scattering process. The bound state in the single-channel calculation may turn to be a resonance after coupling with open channels. Here, we calculate the baryon-meson scattering phase shifts and investigate the resonance states by using the RGM.

From the bound-state calculation shown above, for the $I = 0, J^P = \frac{1}{2}^-$ system, the single channel NK^* is bound, while the NK channel is unbound and is identified as the open channel. For the $I = 1, J^P = \frac{1}{2}^-$ system, there are two open channels (NK, NK^*) and one closed channel (ΔK^*). The $I = 2, J^P = \frac{3}{2}^-$ system is similar to the $I = 0, J^P = \frac{1}{2}^-$ system. The open channel and the closed channel are ΔK and ΔK^*, respectively. Here, we only consider the channel coupling in the S wave, which is through the central force. The channel coupling between the S- and D-wave states is very small, which is through the tensor force, and is ignored here. All the scattering phase shifts of the open channels are shown in Fig. 4.

For the $I = 0, J^P = \frac{1}{2}^-$ system, no resonance state appeared in the phase shifts of the open channel NK, which means that the bound state NK^* in the single-channel calculation turns into a scattering state after coupling with the NK channel. The case is similar for both the $I = 1, J^P = \frac{1}{2}^-$ system and the $I = 2, J^P = \frac{3}{2}^-$ system. As shown in Fig. 4(b), no resonance state appeared in the phase shifts of the open channel NK or NK^*, which indicates that the bound state ΔK^* with $I = 1, J^P = \frac{1}{2}^-$ is not a resonance state by coupling with the open channels. However, there are cusps in NK and NK^* scattering phase shifts, respectively. The appearance of cusp means that the energy of ΔK^* is pushed up just to the threshold of the ΔK^* by coupling to the open channels. In Fig. 4(c), we can also see that ΔK^* with $I = 2, J^P = \frac{3}{2}^-$ is not a resonance by coupling to the open channel ΔK.

IV. SUMMARY

In the framework of the QDCSM, the pentaquark systems with quark contents $uudd\bar{s}$ are investigated by means of RGM. All the effective potentials between baryon and meson are calculated to search for strong attraction, which is a necessary condition for forming bound states or resonances. The dynamic calculations show that the states NK^* with $I = 0, J^P = \frac{1}{2}^-$, ΔK^* with $I = 1, J^P = \frac{1}{2}^-$, and ΔK^* with $I = 2, J^P = \frac{3}{2}^-$ are all bound in the single-channel calculation due to the strong attraction of the states. However, all these bound states turn into scattering states by coupling with the open channels. It indicates that the effect of the coupling with the open channels cannot be neglected, because it will transfer the bound state into a resonance state or a scattering state. There is only one bound state in our calculation, which is ΔK^* with $I = 1, J^P = \frac{5}{2}^-$ with the energy of 2110.5 MeV. However, in the present calculation, we only consider all possible channels in the S wave. The D-wave ΔK channel can couple to ΔK^* through the tensor interaction. The coupling is expected to turn the bound state to a resonance with decay width of several MeV, which is our next work. The ΔK^* state can also decay to $NK\pi\pi$ in P waves (two P waves are needed to conserve the parity).

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