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ΔK, ΛK, and ΣK states in the extended chiral SU(3) quark model

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By use of the resonating group method, the ΔK, ΛK, and ΣK states are further dynamically studied in the extended chiral SU(3) quark model based on our previous work. Similar to the results given by the original chiral SU(3) quark model, the calculated results here still show that the interactions of ΔK with isospin $I = 1$ and ΣK with isospin $I = 1/2$ are attractive, which can consequently lead to ΔK and ΣK quasibound states. When the channel coupling of ΛK and ΣK is considered, the calculated phase shifts show a sharp resonance between the thresholds of these two channels with spin parity $J^P = 1/2^-$.

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As we know, the nonperturbative QCD (NPQCD) effect is very important in the light quark system. Since it is difficult to seriously solve the NPQCD effect, QCD-inspired models are still needed to connect the theoretical results and the experimental observables. 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 nucleon-hyperon (*NY*) cross sections. Recently, we extended the chiral SU(3) quark model to study the baryon-meson systems by solving a resonating group method (RGM) equation. In Refs. [1,2], we studied the kaon-nucleon (*KN*) scattering phase shifts, and a satisfactory agreement with the experiment is obtained. Further, in Refs. [2,3], we dynamically studied the structures of the ΔK, ΛK, and ΣK states. Our results show that the ΔK with isospin $I = 1$ and the ΣK with isospin $I = 1/2$ have quite strong attractions, which can consequently lead to ΔK and ΣK quasibound states with binding energies of about 2 and 17 MeV, respectively. When the channel coupling of ΛK and ΣK is considered, the calculated phase shifts show a sharp resonance between the thresholds of ΛK and ΣK with spin parity $J^P = 1/2^-$ and width $\Gamma \approx 5$ MeV. The strong attraction of ΣK and the sizable off-diagonal matrix elements of ΛK and ΣK are responsible for the appearance of this resonance. Our further analyses reveal that the strong attractions of both ΔK with $I = 1$ and ΣK with $I = 1/2$ dominantly come from the σ exchange and color-magnetic force of the one-gluon exchange (OGE), and the considerably large transition interaction from ΛK to ΣK are dominantly offered by the OGE. In other words, the OGE plays an important role in the ΔK, ΛK, and ΣK systems in the chiral SU(3) quark model study.

For low-energy hadron physics, it remains a controversial problem whether the gluon or the 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]. But Isgur gave a critique of the boson exchange model and insisted that the OGE governs the baryon structure [5]. Nonetheless, it is still a challenging problem in 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.

In Refs. [6,7], the chiral SU(3) quark model is extended to include the coupling between the quark and vector chiral fields. The OGE that dominantly governs the short-range quark-quark interaction in the original chiral SU(3) quark model is now nearly replaced by the vector-meson exchange. By use of this model, we have obtained a satisfactory description of the *NN* and *KN* scattering phase shifts.

The purpose of this work is to perform a further dynamical study on the ΔK, ΛK, and ΣK systems in the extended chiral SU(3) quark model based on Refs. [2,3]. Let us first briefly review the model (the detailed formula of which can be found in Ref. [7]). The total Hamiltonian of baryon-meson systems can be written as

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

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

$$V_{ij} = V_{ij}^{\mathrm{OGE}} + V_{ij}^{\mathrm{conf}} + V_{ij}^{\mathrm{ch}}, \tag{2}$$

where V_{ij}^{OGE} is the OGE interaction, V_{ij}^{conf} is the confinement potential, and V_{ij}^{ch} is the chiral fields induced effective quark-quark potential,

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

Here $\sigma_0, \ldots, \sigma_8$ are the scalar nonet fields, $\pi_0, \ldots, \pi_8$ are the pseudoscalar nonet fields, and $\rho_0, \ldots, \rho_8$ are the vector nonet fields. The expressions for all the interactions can be found in the literature [1–3,7].

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

$$V_{i\bar{5}} = V_{i\bar{5}}^{\mathrm{dir}} + V_{i\bar{5}}^{\mathrm{ann}}, \tag{4}$$

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TABLE I. Model parameters. The meson masses and the cutoff masses are $m_{\sigma'} = 980$ 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
		$f_{\text{chv}} = 0$	$f_{\text{chv}} = 2/3 g_{\text{chv}}$
b_u (fm)	0.5	0.45	0.45
m_u (MeV)	313	313	313
m_s (MeV)	470	470	470
g_u^2	0.781	0.067	0.143
g_s^2	0.865	0.212	0.264
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

with

$$V_{i\bar{5}}^{\text{dir}} = V_{i\bar{5}}^{\text{conf}} + V_{i\bar{5}}^{\text{OGE}} + V_{i\bar{5}}^{\text{ch}} \tag{5}$$

and

$$V_{i\bar{5}}^{\text{ch}} = \sum_j (-1)^{G_j} V_{i\bar{5}}^{\text{ch},j}. \tag{6}$$

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

All the model parameters are fixed before the calculation by some special constraints, such as the mass splits between N, Δ and Λ, Σ, the stability conditions of N, Λ, and Ξ, and the masses of N, Σ, and $\overline{\Xi + \Omega}$. (For details see Refs. [1–3,7].) Their values are listed in Table I, where the first set is for the original chiral SU(3) quark model and the second and third sets are for the extended chiral SU(3) quark model by taking $f_{\text{chv}}/g_{\text{chv}}$ 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. g_u and g_s are the OGE coupling constants and a^c represents the strength of the confinement potential. All three sets of parameters can give a satisfactory description of the masses of the baryon ground states, the binding energy of the deuteron, and the NN scattering phase shifts.

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 in the extended chiral SU(3) quark model, the ΔK, ΛK, and ΣK states can be dynamically studied in the framework of the RGM, a well-established method for studying the interaction between two composite particles.

The ΔK state has already been studied in Ref. [8], where the authors claimed that they find an attractive interaction in the ΔK channel with $L = 0$ and $I = 1$. This state has also been investigated in Ref. [9] based on the χ-BS(3) approach. In Ref. [2], we study the ΔK state in the chiral SU(3) quark model and find that the interaction of ΔK with isospin $I = 1$ is attractive. Such an attraction can lead to a ΔK quasibound state with about 2 MeV binding energy. Our further analysis shows that the attraction dominantly comes from the σ exchange and the color-magnetic force of OGE.

In this work, we further dynamically study the ΔK state in the extended chiral SU(3) quark model, where the vector-meson exchanges play an important role in the short-range interaction. Figure 1 shows the diagonal matrix elements of the Hamiltonian in the generator coordinate method (GCM) [10] calculation, which can describe the interaction between two clusters Δ and K qualitatively. In Fig. 1, s denotes the generator

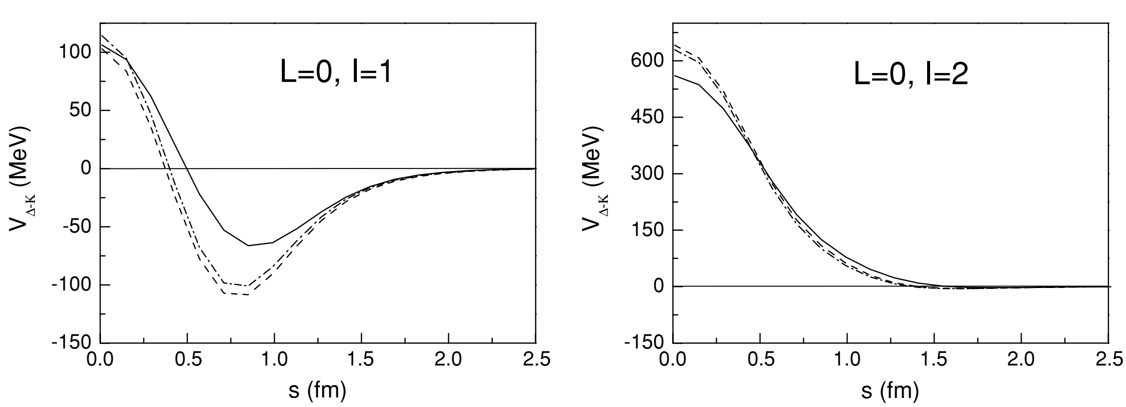

FIG. 1. The GCM matrix elements of the Hamiltonian. The solid curves represent the results obtained in the chiral SU(3) quark model. The dashed and dash-dotted curves show the results from the extended chiral SU(3) quark model by taking $f_{\text{chv}}/g_{\text{chv}}$ as 0 and 2/3, respectively.

TABLE II. Binding energy of ΔK.

Model	$B_{\Delta K}$ (MeV)	Attraction
I	3	OGE + σ
II	20	$\sigma + \rho$
III	15	$\sigma + \rho$

coordinate and $V_{\Delta\text{-}K}$ is the effective potential between the two clusters. From Fig. 1, one sees that the ΔK state with isospin $I = 1$ has an attractive interaction. Such an attraction can consequently make for a ΔK bound state, and the binding energy is tabulated in Table II. As can be seen in Fig. 1, the ΔK interaction for the isospin $I = 1$ channel is more attractive in the extended chiral SU(3) quark model than that in the original chiral SU(3) quark model, and thus the cases II and III give much bigger binding energy than that of case I. In the original chiral SU(3) quark model, the ΔK attraction comes from the σ exchange and the color-magnetic force of OGE. In the extended chiral SU(3) quark model, the OGE is nearly replaced by the vector-meson exchanges and the attraction dominantly comes from the σ and ρ exchanges.

Since the kaon meson is spin zero, the tensor force that plays an important role in reproducing the binding energy of the deuteron [6] now nearly vanishes in the ΔK system. To examine whether $(\Delta K)_{LSJ=0(3/2)(3/2)}$ is a possible resonance or bound state, the channel coupling between $(\Delta K)_{LSJ=0(3/2)(3/2)}$ and $(NK^*)_{LSJ=0(3/2)(3/2)}$ will be considered in future work.

The highlight that attracts our attention to the study of the ΛK system is the nucleon resonance $S_{11}(1535)$, of which the traditional picture is that of an excited three-quark state, with one of the three quarks orbiting in an $l = 1$ state around the other two [4,11]. In contrast from the description in the constituent quark model (CQM), on the hadron level the $S_{11}(1535)$ is argued to be a quasibound ΛK-ΣK state [12,13]. Nevertheless, in Ref. [14], the authors conclude that the $S_{11}(1535)$ is not only generated by coupling to higher baryon-meson channels but appears to require a genuine three-quark component. So up to now the physical nature of the $S_{11}(1535)$—whether it is an excited three-quark state or a quasibound baryon-meson S-wave resonance or a mixing of these two possibilities—is still a stimulating problem. A dynamical study on a quark level of the ΛK and ΣK interactions will undoubtedly make for a better understanding of the $S_{11}(1535)$ and $S_{11}(1650)$.

In Ref. [3], we study the ΛK and ΣK states in the chiral SU(3) quark model and find a strong attraction between Σ and K, which consequently results in a ΣK quasibound state with about 17 MeV binding energy. When the channel coupling of ΛK and ΣK is considered, a sharp resonance appears with spin parity $J^P = 1/2^-$. Further analysis shows that the OGE plays an important role in the ΛK and ΣK systems.

In this work, we further study the ΛK and ΣK systems in the extended chiral SU(3) quark model where the OGE is nearly reduced. Figure 2 shows the ΛK and ΣK scattering phase shifts in the one-channel calculation. The phase shifts denote that the ΣK state has a strong attractive interaction, which is consistent with the chiral Lagrangian calculation on the hadron level [12]. Such an attraction can result in a ΣK bound state, and the binding energy is tabulated in Table III. Similar to the ΔK system, the interaction of ΣK is more attractive in the extended chiral SU(3) quark model than that in the original chiral SU(3) quark model, and thus models II and III give much bigger binding energy than model I. In the original chiral SU(3) quark model,

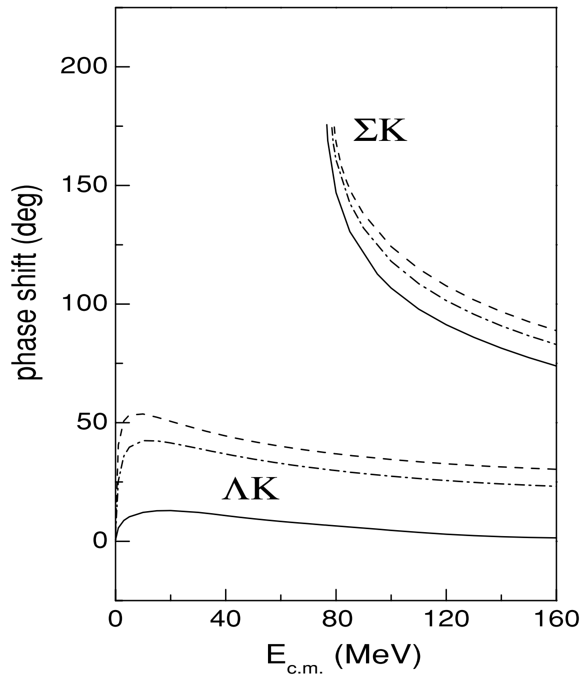

FIG. 2. The S-wave ΛK and ΣK phase shifts in the one-channel calculation. The notation is the same as in Fig. 1.

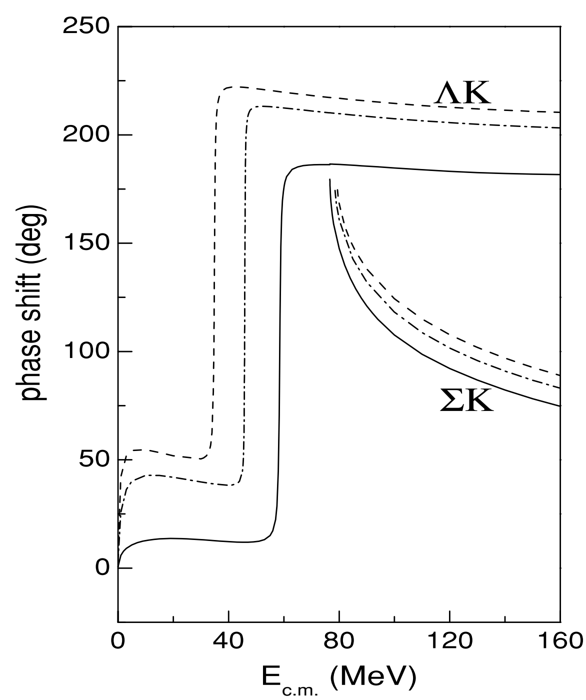

FIG. 3. The S-wave ΛK and ΣK phase shifts in the coupled-channel calculation. The notation is the same as in Fig. 1.

TABLE III. Binding energy of ΣK.

Model	$B_{\Sigma K}$ (MeV)	Attraction
I	18	OGE + σ
II	44	$\sigma + \rho + \phi$
III	33	$\sigma + \rho + \phi$

the ΣK attractive interaction comes from the σ exchange and the color-magnetic force of OGE. In the extended chiral SU(3) quark model, the OGE is nearly replaced by the vector-meson exchanges and the attraction dominantly comes from the σ, ρ, and ϕ exchanges.

We also consider the channel coupling of ΛK and ΣK, the phase shifts of which are shown in Fig. 3. One sees that there is a sharp resonance between the thresholds of ΛK and ΣK. The narrow gap of the ΛK and ΣK thresholds, the strong attraction between Σ and K, and the sizable off-diagonal matrix elements between ΛK and ΣK are responsible for the appearance of this resonance. The spin parity of this resonance is $J^P = 1/2^-$, and its mass and width are tabulated in Table IV. The results from the extended chiral SU(3) quark model are quite similar to those from the original chiral SU(3) quark model, because ρ and ϕ exchanges make contributions similar to OGE in this case. From the mass point of view and considering that the branching ratio of $S_{11}(1650)$ to ΛK is $3\%-11\%$ (With a partial width of about $4.5-16.5$ MeV), the resonance we obtained seems to be an $S_{11}(1650)$, although the calculated width is a little bit small. To draw a final conclusion regarding what the resonance we obtained is and its exact theoretical mass and width, the effects of the s-channel $q\bar{q}$ annihilation interaction as well as the coupling to the $N\pi$, $N\eta$, $N\pi\pi$, and even to the genuine $3q$ component will be considered in future work.

TABLE IV. Mass and width of the ΛK-ΣK resonance.

Model	Mass (MeV)	Γ (MeV)
I	1670	≈ 5
II	1646	≈ 4
III	1655	≈ 4

In summary, we dynamically study the ΔK, ΛK, and ΣK states in the extended chiral SU(3) quark model, where the coupling between the quark and vector chiral fields is considered and thus the OGE is nearly reduced. Although the mechanisms of the quark-quark short-range interactions are quite different in the original chiral SU(3) quark model and the extended chiral SU(3) quark model, the theoretical results from these two models are very similar in these cases. They both show that the interactions of ΔK with isospin $I = 1$ and ΣK with isospin $I = 1/2$ are attractive, which can consequently lead to ΔK and ΣK quasibound states. When the channel coupling of ΛK and ΣK is considered, our calculated phase shifts show a sharp resonance between the thresholds of these two channels with spin parity $J^P = 1/2^-$. Its exact theoretical mass and width await future work where more channel couplings and the decay properties will be studied.

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