

Coupled-channels study of ΛK and ΣK states in the chiral SU(3) quark modelF. Huang,^{1,2,3} D. Zhang,^{2,3} Z. Y. Zhang,² and Y. W. Yu²¹*CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, People's Republic of China*²*Institute of High Energy Physics, P.O. Box 918-4, Beijing 100049, People's Republic of China**³*Graduate School of the Chinese Academy of Sciences, Beijing, People's Republic of China*

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The S -wave ΛK and ΣK states with isospin $I = 1/2$ are dynamically investigated within the framework of the chiral SU(3) quark model by solving a resonating group method 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 the deuteron, and the experimental data of the nucleon-nucleon (NN) and nucleon-hyperon (NY) scattering. Assumed not to give important contributions in the scattering processes, the s -channel quark-antiquark ($q\bar{q}$) annihilation interactions are not included as a first step. The results show a strong attraction between Σ and K , which consequently results in a ΣK quasibound state with about 17-MeV binding energy, unlike the case of ΛK , which is unbound. When the channel coupling of ΛK and ΣK is considered, a sharp resonance state near 1670 MeV with spin-parity $J^P = 1/2^-$ is found. The narrow gap of the ΛK and ΣK thresholds, the strong attraction between Σ and K , and the sizable off-diagonal matrix elements of ΛK and ΣK are responsible for the appearance of this resonance.

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I. INTRODUCTION

Recently the BES Collaboration observed a significant threshold enhancement in the ΛK invariant mass spectrum from $J/\psi \rightarrow K^+ \Lambda \bar{p}$ decays [1–3]. The mass of this threshold structure N_X^* is in the range of 1500 to 1650 MeV, the width is about 70–110 MeV, and its spin-parity favors $1/2^-$. This threshold structure has a very large coupling to the ΛK final state. It is argued to be neither $N^*(1535)$ because of the nonobservation of this state in the SAPHIR experiment $\gamma p \rightarrow \Lambda K^+$ [4], nor $N^*(1650)$ because the branching ratio of $N_X^* \rightarrow \Lambda K^+$ is larger than 20% [for $N^*(1650) \rightarrow \Lambda K^+$ it is 3–11%]. But up to now it has not been confirmed finally. Theoretically, to obtain a proper understanding and a reasonable interpretation of this enhancement, getting some information about the ΛK interaction is necessary.

The other 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 [5–7]. However this scenario has difficulties in explaining the large (30–55%) $N\eta$ decay branching ratio. Differing from the description in the constituent quark model (CQM), on the hadron level the $S_{11}(1535)$ is argued to be a quasibound $\Lambda K - \Sigma K$ state based on an investigation using the so-called effective chiral Lagrangian (ECL) approach [8–10]. In Ref. [8], the authors find a strong attraction between Σ and K , and thus a bound state will be necessarily formed below the ΣK threshold. This state has a strong coupling to the $N\eta$ channel, so it is argued to be the $S_{11}(1535)$ but not $S_{11}(1650)$. Nevertheless, in Ref. [11], the authors conclude that the $S_{11}(1535)$ is not only generated by coupling to higher 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 nucleon resonance $S_{11}(1535)$ and $S_{11}(1650)$.

In spite of great successes, the constituent quark model needs to give a logical explanation, from the underlying theory of the strong interaction [i.e., quantum chromodynamics (QCD)] of the source of the constituent quark mass. Thus spontaneous vacuum breaking has to be considered, and as a consequence the coupling between the quark field and the Goldstone boson is introduced to restore the chiral symmetry. In this sense, the chiral quark model can be regarded as a quite reasonable and useful model to describe the medium-range nonperturbative QCD effect. By generalizing the SU(2) linear σ model, a chiral SU(3) quark model is developed to study the systems with strangeness [12]. This 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 of different partial waves, and the hyperon-nucleon (YN) cross sections by performing the resonating group method (RGM) calculations [12,13]. Inspired by these achievements, we try to extend this model to study the baryon-meson interaction. In Ref. [14,15], we studied the S -, P -, D -, and F -wave kaon-nucleon (KN) phase shifts and fortunately, we got quite reasonable agreement with the experimental data. At the same time, the results also show that the effects of the s -channel quark-antiquark ($q\bar{q}$) annihilation interactions can be neglected in the scattering processes, because they act only in the very short range.

In this work, we dynamically study the ΛK and ΣK states with isospin $I = 1/2$ using our chiral SU(3) quark model by solving the RGM equation. All the model parameters are taken from our previous work [12,13], which gave a satisfactory

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description for the energies of the baryon ground states, the binding energy of the deuteron, the NN scattering phase shifts, and the YN cross sections. It is assumed that the s -channel $q\bar{q}$ interactions do not contribute significantly to a molecular state or a scattering process, which is the subject of our present work, and thus as a preliminary study they are not included in the $\Lambda - K$ and $\Sigma - K$ interactions. Our numerical results show a strong attraction between Σ and K , which is qualitatively consistent with the effective chiral Lagrangian calculation [8]. A ΣK quasibound state is thus consequently formed with a binding energy of about 17 MeV, whereas the ΛK is unbound. Further the channel coupling of ΛK and ΣK is considered and the ΛK scattering phase shifts show a sharp resonance with a mass $M \approx 1669$ MeV and a width $\Gamma \approx 5$ MeV. The small mass difference of the ΛK and ΣK thresholds, the strong attraction between Σ and K , and the sizable off-diagonal matrix elements of ΛK and ΣK are responsible for the appearance of this resonance. Although the effects of the s -channel interactions as well as the coupling to the $N\eta$ and $N\pi$ channels should be considered further, the present results are interesting and helpful for understanding the new observation of BES [1–3] and the structure of the S_{11} nuclear resonances.

The article is organized as follows. In the next section the framework of the chiral SU(3) quark model is briefly introduced. The results for the ΛK and ΣK states are shown in Sec. III, where some discussion is presented as well. Finally, the summary is given in Sec. IV.

II. FORMULATION

As is well known, nonperturbative QCD effects are very important in light quark systems. To consider low-momentum medium-range nonperturbative QCD effects, an SU(2) linear σ model [16,17] is proposed to study the NN interaction. To extend the study to systems with strangeness, we generalized the idea of the SU(2) σ model to the flavor SU(3) case, in which a unified coupling between quarks and all scalar and pseudoscalar chiral fields is introduced, and the constituent quark mass can be understood in principle as the consequence of a spontaneous chiral symmetry breaking of the QCD vacuum [12]. With this generalization, the interacting Hamiltonian between quarks and chiral fields can be written as follows:

$$H_I^{\text{ch}} = g_{\text{ch}} F(\mathbf{q}^2) \bar{\psi} \left(\sum_{a=0}^8 \sigma_a \lambda_a + i \sum_{a=0}^8 \pi_a \lambda_a \gamma_5 \right) \psi, \quad (1)$$

where g_{ch} is the coupling constant between the quark and chiral-field and λ_0 a unitary matrix. $\lambda_1, \dots, \lambda_8$ are the Gell-Mann matrix of the flavor SU(3) group, $\sigma_0, \dots, \sigma_8$ the scalar nonet fields, and π_0, \dots, π_8 the pseudoscalar nonet fields. $F(\mathbf{q}^2)$ is a form factor inserted to describe the chiral-field structure [18–21] and, as usual, it is taken to be the following:

$$F(\mathbf{q}^2) = \left(\frac{\Lambda^2}{\Lambda^2 + \mathbf{q}^2} \right)^{1/2}, \quad (2)$$

with Λ being the cutoff mass of the chiral field. Clearly, H_I^{ch} is invariant under the infinitesimal chiral SU(3) transformation.

From H_I^{ch} , the chiral-field-induced effective quark-quark potentials can be derived, and their expressions are given in the following:

$$V_{\sigma_a}(\mathbf{r}_{ij}) = -C(g_{\text{ch}}, m_{\sigma_a}, \Lambda) X_1(m_{\sigma_a}, \Lambda, r_{ij}) \times [\lambda_a(i)\lambda_a(j)] + V_{\sigma_a}^{l,s}(\mathbf{r}_{ij}), \quad (3)$$

$$V_{\pi_a}(\mathbf{r}_{ij}) = C(g_{\text{ch}}, m_{\pi_a}, \Lambda) \frac{m_{\pi_a}^2}{12m_{q_i}m_{q_j}} X_2(m_{\pi_a}, \Lambda, r_{ij}) \times (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) [\lambda_a(i)\lambda_a(j)] + V_{\pi_a}^{\text{ten}}(\mathbf{r}_{ij}), \quad (4)$$

and

$$V_{\sigma_a}^{l,s}(\mathbf{r}_{ij}) = -C(g_{\text{ch}}, m_{\sigma_a}, \Lambda) \frac{m_{\sigma_a}^2}{4m_{q_i}m_{q_j}} \left\{ G(m_{\sigma_a} r_{ij}) - \left(\frac{\Lambda}{m_{\sigma_a}} \right)^3 G(\Lambda r_{ij}) \right\} [\mathbf{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)] [\lambda_a(i)\lambda_a(j)], \quad (5)$$

$$V_{\pi_a}^{\text{ten}}(\mathbf{r}_{ij}) = C(g_{\text{ch}}, m_{\pi_a}, \Lambda) \frac{m_{\pi_a}^2}{12m_{q_i}m_{q_j}} \left\{ H(m_{\pi_a} r_{ij}) - \left(\frac{\Lambda}{m_{\pi_a}} \right)^3 H(\Lambda r_{ij}) \right\} [3(\boldsymbol{\sigma}_i \cdot \hat{\mathbf{r}}_{ij})(\boldsymbol{\sigma}_j \cdot \hat{\mathbf{r}}_{ij}) - \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j] [\lambda_a(i)\lambda_a(j)], \quad (6)$$

with m_{σ_a} and m_{π_a} for the masses of the scalar and pseudoscalar mesons, respectively, and

$$C(g_{\text{ch}}, m, \Lambda) = \frac{g_{\text{ch}}^2}{4\pi} \frac{\Lambda^2}{\Lambda^2 - m^2} m, \quad (7)$$

$$X_1(m, \Lambda, r) = Y(mr) - \frac{\Lambda}{m} Y(\Lambda r), \quad (8)$$

$$X_2(m, \Lambda, r) = Y(mr) - \left(\frac{\Lambda}{m} \right)^3 Y(\Lambda r), \quad (9)$$

$$Y(x) = \frac{1}{x} e^{-x}, \quad (10)$$

$$G(x) = \frac{1}{x} \left(1 + \frac{1}{x} \right) Y(x), \quad (11)$$

$$H(x) = \left(1 + \frac{3}{x} + \frac{3}{x^2} \right) Y(x). \quad (12)$$

In the chiral SU(3) quark model, in addition to the chiral-field-induced quark-quark interaction, which describes nonperturbative QCD effects for the medium range, to study the baryon structure and hadron-hadron dynamics, one still needs to include an effective one-gluon-exchange interaction V_{ij}^{OGE} for the short range,

$$V_{ij}^{\text{OGE}} = \frac{1}{4} g_i g_j (\lambda_i^c \cdot \lambda_j^c) \left\{ \frac{1}{r_{ij}} - \frac{\pi}{2} \delta(\mathbf{r}_{ij}) \right. \\ \left. \times \left(\frac{1}{m_{q_i}^2} + \frac{1}{m_{q_j}^2} + \frac{4}{3} \frac{1}{m_{q_i} m_{q_j}} (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \right) \right\} + V_{\text{OGE}}^{l,s}, \quad (13)$$

with

$$V_{\text{OGE}}^{l,s} = -\frac{1}{16} g_i g_j (\lambda_i^c \cdot \lambda_j^c) \frac{3}{m_{q_i} m_{q_j} r_{ij}^3} \mathbf{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j), \quad (14)$$

and a confinement potential V_{ij}^{conf} for the long range,

$$V_{ij}^{\text{conf}} = -a_{ij}^c (\lambda_i^c \cdot \lambda_j^c) r_{ij}^2 - a_{ij}^{c0} (\lambda_i^c \cdot \lambda_j^c). \quad (15)$$

For the systems with an antiquark \bar{s} , the total Hamiltonian can be written as follows [14,15,22]:

$$H = \sum_{i=1}^5 T_i - T_G + \sum_{i<j=1}^4 V_{ij} + \sum_{i=1}^4 V_{i\bar{s}}, \quad (16)$$

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

$$V_{ij} = V_{ij}^{\text{OGE}} + V_{ij}^{\text{conf}} + V_{ij}^{\text{ch}}, \quad (17)$$

$$V_{ij}^{\text{ch}} = \sum_{a=0}^8 V_{\sigma_a}(\mathbf{r}_{ij}) + \sum_{a=0}^8 V_{\pi_a}(\mathbf{r}_{ij}). \quad (18)$$

$V_{i\bar{s}}$ in Eq. (16) includes two parts: direct interaction and annihilation parts,

$$V_{i\bar{s}} = V_{i\bar{s}}^{\text{dir}} + V_{i\bar{s}}^{\text{ann}}, \quad (19)$$

with

$$V_{i\bar{s}}^{\text{dir}} = V_{i\bar{s}}^{\text{conf}} + V_{i\bar{s}}^{\text{OGE}} + V_{i\bar{s}}^{\text{ch}}, \quad (20)$$

where

$$V_{i\bar{s}}^{\text{conf}} = -a_{i\bar{s}}^c (-\lambda_i^c \cdot \lambda_{\bar{s}}^{c*}) r_{i\bar{s}}^2 - a_{i\bar{s}}^{c0} (-\lambda_i^c \cdot \lambda_{\bar{s}}^{c*}), \quad (21)$$

$$\begin{aligned} V_{i\bar{s}}^{\text{OGE}} = & \frac{1}{4} g_i g_s (-\lambda_i^c \cdot \lambda_{\bar{s}}^{c*}) \left\{ \frac{1}{r_{i\bar{s}}} - \frac{\pi}{2} \delta(\mathbf{r}_{i\bar{s}}) \left(\frac{1}{m_{q_i}^2} + \frac{1}{m_{q_s}^2} \right) \right. \\ & \left. + \frac{4}{3} \frac{1}{m_{q_i} m_{q_s}} (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_s) \right\} - \frac{1}{16} g_i g_s (-\lambda_i^c \cdot \lambda_{\bar{s}}^{c*}) \\ & \times \frac{3}{m_{q_i} m_{q_s} r_{i\bar{s}}^3} \mathbf{L} \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_s), \end{aligned} \quad (22)$$

and

$$V_{i\bar{s}}^{\text{ch}} = \sum_j (-1)^{G_j} V_{i\bar{s}}^{\text{ch},j}. \quad (23)$$

Here $(-1)^{G_j}$ represents the G parity of the j th meson. The $q\bar{q}$ annihilation interactions, $V_{i\bar{s}}^{\text{ann}}$, are not included in the $\Lambda - K$ and $\Sigma - K$ interactions in this preliminary 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 for the energies of the baryon ground states, the binding energy of the deuteron, the NN scattering phase shifts, and the YN cross sections. Here we briefly give the procedure for the parameter determination. We have three initial input parameters: the harmonic-oscillator width parameter b_u , the up (down) quark mass $m_{u(d)}$, and the strange quark mass m_s . These three parameters are taken

TABLE I. Model parameters. The meson masses and the cutoff masses are as follows: $m_{\sigma'} = 980$ 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, and $\Lambda = 1100$ MeV.

m_u (MeV)	313
m_s (MeV)	470
b_u (fm)	0.5
g_u	0.886
g_s	0.917
m_σ (MeV)	595
a_{uu}^c (MeV/fm ²)	48.1
a_{us}^c (MeV/fm ²)	60.7
a_{ss}^c (MeV/fm ²)	101.2
a_{uu}^{c0} (MeV)	-43.6
a_{us}^{c0} (MeV)	-38.2
a_{ss}^{c0} (MeV)	-36.1

to be the usual values: $b_u = 0.5$ fm, $m_{u(d)} = 313$ MeV, and $m_s = 470$ MeV. By some special constraints, other model parameters are fixed in the following way. The chiral coupling constant g_{ch} is fixed by the following:

$$\frac{g_{\text{ch}}^2}{4\pi} = \left(\frac{3}{5} \right)^2 \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{M_N^2}, \quad (24)$$

with empirical value $g_{NN\pi}^2/4\pi = 13.67$. The masses of the mesons are taken to be the experimental values, except for the σ meson. The m_σ is treated as an adjustable parameter and obtained to be 595 MeV by fitting the binding energy of the deuteron. The cutoff radius Λ^{-1} is taken to be the value close to the chiral symmetry breaking scale [18–21]. After the parameters of chiral fields are fixed, the one-gluon-exchange coupling constants g_u and g_s are determined by the mass splits between N , Δ and Λ , Σ respectively. The confinement strengths a_{uu}^c , a_{us}^c , and a_{ss}^c are fixed by the stability conditions of N , Λ , and Ξ and the zero-point energies a_{uu}^{c0} , a_{us}^{c0} , and a_{ss}^{c0} by fitting the masses of N , Σ and $\Xi + \Omega$, respectively. All the parameters are tabulated in Table I.

With all parameters determined in the chiral SU(3) quark model, the ΛK and ΣK systems can be dynamically studied in the frame work of the RGM. The wave function of the five-quark system is of following form:

$$\Psi = \sum_\beta \mathcal{A}[\hat{\phi}_A(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2) \hat{\phi}_B(\boldsymbol{\xi}_3) \chi_\beta(\mathbf{R}_{AB})], \quad (25)$$

where $\boldsymbol{\xi}_1$ and $\boldsymbol{\xi}_2$ are the internal coordinates for the cluster A (Λ or Σ), and $\boldsymbol{\xi}_3$ the internal coordinate for the cluster B (K). $\mathbf{R}_{AB} \equiv \mathbf{R}_A - \mathbf{R}_B$ is the relative coordinate between the two clusters, A and B , and $\beta \equiv (A, B, I, S, L, J)$ specifies the hadron species (A, B) and quantum numbers of the baryon-meson channel. The $\hat{\phi}_A$ ($\hat{\phi}_B$) is the antisymmetrized internal cluster wave function of A (B), and $\chi_\beta(\mathbf{R}_{AB})$ the relative wave function of the two clusters. The symbol \mathcal{A} is the antisymmetrizing operator defined as follows:

$$\mathcal{A} \equiv 1 - \sum_{i \in A} P_{i4} \equiv 1 - 3P_{34}. \quad (26)$$

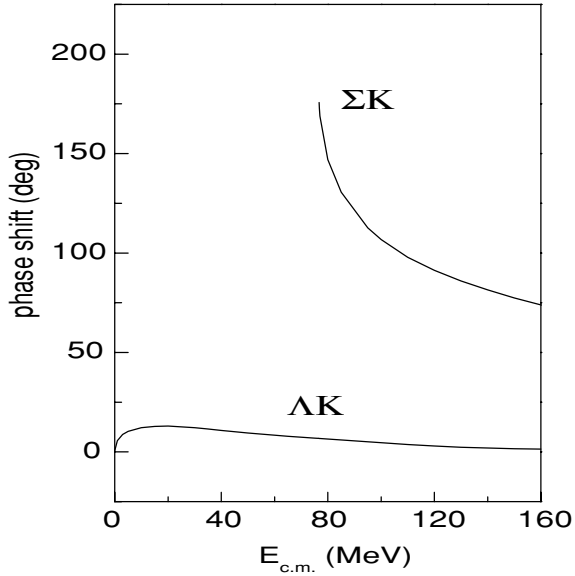


FIG. 1. The S -wave ΛK and ΣK phase shifts in the one-channel calculation.

Substituting Ψ into the projection equation

$$\langle \delta\Psi | (H - E) | \Psi \rangle = 0, \quad (27)$$

we obtain the coupled integrodifferential equation for the relative function χ_β as follows:

$$\sum_{\beta'} \int [\mathcal{H}_{\beta\beta'}(\mathbf{R}, \mathbf{R}') - E\mathcal{N}_{\beta\beta'}(\mathbf{R}, \mathbf{R}')] \chi_{\beta'}(\mathbf{R}') d\mathbf{R}' = 0, \quad (28)$$

where the Hamiltonian kernel \mathcal{H} and normalization kernel \mathcal{N} can, respectively, be calculated by the following:

$$\left\{ \begin{array}{l} \mathcal{H}_{\beta\beta'}(\mathbf{R}, \mathbf{R}') \\ \mathcal{N}_{\beta\beta'}(\mathbf{R}, \mathbf{R}') \end{array} \right\} = \left\langle \left[\hat{\phi}_A(\xi_1, \xi_2) \hat{\phi}_B(\xi_3) \right]_\beta \delta(\mathbf{R} - \mathbf{R}_{AB}) \right. \\ \left. \times \left| \begin{array}{c} H \\ 1 \end{array} \right| \mathcal{A} \left\{ \left[\hat{\phi}_A(\xi_1, \xi_2) \hat{\phi}_B(\xi_3) \right]_{\beta'} \right. \right. \\ \left. \left. \times \delta(\mathbf{R}' - \mathbf{R}_{AB}) \right\} \right\rangle. \quad (29)$$

Equation (28) is the so-called coupled-channel RGM equation. Expanding unknown $\chi_\beta(\mathbf{R}_{AB})$ by employing well-defined basis wave functions, such as Gaussian functions, one can solve the coupled-channel 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. [14,23–26].

III. RESULTS AND DISCUSSIONS

We perform a RGM dynamical study of ΛK and ΣK states with isospin $I = 1/2$ in our chiral $SU(3)$ quark model. Figure 1 shows one-channel-calculation results for the S -wave ΛK and ΣK ($I = 1/2$) elastic scattering phase shifts. Here the one-channel-calculation means without considering the channel coupling of ΛK and ΣK . The phase shifts show up a strong

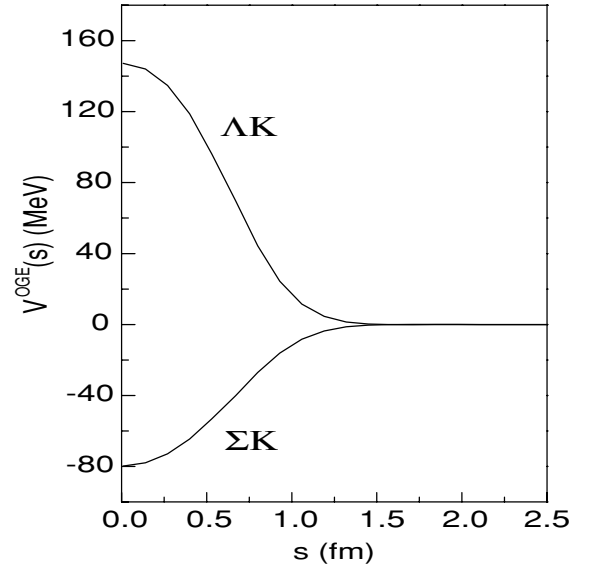


FIG. 2. The GCM matrix elements of OGE.

attractive interaction between Σ and K , which is qualitatively consistent with the effective chiral Lagrangian calculation based on the hadron level [8,9], and a very weak interaction between Λ and K . Our further analysis demonstrates that this strong attraction between Σ and K dominantly comes from the color magnetic force of OGE and the σ meson exchange. Such a strong attraction can consequently result in a ΣK quasibound state. A concrete solution of the RGM equation for a bound state problem shows that ΣK is really bound and its binding energy is about 17 MeV. A similar study to the ΛK system is also made, as we expected it is unbound, because there is not enough attraction between Λ and K .

To understand the results better, an extensive analysis is carried out to see the contributions from various parts of the interactions in the ΛK and ΣK systems. Figure 2 shows the diagonal matrix elements of the one-gluon-exchange potential in the generator coordinate method (GCM) calculation [23], which can describe the interactions between two clusters Λ (Σ) and K qualitatively. In Fig. 2, s denotes the generator coordinate and $V^{\text{OGE}}(s)$ is the OGE effective potential between the two clusters. One sees that the OGE effective potential is attractive for ΣK while repulsive for ΛK . This property is quite interesting because the attraction of OGE in the short distance may as a consequence make Σ and K form a quasibound ΣK state, and simultaneously the short-range strong repulsion indicates that it is difficult to form a ΛK bound state. One may argue that the OGE interaction of NN^3S_1 partial wave is also repulsive, but a weakly bound deuteron is also formed. This is understandable if one notices that the tensor force of the one-pion exchange plays an important role in reproducing the binding energy of the deuteron [13]. But in the ΛK and ΣK systems the tensor force totally vanishes because the kaon meson is spin zero and the total spin of the two clusters is $1/2$. The tensor force can exist only when $|S - 2| = S$, where S is the total spin of two clusters. This holds for investigations on both quark and hadron levels. Note on the hadron level there is no one-pion exchange between Λ and K

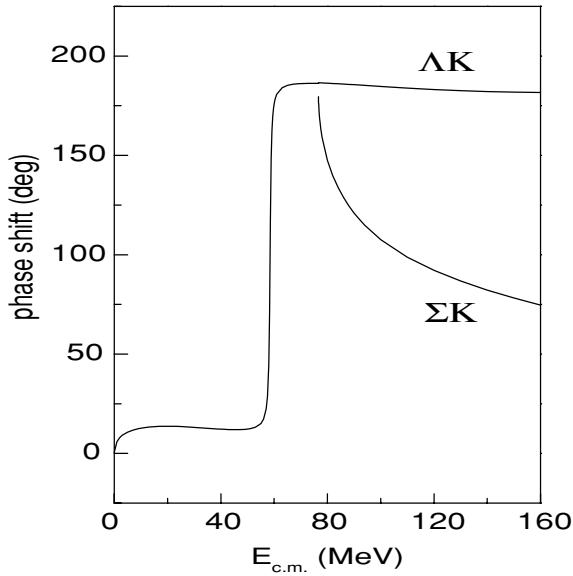


FIG. 3. The S -wave ΛK and ΣK phase shifts in the coupled-channel calculation.

because Λ has isospin zero and π has isospin one, whereas in the quark model study although comparatively weak the one-pion exchange does exist because of the quark exchange [see Eqs. (25)–(26)] required by the Pauli principle.

As a second step, we do a two-channel-coupling calculation of ΛK and ΣK systems. The phase shifts are shown in Fig. 3. One sees that there is a sharp resonance with a mass $M \approx 1669$ MeV and a width $\Gamma \approx 5$ MeV. It is not difficult to understand the appearance of this resonance state if one notices the following three important features. (1) The mass difference of the ΛK and ΣK thresholds is small (about 78 MeV). Generally speaking, the closer the thresholds of these two channels are, the larger the channel-coupling effects could be. (2) There is a strong attractive interaction between Σ and K . Such a strong attraction can result in a ΣK quasibound state with a binding energy of about 17 MeV. Thus when it couples to the ΛK channel, a resonance would possibly appear between the thresholds of ΛK and ΣK . (3) The off-diagonal matrix elements of ΛK and ΣK are comparatively big. Such sizable off-diagonal matrix elements can give a great impact on the ΛK phase shifts in the coupled-channel calculation.

In the coupled-channel study, the transition potential from ΣK to ΛK in our framework is a nonlocal one. In Fig. 4 we give the diagonal matrix elements in the coupled channel of the Hamiltonian in the GCM calculation, which can describe the transition potential qualitatively. In this figure, s denotes the generator coordinate and $V_{\Lambda K-\Sigma K}(s)$ is the effective transition potential of the coupled channel. One can see that the matrix elements of the transition interaction from ΣK to ΛK are really considerably large. Further analysis reveals that this interaction dominantly comes from the color magnetic force of OGE.

The P -wave ΛK and ΣK phase shifts are also investigated. Figure 5 shows the results computed by solving a two-channel RGM equation. The phase shifts of the coupled-channel calculation are almost the same as those without channel

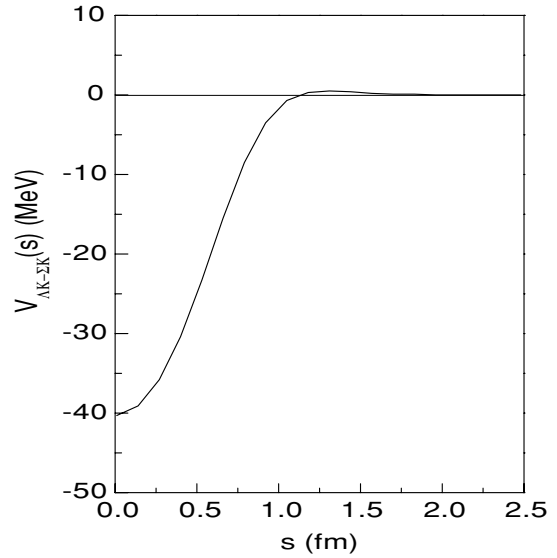


FIG. 4. The GCM matrix elements of the Hamiltonian in the coupled-channel calculation.

coupling. This is reasonable because the $\Lambda K - \Sigma K$ off-diagonal matrix elements come from the color magnetic force of OGE, whereas in the P wave such an interaction nearly vanishes. Thus the channel coupling effect is small enough to be neglected.

One thing should be mentioned: our results are independent of the confinement potential because between two color-singlet clusters the confinement potential scarcely contributes any interactions [14,15]. Thus our numerical results will remain almost unchanged; even the color quadratic confinement is replaced by the color linear one.

We now discuss the resonance obtained from the coupled-channel calculation. The present work is just making a dynamical study on the quark level of the ΛK and ΣK interactions. Surely there are other channels that also couple to these two channels, such as the $N\eta$ and $N\pi$ channels and even a genuine $3q$ component. These channels are significant

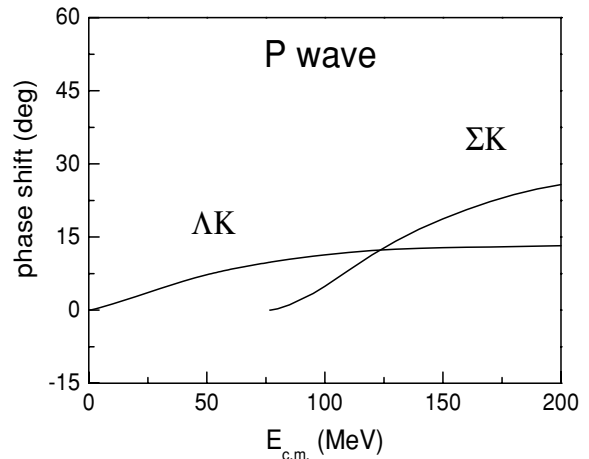


FIG. 5. The P -wave ΛK and ΣK phase shifts in the coupled-channel calculation.

and essential for giving a proper explanation of the states with $J^P = 1/2^-$ and mass between 1500 and 1700 MeV [N_X^* , $S_{11}(1535)$, $S_{11}(1650)$]. The properties of the N^* , such as that of the $N^*(1535)$ coupling strongly to $N\eta$ and the $N^*(1650)$ having a large branching ratio to $N\pi$, should be expected to hold automatically if all the channels were considered. In this work we consider only the ΛK and ΣK channels. Certainly the $N^*(1535)$ can not be explained because the $N\eta$ channel is omitted. From the mass point of view and considering that the branching ratio of $N^*(1650)$ to ΛK is 3–11%, the resonance we obtained prefers to be an $N^*(1650)$, though the calculated width is too small. It is expected that the coupling to $N\pi$ would give rise to a much larger width than the present calculated one because empirically the $N\pi$ channel accounts for 55–90% of the width of $N^*(1650)$. To some extent the possibility of this resonance to be the N_X^* observed by the BES Collaboration cannot be ruled out because preliminarily the N_X^* has a large branching ratio ($>20\%$) to the ΛK final state, and its mass is in the range of 1500 to 1650 MeV though up to now they have not yet been confirmed. Anyhow, the final conclusion regarding what this resonance is [N_X^* , $S_{11}(1535)$, $S_{11}(1650)$, or any other state] and its exact theoretical mass and width must wait for further work where more channel couplings will be included and the decay properties will be studied.

In Refs. [27,28], many low-lying resonances are studied as quasibound meson-baryon states dynamically generated from the interaction of the octet of pseudoscalar mesons with the octet of the $1/2^+$ baryons based on investigations using the effective chiral Lagrangian approach. Two octets and one singlet of dynamically generated resonances are predicted in these works. The interesting thing for us is that, if the $N^*(1535)$ can really be explained as a meson-baryon state as claimed by the authors, then there should be another state with the same quantum numbers and other properties of the $N^*(1535)$.

IV. SUMMARY

In summary, we perform a dynamical study of ΛK and ΣK states in the framework of the chiral SU(3) quark model by solving the RGM equation. The model parameters are taken to be the values determined by the energies of the baryon ground states, the binding energy of the deuteron, the NN scattering phase shifts, and the YN cross sections. Because this is a preliminary study, the s -channel $q\bar{q}$ annihilation interactions are not included. The results show a strong attraction between the sigma and kaon, and a ΣK quasibound state is thus formed as a consequence with a binding energy of about 17 MeV, whereas the ΛK is unbound. When the channel coupling of ΛK and ΣK is considered, the scattering phase shifts show a sharp resonance with a mass $M \approx 1669$ MeV and a width $\Gamma \approx 5$ MeV. The small mass difference of the ΛK and ΣK thresholds, the strong attraction between Σ and K , and the sizable off-diagonal matrix elements of ΛK and ΣK are responsible for the appearance of this resonance. The results are interesting and useful for understanding the new observation of BES [1–3] and the structure of the S_{11} nuclear resonances. The final conclusion regarding the resonance we obtained and its exact theoretical mass and width will wait for further work where the effects of the s -channel $q\bar{q}$ annihilation as well as the coupling to the $N\eta$ and $N\pi$ channels and even to a genuine $3q$ component will be considered and the decay properties will be studied.

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