\[ \Sigma_c \bar{D} \text{ and } \Lambda_c \bar{D} \text{ states in a chiral quark model} \]

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The S-wave \( \Sigma_c \bar{D} \) and \( \Lambda_c \bar{D} \) states with isospin \( I = 1/2 \) and spin \( S = 1/2 \) are dynamically investigated within the framework of a chiral constituent quark model by solving a resonating group method (RGM) equation. The results show that the interaction between \( \Sigma_c \) and \( \bar{D} \) is attractive, which consequently results in a \( \Sigma_c \bar{D} \) bound state with the binding energy of about 5 – 42 MeV, unlike the case of \( \Lambda_c \bar{D} \) state, which has a repulsive interaction and thus is unbound. The channel coupling effect of \( \Sigma_c \bar{D} \) and \( \Lambda_c \bar{D} \) is found to be negligible due to the fact that the gap between the \( \Sigma_c \bar{D} \) and \( \Lambda_c \bar{D} \) transition interaction is weak.

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I. INTRODUCTION

Understanding the structure and dynamical origin of baryon resonances is one of the most important topics within the field of hadron physics. On quark level, several constituent quark models have been developed to investigated the mass spectrum of excited baryon states. Igur, Karl, and Capstick \textit{et al.} described the baryon resonances as excited states of three constituent quarks (\( qqq \)) which are confined by a phenomenological confinement potential and interact through a residual interaction inspired by one gluon exchange (OGE) \([1, 2]\). Glozman and Riska \textit{et al.} proposed a rather different interaction mechanism. In their model, two quarks interact via Goldstone boson exchanges (GBE) in addition to a phenomenological confinement potential, and it is claimed that the flavor-dependent interaction is responsible for the low mass of the Roper resonance \( (N^* (1440)) \) \([3, 4]\). So far it is not clear whether the interactions among the three constituent quarks, which are assumed to form the baryon resonances, should be described by either OGE or GBE or a mixture of both \([3, 8]\). In chiral constituent quark models, it is found that some nucleon resonances are able to be accommodated as baryon-meson dynamically generated resonances \([7, 9]\). In Refs. \([7, 8]\), the \( \Lambda K \) and \( \Sigma K \) states have been dynamically investigated in a chiral \( SU(3) \) quark model, and it is shown that a resonance with the same quantum numbers as the \( S_{11} \) nucleon resonances can be dynamically generated due to the strong \( \Sigma K \) attraction. Also in Ref. \([9]\) the \( K N \) and \( \pi \Sigma \) interactions have been dynamically investigated within the extended chiral \( SU(3) \) quark model, and it is found that both the \( \pi \Sigma \) and \( K N \) are bound and the latter appears as a \( \pi \Sigma \) resonance in the coupled-channels calculation. This resonance is referred to \( \Lambda(1405) \).

On hadron level, various sophisticated coupled-channel approaches are formulated for the study of baryon resonances. In the K-matrix approximation approach \([10-12]\), only on-shell intermediate states are taken into account when solving the scattering equation for two-body scattering, which prevents the virtual two-body interme-

\( qqq \) or \( 5 \)-quark configurations \( (qqqqq) \) or baryon-meson dynamically generated states or a mixture of them.

The study of \( \Sigma_c \bar{D} \) and \( \Lambda_c \bar{D} \) states is of particular interest. If there exists a \( \Sigma_c \bar{D} \) bound state or a \( \Sigma_c \bar{D}-\Lambda_c \bar{D} \) dynamically generated state, its energy will be around 4.3 GeV. Unlike the low energy resonances where the excitation energies, i.e. the energy differences of nucleon
ground state and nucleon resonance states, are hundreds of MeV which are usually comparable to the 3q configuration excitation energy, such a high energy resonance, if it exists, will have more than 3.3 GeV excitation energy and thus will definitely exclude the explanation as three light quark configuration (qqq), and only the description that this state is dominated by hidden charm five constituent quark configuration (qqqcc) or ΣcD bound state or ΣcD–ΛcD resonance state or a mixture of them will be possible.

In Refs. 22, 23, the interaction between ΣcD and ΛcD has been studied within the framework of the coupled-channel unitary approach. There, a ΣcD bound state is obtained with the energy of 4.269 GeV, which is about 52 MeV below the ΣcD threshold. This state is found not to couple to ΛcD channel even its energy is about 114 MeV above the ΛcD threshold. Since the unitary approach used in Refs. 22, 23 is restricted to the contact term interaction only by neglecting the momentum-dependent terms, the study of the ΣcD and ΛcD state in other approaches is imperative in order to check the model dependence and to confirm the possibility of the existence of such a ΣcD bound state.

In the past few years, the chiral SU(3) quark model and its extended version have shown to be quite reasonable and useful models to describe the medium-range non-perturbative QCD effect in light flavor systems. Quite successes have been achieved when these two models were applied to the studies of the energies of the baryon ground states, the binding energy of the deuteron, the nucleon–nucleon (NN) and kaon–nucleon (KN) scattering phase shifts of different partial waves, and the hyperon–nucleon (YN) and anti-kaon–nucleon (K N) cross sections. In the chiral SU(3) quark model, the quark–quark interaction contains OGE, confinement potential, and boson exchanges stemming from scalar and pseudoscalar nonets. In the extended chiral SU(3) quark model, the boson exchanges stemming from the vector nonets are also included, and as a consequence the OGE in largely reduced by fitting to the energies of the octet and decuplet baryon ground states. Recently, these two models have also been applied to study the systems of Nφ, NΩ, ΞK, Ωπ, Ωω, ωφ, and D0D∗0 et al. 21, 31, 33.

In this work, we further extend the chiral SU(3) quark model and its extended version to perform a dynamical coupled-channel study of the ΣcD and ΛcD states in the framework of the resonating group method (RGM), a well established method for studying the interactions among composite particles. The quark configuration of the considered system is (qqc)-(qc) with q being the light-flavor quark u or d. We take the interaction between the light-flavor quark pair qq from our previous works where the parameters are fixed by a fitting of the energies of octet and decuplet baryon ground states, the binding energy of deuteron, the NN scattering phase shifts, and the Y N cross sections. The light-heavy quark pair qc or q̅c and the heavy-heavy quark pair c̅c are considered here to be interacted via OGE and confinement potential. The only adjustable parameter is the charm quark mass m c, while the parameters of OGE and confinement for qc, q ̅c and c ̅c interactions are fixed by the masses of charmed baryons Σc, Λc and charmed mesons D, D∗ and the charmonium J/ψ, ηc, and by the stability conditions of those hadrons. Our results show that the interaction between Σc and D is attractive, which consequently results in a ΣcD bound state with the binding energy of about 5–42 MeV, unlike the case of ΛcD state, which has a repulsive interaction and thus is unbound. The channel coupling effect of ΣcD and ΛcD is found to be negligible due to the fact that the gap between the ΣcD and ΛcD thresholds is relatively large and the ΣcD and ΛcD transition interaction is weak.

The paper is organized as follows. In the next section the framework is briefly introduced. The results for the ΣcD and ΛcD states are shown in Sec. III, where some discussion is presented as well. Finally, the summary is given in Sec. IV.

II. FORMULATION

The chiral quark model used in the present work has been widely described in the literature 21, 28, 29, 30, and we refer the reader to those references for details. Here we just present the salient features of this model. The total Hamiltonian is written as

$$H = \sum_i T_i - T_G + \sum_{i,j} V_{ij},$$

(1)

where $T_i$ is the kinetic energy operator for the ith quark, and $T_G$ the kinetic energy operator for the center-of-mass motion. $V_{ij}$ represents the interactions between quark-quark or quark-antiquark,

$$V_{ij} = \begin{cases} \sum_i V^{OGE}_{ij} + \sum_i V^{conf}_{ij}, & (ij = qq) \\ V^{OGE}_{ij} + V^{conf}_{ij}, & (ij = q\bar{q}, q\bar{Q}, Q\bar{Q}) \end{cases}$$

(2)

where q and Q represent light quark u or d and heavy quark c, respectively; $V^{OGE}_{ij}$ is the OGE potential,

$$V^{OGE}_{ij} = \frac{1}{4} g_i g_j \left( \lambda_i^r \cdot \lambda_j^r \right) \left[ \frac{1}{r_{ij}} - \frac{\pi}{2} \delta_{ij} \right]$$

$$\times \left( \frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4}{3} \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \right),$$

(3)

and $V^{conf}_{ij}$ is the confinement potential which provides the non-perturbative QCD effect in the long distance,

$$V^{conf}_{ij} = (\lambda_i^r \cdot \lambda_j^r) \left( \sigma_i^{(0)} r_{ij} + \sigma_i^{(0)} \right).$$

(4)

$V^{M}_{ij}$ represents the effective quark-quark potential induced by one-boson exchanges, and it is only considered for the light quark pairs. Generally,

$$V^{M}_{ij} = V^{σn}_{ij} + V^{σs}_{ij} + V^{δn}_{ij},$$

(5)
with \( V_{ij}^{\sigma} \), \( V_{ij}^{\pi} \) and \( V_{ij}^{\rho} \) being stemmed from scalar nonets, pseudo-scalar nonets and vector nonets, respectively. Their explicit forms are

\[
V_{ij}^{\sigma}(r_{ij}) = - C(g_{ch}, m_{\sigma_i}, \Lambda) X_1(m_{\sigma_i}, \Lambda, r_{ij}) \left( \frac{m^2}{12m_{\sigma_i}m_{\sigma_j}} \right) , \tag{6}
\]

\[
V_{ij}^{\pi}(r_{ij}) = C(g_{ch}, m_{\sigma_i}, \Lambda) \left[ m^2 \frac{X_2(m_{\pi}, \Lambda, r_{ij})}{(\sigma_i \cdot \sigma_j)} \right] , \tag{7}
\]

\[
V_{ij}^{\rho}(r_{ij}) = C(g_{ch}, m_{\rho}, \Lambda) \left[ X_1(m_{\rho_i}, \Lambda, r_{ij}) + \frac{m^2}{6m_{\rho_i}m_{\rho_j}} \times \left( 1 + \frac{f_{chv} m_{\rho_i} + m_{\rho_j}}{g_{chv} M_N} + \frac{f_{chv}^2 m_{\rho_i} m_{\rho_j}}{g_{chv}^2 M_N^2} \right) \right] \times X_2(m_{\rho_i}, \Lambda, r_{ij}) , \tag{8}
\]

where

\[
C(g_{ch}, m, \Lambda) = \frac{g_{ch}^2}{128\pi} \frac{1}{\Lambda^2} \frac{1}{\Lambda^2 - m^2} m , \tag{9}
\]

\[
X_1(m, \Lambda, r) = Y(mr) - \frac{\Lambda}{m} Y(\Lambda r) , \tag{10}
\]

\[
X_2(m, \Lambda, r) = Y(mr) - \left( \frac{\Lambda}{m} \right)^3 Y(\Lambda r) , \tag{11}
\]

\[
Y(x) = \frac{1}{x} e^{-x} , \tag{12}
\]

with \( m_{\sigma_i} \) being the mass of the scalar meson, \( m_{\pi_i} \) the mass of the pseudoscalar meson and \( m_{\rho_i} \) the mass of the vector meson. \( m_{\rho_i} \) is the constituent quark mass of the \( i \)th quark. \( g_{ch} \) is the coupling constant for the scalar and pseudoscalar nonets, and \( g_{chv} \) and \( f_{chv} \) the coupling constants for vector coupling and tensor coupling of vector nonets.

In this work, we take the parameters for light-flavor quark system from our previous works [8, 33, 34], which gave a satisfactory description for the energies of the octet and decuplet baryon ground state, the binding energy of the deuteron, the NN scattering phase shifts, and the NY cross sections. The main procedure for determination of those parameters is the following. The initial input parameters, i.e., the harmonic-oscillator width parameter \( b_0 \) and the up (down) quark mass \( m_{u(d)} \), are taken to be the usual values: \( b_0 = 0.5 \) 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. The coupling constant for scalar and pseudoscalar chiral field coupling, \( g_{ch} \), is fixed by the relation

\[
\frac{g_{ch}^2}{128\pi} = \left( \frac{3}{5} \right) \frac{2 g_{NN}^2 m_q^2}{4\pi M_N^2} , \tag{13}
\]

with the empirical value \( g_{NN}^2/4\pi = 13.67 \). For the vector meson field coupling, we consider three different cases. In model I, the coupling between vector meson field and quark field is not considered at all, which means \( g_{chv} = 0 \). Then in model II and III, the coupling constant for vector coupling is taken to be \( g_{chv} = 2.351 \) and 1.973, respectively, and the ratio for the tensor coupling and vector coupling is taken to be 0 and 2/3, respectively. The masses of the mesons are taken to be the experimental values, except for the \( \sigma \) meson. The \( m_s \) is obtained by fitting the binding energy of the deuteron. The cutoff radius \( \Lambda^{-1} \) is taken to be the value close to the chiral symmetry breaking scale [44]. The OGE coupling constants and the strengths of the confinement potential are fitted by the baryon masses and their stability conditions.

Note that in light-flavor quark systems, the confinement potential is found to give negligible contributions between two color-singlet hadron clusters [7, 27–29]. Therefore different forms of confinement potential (linear or quadratic) does not make any visible influence on the theoretical results in the light-flavor quark systems. In the present work we adopt a color linear confinement potential. The results from a calculation by using the color quadratic confinement potential are discussed as well. Of course the \( NN \) scattering phase shifts and the \( NY \) cross sections are always well described irrespective of confinement forms due to the negligibility of the contributions of any confinement to these systems.

The additional parameters needed in the present work are those associated with charm quark. The only one adjustable parameter is the charm quark mass \( m_c \). Here we take three typical values, \( m_c = 1.43 \) GeV [45], 1.55 GeV [46] and 1.87 GeV [47], to test the dependence of our results on \( m_c \). The other parameters we need are the coupling constant of OGE and confinement strengths for light quark and heavy quark pair, \( q \bar{c} \) and \( q \bar{q} \). They are fixed by a fitting to the masses and stability conditions of the charmed baryons \( \Sigma_c \), \( \Lambda_c \) and charmed mesons \( D, D^* \) and the charmonium \( J/\psi, \eta_c \). The values of those parameters are listed in Table I. The corresponding masses of \( \Sigma_c, \Lambda_c, D, D^* \), \( J/\psi \) and \( \eta_c \) obtained with \( m_c = 1.55 \) GeV are shown in Table II. There, Model I refers to the model where the coupling for vector nonets is not considered. Models II and III refer to the models where the coupling for vector nonets is included while the ratio for tensor coupling and vector coupling \( f_{chv}/g_{chv} \) is taken to be 0 and 2/3, respectively.

With all parameters determined, the \( \Sigma, \bar{D} \) and \( \Lambda_c \bar{D} \) systems can be dynamically studied in the framework of the RGM, where the wave function of the five-quark system is of the following form:

\[
\Psi = \sum_{\beta} A \left\{ \tilde{\phi}_A(\xi_1, \xi_2) \tilde{\phi}_B(\xi_3) \chi_\beta(R_{AB}) \right\} . \tag{14}
\]

Here \( \xi_1 \) and \( \xi_2 \) are the internal coordinates for the cluster \( A (\Lambda_c \) or \( \Sigma_c \), and \( \xi_3 \) the internal coordinate for the cluster \( B (\bar{D}) \). \( R_{AB} \equiv R_A - R_B \) is the relative
TABLE I: Model parameters. Model I refers to the model where the coupling for vector nonets is not considered. Models II and III refer to the models where the coupling for vector nonets is included while the ratio for tensor coupling and vector coupling $f_{kv}/g_{kv}$ is taken to be 0 and 2/3, respectively.

| $m_c$ (GeV) | $g_c$ | $a_{uc}$ | $a_{uc}$ | $a_{uc}$ | $a_{uc}$ | $a_{uc}$ |
|------------|-------|----------|----------|----------|----------|----------|
| I          | 1.43  | 0.35     | 0.44     | 1.07     | 1.74     | -0.38    | -0.74    | -0.73    |
| I          | 1.55  | 0.37     | 0.44     | 1.08     | 1.77     | -0.38    | -0.85    | -0.93    |
| I          | 1.87  | 0.43     | 0.44     | 1.10     | 1.81     | -0.38    | -1.14    | -1.44    |
| II         | 1.43  | 0.77     | 0.41     | 1.70     | 1.83     | -0.53    | -1.15    | -0.34    |
| II         | 1.55  | 0.82     | 0.41     | 1.72     | 1.68     | -0.53    | -1.27    | -0.40    |
| II         | 1.87  | 0.94     | 0.41     | 1.76     | 1.04     | -0.53    | -1.57    | -0.47    |
| III        | 1.43  | 0.57     | 0.37     | 1.68     | 2.19     | -0.46    | -1.14    | -0.71    |
| III        | 1.55  | 0.60     | 0.37     | 1.69     | 2.16     | -0.46    | -1.25    | -0.85    |
| III        | 1.87  | 0.69     | 0.37     | 1.74     | 1.94     | -0.46    | -1.55    | -1.17    |

TABLE II: The masses (in GeV) of $\Sigma_c$ and $\Lambda_c$ obtained from models I, II and III, respectively, with $m_c$ being taken as 1.55 GeV. Experimental values are taken from PDG [48].

| $\Sigma_c$ | $\Lambda_c$ | $D$ | $D^*$ | $J/\psi$ | $\eta_c$ |
|------------|-------------|-----|-------|---------|---------|
| Exp.       | 2.452       | 2.286 | 1.869 | 2.007   | 3.097   | 2.980   |
| I          | 2.436       | 2.269 | 1.883 | 1.947   | 3.052   | 3.024   |
| II         | 2.450       | 2.283 | 1.869 | 1.932   | 3.129   | 2.946   |
| III        | 2.450       | 2.283 | 1.869 | 1.932   | 3.087   | 2.980   |

Equation (17) is the so-called coupled-channel RGM equation. Expanding unknown $\chi_{\beta}(R_{AB})$ 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 $S$ matrix elements for the two-cluster systems. The details of solving the RGM equation can be found in Refs. [38–40].

III. RESULTS AND DISCUSSIONS

As mentioned in the Introduction, the structures of the nucleon resonances below 2 GeV are not clear so far. Different models may give us different pictures even they fit the same set of data, since each model has its own uncertainties which are usually approximated by fitting parameters. It is still a challenging task for hadron physicist whether the low energy baryon resonances should be described by three constituent quark configuration ($qqq$) or five constituent quark configuration ($qqqq\bar{c}$) or baryon-meson dynamically generated states or a mixture of them. The $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states are of particular interest simply because if there exists a $\Sigma_c\bar{D}$ bound state or a $\Sigma_c\bar{D}-\Lambda_c\bar{D}$ dynamically generated resonance, its energy will be around 4.3 GeV and the explanation of such a high energy state as three constituent quark configuration ($qqq\bar{c}$) will be definitely excluded while only the description that this state is dominated by hidden charm five constituent quark configuration ($qqqq\bar{c}$) or $\Sigma_c\bar{D}-\Lambda_c\bar{D}$ baryon-meson state or a mixture of them will be possible. Thus the system of $\Sigma_c\bar{D}-\Lambda_c\bar{D}$ will be a good place to test whether we could have a nucleon resonance whose configuration is dominated by at least five quarks.

Here we perform a dynamical investigation of the $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states with isospin $I = 1/2$ and spin $S = 1/2$ by solving the RGM equation (Eq. (17)) in our chiral quark models as depicted in Sec. II. Our purpose is to understand the interaction properties of the $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ states and to see whether there exists a $\Sigma_c\bar{D}$ bound state or a $\Sigma_c\bar{D}-\Lambda_c\bar{D}$ dynamically generated resonance within our chiral quark models.

Figure 1 shows the diagonal matrix elements of the Hamiltonian for the $\Sigma_c\bar{D}$ system in the generator coordinate method (GCM) calculation, which can be regarded as the effective Hamiltonian of two color-singlet clusters $\Sigma_c$ and $\bar{D}$ qualitatively. In Fig. 1 $H_{\Sigma_c\bar{D}}$ includes the kinetic energy of $\Sigma_c\bar{D}$ relative motion and the effective potential between $\Sigma_c$ and $\bar{D}$, and $s$ denotes the generator coordinate which can qualitatively describe the distance between the two clusters $\Sigma_c$ and $\bar{D}$. From Fig. 1 one sees that $\Sigma_c$ and $\bar{D}$ are attractive to each other in the medium range for all those three values of charm quark mass $m_c = 1.43$ GeV, 1.55 GeV and 1.87
FIG. 1: The GCM matrix elements of the Hamiltonian for $\Sigma_c \bar{D}$ system. The dotted, solid and dash-dotted lines represent the results obtained in models I, II and III, respectively.

FIG. 2: The GCM matrix elements of the Hamiltonian for $\Lambda_c \bar{D}$ system. The dotted, solid and dash-dotted lines represent the results obtained in models I, II and III, respectively.

GeV and all those three models I, II and III (see Sec. [II] for details of these three models). Our further analysis demonstrates that in model I the attraction between $\Sigma_c$ and $\bar{D}$ is dominated by $\sigma$ exchange and the color magnetic force of OGE; the latter exists between the two color-singlet clusters $\Sigma_c$ and $\bar{D}$ because of the antisymmetrizing (Eq. (14)) of the four constituent quarks in $\Sigma_c \bar{D}$ required by the general Pauli principle. In models II and III, the OGE among light-flavor quarks are largely reduced by vector-meson exchanges and the $\Sigma_c \bar{D}$ attraction is found to be dominated by $\sigma$ and $\rho$ exchanges.

Inspired by the moderately large $\Sigma_c \bar{D}$ attraction, we have solved the RGM equation for a bound state problem to see whether there is a $\Sigma_c \bar{D}$ bound state or not. Our results are listed in Table [III] where the first and second columns denote the model and the charm quark mass, respectively, and the third column shows the corresponding binding energy for each set of parameters. One sees that the $\Sigma_c \bar{D}$ is really bound independent of the types of the models and the values of the charm quark
TABLE III: The binding energy of $\Sigma_c \bar{D}$ (in MeV) in models I, II and III, respectively.

| $m_-$ (GeV) | $r$ confinement | $r^2$ confinement |
|------------|----------------|------------------|
| I          |                |                  |
| 1.43       | 9.3            | 4.5              |
| 1.55       | 10.9           | 6.4              |
| 1.87       | 15.3           | 11.0             |
| II         |                |                  |
| 1.43       | 28.3           | 9.3              |
| 1.55       | 31.8           | 10.3             |
| 1.87       | 41.6           | 10.0             |
| III        |                |                  |
| 1.43       | 19.7           | 7.3              |
| 1.55       | 22.2           | 8.9              |
| 1.87       | 28.6           | 11.3             |

mass we use. The binding energy is around 9 – 42 MeV in various models, which corresponding to an energy of 4.279 – 4.312 GeV for the $\Sigma_c \bar{D}$ bound state (the $\Sigma_c \bar{D}$ threshold is 4.321 GeV).

Here we’d like to discuss the dependence of our results on the phenomenology confinement potential. In light-flavor quark systems, the SU(3) flavor symmetry is approximately respected and thus the confinement potential is found to give negligible contributions between two color-singlet hadron clusters \[ \vec{r} \cdot \vec{r} \] . As far as the charm quark is included, the SU(4) flavor symmetry is strongly violated since the charm quark mass is much bigger than that of light-flavor quark. The consequence of this flavor symmetry violation is that the contribution of the confinement potential to the interaction between two hadron clusters may not be negligible. In the present work, we check the dependence of our results on the forms of the confinement potential by replacing the linear confinement (Eq. (19)) with the quadratic one,

$$ V_{ij}^{\text{conf}} = -\left( \lambda_{\vec{r}} \cdot \lambda_{\vec{r}} \right) \left( a_{ij}^2 + a_{ij}^0 \right), $$

(19)

with the parameters being fitted by using the same procedure as given in the previous section. With the quadratic confinement Eq. (19), we re-solve the RGM equation for $\Sigma_c \bar{D}$ bound state problem, and the results are shown in the fourth column of Table III. One sees that the $\Sigma_c \bar{D}$ is still bound in various models and the binding energy is around 5 – 11 MeV which is a little smaller than that for the linear confinement. The corresponding energy of $\Sigma_c \bar{D}$ bound state is 4.310 – 4.316 GeV.

We have also studied the $\Delta_c \bar{D}$ system. Figure 2 shows the diagonal matrix elements of the Hamiltonian for the $\Delta_c \bar{D}$ system in the GCM calculation, which can be regarded as the effective Hamiltonian of two color-singlet clusters $\Delta_c$ and $\bar{D}$ qualitatively. One sees that unlike the $\Sigma_c \bar{D}$ system which is attractive in the medium range, the $\Delta_c \bar{D}$ system is strongly repulsive for all those three models and all those three values of charm quark mass. No $\Delta_c \bar{D}$ bound state will be found as a matter of course due to this repulsion.

Is there a $\Sigma_c \bar{D}-\Delta_c \bar{D}$ resonance in the coupled-channel study? In Refs. 7, 8, we have dynamically investigated the $\Sigma K$ and $\Lambda K$ systems by using RGM in our chiral quark model. There, it is found that the $\Sigma K$ interaction is attractive and a $\Sigma K$ bound state can be formed as a consequence with the binding energy of about 17 – 44 MeV, while the $\Lambda K$ is repulsive and unbound. In the coupled-channel calculation, a $\Sigma K-\Lambda K$ dynamically generated resonance is obtained which is located between the thresholds of $\Sigma K$ and $\Lambda K$ and has the quantum numbers the same as those for nucleon $S_{11}$ resonances. Analogically, one may expect a $\Sigma_c \bar{D}-\Lambda_c \bar{D}$ dynamically generated resonance in the coupled-channel calculation since $\Sigma_c \bar{D}$ is also attractive and bound just like $\Sigma K$. But actually, the coupled-channel effect of $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ is found to be negligible, and no $\Sigma_c \bar{D}-\Lambda_c \bar{D}$ resonance is found in our coupled-channel calculation. This is because the gap of the $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ thresholds, 166 MeV, is comparatively big and the transition matrix elements between $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ are too weak, contrary to the case of $\Sigma K-\Lambda K$ system, where the gap of two channel thresholds is only 78 MeV and the transition matrix elements between $\Sigma K$ and $\Lambda K$ are relatively large.

In brief, we obtain a $\Sigma_c \bar{D}$ bound state in our model with the energy of about 4.279 – 4.316 MeV, and the effect from $\Lambda_c \bar{D}$ channel to this state is negligible. In Refs. 22, 23, the $\Sigma_c \bar{D}$ and $\Lambda_c \bar{D}$ states have been studied on hadron level within the framework of the coupled-channel unitary approach. There, a $\Sigma_c \bar{D}$ bound state is also found with the energy of about 4.240 – 4.291 GeV, and this state does not couple to $\Lambda_c \bar{D}$ channel. Although the binding energy given by Refs. 22, 23 is bigger than what we get from the present work, it makes sense that the results from different theoretical approaches are qualitatively similar. Note that the $\Sigma_c \bar{D}$ bound state, if it exists, cannot be accommodated in three light flavor quark configuration (qqq), unlike the nucleon resonances below 2 GeV. Whether it can be explained as hidden charm five constituent quark configuration (qqqqc) or not needs further detailed scrutiny. Investigations from other approaches and experiments are needed to further confirm the existence of this state and to pin down its structure and mass. Since its mass is above the $\eta_c N$ and $J/\psi N$ thresholds, it is much easier for their experimental searches 22, 23, compared with those baryons with hidden charms below the $\eta_c N$ threshold proposed by other approaches 19.

IV. SUMMARY

In this work, we perform a dynamical coupled-channel study of $\Sigma_c \bar{D}$ and $\Delta_c \bar{D}$ states by solving the RGM equation in the framework of a chiral quark model. The model parameters for light-flavor quarks are taken from our previous work 8, which gave a satisfactory description of the energies of the octet and decuplet baryon ground states, the binding energy of the deuteron, the $NN$ scattering phase shifts, and the $NY$ cross sections. The pa-
rameters associated with charm quark are determined by fitting the energies and the stability conditions of $\Sigma_c$, $\Lambda_c$, $D$, $D^*$, $J/\psi$ and $\eta_c$. Our results show that the $\Sigma_c$ and $\bar{D}$ interaction is attractive and a $\Sigma_c\bar{D}$ bound state can be formed as a consequence with the energy of about $4.279 - 4.316$ GeV, while the $\Lambda_c\bar{D}$ is repulsive and unbound. The channel-coupling effects between $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ is negligible due to the large mass difference between the $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ thresholds and the small off-diagonal matrix elements of $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$. This $\Sigma_c\bar{D}$ bound state, if it really exists, cannot be accommodated in three light flavor quark configuration (qqq). Further investigations from other approaches and experiments are needed to confirm the existence of this state and to pin down its structure and mass.

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