Hidden charm pentaquarks $\Lambda_{c\bar{c}}$ above 4 GeV

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A dynamical calculation of the strange hidden charm pentaquark systems $\Lambda_{c\bar{c}}$ is performed in the framework of the quark delocalization color screening model. The effective potentials between two clusters are calculated to investigate the interaction between the baryons and mesons. The dynamic calculations indicate that the strange hidden charm pentaquark system with $IJ^P = 0\frac{1}{2}^-$ and $IJ^P = 0\frac{3}{2}^-$ can form bound states with the help of the channel coupling. The energies of these two system are 4068.7 and 4186.3 MeV, respectively. These two $\Lambda_{c\bar{c}}$ states are possible intriguing pentaquark candidates, which are worth searching for in experiments. In contrast, for the systems with isospin $I = 1$, the effective potentials of all channels are repulsive, and there are no bound states for these systems.

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I. INTRODUCTION

There has been tremendous progress in the experimental and theoretical explorations of the multiquark states. The possible existence of multiquark states beyond the ordinary hadrons was first proposed by Gell-Mann and Zweig [1,2]. The study of exotic hadronic states is attractive for both experimentalists and theorists. More and more charmonium-like and bottomonium-like states and states with open-charm and open-bottom quantum numbers have been reported in experiments. Nowadays, it is an important and interesting topic to look for such states [3].

In fact, since 2003, experimentalists have announced more and more exotic states [4–17], which provide good opportunities to study the nonperturbative color interactions. Some of the states have been considered good tetraquark candidates [18–26]. For the pentaquark states, in 2015, the hidden charm pentaquarks (named P_c states) were obtained in the decay $\Lambda_b^0 \rightarrow J/\psi K^- p$ by the LHCb Collaboration [27–29]. Then the P_c states attracted much attention and became a hot topic. The main reason is that they are the first exotic baryons discovered experimentally. Four years later, the LHCb Collaboration updated their results on P_c states, and reported the observation of three new pentaquarks, named $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ [30]. All of them are observed in the $J/\psi p$ invariant mass spectrum from the $\Lambda_b \rightarrow J/\psi p K^-$ decay, corresponding to three peaks in the $J/\psi p$ invariant mass distributions.

To identify the internal structure of P_c is the most fundamental problem currently. There are a large number of theoretical studies about hidden charm pentaquarks in the literature, although there is not yet a conclusive picture about the structure of P_c , including models of hadronic molecules [31–36], compact pentaquark states [37–42], and hadrocharmonium states [43]. In the framework of the quark delocalization color screening model, by considering the baryon-meson scattering process, $P_c(4312)$ was proposed as a hidden-charm molecular state $\Sigma_c \bar{D}$ with $J^P = \frac{1}{2}^-$; $P_c(4380)$ was identified as a $\Sigma_c^* \bar{D}$ state with $J^P = \frac{3}{2}^-$, and two resonance states around 4450 MeV were predicted: they were $\Sigma_c \bar{D}^*$ with $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$, respectively [44]. In Ref. [32], three narrow structures, $P_c(4312)$, $P_c(4440)$ and $P_c(4457)$, were depicted as the molecular $\Sigma_c \bar{D}$ with $I = \frac{1}{2}, J = \frac{1}{2}$; $\Sigma_c \bar{D}^*$ with $I = \frac{1}{2}, J = \frac{1}{2}$; and $\Sigma_c \bar{D}$ with $I = \frac{1}{2}, J = \frac{3}{2}$, respectively. Meanwhile, some different opinions also appeared; in Ref. [45], the authors inferred that the $P_c(4312)$ peak was more likely to be a virtual state instead. It is clear that, theoretically, different interpretations are often not consistent with each other. Sometimes, searches for the counterparts of these states may offer new insight into their true nature. The hidden charm pentaquark with strangeness -1 is one of the counterparts of P_c states; the quark component of the system is $udsc\bar{c}$. We label the system as $\Lambda_{c\bar{c}}$ in this work.

Actually, there are a lot of works on the P_c counterparts $\Lambda_{c\bar{c}}$. By using the unitary approach, Refs. [46,47] predicted both the narrow N^* resonances and the Λ^* resonances with hidden charm, where the N^* represents the pentaquark composed of $uudc\bar{c}$ and Λ^* means the pentaquark composed of $udsc\bar{c}$. The impact of the existence of such states was also discussed in Refs. [48,49], which showed that it was possible to observe the states by a careful study of the $\Xi_b^- \rightarrow J/\psi K^- \Lambda$ decay and the $\Lambda_b \rightarrow J/\psi \eta \Lambda$ decay. In Ref. [50], a neat peak was observed in the $J/\psi \Lambda$ invariant mass distribution by studying the $\Lambda_b \rightarrow J/\psi K^0 \Lambda$ reaction. Reference [51] investigated the $\Lambda_{c\bar{c}}$ in the quark model, and found that the $\Lambda_{c\bar{c}}$

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states below 4400 MeV were all formed from two colorful clusters, color octets uds and $c\bar{c}$, and the spin and parity could be $\frac{1}{2}^-$ and $\frac{3}{2}^-$. Several possible decay process of $udsc\bar{c}$ were discussed, and they found many channels should be suppressed by light flavor SU(3) symmetry or by the heavy quark symmetry or by both of them. Reference [52] calculated the $\Lambda_c\bar{D}_s^*$, $\Sigma_c\bar{D}_s^*$, $\Sigma_c^*\bar{D}_s^*$, $\Xi_c\bar{D}^*$, $\Xi'_c\bar{D}^*$, $\Xi_c^*\bar{D}^*$ interactions in the one-boson-exchange model. The results showed that the most promising strange hidden-charm molecular pentaquarks were the $\Xi'_c\bar{D}^*$ state with $IJ^P = 0\frac{1}{2}^-$ and the $\Xi_c^*\bar{D}^*$ states with $0\frac{1}{2}^-$ and $0\frac{3}{2}^-$. In Ref. [53], the authors calculated the partial widths of possible decay channels, and the results showed that the $\Lambda_{c\bar{c}}(4213)$ and $\Lambda_{c\bar{c}}(4403)$ were formed as pseudoscalar meson baryon molecules, and $\Lambda_{c\bar{c}}(4370)$ could be considered as a $\Lambda_c D_s^*$ or $\Xi_c \bar{D}^*$ molecule state. $\Lambda_{c\bar{c}}(4490)$ was assumed to be a $\Xi_c^* \bar{D}$ bound state. Within the theoretical uncertainties, all of these studies show that there would be rather stable signals of the hidden charm strange states.

To deal with the same hadronic states in different models, it is helpful to check the model dependence of the results and to figure out the nature of these $\Lambda_{c\bar{c}}$ states. In this paper, we systematically study the properties of the hidden charm

strange pentaquark by using the quark delocalization color screening model (QDCSM), which was proposed particularly to study the multi-quark system. Our purpose is to investigate whether a bound state or resonance state exists or not. To be more convincing, the channel coupling effect of the hidden charm strange pentaquark is also included.

This paper is organized as follows. In Sec. II, a brief introduction of QDCSM is given. In Sec. III, we calculate the relevant Hamiltonian elements and present the corresponding results for the hidden charm strange pentaquark, and some discussion is presented as well. The summary is given in the last section.

II. THE QUARK DELOCALIZATION COLOR SCREENING MODEL (QDCSM)

The quark delocalization color screening model (QDCSM) is an extension of the native quark cluster model [54] and was developed with the aim of addressing multi-quark systems. The details of QDCSM can be found in Refs. [55,56]. Here, we just present the salient features of the model. The model Hamiltonian is

$$H = \sum_{i=1}^5 \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - T_{CM} + \sum_{j>i=1}^5 [V^C(r_{ij}) + V^G(r_{ij}) + V^B(r_{ij}) + V^{HM}(r_{ij})], \quad (1)$$

$$V^G(r_{ij}) = \frac{1}{4} \alpha_s \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}} - \frac{\pi}{2} \delta(r_{ij}) \left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\sigma_i \cdot \sigma_j}{3m_i m_j} \right) - \frac{3}{4m_i m_j r_{ij}^3} S_{ij} \right], \quad (2)$$

$$V^B(r_{ij}) = v_{ij}^{\pi} \sum_{a=1}^3 \lambda_i^a \cdot \lambda_j^a + v_{ij}^K \sum_{a=4}^7 \lambda_i^a \cdot \lambda_j^a + v_{ij}^{\eta} [(\lambda_i^8 \cdot \lambda_j^8) \cos \theta_P - (\lambda_i^0 \cdot \lambda_j^0) \sin \theta_P], \quad (3)$$

$$V^{HM}(r_{ij}) = v_{ij}^D \sum_{a=9}^{12} \lambda_i^a \cdot \lambda_j^a + v_{ij}^{D_s} \sum_{a=13}^{14} \lambda_i^a \cdot \lambda_j^a + v_{ij}^{\eta_c} \lambda_i^{15} \cdot \lambda_j^{15}, \quad (4)$$

$$v_{ij}^{\chi} = \frac{g_{ch}^2}{4\pi} \frac{m_{\chi}^2}{12m_i m_j} \frac{\Lambda_{\chi}^2}{\Lambda_{\chi}^2 - m_{\chi}^2} m_{\chi} \left\{ (\sigma_i \cdot \sigma_j) \left[Y(m_{\chi} r_{ij}) - \frac{\Lambda_{\chi}^3}{m_{\chi}^3} Y(\Lambda_{\chi} r_{ij}) \right] + \left[H(m_{\chi} r_{ij}) - \frac{\Lambda_{\chi}^3}{m_{\chi}^3} H(\Lambda_{\chi} r_{ij}) \right] S_{ij} \right\}, \quad \chi = \pi, K, \eta, D, D_s, \eta_c, \quad (5)$$

$$V^C(r_{ij}) = -a_c \lambda_i \cdot \lambda_j [f(r_{ij}) + V_0], \quad (6)$$

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

$$S_{ij} = \left\{ \frac{(\sigma_i \cdot \mathbf{r}_{ij})(\sigma_j \cdot \mathbf{r}_{ij})}{r_{ij}^2} - \frac{1}{3} \sigma_i \cdot \sigma_j \right\}, \quad (7)$$

$$H(x) = (1 + 3/x + 3/x^2)Y(x), \quad Y(x) = e^{-x}/x, \quad (8)$$

Where $V^B(r_{ij})$ is the π, K, η exchange potential, which acts only between light quarks, and $V^{HM}(r_{ij})$ represents heavy meson D, D_s, η_c exchange potential, which can be used between the heavy quarks and and between a heavy quark and light

quark. S_{ij} is quark tensor operator; $Y(x)$ and $H(x)$ are standard Yukawa functions; T_{cm} is the kinetic energy of the center-of-mass motion, and $\sigma, \lambda^c, \lambda^a$ are the SU(2) Pauli, SU(3) color, SU(3) flavor Gell-Mann matrices, respectively. The Λ_{χ} is

TABLE I. Model parameters. The masses of mesons take their experimental values. $m_\pi = 0.7 \text{ fm}^{-1}$, $m_K = 2.51 \text{ fm}^{-1}$, $m_\eta = 2.77 \text{ fm}^{-1}$, $m_D = 9.46 \text{ fm}^{-1}$, $m_{D_s} = 9.98 \text{ fm}^{-1}$, $m_{\eta_c} = 15.12 \text{ fm}^{-1}$.

$b \text{ (fm)}$	$m_u \text{ (MeV)}$	$m_s \text{ (MeV)}$	$m_c \text{ (MeV)}$
0.518	313	573	1700
$a_c \text{ (MeV fm}^{-2}\text{)}$	$V_0^{qq} \text{ (fm}^2\text{)}$	$V_0^{q\bar{q}} \text{ (fm}^2\text{)}$	α_s^{uu}
58.03	-1.2883	-0.2012	0.5652
α_s^{us}	α_s^{ss}	$\alpha_s^{u\bar{u}}$	$\alpha_s^{u\bar{s}}$
0.5239	0.4506	1.7930	1.7829
$\alpha_s^{s\bar{s}}$	α_s^{uc}	α_s^{sc}	$\alpha_s^{u\bar{c}}$
1.5114	0.2031	0.5675	1.2859
$\alpha_s^{c\bar{c}}$	$\alpha_s^{s\bar{s}}$	$g_{ch}^2/(4\pi)$	θ_p
1.6278	1.5098	0.54	-15°
$\Lambda_\pi \text{ (fm}^{-1}\text{)}$	$\Lambda_K = \Lambda_\eta \text{ (fm}^{-1}\text{)}$	$\Lambda_D = \Lambda_{D_s} = \Lambda_{\eta_c} \text{ (fm}^{-1}\text{)}$	
4.2	5.2	2.4	

the chiral symmetry breaking scale, and α_s is the effective scale-dependent running quark-gluon coupling constant [57], $\frac{g_{ch}^2}{4\pi}$ is the chiral coupling constant for scalar and pseudoscalar chiral field coupling, determined from the π -nucleon coupling constant through

$$\frac{g_{ch}^2}{4\pi} = \left(\frac{3}{5}\right)^2 \frac{g_{\pi NN}^2}{4\pi} \frac{m_{u,d}^2}{m_N^2}. \quad (9)$$

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 . When extending to the heavy-quark case, there are no experimental data available, so we take it as an adjustable parameter. In the present work, we take $\mu_{cc} = 0.001$, and μ_{uc} is also obtained by the relation $\mu^2 = \mu_{uu}\mu_{cc}$. The other symbols in the above expressions have their usual meanings. All parameters, except the masses of mesons which take their experimental values, are fixed by fitting the masses of baryons with light flavors, are taken from our previous work [58], except for the charm quark mass, which is fixed by fitting to the mass of the heavy baryons and mesons. The values of those parameters are listed in Table I. The calculated masses of baryons and mesons in comparison with experimental values are shown in Table II.

In QDCSM, the quark delocalization is realized by specifying the single-particle orbital wave function of QDCSM as a linear combination of left and right Gaussians, which are the single-particle orbit wave functions used in the ordinary quark cluster model:

$$\psi_r(\mathbf{r}, \mathbf{s}_i, \epsilon) = [\phi_R(\mathbf{r}, \mathbf{s}_i) + \epsilon \phi_L(\mathbf{r}, \mathbf{s}_i)]/N(\epsilon), \quad (10)$$

$$\psi_l(\mathbf{r}, \mathbf{s}_i, \epsilon) = [\phi_L(\mathbf{r}, \mathbf{s}_i) + \epsilon \phi_R(\mathbf{r}, \mathbf{s}_i)]/N(\epsilon), \quad (11)$$

$$N(\epsilon) = \sqrt{1 + \epsilon^2 + 2\epsilon e^{-s_i^2/4b^2}}, \quad (12)$$

TABLE II. The masses (in MeV) of the ground baryons and mesons. Experimental values are taken from the Particle Data Group (PDG) [59].

	J/ψ	η_c	$\bar{D}$	$\bar{D}^*$	D_s	D_s^*				
Expt.	3096	2983	1869	2007	1968	2112				
Model	3005	2983	1913	2007	1967	2027				
	Λ	Λ_c	Ξ_c	$\Xi_{c'}$	Ξ_c^*	Σ_c	Σ_c^*	Σ	Σ^*	
Expt.	1115	2286	2467	2577	2645	2455	2520	1189	1385	
Model	1123	2286	2467	2538	2552	2474	2485	1232	1361	

$$\phi_R(\mathbf{r}, \mathbf{s}_i) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{1}{2b^2}(\mathbf{r} - \frac{2}{5}\mathbf{s}_i)^2}, \quad (13)$$

$$\phi_L(\mathbf{r}, \mathbf{s}_i) = \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{1}{2b^2}(\mathbf{r} + \frac{3}{5}\mathbf{s}_i)^2}, \quad (14)$$

The $\mathbf{s}_i$, $i = 1, 2, \dots, n$, are the generating coordinates, which are introduced to expand the relative motion wave function [60–62]. The mixing parameter $\epsilon(\mathbf{s}_i)$ is not an adjusted one but determined variationally by the dynamics of the multi-quark system itself. This assumption allows the multi-quark 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 [63].

III. RESULTS AND DISCUSSIONS

In present work, we systematically investigate the low-lying S -wave hidden charm strange pentaquark $\Lambda_{c\bar{c}}$ systems. We consider the states with baryon-meson molecular structure, and the parity of the states is negative. The orbital angular momentum L between two clusters is set to 0, and the total angular momentum and parity can be $J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$. The isospin of the pentaquark states can be 0 and 1. All possible channels are listed in Table III.

A. The effective potential calculation

Since an attractive potential is necessary for forming bound states or resonance states. As the first step, the effective

TABLE III. All possible channels for $udsc\bar{c}$ systems.

$IJ = 0\frac{1}{2}$	$\Lambda_c D_s$	$\Lambda_c D_s^*$	$\Xi_c \bar{D}$	$\Xi_{c'} \bar{D}$	$\Xi_c \bar{D}^*$	$\Xi_{c'} \bar{D}^*$	$\Xi_c^* \bar{D}^*$
		$\Lambda \eta_c$	$\Lambda J/\psi$				
$IJ = 0\frac{3}{2}$	$\Lambda_c D_s^*$	$\Xi_c \bar{D}^*$	$\Xi_{c'} \bar{D}^*$	$\Xi_c^* \bar{D}^*$	$\Xi_{c'} \bar{D}^*$	$\Lambda J/\psi$	
$IJ = 0\frac{5}{2}$	$\Xi_c^* \bar{D}^*$						
$IJ = 1\frac{1}{2}$	$\Xi_c \bar{D}$	$\Xi_{c'} \bar{D}$	$\Xi_c \bar{D}^*$	$\Xi_{c'} \bar{D}^*$	$\Xi_c^* \bar{D}^*$	$\Sigma \eta_c$	$\Sigma J/\psi$
		$\Sigma_c D_s$	$\Sigma_c D_s^*$	$\Sigma^* J/\psi$	$\Sigma_c^* D_s^*$		
$IJ = 1\frac{3}{2}$	$\Xi_c \bar{D}^*$	$\Xi_{c'} \bar{D}^*$	$\Xi_c^* \bar{D}^*$	$\Xi_{c'} \bar{D}^*$	$\Sigma^* \eta_c$	$\Sigma J/\psi$	$\Sigma_c^* D_s^*$
		$\Sigma_c \eta_c$	$\Sigma^* J/\psi$	$\Sigma_c^* J/\psi$			
$IJ = 1\frac{5}{2}$	$\Xi_c^* \bar{D}^*$	$\Sigma J/\psi$	$\Sigma_c \bar{D}_s^*$

FIG. 1. The effective potentials of every channel in the $\Lambda_{c\bar{c}}$ system with $I = 0$.

potentials of all the channels are calculated. The effective potential between two colorless clusters is defined as $V(s) = E(s) - E(\infty)$, where $E(s)$ is the diagonal matrix element of the Hamiltonian of the system at given generating coordinate S . The effective potentials of the S -wave $\Lambda_{c\bar{c}}$ systems with $I = 0, 1$ are shown in Figs. 1 and 2 respectively.

For the $IJ^P = 0\frac{1}{2}^-$ system, the effective potentials of nine channels are shown in Fig. 1(a). One can see that the potentials are attractive for the channels $\Xi_c \bar{D}$, $\Xi'_c \bar{D}$, $\Xi_c \bar{D}^*$, $\Xi'_c \bar{D}^*$, $\Xi_c^* \bar{D}^*$, $\Lambda \eta_c$, and $\Lambda J/\psi$. For the channels $\Lambda_c \bar{D}_s$ and $\Lambda_c \bar{D}_s^*$, the potentials are repulsive, so no bound states or resonances can be formed in these two channels. However, for other channels, the bound states or resonances are possible due to the attractive nature of the interaction between two hadrons.

The attraction between Ξ_c and $\bar{D}$ is largest one, followed by that of the $\Xi'_c \bar{D}$ and $\Xi_c \bar{D}^*$ channel. The $\Xi'_c \bar{D}^*$ and $\Xi_c^* \bar{D}^*$ have very weak attractions comparing with $\Xi_c \bar{D}$, $\Xi'_c \bar{D}$, $\Xi_c \bar{D}^*$. In addition, the attraction of $\Lambda \eta_c$ is almost the same as that of $\Lambda J/\psi$, which is the smallest one among these channels. To confirm whether these states are bound states or not, a dynamic calculation is needed.

For the $IJ^P = 0\frac{3}{2}^-$ system [see Fig. 1(b)], the potentials of the $\Lambda J/\psi$, $\Xi'_c \bar{D}^*$, $\Xi_c^* \bar{D}^*$, and $\Xi_c \bar{D}$ channels show an attractive property, while the potentials of the other channels are repulsive. The attraction of the $\Xi'_c \bar{D}^*$ channel is the strongest, which indicates that the $\Xi'_c \bar{D}^*$ is more possible to be a bound state. The attractions of both the $\Xi_c^* \bar{D}^*$ and the $\Xi_c \bar{D}$ channels are smaller than that of $\Xi'_c \bar{D}^*$, but it is interesting to explore

FIG. 2. The effective potentials of every channel in the $\Lambda_{c\bar{c}}$ system with $I = 1$.

TABLE IV. The binding energies of the $udsc\bar{c}$ systems.

Channel	$IJ^P=0\frac{1}{2}^-$	$IJ^P=0\frac{3}{2}^-$	$IJ^P=0\frac{5}{2}^-$
$\Lambda_c D_s$	ub	...	...
$\Lambda_c D_s^*$	ub	ub	...
$\Xi_c \bar{D}$	ub	...	...
$\Xi'_c \bar{D}$	ub	...	...
$\Xi_c \bar{D}^*$	ub	ub	...
$\Xi'_c \bar{D}^*$	ub	ub	...
$\Xi_c^* \bar{D}^*$	ub	ub	ub
$\Xi_c^* \bar{D}$	...	ub	...
$\Lambda \eta_c$	ub	...	...
$\Lambda J/\psi$	ub	ub	...
$B_{c.c}$	-29.9 MeV	-25.8 MeV	...
$E_{c.c}$	4068.7 MeV	4186.3 MeV	...

the possibility of the bound or resonance states of those two channels. For the $\Lambda J/\phi$, although the attraction of the potential is very small, a bound state is also possible.

For the $IJ^P = 0\frac{5}{2}^-$ system, there is only one channel, which is the $\Xi_c^* \bar{D}^*$. Obviously the potential of the $\Xi_c^* \bar{D}^*$ is repulsive, which means that it is impossible for the $\Xi_c^* \bar{D}^*$ to form a bound state.

For the $IJ^P = 1\frac{1}{2}^-, 1\frac{3}{2}^-,$ and $1\frac{5}{2}^-$ systems, the potentials of all channels show the repulsive property, so it is difficult for the systems with $I = 1$ to form any bound state.

B. The bound-state calculation

In order to check whether or not there is any bound state, a dynamical calculation is needed. The resonating group method (RGM) [64], a well established method for studying a bound state problem or a scattering one, is employed here. After expanding the relative motion wave function between two clusters by Gaussians, the integro-differential equation of RGM can be reduced to an algebraic equation, which is the generalized eigen-equation. The energy of the system can be obtained by solving the eigen-equation. Besides, to keep the matrix dimension manageably small, the baryon-meson separation is taken to be less than 6 fm in the calculation. The details of RGM can be found in Refs. [64,65]. The binding energies of every single channel and those with channel coupling are listed in Table IV, where $E_{c.c}$ stands for the result of channel-coupling calculation, and “ub” means that the state is unbound. The symbol of “...” represents that the corresponding channel does not exist in the system. Before discussing the features of the states, we should mention how we obtain the masses of these states. 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 are different (the threshold is the sum of the masses of the baryon and the meson in the given channel). So, for the single calculation, we define the binding energy by $B = M^{\text{theo}} - M_B^{\text{theo}} - M_M^{\text{theo}}$, where M^{theo} , M_B^{theo} , and M_M^{theo} stand for the theoretical mass of a five-quark

state, a baryon, and a meson, respectively. To minimize the theoretical errors, the mass of a bound state can be defined as $M = B + M_B^{\text{exp}} + M_M^{\text{exp}}$, where the experimental values of a baryon and a meson are used. However, for the multichannel calculation, the corrected mass of the bound state is defined as

$$M = M^{\text{theo}} + \sum_{i=1}^N c_i (M_{B_i}^{\text{exp}} + M_{M_i}^{\text{exp}} - M_{B_i}^{\text{theo}} - M_{M_i}^{\text{theo}}), \quad (15)$$

where M^{theo} is the calculated mass of the eigenstate and c_i is the probability of the i th channel in the eigenstate. N is the number channels involved in the calculation. The binding energy is obtained as

$$B = M - M_{\text{threshold}}^{\text{exp}}, \quad (16)$$

where $M_{\text{threshold}}^{\text{exp}}$ is the lowest sum of M_B^{exp} and M_M^{exp} .

For the $I = 0, J^P = \frac{1}{2}^-$ system, the single-channel calculation shows that none of the single channels are bound, which means that the attractive interaction of these channels does not lead to the energy of those channels being below their corresponding threshold, respectively. For example, for the $\Xi_c \bar{D}$ channels, the interaction between Ξ_c and $\bar{D}$ is attractive as shown in Fig. 1(a), but it is not large enough to form a bound state. At the same time, we also do a channel-coupling calculation, the results of which are shown in Table IV. A stable state is obtained, the mass of which is lower than the threshold of the lowest channel $\Lambda \eta_c$. This indicates that the $\Lambda_{c\bar{c}}$ system with $I = 0, J^P = \frac{1}{2}^-$ is bound by channel coupling in our quark-model calculation, and the energy is 4068.7 MeV. This result shows that the channel coupling effect has an important impact on the existence of the bound state.

For the $I = 0, J^P = \frac{3}{2}^-$ system, although the attraction of the $\Xi'_c \bar{D}^*$ channel is the largest one, the attraction is still not large enough to form a bound state. The single-channel calculation of other channels shows that none of them can form any bound state due to the weak attraction. The channel coupling is also considered, which can make the $I = 0, J^P = \frac{3}{2}^-$ system be bound with a binding energy of -25.8 MeV. By using the subtraction procedure we finally obtain the mass of this system, which is 4186.3 MeV. This result is consistent with the prediction in Ref. [47], where the $\Lambda_{c\bar{c}}$ state has a mass around 4213 MeV.

For the $I = 0, J^P = \frac{5}{2}^-$ system, there is only one channel: $\Xi_c^* \bar{D}^*$. As mentioned in last section, the interaction between Ξ_c^* and $\bar{D}^*$ is repulsive, so it cannot be a bound state here.

For the $IJ^P = 1\frac{1}{2}^-, 1\frac{3}{2}^-,$ and $1\frac{5}{2}^-$ systems, none of the systems is bound whether it is single- or multichannel coupling computation because of the repulsive interaction.

To check the boundness of the states, we also calculate the low-energy scattering phase shifts of the $\Lambda_{c\bar{c}}$ system with the help of the well-developed Kohn-Hulthen-Kato variational method [64]. Figure 3 illustrates the low-energy scattering phase shifts of the $\Lambda \eta_c$ with $IJ^P = 0\frac{1}{2}^-$ and $\Lambda J/\psi$ with $IJ^P = 0\frac{3}{2}^-$ with channel coupling. It is obvious that in QDCSM the scattering phase shifts go to 180° at $E_{c.m} \sim 0$ and rapidly decrease as $E_{c.m}$ increases, which implies the existence of a

FIG. 3. The phase shifts of the $IJ^P = 0 \frac{1}{2}^- \Lambda \eta_c$ state and $IJ^P = 0 \frac{3}{2}^- \Lambda J/\psi$ state

bound state. The results are consistent with the bound state calculation shown above.

In order to analyze the spatial structure of the $udsc\bar{c}$ pentaquark, we calculated the distances between two subclusters of the $udsc\bar{c}$ systems. From Table V, the distances between the two subclusters for the two states mentioned above in the channel-coupling calculations are around 1.4 fm, which is larger than the size of two subclusters. This phenomenon shows that two subclusters tend to stay away from each other, so the structure of the $udsc\bar{c}$ pentaquark is a molecular state.

IV. SUMMARY

Searching for exotic hadronic states is a research field full of challenges and opportunities. With recent experimental progress, more and more novel phenomena have been revealed in experiments, which has stimulated theorists' extensive interest in studying exotic states. The observation of P_c states at LHCb has inspired many new investigations of the hidden charm pentaquarks. In this situation, it is also interesting to investigate the partners of P_c states. Thus, in

TABLE V. Distance between two clusters of $udsc\bar{c}$ systems.

Channel	Separation (fm)
$IJ^P = 0 \frac{1}{2}^-$	1.35
$IJ^P = 0 \frac{3}{2}^-$	1.45

the framework of the QDCSM, we performed a theoretical study of the pentaquark systems with quark contents of $udsc\bar{c}$ ($\Lambda_{c\bar{c}}$) with the aim of looking for any strange hidden charm pentaquarks.

The dynamic calculations show that although all channels with $IJ^P = 0 \frac{1}{2}^-$ are unbound in the single channel calculation, a bound state can be obtained by the effect of channel coupling, and the energy of this system is 4068.7 MeV. For the $IJ^P = 0 \frac{3}{2}^-$ system, results similar to the case of the $IJ^P = 0 \frac{1}{2}^-$ system are obtained. There also exists a bound state by multichannel coupling, with the mass of this system being 4186.3 MeV, which is consistent with the $\Lambda_{c\bar{c}}$ (4213) of Ref. [47]. In addition, these results also indicate that the channel coupling effect in this system has an important influence on existence of the bound state. The low-energy scattering phase shifts of $\Lambda \eta_c$ with $IJ^P = 0 \frac{1}{2}^-$ and $\Lambda J/\psi$ with $IJ^P = 0 \frac{3}{2}^-$ with channel coupling confirm the existence of the bound states. For the system with $IJ^P = 1 \frac{1}{2}^-$, $1 \frac{3}{2}^-$, and $1 \frac{5}{2}^-$, since the interaction of all channels is repulsive, there is no bound state.

In summary, the observed P_c states from LHCb have opened fascinating new avenues of research. In the present work, the result show that the strange hidden charm pentaquarks $\Lambda_{c\bar{c}}$ with $IJ^P = 0 \frac{1}{2}^-$ and $IJ^P = 0 \frac{3}{2}^-$ are also intriguing candidates which should be searched in experimental studies. This is an interesting subject for experiments at high energy accelerator facilities.

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