

Investigation of the doubly charmed analog of the P_c states

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Motivated by the LHCb Collaboration's observation of the doubly charmed tetraquark state $T_{cc}(3875)$, we systematically explore the potential existence of doubly charmed pentaquark states using the resonating group method within the quark delocalization color screening model framework. The effective potential of the two involved hadrons and the bound-state dynamics are included in the present work. Moreover, we have also calculated the scattering phase shifts of open channels with channel coupling, aiming to identify possible resonance states. Our estimations suggest that the existence of a bound state with quantum numbers $I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ and a mass of approximately 4461.7 MeV. Furthermore, five resonance states are predicted through coupled-channels analysis, which are $\Xi_{cc}\rho$ and $\Sigma_c D^*$ with $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$, $\Lambda_c D^*$ and $\Sigma_c^* D^*$ with $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$, and $\Sigma_c D^*$ with $I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$, respectively. The existence of these predicted doubly charmed pentaquark states needs to be supported by experimental measurements and discoveries. We hope future experiments will provide evidence for these states.

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I. INTRODUCTION

The discovery of an unexpected charmonium state $X(3872)$ in 2003 marked the beginning of intensive studies on exotic hadrons. Since then, numerous charmonium-like states have been experimentally reported. These states cannot be accommodated within the conventional quark model of qqq baryons and $q\bar{q}$ mesons, thereby challenging our understanding of the strong interaction. Hence, exploring the structure and properties of these exotic states is a particularly hot topic in hadron physics.

Among the exotic states, the $Z_c(3900)$ is particularly noteworthy, as it is the first confirmed charged charmonium-like state. It was discovered in 2013 by two independent experimental collaborations, BESIII [1] and Belle [2], in the $\pi^+ J/\psi$ invariant mass spectrum of the process $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at a center-of-mass energy of 4.26 GeV. In addition, the au-

thor of Ref. [3] analyzed the decay $\psi(4160) \rightarrow J/\psi \pi^+\pi^-$ using data of CLEO-c and observed the charged $Z_c(3900)$, which further confirmed the existence of $Z_c(3900)$. Besides, further experimental evidence for the $Z_c(3900)^\pm \rightarrow J/\psi \pi^\pm$ came from the semi-inclusive decay of b -flavored hadrons in the D0 experiment [4], with the $J/\psi \pi^+\pi^-$ invariant mass also constrained around the $Y(4260)$ mass region. The spin-parity quantum numbers of $Z_c(3900)$ have been measured to be $J^P = 1^+$. Extensive theoretical research has been done to understand the nature of the $Z_c(3900)$ structure. Some different interpretations have been proposed, such as compact tetraquark [5–8], $D\bar{D}^*$ resonance or virtual molecular state [9–21], and special kinematical near-threshold cusp [22–26].

The discovery of the $Z_c(3900)$ with the most possible quark component $c\bar{c}q\bar{q}$ further inspires the investigations of multiquark states, especially the possible hidden charm pentaquark states. In 2015, the LHCb Collaboration announced the first evidence of two hidden charm pentaquark states $P_\psi^N(4380)$ and $P_\psi^N(4450)$ in the $J/\psi p$ -invariant mass spectrum measured of the decay process $\Lambda_b \rightarrow J/\psi p K^-$ [27]. With higher statistics data, the LHCb Collaboration further reported the observation of three new pentaquarks states, $P_\psi^N(4312)^+$, $P_\psi^N(4440)^+$, and $P_\psi^N(4457)^+$ in 2019 [28]. The obtained hidden charm pentaquark states masses are below and close to the corresponding threshold of the S -wave charmed baryon $\Sigma_c^{(*)}$ and the S -wave anticharmed meson $\bar{D}^{(*)}$, which provides the compelling experimental evidence for the existence of $\Sigma_c^{(*)}\bar{D}^{(*)}$ -type hidden charm molecular pentaquark states. Thus, the molecular scheme is one of the most popular explanations [29–58]. However, other interpretations cannot

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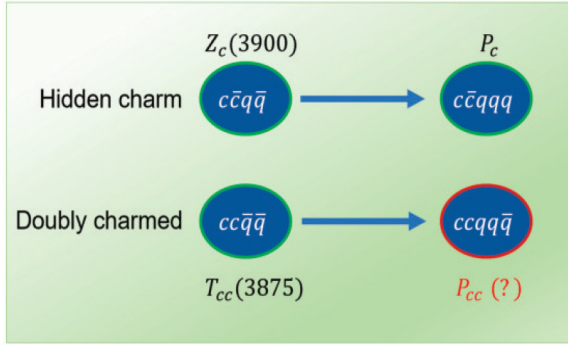


FIG. 1. The similarity of the hidden charm and doubly charmed states.

be ruled out, such as the diquark-triquark states [59,60], the diquark-diquark-antiquark states [61–64], the genuine multi-quark states [65], the topological soliton [66], the kinematical threshold effects in the triangle singularity mechanism [67–69]. To date, the internal structure and properties of the P_c states remain open questions.

Furthermore, from the perspective of a multi-quark state, the existence of multi-quark states with quark content $c\bar{c}q\bar{q}$ implies the possibility of multi-quark states composed of $cc\bar{q}\bar{q}$. Indeed, a new exotic state, $T_{cc}(3875)$, containing two charm quarks, was reported by the LHCb Collaboration in the $D^0 D^0 \pi^+$ mass distribution [70,71]. The observed mass of this extremely narrow state is very close to the threshold of $D^0 D^{*+}$, which stimulated theorists' great interests in the molecular interpretations of $T_{cc}(3875)$ [72–83]. However, a few investigations in the compact tetraquark picture have been accomplished [84–88], even before the $T_{cc}(3875)$ discovery [84,85].

As shown in Fig. 1, the relation between $Z_c(3900)$ and P_c suggests that $T_{cc}(3875)$ should also possess corresponding counterparts, namely, there should exist multi-quark states involving $ccqq\bar{q}$. Some earlier investigations on such systems have been performed in the literature [51,72,89–100]. In Ref. [89], the authors obtained the masses of the meson-baryon-type doubly charmed pentaquark states with $J^P = \frac{1}{2}^-$ below 4.2 GeV based on the unitarized coupled-channels approach. While some deeply bound states of $\Sigma_c^{(*)} D^{(*)}$ with binding energies of about 100 MeV were found through the extension of the chiral unitary approach to describe meson-baryon interactions [90]. Such conclusions are qualitatively consistent with the results of Ref. [72]. In addition, the meson-baryon transitions between the coupled channels $\Lambda_c D^* - \Sigma_c^{(*)} D - \Sigma_c D^* - \Sigma_c^{(*)} D^*$ were performed and a doubly charmed state $\Xi_{cc}^*(4380)$ exists with almost the same mass as $P_c(4380)$ in Ref. [91]. Several doubly charmed baryon resonance states can also be found from the S -wave scattering of ground states doubly charmed baryons and light pseudoscalar mesons within chiral effective theory [92]. Systematic studies on the $\Sigma_c^{(*)} D^{(*)}$ interaction within the one boson exchange model [93,94], the chiral effective field theory [95], and the unitarized coupled-channels approach [96] were carried out. All the $\Sigma_c^{(*)} D^{(*)}$ systems with isospin $I = \frac{1}{2}$ can be possible doubly charmed molecular pentaquarks with binding energies

of about several or dozens of megaelectronvolts, the similar conclusion also can be obtained in Ref. [72]. Furthermore, some compact pentaquark states with doubly heavy quarks were proposed in various models, such as quark model with color magnetic interaction [97,98], nonrelativistic constituent quark model [51,99], and QCD sum rules [100].

In the present work, the possible existence of doubly charmed pentaquark states is systematically investigated by using the resonating group method within the framework of the quark delocalization color screening model (QDCSM). The model has found extensive application in describing the deuteron's properties, investigating nucleon-nucleon (NN) and hyperon-nucleon interactions, and exploring various exotic hadron systems like dibaryon candidates [101–104], pentaquark [37,105], and tetraquark systems [106–108]. Notably, the model's predictive power was significantly validated by its successful dynamical prediction of the $d^*(2380)$ dibaryon's properties, which accurately captured the resonance mass and width years before experimental confirmation and resolved discrepancies found in earlier, less complete calculations [103,104]. In this study, we extend its application to the doubly charmed sector, where the interactions between two hadrons with different quantum numbers are analyzed through their effective potentials. Based on these interactions, we perform bound-state and coupled-channels calculations to identify possible bound and resonance states of doubly charmed pentaquarks. Our specific goal is to determine which quantum numbers are most favorable for the formation of such states, to estimate their masses and widths, and thereby to provide theoretical predictions that can be confronted with future experimental measurements.

The work is organized as follows. The details of the QDCSM are given in Sec. II. In Sec. III, we present the numerical results and discussions, and the last section is devoted to a short summary.

II. THE QUARK DELOCALIZATION COLOR SCREENING MODEL

The QDCSM is an extension of the native quark cluster model [109–112] and was developed with aim of addressing multi-quark systems (more details can be found in Refs. [113–117]). Within QDCSM, the Hamiltonian of the pentaquark system takes the general form:

$$H = \sum_{i=1}^5 \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - T_{c.m.} + \sum_{j>i=1}^5 V(r_{ij}), \quad (1)$$

where the center-of-mass kinetic energy, $T_{c.m.}$, is subtracted without losing generality since we mainly focus on the internal relative motions of the multi-quark system. The two body potentials include the color-confining potential, V_{CON} , one-gluon exchange potential, V_{OGE} , and Goldstone-boson exchange potential, V_χ , respectively, i.e.,

$$V(r_{ij}) = V_{CON}(r_{ij}) + V_{OGE}(r_{ij}) + V_\chi(r_{ij}). \quad (2)$$

It should be emphasized that the potentials include the central, spin-spin, spin-orbit, and tensor contributions, respectively. In the present estimations, we mainly focus on the

S-wave states, and, thus, only the first two terms of potentials will be considered attending the goal of the present calculation and for clarity in our discussion. In particular, the one-gluon-exchange potential, $V_{\text{OGE}}(r_{ij})$, reads

$$V_{\text{OGE}}(r_{ij}) = \frac{1}{4} \alpha_{ij} \lambda_i^c \cdot \lambda_j^c \left[\frac{1}{r_{ij}} - \frac{\pi}{2} \delta(r_{ij}) \times \left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\sigma_i \cdot \sigma_j}{3m_i m_j} \right) \right], \quad (3)$$

where m_i is the quark mass and σ and λ^c are the Pauli matrices and $SU(3)$ color matrices, respectively. The QCD-inspired effective scale-dependent strong-coupling constant, α_{ij} , offers a consistent description of mesons and baryons from the light to the heavy quark sectors. Their values are associated with the quark flavor and determined by the mass difference of the hadrons. It is worth mentioning that a conventional meson contains only one quark and one antiquark, while a baryon has three quarks, which suggests the existence of three-body interactions in the baryon system. Therefore, when using a simple two-body interaction to reproduce the meson and baryon spectrum in a nonrelativistic quark model with OGE potential, the parameter values $\alpha_{qq'}$ and $\alpha_{q\bar{q}'}$, which are determined individually by the baryon and meson spectrum, are not the same.

In the QDCSM, the confining interaction $V_{\text{CON}}(r_{ij})$ can be expressed as

$$V_{\text{CON}}(r_{ij}) = -a_c \lambda_i^c \cdot \lambda_j^c [f(r_{ij}) + V_{0_{ij}}], \quad (4)$$

where a_c represents the strength of the confinement potential and $V_{0_{ij}}$ refers to the zero-point potential. In the case of quark-quark interactions, the value of $V_{0_{qq}}$ is determined based on the differences between theoretical estimations and experimental measurements of baryon spectrum. This value is the same for quarks with different flavors. On the other hand, for quark-antiquark interactions, the value of $V_{0_{q\bar{q}}}$ is determined by reproducing the mass differences between theoretical estimations and experimental measurements of the meson spectrum, which is also flavor-independent. Moreover, in the QDCSM, the quarks in the considered pentaquark state $c\bar{c}nn\bar{n}$ are first divided into two clusters, which are baryon cluster composed of three quarks and meson cluster composed of one quark and one antiquark. And then the five-body problem can be simplified as a two-body problem. In this case, the function $f(r_{ij})$ in the confining interaction reads

$$f(r_{ij}) = \begin{cases} r_{ij}^2 & \text{if } i, j \text{ occur in the same cluster,} \\ \frac{1 - e^{-\mu_{ij} r_{ij}^2}}{\mu_{ij}} & \text{if } i, j \text{ occur in different cluster,} \end{cases} \quad (5)$$

where the color screening parameter μ_{ij} is determined by fitting the deuteron properties, nucleon-nucleon and nucleon-hyperon scattering phase shifts [117–119], with $\mu_{nn} = 0.45 \text{ fm}^{-2}$, $\mu_{ns} = 0.19 \text{ fm}^{-2}$, and $\mu_{ss} = 0.08 \text{ fm}^{-2}$, satisfying the relation $\mu_{ns}^2 = \mu_{nn}\mu_{ss}$, where n represents u or d quark. From this relation, a fact can be found that the heavier the quark, the smaller the parameter μ_{ij} . When extending to the heavy-quark case, we investigate the mass spectrum of P_{ψ}^N with μ_{cc} varying from 10^{-4} to 10^{-2} fm^{-2} [37], and our estimation indicated that the dependence of the parameter μ_{cc}

is not very significant.¹ In the present work, we take $\mu_{cc} = 0.01 \text{ fm}^{-2}$. Then μ_{sc} and μ_{nc} are obtained by the relations $\mu_{sc}^2 = \mu_{ss}\mu_{cc}$ and $\mu_{nc}^2 = \mu_{nn}\mu_{cc}$, respectively.

The Goldstone-boson exchange interactions between light quarks appear because of the dynamical breaking of chiral symmetry. The following π , K , and η exchange terms work between the chiral quark-(anti)quark pair, which read

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

with

$$v_{ij}^{\text{GB}} = \frac{g_{\text{ch}}^2}{4\pi} \frac{m_{\text{GB}}^2}{12m_i m_j} \frac{\Lambda_{\text{GB}}^2}{\Lambda_{\text{GB}}^2 - m_{\text{GB}}^2} m_{\text{GB}} \times \left\{ (\sigma_i \cdot \sigma_j) \left[Y(m_{\text{GB}} r_{ij}) - \frac{\Lambda_{\text{GB}}^3}{m_{\text{GB}}^3} Y(\Lambda_{\text{GB}} r_{ij}) \right] \right\}, \quad (9)$$

the subscript GB in m_{GB} and Λ_{GB} represents the meson π , K , and η , while m_{GB} used in the interaction potential V_{χ} are the experimental values [120] and Λ_{GB} serves as the cutoff parameter. $Y(x) = e^{-x}/x$ is the standard Yukawa function. λ^a is the $SU(3)$ flavor Gell-Mann matrix. The masses of the η , K , and π mesons are taken from the experimental value [120]. By matching the pion exchange diagram of the NN elastic scattering process at the quark level and at the hadron level, one can relate the πqq coupling with the one of πNN , which is [121,122]

$$\frac{g_{\text{ch}}^2}{4\pi} = \left(\frac{3}{5} \right)^2 \frac{g_{\pi NN}^2}{4\pi} \frac{m_{u,d}^2}{m_N^2}, \quad (10)$$

which assumes that the flavor $SU(3)$ is an exact symmetry and only broken by the masses of the strange quark. As for the coupling $g_{\pi NN}$, it was determined by the NN elastic scattering [122]. Besides, the QDCSM parameters and their associated uncertainties were determined via a global fit to the masses

¹The typical size of the multi-quark system should be several femtometres, for example, if the size of the multi-quark system to be 2 fm, then one can find $\mu_{cc} r^2 \propto (10^{-4} - 10^{-2})$, $\mu_{cn} r^2 = \sqrt{\mu_{cc}\mu_{nn}} r^2 \propto (10^{-2} - 10^{-1})$, and $\mu_{cs} r^2 = \sqrt{\mu_{cc}\mu_{ss}} r^2 \propto (10^{-2} - 10^{-1})$, thus the value of the $\mu_{ij} r^2$ is rather small when at least one charm quark included, and in this case, the exponential function can be approximated to be

$$e^{-\mu_{ij} r_{ij}^2} = 1 - \mu_{ij} r_{ij}^2 + \mathcal{O}(\mu_{ij}^2 r_{ij}^4). \quad (9)$$

Accordingly, the confinement potential between two clusters is approximated to be,

$$V_{\text{CON}}(r_{ij}) = -a_c \lambda_i^c \cdot \lambda_j^c \left(\frac{1 - e^{-\mu_{ij} r_{ij}^2}}{\mu_{ij}} + V_{0_{ij}} \right) \approx -a_c \lambda_i^c \cdot \lambda_j^c (r_{ij}^2 + V_{0_{ij}}), \quad (7)$$

which is the same as the expression of two quarks in the same cluster. Thus, when the value of the μ_{cc} is very small, the screened confinement will return to the quadratic form, which is why the results are insensitive to the value of μ_{cc} .

TABLE I. All possible channels for doubly charmed pentaquark systems with different quantum numbers.

	$I = \frac{1}{2}$						$I = \frac{3}{2}$					
$S = \frac{1}{2}$	$\Xi_{cc}\eta$	$\Xi_{cc}\omega$	$\Xi_{cc}^*\omega$	$\Xi_{cc}\pi$	$\Xi_{cc}\rho$	$\Xi_{cc}^*\rho$	$\Xi_{cc}\pi$	$\Xi_{cc}\rho$	$\Xi_{cc}^*\rho$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$
	$\Lambda_c D$	$\Lambda_c D^*$	$\Sigma_c D$	$\Sigma_c D^*$	$\Sigma_c^* D^*$							
$S = \frac{3}{2}$	$\Xi_{cc}\omega$	$\Xi_{cc}^*\eta$	$\Xi_{cc}^*\omega$	$\Xi_{cc}\rho$	$\Xi_{cc}^*\pi$	$\Xi_{cc}^*\rho$	$\Xi_{cc}^*\rho$	$\Xi_{cc}^*\pi$	$\Xi_{cc}^*\rho$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$
	$\Lambda_c D^*$	$\Sigma_c D^*$	$\Sigma_c^* D$	$\Sigma_c^* D^*$								
$S = \frac{5}{2}$	$\Xi_{cc}^*\omega$	$\Xi_{cc}^*\rho$	$\Sigma_c^* D^*$				$\Xi_{cc}^*\rho$	$\Sigma_c^* D^*$				

of ground-state mesons and baryons, utilizing the Minuit program. The optimized parameters resulting from this procedure and the resulting mass spectrum are presented in Appendix. While this global fit provides a reasonable overall description of the hadron spectrum—especially for the charmed hadrons crucial to this investigation—it possesses known limitations for certain states, most notably the η meson (see Appendix for further discussion).

In the QDCSM, the quark delocalization is realized by specifying the single-particle orbital wave function as a linear combination of left and right Gaussian basis, the single-particle orbital wave functions used in the ordinary quark cluster model reads

$$\begin{aligned}
\psi_\alpha(s_i, \epsilon) &= (\Phi_\alpha(s_i) + \epsilon \Phi_\beta(s_i))/N(\epsilon), \\
\psi_\beta(s_i, \epsilon) &= (\Phi_\beta(s_i) + \epsilon \Phi_\alpha(s_i))/N(\epsilon), \\
N(\epsilon) &= \sqrt{1 + \epsilon^2 + 2\epsilon e^{-s_i^2/4b^2}}, \\
\Phi_\alpha(s_i) &= \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{1}{2b^2}(\mathbf{r}_\alpha - \frac{2}{5}\mathbf{s}_i)^2}, \\
\Phi_\beta(-s_i) &= \left(\frac{1}{\pi b^2}\right)^{\frac{3}{4}} e^{-\frac{1}{2b^2}(\mathbf{r}_\beta + \frac{3}{5}\mathbf{s}_i)^2},
\end{aligned} \tag{11}$$

with s_i , $i = (1, 2, \dots, n)$, to be the generating coordinates, which are introduced to expand the relative motion wave function [123–125]. The parameter b indicates the size of the baryon and meson clusters, which is determined by fitting the radius of the baryon and meson by the variational method [126]. In addition, The mixing parameter $\epsilon(s_i)$ is not an adjusted one but determined variationally by the dynamics of the multiquark system itself. This assumption allows the multiquark system to choose its favorable configuration in the interacting process. It has been used to explain the cross-over of the transition between the hadron phase and the quark-gluon plasma phase [116,127]. Due to the effect of the mixing parameter $\epsilon(s_i)$, there is a certain probability for the quarks between the two clusters to run, which leads to the existence of color octet states for the two clusters. Therefore, this model also includes the hidden color channel effect, which is confirmed by Refs. [128,129].

III. RESULTS AND DISCUSSIONS

In the present work, we investigate the lowest-lying possible bound and resonance states of the $ccnn\bar{n}$ [where $n = (u, d)$] pentaquark systems within the QDCSM framework. Specifically, we focus on the S -wave pentaquark states with

negative parity. Consequently, the total angular momentum, J , aligns with the total spin, S , and its values can be $1/2$, $3/2$, and $5/2$. The isospin of the $ccnn\bar{n}$ pentaquark system could be $1/2$ and $3/2$. In addition, all estimations are based on the molecular-state scenario. The possible baryon-meson channels involved in the present estimations are listed in Table I.

A. The effective potentials

Given that an attractive potential is essential for the formation of a bound state or resonance state, we initially estimate the effective potential between hadron pairs as detailed listed in Table I. The effective potential is defined as

$$V(S_m) = E(S_m) - E(\infty), \tag{12}$$

where $E(S_m)$ represents the diagonal matrix element of the system's Hamiltonian, evaluated at specific generator coordinate. So the potential is obtained by

$$E(S_m) = \frac{\langle \Psi_{5q}(S_m) | H | \Psi_{5q}(S_m) \rangle}{\langle \Psi_{5q}(S_m) | \Psi_{5q}(S_m) \rangle}, \tag{13}$$

where S_m denotes the separation between the meson and baryon clusters and $\Psi_{5q}(S_m)$ represents the wave function of a certain given channel. The terms $\langle \Psi_{5q}(S_m) | H | \Psi_{5q}(S_m) \rangle$ and $\langle \Psi_{5q}(S_m) | \Psi_{5q}(S_m) \rangle$ correspond to the Hamiltonian matrix and the overlap of the states, respectively. Furthermore, $E(\infty)$ corresponds to the sum of the energies of the two individual hadron clusters when they are separated by a sufficiently larger distance, effectively meaning they are not interacting with each other. The central effective potentials for doubly charmed pentaquark systems with isospins $I = 1/2$ and $I = 3/2$ are depicted in Figs. 2 and 3, respectively.

For the case of $I(J)^P = \frac{1}{2}(\frac{1}{2})^-$, there are 11 channels, which are listed in Table I. From Fig. 2(a), one can find that all the physical channels show attractive interactions expect for $\Xi_{cc}\eta$, $\Xi_{cc}\pi$, and $\Xi_{cc}^*\omega$ channels. In particular, the attraction between Σ_c and D^* is the largest one, followed by the $\Xi_{cc}\rho$ channel, which is a little larger than that of the $\Xi_{cc}\omega$ channel. The attractive interactions of the remaining physical channels are small compared to the above-mentioned three channels. These phenomena indicate that the $\Sigma_c D^*$, $\Xi_{cc}\rho$, and $\Xi_{cc}\omega$ are more likely to form bound or resonant states owing to their stronger attractive interactions. For the case of the $I(J)^P = \frac{1}{2}(\frac{3}{2})^-$, as shown in Fig. 2(b), the potential of the $\Xi_{cc}^*\eta$ channel is repulsive while the potentials of the remaining channels are attractive. Among the channels with attractive potentials, $\Lambda_c D^*$ and $\Sigma^* D^*$ channels have relative strong interactions,

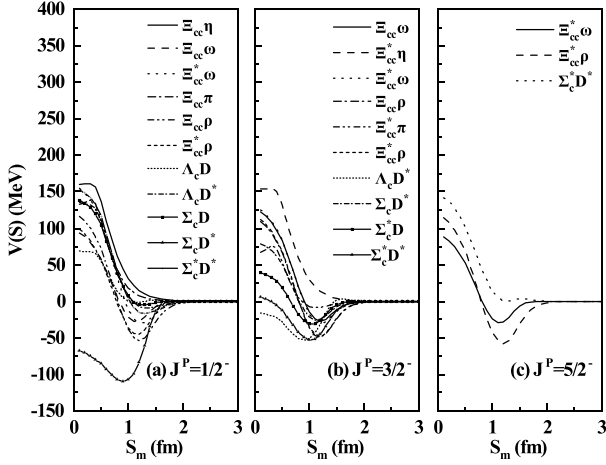


FIG. 2. The effective potentials defined in Eq. (12) for different channels of the doubly charmed pentaquark systems with $I = 1/2$ in QDCSM.

which implies that one may observe bound or resonance states in the $\Lambda_c D^*$ and $\Sigma^* D^*$ channels. The estimated potentials for the case of $I(J)^P = \frac{1}{2}(\frac{5}{2}^-)$ are presented in Fig. 2(c), the potentials are attractive for both $\Xi_{cc}^* \rho$ and $\Xi_{cc}^* \omega$ channels, while for the $\Sigma_c^* D^*$ channel, it is strongly repulsive. Furthermore, the effective potentials shown in Fig. 2 indicate that channels containing the η meson display a repulsive character. Consequently, the possibility of forming a bound state exclusively in these channels is excluded.

In addition, we also estimate the effective potentials for systems with $I = \frac{3}{2}$ and all possible angular momenta, as depicted in Fig. 3. For the case of $J^P = \frac{1}{2}^-$, the $\Xi_{cc} \pi$ channel exhibits a repulsive interaction, indicating that neither bound states nor resonances can be anticipated in this channel. Conversely, the remaining channels demonstrate attractive interactions, suggesting the potential existence of bound or resonance states. Notably, as shown in Fig. 3(a), the attraction between Σ_c and D^* is the most pronounced, closely followed

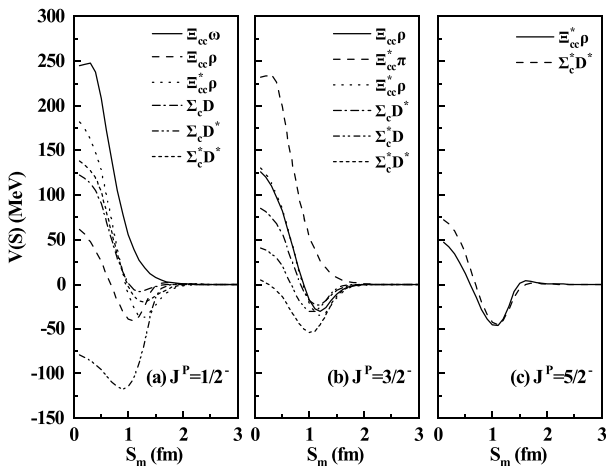


FIG. 3. The effective potentials defined in Eq. (12) for different channels of the doubly charmed pentaquark systems with $I = 3/2$ in QDCSM.

by the $\Xi_{cc} \rho$ and $\Xi_{cc}^* \rho$. The interactions in the $\Sigma_c^* D^*$ and $\Sigma_c D^*$ channels are the least attractive among these channels. For the case of $J^P = \frac{3}{2}^-$, similar outcomes to the the $J^P = \frac{1}{2}^-$ system are observed. Here all channels expect for $\Xi_{cc} \pi$ are characterized by attractive potentials. As illustrated in Fig. 3(b), the $\Sigma_c^* D^*$ channel manifests the strongest attraction, with the other channels exhibiting comparable attractions. For the case of $J^P = \frac{5}{2}^-$, the effective potentials for the $\Xi_{cc}^* \rho$ and $\Sigma_c^* D^*$ channels, as presented in Fig. 3(c), indicate attractive interactions. This suggests that the formation of a bound or resonance state is plausible within these channels due to the attractive nature of the hadron pairs.

B. Possible bound states

To search for possible bound or resonance states, we perform dynamical calculations of doubly charmed pentaquark systems under the QDCSM employing the resonating group method (RGM) [130–132]. Here the doubly charmed pentaquark states can be divided into two kinds of structures, which are $ccn-n\bar{n}$ and $cnn-c\bar{n}$, respectively. Here it should be noted that the definition of different structures just represents the coupling sequences, for convenience, we use the kind of representation of each channel in the following discussions. The estimated results are listed in Tables II and III, which correspond to the states with $I = 1/2$ and $I = 3/2$, respectively. In these tables, E_{sc} is the single-channel eigenenergy for different channels, E_{cc1} and E_{cc2} stand for the eigenenergies of the channel coupling for each kind of structure, and the estimated eigenenergies by simultaneously considering the two types of structure. E_{th}^{Model} and E_{th}^{Exp} represent theoretical estimates and experimental measurements of channel thresholds, respectively. However, considering the uncertainty of the model estimation, the corrected estimates are based on the relative corrective error calculation. The single-channel corrected estimations E'_{sc} can be derived from $E_{th}^{Exp} + E_B$ where E_B is the binding energy. Similarly, taking the lowest threshold of the channels involved as a reference, the corrected eigenenergy of the coupled-channels estimations E'_{cc1} and E'_{cc2} can be obtained. This relative correction method effectively cancels systematic uncertainties originating from the global parameter fit (detailed in Appendix), as constituent quark models are generally more reliable in predicting relative energy differences (E_B) than absolute mass scales (E_{th}^{Model} vs E_{th}^{Exp}). It anchors our final predictions (E') to the physical mass scale defined by experimental thresholds. Furthermore, we have specifically verified the dynamical of the η -containing channels. As shown in Fig. 2, the effective potential for channels such as $\Xi_{cc} \eta$ is repulsive. In the full channel-coupling calculation, we confirmed that the numerical contribution of these channels is negligible. Therefore, the η mass issue in Appendix does not affect the final conclusion of this study.

As for the $I(J)^P = \frac{1}{2}(\frac{1}{2}^-)$ system, the single-channel estimations indicate that the obtained central eigenenergies of the $\Sigma_c D^*$ in the $cnn-c\bar{n}$ structure and $\Xi_{cc} \rho$ in the $ccn-n\bar{n}$ structure are lower than the corresponding theoretical threshold of those channels, and the binding energies are approximately -42.1 and -0.7 MeV, respectively, which is consistent with the

TABLE II. The masses of every single channel and those of channel coupling for the pentaquarks with $I = 1/2$. The values are provided in units of megaelectronvolts.

$I(J^P)$	Structure	Channel	E_{sc}	E_{cc1}	E_{cc2}	E'_{sc}	E'_{cc1}	E'_{cc2}	E_{th}^{Model}	E_{th}^{Exp}
$\frac{1}{2}(\frac{1}{2}^-)$	$ccn-n\bar{n}$	$\Xi_{cc}\eta$	3907.3 ± 6.2	3762.5 ± 3.4	3759.8 ± 4.2	4172.8 ± 6.2	3764.5 ± 3.4	3764.3 ± 4.2	3903.7	4169.2
		$\Xi_{cc}\omega$	4345.3 ± 13.4			4407.1 ± 13.4			4342.4	4404.1
		$\Xi_{cc}^*\omega$	4356.6 ± 12.7			4481.8 ± 12.7			4353.9	4479.2
		$\Xi_{cc}\pi$	3762.9 ± 3.7			3764.5 ± 3.7			3759.5	3761.0
		$\Xi_{cc}\rho$	4389.8 ± 13.8			4396.0 ± 13.8			4390.5	4396.7
		$\Xi_{cc}^*\rho$	4403.2 ± 13.2			4473.0 ± 13.2			4402.0	4471.8
	$cnn-c\bar{n}$	$\Lambda_c D$	4157.3 ± 14.6	4157.0 ± 6.2		4159.5 ± 14.6	4158.1 ± 6.2		4153.9	4156.1
		$\Lambda_c D^*$	4228.2 ± 15.4			4296.7 ± 15.4			4224.9	4293.4
		$\Sigma_c D$	4345.0 ± 12.3			4328.0 ± 12.3			4341.6	4324.6
		$\Sigma_c D^*$	4370.4 ± 11.0			4419.7 ± 11.0			4412.5	4461.9
		$\Sigma_c^* D^*$	4427.3 ± 11.9			4530.2 ± 11.9			4424.1	4526.9
$\frac{1}{2}(\frac{3}{2}^-)$	$ccn-n\bar{n}$	$\Xi_{cc}\omega$	4345.3 ± 13.9	3773.6 ± 3.1	3772.5 ± 3.2	4407.0 ± 13.9	3838.8 ± 3.1	3837.6 ± 3.2	4342.4	4404.1
		$\Xi_{cc}^*\eta$	3918.9 ± 5.1			4247.9 ± 5.1			3915.3	4244.3
		$\Xi_{cc}^*\omega$	4356.7 ± 12.7			4481.9 ± 12.7			4353.9	4479.2
		$\Xi_{cc}\rho$	4390.9 ± 14.1			4397.1 ± 14.1			4390.4	4396.7
		$\Xi_{cc}^*\pi$	3774.1 ± 2.6			3839.2 ± 2.6			3771.0	3836.1
		$\Xi_{cc}^*\rho$	4402.8 ± 13.1			4472.5 ± 13.1			4402.0	4471.8
	$cnn-c\bar{n}$	$\Lambda_c D^*$	4222.2 ± 14.9	4219.9 ± 14.2		4290.6 ± 14.9	4288.5 ± 14.2		4224.9	4293.4
		$\Sigma_c D^*$	4415.4 ± 12.9			4464.7 ± 12.9			4412.5	4461.9
		$\Sigma_c^* D$	4355.5 ± 11.1			4392.0 ± 11.1			4353.1	4389.6
		$\Sigma_c^* D^*$	4421.4 ± 11.4			4524.2 ± 11.4			4424.1	4526.9
$\frac{1}{2}(\frac{5}{2}^-)$	$ccn-n\bar{n}$	$\Xi_{cc}^*\omega$	4356.9 ± 12.7	4402.2 ± 13.1	4402.1 ± 12.5	4482.2 ± 12.7	4471.9 ± 13.1	4471.8 ± 12.5	4353.9	4479.2
		$\Xi_{cc}^*\rho$	4402.2 ± 12.5			4471.9 ± 12.5			4402.0	4471.8
	$cnn-c\bar{n}$	$\Sigma_c^* D^*$	4425.2 ± 10.9			4527.9 ± 10.9			4424.1	4526.9

expectations of the effective potentials presented in Fig. 2. In addition, the estimations in Refs. [72,93–96] showed that $\Sigma_c D^*$ may be a good candidate for a doubly charmed molecular state, which accords with that of $\Sigma_c D^*$ single-channel estimation. However, for the remaining channel in the $cnn-c\bar{n}$ structure, along with $\Xi_{cc}\omega$ and $\Xi_{cc}^*\rho$ in the $ccn-n\bar{n}$ structure, although the effective potentials are attractive, no bound states have been found in those channels because the attractive

interactions between hadrons are too weak. For the $\Xi_{cc}\eta$, $\Xi_{cc}\pi$, and $\Xi_{cc}^*\omega$, the obtained central eigenenergies are higher than the corresponding theoretical threshold due to the repulsive nature. After considering the coupling between channels in the same structures, we find that the central eigenenergies are estimated to be 3764.5 and 4158.1 MeV for the $ccn-n\bar{n}$ and $cnn-c\bar{n}$ structures, respectively. Further complete coupled-channels estimations predict a state with a mass to be

TABLE III. The masses of every single channel and those of channel coupling for the pentaquarks with $I = 3/2$. The values are provided in units of megaelectronvolts.

$I(J^P)$	Structure	Channel	E_{sc}	E_{cc1}	E_{cc2}	E'_{sc}	E'_{cc1}	E'_{cc2}	E_{th}^{Model}	E_{th}^{Exp}
$\frac{3}{2}(\frac{1}{2}^-)$	$ccn-n\bar{n}$	$\Xi_{cc}\pi$	3763.2 ± 3.7	3763.2 ± 3.9	3763.1 ± 3.7	3764.7 ± 3.7	3764.7 ± 3.9	3764.6 ± 3.7	3759.5	3761.0
		$\Xi_{cc}\rho$	4393.1 ± 14.5			4399.3 ± 14.5			4390.5	4396.7
		$\Xi_{cc}^*\rho$	4404.2 ± 13.4			4474.0 ± 13.4			4402.0	4471.8
	$cnn-c\bar{n}$	$\Sigma_c D$	4344.9 ± 12.3	4344.8 ± 5.2		4328.0 ± 12.3	4327.9 ± 5.2		4341.6	4324.6
		$\Sigma_c D^*$	4363.7 ± 10.9			4413.1 ± 10.9			4412.5	4461.9
		$\Sigma_c^* D^*$	4427.3 ± 11.8			4530.1 ± 11.8			4424.1	4526.9
$\frac{3}{2}(\frac{3}{2}^-)$	$ccn-n\bar{n}$	$\Xi_{cc}\rho$	4393.3 ± 14.6	3774.8 ± 2.7	3774.7 ± 2.7	4399.6 ± 14.6	3839.8 ± 2.7	3839.7 ± 2.7	4390.5	4396.7
		$\Xi_{cc}^*\pi$	3774.7 ± 2.6			3839.8 ± 2.6			3771.0	3836.1
		$\Xi_{cc}^*\rho$	4404.5 ± 13.4			4474.3 ± 13.4			4402.0	4471.8
	$cnn-c\bar{n}$	$\Sigma_c D^*$	4415.4 ± 12.9	4355.0 ± 7.1		4464.8 ± 12.9	4391.5 ± 7.1		4412.5	4461.9
		$\Sigma_c^* D$	4355.6 ± 11.0			4392.1 ± 11.0			4353.1	4389.6
		$\Sigma_c^* D^*$	4421.1 ± 11.4			4523.9 ± 11.4			4424.1	4526.9
$\frac{3}{2}(\frac{5}{2}^-)$	$ccn-n\bar{n}$	$\Xi_{cc}^*\rho$	4404.4 ± 13.7		4391.9 ± 11.2	4474.1 ± 13.7		4461.7 ± 11.2	4402.0	4471.8
		$\Sigma_c^* D^*$	4425.5 ± 11.3			4528.3 ± 11.3			4424.1	4526.9

3764.3 MeV, which is still above the lowest threshold of $\Xi_{cc}\pi$. In addition, from the estimation of the channel coupling, the obtained central eigenenergies are close to that of single-channel results, which indicates that the effect of channel coupling is minimal in the estimation of the dynamic.

For the $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ system, there are 10 channels in this system as shown in Table II. In the $ccn-c\bar{n}$ structure, the single-channel estimations show that the $\Lambda_c D^*$ and $\Sigma_c^* D^*$ could be bound states with a binding energy of approximately -2.7 MeV. The existence of the two bound states can be attributed to the strong attractive interactions of $\Lambda_c D^*$ and $\Sigma_c^* D^*$. Similar conclusions are reported in Refs. [72,93–96], where the authors proposed that $\Sigma_c^* D^*$ [72,93–96] and $\Lambda_c D^*$ [72] with quantum numbers $1/2(3/2^-)$ could be good candidates for doubly charmed molecular pentaquarks. For other channels in two structures, except for the $\Xi_{cc}^* \eta$, no bound states are derived due to the weak attraction interactions. In the case of $\Xi_{cc}^* \eta$, the potential is repulsive, leading to a central eigenenergy above the corresponding threshold. When considering the channel coupling within the same structure, the central eigenenergy obtained falls below the lowest physical channel $\Lambda_c D^*$ threshold in the $ccn-n\bar{n}$ structure, with a binding energy of -4.9 MeV. Conversely, in the $ccn-n\bar{n}$ structure, the coupled-channels estimations identify the lowest state with a central energy of 3837.6 MeV, approaching the lowest physical threshold. For the $I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ system, no pentaquark states below the respective physical thresholds are obtained in either single-channel or multichannel calculations.

For the $I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ system, a pentaquark molecular state composed of $\Sigma_c^* D^*$ with a binding energy of approximately -48.8 MeV is identified through dynamical single-channel calculations, driven by the strong attraction between Σ_c and D^* . In comparison, the central eigenenergies obtained from other single-channel calculations surpass their corresponding physical thresholds. Furthermore, a comparison of the above results with those of Ref. [94] shows consistent conclusions regarding the $\Sigma_c D^*$ state with $3/2(1/2^-)$, supporting its candidacy as a hadronic molecular state. Channel-coupling estimations for different structures demonstrate that the central eigenenergies for the $ccn-n\bar{n}$ and $ccn-c\bar{n}$ structures are 3764.7 and 4327.9 MeV, respectively, which are above the lowest physical threshold of the corresponding structure. The channel-coupling calculations with both structures yield a central eigenenergy of 3764.6 MeV, approximately 4 MeV above the threshold of the lowest channel, $\Xi_{cc}\pi$. For the $I(J^P) = \frac{3}{2}(\frac{3}{2}^-)$ system, single-channel calculations indicate that all central eigenenergies are above their respective physical thresholds, except for $\Sigma_c^* D^*$, whose central eigenenergy is 4392.1 MeV, about -3.0 MeV below its threshold. Neither the $ccn-n\bar{n}$ structure nor the $ccn-c\bar{n}$ structure in channel-coupling calculations produces any bound states. The central eigenvalue from coupling across both structures is 3839.7 MeV, which is also above the threshold of the lowest channel, $\Xi_{cc}\pi$. For the $I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ system, two channels, $\Xi_{cc}^* \rho$ and $\Sigma_c^* D^*$, are considered, as shown in Table III. Initially, single-channel estimations show that the central eigenenergies for both $\Xi_{cc}^* \rho$ and $\Sigma_c^* D^*$ exceed their respective physical thresholds. However, the channel-coupling estimations re-

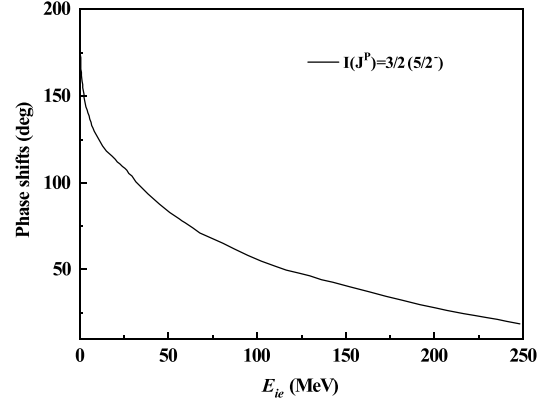


FIG. 4. The low-energy scattering phase shifts of the doubly charmed pentaquark systems with $I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ in QDCSM.

veal a bound state with a central mass of approximately 4461.7 MeV. To determine the composition of the bound state, we calculate the proportion of each channel in the total wave function. Due to the nonorthogonality of RGM basis states, this proportion (P_i) is calculated using the overlap kernel N_{ij} as $P_i = \sum_j c_i c_j N_{ij}$. Applying this method, we find that the $\Xi_{cc}^* \rho$ channel constitutes 97% of the wave function's norm, confirming it as the overwhelmingly dominant component of this bound state.

To further check the possibility of this bound state with $I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ system, the low-energy scattering phase shifts of this state are investigated by the variational method, which is shown in Fig. 4. From the Fig. 4, one can find that the low-energy phase shifts of $\Xi_{cc}^* \rho$ in the channel-coupling estimation can reach up to 180° at $E_{ie} \sim 0$ (E_{ie} is the incident energy of the relevant open channel), and the valuation of the low-energy phase shifts scattering is intensely reduced at gradually increasing incident energies. Such behavior is a well-known signature of a near-threshold bound state, consistent with our dynamical calculations.

In addition, we can also estimate the bounding energies of the bound states in the following way. First, based on the low-energy scattering phase shifts calculation, we can obtain the scattering length a_0 and the effective range r_0 at the low-energy scattering phase shifts by

$$k \cot \delta_L = -\frac{1}{a_0} + \frac{1}{2} r_0 k^2 + O(k^4), \quad (14)$$

where $k = \sqrt{2\mu E_{ie}}$, μ , and E_{ie} are the reduced mass of two hadrons and the incident energy, respectively.

According to above results, the wave number α can be available by the relation [133],

$$r_0 = \frac{2}{\alpha} \left(1 - \frac{1}{\alpha a_0} \right). \quad (15)$$

Finally, the binding energy E'_B is calculated according to the relation,

$$E'_B = \frac{\hbar^2 \alpha^2}{2\mu}. \quad (16)$$

TABLE IV. The scattering length a_0 , the effective range r_0 , and the binding energy E'_B determined by the variation method.

$I(J^P)$	Channel	a_0 (fm)	r_0 (fm)	E'_B (MeV)
$\frac{3}{2}(\frac{5}{2}^-)$	$\Xi_{cc}^*\rho - \Sigma_c^*D^*$	2.335 ± 0.092	0.933 ± 0.003	-12.2 ± 0.004

For the bound state, the scattering length a_0 , the effective range r_0 , and the binding energy E'_B are calculated, which are presented in Table IV, where one can find that the scattering length of the bound state is positive, and the binding energy estimated by the variational method, E'_B , is 12.2 ± 0.004 MeV, which is close to the one obtained by the RGM calculations. These results further confirm the existence of the bound state in the doubly charmed pentaquark system.

C. Possible resonance states

From the above bound-state estimation, some bound states have been obtained from the single-channel calculation due to the strong attraction of two hadrons. However, these states are not stable, which can decay into the corresponding open channels through coupling, potentially forming resonance or scattering states. So in the present work, we further check whether the bound states can transform into resonance states after coupling to the open channels by investigating the scattering phase shifts of the open channels. It is worth mentioning that only the S -wave pentaquark states composed of $ccnn\bar{n}$ are considered in the present work because the width of the high partial waves is almost negligible. Besides, we only consider the two-body decay channels, so the total decay widths of the states estimated in the present work are the lower limits. The phase shifts of the corresponding open channels are shown in Figs. 5–7. The corrected masses and widths of resonance states, along with their central values and associated errors, are summarized in Table V.

For the $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ system, two bound states, $\Xi_{cc}\rho$ and $\Sigma_c D^*$, can be found in the single-channel calculations. From Table II, the bound state $\Xi_{cc}\rho$ can couple to five open channels, which are $\Xi_{cc}\eta$, $\Xi_{cc}\pi$, $\Lambda_c D$, $\Lambda_c D^*$, and $\Sigma_c D$, respectively. While the bound state $\Sigma_c D^*$ can couple to $\Xi_{cc}\eta$,

$\Xi_{cc}\omega$, $\Xi_{cc}\pi$, $\Lambda_c D$, $\Lambda_c D^*$, and $\Sigma_c D$ channels. The phase shifts of two-channel coupling with a single bound state and the corresponding open channel depending on the incident energy E_i are shown in Fig. 5. From Fig. 5(a), one can find that the $\Xi_{cc}\rho$ resonance state appears in the phase shifts of $\Lambda_c D^*$ and $\Sigma_c D$ channels, while there is no resonance state in the phase shifts of $\Xi_{cc}\eta$, $\Xi_{cc}\pi$, and $\Lambda_c D$ channels. For the bound state $\Sigma_c D^*$, one can find that it only behaves as a resonance in the scattering phase shifts of $\Lambda_c D$, $\Lambda_c D^*$, and $\Sigma_c D$ in Fig. 5(b). The resonance mass and decay width can be obtained from the shape of the scattering phase shift. Particularly, the resonance mass M_{R1} can be acquired by summing the threshold of the corresponding open channel with the incident energy at a scattering phase of $\pi/2$. Still, to facilitate better comparison with further experimental results, the corrected resonance masses obtained M_R using $M_{R1} - \sum_i c_i (E_{th}^{Model}(i) - E_{th}^{Exp}(i))$ are listed in Table V, where the decay width of the resonance states are also listed. The corrected central masses of resonance states $\Xi_{cc}\rho$ and $\Sigma_c D^*$ are approximately (~ 4391.8 – 4395.5) MeV and (~ 4420.3 – 4461.3) MeV, with decay widths of 3.7 and 13.0 MeV, respectively. These estimations indicate that the mass shifts of each resonance state are relatively small, suggesting a weak channel-coupling effect between the bound state and the corresponding open channel. This phenomenon can be attributed to the significant mass difference between the two channels.

For the $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ system, it is in a similar situation as the one of the $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ system. In the single-channel estimations, two bound states composed of $\Lambda_c D^*$ and $\Sigma_c^* D^*$ are identified. The $\Lambda_c D^*$ bound state can decay into $\Xi_{cc}^*\eta$ and $\Xi_{cc}^*\pi$, with their scattering phase shifts illustrated in Fig. 6(a). From the figure, one can find that no resonance state

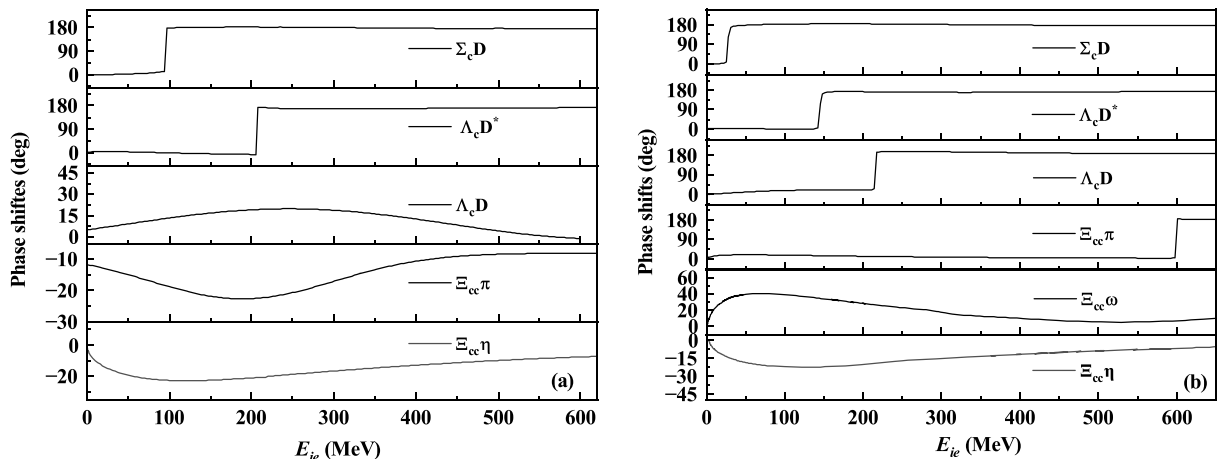


FIG. 5. The scattering phase shifts of the open channels with $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ in QDCSM. (a) Two-channel coupling with the $\Xi_{cc}\rho$ and the associated five open channels; (b) two-channel coupling with the $\Sigma_c D^*$ and the related six open channels shown in the figure.

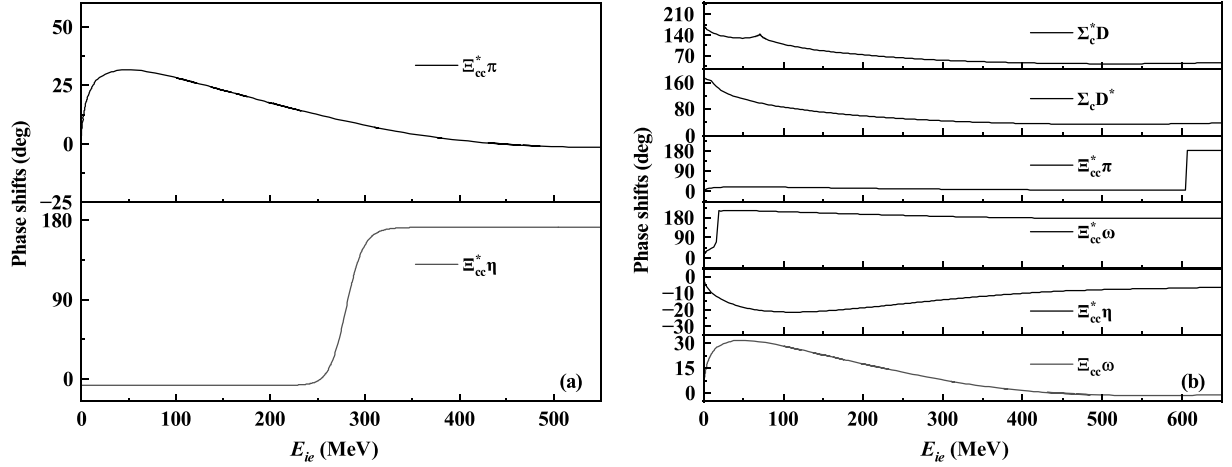


FIG. 6. The scattering phase shifts of the open channels with $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ in QDCSM. (a) Two-channel coupling with the $\Lambda_c D^*$ and the associated two open channels; (b) two-channel coupling with the $\Sigma_c^* D^*$ and the related six open channels shown in the figure;

is observed in the scattering phase shifts of $\Xi_{cc}^* \pi$, whereas a resonance state of $\Lambda_c D^*$ is present in the scattering phase shifts of $\Xi_{cc}^* \eta$. The obtained central mass and width of the resonance state are approximately 4286.6 and 8.9 MeV, respectively. The bound state $\Sigma_c^* D^*$ can be investigated through the scattering phase shifts of the open channels $\Xi_{cc} \omega$, $\Xi_{cc}^* \eta$, $\Xi_{cc}^* \omega$, $\Xi_{cc}^* \pi$, $\Sigma_c D^*$, and $\Sigma_c^* D$, respectively. From Fig. 6(b), the resonance state of $\Sigma_c^* D^*$ appears only in the scattering phase shifts of $\Xi_{cc}^* \omega$ and $\Xi_{cc}^* \pi$ with the corrected mass and width approximately being (~ 4522.2 – 4526.1) MeV and 7.6 MeV, respectively, while the bound state vanishes in the other open channels. This is attributed to the channel-coupling effect, which pushes the bound state $\Sigma_c^* D^*$ above its threshold, converting it into a scattering state.

For the $I = \frac{3}{2}$ system, all possible scattering phase shifts for the open channels are presented in Fig. 7. A $\Sigma_c D^*$ bound state is obtained from $J^P = \frac{1}{2}^-$ in the single-channel calculation, which can decay into open channels, $\Xi_{cc} \pi$ and $\Sigma_c D$. Analyzing the scattering phase shifts of two-channel coupling

with a bound state and an open channel in Fig. 7(a) reveals that the resonance state of $\Sigma_c D^*$ appears in the scattering phase shifts of $\Sigma_c D$ channel, and the corrected central resonance mass and decay width are approximately 4431.1 and 5.2 MeV, respectively. For the $J^P = \frac{3}{2}^-$ system, a bound state $\Sigma_c^* D^*$ is identified in the single-channel calculation, which can couple with open channels $\Xi_{cc}^* \pi$, $\Sigma_c D^*$, and $\Sigma_c^* D$. A detailed analysis of Fig. 7(b) indicates the absence of the resonance state in the scattering phase shift of $\Xi_{cc}^* \pi$, $\Sigma_c D^*$, and $\Sigma_c^* D$. This observation implies that the $\Sigma_c^* D^*$ bound state has transitioned into a scattering state as a result of the two-channel coupling effect.

To provide a broader perspective on the nature of doubly charmed pentaquarks, it is instructive to compare our results with those obtained from other theoretical frameworks, such as heavy quark spin symmetry (HQSS) [72], the one-boson-exchange (OBE) model [93,94], chiral effective field theory (ChEFT) [95], the unitarized coupled-channels approach (UCC) [96], the chiral quark model (ChQM) [134],

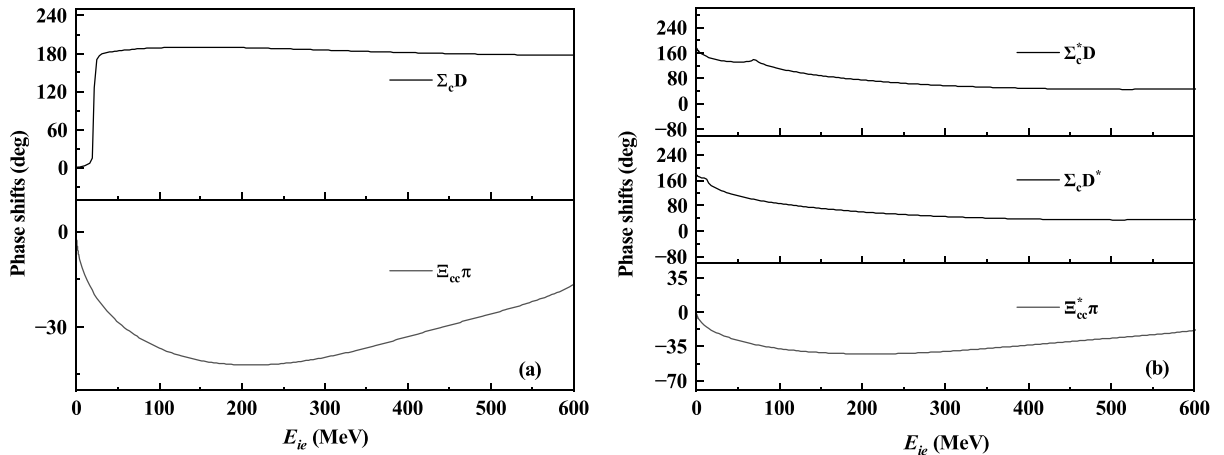


FIG. 7. The scattering phase shifts of the open channels with $I = \frac{3}{2}$ in QDCSM. (a) Two-channel coupling involving the $\Sigma_c D^*$ and the concerned two open channels with $J^P = 1/2^-$; (b) two-channel coupling involving the $\Sigma_c^* D^*$ and the respective three open channels with $J^P = 3/2^-$.

TABLE V. The masses and decay widths (in megaelectronvolts) of resonance states with the difference scattering process. m_R stands for the modified resonance mass. Γ is the partial decay width of the resonance state decaying to an open channel. Γ_{Total} is the total decay width of the resonance state.

Open channels	$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$				$I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$				$I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$	
	$\Xi_{cc}\rho$		$\Sigma_c D^*$		$\Lambda_c D^*$		$\Sigma_c^* D^*$		$\Sigma_c D^*$	
	M_R	Γ	M_R	Γ	M_R	Γ	M_R	Γ	M_R	Γ
$\Xi_{cc}\eta$	...	...	...	...	...	...	...	...	...	...
$\Xi_{cc}\omega$	...	...	...	...	...	...	...	...	...	...
$\Xi_{cc}\pi$	...	...	4461.3 ± 0.1	3.4 ± 2.1	...	...	...	...	...	...
$\Lambda_c D$	...	...	4420.3 ± 5.2	1.3 ± 0.3	...	...	...	...	...	...
$\Lambda_c D^*$	4391.8 ± 1.2	2.5 ± 0.5	4455.3 ± 2.3	3.2 ± 1.4	...	...	...	...	...	...
$\Sigma_c D$	4395.5 ± 1.4	1.2 ± 0.9	4458.1 ± 1.1	5.1 ± 2.3	...	...	...	...	4431.1 ± 6.7	5.2 ± 3.4
$\Xi_{cc}^* \eta$	...	...	...	...	4286.6 ± 2.5	8.9 ± 2.1	...	...	...	...
$\Xi_{cc}^* \pi$	...	...	...	...	...	...	4522.2 ± 1.9	1.2 ± 0.2	...	...
$\Xi_{cc}^* \omega$	...	...	...	...	...	...	4526.1 ± 0.1	6.4 ± 3.4	...	...
$\Sigma_c^* D^*$	...	...	...	...	...	...	...	...	...	...
$\Sigma_c^* D$	...	...	...	...	...	...	...	...	...	...
Γ_{Total}	3.7 ± 1.4		13.0 ± 6.1		8.9 ± 2.1		7.6 ± 3.6		5.2 ± 3.4	

and QCD sum rules (QCDSR) [135]. A summary of these comparisons is presented in Table VI.

IV. SUMMARY

Recently, the LHCb Collaboration reported the observation of a tetraquark state, $T_{cc}(3875)$, with doubly charmed components and a mass slightly below the $D^{*+}D^0$ threshold. The observation of $T_{cc}(3875)$ suggests the possible existence of the doubly charmed pentaquark states. In this work, we investigated the possible existence of doubly charmed pentaquark states within the QDCSM, employing the resonating group method. The interactions between hadrons were analyzed through effective potentials, and both bound-state and coupled-channels calculations were performed to explore their spectrum. A summary of our main findings and a comparison with other theoretical frameworks (detailed in Table VI) is presented below.

Our estimations suggest the presence of a bound state with quantum numbers $I(J^P) = \frac{3}{2}(\frac{5}{2}^-)$ and a central mass of approximately 4461.7 MeV. As shown in Table VI, this prediction for a high-spin, high-isospin bound state appears unique to the QDCSM framework. In addition, five resonance states are predicted;

- (1) For $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ system: We predict two resonance states, a $\Xi_{cc}\rho$ resonance could be observed in $\Lambda_c D^*$ and $\Sigma_c D$ channels with a mass around (~ 4391.8 – 4395.5) MeV and a width of 3.7 ± 1.4 MeV and $\Sigma_c D^*$ resonance with a mass of (~ 4420.3 – 4461.3) MeV and width (13.0 ± 6.1) MeV in four channels. As shown in Table VI, there is a qualitative consensus among various models that structures related to the $\Sigma^{(*)}D^{(*)}$ system should exist. However, many models predict bound states, whereas our QDCSM estimation points to resonance structures.
- (2) For $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ system: $\Lambda_c D^*$ resonance could appear in the $\Xi_{cc}^* \eta$ channel, and the mass and width of this resonance could be 4286.6 ± 2.5 MeV and 8.9 ± 2.1 , respectively. While in the $\Xi_{cc}^* \pi$ and $\Xi_{cc}^* \omega$ channels, there exists a $\Sigma_c^* D^*$ resonance with $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$, whose mass and width are estimated to be (4522.2 – 4526.1) MeV and 7.6 ± 3.6 MeV, respectively. The $\Lambda_c D^*$ resonance mass is consistent with predictions from HQSS. Similarly, ChEFT and UCC approaches also predict bound states in the $\Sigma_c^* D^*$
- (3) For $I(J^P) = \frac{3}{2}(\frac{1}{2}^-)$ system: A $\Sigma_c D^*$ resonance appears in the $\Sigma_c D$ channel, with a mass of 4431.1 ± 6.7 MeV

TABLE VI. Comparison of the predicted doubly charmed pentaquark states (masses in megaelectronvolt) from different theoretical models. “B” denotes a bound state, and “R” denotes a resonance.

$I(J^P)$	Channel	This work	HQSS [72]	OBE [93,94]	ChEFT [95]	UCC [96]	ChQM [134]	QCDSR [135]
$\frac{1}{2}(\frac{1}{2}^-)$	$\Sigma_c D^*$	R(4458–4461)	B(4412–4456)	B(4451–4461)	B(4430–4432)	B(4444–4453)	—	—
	$\Xi_{cc}\rho$	R(4391–4395)	—	—	—	—	—	—
$\frac{1}{2}(\frac{3}{2}^-)$	$\Lambda_c D^*$	R(4286)	B(4287–4291)	—	—	—	—	—
	$\Sigma_c^* D^*$	R(4522–4526)	B(4477–4521)	—	B(4502–4509)	B(4498–4520)	—	—
$\frac{3}{2}(\frac{1}{2}^-)$	$\Sigma_c D^*$	R(4431)	B(4412–4456)	B(4446–4461)	—	—	—	B(4460)
$\frac{3}{2}(\frac{3}{2}^-)$	$\Xi_{cc}^* \rho$	B(4461)	—	—	—	—	R(4461)	—

TABLE VII. The values of the model parameters. The masses of mesons and baryons take their experimental values. $m_\pi = 0.7 \text{ fm}^{-1}$, $m_K = 2.51 \text{ fm}^{-1}$, $m_\eta = 2.77 \text{ fm}^{-1}$, $\Lambda_\pi = 4.2 \text{ fm}^{-1}$, $\Lambda_{\eta/K} = 5.2 \text{ fm}^{-1}$.

	Parameter	Value
Quark masses	m_u (MeV)	313 ± 0.346
	m_s (MeV)	573 ± 0.035
	m_c (MeV)	1788 ± 0.891
Confinement	a_c (MeV fm^{-2})	58.03 ± 0.589
	$V_{0q\bar{q}}$ (fm^2)	-1.2883 ± 0.001
	$V_{0q\bar{q}}$ (fm^2)	-0.7432 ± 0.005
	α_{uu}	0.5652 ± 0.033
	α_{uc}	0.2091 ± 0.025
OGE	α_{cc}	0.5501 ± 0.018
	$\alpha_{u\bar{u}}$	1.4914 ± 0.003
	$\alpha_{u\bar{c}}$	0.9629 ± 0.008
Wave function	b (fm)	0.518 ± 0.003

and a width of $5.2 \pm 3.4 \text{ MeV}$. This finding, along with the QCDSR prediction, suggests the existence of an $I = \frac{3}{2}$ state, although other models like OBE also predict a bound state here, highlighting the model dependence in this sector.

In conclusion, our QDCSM estimations support a rich spectrum of doubly charmed pentaquarks, including both novel bound states and several resonance states whose existence is qualitatively supported by other theoretical frameworks. These predictions concrete targets for experimental searches. Future measurements at LHCb and other facilities will be crucial for testing the existence of these states and for deepening our understanding of the multi-quark dynamics in the doubly charmed sector.

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TABLE VIII. The masses of the ground baryons and mesons in the unit of megaelectronvolts. Experimental values are taken from the Particle Data Group (PDG) [120].

States	$M + \Delta M$	PDG	States	$M + \Delta M$	PDG
N	939.1 ± 19.5	939.5	π	139.1 ± 7.5	139.6
Δ	1232.2 ± 15.2	1232.0	ρ	770.0 ± 3.7	775.3
Ξ_{cc}	3620.5 ± 11.2	3621.4	ω	721.9 ± 2.8	782.7
Ξ_{cc}^*	3632.1 ± 10.1	3696.5	η^a	283.2 ± 5.1	547.8
Λ_c	2284.7 ± 16.6	2286.5	D^*	1940.2 ± 1.4	2006.9
Σ_c	2472.4 ± 14.2	2455.0	D	1869.2 ± 2.1	1869.6
Σ_c^*	2483.9 ± 13.1	2520.0			

^aHere η denotes the pseudoscalar isoscalar meson $\eta(548)$. The PDG value corresponds to the physical η after η_8 - η_1 mixing; our model mass $M + \Delta M$ is obtained from the fitted parameters. This procedure does not incorporate the effect of the $U(1)_A$ axial anomaly or $SU(3)$ flavor mixing, which are essential for accurately describing the physical η mass.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX: SUMMARY OF DIAGNOSTIC GLOBAL PARAMETER FIT

The primary model parameters listed in Table VII were determined via a global fit to a range of ground-state hadron masses using the Minuit program, aiming for a reasonable overall description, particularly for the baryon and charmed meson sectors relevant to this work. The resulting diagnostic mass spectrum from this fit is presented in Table VIII below.

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