P_c states in the mixture of molecular and pentaquark pictures

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We systematically study hidden charm pentaquark states in the constituent quark model with a general Hamiltonian for multiquark systems, considering the coupling between the $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular states and the $q^3c\bar{c}$ compact pentaquark states by the one-gluon exchange hyperfine interaction. The ground state hidden-charm pentaquark mass spectra and the strong decay widths are calculated. This work suggests that $P_c(4312)$, $P_c(4457)$, and $P_c(4380)$ resonances might be mainly $\Sigma_c\bar{D}$, $\Sigma_c\bar{D}^*$, and $\Sigma_c^*\bar{D}$ hadronic molecules respectively, and $P_c(4440)$ might include sizable pentaquark components.

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I. INTRODUCTION

The pentaquark-like states, $P_c(4380)$, $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$, have been studied widely in both the hadronic molecular and compact pentaquark scenarios since their discovery by LHCb [1–3]. One may see some good reviews in Refs. [4–9]. As the masses of the P_c states are several MeV below the $\Sigma_C\bar{D}$ and $\Sigma_c\bar{D}^*$ mass thresholds, the P_c states have been interpreted as hadronic molecules in various approaches such as QCD sum rules [10–14], potential models [15–19], effective field theory [20,21], heavy hadron chiral perturbation theory [22], heavy quark spin multiplet structures [23], phenomenological Lagrangian approach [24], and constituent quark models [25]. In the compact pentaquark picture, the $uudc\bar{c}$ pentaquark mass spectrum and decay widths have been studied as diquark-diquark-antiquark structures in the constituent quark-diquark model [26], a potential model [27], QCD sum rules [28], chromomagnetic model [29], and nonrelativistic constituent quark model [30]. The P_c states have been studied in the mixing scenario of the baryon-meson molecule and compact pentaquark states [31–33] in effective potential models, and also a superposition of a heavy hadronic molecule and a hadrocharmonium state in a string model with Born-Oppenheimer potentials [34]. The masses and widths of the P_c resonances are explained by coupling the $\Sigma_c^{(*)}\bar{D}^{(*)}$ hadronic molecule with a compact five-quark state in Refs. [32,33].

In the present work, we extend the nonrelativistic constitute quark model, where a Cornell-like potential with one-gluon hyperfine interaction is employed [35], to study the ground state $q^3c\bar{c}$ pentaquark mass spectrum, the coupling between the compact pentaquark states and charmed baryon-meson molecules, and decays of the coupled states. It is found that one-gluon exchange hyperfine interactions not only mix up compact pentaquark states of the different configurations, but also couple the hadronic molecules and the compact pentaquark states of the same quantum numbers.

The paper is arranged as follows. In Sec. II, we briefly introduce the Hamiltonian for multiquark systems. The $q^3c\bar{c}$ pentaquark mass spectra are evaluated in the mixing picture of molecular and pentaquark states and presented in Sec. II. In Sec. III we calculate the partial strong decay widths of the P_c states. Discussion and summary are given in Secs. III and IV.

II. THEORETICAL MODEL AND PENTAQUARK MASS SPECTRUM

We start with the general Hamiltonian [35–37],

$$H = H_0 + H_{\rm hyp}^{\rm OGE},$$
$$H_0 = \sum_{k=1}^{N}\left(m_k + \frac{p_k^2}{2m_k}\right) + \sum_{i<j}^{N}\left(-\frac{3}{8}\lambda_i^C\cdot\lambda_j^C\right)\left(A_{ij}r_{ij} - \frac{B_{ij}}{r_{ij}}\right),$$
$$H_{\rm hyp}^{\rm OGE} = -\frac{C_m}{m_u^2}\sum_{i<j}\frac{\lambda_i^C\cdot\lambda_j^C}{m_i m_j}\vec{\sigma}_i\cdot\vec{\sigma}_j, \quad (1)$$

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where λ_i^C are the generators of color SU(3) group, and A_{ij} and B_{ij} are mass-dependent coupling constants, taking the form

$$A_{ij} = a\sqrt{\frac{m_{ij}}{m_u}}, \qquad B_{ij} = b\sqrt{\frac{m_u}{m_{ij}}}, \tag{2}$$

with m_{ij} being the reduced mass of the ith and jth quarks, defined as $m_{ij} = \frac{2m_i m_j}{m_i + m_j}$. The hyperfine interaction $H_{\rm hyp}^{\rm OGE}$, including only the one-gluon exchange contribution, couples together the hadronic molecules and compact pentaquark states. In the study, the model parameters of the three coupling constants and four constituent quark masses, taken directly from the previous works [35,36], are determined by fitting the theoretical results to the mass of the ground state baryons and mesons. They are

$$m_u = m_d = 327\ \text{MeV}, \qquad m_s = 498\ \text{MeV},$$
$$m_c = 1642\ \text{MeV}, \qquad m_b = 4960\ \text{MeV},$$
$$C_m = 18.3\ \text{MeV}, \quad a = 49500\ \text{MeV}^2, \quad b = 0.75. \tag{3}$$

We consider the coupling of the S-wave molecular states, $\Sigma_c^*\bar{D}^*$, $\Sigma_c\bar{D}^*$, $\Sigma_c\bar{D}$, with the ground hidden-charm pentaquarks. The $\Lambda_c^+\bar{D}^{(*)}$ interactions are investigated in the works [21,25,38–41]. It is claimed in Ref. [38] that the Λ_c^+ and $\bar{D}$ interaction is likely repulsive, while in Refs. [39,40] that the Λ_c^+ and $\bar{D}$ bound state is possible with very large cutoffs in the framework of exchange models and the possible bound states are very close to the threshold. In a chiral quark model with the Gaussian expansion method [41], both $\Lambda_c^+\ \bar{D}$ and $\Lambda_c^+\ \bar{D}^*$ interactions are claimed to be strongly repulsive. The works [21,25] reveal that $\Lambda_c\bar{D}^{(*)}$ is still unbound when considering the coupling effect between the $\Sigma_c^{(*)}\bar{D}^{(*)}$ and $\Lambda_c\bar{D}^{(*)}$ channels and the coupling effect would not lead to any quantitative change. Thus in the present work, we assume that $\Lambda_c^+\bar{D}^{(*)}$ states are unbound and excluded from discussion and consider the simplest case that the single $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular state mixes with possible compact pentaquark states of the same quantum numbers.

The wave functions of the baryon-meson molecular states take the form in the calculations,

$$\psi_{\rm Mole} = \psi_B(\vec{\rho},\vec{\lambda})\psi_M(\vec{\sigma})\psi(\vec{R}) \tag{4}$$

with

$$\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r}_1 - \vec{r}_2)$$
$$\vec{\lambda} = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)$$
$$\vec{\sigma} = \frac{1}{\sqrt{2}}(\vec{r}_4 - \vec{r}_5)$$
$$\vec{R} = \frac{1}{\sqrt{30}}(2(\vec{r}_1 + \vec{r}_2 + \vec{r}_3) - 3(\vec{r}_4 + \vec{r}_5)), \tag{5}$$

where $\psi_B(\vec{\rho},\vec{\lambda})$ and $\psi_M(\vec{\sigma})$ are the baryon and meson wave functions, and $\psi(\vec{R})$ describes the relative motion between the baryon and meson states. In the work, the full wave functions of the compact $q^3c\bar{c}$ pentaquark states, $\Sigma_c^{(*)}$, and $\bar{D}^{(*)}$ are directly taken from Refs. [35,37]. The general mass matrix of the mixing states has the form

$$H = \begin{pmatrix} M_{\rm Mole} & \Delta_{\rm hyp} \\ \Delta_{\rm hyp} & M_{\rm Penta} \end{pmatrix}, \tag{6}$$

where $M_{\rm Penta}$ is the mass of the coupled pentaquark state derived from the Hamiltonian in Eq. (1), $M_{\rm Mole}$ is the mass of the baryon-meson molecular state, and $\Delta_{\rm hyp}$ is contributed by the hyperfine interaction $H_{\rm hyp}^{\rm OGE}$ in Eq. (1). It is found that the mixing between the baryon-meson molecular state and the pentaquark state is independent of their spatial wave functions due to the form of the hyperfine interaction. Thus we have

$$\Delta_{\rm hyp} = \langle\psi_{\rm BM}^{\rm CSF}|H_{\rm hyp}^{\rm OGE}|\psi_{P_c}^{\rm CSF}\rangle,$$

where $\psi_{\rm BM}^{\rm CSF}$ and $\psi_{P_c}^{\rm CSF}$ are the color, spin, and flavor parts of the baryon-meson molecule and the compact pentaquark state, respectively. $M_{\rm Mole}$ is defined

$$M_{\rm Mole} = \langle\psi_B\psi_M\psi_R|H|\psi_B\psi_M\psi_R\rangle$$
$$= M_B + M_M + E_B. \tag{7}$$

In the present work, we vary the binding energy E_B from −40 to −1 MeV, which covers almost all the binding energies in Refs. [38,42–44], to check the dependence of the mixed states on the binding energy of the molecular part.

By solving the coupled Schrödinger equations, we derive the eigenstates of the $\Sigma_c^*\bar{D}^*$, $\Sigma_c\bar{D}^*$, $\Sigma_c\bar{D}$ systems plus compact pentaquark states. The results are presented in Tables I and II for isospin 1/2 and 3/2, respectively, where M stands for the eigenvalues and $|A_i|^2$ for the contribution of all coupled configurations. We have applied the approximation that the mass of the S-wave molecular components, $\Sigma_c^*\bar{D}^*$, $\Sigma_c\bar{D}^*$, $\Sigma_c\bar{D}$, is set to the mass threshold.

Found in Table I are six mass eigenstates of isospin 1/2 below the mass threshold. One may name them $X(4298)$, $X(4426)$, $X(4444)$, $X(4457)$, $X(4378)$ and $X(4509)$. Except for the two spin 1/2 states of 4444 and 4426 MeV, others are dominated by hadronic molecules since the main contribution of their wave functions is from the molecular structure.

To check the stability of the X states, we vary the mass of the compact pentaquark states as well as the hadronic molecules. First, the dependence of the mass of the X states on the pentaquark mass change, $\Delta E_{\rm Penta}$ is shown in Fig. 1, where the mass of all the pure compact pentaquark states in

TABLE I. Mixtures of all hadronic molecules and compact pentaquark states for spin $3/2$ and $1/2$ of $I = 1/2$. All mass units are in MeV.

J^P	Mixing states	$\lvert A_i\rvert^2$				Mass
$\frac{1}{2}^-$	$\Sigma_c^*\bar{D}^*(4526)$	0.50	0.18	0.04	0.28	4535
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$	0.47	0.33		0.21	4517
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$	0.03	0.18	0.71	0.08	4455
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$		0.31	0.26	0.43	4433
	$\Sigma_c\bar{D}^*(4462)$		0.48	0.02	0.50	4526
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$	0.55	0.04	0.42		4479
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$	0.22	0.38	0.10	0.30	4444
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.24	0.10	0.47	0.20	4426
	$\Sigma_c\bar{D}(4322)$		0.49	0.02	0.49	4526
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$	0.03	0.38	0.34	0.25	4458
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$	0.09	0.09	0.61	0.21	4451
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.88	0.05	0.02	0.06	4298
$\frac{3}{2}^-$	$\Sigma_c^*\bar{D}^*(4526)$	0.20	0.12	0.64	0.04	4586
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$		0.08	0.11	0.81	4532
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.77	0.10	0.13		4509
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.02	0.70	0.13	0.16	4473
	$\Sigma_c^*\bar{D}(4386)$		0.18	0.77	0.05	4571
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$		0.08	0.13	0.79	4532
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.05	0.69	0.11	0.16	4479
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.95	0.05			4376
	$\Sigma_c\bar{D}^*(4462)$		0.17	0.78	0.04	4570
	$\Psi^{csf}_{[21]_C[21]_F[21]_S}$	0.01	0.08	0.11	0.80	4533
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.03	0.73	0.11	0.13	4474
	$\Psi^{csf}_{[21]_C[21]_F[3]_S}$	0.95	0.02		0.02	4457

TABLE II. Mixtures of hadronic molecules and compact pentaquark states for $I = 3/2$.

J^P	Mixing states	$\lvert A_i\rvert^2$			Mass
$\frac{1}{2}^-$	$\Sigma_c^*\bar{D}^*(4526)$	0.20	0.47	0.33	4813
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.01	0.37	0.62	4661
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.80	0.15	0.05	4452
	$\Sigma_c\bar{D}^*(4462)$	0.05	0.31	0.64	4755
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.08	0.68	0.24	4683
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.88	0.01	0.11	4423
	$\Sigma_c\bar{D}(4322)$		0.52	0.48	4744
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.02	0.47	0.52	4665
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.98	0.01	0.01	4311
$\frac{3}{2}^-$	$\Sigma_c^*\bar{D}^*(4526)$	0.16	0.84		4745
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.84	0.16		4480
	$\Sigma_c\bar{D}^*(4462)$	0.02	0.98		4706
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.98	0.02		4454
	$\Sigma_c^*\bar{D}(4386)$	0.04	0.96		4714
	$\Psi^{csf}_{[21]_C[3]_F[21]_S}$	0.96	0.04		4369

Table I is changed the same, the molecular states all take the baryon-meson threshold mass, and the model parameters including the constituent quark masses are not changed. Second, the dependence of the mass of the X states on the binding energy E_B below the threshold mass is plotted in Fig. 2, where the pentaquark mass and model parameters are kept the same, and the binding energy for the $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular states is varied with a large range from -40 to -1 MeV.

It is found that for X(4298), X(4457), X(4378) and X(4509) states, the masses are very stable with the change of compact pentaquark masses, but change according to the E_B. The X(4444) and X(4426) are sensitive to the mass change ΔE_{Penta}, but quite stable with the change of E_B since they have larger components of compact pentaquarks. When the mass of all the pentaquark states coupled with the $\Sigma_c\bar{D}^*$ system is increased by over 25 MeV, $X(4444)$ goes above the $\Sigma_c\bar{D}^*$ mass threshold. That the mass eigenstate of $X(4444)$ with the varied E_B keeps the same indicates that the $X(4444)$ is unlikely to be a hadronic molecule dominant state. The hadronic molecular component likely plays an important role in $X(4426)$ since the $X(4426)$ is still well below the $\Sigma_c\bar{D}^*$ mass threshold even when the mass of the coupled compact pentaquark components is increased by 50 MeV.

Considering only the mass closeness, one may propose a very tentative assignment: X(4298) to $P_c(4312)^+$ being a $\Sigma_c\bar{D}$ hadronic molecule with $J^P = 1/2^-$, $X(4378)$ to $P_c(4380)^+$ being a $\Sigma_c^*\bar{D}$ hadronic molecule with $J^P = 3/2^-$, $X(4457)$ to $P_c(4457)^+$ being a $\Sigma_c\bar{D}^*$ hadronic molecule with quantum numbers $3/2^-$, and $X(4444)$ and/or $X(4426)$ to $P_c(4440)^+$ being a compact pentaquark dominant state with a considerable $\Sigma_c\bar{D}^*$ component.

Hadronic molecular states with isospin $I = 3/2$ are also predicted, as shown in Table II. We do not discuss them here since there is not any experimental data available in the market.

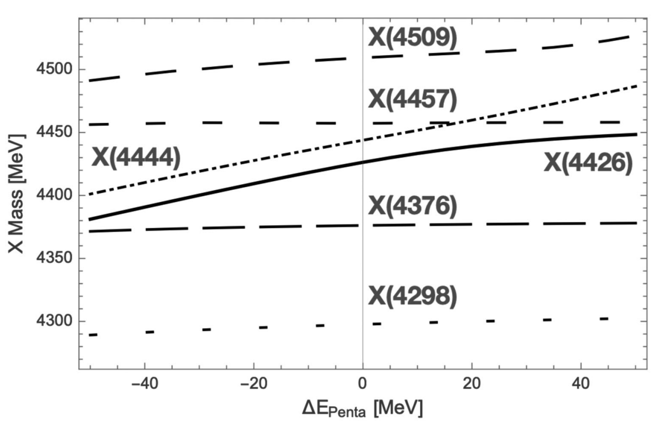

FIG. 1. X mass dependence on the mass of pentaquark components.

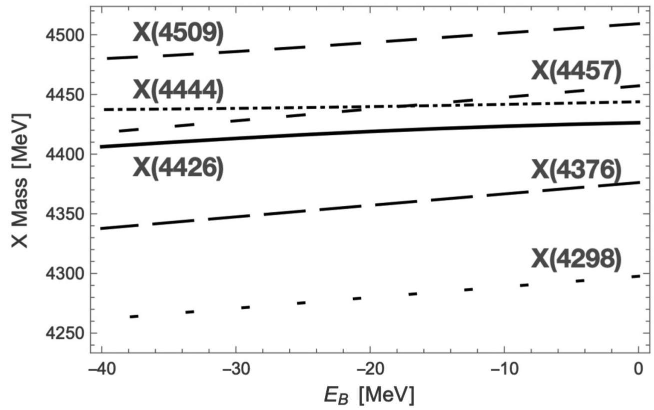

FIG. 2. X mass dependence on the binding energy of molecular states. E_B is the binding energy below the threshold mass of $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular states.

III. DECAY WIDTHS

We study in this section the two-body strong decay property of the bound states, $X(4298)$, $X(4426)$, $X(4444)$, $X(4457)$, $X(4378)$ and $X(4509)$ in the rearrangement mechanism. The transition amplitude may be defined

$$T = T^{\rm CSF}\langle\psi_f|\hat{O}|P_c\rangle, \tag{8}$$

with $\hat{O}$ taking the form,

$$\hat{O}_d = \delta^3(\vec{p}_1 - \vec{p}_1')\delta^3(\vec{p}_2 - \vec{p}_2')\delta^3(\vec{p}_3 - \vec{p}_3')\delta^3(\vec{p}_4 - \vec{p}_4') \times \delta^3(\vec{p}_5 - \vec{p}_5'), \tag{9}$$

$$\hat{O}_c = \delta^3(\vec{p}_1 - \vec{p}_1')\delta^3(\vec{p}_2 - \vec{p}_2')\delta^3(\vec{p}_3 - \vec{p}_4')\delta^3(\vec{p}_4 - \vec{p}_3') \times \delta^3(\vec{p}_5 - \vec{p}_5'), \tag{10}$$

for the processes in Fig. 3. $|P_c\rangle$ are the spatial wave functions of the P_c states, $X(4298)$, $X(4426)$, $X(4457)$, $X(4378)$ and $X(4509)$, which are derived by solving the coupled Schrödinger equations in the mixing picture of hadronic molecules and compact pentaquark states. ψ_f are the spatial wave functions of the final states of all possible two-body strong decay channels: NJ/ψ, $N\eta_c$, $\Sigma_c^*\bar{D}^*$, $\Sigma_c\bar{D}^*$, $\Lambda_c^+\bar{D}^*$, $\Sigma_c^*\bar{D}$, $\Sigma_c\bar{D}$, and $\Lambda_c^+\bar{D}$. The wave functions of the baryons and mesons of the final states are taken from the works [35,37] where their mass spectra are fitted. $T^{\rm CSF}$ are the color-spin-flavor transition factors of the two-body strong decay channels, as obtained in Ref. [45].

The partial decay width can be evaluated in the nonrelativistic approximation [46,47],

$$\Gamma_{P_c\to BM} = \frac{2\pi E_1 E_2}{M}\frac{k}{2S_i+1}\sum_{m_i,m_j}|T(k)|^2, \tag{11}$$

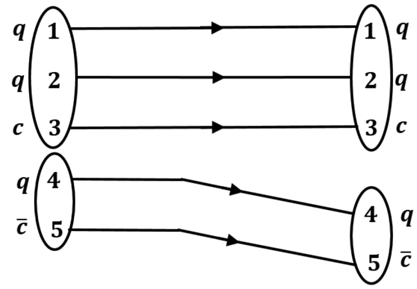

FIG. 3. Quark rearranged diagrams for P_c in (a) the open-charm decay modes and (b) the hidden-charm decay modes.

where S_i, m_i, and M are the spin, spin projection quantum number, and mass of the initial pentaquark states, respectively. E_1 and E_2 are the energies of the baryon and meson in the final states. $T(k)$ is the transition amplitude derived in Eq. (8). The summation is over the spins of the initial and final states. k is the momentum of baryons or mesons at the rest frame of the initial state.

The mass eigenvalues and relative partial and total decay widths of $X(4298)$, $X(4426)$, $X(4444)$, $X(4457)$, $X(4378)$, and $X(4509)$ are presented in Table III, with the threshold mass of the $\Sigma_c^{(*)}\bar{D}^{(*)}$ molecular states and binding energies of 0, −5 and −10 MeV which represent most of the values in Refs. [38,42–44]. The total decay width of the state $X(4457)$ is set to be 1, and the other total and partial decay widths are all normalized according to this state. It is found in Table III that the decay widths of X(4298), X(4378), X(4457), and X(4509) are in the same order while X(4426) has a much bigger decay width.

As shown in Table III, all the total decay widths are very stable while we increase the binding energies, except for one case where the $\Sigma_c\bar{D}$ molecular state gets below the threshold mass of $\Lambda_c^+\bar{D}^*(4296)$. The pJ/ψ partial decay widths are almost unchanged except for the state X(4426) whose molecular component changes significantly, which is consistent with the results in Ref. [45] that the pJ/ψ decay channel is dominant by the hadronic molecule and the compact pentaquark component gives a negligible contribution. The results of decay widths may confirm the conclusion, drawn in the mass spectrum calculations in Sec. II, that X(4298), X(4378), X(4457), and X(4509) are

TABLE III. The relative partial decay width of bound states X with different binding energies of isospin $1/2$ which are normalized to the total decay width of X(4457). All mass units are in MeV.

J	Threshold	E_B	Mass	Eigenvector^2	Total	$p\eta_c$	pJ/ψ	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}$	$\Lambda_c^+\bar{D}$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c\bar{D}^*$	$\Lambda_c^+\bar{D}^*$
$\frac{1}{2}$	$\Sigma_c\bar{D}(4322)$	0	4298	(0.88,0.05,0.02,0.06)	0.57	0.21	0.11						0.25
		−5	4293	(0.88,0.04,0.02,0.05)	0.33	0.22	0.11						
		−10	4289	(0.89,0.04,0.02,0.05)	0.34	0.22	0.11						
	$\Sigma_c\bar{D}^*(4462)$	0	4444	(0.22,0.38,0.10,0.30)	14.71	0.01	0.13		9.99	2.74			1.85
		−5	4443	(0.22,0.39,0.05,0.33)	16.11	0.01	0.13		11.42	2.19			2.36
		−10	4442	(0.21,0.40,0.02,0.36)	17.67	0.01	0.13		12.92	1.66			2.95
	$\Sigma_c\bar{D}^*(4462)$	0	4426	(0.24,0.10,0.47,0.20)	17.53	0.01	0.15		10.61	1.63			5.13
		−5	4425	(0.29,0.08,0.46,0.17)	15.72	0.01	0.19		9.18	1.74			4.60
		−10	4423	(0.36,0.06,0.44,0.14)	13.77	0.02	0.23		7.68	1.82			4.02
$\frac{3}{2}$	$\Sigma_c^*\bar{D}^*(4526)$	0	4509	(0.77,0.10,0.13,0)	1.87		0.28	0.08				0.43	1.08
		−5	4505	(0.79,0.11,0.11,0)	1.82		0.29	0.03				0.34	1.16
		−10	4501	(0.79,0.12,0.09,0)	1.86		0.30					0.27	1.28
	$\Sigma_c^*\bar{D}(4386)$	0	4376	(0.95,0.05,0,0)	1.06		0.35						0.71
		−5	4371	(0.95,0.05,0,0)	1.01		0.36						0.65
		−10	4367	(0.95,0.04,0,0)	0.96		0.36						0.60
	$\Sigma_c\bar{D}^*(4462)$	0	4457	(0.95,0.02,0.01,0.02)	1.00		0.09	0.61					0.31
		−5	4452	(0.97,0.01,0,0.02)	0.65		0.09	0.37					0.19
		−10	4448	(0.97,0.01,0,0.01)	0.47		0.09	0.25					0.13

dominantly hadronic molecules while X(4426) has considerable both molecular and compact pentaquark components.

IV. DISCUSSION AND SUMMARY

We have calculated the mass spectrum and strong decay widths of the ground hidden-charm pentaquark states in the mixing picture of hadronic molecules and compact pentaquark states coupled by the one-gluon exchange hyperfine interaction. We have checked the stability of X states by varying the mass of both the compact pentaquark states and the hadronic molecules. The work predicts that four $I = 1/2$ states, X(4298), X(4378), X(4457), and X(4509), are dominantly hadronic molecules, and one $I = 1/2$ state, X(4426), has sizable components of both the compact pentaquark states and hadronic molecules. The X(4298), X(4378), X(4457), and X(4509) have much smaller decay widths than the X(4426).

Considering our previous work [45] and the work of others [27,29,30,34] which predict that the mass of compact charmonium-like pentaquarks is well above the $P_c(4312)$, we may assign the $X(4298)$ to be the $P_c(4312)$, and accordingly $X(4457)$ to be the $P_c(4457)$.

The work predicts a $J^P = 3/2^-$ $\Sigma_c^*\bar{D}$ molecular state, X(4378), which has a decay width in the same order as X(4298) and X(4457). The present result is consistent with Ref. [48] where a narrow $P_c(4380)$ of $3/2^-$ is predicted in the coupled channel analysis with one-pion exchange and heavy quark spin symmetry. The X(4378) in the work can not be assigned to the $P_c(4380)$ reported by LHCb if one has assigned the $X(4298)$ to be the $P_c(4312)$. The existence of the wide pentaquark state, $P_c(4380)$, still awaits for the verification of larger dataset in the future.

We suggest that charmonium-like pentaquarks may be searched in the $\eta_c p$ and $\Lambda_c\bar{D}^{(*)}$ channels in future experiments.

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