Rich structure of the hidden-charm pentaquarks near threshold regions

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The recent discoveries and observations of pentaquarks and tetraquarks by high-energy accelerator facilities have accumulated evidence of the existence of multiquark hadrons with heavy quarks, as discussed from the early stage of the prediction of quarks. We construct a coupled-channel model for the hidden-charm pentaquarks with strangeness whose quark content is $udsc\bar{c}$, P_{cs}, described as $\Lambda_c\bar{D}_s^{(*)}$, $\Xi_c^{(\prime *)}\bar{D}^{(*)}$ molecules, produced by the cooperation of the heavy quark and chiral symmetries, coupled to a five-quark core. We reproduce the experimental mass of P_{cs}, of which LHCb has announced the discovery. Furthermore, our result supports the quantum numbers that are preferred by the experiment. Our predictions indicate the existence of additional P_{cs}'s in proximity to molecular threshold regions, which can be further investigated by LHCb.

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The past decade has witnessed tremendous progress in the experimental and theoretical explorations of the exotic hadrons. These are strongly interacting particles made up of quarks, but are considered to have more complicated structures than ordinary hadrons such as protons and neutrons, which were already mentioned in the early stages of the prediction of quarks and soon after the discovery of the charm quark [1,2]. Intensive activity has been triggered by the observation of exotic candidates with heavy quarks, such as $X(3872)$ [3–8]. While further studies are ongoing, the Large Hadron Collider beauty (LHCb) experiment has revealed as many as 62 signals for new hadrons [9].

A new phase of the quest was opened up in 2015 by the LHCb Collaboration: the observation of two pentaquark states, $P_c^+(4380)$ and $P_c^+(4450)$ [10]. From the decay channel $\Lambda_b^0 \to P_c^+K^- \to (J/\psi p)K^-$, the quark content of these states is implied as $J/\psi p \sim \bar{c}cuud$. Four years later, an updated analysis [11] with nine times more statistics was performed; this revealed $P_c^+(4312)$ with a statistical significance of 7.3σ, and the splitting of the former $P_c^+(4450)$ into two narrow peaks, $P_c^+(4440)$ and $P_c^+(4457)$, with the two-peak structure hypothesis having a statistical significance of 5.4σ with respect to the single-peak structure hypothesis.

Yet in 2020, the first evidence of a pentaquark with strangeness, $P_{cs}(4459)$, was reported in the decay $\Xi_b^- \to P_{cs}(4459)K^- \to (J/\psi\Lambda)K^-$ with a statistical significance of 3.1σ [12]. This resonance can be equally well described by a two-peak structure, $P_{cs}(4455)$ and $P_{cs}(4468)$ [12,13]. The experimental masses of $P_{cs}(4455)$ and $P_{cs}(4468)$ are $M = 4454.9 \pm 2.7$ MeV and $M = 4467.8 \pm 3.7$ MeV. LHCb has further reported the discovery of another pentaquark state in the $B^- \to (J/\psi\Lambda)\bar{p}$ decay channel

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with a statistical significance greater than 15σ. Its mass and decay width are $M = 4338.2 \pm 0.7 \pm 0.4$ MeV and $\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV, respectively, thus $P_{cs}(4338)$ [14]. This peak corresponds to the $\Xi_c^+ D^-$ threshold energy, 4337.37 ± 0.24 MeV [15], within the error bars. The amplitude analysis performed by LHCb favors spin and parity $J^P = \frac{1}{2}^-$ [14].

It is noticeable that all of these states exhibit a remarkable proximity to a two-hadron threshold, suggesting the emergence of a qualitatively distinct structure that deviates from the three quark standard baryon structure. This observation holds true not only for pentaquarks but also for some tetraquarks, such as the well-known candidates $X(3872)$ and $T_{cc}(3875)$ [16,17]. Such threshold phenomena have been known for a long time in various physical systems in atomic and nuclear physics [18,19]. Another interesting characteristic of the pentaquark states is that they have narrow decay widths despite a significant available phase space. This is particularly the case of the latest $P_{cs}(4338)$.

In Refs. [20–24], coupled-channel analyses for meson-baryon molecules were performed by focusing on various symmetry and dynamical aspects, such as heavy quark spin symmetry, extended flavor SU(4) symmetry, model parameter dependences, and so on. Other related studies concern the chiral effective field theory with leading-order contact interactions [25], QCD sum rule [26], compact diquark model [27], and the hadrocharmonium model [28]. After LHCb's latest announcement of $P_{cs}(4338)$, there appeared a quark model interpretation [13], a molecular interpretation [29], and a coupled-channel model using contact interactions [30]. Amplitude analyses have also been performed to extract the nature of the peak structures [31–35], but as yet there is no consensus among these studies. For the interested reader, we quote Ref. [8] as an updated review on the pentaquark states.

In this paper, we use a hybrid scheme for the pentaquark states [36,37] as quantum superpositions of a five-quark core, which encodes the short-range dynamics driven by color forces, and the $\Lambda_c \bar{D}_s^{(*)}, \Xi_c^{(\prime *)} \bar{D}^{(*)}$ meson-baryon (MB) channels, which encode the long-range interactions driven by the light meson exchange, i.e., pions and kaons. As explained in the following, our model has one unknown parameter (called overall strength), which is proportional to the coupling between the core and the MB channels.[1] Moreover, our model can give an overall description of all the available experimental data both in the nonstrange and in the strange sector with the same one parameter. The bound and resonant states are obtained by means of the Gaussian expansion method with complex scaling method [38,39]. Incidentally, by solving the coupled-channel Schrödinger equation, unitarity is always guaranteed.

In our model construction, the reason to include only the pions and kaons is that they give the minimum meson-exchange forces that mix the coupled channels that we have in our model setup, as shown in Table II. Many studies have been performed by including various mesons, such as the 16 vector mesons of SU(4) [20,21], π, η [40], π, σ, η, ρ, ω [24,29], and even contact $+\pi + 2\pi$ exchange [25]. Reference [20] has the merit to be the first work which predicted the hidden-charm pentaquark states with and without strangeness even if in a qualitative way. In Ref. [25], the authors predict the $P_{cs}(4455)$ and $P_{cs}(4468)$ masses in agreement with the experimental data, but they underestimate the $P_{cs}(4338)$ mass by about 20 MeV. Furthermore, their predictions indicate that all of these states are bound, which contrasts with the experimental fact that those states decay strongly. In Ref. [21] the authors extend to the strange sector the analysis performed in Ref. [41] for the hidden-charm pentaquarks without strangeness. Interestingly enough, they use the same parameters fitted to the best reproduction of the $P_c(4312)$, $P_c(4440)$, and $P_c(4457)$ masses in order to predict the masses of the P_{cs} states: the predicted masses of $P_{cs}(4338)$, $P_{cs}(4455)$, and $P_{cs}(4468)$ are 4276, 4429, and 4436 MeV respectively, while their predicted decay widths are 15.3, 15.8, and 2.3 MeV [21], respectively. In Ref. [40], the authors considered the $\Lambda_c \bar{D}^*, \Sigma_c \bar{D}^*, \Sigma_c^* \bar{D}^*, \Xi_c \bar{D}^*, \Xi_c' \bar{D}^*$ and $\Xi_c^* \bar{D}^*$, coupled channels but they did not include the $\Xi_c \bar{D}$ channel, which is the closest threshold to the $P_{cs}(4338)$ state, and thus its contribution is far from negligible. In Ref. [24], the same authors performed a new analysis by coupling the $\Xi_c^{(\prime,*)} \bar{D}^{(*)}$ channels; they reproduced the $P_{cs}(4338)$ experimental mass, but the mass predictions for $P_{cs}(4455)$ and $P_{cs}(4468)$ were quite far from the experimental data, in both the one-peak and the two-peak hypotheses. In addition, all the states predicted in Ref. [24] are bound states without decay widths. In Ref. [29], the authors performed a coupled-channel calculation involving $\Xi_c^{(\prime)} \bar{D}^{(*)}$ interactions: they found that setting the cutoff parameter to approximately 1.41 GeV allowed them to reproduce the mass of $P_{cs}(4338)$. However, in order to accurately replicate the experimental masses of $P_{cs}(4455)$ and $P_{cs}(4468)$, they needed to adjust the cutoff to 1.39 GeV.

Now, after observing the above situation, in this article we employ a model that relies on the coupling of the MB channels with the five-quark core. The interactions between the heavy mesons (H) and the heavy baryons (S, Λ) are derived from the effective Lagrangians that satisfy the heavy quark and SU(3) chiral symmetries [42–44]:

$$\mathcal{L}_{mHH} = g_A^M \mathrm{Tr}[H_b \gamma_\mu \gamma_5 A^\mu_{ba} \bar{H}_a],$$
$$\mathcal{L}_{mBB} = \frac{3}{2} g_1 (i v_\kappa) \varepsilon^{\mu\nu\lambda\kappa} \mathrm{tr}[\bar{S}_\mu A_\nu S_\lambda] + g_4 \mathrm{tr}[\bar{S}^\mu A_\mu \hat{\Lambda}_c] + \mathrm{H.c.}, \quad (1)$$

[1] Strictly speaking, we have other parameters such as hadron coupling constants, which are, however, determined by other inputs.

TABLE I. Spectroscopic factors $\langle i|\alpha\rangle$ for isosinglet P_{cs} states with spin-parity $J^P = 1/2^-, 3/2^-$ and $5/2^-$. $\alpha = [fs]_c$, where f, s, and c are, respectively, the flavor, spin, and color representations of three light quarks qqq, and i corresponds to the MB channels.

α $[fs]_c$	i: $\Lambda_c\bar{D}_s$	$\Xi_c\bar{D}$	$\Lambda_c\bar{D}_s^*$	$\Xi_c'\bar{D}$	$\Xi_c\bar{D}^*$	$\Xi_c^*\bar{D}$	$\Xi_c'\bar{D}^*$	$\Xi_c^*\bar{D}^*$
$J^P = 1/2^-$								
$[1\frac{1}{2}]_8$	$-\frac{1}{\sqrt{3}}$	$\sqrt{\frac{2}{3}}$						
$[1\frac{1}{2}]_8$			$-\frac{1}{\sqrt{3}}$		$\sqrt{\frac{2}{3}}$			
$[8\frac{1}{2}]_8$			$\frac{1}{\sqrt{3}}$	$-\frac{1}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$		$\frac{\sqrt{2}}{3}$	$-\frac{1}{3}$
$[8\frac{1}{2}]_8$	$\frac{1}{\sqrt{3}}$	$\frac{1}{\sqrt{6}}$					$-\frac{1}{\sqrt{6}}$	$-\frac{1}{\sqrt{3}}$
$[8\frac{3}{2}]_8$				$\sqrt{\frac{2}{3}}$			$\frac{\sqrt{2}}{3}$	$-\frac{1}{3}$
$J^P = 3/2^-$								
$[1\frac{1}{2}]_8$			$-\frac{1}{\sqrt{3}}$		$\sqrt{\frac{2}{3}}$			
$[8\frac{1}{2}]_8$			$\frac{1}{\sqrt{3}}$		$\frac{1}{\sqrt{6}}$	$\frac{1}{\sqrt{6}}$	$-\frac{1}{3\sqrt{2}}$	$-\frac{1}{3}\sqrt{\frac{5}{2}}$
$[8\frac{3}{2}]_8$						$\frac{1}{2}$	$\frac{\sqrt{3}}{2}$	
$[8\frac{3}{2}]_8$						$\frac{1}{2}\sqrt{\frac{5}{3}}$	$-\frac{\sqrt{5}}{6}$	$\frac{2}{3}$
$J^P = 5/2^-$								
$[8\frac{3}{2}]_8$								1

where $m = \pi$ or K meson and A is the axial current written by the pion and kaon fields. These interactions describe the long-range dynamics of the MB channels. The coupling strengths, form factors, and their cutoff parameters are those of Ref. [36].

In the short range, a quark core is assumed to be formed by the color octet $c\bar{c}$ and qqq coupled to a color singlet [45]. The interplay between long-range and short-range dynamics is encoded by the coupled-channel Hamiltonian, which can be expressed in a block matrix form as [36,37]

$$H = \begin{pmatrix} H^{MB} & V \\ V^\dagger & H^{5q} \end{pmatrix} \tag{2}$$

where $H^{MB} = K + V^m$ stands for the MB channels, including their kinetic energies, K, and the meson-exchange potential V^m, H^{5q} for the five-quark ($5q$) channels, and $V, V^\dagger$ for the couplings between MB and $5q$ states. The couplings of the (ith) MB and (αth) five-quark channel, $V_{i\alpha}$, are expressed by the product of the overlaps $\langle i|\alpha\rangle$, often called spectroscopic factors (which contain the color, spin, flavor, and the orbital part) [36,43] and the strength v: $V_{i\alpha} = v\langle i|\alpha\rangle$. The values of the spectroscopic factors are reported for completeness in Table I. By defining the full-component wave function, $\psi = (\psi^{MB}, \psi^{5q})$, we obtain a set of coupled Schrödinger equations

$$\begin{aligned} H^{MB}\psi^{MB} + V\psi^{5q} &= E\psi^{MB}, \\ V^\dagger\psi^{MB} + H^{5q}\psi^{5q} &= E\psi^{5q}. \end{aligned} \tag{3}$$

On solving the second equation for ψ^{5q}, $\psi^{5q} = (E - H^{5q})^{-1}V^\dagger\psi^{MB}$ and plugging it into the first, we find the equation for ψ^{MB},

$$(K_{ij} + U_{ij})\psi_j^{MB} = E\psi_j^{MB}, \tag{4}$$

where K_{ij} and $\psi^{MB} \equiv \psi^{MB}(r)$ are the kinetic energy and the wave functions, with r being the relative distance between the meson and the baryon, and

$$U_{ij} = V_{ij}^m + \sum_\alpha V_{i\alpha}\frac{1}{E - H_\alpha^{5q}}V_{\alpha j}^* \tag{5}$$

is the total interaction for the MB channels [36,37]. The energy dependence of the nonlocal potential on the right-hand side of Eq. (5) can be safely ignored because the energies of five-quark states, $\langle\alpha|H^{5q}|\alpha\rangle$, are about 400–500 MeV higher than the meson-baryon threshold energies, $E^{5q} \gg E$, as one can see by comparing the energies of the five quarks confined in a single region and those of the two and three quarks in the meson and baryon.

$$\langle i|V\frac{1}{E - H^{5q}}V^\dagger|j\rangle \to -f\sum_\alpha\langle i|\alpha\rangle\langle\alpha|j\rangle e^{-r^2/a^2} \tag{6}$$

where $f = v^2$, r is the distance between the meson and the baryon, and a is fixed at a typical value of hadron size $\sim$1 fm, which takes account of the spatial overlap of a meson and baryon. The overall strength, $f = 98$ MeV, is fitted to the experimental masses of $P_{cs}(4338)$, $P_{cs}(4455)$, and $P_{cs}(4468)$. This value is consistent with the one used in the previous analysis of P_c [36,37],[2] which means that the model can qualitatively describe all the available experimental data both in the nonstrange and in the strange sector by means of the same only one parameter.

The coupled channels for $J^P = 1/2^-$, $3/2^-$, and $5/2^-$ states are summarized in Table II. Note that we averaged over the possible states of charge on assuming that isospin symmetry holds well.

The comparison between our predictions and the experimental data is shown in Fig. 1 and Table III.

The model predicts its spin parity as $J^P = 1/2^-$, with a mass of 4329.1 MeV and a binding energy of 7.6 MeV as shown in Table III. This state appears as a Feshbach resonance below the $\Xi_c\bar{D}$ threshold, a quasibound state of

[2]In the previous works [36,37] $f = 50 \times f_0$ but we erroneously quoted $f_0 \sim 6$ MeV; this should be corrected as $f_0 = 1.92$ MeV, and hence $f = 50 \times f_0 = 96$ MeV, which is consistent with the currently used value $f = 98$ MeV.

TABLE II. Meson-baryon channels coupled to strange P_{cs} of J^P with $I = 0$.

J^P	Channels
$1/2^-$	$\Lambda_c\bar{D}_s, \Xi_c\bar{D}, \Lambda_c\bar{D}_s^*, \Xi_c\bar{D}^*, \Xi_c'\bar{D}, \Xi_c^*\bar{D}, \Xi_c'\bar{D}^*, \Xi_c^*\bar{D}^*$
$3/2^-$	$\Lambda_c\bar{D}_s\Xi_c\bar{D}, \Lambda_c\bar{D}_s^*, \Xi_c'\bar{D}, \Xi_c\bar{D}^*, \Xi_c^*\bar{D}, \Xi_c'\bar{D}^*, \Xi_c^*\bar{D}^*$
$5/2^-$	$\Lambda_c\bar{D}_s, \Xi_c\bar{D}, \Lambda_c\bar{D}_s^*, \Xi_c'\bar{D}, \Xi_c\bar{D}^*, \Xi_c^*\bar{D}, \Xi_c'\bar{D}^*, \Xi_c^*\bar{D}^*$

$\Xi_c\bar{D}$ coupled by the lower $\Lambda_c\bar{D}_s$ channel. Additionally, our model predicts the existence of a heavy quark doublet in the form of $J^P = 1/2^-$ and $3/2^-$ pentaquark states, specifically involving the Ξ_c baryon (with $J = 1/2$) and $\bar{D}^*$ meson (with $J = 1$) in an S-wave configuration. This prediction aligns with the interpretation of the experimental analysis conducted by LHCb, which observed two distinct peaks in their data [12]. We suggest conducting an improved higher statistical analysis for $P_{cs}(4455)$ and $P_{cs}(4468)$.

To obtain the above results, both terms of Eq. (5) are important. For instance, the meson exchange potential V_{ij}^m alone cannot hold any bound states nor resonances shown in Fig. 1 and in Table III.

In this study, we decided not to include the coupling to the $\Lambda J/\psi$ channel. This choice is motivated by the fact that the inclusion of the coupling to the $\Lambda J/\psi$ channel does not affect the final results in a relevant way, as it will be illustrated in the following. The Flatté formula is widely used to parametrize a resonance shape by properly accounting for the opening of one or more thresholds, which, in the case of $P_{cs}(4338)$, are the $\Xi_c^+\bar{D}^-$ and the $\Xi_c^0\bar{D}^0$ thresholds; thus we have parametrized the $P_{cs}(4338) \to \Lambda J/\psi$ decay amplitude as

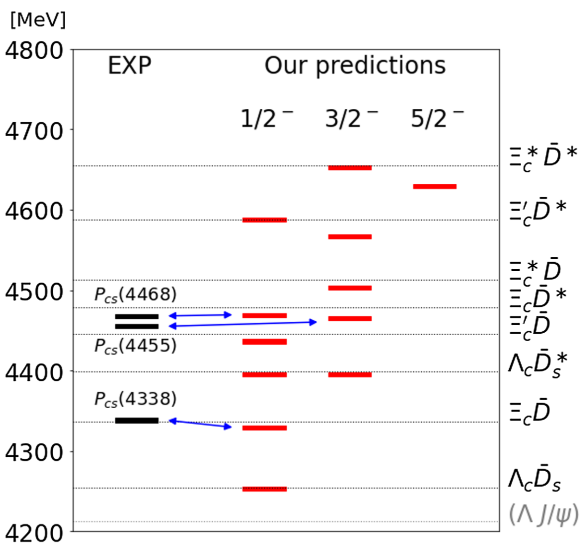

FIG. 1. Comparison between experimental masses of P_{cs} and theoretical predictions of our model when $f = 98$ MeV is employed. Correspondence between the theoretical predictions and experimental data is indicated by arrows.

TABLE III. Comparison of the experimental masses and decay widths with our numerical results for isospin $I = 0$ in units of MeV.

EXP [12,14]			Our results for $f = 98$ MeV		
State	Mass	Width	J^P	Mass	Width
...	...	...	$1/2^-$	4252.65	...
$P_{cs}(4338)$	4338.2	7.0	$1/2^-$	4329.11	1.54
...	...	...	$1/2^-$	4394.97	7.31×10^{-4}
...	...	...	$3/2^-$	4395.76	8.78×10^{-4}
...	...	...	$1/2^-$	4436.24	2.12
$P_{cs}(4455)$	4454.9	7.5	$3/2^-$	4465.24	1.08
$P_{cs}(4468)$	4467.8	5.2	$1/2^-$	4469.24	2.31
...	...	...	$3/2^-$	4502.91	4.09
...	...	...	$3/2^-$	4567.12	9.95
...	...	...	$1/2^-$	4587.53	1.25
...	...	...	$5/2^-$	4629.81	14.7
...	...	...	$3/2^-$	4653.02	5.52

$$F \sim \frac{1}{E - M + \frac{i}{2}g_1k_1 + \frac{i}{2}g_2k_2 + \frac{i}{2}\Gamma} \tag{7}$$

where the energy E is measured from the threshold of the neutral channel. The two momenta are defined by $k_1 = \sqrt{2\mu_1 E}, k_2 = \sqrt{2\mu_2(E - \Delta)}$, with $\Delta \sim 2$ MeV being the energy difference in the two thresholds, and $\mu_{1,2}$ the reduced masses of the two channels, respectively. The mass and width parameters M and Γ are those calculated for $P_{cs}(4338)$ as shown in Fig. 1 and Table III. The parameters g_1, g_2 are the couplings of the scattering $\Lambda J/\psi$ state to the neutral ($\Xi_c^0\bar{D}^0$) and charged ($\Xi_c^+ D^-$) components in the physical $P_{cs}(4338)$, respectively. The specific strengths of these couplings, which involve charm-quark exchange, are currently unknown. However, we can make an estimation based on the values observed for $X(3872)$ [46] in a similar charm-quark exchange scenario involving $J/\psi\rho$ and $D\bar{D}^*$ interactions [1]. In that case, the couplings were found to be in the order of 0.1, and we expect similar magnitudes for g_1 and g_2. Consistent with expectations, increasing the values of g_1 and g_2 leads to an upward shift in the peak position. In Fig. 2, it can be observed that when $g_1 \sim 0.1$ and $g_2 \sim 0.4$, the peak position closely approaches the threshold of the charged channel. Notably, in the latter case, the peak appears between the two thresholds, with a half-width of approximately 1.5 MeV. These findings are in line with the experimental results, providing further consistency with the observed data.

In addition to $P_{cs}(4338)$, we found 11 more states with various spin and parity $J^P = 1/2^-, 3/2^-, 5/2^-$, as shown in Fig. 1. All of these are molecular states dominated by the nearest meson-baryon thresholds. As discussed above,

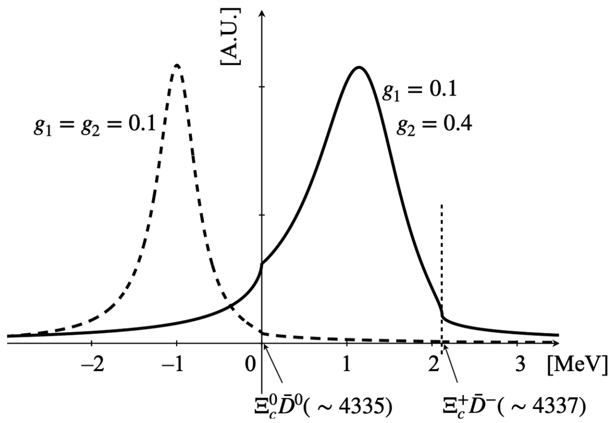

FIG. 2. A sample plot of the amplitude (7). For details, see text.

these states may also couple to the $\Lambda J/\psi$ channel. However, the energy shifts affecting the predicted states above $P_{cs}(4338)$ will be smaller as long as the distance between the real part of the poles and the $\Lambda J/\psi$ threshold increases, thus making the coupling to the $\Lambda J/\psi$ channel most likely negligible. The explicit inclusion of $\Lambda J/\psi$ channel in a complete calculation, would have the effect of slightly increasing the predicted masses, in alignment with what one would expect from a basic quantum mechanics example of level repulsion in the two-level problems, and it will be the subject of a subsequent article.

Let us now comment on the relation between $P_{cs}(4338)$ and $P_c(4312)$ from the point of view of the $SU(3)$ flavor symmetry with respect to a molecular charmed meson and charmed baryon description. In the $SU(3)$ limit, the $P_c(4312)$ of isospin $1/2$ is a member of the flavor octet resulting from the $3_M \times 6_B$ decomposition, since it is dominated by the $\Sigma_c \bar{D}$ molecular component and Σ_c belongs to the SU(3) flavor baryon sextet, 6_B. In the same way, if the SU(3) symmetry is exact, the $P_{cs}(4338)$ with zero isospin could be either a member of the flavor singlet or a member of the flavor octet resulting from the $3_M \times \bar{3}_B$ decomposition, since it is dominated by the $\Xi_c \bar{D}$ molecular component and Ξ_c belongs to the SU(3) flavor baryon antitriplet, $\bar{3}_B$.

Our present analysis has important implications: (1) The coupling to the compact five-quark core is effectively expressed as a short-range attraction in the hadronic molecules. It is noticeable that this interaction plays a dominant role in generating bound and resonant states. (2) The tensor force of the pion exchange causes SD-wave channel-couplings, which provides additional attraction. More interestingly, it controls decay widths, which are the inverse of the lifetime. Indeed, without the tensor force, the decay width of, for instance, $\Xi_c' \bar{D}^*$ $(3/2^-)$ and $\Xi_c^* \bar{D}^*$ $(5/2^-)$ molecules becomes smaller by 1 order of magnitude. (3) We now possess an understanding of the composition of pentaquarks in the vicinity of the threshold region, wherein the molecular element assumes prominence, nevertheless the presence of a compact component is crucial to their formation. (4) The new $P_{cs}(4338)$ state is very intriguing because, as discussed by LHCb [14], its mass is very close to the $\Xi_c^+ \bar{D}^-$ meson-baryon threshold, which lies at $2467.7 + 1869.7 = 4337.4$ MeV, and in fact its more favorable quantum numbers, $J^P = \frac{1}{2}^-$, are just what one expects for the $\Xi_c^+ \bar{D}^-$ meson-baryon system in an S wave. The most natural decay channel for such a state is the $J/\Psi\Lambda$ channel whose threshold is located 126 MeV below the $P_{cs}(4338)$ mass; thus, the available phase space for this decay channel is very large and a large decay width is expected. However, the experimental decay width of $P_{cs}(4338)$, $\Gamma \simeq 7$ MeV, is unnaturally small if compared to such a large phase space, so there is some decay-suppressing mechanism which prevents that $P_{cs}(4338)$ decays into hidden-charm states. This behavior is a clear indication that $P_{cs}(4338)$ is a molecular $\Xi_c^+ \bar{D}^-$ state, which is the decay into $J/\Psi\Lambda$ suppressed by a necessary strong rearrangement with respect to the molecular $\Xi_c^+ \bar{D}^-$ initial state.

The above features are characteristic of hadrons that contain both heavy and light quarks, and hence are a result of the cooperation of chiral and heavy quark symmetries with colorful and colorless forces of the strong interaction, QCD. The current analysis in the hidden-charm sector will be extended to encompass the hidden-bottom sector, thus leading to a greater depth to our exploration of hadron spectroscopy.

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[1] M. Gell-Mann, Phys. Lett. **8**, 214 (1964).
[2] G. Zweig, Report No. CERN-TH-412, No. NP-14146, No. PRINT-64-170 (1964).
[3] S. K. Choi *et al.* (Belle Collaboration), Phys. Rev. Lett. **91**, 262001 (2003).
[4] A. Hosaka, T. Iijima, K. Miyabayashi, Y. Sakai, and S. Yasui, Prog. Theor. Exp. Phys. **2016**, 062C01 (2016).
[5] F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, and B.-S. Zou, Rev. Mod. Phys. **90**, 015004 (2018); **94**, 029901(E) (2022).
[6] N. Brambilla, S. Eidelman, C. Hanhart, A. Nefediev, C.-P. Shen, C. E. Thomas, A. Vairo, and C.-Z. Yuan, Phys. Rep. **873**, 1 (2020).
[7] L. Meng, B. Wang, G.-J. Wang, and S.-L. Zhu, Phys. Rep. **1019**, 1 (2023).
[8] H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, and S.-L. Zhu, Rep. Prog. Phys. **86**, 026201 (2023).
[9] T. Gershon (LHCb Collaboration), Exotic hadron naming convention, arXiv:2206.15233.
[10] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **115**, 072001 (2015).
[11] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **122**, 222001 (2019).
[12] R. Aaij *et al.* (LHCb Collaboration), Sci. Bull. **66**, 1278 (2021).
[13] M. Karliner and J. L. Rosner, Phys. Rev. D **106**, 036024 (2022).
[14] LHCb Collaboration, Phys. Rev. Lett. **131**, 031901 (2023).
[15] R. L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022).
[16] R. Aaij *et al.* (LHCb Collaboration), Nat. Phys. **18**, 751 (2022).
[17] R. Aaij *et al.* (LHCb Collaboration), Nat. Commun. **13**, 3351 (2022).
[18] K. Ikeda, N. Takigawa, and H. Horiuchi, Prog. Theor. Phys. Suppl. **E68**, 464 (1968).
[19] P. Naidon and S. Endo, Rep. Prog. Phys. **80**, 056001 (2017).
[20] J.-J. Wu, R. Molina, E. Oset, and B. S. Zou, Phys. Rev. Lett. **105**, 232001 (2010).
[21] C. W. Xiao, J. Nieves, and E. Oset, Phys. Lett. B **799**, 135051 (2019).
[22] M.-Z. Liu, Y.-W. Pan, F.-Z. Peng, M. Sánchez Sánchez, L.-S. Geng, A. Hosaka, and M. Pavon Valderrama, Phys. Rev. Lett. **122**, 242001 (2019).
[23] M.-L. Du, V. Baru, F.-K. Guo, C. Hanhart, U.-G. Meißner, J. A. Oller, and Q. Wang, J. High Energy Phys. 08 (2021) 157.
[24] R. Chen and X. Liu, Phys. Rev. D **105**, 014029 (2022).
[25] B. Wang, L. Meng, and S.-L. Zhu, Phys. Rev. D **101**, 034018 (2020).
[26] H.-X. Chen, W. Chen, X. Liu, and X.-H. Liu, Eur. Phys. J. C **81**, 409 (2021).
[27] A. Ali, I. Ahmed, M. J. Aslam, A. Y. Parkhomenko, and A. Rehman, J. High Energy Phys. 10 (2019) 256.
[28] J. Ferretti and E. Santopinto, Sci. Bull. **67**, 1209 (2022).
[29] F.-L. Wang and X. Liu, Phys. Lett. B **835**, 137583 (2022).
[30] M.-J. Yan, F.-Z. Peng, M. Sánchez Sánchez, and M. Pavon Valderrama, Phys. Rev. D **107**, 074025 (2023).
[31] C. Fernández-Ramírez, A. Pilloni, M. Albaladejo, A. Jackura, V. Mathieu, M. Mikhasenko, J. A. Silva-Castro, and A. P. Szczepaniak (JPAC Collaboration), Phys. Rev. Lett. **123**, 092001 (2019).
[32] S. X. Nakamura, Phys. Rev. D **103**, L111503 (2021).
[33] S. X. Nakamura, A. Hosaka, and Y. Yamaguchi, Phys. Rev. D **104**, L091503 (2021).
[34] S. X. Nakamura and J. J. Wu, Phys. Rev. D **108**, L011501 (2023).
[35] T. J. Burns and E. S. Swanson, Phys. Lett. B **838**, 137715 (2023).
[36] Y. Yamaguchi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, and M. Takizawa, Phys. Rev. D **96**, 114031 (2017).
[37] Y. Yamaguchi, H. García-Tecocoatzi, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, and M. Takizawa, Phys. Rev. D **101**, 091502 (2020).
[38] E. Hiyama, Y. Kino, and M. Kamimura, Prog. Part. Nucl. Phys. **51**, 223 (2003).
[39] S. Aoyama, T. Myo, K. Katō, and K. Ikeda, Prog. Theor. Phys. **116**, 1 (2006).
[40] R. Chen, J. He, and X. Liu, Chin. Phys. C **41**, 103105 (2017).
[41] C. W. Xiao, J. Nieves, and E. Oset, Phys. Rev. D **100**, 014021 (2019).
[42] R. Casalbuoni, A. Deandrea, N. Di Bartolomeo, R. Gatto, F. Feruglio, and G. Nardulli, Phys. Rep. **281**, 145 (1997).
[43] Y. Yamaguchi, A. Hosaka, S. Takeuchi, and M. Takizawa, J. Phys. G **47**, 053001 (2020).
[44] M.-L. Du, M. Albaladejo, F.-K. Guo, and J. Nieves, Phys. Rev. D **105**, 074018 (2022).
[45] S. Takeuchi and M. Takizawa, Phys. Lett. B **764**, 254 (2017).
[46] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **102**, 092005 (2020).