Identifying Exotic Hidden-Charm Pentaquarks

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The LHCb Collaboration at the Large Hadron Collider at CERN discovered two pentaquark states $P_c(4380)$ and $P_c(4450)$. These two hidden-charm states are interpreted as the loosely bound $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ molecular states in the boson exchange interaction model, which provides an explanation for why the experimental width of $P_c(4450)$ is much narrower than that of $P_c(4380)$. The discovery of the new resonances $P_c(4380)$ and $P_c(4450)$, indeed, opens a new page for hadron physics. The partners of $P_c(4380)$ and $P_c(4450)$ should be pursued in future experiments.

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In the pioneer paper [1], Gell-Mann indicated that the multiquark states should exist along with the simplest structures for baryons which are composed of three valence quarks and mesons which contain a quark and an antiquark. Indeed, from the point of either mathematics or physics, there is nothing to forbid the existence of such exotic states. In quantum mechanics, the multiquark states are nothing new but just higher Fock states. In gauge field theory, the QCD principle allows the existence of multiquark states and hybrids which contain not only quarks, but also gluonic degrees of freedom. The multiquark states might be suppressed by higher orders of α_s in perturbative QCD. However, the confinement is a totally nonperturbative QCD effect. Such suppression is not so drastic. Unless nature prefers the simplest structures, one has reason to believe that the multiquark states should exist.

From the aspects of both theory and experiment, the ground state mesons and baryons are well arranged in the simplest structures: singlets and octets for mesons, octets and decuplets for baryons. No flavor exotic states have been observed or required to exist. However, for the mesons, whose masses are above 1 GeV, the mixtures among regular quark structures and hybrids, glueballs, and multiquark states should be nonzero in order to fit the spectra [2,3].

In 2003, the LEPS Collaboration reported the evidence of the strange pentaquark state with the quark content $uudd\bar{s}$ and very narrow width [4]. Unfortunately this flavor exotic state was not confirmed by subsequent experiments [5,6]. In fact, the possible theoretical arguments for the nonexistence of the stable strange pentaquarks were given in Refs. [7,8]. Up to now, no stable light flavor pentaquark states have been found, but light flavor baryons probably have significant pentaquark components [9].

In the past decade, the researches have rounded the corner. Many mesonic X, Y, Z particles have been observed at Belle, *BABAR*, BESIII, and LHCb. Some of them are identified as exotic candidates because they cannot be accommodated in the regular $q\bar{q}$ structures. Corresponding review papers can be found in recent literature (for example, see a recent review in Ref. [10]). A common point is that all those exotic states which are interpreted as molecular states, tetraquarks, or even four quarks in an anarchy state, contain heavy quarks and antiquarks.

In other words, the heavy quarks play an important role in stabilizing the multiquark systems, just as in the case of the hydrogen molecule in QED. There were the theoretical predictions of hidden-charm pentaquarks [11–14], especially the possible hidden-charm molecular baryons with the components of an anticharmed meson and a charmed baryon which were investigated systematically within the one boson exchange model in Ref. [12].

Because of the existence of heavy quarks, the multiquark exotic states can survive, and light exotic states must mix with the regular ones, instead [15]. This conjecture is consistent with the fact that all the exotic states which have been experimentally observed contain hidden charm or bottom. Of course, if the allegation that the heavy components stabilize multiquark systems, is valid, one suggestion would be natural, that we should persuade our experimental colleagues to search for exotic states which contain open charm or bottom, for example, $b\bar{c}qq'$, etc. Another trend is also obvious, that one should be convinced that even though the light pentaquark does not individually exist, a pentaquark containing heavy flavors would be possible and has a large probability to be observed in sophisticated experimental facilities.

Very recently, the LHCb Collaboration observed two resonance structures $P_c(4380)$ and $P_c(4450)$ in the $J/\psi p$ invariant mass spectrum of $\Lambda_b \to J/\psi p K$ [16], and their resonance parameters are $M_{P_c(4380)} = 4380 \pm 8 \pm 29$ MeV, $\Gamma_{P_c(4380)} = 205 \pm 18 \pm 86$ MeV, $M_{P_c(4450)} = 4449.8 \pm 1.7 \pm 2.5$ MeV, and $\Gamma_{P_c(4450)} = 39 \pm 5 \pm 19$ MeV. According to their final state $J/\psi p$, we conclude that the two observed P_c must not be an isosinglet state, and the two P_c states contain hidden-charm quantum numbers. A more important feature of these two P_c states is that $P_c(4380)$ and $P_c(4450)$ are close to the thresholds of $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$, respectively.

In this Letter, we propose that the novel resonances reported by the LHCb Collaboration can be identified as the exotic hidden-charm pentaquarks with the $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$ molecular configurations. For the $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$ systems, the flavor wave functions $|I, I_3\rangle$ are defined as

$$\left|\frac{1}{2},\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}|\Sigma_c^{(*)++}D^{*-}\rangle - \frac{1}{\sqrt{3}}|\Sigma_c^{(*)+}\bar{D}^{*0}\rangle,$$
$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle = \frac{1}{\sqrt{3}}|\Sigma_c^{(*)+}D^{*-}\rangle - \sqrt{\frac{2}{3}}|\Sigma_c^{(*)0}\bar{D}^{*0}\rangle, \tag{1}$$

$$\left|\frac{3}{2},\frac{3}{2}\right\rangle = |\Sigma_c^{(*)++}\bar{D}^{*0}\rangle,$$
$$\left|\frac{3}{2},\frac{1}{2}\right\rangle = \frac{1}{\sqrt{3}}|\Sigma_c^{(*)++}D^{*-}\rangle + \sqrt{\frac{2}{3}}|\Sigma_c^{(*)+}\bar{D}^{*0}\rangle,$$
$$\left|\frac{3}{2},-\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}|\Sigma_c^{(*)+}D^{*-}\rangle + \frac{1}{\sqrt{3}}|\Sigma_c^{(*)0}\bar{D}^{*0}\rangle,$$
$$\left|\frac{3}{2},-\frac{3}{2}\right\rangle = |\Sigma_c^{(*)0}D^{*-}\rangle, \tag{2}$$

where only these flavors of wave functions with isospin $I = 1/2$ match the discussed $P_c(4380)$ and $P_c(4450)$. In the following, we perform a dynamical calculation of the structures of $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$ where the constituents interact via one pion exchange (OPE) [12,17,18]. The solution might help to confirm whether or not bound states for these S wave $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$ systems exist. To establish the effective potential which is responsible for binding the constituents, we adopt the following effective Lagrangians:

$$\mathcal{L}_{\mathbb{P}} = ig\mathrm{Tr}[\bar{H}_a^{(\bar{Q})}\gamma^\mu A_{ab}^\mu \gamma_5 H_b^{(\bar{Q})}], \tag{3}$$

$$\mathcal{L}_{\mathcal{S}} = -\frac{3}{2}g_1\varepsilon^{\mu\nu\lambda\kappa}v_\kappa \mathrm{Tr}[\bar{\mathcal{S}}_\mu A_\nu \mathcal{S}_\lambda], \tag{4}$$

which are constructed under the heavy quark limit and chiral symmetry [19–24]. Here, the notation $H_a^{(\bar{Q})} = [P_a^{*(\bar{Q})\mu}\gamma_\mu - P_a^{(\bar{Q})}\gamma_5][(1-\not{v})/2]$ with $v = (1, \vec{0})$ stands for the multiplet field composed of the pseudoscalar P and vector $P^{*(\bar{Q})}$ with $P^{*(\bar{Q})} = (\bar{D}^{*0}, D^{*-})^T$. And the next superfield $\mathcal{S}_\mu$ is composed of spinor operators as $\mathcal{S}_\mu = -\sqrt{\frac{1}{3}}(\gamma_\mu + v_\mu)\gamma^5\mathcal{B}_6 + \mathcal{B}_{6\mu}^*$, where the notations $\mathcal{B}_6$ and $\mathcal{B}_6^*$ are defined as multiplets which, respectively, correspond to $J^P = 1/2^+$ and $J^P = 3/2^+$ in 6_F flavor representations. The axial current A_μ is defined as $A_\mu = \frac{1}{2}(\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger)$ with $\xi = \exp(i\mathbb{P}/f_\pi)$, and the pion decay constant $f_\pi = 132$ MeV is taken. Additionally, the matrices $\mathbb{P}$, $\mathcal{B}_6$, and $\mathcal{B}_6^*$ read as

$$\mathbb{P} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} & \pi^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} \end{pmatrix}, \qquad \mathcal{B}_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{\Sigma_c^+}{\sqrt{2}} \\ \frac{\Sigma_c^+}{\sqrt{2}} & \Sigma_c^0 \end{pmatrix},$$
$$\mathcal{B}_6^* = \begin{pmatrix} \Sigma_c^{*++} & \frac{\Sigma_c^{*+}}{\sqrt{2}} \\ \frac{\Sigma_c^{*+}}{\sqrt{2}} & \Sigma_c^{*0} \end{pmatrix}.$$

Expanding Eqs. (3) and (4), we can, further, get the direct effective Lagrangian which will be applied to our later calculation, i.e.,

$$\mathcal{L}_{\bar{D}^*\bar{D}^*\mathbb{P}} = i\frac{2g}{f_\pi}v^\alpha\varepsilon_{\alpha\mu\nu\lambda}\bar{D}_a^{*\mu\dagger}\bar{D}_b^{*\lambda}\partial^\nu\mathbb{P}_{ab}, \tag{5}$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = i\frac{g_1}{2f_\pi}\varepsilon^{\mu\nu\lambda\kappa}v_\kappa\mathrm{Tr}[\bar{\mathcal{B}}_6\gamma_\mu\gamma_\lambda\partial_\nu\mathbb{P}\mathcal{B}_6], \tag{6}$$

$$\mathcal{L}_{\mathcal{B}_6^*\mathcal{B}_6^*\mathbb{P}} = -i\frac{3g_1}{2f_\pi}\varepsilon^{\mu\nu\lambda\kappa}v_\kappa\mathrm{Tr}[\bar{\mathcal{B}}_{6\mu}^*\partial_\nu\mathbb{P}\mathcal{B}_{6\nu}^*], \tag{7}$$

where $g = 0.59 \pm 0.07 \pm 0.01$ is extracted from the width of D^* [25] as is done in Ref. [26], and $g_1 = 0.94$ was fixed in Refs. [12,24].

With the above preparation, the OPE-based potentials for the $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$ systems are deduced, which can be related to the scattering amplitude of the $\Sigma_c\bar{D}^* \to \Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^* \to \Sigma_c^*\bar{D}^*$ processes under adopting the Breit approximation and performing the Fourier transformation [27], where the monopole form factor $\mathcal{F}(q^2, m_\pi^2) = (\Lambda^2 - m_\pi^2)/(\Lambda^2 - q^2)$ is introduced to compensate the off shell effect of the exchanged meson and describe the structure effect of each effective vertex. In this form factor, there is a phenomenological parameter Λ which plays an equivalent role as the cutoff in the Pauli-Villas renormalization scheme and must be fixed by fitting data. We will discuss this, further, later. Finally, the general expressions of effective potentials for the $\Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^*$ systems are

TABLE I. The values of the $\mathcal{J}_i$ and $\mathcal{G}_i$ coefficients. Here, S, L, and J denote the spin, orbital, and total angular quantum numbers, respectively. $\mathbb{S}$ denotes $L=1$ since we are interested in the S-wave interaction of the $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$ systems.

I	$\mathcal{G}_0$	$\mathcal{G}_1$	$\lvert{}^{2S+1}L_J\rangle$	$\mathcal{J}_0$	$\mathcal{J}_1$
1/2	1	−1	$\lvert{}^2\mathbb{S}_{(1/2)}\rangle$	−2	5/3
3/2	−1/2	1/2	$\lvert{}^4\mathbb{S}_{(3/2)}\rangle$	1	2/3
…	…	…	$\lvert{}^6\mathbb{S}_{(5/2)}\rangle$	…	−1

$$V_{\Sigma_c\bar{D}^*}(r) = \frac{1}{3}\frac{gg_1}{f_\pi^2}\nabla^2 Y(\Lambda, m_\pi, r)\mathcal{J}_0\mathcal{G}_0, \tag{8}$$

$$V_{\Sigma_c^*\bar{D}^*}(r) = \frac{1}{2}\frac{gg_1}{f_\pi^2}\nabla^2 Y(\Lambda, m_\pi, r)\mathcal{J}_1\mathcal{G}_1, \tag{9}$$

respectively, where the $Y(\Lambda, m, r)$ function is defined as

$$Y(\Lambda, m, r) = \frac{1}{4\pi r}(e^{-mr} - e^{-\Lambda r}) - \frac{\Lambda^2 - m^2}{8\pi\Lambda}e^{-\Lambda r}.$$

In Eqs. (8) and (9), coefficients $\mathcal{J}_i$ and $\mathcal{G}_i$ $(i = 0, 1)$ are related to the isospin and ${}^{2S+1}L_J$ quantum numbers of the concerned systems. We list them in Table I.

By solving the Schrödinger equation with the obtained effective potentials [28,29], we can reproduce the masses of $P_c(4380)$ and $P_c(4450)$ as shown in Figs. 1(a) and 1(b), which supports the allegation that $P_c(4380)$ and $P_c(4450)$ are hidden-charm molecular states $\Sigma_c\bar{D}^*$ with $(I = 1/2, J = 3/2)$ and $\Sigma_c^*\bar{D}^*$ with $(I = 1/2, J = 5/2)$, respectively.

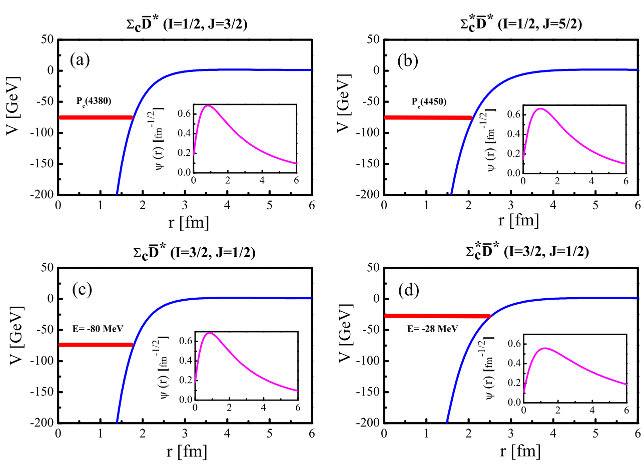

FIG. 1 (color online). The variations of the obtained OPE effective potentials for the $\Sigma_c^{(*)}\bar{D}^*$ systems to r, and obtained bound state solutions. Here, the masses of $P_c(4380)$ and $P_c(4450)$ can be reproduced well under the $\Sigma_c\bar{D}^*$ with $(I = 1/2, J = 3/2)$ and $\Sigma_c^*\bar{D}^*$ with $(I = 1/2, J = 5/2)$ molecular assignments, respectively. $\Lambda = 2.35$ GeV and $\Lambda = 1.77$ GeV are taken for the $\Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^*$ systems, respectively. The blue curves are the effective potentials, and the red line stands for the corresponding energy levers. Additionally, the obtained spatial wave functions are given here.

With these assignments to the two observed $P_c(4380)$ and $P_c(4450)$, their $J/\psi p$ decay modes can be naturally interpreted as the $\Sigma_c\bar{D}^*$ in $(I = 1/2, J = 3/2)$ and the $\Sigma_c^*\bar{D}^*$ in $(I = 1/2, J = 5/2)$; the molecular states can transit into $J/\psi p$ via exchanging an S-wave charmed meson.

Let us investigate the decays further, where the $\Sigma_c\bar{D}^*$ state with $(I = 1/2, J = 3/2)$ and the $\Sigma_c^*\bar{D}^*$ state with $(I = 1/2, J = 5/2)$ transit into $J/\psi p$. In the first process, the products J/ψ and p reside in an S wave, whereas, for the second mode, because the spin of $P_c(4450)$ is 5/2, the final J/ψ and p must be in a D wave to guarantee conservation of total angular momentum.

Usually, a D-wave decay is suppressed compared with an S-wave decay. Thus, we can qualitatively explain why the width of $P_c(4450)$ is much narrower than that of $P_c(4380)$ [16]. (The $J/\psi p$ invariant mass spectrum around 4450 MeV is very complicated [16]. Another possibility is that $P_c(4450)$ could be the P-wave excitation of the S-wave $\Sigma_c\bar{D}^*$ molecular states which decays into $J/\psi p$ mainly via the P wave. Hence, its decay width is not very large.) Additionally, a similar decay mode of these two hidden-charm molecular pentaquarks is $\eta_c N$, which is a D-wave decay mode, where N denotes a nucleon.

Besides explaining the observed $P_c(4380)$ and $P_c(4450)$, we further predict two hidden-charm molecular pentaquarks [see Figs. 1(c) and 1(d)]. We notice that the OPE effective potential is the same for the $\Sigma_c\bar{D}^*$ system with $(I = 1/2, J = 3/2)$ and the $\Sigma_c\bar{D}^*$ system with $(I = 3/2, J = 1/2)$, and the only difference comes from their isospin and spin combinations. If taking the same parameters as input, we find that a binding energy $(E = -80$ MeV) of the $\Sigma_c\bar{D}^*$ system with $(I = 3/2, J = 1/2)$ is the same as that of the $\Sigma_c\bar{D}^*$ system with $(I = 1/2, J = 3/2)$. In addition, we also find a bound-state solution for the $\Sigma_c^*\bar{D}^*$ system with $(I = 3/2, J = 1/2)$ with a binding energy of −28 MeV if taking the same parameters as for the case of the $\Sigma_c^*\bar{D}^*$ system with $(I = 1/2, J = 5/2)$. Thus, there may exist two extra hidden-charm molecular pentaquarks, the $\Sigma_c\bar{D}^*$ state with $(I = 3/2, J = 1/2)$ and the $\Sigma_c^*\bar{D}^*$ state with $(I = 3/2, J = 1/2)$, which are the isospin parters of $P_c(4380)$ and $P_c(4450)$, respectively.

The experimental search for these two predicted isospin parters of $P_c(4380)$ and $P_c(4450)$ is an intriguing issue which can be taken as a crucial test of the molecular assignment of $P_c(4380)$ and $P_c(4450)$. Since the predicted two hidden-charm molecular pentaquarks are isospin −3/2 states, $\Delta(1232)J/\psi$ and $\Delta(1232)\eta_c$ can naturally be their decay products.

If the hidden-charm molecular pentaquarks, indeed, exist, there should also exist the hidden-bottom pentaquarks in analog to $P_c(4380)$ and $P_c(4450)$. Based on the obtained OPE effective potentials shown in Eqs. (8) and (9), we extend the same formalism to the $\Sigma_b^{(*)}B^*$ pentaquark system.

We need to specify that the hidden-charm $\Sigma_c^{(*)}\bar{D}^*$ and hidden-bottom $\Sigma_b^{(*)}B^*$ have the same quantum numbers. Thus, the OPE effective potentials are completely the same. The reduced masses of the hidden-bottom molecular pentaquarks are larger than that of hidden-charm molecular pentaquarks, which means that the binding of $\Sigma_b^{(*)}B^*$ should be more stable than that of the hidden charm pentaquark. (Equivalently, the cutoff Λ in the form factor for the $\Sigma_b^{(*)}B^*$, $\Sigma_b^{(*)}B^*$ systems could be smaller than that for the $\Sigma_c^{(*)}\bar{D}^*$ systems if a solution for the bound states containing $b\bar{b}$ and $c\bar{c}$ of the same quantum numbers is reached. According to experience for studying the S-wave $\Sigma_c^{(*)}\bar{D}^*$ systems, we try to search for the bound state solution in the range of $\Lambda < 2.35$ GeV for $\Sigma_b B^*$ and the range of $\Lambda < 1.77$ GeV for $\Sigma_b^* B^*$.)

In the above discussion, we mainly focus on the exotic pentaquarks which possess hidden charm or bottom. We can also extend the whole scenario to discuss the exotic states with open charm and bottom. The $\Sigma_c^{(*)}B^*$ and $\Sigma_b^{(*)}\bar{D}^*$ systems which are B_c-like molecular pentaquarks may also exist. In our later works, we will carry out more research on the exotic states with open charm and bottom and make predictions on the spectra of the B_c-like $\Sigma_c^{(*)}B^*$ and $\Sigma_b^{(*)}\bar{D}^*$ pentaquarks and their decay behaviors as well as the corresponding B_c-like mesons.

According to the results presented in Table II, we draw our conclusions: (1) There exist the $\Sigma_b B^*$, $\Sigma_c B^*$, and $\Sigma_b\bar{D}^*$ bound states with either $(I = 1/2, J = 3/2)$ or $(I = 3/2, J = 1/2)$. The $\Sigma_b B^*$, $\Sigma_c B^*$, and $\Sigma_b\bar{D}^*$ states with $(I = 1/2, J = 3/2)$ mainly decay into $\Upsilon(1S)N/\Upsilon(2S)N$, $B_c(1^-)N$, and $\bar{B}_c(1^-)N$, respectively, while the typical decay modes of the $\Sigma_b B^*$, $\Sigma_c B^*$, and $\Sigma_b\bar{D}^*$ states with $(I=3/2, J=1/2)$ include $\Upsilon(1S)\Delta(1232)$, $B_c(1^-)\Delta(1232)$, and $\bar{B}_c(1^-)\Delta(1232)$, respectively. (2) We can also find bound state solutions for the $\Sigma_b^* B^*$, $\Sigma_c^* B^*$, and $\Sigma_b^*\bar{D}^*$ S-wave systems with quantum numbers $(I = 1/2, J = 3/2)$ and $(I = 3/2, J = 1/2)$. In addition, the $\Sigma_b^* B^*$ state with $(I = 3/2, J = 3/2)$ also exists. The main decay modes of $\Sigma_b^* B^*$, $\Sigma_c^* B^*$, and $\Sigma_b^*\bar{D}^*$ with $(I = 1/2, J = 3/2)$ are $\Upsilon(1S)N/\Upsilon(2S)N$, $B_c(1^-)N$, and $\bar{B}_c(1^-)N$, respectively. The $\Sigma_b^* B^*$, $\Sigma_c^* B^*$, and $\Sigma_b^*\bar{D}^*$ states with $(I = 3/2, J = 1/2)$ mainly decay into $\Upsilon(1S)\Delta(1232)$, $B_c(1^-)\Delta(1232)$, and $\bar{B}_c(1^-)\Delta(1232)$, respectively. $\Upsilon(1S)\Delta(1232)$ is the main decay channel of the $\Sigma_b^* B^*$ state with $(I = 3/2, J = 3/2)$.

In summary, the two newly observed resonant structures $P_c(4380)$ and $P_c(4450)$ in the $J/\psi p$ invariant mass spectrum of $\Lambda_b \to J/\psi pK$ [16] are first identified as the hidden-charm molecular pentaquarks $\Sigma_c\bar{D}^*$ with $(I = 1/2, J = 3/2)$ and $\Sigma_c^*\bar{D}^*$ with $(I = 1/2, J = 5/2)$, respectively. Their mass spectrum and qualitative decay behaviors are consistent with the existing experimental findings.

The observation of $P_c(4380)$ and $P_c(4450)$ has opened a new portal for investigating fermionic exotic states, i.e., the long-searched mysterious pentaquarks. We propose that they are loosely bound molecular states composed of $\Sigma_c^{(*)}$ and $D^{(*)}$. Our study indicates that there should exist a $\Sigma_c\bar{D}^*$ state with $(I = 3/2, J = 1/2)$ and a $\Sigma_c^*\bar{D}^*$ state with $(I = 3/2, J = 1/2)$, which can be searched for via the $\Delta(1232)J/\psi$ final state. The isospin partners of $P_c(4380)$ and $P_c(4450)$ shall be a crucial test of the present proposal.

Under the present molecular assignments, the parity quantum numbers of both $P_c(4380)$ and $P_c(4450)$ should be negative. Although the present data of LHCb favor that $P_c(4380)$ and $P_c(4450)$ have opposite parities, they also mention in their paper that the same parities are not excluded [16]. It is highly probable that both states may be identified as possessing the same negative parity when more data and analysis are available in the near future. If it really turns out that $P_c(4380)$ and $P_c(4450)$ have opposite parities, the physics will be very interesting. There are several options: (a) both of them are pentaquark states instead of loosely bound molecular baryons, as discussed in Ref. [30], (b) the lower state is an S-wave molecule while the higher state is a pentaquark state, or (c) the lower one is the S-wave molecule while the higher state is the P-wave excitation. Then, one has to determine why the energy of the P-wave excitation is as large as 70 MeV.

Besides the above predictions, we also extend our formalism to the hidden-bottom $\Sigma_b^{(*)}B^*$ pentaquark and the B_c-like $\Sigma_c^{(*)}B^*$ and $\Sigma_b^{(*)}\bar{D}^*$ molecular pentaquark systems which contain open charm and bottom quarks.

TABLE II. The typical values of the obtained bound state solutions $[E(\mathrm{MeV}), \Lambda(\mathrm{GeV})]$ for hidden-bottom $\Sigma_b^{(*)}B^*$ and B_c-like $\Sigma_c^{(*)}B^*$ and $\Sigma_b^{(*)}\bar{D}^*$ systems.

(I, J)	$\Sigma_c B^*$	$\Sigma_b\bar{D}^*$	$\Sigma_b B^*$
$(1/2, 1/2)$			
$(1/2, 3/2)$	$[-0.27, 1.22]$	$[-0.26, 1.34]$	$[-0.27, 0.84]$
	$[-2.58, 1.32]$	$[-2.62, 1.44]$	$[-2.36, 0.94]$
	$[-7.48, 1.42]$	$[-7.63, 1.54]$	$[-6.88, 1.04]$
$(3/2, 1/2)$	$[-0.27, 1.22]$	$[-0.26, 1.34]$	$[-0.27, 0.84]$
	$[-2.58, 1.32]$	$[-2.62, 1.44]$	$[-2.36, 0.94]$
	$[-7.48, 1.42]$	$[-7.63, 1.54]$	$[-6.88, 1.04]$
$(3/2, 3/2)$			
(I, J)	$\Sigma_c^* B^*$	$\Sigma_b^*\bar{D}^*$	$\Sigma_b^* B^*$
$(1/2, 1/2)$			
$(1/2, 3/2)$			
$(1/2, 5/2)$	$[-0.28, 0.88]$	$[-0.14, 0.96]$	$[-0.30, 0.64]$
	$[-3.18, 0.98]$	$[-2.78, 1.06]$	$[-3.11, 0.74]$
	$[-9.67, 1.08]$	$[-8.97, 1.16]$	$[-9.51, 0.84]$
$(3/2, 1/2)$	$[-0.42, 1.02]$	$[-0.30, 1.12]$	$[-0.28, 0.72]$
	$[-3.33, 1.12]$	$[-3.03, 1.22]$	$[-2.74, 0.82]$
	$[-9.37, 1.22]$	$[-8.91, 1.32]$	$[-8.19, 0.92]$
$(3/2, 3/2)$			$[-0.28, 1.44]$
			$[-3.28, 1.60]$
			$[-9.13, 1.74]$
$(3/2, 5/2)$			

Several pentaquarks with hidden-bottom $\Sigma_b^{(*)}B^*$ and the B_c-like pentaquarks $\Sigma_c^{(*)}B^*$ and $\Sigma_b^{(*)}\bar{D}^*$, which can be considered as the partners of $P_c(4380)$ and $P_c(4450)$, are predicted. Experimental exploration of these predicted exotic states is a potential and important research topic for future LHCb experiments.

Certainly, it is not the end of the story for the charmed and bottom pentaquarks. The discovery and theoretical studies on $P_c(4380)$ and $P_c(4450)$ are just opening a new page of hadron physics. In the coming years, joint theoretical and experimental efforts will be helpful in pushing the relevant study on pentaquarks with heavy flavors, which will deepen our understanding of non-perturbative QCD behavior further.

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