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P_c pentaquarks with chiral tensor and quark dynamics

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We investigate the hidden-charm pentaquarks as superpositions of $\Lambda_c\bar{D}^{(*)}$ and $\Sigma_c^{(*)}\bar{D}^{(*)}$ (isospin $I = 1/2$) meson-baryon channels coupled to a $uudc\bar{c}$ compact core by employing an interaction satisfying the heavy quark and chiral symmetries. Our model can consistently explain the masses and decay widths of $P_c^+(4312)$, $P_c^+(4440)$ and $P_c^+(4457)$ with the dominant components of $\Sigma_c\bar{D}$ and $\Sigma_c\bar{D}^*$ with spin parity assignments $J^P = 1/2^-, 3/2^-$ and $1/2^-$, respectively. We analyze basic properties of the P_c's such as masses and decay widths, and find that the mass ordering is dominantly determined by the quark dynamics while the decay widths by the tensor force of the one-pion exchange.

In 2015, the Large Hadron Collider beauty experiment (LHCb) collaboration observed two hidden-charm pentaquarks, $P_c^+(4380)$ and $P_c^+(4450)$, in $\Lambda_b^0 \to J/\psi K^- p$ decay [1] and reported additional analysis efforts [2, 3]. These results have motived hundreds of theoretical articles (just to make some examples see [4–33]). Recently a new analysis has been reported [34] using nine times more data from the Large Hadron Collider than the 2015 analysis. The data set was first analyzed in the same way as before and the parameters of the previously reported $P_c^+(4450)$, and $P_c^+(4380)$ structures were consistent with the original results. As well as revealing the new $P_c^+(4312)$ state, the analysis also uncovered a more complex structure of $P_c^+(4450)$, consisting of two narrow nearby separate peaks, $P_c^+(4440)$ and $P_c^+(4457)$, with the two-peak structure hypothesis having a statistical significance of 5.4 sigma with respect to the single-peak structure hypothesis. As for a broad state $P_c^+(4380)$ (width ~ 200MeV), in the new analysis using higher-order polynomial functions for the background, data can be fitted equally well without the Breit-Wigner contribution corresponding to broad $P_c^+(4380)$ state. In this situation, more experimental and theoretical studies are needed to fully understand the structure of the observed states.

The masses and widths of the three narrow pentaquark states are as follows [34].

$$
\begin{aligned}
P_c^+(4312) : M &= 4311.9 \pm 0.7^{+6.8}_{-0.6}\ \text{MeV}\,, \\
\Gamma &= 9.8 \pm 2.7^{+3.7}_{-4.5}\ \text{MeV}\,; \\
P_c^+(4440) : M &= 4440.3 \pm 1.3^{+4.1}_{-4.7}\ \text{MeV}\,, \\
\Gamma &= 20.6 \pm 4.9^{+8.7}_{-10.1}\ \text{MeV}\,; \\
P_c^+(4457) : M &= 4457.3 \pm 0.6^{+4.1}_{-1.7}\ \text{MeV}\,, \\
\Gamma &= 6.4 \pm 2.0^{+5.7}_{-1.9}\ \text{MeV}\,.
\end{aligned}
$$

As discussed by LHCb [34], $P_c^+(4312)$ is just below the $\Sigma_c\bar{D}$ threshold, while the higher ones $P_c^+(4440)$ and $P_c^+(4457)$ are both below the $\Sigma_c\bar{D}^*$ threshold. This change of the experimental observation motivated new theoretical investigations [35–44]. Among them, [35, 36, 41, 44] are taking the hadronic molecule approach. In [35] the authors explore several scenarios for the structures of the pentaquark states by means of QCD sum rules. They propose to interpret all the four pentaquarks as molecular states, in particular they interpret $P_c^+(4440)$ and $P_c^+(4457)$ as $\Sigma_c^{*++}\bar{D}^-$ and $\Sigma_c^+\bar{D}^{*0}$ molecular states, both with $J^P = 3/2^-$. In [36] pentaquark states are studied with a local hidden gauge based interaction in a coupled channel approach by including the $N\eta_c$, NJ/ψ, $\Lambda_c\bar{D}^{(*)}$ and $\Sigma_c^{(*)}\bar{D}^{(*)}$ meson-baryon channels. They assign $P_c^+(4440)$ to $J^P = 1/2^-$ and $P_c^+(4457)$ to $J^P = 3/2^-$. Although these assignments agree with experimental decay widths, the mass of $P_c^+(4440)$ is overestimated by about 13 MeV, which is more than the double of the experimental error on the $P_c^+(4440)$ mass of about 5 MeV. Most importantly, the mass difference between $P_c^+(4440)$ and $P_c^+(4457)$, approximately 17 MeV, is not reproduced by this model in which, instead, the two states are almost degenerate. $P_c^+(4440)$ and $P_c^+(4457)$ are considered as the $\Sigma_c^{(*)}\bar{D}^{(*)}$ hadronic molecule states in a quasipotential Bethe-Salpeter equation approach [41]. They use the meson-exchange interaction with π, η, ρ, ω and σ mesons and reproduce the observed masses reasonably. Their spin-parity assignments are $P_c^+(4440)$ as $1/2^-$ and $P_c^+(4457)$ as $3/2^-$, respectively. Coupled-channel molecular states of the relative S-$D(P)$-

wave $\Sigma_c\bar{D}^*$ and the relative $P(S\text{-}D)$-wave $\Lambda_c(2595)\bar{D}$ are studied with OPEP in [44] as the $\Lambda_c(2595)\bar{D}$ threshold is very closed to the $P_c^+(4457)$ mass. The model predicts two bound states, which they argue correspond to $P_c^+(4440)(J^P = 3/2^-)$ and $P_c^+(4457)(J^P = 1/2^+)$.

In Ref. [45] we studied the hidden-charm pentaquarks by coupling the $\Lambda_c\bar{D}^{(*)}$ and $\Sigma_c^{(*)}\bar{D}^{(*)}$ meson-baryon channels to a $uudc\bar{c}$ compact core with a meson-baryon binding interaction satisfying the heavy quark and chiral symmetries. In that work we expressed the hidden-charm pentaquark masses and decay widths as functions of one free parameter, which is proportional to the coupling strength between the meson-baryon and 5-quark-core states. Interestingly enough, we find that the model has predicted the masses and decay widths consistently with the new data with the following quantum number assignments: $J^P_{P_c^+(4312)} = 1/2^-$, $J^P_{P_c^+(4440)} = 3/2^-$ and $J^P_{P_c^+(4457)} = 1/2^-$. Our assignments of the quantum numbers for the $P_c^+(4440)$ and $P_c^+(4457)$ states are different from those in other hadronic-molecule approaches.

The purpose of the present article is to study the origin of the mass difference between $P_c^+(4440)$ and $P_c^+(4457)$ by performing the calculations with and without the tensor term of the one-pion exchange potential (OPEP). The importance of the tensor force is emphasized as "chiral tensor dynamics".

Let us briefly overview the main ingredients of the model of Ref. [45]. The best established interaction between the meson and the baryon is provided by OPEP, which is obtained by the effective Lagrangians satisfying the heavy quark and chiral symmetries. The interaction Lagrangian between the ground state heavy mesons, $\bar{D}$ and $\bar{D}^*$, and the pions can be written in a compact form [46–49],

$$\mathcal{L}_{\pi HH} = g_A^M \mathrm{Tr}\left[H_b\gamma_\mu\gamma_5 A^\mu_{ba}\bar{H}_a\right], \tag{1}$$

where $H_a = [\bar{D}^*_{a\mu}\gamma^\mu - \bar{D}_a\gamma_5](1+\gamma_\mu v^\mu)/2$ and $\bar{H}_a = \gamma_0 H_a^\dagger\gamma_0$ are the heavy meson fields containing the spin multiplet of pseudoscalar and vector meson fields $\bar{D}_a$ and $\bar{D}^*_{a\mu}$. The trace $\mathrm{Tr}[\cdots]$ is taken over the gamma matrices. The subscript a denotes the light quark flavor, and v_μ is the four-velocity of the heavy quark inside the heavy meson; g_A^M is the the axial vector coupling constant for heavy mesons, which was determined by the $D^*\to D\pi$ strong decay to be $g_A^M = 0.59$ [48–50], and $A^\mu = \frac{i}{2}\left[\xi^\dagger\partial_\mu\xi - \xi\partial_\mu\xi^\dagger\right]$, with $\xi = \exp\left(\frac{i\hat{\pi}}{2f_\pi}\right)$, is the pion axial vector current; $\hat{\pi}$ is the flavor matrix of the pion field and $f_\pi = 92.3$ MeV is the pion decay constant. The effective Lagrangian which describes the interaction between Σ_c and Λ_c heavy baryons and the pions is [51, 52]

$$\mathcal{L}_{\pi BB} = \frac{3}{2}g_1(iv_\kappa)\varepsilon^{\mu\nu\lambda\kappa}\mathrm{tr}\left[\bar{S}_\mu A_\nu S_\lambda\right] + g_4\mathrm{tr}\left[\bar{S}^\mu A_\mu\hat{\Lambda}_\mathrm{c}\right] + \mathrm{H.c.}, \tag{2}$$

where $\mathrm{tr}[\cdots]$ denotes the trace performed in flavor space. The superfields S_μ and $\bar{S}_\mu$ are represented by

$$S_\mu = \hat{\Sigma}^*_{\mathrm{c}\mu} - \frac{1}{\sqrt{3}}(\gamma_\mu + v_\mu)\gamma_5\hat{\Sigma}_\mathrm{c},\ \bar{S}_\mu = S^\dagger_\mu\gamma_0. \tag{3}$$

Here, the heavy baryon fields $\hat{\Lambda}_\mathrm{c}$ and $\hat{\Sigma}^{(*)}_{\mathrm{c}(\mu)}$, are

$$\hat{\Lambda}_\mathrm{c} = \begin{pmatrix} 0 & \Lambda_\mathrm{c}^+ \\ -\Lambda_\mathrm{c}^+ & 0 \end{pmatrix}, \tag{4}$$

$$\hat{\Sigma}^{(*)}_{\mathrm{c}(\mu)} = \begin{pmatrix} \Sigma^{(*)++}_{\mathrm{c}(\mu)} & \frac{1}{\sqrt{2}}\Sigma^{(*)+}_{\mathrm{c}(\mu)} \\ \frac{1}{\sqrt{2}}\Sigma^{(*)+}_{\mathrm{c}(\mu)} & \Sigma^{(*)0}_{\mathrm{c}(\mu)} \end{pmatrix}. \tag{5}$$

As shown in [52], $g_1 = (\sqrt{8}/3)g_4 = 1$. The internal structure of hadrons is parametrized by a dipole form factor at each vertex, $F(\Lambda,\boldsymbol{q}) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2+\boldsymbol{q}^2}$, where m_π and $\boldsymbol{q}$ are the mass and three-momentum of an incoming pion and the heavy hadron cut-offs Λ_H are determined by the ratio between the sizes of the heavy hadron, r_H, and the nucleon, r_N, $\Lambda_N/\Lambda_H = r_H/r_N$, We obtained $\Lambda_{\Lambda_\mathrm{c}} \sim \Lambda_{\Sigma_\mathrm{c}} \sim \Lambda_N$ for the charmed baryons and $\Lambda_{\bar{D}} = 1.35\Lambda_N$ for the $\bar{D}^{(*)}$ meson, where the nucleon cutoff is determined to reproduce the deuteron-binding energy by the one-pion exchange potential(OPEP) as $\Lambda_N = 837$ MeV [53–55]. The explicit form of the OPEP $V^\pi(\boldsymbol{q})$ between the meson-baryon (MB) channels in the momentum space is as follows,

$$V^\pi(\boldsymbol{q}) = -\left(\frac{g_A^M g_A^B}{4f_\pi^2}\right)\frac{(\hat{\boldsymbol{S}}_1\cdot\boldsymbol{q})(\hat{\boldsymbol{S}}_2\cdot\boldsymbol{q})}{\boldsymbol{q}^2+m_\pi^2}\hat{\boldsymbol{T}}_1\cdot\hat{\boldsymbol{T}}_2, \tag{6}$$

where $\hat{\boldsymbol{S}}$ is the spin operator and $\hat{\boldsymbol{T}}$ is the isospin operator. g_A^B is the axial vector coupling constant of the corresponding baryons. [1]

The coupling of the MB channels, i and j, to the five-quark ($5q$) channels, α, gives rise to an effective interaction, V^{5q},

$$\left\langle i\,\middle|\,V^{5q}\,\middle|\,j\right\rangle = \sum_\alpha \langle i\,|\,V\,|\,\alpha\rangle\frac{1}{E-E_\alpha^{5q}}\left\langle \alpha\,\middle|\,V^\dagger\,\middle|\,j\right\rangle, \tag{7}$$

where V represents the transitions between the MB and $5q$ channels and E_α^{5q} is the eigenenergy of a $5q$ channel. We further introduced the following assumption,

$$\langle i\,|\,V\,|\,\alpha\rangle = f\,\langle i\,|\,\alpha\rangle, \tag{8}$$

where f is the only free parameter which determines the overall strength of the matrix elements. In order to calculate the $\langle i\,|\,\alpha\rangle$, we construct the meson-baryon and

[1] In our previous publication [20], there were a few errors in the matrix elements, which are corrected in this paper. After the corrections, however, important results of our discussions remain unchanged.

five-quark wave functions explicitly in the standard non-relativistic quark model with a harmonic oscillator confining potential. The derived potential $\langle i \,|\, V^{5q} \,|\, j \rangle$ turned out to give similar results to those derived from the quark cluster model [7].

The energies and widths of the bound and resonant states were obtained by solving the coupled-channel Schrödinger equation with the OPEP, $V^{\pi}(\boldsymbol{r})$, and $5q$ potential $V^{5q}(\boldsymbol{r})$,

$$\left(K + V^{\pi}(\boldsymbol{r}) + V^{5q}(\boldsymbol{r})\right) \Psi(\boldsymbol{r}) = E\Psi(\boldsymbol{r}) \,, \tag{9}$$

where K is the kinetic energy of the meson-baryon system and $\Psi(\boldsymbol{r})$ is the wave function of the meson-baryon systems with $\boldsymbol{r}$ being the relative distance between the center of mass of the meson and that of the baryon. The coupled channels included are all possible ones of $\Sigma_c^{(*)}\bar{D}^{(*)}$ and $\Lambda_c\bar{D}^{(*)}$ which can form a given J^P and isospin $I = 1/2$.

Eq. (9) is solved by using variational method. We used the Gaussian basis functions as trial functions [56]. In order to obtain resonance states, we employed the complex scaling method [57].

In Fig. 1 and Table I, experimental data [1, 34] and our predictions are compared. The centers of the bars in Fig. 1 are located at the central values of pentaquark masses while their lengths correspond to the pentaquark widths with the exception of $P_c(4380)$ width, which is too large and does not fit into the shown energy region. The boxed numbers are the masses of the recently observed states [34], and the corresponding predictions in our model. The dashed lines are for threshold values. Our predicted masses and the decay widths are shown for the parameters $f/f_0 = 50$ and $f/f_0 = 80$. Here, f_0 is the strength of the one-pion exchange diagonal term for the $\Sigma_c\bar{D}^*$ meson-baryon channel, $f_0 = \left|C^{\pi}_{\Sigma_c\bar{D}^*}(r=0)\right| \sim$ 6 MeV (see Ref. [45]). Setting the free parameter f/f_0 at $f/f_0 = 50$, we observe that both masses and widths of $P_c^+(4312)$ and $P_c^+(4440)$ are reproduced within the experimental errors. However, the state corresponding to $P_c^+(4457)$ is absent in our results, where the attraction is not enough. Increasing the value of f/f_0 to 70, the state with $J^P = 1/2^-$ appears below the $\Sigma_c\bar{D}^*$ threshold, and at $f/f_0 = 80$ the mass and width of this state are in reasonable agreement with $P_c^+(4457)$. However, as shown in Fig. 1, the attraction at $f/f_0 = 80$ is stronger than that at $f/f_0 = 50$ and hence the masses of the other states shift downward.

We find as expected that the dominant components of these states are nearby threshold channels and with the quantum numbers as follows; $\Sigma_c\bar{D}$ with $J^P = 1/2^-$ ($P_c^+(4312)$), $\Sigma_c\bar{D}^*$ with $J^P = 3/2^-$ ($P_c^+(4440)$) and with $J^P = 1/2^-$ ($P_c^+(4457)$) meson-baryon molecular states.

Let us compare our results with the ones reported by other works. In Ref. [36], the assignments of the quantum numbers for $P_c(4440)$ and $P_c(4457)$ are different from

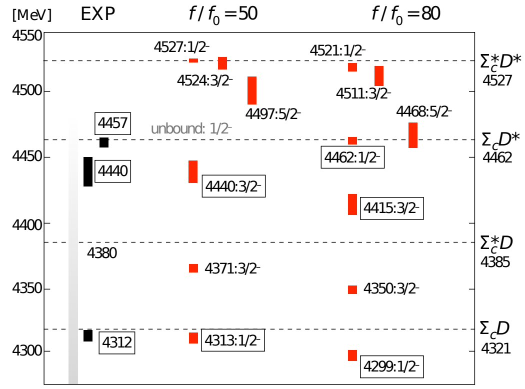

FIG. 1. (Color online) Experimental data (EXP) [1, 34] and our results of masses and widths for various P_c states. The horizontal dashed lines show the thresholds for corresponding channels and values in the right axis are isospin averaged ones in units of MeV. The centers of the bars are located at the central values of pentaquark masses while their lengths correspond to the pentaquark widths with the exception of $P_c(4380)$ width.

ours. Since these two states are located near $\Sigma_c\bar{D}^*$ threshold and both states have the narrow widths, it is natural to consider them to form the $J = 1/2$ and $3/2$ states in S-wave. It is emphasized that in our model the spin 3/2 state (4440) is lighter than the spin 1/2 state (4457). In Ref. [37], they studied seven heavy quark multiplets of $\Sigma_c\bar{D}$, $\Sigma_c\bar{D}^*$, $\Sigma_c^*\bar{D}$, and $\Sigma_c^*\bar{D}^*$, and considered two options of inputs, $P_c(4440, 4457) \sim (3/2, 1/2)$ which they call set A and (1/2, 3/2) set B. In the heavy quark limit, there are two parameters in the Hamiltonian and so the above inputs for the two states are enough to fix the two parameters. The other five states are predicted. Interestingly, their set A predicts the other five states similarly to what our model predicts.

Therefore, new LHCb results give us an opportunity to study the spin-dependent forces between the Σ_c and $\bar{D}^*$. It is important to determine which of the above spin 1/2 and 3/2 states is more deeply bound. There are two sources for the spin-dependent force in our model. One is the short range interaction by the coupling to the 5-quark-core states. The other is the long range interaction by the OPEP, especially the tensor term.

To examine the effects of the tensor interaction of the OPEP, we have investigated the energy of the resonant P_c states of $J = 1/2$ and $3/2$ around the $\Sigma_c\bar{D}^*$ threshold, and of $J = 1/2$, $3/2$ and $5/2$ around the $\Sigma_c^*\bar{D}^*$ threshold without the OPEP tensor term as shown in Fig. 2. In that plot, we have used $f/f_0 = 80$. From Fig. 2, we observe the following facts. (1) The tensor force provides attraction as indicated by the results with T in Fig. 2. This is because it contributes to the energy in the second order due to channel couplings. (2) The role of the tensor force is further prominent in the decay width; the agreement with the experimental data is significantly im-

TABLE I. Comparison between the experimental mass spectrum and decay widths with our results. For our results for $f/f_0 = 80$, the values in parentheses are obtained without the OPEP tensor force, which are also shown in Fig. 2. All values except J^P are in units of MeV.

EXP [1, 34]			Our results for $f/f_0 = 50$			Our results for $f/f_0 = 80$		
State	Mass	Width	J^P	Mass	Width	J^P	Mass	Width
$P_c^+(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$1/2^-$	4313	9.6	$1/2^-$	4299 (4307)	9.4 (12)
$P_c^+(4380)$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$	4371	5.0	$3/2^-$	4350 (4365)	5.0 (3.6)
$P_c^+(4440)$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$3/2^-$	4440	16	$3/2^-$	4415 (4433)	15 (1.8)
$P_c^+(4457)$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	—	—	—	$1/2^-$	4462 (4462)	3.2 (0.96)
			$1/2^-$	4527	0.88	$1/2^-$	4521 (4526)	2.8 (0.18)
			$3/2^-$	4524	7.6	$3/2^-$	4511 (4521)	14 (3.4)
			$5/2^-$	4497	20	$5/2^-$	4468 (4491)	18 (0.0)

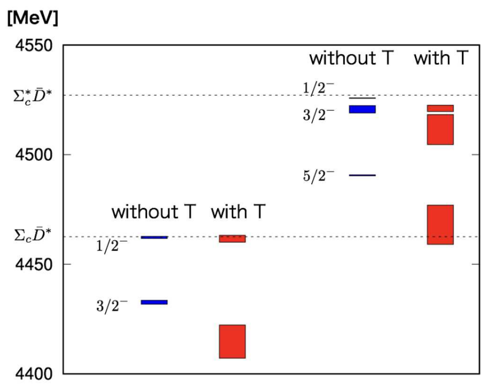

FIG. 2. (Color online) Comparing the results with and without the tensor force of the OPEP for the states around the $\Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^*$ thresholds. The label 'without T' stands for the result without the OPEP tensor force, while the label 'with T' stands that with the OPEP tensor force. The same convention is adopted as in Fig. 1.

proved. Moreover, the decay width increases as the spin value increases. We consider it again because of coupled-channel effects due to the OPEP tensor force. The dominant components of the obtained resonances are the S-wave state of the nearby threshold channel. The tensor coupling allows the resonances to decay into the D-wave channels below the resonances. Since there are many D-wave coupled channels in the higher spin states, the decay widths of these states are increased. In fact, the number of the D-wave coupled channels below the $\Sigma_c^*\bar{D}^*$ threshold is 3 for $J^P = 1/2^-$, while 7 for $J^P = 3/2^-, 5/2^-$.

From the observation in Fig. 2, we find that the short range interaction is more attractive in the $3/2^-$ state in the present model. This contrasts with what is expected for the color-spin interaction that provides more attraction for the $1/2^-$ state. The reason is in the quark structure of hadrons as explained below. In the quark cluster model, the hadron interaction is due mainly to the two terms: one is the Pauli-blocking effect which is measured by the norm (overlap) kernels and the other is the color-spin interaction from the one gluon exchange. The former is included in the present study, and is usually dominant when the norm of the two-hadron state deviates largely from 1 [58, 59]. It can be less than 1 due to the Pauli-blocking (repulsive) but also can be more than 1 (attractive) because of the spectroscopic factor. For the $\Sigma_c\bar{D}^*$ channel, the norm is 23/18 for the $3/2^-$ state while 17/18 for the $1/2^-$ state [45]. Namely, this contribution of the spectroscopic factor is strongly attractive in the $\Sigma_c\bar{D}^*3/2^-$ state and slightly repulsive in the $\Sigma_c\bar{D}^*1/2^-$ state.

To estimate the effect of the color-spin interaction, which is not included in the present study, we revisit the coupled-channel dynamical calculation where both the Pauli-blocking and color-spin effects are included (but without the OPEP) [7]. There a sharp cusp structure was observed for the $3/2^-$ state at the $\Sigma_c\bar{D}^*$ threshold while not for $1/2^-$ state, implying some attraction for the $3/2^-$ state while little for $1/2^-$ state. This is because the color-spin force which is attractive for the spin $1/2^-$ state has been overcome by the Pauli-blocking effect that acts reversed manner. Therefore, the effect of the color-spin force is not dominant for these resonant states. It is interesting to investigate the system with a model which includes both of the above quark model features with the OPEP, which is now underway.

Although we have obtained the $J^P = 3/2^-$ state at 4371 MeV and at 4350 MeV when $f = 50$ and 80, respectively, we do not consider that this state corresponds to the LHCb's $P_c^+(4380)$ state. The observed $P_c^+(4380)$ has a width of about 200 MeV while that of our predicted state is only about 5 MeV. In the first LHCb analysis [1], though the higher P_c states were treated as one state, the opposite parity assignments were preferred for lower and higher P_c states. On the other hand, all the states we have obtained here have the same parity minus. In the new LHCb analysis [34], using higher-order polynomials for the background, data could be fitted without the broad $P_c^+(4380)$ Breit-Wigner resonance contribution. Therefore, further theoretical as well as experimental studies are necessary for the $P_c^+(4380)$ state.

In addition to the three states observed in the LHCb, we obtained four more states including the one corresponding to $P_c^+(4380)$ near (below) the $\Sigma_c^*\bar{D}^{(*)}$ thresholds as shown in Fig. 1 and Table I. Due to the spins of Σ_c^* and $\bar{D}^{(*)}$, $J = 3/2$ and 1 (or 0), respectively, they naturally form either triplet states, $J = 5/2, 3/2, 1/2$, or a singlet state of $J = 3/2$. A possible reason that those states are not seen would be due to a wider width of Σ_c^*. In fact, the width of the Σ_c^* is about 15 MeV, while that of the Σ_c is less than 2 MeV [50]. Furthermore Σ_c^* decays to $\Lambda_c\pi$. Therefore, it may be difficult to observe the $\Sigma_c^*\bar{D}^{(*)}$ resonance states in the $J/\psi p$ channel. One may have to look into the $J/\psi p\pi$ channel to observe the pentaquark states consisting mostly of the $\Sigma_c^*\bar{D}^{(*)}$ components.

In addition to the seven $\Sigma_c^{(*)}\bar{D}^{(*)}$ states predicted in the present study, we obtained two more narrow resonance states below the $\Lambda_c\bar{D}^*$ threshold in Ref. [45], while such resonances have not been reported in experiments yet. Although the OPEP does not contribute to the diagonal terms of the $\Lambda_c\bar{D}^*$ potential, the $\Lambda_c\bar{D}^{(*)} - \Sigma_c^{(*)}\bar{D}^{(*)}$ coupling induces the OPEP and the attraction from the tensor term is also produced in the $\Lambda_c\bar{D}^{(*)}$ channel. In future experiments, it is interesting to search for such resonances below the $\Lambda_c\bar{D}^*$ threshold.

In conclusion, by coupling the open charm meson-baryon channels to a compact $uudc\bar{c}$ core with an interaction satisfying the heavy quark and chiral symmetries, we predict the masses and decay widths of the three new pentaquark states reported in [34]. Both the masses and widths of these three hidden-charm pentaquark states we have obtained are in reasonable agreement with the experimental results. We point out that the three pentaquark states have quantum numbers $J^P_{P_c^+(4312)} = 1/2^-$, $J^P_{P_c^+(4440)} = 3/2^-$, and $J^P_{P_c^+(4457)^+} = 1/2^-$ and the dominant molecular component of $P_c^+(4312)$ is the $\Sigma_c\bar{D}$ and that of $P_c^+(4440)$ and $P_c^+(4457)$ is $\Sigma_c\bar{D}^*$. We find that the short range interaction by the coupling to the 5-quark-core states plays a major role in determining of the ordering of the multiplet states, while the long range force of the pion tensor force does in producing the decay widths, which are consistent with the data. The importance of what we referred to as the chiral tensor dynamics is a universal feature for the heavy hadrons with light quarks. Such dynamical studies in coupled channel problems should be properly performed for further understanding of heavy hadron systems.

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