Heavy quark spin symmetry with chiral tensor dynamics in the light of the recent LHCb pentaquarks

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Abstract

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 $uudcc$ compact core by employing an interaction satisfying the heavy quark and chiral symmetries. Our model can reproduce 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 find that the mass difference between $P^+_c(4440)$ and $P^+_c(4457)$ comes mainly from the tensor interaction by the one-pion exchange potential.

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In 2015, the Large Hadron Collider beauty experiment (LHCb) collaboration observed two hidden-charm pentaquarks, $P_c^+(4380)$ and $P_c^+(4450)$, in $\Lambda_0^0 \rightarrow J/\psi K^- p$ decay and reported additional analysis efforts. These results have motivated hundreds of theoretical articles (just to make some examples see [4–33]). Recently a new analysis has been reported 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 $\sim 200$ MeV), 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:

$P_c^+(4312) : M = 4311.9 \pm 0.7^{+6.8}_{-0.6}$ MeV,
$\Gamma = 9.8 \pm 2.7^{+3.7}_{-4.5}$ MeV;

$P_c^+(4440) : M = 4440.3 \pm 1.3^{+4.1}_{-4.7}$ MeV,
$\Gamma = 20.6 \pm 4.9^{+8.7}_{-10.1}$ MeV;

$P_c^+(4457) : M = 4457.3 \pm 0.6^{+4.1}_{-1.7}$ MeV,
$\Gamma = 6.4 \pm 2.0^{+5.7}_{-1.9}$ MeV.

As discussed by LHCb, $P_c^+(4312)$ 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. Among them, [35, 36, 41] 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 $\eta_c N, J/\psi N, \bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$ 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 $Σ^{(*)}_c D^{(*)}$ hadronic molecule states in a quasipotential Bethe-Salpeter equation approach \cite{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.

In Ref. \cite{44} we studied the hidden-charm pentaquarks by coupling the $D^{(*)}_c Λ_c$ and $D^{(*)}_c Σ_c^{(*)}$ 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. The novelty of the present article is in that once the parameter is determined, we can predict the masses and widths of various pentaquark states and discuss the underlying dynamics. 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 $J^P_{P_c^+(4457)} = 1/2^−$. As far as we know, our results are the only ones which reproduce not only masses but also the widths of the new LHCb pentaquark states in the dynamical model calculations. 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 our model of Ref. \cite{44}. 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, $D$ and $D^*$, and the pions can be
which was determined by the $D$ quark inside the heavy meson; as shown in [51], a dipole form factor at each vertex, the ratio between the sizes of the heavy hadron, three-momentum of an incoming pion and the heavy hadron cut-offs $\Lambda$. The trace $\text{Tr} \ldots$ is taken over the gamma matrices.

The subscript $a$ denotes the light quark flavor, and $v_\mu$ is the four-velocity of the heavy quark inside the heavy meson; $g_A^M$ is the axial vector coupling constant for heavy mesons, which was determined by the $D^* \rightarrow D\pi$ strong decay to be $g_A^M = 0.59$ [47–49], and $A^\mu = \frac{1}{2} \left[ \xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger \right]$; with $\xi = \exp \left( \frac{i\pi}{2f_\pi} \right)$, 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 $\Sigma_c$ and $\Lambda_c$ heavy baryons and the pions is [50, 51]

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

(2)

where $\text{tr} […]$ denotes the trace performed in flavor space. The superfields $S_\mu$ and $\tilde{S}_\mu$ are represented by

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

(3)

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

$$\hat{\Lambda}_c = \begin{pmatrix} 0 & \Lambda_c^+ \\ -\Lambda_c^+ & 0 \end{pmatrix}, \quad \hat{\Sigma}_{c(\mu)}^{(s)} = \begin{pmatrix} \Sigma_{c(\mu)}^{(s)+} & \frac{1}{\sqrt{2}} \Sigma_{c(\mu)}^{(s)0} \\ \frac{1}{\sqrt{2}} \Sigma_{c(\mu)}^{(s)+} & \Sigma_{c(\mu)}^{(s)0} \end{pmatrix}.$$  

(4)

As shown in [51], $g_1 = (\sqrt{3}/3)g_4 = 1$. The internal structure of hadrons is parametrized by a dipole form factor at each vertex, $F(\Lambda, q) = \frac{\Lambda^2 - m^2_\pi}{\Lambda^2 + q^2}$, where $m_\pi$ and $q$ are the mass and three-momentum of an incoming pion and the heavy hadron cut-offs $\Lambda_H$ 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 $\Lambda_{\Lambda_c} \sim \Lambda_{\Sigma_c} \sim \Lambda_N$ 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 [52–54]. The explicit form of the OPEP $V^\pi(q)$ between the meson-baryon (MB) channels in the momentum space is as follows,

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

(5)

\[\text{5}\]
where $\hat{S}$ is the spin operator and $\hat{T}$ is the isospin operator. $g_A^P$ is the axial vector coupling constant of the corresponding baryons.

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

$$\langle i \mid V^{5q} \mid j \rangle = \sum_\alpha \langle i \mid V \mid \alpha \rangle \frac{1}{E - E^{5q}_\alpha} \langle \alpha \mid V^\dagger \mid j \rangle ,$$

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

$$\langle i \mid V \mid \alpha \rangle = f \langle i \mid \alpha \rangle ,$$

where $f$ is the only free parameter which determines the overall strength of the matrix elements. In order to calculate the $\langle i \mid \alpha \rangle$, we construct the meson-baryon and five-quark wave functions explicitly in the standard non-relativistic quark model with a harmonic oscillator confining potential. The derived potential $\langle i \mid V^{5q} \mid j \rangle$ turned out to give similar results to those derived from the quark cluster model.

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

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

where $K$ is the kinetic energy of the meson-baryon system and $\Psi(r)$ is the wave function of the meson-baryon systems with $r$ 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 $\Sigma_c^{(*)} D^{(*)}$ and $\Lambda_c \bar{D}^{(*)}$ which can form a given $JP$ and isospin $I = 1/2$.

Eq. (8) is solved by using the variational method. We used the Gaussian basis functions as trial functions. In order to obtain the resonance states, we employed the complex scaling method.

In Fig. 1 experimental data and our predictions are compared. The center of the bars are located at the central values of pentaquark masses whiles 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, and the corresponding predictions in our model. The dashed lines are for threshold values. Our predicted masses and the decay widths are obtained by setting the free
FIG. 1: Experimental data (EXP) and our predictions for various $P_c$ states.

parameter $f/f_0$ at $f/f_0 = 45$, which corresponds to the minimum value necessary to have all the three new LHCb states. Here, $f_0$ is the strength of the one-pion exchange diagonal term for the $\Sigma_c^* \bar{D}$ meson-baryon channel, $f_0 = \left| C_{\bar{D}^* \Sigma_c}^\pi (r = 0) \right| \sim 6$ MeV (see Ref. [44]). We observe that not only the masses of all the three new states but also their small widths are reproduced within the experimental errors. 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.

In Table I the experimental mass spectrum and decay widths are compared with our predictions and the ones reported in Ref. [36] and scenario A of Ref. [37]. The mass difference between $P_c(4440)$ and $P_c(4457)$ is not reproduced in [36] and the assignments of the quantum numbers for these states are different from 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 spin doublet of 1/2 and 3/2 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 $D\Sigma_c, D^*\Sigma_c, D\Sigma_c^*, D^*\Sigma_c^*$, and considered two
TABLE I: Comparison between the experimental mass spectrum and decay widths with our predictions and the ones reported in Ref. [36] and scenario A of Ref. [37]. Numbers with asterisk are used as inputs. All values except $J^P$ are in units of MeV.

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<td>$P_c(4312)^+$</td>
<td>$4311.9 \pm 0.7^{+6.8}_{-0.6}$</td>
<td>$9.8 \pm 2.7^{+3.7}_{-4.5}$</td>
<td>(4306.4, $\frac{1}{2}^-$, 15.2)</td>
<td>(4306, $\frac{1}{2}^-$)</td>
<td>(4312, $\frac{1}{2}^-$, 5)</td>
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<td>$P_c(4380)^+$</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$205 \pm 18 \pm 86$</td>
<td>(4374, $\frac{3}{2}^-$, 13.7)</td>
<td>(4371, $\frac{3}{2}^-$)</td>
<td>(4376, $\frac{3}{2}^-$, 8)</td>
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<td>$P_c(4440)^+$</td>
<td>$4440.3 \pm 1.3^{+4.1}_{-4.7}$</td>
<td>$20.6 \pm 4.9^{+8.7}_{-10.1}$</td>
<td>(4453.0, $\frac{1}{2}^-$, 23.4)</td>
<td>(4440*, $\frac{3}{2}^-$)</td>
<td>(4442, $\frac{3}{2}^-$, 26)</td>
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<tr>
<td>$P_c(4457)^+$</td>
<td>$4457.3 \pm 0.6^{+4.1}_{-1.7}$</td>
<td>$6.4 \pm 2.0^{+5.7}_{-1.9}$</td>
<td>(4452.5, $\frac{3}{2}^-$, 3.0)</td>
<td>(4457*, $\frac{1}{2}^-$)</td>
<td>(4462, $\frac{1}{2}^-$, 6.6)</td>
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<td>(4520.5, $\frac{1}{2}^-$, 22.2)</td>
<td>(4523, $\frac{1}{2}^-$)</td>
<td>(4524, $\frac{1}{2}^-$, 1.5)</td>
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<td>(4519.0, $\frac{3}{2}^-$, 13.7)</td>
<td>(4516, $\frac{3}{2}^-$)</td>
<td>(4521 $\frac{3}{2}^-$, 23)</td>
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<td>(4500 $\frac{5}{2}^-$)</td>
<td>(4511 $\frac{5}{2}^-$, 55)</td>
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follows. The $J^P = 3/2^-$ state consists of $^4S,^2D,^4D$ channels, while the $J^P = 1/2^-$ state consists of $^2S,^4D$. The tensor interaction provides attraction through channel couplings such as $S-D$ and $D-D$. For the $J^P = 3/2^-$ state there are three combinations of such channel couplings, while for $1/2^-$ state there is only one. Considering the strengths of these couplings, the $J^P = 3/2^-$ state receives more attraction than the $1/2^-$ state. It is interesting and emphasized that the present set of heavy baryon states is the first example where the role of the tensor force can be compared in two partner states. For nucleon systems only spin 1 state (deuteron) is available without partners.

The short range interaction by the coupling to the 5-quark-core states without the tensor interaction by OPEP produces the state with the mass of 4462 MeV for $f/f_0 = 75$ below the $\Sigma_c$ and $\bar{D}^*$ threshold in the $J^P = 1/2^-$ channel. On the other hand, it gives the state with mass of 4435 MeV for $f/f_0 = 75$ below the $\Sigma_c$ and $\bar{D}^*$ threshold in the $J^P = 3/2^-$ channel. It means that the short range interaction by the coupling to the 5-quark-core states has the spin dependence. In the present model, this spin dependence comes mainly from the difference in size of the Pauli-forbidden 5-quark states in each of the channels. The mass difference between $J^P = 1/2^-$ state and $J^P = 3/2^-$ by this short range interaction depends on the strength $f/f_0$. It is 47 MeV at $f/f_0 = 100$ and 27 MeV at $f/f_0 = 75$. If we extrapolate, the mass difference is 3 MeV at $f/f_0 = 45$. Therefore, the dominant contribution to the mass difference between $J^P = 1/2^-$ and $J^P = 3/2^-$ states is from the tensor interaction by the OPEP.

Although we have obtained the $J^P = 3/2^-$ state at 4376 MeV, we do not consider that this meson-baryon molecular 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 the state at 4376 MeV that we obtained is of order 10 MeV. 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.

Besides the three states observed in the LHCb, we obtained four additional narrow molecular states as shown in Fig. [4] and Table 1. If we exclude the $P_c^+(4380)$ as $\Sigma_c^*\bar{D}$ molecular state, we see that all the three pentaquarks observed lie below $\Sigma_c\bar{D}^{(*)}$ threshold and the molecular states that contain $\Sigma_c^*$ are not seen. In addition to these seven states, we obtained two more narrow resonance states below $\Lambda_c\bar{D}^*$ threshold [44]. Since $\Lambda_c$ is isoscalar, and no
diagonal terms of the OPEP contribute to the $\Lambda_c\bar{D}^*$ channel, we do not discuss them here. We only point out that these states are also not observed experimentally.

In order to clarify why those states cannot be observed in the LHCb experiment, the study of the non-leptonic weak decay process $\Lambda_b^0 \to P_c^+ K^-$ is desired as well as the higher statistics observations and full amplitude analysis.

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 good 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 both the short range interaction by the coupling to the 5-quark-core states and the long range interaction by the one-pion exchange potential make contributions to the attraction between $\Sigma_c$ and $\bar{D}^(*)$. The mass difference between $P_c^+(4440)$ and $P_c^+(4457)$ comes mainly from the tensor interaction by the one-pion exchange potential. Because of the importance of the tensor interaction mediated by the pion in the heavy-hadron dynamics, we call it “chiral tensor dynamics”.

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