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Mass spectrum of spin-1/2 pentaquarks with a $c\bar{c}$ component and their anticipated discovery modes in b-baryon decays

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Abstract

The LHCb discovery of the two baryonic states $P_c^+(4380)$ and $P_c^+(4450)$, having $J^P = 3/2^-$ and $J^P = 5/2^+$, respectively, in the process $pp \to b\bar{b} \to \Lambda_b X$, followed by the decay $\Lambda_b \to J/\psi\ p\ K^-$, has motivated a number of theoretical models. Interpreting them as compact $\{\bar{c}\ [cu]\ [ud]; L_{\mathcal{P}} = 0, 1\}$ objects, the mass spectroscopy of the $J^P = 3/2^-$ and $J^P = 5/2^+$ pentaquarks was worked out by us for the pentaquarks in the $SU(3)_F$ multiplets, using an effective Hamiltonian based on constituent diquarks and quarks. Their possible discovery modes in b-baryon decays were also given using the heavy quark spin symmetry. In this paper, we calculate the mass spectrum of the hidden $c\bar{c}$ pentaquarks having $J^P = \frac{1}{2}^\pm$ for the $SU(3)_F$ multiplets and their anticipated discovery modes in b-baryon decays. Some of the $P_c^+(J^P = 1/2^\pm)$ pentaquarks, produced in the Λ_b decays may have their masses just below the $J/\psi\, p$ threshold, in which case they should be searched for in the modes $P_c^+(J^P = 1/2^\pm) \to \eta_c\, p,\ \ \mu^+\mu^-\ p,\ \ e^+e^-\ p$.

I. INTRODUCTION

In 2015, LHCb reported the first observation of two hidden charm pentaquark states $P_c^+(4380)$ and $P_c^+(4450)$ in the decay $\Lambda_b^0 \to J/\psi\, p\, K^-$ [1], having the masses $4380 \pm 8 \pm 29$ MeV and $4449.8 \pm 1.7 \pm 2.5$ MeV, and widths $205 \pm 18 \pm 86$ MeV and $39 \pm 5 \pm 19$ MeV, with the preferred spin-parity assignments $J^P = \frac{3}{2}^-$ and $J^P = \frac{5}{2}^+$, respectively. These states have the quark composition $c\bar{c}uud$, and their masses lie close to several (charm meson-baryon) thresholds. This has led to a number of theoretical proposals for their interpretation, which include rescattering-induced kinematical effects [2], open charm-baryon and charm-meson bound states [3], and baryocharmonia [4]. They have also been interpreted as compact pentaquark hadrons with the internal structure organized as diquark-diquark-anti-charm quark [5, 6] or as diquark-triquark [7, 8].

In an earlier paper [9] we followed the compact pentaquark interpretation, following the basic idea that highly correlated diquarks play a key role in the physics of multiquark states [10–12]. The diquarks resulting from the direct product $\mathsf{3} \otimes \mathsf{3} = \bar{\mathsf{3}} \oplus \mathsf{6}$, are either a color anti-triplet $\bar{\mathsf{3}}$ or a color sextet $\mathsf{6}$. Of these only the color $\bar{\mathsf{3}}$ configuration is kept, as suggested by perturbative arguments. Both spin-1 and spin-0 diquarks are, however, allowed. In the case of a diquark $[qq']$ consisting of two light quarks, the spin-0 diquarks are believed to be more tightly bound than the spin-1, but for the heavy-light diquarks, such as $[cq]$ or $[bq]$, this splitting is suppressed by $1/m_c$ for a $[cq]$ or by $1/m_b$ for a $[bq]$ diquark, and hence both spin-configurations are treated at par. For the pentaquarks, the mass spectrum will depend upon how the five quarks, i.e., the 4 quarks and an antiquark, are dynamically structured. A diquark-triquark picture, in which the two observed pentaquarks consist of a rapidly separating pair of a color-$\bar{\mathsf{3}}$ $[cu]$ diquark and a color-$\mathsf{3}$ triquark $\bar{\theta} = \bar{c}[ud]$, has been presented in [7].

In [9], we used the template in which the 5q baryons, such as the two P_c states, are assumed to be four quarks, consisting of two highly correlated diquark pairs, and an antiquark. For the present discussion, it is an anti-charm quark $\bar{c}$ which is correlated with the two diquarks $[cq]$ and $[q'q'']$, where q, q', q'' can be u or d. The tetraquark formed by the diquark-diquark $([cq]_{\bar{3}}[q'q'']_{\bar{3}})$ is a color-triplet object,with orbital and spin quantum numbers, denoted by $L_{\mathcal{QQ}}$ and $S_{\mathcal{QQ}}$, which combines with the color-anti-triplet $\bar{\mathsf{3}}$ of the $\bar{c}$ to form an overall color-singlet pentaquark, with the corresponding quantum numbers $L_{\mathcal{P}}$ and $S_{\mathcal{P}}$. (See, Fig. 1 in [9].) An effective Hamiltonian based on this picture was constructed in [9], extending the underlying tetraquark Hamiltonian developed for the X, Y, Z states by Maiani *et al.* [10]. We explained how the various input parameters in this Hamiltonian were determined. Subsequently, we worked out the mass spectrum of the low-lying S- and P-wave pentaquark states, with a $c\bar{c}$ and three light quarks (u, d, s) in their Fock space, but restricted ourselves to the $J^P = 3/2^-$ and $J^P = 5/2^+$ states. The pentaquark states reported by the LHCb are produced in Λ_b^0 decays, $\Lambda_b^0 \to \mathcal{P}^+ K^-$, where $\mathcal{P}$ denotes a generic pentaquark state, a symbol we use subsequently in this work. In addition to the $\Lambda_b^0 = (udb)$, which is the lightest of the b-baryons in which the light quark pair ub has $j^P = 0^+$, there are two others in this $SU(3)_F$ triplet with strangeness $S = -1$, $\Xi_b^0(5792) = (usb)$, having isospin $I = I_3 = 1/2$ and $\Xi_b^-(5794) = (dsb)$, having isospin $I = -I_3 = 1/2$. Likewise, there are six b-baryons with the light quark pair having $j^P = 1^+$, with $S = 0$ ($\Sigma_b^- = (ddb)$, $\Sigma_b^0 = (udb)$, $\Sigma_b^+ = (uub)$), $S = -1$ ($\Xi_b' = (dsb)$, $\Xi_b'^0 = (usb)$), and one with $S = -2$ ($\Omega_b^- = (ssb)$.) These bottom baryon multiplets are shown in Fig. 2 of ref. [9]. We presented the discovery modes of the $J^P = 3/2^-$ and $J^P = 5/2^+$ pentaquarks in b-baryon decays in [9]. In doing this, we assumed heavy quark symmetry, i.e., for $m_b \gg \Lambda_{\rm QCD}$, b-quark becomes a static quark and the light diquark spin becomes a good quantum number, constraining the states which can otherwise be produced in these decays. In particular, we found that in the diquark picture, one expects a lower-mass $J^P = \frac{3}{2}^-$ pentaquark state with the quantum numbers $\{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_{\mathcal{P}} = 0, J^{\rm P} = \frac{3}{2}^-\}$, which has the correct light diquark spin to be produced in the decay $\Lambda_b^0 \to J/\psi\, p\, K^-$, compatible with the heavy quark symmetry. We estimated its mass in the range 4110 - 4130 MeV, and suggested to search for the lower mass $P_c^+(J^P = \frac{3}{2}^-)$ state decaying into $J/\psi\, p$ in the LHCb data on $\Lambda_b^0 \to J/\psi\, pK^-$.

In this paper, we extend the mass spectrum calculation to the $J^P = 1/2^\pm$ pentaquark case. The S (P)- wave pentaquark states are called $\mathcal{P}_{X_i}$ ($\mathcal{P}_{Y_i}$), and their spin- and orbital angular momentum quantum numbers are given in Tables I and II. There are five S-wave pentaquark states with $J^P = \frac{1}{2}^-$, four S-wave pentaquark states with $J^P = \frac{3}{2}^-$, and nine P-wave states with $J^P = \frac{1}{2}^+$. The input constituent quark masses and inter-diquark and intra-diquark spin-spin couplings are given in Tables II and III of ref. [9] and the quark flavors for the pentaquark multiplets are given in Table III. The mass term ΔM that arises from different spin-spin interactions is given in Table IV. The masses of the five S-wave pentaquarks with $J^P = \frac{1}{2}^-$ are given in Table V, and the masses of the nine P-wave pentaquarks with $J^P = \frac{1}{2}^+$ are given in Tables VI and VII. We also work out the discovery modes of the pentaquarks with $J^P = \frac{1}{2}^\pm$ in various b-baryon decays. In doing this, we have used $SU(3)_F$ and heavy quark symmetries, discussed in [9]. We find that some of the lowest-lying pentaquarks may have their masses below the threshold to decay into a $J/\psi p$ (and similar thresholds in other pentaquarks). In this case, the discovery modes are expected to be $\eta_c\, p$, $\mu^+\mu^-\, p$ and $e^+e^-\, p$. Estimate of the ratios of decay widths $\Gamma(\mathcal{B}(\mathcal{C}) \to \mathcal{P}^{1/2^-}\mathcal{M})/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$ for $\Delta S = 1$ transitions are given in Table VIII. Here $\mathcal{M}$ is the lightest pseudoscalar meson nonet and $P_p^{\{Y_2\}_{c_1}}$ is the state with the mass 4450 MeV and $J^P = \frac{5}{2}^+$, measured recently by the LHCb [1]. The symbols $\mathcal{B}$ and $\mathcal{C}$ represent the flavor-antitriplet b-baryons with the light-quark spin $j^P = 0^+$, and the flavor-sextet b-baryons with $j^P = 1^+$, respectively. The corresponding $\Delta S = 0$ transitions are given in Table IX. Those involving pentaquarks with $\mathcal{P}^{1/2^+}$ are given in Tables X (for $\Delta S = 1$ transitions), and in Table XI (for $\Delta S = 0$ transitions).

This paper is organized as follows. In section II, we work out the pentaquark mass spectrum with a hidden $c\bar{c}$ component and having $J^P = 1/2^\pm$, using the effective Hamiltonian [9]. Numerical estimates of the pentaquark masses are given in section III. In section IV, we present the weak decays of the b-baryons, into a pseudoscalar meson and a pentaquark state with $\mathcal{P}^{1/2^\pm}$. We conclude in section V with a discussion of the $J = \frac{1}{2}$ pentaquark decays and the various corresponding meson-baryon thresholds.

II. EFFECTIVE HAMILTONIAN FRAMEWORK FOR PENTAQUARK SPECTRUM

Assuming that the underlying structure of the pentaquarks is given by $\bar{c}[cq][q'q'']$, we calculate the mass spectrum of these states by extending the effective Hamiltonian proposed for the tetraquark spectroscopy by Maiani *et al.* [13]. The resulting Hamiltonian for pentaquarks is [9]

$$H = H_{[\mathcal{Q}\mathcal{Q}']} + H_{\bar{c}[\mathcal{Q}\mathcal{Q}']} + H_{S_\mathcal{P} L_\mathcal{P}} + H_{L_\mathcal{P} L_\mathcal{P}}, \tag{1}$$

where $\mathcal{Q}$ and $\mathcal{Q}'$ denote the diquarks $[cq]$ and $[q'q'']$ having masses $m_\mathcal{Q}$ and $m_{\mathcal{Q}'}$, respectively. The individual terms in the Hamiltonian (1) are

$$H_{[\mathcal{Q}\mathcal{Q}']} = m_\mathcal{Q} + m_{\mathcal{Q}'} + H_{SS}(\mathcal{Q}\mathcal{Q}') + H_{SL}(\mathcal{Q}\mathcal{Q}') + H_{LL}(\mathcal{Q}\mathcal{Q}'),\ H_{S_\mathcal{P} L_\mathcal{P}} = 2A_\mathcal{P}(\mathbf{S}_\mathcal{P}\cdot\mathbf{L}_\mathcal{P}),\ H_{L_\mathcal{P} L_\mathcal{P}} = B_\mathcal{P}\frac{L_\mathcal{P}(L_\mathcal{P}+1)}{2}, \tag{2}$$

with

$$H_{SS}(\mathcal{Q}\mathcal{Q}') = 2(\mathcal{K}_{cq})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_q) + 2(\mathcal{K}_{q'q''})_{\bar{3}}(\mathbf{S}_{q'}\cdot\mathbf{S}_{q''}), \tag{3}$$

$$H_{\bar{c}[\mathcal{Q}\mathcal{Q}']} = m_c + 2\,\mathcal{K}_{\bar{c}c}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_c) + 2\mathcal{K}_{\bar{c}q}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_q) + 2\mathcal{K}_{\bar{c}q'}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_{q'}) + 2\mathcal{K}_{\bar{c}q''}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_{q''}). \tag{4}$$

$L_\mathcal{P}$ and $S_\mathcal{P}$ are the orbital angular momentum and the spin of the pentaquark state, and the quantities $A_\mathcal{P}$ and $B_\mathcal{P}$ indicate the strength of their spin-orbit and orbital angular momentum couplings, respectively. The values of diquark masses and that of $A_{\mathcal{P}}$ and $B_{\mathcal{P}}$ are given in ref. [9]. The parameters $(\mathcal{K}_{cq})_{\bar{3}}$ and $(\mathcal{K}_{q'q''})_{\bar{3}}$ correspond to the couplings of spin-spin interactions between the quarks within the diquarks. The other terms that correspond to the spin and orbital angular momentum couplings of the tetraquark are

$$H_{SL}(\mathcal{Q}\mathcal{Q}') = 2A_{\mathcal{Q}\mathcal{Q}'}\mathbf{S}_{\mathcal{Q}\mathcal{Q}'}\cdot\mathbf{L}_{\mathcal{Q}\mathcal{Q}'}, \quad H_{LL} = B_{\mathcal{Q}\mathcal{Q}'}\frac{L_{\mathcal{Q}\mathcal{Q}'}(L_{\mathcal{Q}\mathcal{Q}'}+1)}{2}. \tag{5}$$

In Model II proposed by Maiani *et al.* [13], it is assumed that the quarks in a diquark are tightly bound, and only their spin-spin coupling is kept, whereas in their earlier model [10] (called Model 1), the couplings among the quarks of the two diquarks were also included. This amounts to adding four additional spin-spin terms in the $H_{SS}(\mathcal{Q}\mathcal{Q}')$ part of Hamiltonian given in Eq. (3).

$$H_{SS}(\mathcal{Q}\mathcal{Q}') = 2(\mathcal{K}_{cq})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_q)+2(\mathcal{K}_{q'q''})_{\bar{3}}(\mathbf{S}_{q'}\cdot\mathbf{S}_{q''})+2(\mathcal{K}_{cq'})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_{q'})+2(\mathcal{K}_{cq''})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_{q''})+2(\mathcal{K}_{qq'})_{\bar{3}}(\mathbf{S}_q\cdot\mathbf{S}_{q'})+2(\mathcal{K}_{qq''})_{\bar{3}}(\mathbf{S}_q\cdot\mathbf{S}_{q''}). \tag{6}$$

We have taken all the couplings to be positive.

The mass formula for the pentaquark state which contains a ground state tetraquark ($L_{\mathcal{Q}\mathcal{Q}'} = 0$) can be determined by the following formula

$$M = M_0 + \frac{B_{\mathcal{P}}}{2}L_{\mathcal{P}}(L_{\mathcal{P}}+1) + 2A_{\mathcal{P}}\frac{J_{\mathcal{P}}(J_{\mathcal{P}}+1) - L_{\mathcal{P}}(L_{\mathcal{P}}+1) - S_{\mathcal{P}}(S_{\mathcal{P}}+1)}{2} + \Delta M, \tag{7}$$

where $M_0 = m_{\mathcal{Q}} + m_{\mathcal{Q}'} + m_c$ and ΔM is the mass term that emerges from different spin-spin interactions.

We have classified the states in terms of the diquarks spins, $S_{\mathcal{Q}}$ and $S_{\mathcal{Q}'}$, the spin of the anti-charm quark $S_{\bar{c}} = 1/2$, the orbital angular momentum $L_{\mathcal{P}}$, and the total J of the pentaquark $|S_{\mathcal{Q}}, S_{\mathcal{Q}'}, S_{\bar{c}}, L_{\mathcal{P}}; J\rangle$:

$$\begin{aligned}
|0_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, L_{\mathcal{P}}; \frac{1}{2}\rangle_1 &= \frac{1}{2}[(\uparrow)_c(\downarrow)_q - (\downarrow)_c(\uparrow)_q][(\uparrow)_{q'}(\downarrow)_{q''} - (\downarrow)_{q'}(\uparrow)_{q''}](\uparrow)_{\bar{c}} \\
|0_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, L_{\mathcal{P}}; \frac{1}{2}\rangle_2 &= \frac{1}{\sqrt{3}}[(\uparrow)_c(\downarrow)_q - (\downarrow)_c(\uparrow)_q]\{(\uparrow)_{q'}(\uparrow)_{q''}(\downarrow)_{\bar{c}} - \frac{1}{2}[(\uparrow)_{q'}(\downarrow)_{q''} + (\downarrow)_{q'}(\uparrow)_{q''}](\uparrow)_{\bar{c}}\} \\
|1_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, L_{\mathcal{P}}; \frac{1}{2}\rangle_3 &= \frac{1}{\sqrt{3}}[(\uparrow)_{q'}(\downarrow)_{q''} - (\downarrow)_{q'}(\uparrow)_{q''}]\{(\uparrow)_c(\uparrow)_q(\downarrow)_{\bar{c}} - \frac{1}{2}[(\uparrow)_c(\downarrow)_q + (\downarrow)_c(\uparrow)_q](\uparrow)_{\bar{c}}\} \\
|1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, L_{\mathcal{P}}; \frac{1}{2}\rangle_4 &= \frac{1}{3}(\uparrow)_c(\uparrow)_q\{[(\uparrow)_{q'}(\downarrow)_{q''} + (\downarrow)_{q'}(\uparrow)_{q''}](\downarrow)_{\bar{c}} - 2(\downarrow)_{q'}(\downarrow)_{q''}(\uparrow)_{\bar{c}}\} \\
&\quad -\frac{1}{6}[(\uparrow)_c(\downarrow)_q + (\downarrow)_c(\uparrow)_q]\{2(\uparrow)_{q'}(\uparrow)_{q''}(\downarrow)_{\bar{c}} - [(\uparrow)_{q'}(\downarrow)_{q''} + (\downarrow)_{q'}(\uparrow)_{q''}](\uparrow)_{\bar{c}}\} \\
|1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, L_{\mathcal{P}}; \frac{1}{2}\rangle_5 &= \frac{1}{\sqrt{2}}(\downarrow)_c(\downarrow)_q(\uparrow)_{q'}(\uparrow)_{q''}(\uparrow)_{\bar{c}} + \frac{1}{3\sqrt{2}}(\uparrow)_c(\uparrow)_q\{[(\uparrow)_{q'}(\downarrow)_{q''} + (\downarrow)_{q'}(\uparrow)_{q''}](\downarrow)_{\bar{c}} + (\downarrow)_{q'}(\downarrow)_{q''}(\uparrow)_{\bar{c}}\} \\
&\quad -\frac{1}{3\sqrt{2}}[(\uparrow)_c(\downarrow)_q + (\downarrow)_c(\uparrow)_q]\{(\uparrow)_{q'}(\uparrow)_{q''}(\downarrow)_{\bar{c}} + [(\uparrow)_{q'}(\downarrow)_{q''} + (\downarrow)_{q'}(\uparrow)_{q''}](\uparrow)_{\bar{c}}\}.
\end{aligned} \tag{8}$$

Using $L_{\mathcal{P}} = 0$ and $L_{\mathcal{P}} = 1$ in the basis defined in Eq. (8), we have five S-wave pentaquark states for $J^P = \frac{1}{2}^-$ and five P-wave states with $J^P = \frac{1}{2}^+$, respectively. In all these states the net spin of pentaquark state $S_{\mathcal{P}} = \frac{1}{2}$.

Using the states given in Eq. (8), the mass splitting matrix ΔM is a symmetric (5×5) matrix. Denoting its elements by m_{ij} $(i, j = 1, \cdots, 5)$, their diagonal entries can be written in terms of the spin-spin couplings as follows:

$$\begin{aligned}
m_{11} &= -\frac{3}{4}((\mathcal{K}_{q'q''})_{\bar{3}} + (\mathcal{K}_{cq})_{\bar{3}}), \; m_{22} = \frac{1}{4}(-3(\mathcal{K}_{cq})_{\bar{3}} + (\mathcal{K}_{q'q''})_{\bar{3}} - 5(\mathcal{K}_{\bar{c}q'} + \mathcal{K}_{\bar{c}q''})), \\
m_{33} &= \frac{1}{4}(-3(\mathcal{K}_{q'q''})_{\bar{3}} + (\mathcal{K}_{cq})_{\bar{3}} - \frac{5}{3}(\mathcal{K}_{\bar{c}q'} + \mathcal{K}_{\bar{c}c})), \\
m_{44} &= \frac{1}{4}((\mathcal{K}_{cq})_{\bar{3}} + (\mathcal{K}_{q'q''})_{\bar{3}}) - \frac{1}{36}(\mathcal{K}_{\bar{c}q} + \mathcal{K}_{\bar{c}c}) - \frac{2}{3}((\mathcal{K}_{qq'})_{\bar{3}} + (\mathcal{K}_{qq''})_{\bar{3}}) - \frac{1}{2}(\mathcal{K}_{\bar{c}q'} + \mathcal{K}_{\bar{c}q''}), \\
m_{55} &= -\frac{4}{9}(\mathcal{K}_{\bar{c}q} + \mathcal{K}_{\bar{c}c}) - \frac{5}{12}((\mathcal{K}_{cq'})_{\bar{3}} + (\mathcal{K}_{cq''})_{\bar{3}} + (\mathcal{K}_{qq'})_{\bar{3}} + (\mathcal{K}_{qq''})_{\bar{3}}) + \frac{1}{6}(\mathcal{K}_{\bar{c}q'} + \mathcal{K}_{\bar{c}q''}) + \frac{47}{72}((\mathcal{K}_{cq})_{\bar{3}} + (\mathcal{K}_{q'q''})_{\bar{3}}).
\end{aligned} \tag{9}$$

TABLE I: S (P)- wave pentaquark states $\mathcal{P}_{X_i}$ ($\mathcal{P}_{Y_i}$) and their spin- and orbital angular momentum quantum numbers. In the expressions for the masses of the $\mathcal{P}_{Y_i}$ states, $M_{\mathcal{P}_{X_i}} = M_0 + \Delta M_i$ with $i = 1, ..., 5$.

Label	$\lvert S_{\mathcal{Q}}, S_{\mathcal{Q}'}, S_{\bar{c}}, L_{\mathcal{P}}\ ; J^P\rangle_i$	Mass	Label	$\lvert S_{\mathcal{Q}}, S_{\mathcal{Q}'}, S_{\bar{c}}, L_{\mathcal{P}}\ ; J^P\rangle_i$	Mass
$\mathcal{P}_{X_1}$	$\lvert 0_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{1}{2}^-\rangle_1$	$M_0 + \Delta M_1$	$\mathcal{P}_{Y_1}$	$\lvert 0_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_1$	$M_{\mathcal{P}_{X_1}} - 2A_{\mathcal{P}} + B_{\mathcal{P}}$
$\mathcal{P}_{X_2}$	$\lvert 0_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{1}{2}^-\rangle_2$	$M_0 + \Delta M_2$	$\mathcal{P}_{Y_2}$	$\lvert 0_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_2$	$M_{\mathcal{P}_{X_2}} - 2A_{\mathcal{P}} + B_{\mathcal{P}}$
$\mathcal{P}_{X_3}$	$\lvert 1_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{1}{2}^-\rangle_3$	$M_0 + \Delta M_3$	$\mathcal{P}_{Y_3}$	$\lvert 1_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_3$	$M_{\mathcal{P}_{X_3}} - 2A_{\mathcal{P}} + B_{\mathcal{P}}$
$\mathcal{P}_{X_4}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{1}{2}^-\rangle_4$	$M_0 + \Delta M_4$	$\mathcal{P}_{Y_4}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_4$	$M_{\mathcal{P}_{X_4}} - 2A_{\mathcal{P}} + B_{\mathcal{P}}$
$\mathcal{P}_{X_5}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{1}{2}^-\rangle_5$	$M_0 + \Delta M_5$	$\mathcal{P}_{Y_5}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_5$	$M_{\mathcal{P}_{X_5}} - 2A_{\mathcal{P}} + B_{\mathcal{P}}$

TABLE II: S (P)- wave pentaquark states $\mathcal{P}_{X_i}$ ($\mathcal{P}_{Y_i}$) and their spin- and orbital angular momentum quantum numbers. In the expressions for the masses of the $\mathcal{P}_{Y_i}$ states, the terms $M_{\mathcal{P}_{X_i}} = M_0 + \Delta M_i$ with $i = 6, \cdots, 9$. The ΔM_i are values of the 4×4 matrix given in [9] (c.f. Eq. (10)).

Label	$\lvert S_{\mathcal{Q}}, S_{\mathcal{Q}'}, S_{\bar{c}}, L_{\mathcal{P}}\ ; J^P\rangle_i$	Mass	Label	$\lvert S_{\mathcal{Q}}, S_{\mathcal{Q}'}, S_{\bar{c}}, L_{\mathcal{P}}\ ; J^P\rangle_i$	Mass
$\mathcal{P}_{X_6}$	$\lvert 0_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{3}{2}^-\rangle_6$	$M_0 + \Delta M_6$	$\mathcal{P}_{Y_6}$	$\lvert 0_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_6$	$M_{\mathcal{P}_{X_6}} - 5A_{\mathcal{P}} + B_{\mathcal{P}}$
$\mathcal{P}_{X_7}$	$\lvert 1_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{3}{2}^-\rangle_7$	$M_0 + \Delta M_7$	$\mathcal{P}_{Y_7}$	$\lvert 1_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_7$	$M_{\mathcal{P}_{X_7}} - 5A_{\mathcal{P}} + B_{\mathcal{P}}$
$\mathcal{P}_{X_8}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{3}{2}^-\rangle_8$	$M_0 + \Delta M_8$	$\mathcal{P}_{Y_8}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_8$	$M_{\mathcal{P}_{X_8}} - 5A_{\mathcal{P}} + B_{\mathcal{P}}$
$\mathcal{P}_{X_9}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 0; \frac{3}{2}^-\rangle_9$	$M_0 + \Delta M_9$	$\mathcal{P}_{Y_9}$	$\lvert 1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{1}{2}^+\rangle_9$	$M_{\mathcal{P}_{X_9}} - 5A_{\mathcal{P}} + B_{\mathcal{P}}$

Similarly, the off-diagonal entries take the form

$$
\begin{aligned}
m_{12} &= -\frac{3}{4\sqrt{3}}(\mathcal{K}_{\bar{c}q'} - \mathcal{K}_{\bar{c}q''}), \quad m_{13} = -\frac{3}{4\sqrt{3}}(\mathcal{K}_{\bar{c}c} - \mathcal{K}_{\bar{c}q}), \quad m_{14} = \frac{1}{4}((\mathcal{K}_{cq'})_{\bar{3}} - (\mathcal{K}_{cq''})_{\bar{3}} + (\mathcal{K}_{qq'})_{\bar{3}} - (\mathcal{K}_{qq''})_{\bar{3}}), \\
m_{15} &= -\frac{1}{2\sqrt{2}}((\mathcal{K}_{cq'})_{\bar{3}} - (\mathcal{K}_{cq''})_{\bar{3}} + (\mathcal{K}_{qq'})_{\bar{3}} - (\mathcal{K}_{qq''})_{\bar{3}}), \quad m_{23} = \frac{1}{4}((\mathcal{K}_{cq'})_{\bar{3}} + (\mathcal{K}_{cq''})_{\bar{3}} - (\mathcal{K}_{qq'})_{\bar{3}} - (\mathcal{K}_{qq''})_{\bar{3}}), \\
m_{24} &= -\frac{5}{6\sqrt{3}}((\mathcal{K}_{cq'})_{\bar{3}} + (\mathcal{K}_{cq''})_{\bar{3}} - (\mathcal{K}_{qq'})_{\bar{3}} - (\mathcal{K}_{qq''})_{\bar{3}}), \\
m_{25} &= -\frac{1}{2\sqrt{6}}(2\mathcal{K}_{\bar{c}c} - 2\mathcal{K}_{\bar{c}q} - (\mathcal{K}_{cq'})_{\bar{3}} - (\mathcal{K}_{cq''})_{\bar{3}} + (\mathcal{K}_{qq'})_{\bar{3}} + (\mathcal{K}_{qq''})_{\bar{3}}), \\
m_{34} &= -\frac{5}{6\sqrt{3}}((\mathcal{K}_{cq'})_{\bar{3}} + (\mathcal{K}_{cq''})_{\bar{3}} - (\mathcal{K}_{qq'})_{\bar{3}} - (\mathcal{K}_{qq''}))_{\bar{3}}), \\
m_{35} &= \frac{1}{2\sqrt{6}}(2\mathcal{K}_{\bar{c}q'} - 2\mathcal{K}_{\bar{c}q''} + (\mathcal{K}_{cq'})_{\bar{3}} + (\mathcal{K}_{cq''})_{\bar{3}} - (\mathcal{K}_{qq'})_{\bar{3}} + (\mathcal{K}_{qq''})_{\bar{3}}), \\
m_{45} &= \frac{1}{\sqrt{2}}(-\frac{2}{9}(\mathcal{K}_{\bar{c}q} + \mathcal{K}_{\bar{c}c}) + \frac{1}{6}((\mathcal{K}_{cq'})_{\bar{3}} + (\mathcal{K}_{cq''})_{\bar{3}}) + \frac{1}{6}((\mathcal{K}_{qq'})_{\bar{3}} + (\mathcal{K}_{qq''})_{\bar{3}})). \qquad (10)
\end{aligned}
$$

From the above expressions, given for Model I, one obtains the expressions for Model II [13] by setting the couplings $(\mathcal{K}_{cq'})_{\bar{3}}$, $(\mathcal{K}_{cq''})_{\bar{3}}$, $(\mathcal{K}_{qq'})_{\bar{3}}$ to zero. In Table I, ΔM_i (i runs from 1 to 5) are the mass splitting terms that arise after the diagonalization of the 5×5 matrix whose entries are given in Eqs. (9) and (10). In addition to this, there are four $J^p = \frac{1}{2}^+$ states, which result on combining the spin $S_{\mathcal{P}} = \frac{3}{2}$ with the orbital angular momentum $L_{\mathcal{P}} = 1$. In these state the value of $A_{\mathcal{P}}(\mathbf{S}_{\mathcal{P}} \cdot \mathbf{L}_{\mathcal{P}})$ is $-5A_{\mathcal{P}}$ and these are listed in Table II.

III. S- AND P-WAVE PENTAQUARK SPECTRUM WITH $J^P = \frac{1}{2}^\pm$

In this section, we present the mass spectrum for the pentaquarks with a $c\bar{c}$ and three light quarks, having $J^P = \frac{1}{2}^\pm$. The mass spectrum of some of the states with $J^P = \frac{1}{2}^\pm$ has already been calculated using QCD sum rules [14–16]. The determination of the various input parameters is explained in [9] and for one particular case when the contents

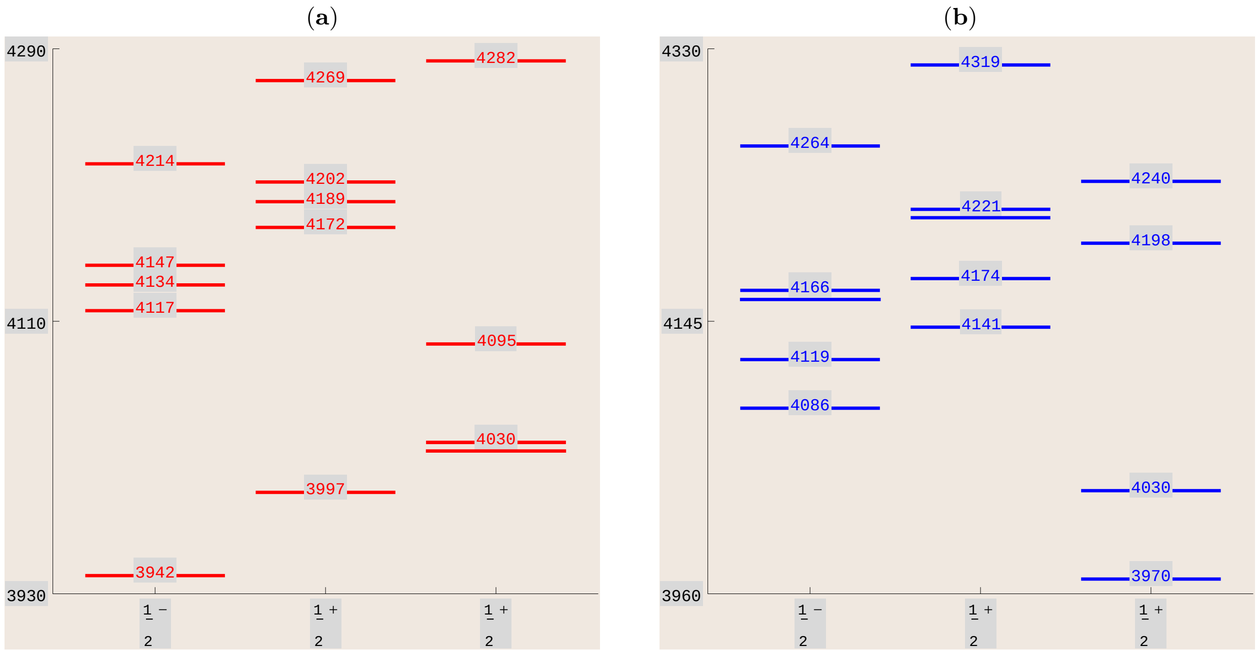

FIG. 1: The mass spectrum (in MeV) of the lowest S- and P-wave pentaquark states in the diquark-diquark-antiquark picture for the charmonium sector using the tetraquark type I (a) and II (b) models having the quark flavor $\bar{c}[cq][qq]$, denoted as c_1 in Tab. III. Note that the doubly drawn lines indicate states which are (almost) mass degenerate.

TABLE III: Quark flavor contents of the pentaquarks (with $q = u$ or d) arranged as $\bar{c}$ and two diquarks, and the corresponding flavor labels c_i $(i = 1, ..., 5)$ used to characterize these states in the text.

Quark contents	$\bar{c}[cq][qq]$	$\bar{c}[cq][sq]$	$\bar{c}[cs][qq]$	$\bar{c}[cs][sq]$	$\bar{c}[cq][ss]$
Label	c_1	c_2	c_3	c_4	c_5

of pentaquark state is $\{\bar{c}\ [cq]\ [qq]; L_{\mathcal{P}} = 0, 1\}$ with $q = u\ , d$ the spectrum is shown in Fig. 1. The five S-wave states have $J^P = 1/2^-$ (left-most group), and the two groups having $J^P = 1/2^+$ are the P-wave states, defined in Table I (shown in the middle of the frame) and in Table II (shown as the right-most group).

For all the other possibilities of the light quark contents given in Table III, the values of the estimated masses of the $J^P = \frac{1}{2}^{\pm}$ are presented in Tables V - VII. In order to calculate these spectra, the corresponding values of ΔM_i for $i = 1, \cdots, 9$, obtained on diagonalizing the symmetric 5×5 matrix whose entries are given in Eqs. (9) and (10), for $i = 1, \cdots, 5$, and the 4×4 matrix given in [9] (c.f. Eq. (10)), for $i = 6, \cdots, 9$, are mentioned in Table IV.

TABLE IV: Numerical value of ΔM_i (in MeV) for $i = 1, \cdots, 9$ for the five different light quark combinations given in Table III.

ΔM_i	ΔM_1	ΔM_2	ΔM_3	ΔM_4	ΔM_5	ΔM_6	ΔM_7	ΔM_8	ΔM_9
c_1	-278 (-126)	-95 (-93)	-78 (-50)	-65 (-46)	2 (52)	-79 (-140)	-79 (-79)	-15 (88)	175 (130)
c_2	-224 (-98)	-96 (-64)	-55 (-60)	-53 (-58)	-24 (28)	-77 (-161)	-54 (-20)	-1 (70)	132 (111)
c_3	-182 (-126)	-96 (-93)	-87 (-50)	-40 (-46)	-15 (52)	-79 (-140)	-54 (-79)	-17 (88)	134 (130)
c_4	-252 (-98)	-111 (-64)	-49 (-60)	-49 (-58)	-16 (28)	-111 (-161)	-42 (-20)	10 (70)	144 (111)
c_5	-186 (-144)	-112 (-110)	-97 (-45)	-34 (-42)	-4 (67)	-112 (-131)	-44 (-112)	13 (102)	145 (143)

TABLE V: Masses of the hidden charm S-wave pentaquark states $\mathcal{P}_{X_i}$ (in MeV) formed through different diquark-diquark-anti-charm quark combinations in type I and type II models of tetraquarks. The masses given in the parentheses are for the input values taken from the type II model and the quoted errors are obtained from the uncertainties in the input parameters in the effective Hamiltonian.

$\mathcal{P}_{X_i}$	$\mathcal{P}_{X_1}$	$\mathcal{P}_{X_2}$	$\mathcal{P}_{X_3}$	$\mathcal{P}_{X_4}$	$\mathcal{P}_{X_5}$
c_1	3942 ± 72 (4086 ± 42)	4117 ± 42 (4119 ± 42)	4134 ± 38 (4162 ± 38)	4147 ± 38 (4166 ± 38)	4214 ± 45 (4264 ± 41)
c_2	3967 ± 55 (4094 ± 44)	4096 ± 46 (4128 ± 44)	4137 ± 44 (4132 ± 43)	4139 ± 43 (4134 ± 42)	4168 ± 44 (4220 ± 43)
c_3	4262 ± 48 (4318 ± 42)	4348 ± 41 (4351 ± 42)	4357 ± 39 (4392 ± 38)	4404 ± 39 (4398 ± 38)	4429 ± 40 (4496 ± 41)
c_4	4172 ± 48 (4326 ± 44)	4313 ± 44 (4360 ± 43)	4375 ± 43 (4364 ± 43)	4375 ± 43 (4366 ± 43)	4408 ± 44 (4452 ± 43)
c_5	4522 ± 51 (4564 ± 44)	4596 ± 44 (4598 ± 44)	4611 ± 43 (4662 ± 43)	4674 ± 43 (4666 ± 43)	4704 ± 43 (4775 ± 44)

TABLE VI: Masses of the hidden charm P-wave pentaquark states $\mathcal{P}_{Y_i}$ (in MeV) formed through different diquark-diquark-anti-charm quark combinations in type I and type II models of tetraquarks. The masses given in the parentheses are for the input values taken from the type II model and the quoted errors are obtained from the uncertainties in the input parameters in the effective Hamiltonian.

$\mathcal{P}_{Y_i}$	$\mathcal{P}_{Y_1}$	$\mathcal{P}_{Y_2}$	$\mathcal{P}_{Y_3}$	$\mathcal{P}_{Y_4}$	$\mathcal{P}_{Y_5}$
c_1	3997 ± 73 (4141 ± 44)	4172 ± 44 (4174 ± 44)	4189 ± 40 (4217 ± 40)	4202 ± 39 (4221 ± 40)	4269 ± 47 (4319 ± 43)
c_2	4023 ± 56 (4149 ± 45)	4151 ± 47 (4183 ± 45)	4192 ± 45 (4187 ± 44)	4194 ± 45 (4189 ± 44)	4223 ± 46 (4275 ± 45)
c_3	4317 ± 50 (4373 ± 44)	4403 ± 43 (4406 ± 44)	4412 ± 41 (4449 ± 40)	4459 ± 41 (4453 ± 40)	4484 ± 42 (4551 ± 43)
c_4	4227 ± 50 (4381 ± 45)	4368 ± 45 (4415 ± 45)	4430 ± 45 (4419 ± 44)	4430 ± 45 (4421 ± 44)	4463 ± 45 (4507 ± 45)
c_5	4577 ± 52 (4619 ± 45)	4651 ± 45 (4653 ± 45)	4666 ± 44 (4717 ± 44)	4729 ± 44 (4721 ± 44)	4759 ± 45 (4830 ± 45)

IV. PRODUCTION OF $J^P(\frac{1}{2}^{\pm})$ PENTAQUARK STATES IN THE WEAK DECAYS OF THE b-BARYONS

The possible production of these charmed pentaquark states is possible through the weak decays of b-baryon. The effective weak Hamiltonian inducing $b \to c\bar{c}q$ transition:

$$H_{\text{eff}}^{W} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V_{cb}V_{cq}^{*} \left(C_1\, O_1^{(q)} + C_2\, O_2^{(q)}\right), \tag{11}$$

with q being s and d quarks correspond to the Cabibbo-allowed $\Delta I = 0$, $\Delta S = -1$ and the Cabibbo-suppressed $\Delta I = -1/2$, $\Delta S = 0$ transitions, respectively. In Eq. (11), G_F is the Fermi coupling constant, V_{ij} are the CKM

TABLE VII: Masses of the hidden charm P-wave pentaquark states $\mathcal{P}_{Y_i}$ (in MeV) formed through different diquark-diquark-anti-charm quark combinations in type I and type II models of tetraquarks. These states are obtained by combining the spin $\frac{3}{2}$ of pentaquark with $L = 1$ to have the final pentaquark states with $J^P = \frac{1}{2}^{+}$. The masses given in the parentheses are for the input values taken from the type II model and the quoted errors are obtained from the uncertainties in the input parameters in the effective Hamiltonian.

$\mathcal{P}_{Y_i}$	$\mathcal{P}_{Y_6}$	$\mathcal{P}_{Y_7}$	$\mathcal{P}_{Y_8}$	$\mathcal{P}_{Y_9}$
c_1	4030 ± 62 (3970 ± 50)	4030 ± 62 (4030 ± 62)	4095 ± 63 (4198 ± 50)	4282 ± 63 (4240 ± 50)
c_2	4012 ± 65 (3929 ± 53)	4036 ± 56 (4069 ± 56)	4088 ± 61 (4159 ± 53)	4222 ± 56 (4201 ± 52)
c_3	4263 ± 62 (4202 ± 50)	4288 ± 52 (4262 ± 63)	4341 ± 57 (4430 ± 50)	4475 ± 52 (4472 ± 50)
c_4	4210 ± 56 (4161 ± 53)	4279 ± 54 (4301 ± 56)	4332 ± 60 (4391 ± 53)	4465 ± 55 (4433 ± 52)
c_5	4493 ± 56 (4474 ± 53)	4561 ± 54 (4493 ± 56)	4618 ± 59 (4707 ± 53)	4750 ± 55 (4748 ± 52)

TABLE VIII: Estimate of the ratios of decay widths $\Gamma(\mathcal{B}(\mathcal{C}) \to \mathcal{P}^{1/2^-}\mathcal{M})/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$ for $\Delta S = 1$ transitions by using the masses of pentaquark states $\mathcal{P}_{X_3}^{c_i}$ worked out in this work. Here $P_p^{\{Y_2\}_{c_1}}$ is the state with mass 4450 MeV and $J^P = \frac{5}{2}^+$ that has been measured recently at the LHCb [1].

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$
$\Lambda_b \to P_p^{\{X_3\}_{c_1}} K^-$	0.61	$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \bar{K}^0$	0.83
$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \bar{K}^0$	0.61	$\Xi_b^0 \to P_{\Sigma^+}^{\{X_3\}_{c_2}} K^-$	0.83
$\Lambda_b \to P_{\Lambda^0}^{\{X_3\}_{c_3}} \eta'$	0.04	$\Lambda_b \to P_{\Lambda^0}^{\{X_3\}_{c_3}} \eta$	0.08
$\Xi_b^- \to P_{\Sigma^0}^{\{X_3\}_{c_2}} K^-$	1	$\Xi_b^- \to P_{\Lambda^0}^{\{X_3\}_{c_2}} K^-$	0.10
$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_4\}_{c_5}} \bar{K}^0$	0.3	$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_4\}_{c_5}} K^-$	0.3

matrix elements, and C_i are the Wilson coefficients of the four-quark operators $O_i^{(q)}$ $(q = d,\ s)$, defined as

$$O_1^{(q)} = (\bar{q}_\alpha c_\beta)_{V-A}(\bar{c}_\alpha b_\beta)_{V-A}, \quad O_2^{(q)} = (\bar{q}_\alpha c_\alpha)_{V-A}(\bar{c}_\beta b_\beta)_{V-A}, \tag{12}$$

where $(\bar{q}_\alpha q'_\beta)_{V-A} = [\bar{q}_\alpha \gamma_\mu (1-\gamma_5)\, q'_\beta]$ are the left handed charged currents, α and β are $SU(3)_C$ color indices.

The amplitude corresponding to the decay of b-baryon from the flavor anti-triplet and sextet according to the $SU(3)_F$-group, denoted by $\mathcal{B}$ and $\mathcal{C}$, respectively, into pentaquark state from the $SU(3)_F$ octet ($\mathcal{P}$) along with a light pseudoscalar meson ($\mathcal{M}$) can be written as

$$\mathcal{A} = \left\langle \mathcal{P}\mathcal{M} \left| H_{\text{eff}}^W \right| \mathcal{B}(\mathcal{C}) \right\rangle, \tag{13}$$

where H_{eff}^W is defined in Eq. (11). In (13), $\mathcal{B}$ is a flavor anti-triplet b-baryon with the light-quark spin $j^P = 0^+$. The explicit expressions of $\mathcal{B}$, a light pseudoscalar meson in the $SU(3)_F$ octet $\mathcal{M}$ and the final state pentaquark $\mathcal{P}$ are given in [9].

In the limit of heavy quark symmetry, the tree amplitudes for the anti-triplet b-baryon decays into an octet pentaquark and a pseudoscalar meson can be decomposed as follows ($q = d$ or s) [9]:

$$\mathcal{A}_{t8}^J(q) \;=\; T_3^J \left\langle \mathcal{P}_k^i \mathcal{M}_j^k \left| H(\bar{3})^j \right| \mathcal{B}_{lm} \right\rangle \varepsilon^{ilm} + T_5^J \left\langle \mathcal{P}_{j'}^l \mathcal{M}_j^i \left| H(\bar{3})^j \right| \mathcal{B}_{mj'} \right\rangle \varepsilon_{ilm}, \tag{14}$$

where the superscript J represents the spin of the final-state pentaquark, $J = \frac{1}{2}$. The Feynman diagrams corresponding to the above amplitudes are shown in Fig. 7 [9]. Similarly, in the case of the sextet b-baryons from $\mathcal{C}_{ij}(6)$ decaying into decuplet pentaquark states from $\mathcal{P}_{ijk}$, the decay amplitude in the heavy quark symmetry approximation can be written in the form ($q = d$ or s):

$$\mathcal{A}_{t10}^J(q) = T_5^{s\,J} \left\langle \mathcal{P}_{kj'm} \mathcal{M}_l^k \left| H(\bar{3})^l \right| \mathcal{C}_{mj'} \right\rangle. \tag{15}$$

where $\mathcal{C}_{ij}(6)$ and decuplet $\mathcal{P}_{ijk}$ (symmetric in all indices) are listed in [9].

With these amplitudes, the estimates of the ratios of decay widths $\Gamma(\mathcal{B}(\mathcal{C}) \to \mathcal{P}^{1/2^\pm}\mathcal{M})/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$, where $P_p^{\{Y_2\}_{c_1}}$ is the measured state with the mass 4450 MeV and $J^P = \frac{5}{2}^+$, are given in Tables VIII - XI.

V. DECAYS OF $J = \frac{1}{2}$ PENTAQUARK STATES AND CORRESPONDING THRESHOLDS

The pentaquark states discussed here can be produced through the decays of the b-baryons, and they decay further into stable baryons and mesons. The mass of the $J = \frac{1}{2}$ pentaquark state having the flavor content of a proton (p)

TABLE IX: Estimate of the ratios of the decay widths $\Gamma(\mathcal{B}(\mathcal{C}) \to \mathcal{P}^{1/2^-}\mathcal{M})/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$, where $P_p^{\{Y_2\}_{c_1}}$ is a state with mass 4450 MeV that has recently been measured at LHCb [1], for $\Delta S = 0$ transitions. In comparison to the $\Delta S = 1$ transitions, these transitions are suppressed by a factor $|V_{cd}^*/V_{cs}^*|^2$. Other input values are the same as in Table VIII.

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$
$\Lambda_b \to P_p^{\{X_3\}_{c_1}} \pi^-$	0.04	$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \pi^0$	0.02
$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \eta$	0.01	$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \eta'$	0
$\Xi_b^- \to P_{\Xi^-}^{\{X_3\}_{c_4}} K^0$	0.03	$\Xi_b^- \to P_{\Sigma^0}^{\{X_3\}_{c_2}} \pi^-$	0.01
$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \eta$	0.01	$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \eta'$	0.01
$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \pi^0$	0.02	$\Xi_b^0 \to P_{\Sigma^0}^{\{X_3\}_{c_2}} \pi^0$	0.01
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_3\}_{c_2}} \eta$	0	$\Xi_b^0 \to P_{\Lambda^0}^{\{X_3\}_{c_2}} \eta'$	0
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_3\}_{c_2}} \pi^0$	0.01	$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_3\}_{c_5}} \pi^0$	0.01
$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_4\}_{c_5}} \pi^-$	0.02		

TABLE X: Estimate of the ratios of decay widths $\Gamma(\mathcal{B}(\mathcal{C}) \to \mathcal{P}^{1/2^+}\mathcal{M})/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$ for $\Delta S = 1$ transitions by using the masses of pentaquark states $\mathcal{P}_{Y_3}^{c_i}$ worked out in this work. Here $P_p^{\{Y_2\}_{c_1}}$ is the state with mass 4450 MeV and $J^P = \frac{5}{2}^+$ that has been measured recently at the LHCb [1].

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$
$\Lambda_b \to P_p^{\{X_3\}_{c_1}} K^-$	0.39	$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \bar{K}^0$	0.43
$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \bar{K}^0$	0.39	$\Xi_b^0 \to P_{\Sigma^+}^{\{X_3\}_{c_2}} K^-$	0.43
$\Lambda_b \to P_{\Lambda^0}^{\{X_3\}_{c_3}} \eta'$	0.07	$\Lambda_b \to P_{\Lambda^0}^{\{X_3\}_{c_3}} \eta$	0.07
$\Xi_b^- \to P_{\Sigma^0}^{\{X_3\}_{c_2}} K^-$	0.3	$\Xi_b^- \to P_{\Lambda^0}^{\{X_3\}_{c_2}} K^-$	0.1
$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_4\}_{c_5}} \bar{K}^0$	0.29	$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_4\}_{c_5}} K^-$	0.29

and a J/ψ, denoted by $P_p^{\{X_3\}_{c_1}}$, is estimated as 4134 ± 38 MeV. The error arise from the ranges of the different input parameters in the effective Hamiltonian framework, assuming that the parameters subsume the essential underlying physics. Within this framework, the nominal mass of $P_p(4134)$ is about 100 MeV above the $J/\psi\, p$ threshold, 4035 MeV [17]. If the mass of $P_p^{\{X_3\}_{c_1}}$ is indeed higher than the $J/\psi\, p$ threshold, as anticipated here, then it can be

TABLE XI: Estimate of the ratios of the decay widths $\Gamma(\mathcal{B}(\mathcal{C}) \to \mathcal{P}^{1/2^+}\mathcal{M})/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$, where $P_p^{\{Y_2\}_{c_1}}$ is a state with mass 4450 MeV that has recently been measured at LHCb [1], for $\Delta S = 0$ transitions. In comparison to the $\Delta S = 1$ transitions, these transitions are suppressed by a factor $|V_{cd}^*/V_{cs}^*|^2$. Other input values are the same as in Table X.

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{Y_2\}_{c_1}} K^-)$
$\Lambda_b \to P_p^{\{X_3\}_{c_1}} \pi^-$	0.02	$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \pi^0$	0.02
$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \eta$	0.01	$\Lambda_b \to P_n^{\{X_3\}_{c_1}} \eta'$	0
$\Xi_b^- \to P_{\Xi^-}^{\{X_3\}_{c_4}} K^0$	0.02	$\Xi_b^- \to P_{\Sigma^0}^{\{X_3\}_{c_2}} \pi^-$	0.01
$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \eta$	0.01	$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \eta'$	0
$\Xi_b^- \to P_{\Sigma^-}^{\{X_3\}_{c_2}} \pi^0$	0.01	$\Xi_b^0 \to P_{\Sigma^0}^{\{X_3\}_{c_2}} \pi^0$	0.01
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_3\}_{c_2}} \eta$	0	$\Xi_b^0 \to P_{\Lambda^0}^{\{X_3\}_{c_2}} \eta'$	0
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_3\}_{c_2}} \pi^0$	0	$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_3\}_{c_5}} \pi^0$	0.00
$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_4\}_{c_5}} \pi^-$	0.01		

observed in the future by the LHCb in the $J/\psi\, p$ channel. If not, this state may lie just below the $J/\psi\, p$ threshold, and the channel to look for is the $(J/\psi)^*\, p$ where the virtual $(J/\psi)^*$ decays, among other states, to the dileptons $\mu^+\mu^-$ and e^+e^-. There is another possible decay of the state $P_p^{\{X_3\}_{c_1}}$, $P_p^{\{X_3\}_{c_1}}(4134) \to \eta_c\, p$, which has the threshold of 3963 MeV [17].

Similarly, in the case of the pentaquark $P_{\Lambda^0(\Sigma^0)}^{\{X_3\}_{c_2}}$, which could be produced in the decays of Ξ_b^- along with a π^-, the mass estimated here is 4137 ± 44 MeV. The nominal mass of this state is below the corresponding threshold for $J/\psi\, \Lambda^0(\Sigma^0)$ which is around 4211 (4290) MeV [17]. Thus, the final states to look for are $(J/\psi)^*\, \Lambda^0(\Sigma^0)$, where the virtual $(J/\psi)^*$ is measured in the $\mu^+\mu^-$ and e^+e^- modes. However, the state with the same overall quark flavor quantum numbers $P_{\Lambda^0(\Sigma^0)}^{\{X_3\}_{c_3}}$ (see Table III) is estimated to have the mass 4357 ± 39 MeV. This can be produced along with an η_8 in the decays of Λ_b^0 through $\Delta S = 1$ transitions. This lies above the $J/\psi\, \Lambda^0(\Sigma^0)$ threshold by almost 120 (70) MeV [17]. Therefore, there is a possibility to observe this state in the Λ_b^0 decays. Again, if the mass of this state turns out to be below the stated thresholds, then the search decay modes are $P_c^+(J^P = 1/2^\pm) \to \eta_c\, \Lambda^0(\Sigma^0)$, $\mu^+\mu^-\ \Lambda^0(\Sigma^0)$, $e^+e^-\ \Lambda^0(\Sigma^0)$.

In the case of the decays $\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_3\}_{c_5}}\pi^0$ and $\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_4\}_{c_5}}K^-$, which are $\Delta S = 0$ and $\Delta S = 1$ transitions, respectively, the masses of the $P_{\Xi_{10}^0}^{\{X_4\}_{c_5}}$ and $P_{\Xi_{10}^-}^{\{X_3\}_{c_5}}$ are estimated to be significantly above the $(\Xi_{10}\ J/\psi)$-threshold. Thus, there exist exciting possibilities to search for spin-1/2 pentaquarks in various b-baryon decays at the LHCb.

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