Heavy Quark Symmetry and Hidden Charm Pentaquarks

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[arXiv:1607.00987] in collaboration with:

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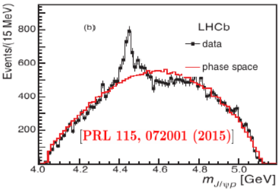
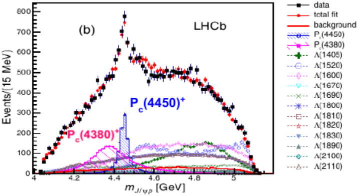
- **Introduction**
- **Closer look at the data on Λ_b^0 decays**
- **Heavy quark symmetry and observed pentaquarks**
- **Spectrum: $\bar{c}[cq][q'q'']$ with $q, q', q'' \in [u, d, s]$**
- **Weak decays of the *b*-baryons into pentaquark states**
- **Summary**

Introduction

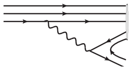
$P_c^+(4380)$ and $P_c^+(4450)$: $pp \to b\bar{b} \to \Lambda_b^0\, X$, $\Lambda_b^0 \to J/\psi\; p\; K^-$, $c\bar{c}uud$
with preferred J^P: $\frac{3}{2}^-$ and $\frac{5}{2}^+$, [arXiv:1507.03414].



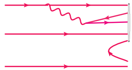


Maiani *et al.* [arXiv:1507.08252] assignments:

$$P_c^+(4450) = \{\bar{c}[cu]_{s=1}[ud]_{s=0};\, L_{\mathcal{P}} = 1,\, J^P = \frac{5}{2}^+\}$$



$$P_c^+(4380) = \{\bar{c}[cu]_{s=1}[ud]_{s=1};\, L_{\mathcal{P}} = 0,\, J^P = \frac{3}{2}^-\}$$



◇ $P = (-1)^{L+1}$, $\Delta M^{\{Meson, Baryon, X, Y, Z\}}(L: 0 \to 1) \sim 300$ MeV. The bad-diquark, $s = 1$, is heavier than good-diquark, $s = 0$, by 200 MeV.

Explains mass difference between two states of about 70 MeV.

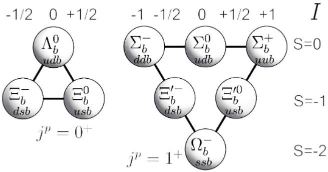
Closer look at the data on Λ_b^0 decays

K. A. Olive *et al.* (PDG), Chin. Phys. C, 38, 090001 (2014)

$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell) = (\mathbf{6.2^{+1.4}_{-1.2}})\%$ $j^P : 0^+ \to 0^+$

$\mathcal{B}(\Lambda_b^0 \to \Sigma_c^+ \ell^- \bar{\nu}_\ell) =$ **non-existent** $j^P : 0^+ \to 1^+$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^0(2455)\pi^+\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \simeq 0.1 \quad j^P : 0^+ \to 1^+$$



$$\frac{\frac{1}{2}\Gamma(\Lambda_b^0 \to \Sigma^0\pi^+\ell^-\bar{\nu}_\ell) + \frac{1}{2}\Gamma(\Lambda_b^0 \to \Sigma^{++}\pi^-\ell^-\bar{\nu}_\ell)}{\Gamma(\Lambda_b^0 \to \Lambda_c^+\ell^-\bar{\nu}_\ell)} = \mathbf{0.054 \pm 0.022^{+0.021}_{-0.018}}$$

The $\Lambda_b^0 \to \Sigma^0\pi^+\ell^-\bar{\nu}_\ell$ and $\Lambda_b^0 \to \Sigma^{++}\pi^-\ell^-\bar{\nu}_\ell$, facilitating an $\mathbf{0^+ \to 1^+}$ transition are suppressed.

In heavy quark limit, the spin of the light diquark in heavy baryons has consequences for the *b*-baryon decays i.e., constraining the states which can otherwise be produced in *b*-baryon decays.

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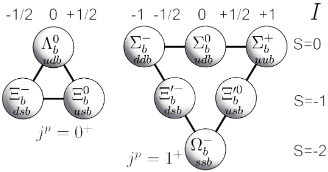

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Whether the HQS holds in *b*-baryon decays to pentaquarks? We currently lack data to test it, but it is worthwhile to work out its implications for the interpretation of the LHCb data and the pentaquark phenomenology.

Heavy quark symmetry and observed pentaquarks

Selection rules from the the data on $b \to c$ baryonic decays and so HQS.

$$P_c^+(4450) = \{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_{\mathcal{P}} = 1, J^{\mathrm{P}} = \frac{5}{2}^+\} \quad \textbf{Favored}$$

$$P_c^+(4380) = \{\bar{c}[cu]_{s=1}[ud]_{s=1}; L_{\mathcal{P}} = 0, J^{\mathrm{P}} = \frac{3}{2}^-\} \quad \textbf{Disfavored}$$

$\Longrightarrow$ $\mathbf{\frac{3}{2}^-}$ **state may be required a different interpretation**.

Look, $m[\Lambda_c^+(2625); J^P = \frac{3}{2}^-] - m[\Lambda_c^+(2286); J^P = \frac{1}{2}^+] \simeq 341$ MeV, $\Longrightarrow$ the mass of $J^P = 3/2^-$ state to be about 4110 MeV.

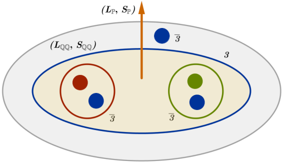
In **diquark-diquark-antiquark** spectrum, $\frac{3}{2}^-$ state is accomodated favored by HQS,

$$4130 \to \{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_{\mathcal{P}} = 0, J^{\mathrm{P}} = \frac{3}{2}^-\},$$

Third state anticipated in 4110-4130 MeV range. A renewed fit of the LHCb data by allowing a third resonance is called for.

Diquark-diquark-antiquark model

$$H_{\bar{c}[cq][q'q'']} = H_{[\mathcal{Q}\mathcal{Q}']} + H_{\bar{c}[\mathcal{Q}\mathcal{Q}']} + H_{S_{\mathcal{P}}L_{\mathcal{P}}} + H_{L_{\mathcal{P}}L_{\mathcal{P}}},$$



Diquark – Diquark – Antiquark Model of Pentaquarks

Parameters are fixed from X, Y, Z states, under the assumption that they are diquark-antidiquark states, Type-I: L. Maiani *et al.* [hep-ph/0412098], Type-II: L. Maiani *et al.* [arXiv:1405.1551].

$$
\begin{aligned}
H_{[\mathcal{Q}\mathcal{Q}']} &= m_{\mathcal{Q}} + m_{\mathcal{Q}'} + H_{SS}(\mathcal{Q}\mathcal{Q}') + H_{SL}(\mathcal{Q}\mathcal{Q}') + H_{LL}(\mathcal{Q}\mathcal{Q}'),\\
H^{\mathrm{II}}_{\bar{c}[\mathcal{Q}\mathcal{Q}']} &= m_c + 2\,\mathcal{K}_{\bar{c}c}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_c) + 2\mathcal{K}_{\bar{c}q}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_q) + 2\mathcal{K}_{\bar{c}q'}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_{q'}) + 2\mathcal{K}_{\bar{c}q''}(\mathbf{S}_{\bar{c}}\cdot\mathbf{S}_{q''})\\
H_{S_{\mathcal{P}}L_{\mathcal{P}}} &= 2A_{\mathcal{P}}(\mathbf{S}_{\mathcal{P}}\cdot\mathbf{L}_{\mathcal{P}}),\ \ H_{L_{\mathcal{P}}L_{\mathcal{P}}} = B_{\mathcal{P}}\frac{L_{\mathcal{P}}(L_{\mathcal{P}}+1)}{2},\\
H_{SS}(\mathcal{Q}\mathcal{Q}') &= 2(\mathcal{K}_{cq})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_q) + 2(\mathcal{K}_{q'q''})_{\bar{3}}(\mathbf{S}_{q'}\cdot\mathbf{S}_{q''})\\
H_{SL}(\mathcal{Q}\mathcal{Q}') &= 2A_{\mathcal{Q}\mathcal{Q}'}\mathbf{S}_{\mathcal{Q}\mathcal{Q}'}\cdot\mathbf{L}_{\mathcal{Q}\mathcal{Q}'},\ \ H_{LL} = B_{\mathcal{Q}\mathcal{Q}'}\frac{L_{\mathcal{Q}\mathcal{Q}'}(L_{\mathcal{Q}\mathcal{Q}'}+1)}{2},\\
H^{\mathrm{I}}_{\bar{c}[\mathcal{Q}\mathcal{Q}']} &= H^{\mathrm{II}}_{\bar{c}[\mathcal{Q}\mathcal{Q}']} + 2(\mathcal{K}_{cq})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_q) + 2(\mathcal{K}_{q'q''})_{\bar{3}}(\mathbf{S}_{q'}\cdot\mathbf{S}_{q''}) + 2(\mathcal{K}_{cq'})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_{q'})\\
&\quad + 2(\mathcal{K}_{cq''})_{\bar{3}}(\mathbf{S}_c\cdot\mathbf{S}_{q''}) + 2(\mathcal{K}_{qq'})_{\bar{3}}(\mathbf{S}_q\cdot\mathbf{S}_{q'}) + 2(\mathcal{K}_{qq''})_{\bar{3}}(\mathbf{S}_q\cdot\mathbf{S}_{q''})
\end{aligned}
$$

The $B_{\mathcal{P}}$ is estimated by identify $|1_{\mathcal{Q}}, 0_{\mathcal{Q}'}, 1; \frac{5}{2}^+\rangle_2$ as the pentaquark state having a mass 4450 MeV. **This yields 160 MeV and 220 MeV for $B_{\mathcal{P}}$ in type-I and -II models, respectively.**

Fifty states having masses estimated to lie in range 4100-5100 MeV.

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

Label	$\lvert S_\mathcal{Q}, S_{\mathcal{Q}'}; L_\mathcal{P}, J^P\rangle_i$	Mass	Label	$\lvert S_\mathcal{Q}, S_{\mathcal{Q}'}; L_\mathcal{P}, J^P\rangle_i$	Mass
$\mathcal{P}_{X_1}$	$\lvert 0_\mathcal{Q}, 1_{\mathcal{Q}'}, 0; \frac{3}{2}^-\rangle_1$	$M_0 + \Delta M_1$	$\mathcal{P}_{Y_1}$	$\lvert 0_\mathcal{Q}, 1_{\mathcal{Q}'}, 1; \frac{5}{2}^+\rangle_1$	$M_{\mathcal{P}_{X_1}} + 3A_\mathcal{P} + B_\mathcal{P}$
$\mathcal{P}_{X_2}$	**$\lvert 1_\mathcal{Q}, 0_{\mathcal{Q}'}, 0; \frac{3}{2}^-\rangle_2$**	$M_0 + \Delta M_2$	**$\mathcal{P}_{Y_2}$**	**$\lvert 1_\mathcal{Q}, 0_{\mathcal{Q}'}, 1; \frac{5}{2}^+\rangle_2$**	$M_{\mathcal{P}_{X_2}} + 3A_\mathcal{P} + B_\mathcal{P}$
$\mathcal{P}_{X_3}$	$\lvert 1_\mathcal{Q}, 1_{\mathcal{Q}'}, 0; \frac{3}{2}^-\rangle_3$	$M_0 + \Delta M_3$	$\mathcal{P}_{Y_3}$	$\lvert 1_\mathcal{Q}, 1_{\mathcal{Q}'}, 1; \frac{5}{2}^+\rangle_3$	$M_{\mathcal{P}_{X_3}} + 3A_\mathcal{P} + B_\mathcal{P}$
$\mathcal{P}_{X_4}$	**$\lvert 1_\mathcal{Q}, 1_{\mathcal{Q}'}, 0; \frac{3}{2}^-\rangle_4$**	$M_0 + \Delta M_4$	$\mathcal{P}_{Y_4}$	$\lvert 1_\mathcal{Q}, 1_{\mathcal{Q}'}, 1; \frac{5}{2}^+\rangle_4$	$M_{\mathcal{P}_{X_4}} + 3A_\mathcal{P} + B_\mathcal{P}$
$\mathcal{P}_{X_5}$	$\lvert 1_\mathcal{Q}, 1_{\mathcal{Q}'}, 0; \frac{5}{2}^-\rangle_5$	$M_0 + \Delta M_5$	$\mathcal{P}_{Y_5}$	$\lvert 1_\mathcal{Q}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}, 1; \frac{5}{2}^+\rangle_5$	$M_{\mathcal{P}_{X_5}} - 2A_\mathcal{P} + B_\mathcal{P}$

$\mathcal{P}_{X_i}$	$\mathcal{P}_{X_1}$	$\mathcal{P}_{X_2}$	$\mathcal{P}_{X_3}$	$\mathcal{P}_{X_4}$	$\mathcal{P}_{X_5}$
c_1	4133 ± 55 (4072 ± 40)	**4133 ± 55 (4133 ± 55)**	4197 ± 55 (4300 ± 40)	**4385 ± 55 (4342 ± 40)**	4534 ± 55 (4409 ± 40)
c_2	4115 ± 58 (4031 ± 43)	4138 ± 47 (4172 ± 47)	4191 ± 53 (4262 ± 43)	4324 ± 47 (4303 ± 43)	4478 ± 47 (4370 ± 43)
c_3	4365 ± 55 (4304 ± 55)	4390 ± 42 (4365 ± 40)	4443 ± 49 (4532 ± 40)	4578 ± 43 (4574 ± 40)	4727 ± 42 (4641 ± 40)
c_4	4313 ± 47 (4263 ± 43)	4382 ± 45 (4404 ± 47)	4434 ± 51 (4494 ± 43)	4568 ± 46 (4535 ± 43)	4721 ± 45 (4602 ± 43)
c_5	4596 ± 47 (4577 ± 43)	4664 ± 46 (4596 ± 47)	4721 ± 51 (4810 ± 43)	4853 ± 46 (4851 ± 43)	5006 ± 45 (4918 ± 47)
$\mathcal{P}_{Y_i}$	$\mathcal{P}_{Y_1}$	$\mathcal{P}_{Y_2}$	$\mathcal{P}_{Y_3}$	$\mathcal{P}_{Y_4}$	$\mathcal{P}_{Y_5}$
c_1	4450 ± 57 (4450 ± 44)	**4450 ± 57 (4510 ± 57)**	4515 ± 57 (4678 ± 44)	4702 ± 58 (4720 ± 44)	4589 ± 56 (4524 ± 41)
c_2	4432 ± 61 (4409 ± 47)	4456 ± 50 (4549 ± 51)	4508 ± 56 (4639 ± 47)	4642 ± 50 (4681 ± 47)	4532 ± 48 (4486 ± 45)
c_3	4682 ± 57 (4682 ± 44)	4708 ± 46 (4742 ± 57)	4760 ± 52 (4910 ± 44)	4895 ± 47 (4952 ± 44)	4782 ± 44 (4756 ± 41)
c_4	4603 ± 51 (4641 ± 47)	4699 ± 49 (4781 ± 51)	4752 ± 54 (4871 ± 47)	4885 ± 49 (4913 ± 47)	4776 ± 47 (4718 ± 45)
c_5	4913 ± 51 (4954 ± 47)	4981 ± 49 (4973 ± 51)	5038 ± 54 (5187 ± 47)	5170 ± 49 (5228 ± 47)	5061 ± 47 (5033 ± 47)

Maiani *et al.* assignments of $P_c^+(4380)$ and $P_c^+(4450)$ correspond to $\mathcal{P}_{X_4}$ and $\mathcal{P}_{Y_2}$, resp. $\Lambda_b^0 \to \mathcal{P}_{X_4} K^-$ suppressed due to HQS and $\frac{3}{2}^-$ state favored by HQS is $\mathcal{P}_{X_2}$.

Weak decays of the b-baryons into pentaquark states

$$\mathcal{A} = \langle \mathcal{P}\mathcal{M} \left| H_{\rm eff}^W \right| \mathcal{B} \rangle, \text{ with } H_{\rm eff}^W = \frac{4G_F}{\sqrt{2}} \left[V_{cb} V_{cq}^* (c_1 O_1^{(q)} + c_2 O_2^{(q)}) \right]$$

$H_{\rm eff}^W$ inducing the Cabibbo-allowed $\Delta I = 0, \Delta S = -1$ transition $b \to c\bar{c}s$, and the Cabibbo-suppressed $\Delta S = 0$ transition $b \to c\bar{c}d$.

$$O_1^{(q)} = (\bar{q}_\alpha c_\beta)_{V-A} (\bar{c}_\alpha b_\beta)_{V-A} \text{ and } O_2^{(q)} = (\bar{q}_\alpha c_\alpha)_{V-A} (\bar{c}_\beta b_\beta)_{V-A}$$

$\mathcal{B}_{ij}$ $(\bar{\mathbf{3}}) = \Lambda_b^0(udb),\ \Xi_b^0(usb),\ \Xi_b^-(dsb)$, $\mathcal{C}_{ij}$ $(\mathbf{6}) = \Sigma_b^-(ddb),\ \Sigma_b^0(udb),\ \Sigma_b^+(uub)),\ \Xi_b'(dsb),\ \Xi_b'^0(usb),\ \Omega_b^-(ssb)$

$$\mathcal{M}_i^j = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}, \quad \mathcal{P}_i^j\ (J^P) = \begin{pmatrix} \frac{P_{\Sigma^0}}{\sqrt{2}} + \frac{P_\Lambda}{\sqrt{6}} & P_{\Sigma^+} & P_p \\ P_{\Sigma^-} & -\frac{P_{\Sigma^0}}{\sqrt{2}} + \frac{P_\Lambda}{\sqrt{6}} & P_n \\ P_{\Xi^-} & P_{\Xi^0} & -\frac{P_\Lambda}{\sqrt{6}} \end{pmatrix}.$$

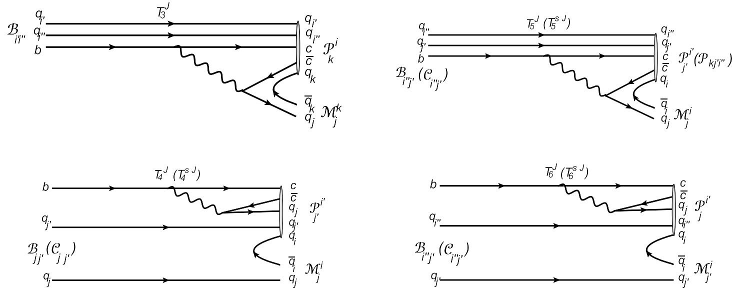
A decuplet $\mathcal{P}_{ijk}$: $\mathcal{P}_{111} = P_{\Delta_{10}^{++}}$, $\mathcal{P}_{112} = P_{\Delta_{10}^{+}}/\sqrt{3}$, $\mathcal{P}_{122} = P_{\Delta_{10}^{0}}/\sqrt{3}$, $\mathcal{P}_{222} = P_{\Delta_{10}^{-}}$, $\mathcal{P}_{113} = P_{\Sigma_{10}^{+}}/\sqrt{3}$, $\mathcal{P}_{123} = P_{\Sigma_{10}^{0}}/\sqrt{6}$, $\mathcal{P}_{223} = P_{\Sigma_{10}^{-}}/\sqrt{3}$, $\mathcal{P}_{133} = P_{\Xi_{10}^{0}}/\sqrt{3}$, $\mathcal{P}_{233} = P_{\Xi_{10}^{-}}/\sqrt{3}$ and $\mathcal{P}_{333} = P_{\Omega_{10}^{-}}$.

◇ **Calculating the decay amplitudes is a formidable challenge.**
◇ $SU(3)_F$ **symmetry relations provided useful guide for pentaquark searches**, Li *et al.* [arXiv:1507.08252]

◇ **Only those states obeying the flavor constraints following from the weak Hamiltonian and having the internal spin quantum numbers compatible with the HQS will actually be produced in b-baryon decays.**

Cheng *et al.* [arXiv:1509.03708], Li *et al.* [arXiv:1507.08252]

$$
\begin{aligned}
\mathcal{A}^{J}_{t8}(q) &= T^{J}_{1}\left\langle \mathcal{P}^{k}_{l}\mathcal{M}^{l}_{k}\left|H(\bar{3})^{i}\right|\mathcal{B}_{i'i''}\right\rangle \varepsilon^{ii'i''} + T^{J}_{2}\left\langle \mathcal{P}^{k}_{j}\mathcal{M}^{i}_{k}\left|H(\bar{3})^{j}\right|\mathcal{B}_{i'i''}\right\rangle \varepsilon^{ii'i''} \\
&+T^{J}_{3}\left\langle \mathcal{P}^{i}_{k}\mathcal{M}^{k}_{j}\left|H(\bar{3})^{j}\right|\mathcal{B}_{i'i''}\right\rangle \varepsilon^{ii'i''} + T^{J}_{4}\left\langle \mathcal{P}^{i'}_{j'}\mathcal{M}^{i}_{j}\left|H(\bar{3})^{i''}\right|\mathcal{B}_{jj'}\right\rangle \varepsilon_{ii'i''} \\
&+T^{J}_{5}\left\langle \mathcal{P}^{i'}_{j'}\mathcal{M}^{i}_{j}\left|H(\bar{3})^{j}\right|\mathcal{B}_{i''j'}\right\rangle \varepsilon_{ii'i''} + T^{J}_{6}\left\langle \mathcal{P}^{i'}_{j}\mathcal{M}^{i}_{j'}\left|H(\bar{3})^{j}\right|\mathcal{B}_{i''j'}\right\rangle \varepsilon_{ii'i''}, \\
\mathcal{A}^{J}_{t10}(q) &= T^{s\,J}_{5}\left\langle \mathcal{P}_{kj'i''}\mathcal{M}^{k}_{l}\left|H(\bar{3})^{l}\right|\mathcal{C}_{i''j'}\right\rangle
\end{aligned}
$$



◇ **HQS reduce number of penta-states can be reached in *b*-baryon decays.** ◇ **HQS reduce the number of unknown matrix elements by providing a better understanding of why some diagrams are disfavored.**

With $T_8^J \equiv 2T_3^J + T_5^J$,

Decay Mode	Amplitude	Decay Mode	Amplitude
$\Lambda_b \to P_p^{\{X_2;Y_2\}c_1}\pi^-$	T_8^J	$\Xi_b^- \to P_{\Xi^-}^{\{X_2;Y_2\}c_4}K^0$	T_8^J
$\Lambda_b \to P_n^{\{X_2;Y_2\}c_1}\eta_8$	$\frac{1}{\sqrt{6}}T_8^J$	$\Xi_b^- \to P_{\Sigma^-}^{\{X_2;Y_2\}c_2}\eta_8$	$\frac{1}{\sqrt{6}}T_8^J$
$\Lambda_b \to P_n^{\{X_2;Y_2\}c_1}\pi^0$	$-\frac{1}{\sqrt{2}}T_8^J$	$\Xi_b^- \to P_{\Lambda^0}^{\{X_2;Y_2\}c_2}\pi^-$	$\frac{1}{\sqrt{6}}T_8^J$
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2;Y_2\}c_2}\eta_8$	$-\frac{1}{6}T_8^J$	$\Xi_b^- \to P_{\Sigma^0}^{\{X_2;Y_2\}c_2}\pi^-$	$\frac{1}{\sqrt{2}}T_8^J$
$\Xi_b^0 \to P_{\Sigma^0}^{\{X_2;Y_2\}c_2}\eta_8$	$\frac{1}{\sqrt{12}}T_8^J$	$\Xi_b^- \to P_{\Sigma^-}^{\{X_2;Y_2\}c_2}\pi^0$	$-\frac{1}{\sqrt{2}}T_8^J$
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2;Y_2\}c_2}\pi^0$	$\frac{1}{\sqrt{12}}T_8^J$	$\Xi_b^0 \to P_{\Sigma^0}^{\{X_2;Y_2\}c_2}\pi^0$	$-\frac{1}{2}T_8^J$
$\Omega_b^- \to P_{\Xi^-_{10}}^{\{X_3;Y_3\}c_5}\pi^0$	$\frac{1}{\sqrt{6}}\left(-T_5^{s\,J}\right)$	$\Omega_b^- \to P_{\Xi^0_{10}}^{\{X_3;Y_3\}c_5}\pi^-$	$\frac{1}{\sqrt{3}}T_5^{s\,J}$

Decay Mode	Amplitude	Decay Mode	Amplitude
$\Lambda_b \to P_p^{\{X_2;Y_2\}c_1}K^-$	T_8^J	$\Xi_b^- \to P_{\Sigma^-}^{\{X_2;Y_2\}c_2}\bar{K}^0$	T_8^J
$\Lambda_b \to P_n^{\{X_2;Y_2\}c_1}\bar{K}^0$	T_8^J	$\Xi_b^- \to P_{\Xi^-}^{\{X_2;Y_2\}c_2}\eta_8$	$-\frac{2}{\sqrt{6}}T_8^J$
$\Lambda_b \to P_{\Sigma^0}^{\{X_2;Y_2\}c_3}\pi^0$	0	$\Xi_b^- \to P_{\Lambda^0}^{\{X_2;Y_2\}c_2}K^-$	$\frac{1}{\sqrt{6}}T_8^J$
$\Lambda_b \to P_{\Lambda^0}^{\{X_2;Y_2\}c_3}\eta_8$	$\frac{2}{3}T_8^J$	$\Xi_b^- \to P_{\Sigma^0}^{\{X_2;Y_2\}c_2}K^-$	$\frac{1}{\sqrt{2}}T_8^J$
$\Xi_b^0 \to P_{\Sigma^+}^{\{X_2;Y_2\}c_2}K^-$	$-T_8^J$	$\Xi_b^0 \to P_{\Xi^0}^{\{X_2;Y_2\}c_2}\eta_8$	$\frac{2}{\sqrt{6}}T_8^J$
$\Omega_b^- \to P_{\Xi^0_{10}}^{\{X_3;Y_3\}c_5}K^-$	$\frac{1}{\sqrt{3}}T_5^{s\,J}$	$\Omega_b^- \to P_{\Xi^-_{10}}^{\{X_3;Y_3\}c_5}\bar{K}^0$	$\frac{1}{\sqrt{3}}T_5^{s\,J}$

Sexet-2-decuplet:

$$-\sqrt{2}\mathcal{A}^J_{t10}(\Omega_b^- \to P_{\Xi^-_{10}}^{\{X_3;Y_3\}c_5}\pi^0) = \mathcal{A}^J_{t10}(\Omega_b^- \to P_{\Xi^0_{10}}^{\{X_3;Y_3\}c_5}\pi^-), \quad \Delta S = 0$$

$$\mathcal{A}^J_{t10}(\Omega_b^- \to P_{\Xi^0_{10}}^{\{X_3;Y_3\}c_5}K^-) = \mathcal{A}^J_{t10}(\Omega_b^- \to P_{\Xi^-_{10}}^{\{X_3;Y_3\}c_5}\bar{K}^0), \qquad \Delta S = 1$$

The $\Omega_b^- \to K^-(J/\psi\ \Xi^0)$, $K^0(J/\psi\ \Xi^-)$ in decuplet only with $\{\bar{c}\,[cu]_{s=1}\,[ss]_{s=1}\}$.

Antitriplet-2-octet: $\Delta S = 0$

$$\mathcal{A}^J_{t8}(\Lambda_b \to P_p^{\{X_2;Y_2\}c_1}\pi^-) = -\sqrt{2}\mathcal{A}^J_{t8}(\Lambda_b \to P_n^{\{X_2;Y_2\}c_1}\pi^0) = \sqrt{6}\mathcal{A}^J_{t8}(\Lambda_b \to P_n^{\{X_2;Y_2\}c_1}\eta_8),$$

$$\mathcal{A}^J_{t8}(\Xi_b^0 \to P_{\Lambda^0}^{\{X_2;Y_2\}c_2}\pi^0) = -\mathcal{A}^J_{t8}(\Xi_b^0 \to P_{\Sigma^0}^{\{X_2;Y_2\}c_2}\eta_8),$$

$$\mathcal{A}^J_{t8}(\Xi_b^- \to P_{\Xi^-}^{\{X_2;Y_2\}c_4}K^0) = \sqrt{6}\mathcal{A}^J_{t8}(\Xi_b^- \to P_{\Sigma^-}^{\{X_2;Y_2\}c_2}\eta_8) = \sqrt{6}\mathcal{A}^J_{t8}(\Xi_b^- \to P_{\Lambda^0}^{\{X_2;Y_2\}c_2}\pi^-),$$

$$\mathcal{A}^J_{t8}(\Xi_b^- \to P_{\Xi^-}^{\{X_2;Y_2\}c_4}K^0) = \sqrt{2}\mathcal{A}^J_{t8}(\Xi_b^- \to P_{\Sigma^0}^{\{X_2;Y_2\}c_2}\pi^-) = -\sqrt{2}\mathcal{A}^J_{t8}(\Xi_b^- \to P_{\Sigma^-}^{\{X_2;Y_2\}c_2}\pi^0).$$

The $P_c^+(4450)$ $[P_{Y_2}]$ and proposed P_{X_2} belong to the $SU(3)_F$ octet.

Combining $SU(3)_F$-symmetry with HQS provided simplified predictive relations.

Estimates of the ratio of decay widths for $J^P = \frac{5}{2}^+$:

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$
$\Lambda_b \to P_p^{\{Y_2\}_{c_1}} K^-$	1	$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}_{c_2}} \bar{K}^0$	2.07
$\Lambda_b \to P_n^{\{(Y_2\}_{c_1}} \bar{K}^0$	1	$\Xi_b^0 \to P_{\Sigma^+}^{\{Y_2\}_{c_2}} K^-$	2.07
$\Lambda_b \to P_{\Lambda^0}^{\{Y_2\}_{c_3}} \eta'$	0.03	$\Lambda_b \to P_{\Lambda^0}^{\{Y_2\}_{c_3}} \eta$	0.19
$\Xi_b^- \to P_{\Sigma^0}^{\{Y_2\}_{c_2}} K^-$	1.04	$\Xi_b^- \to P_{\Lambda^0}^{\{Y_2\}_{c_2}} K^-$	0.34
$\Omega_b^- \to P_{\Xi_{10}^-}^{\{Y_3\}_{c_5}} \bar{K}^0$	0.14	$\Omega_b^- \to P_{\Xi_{10}^0}^{\{Y_3\}_{c_5}} K^-$	0.14

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{5/2} K^-)$
$\boldsymbol{\Lambda_b \to P_p^{\{Y_2\}_{c_1}} \pi^-}$	**0.08**	$\Lambda_b \to P_n^{\{Y_2\}_{c_1}} \pi^0$	0.04
$\Lambda_b \to P_n^{\{Y_2\}_{c_1}} \eta$	0.01	$\Lambda_b \to P_n^{\{Y_2\}_{c_1}} \eta'$	0
$\Xi_b^- \to P_{\Xi^-}^{\{Y_2\}_{c_4}} K^0$	0.02	$\Xi_b^- \to P_{\Sigma^0}^{\{Y_2\}_{c_2}} \pi^-$	0.08
$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}_{c_2}} \eta$	0.02	$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}_{c_2}} \eta'$	0.01
$\Xi_b^- \to P_{\Sigma^-}^{\{Y_2\}_{c_2}} \pi^0$	0.08	$\Xi_b^0 \to P_{\Sigma^0}^{\{Y_2\}_{c_2}} \pi^0$	0.04
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\ (Y_2)\}_{c_2}} \eta$	0.01	$\Xi_b^0 \to P_{\Lambda^0}^{\{Y_2\}_{c_2}} \eta'$	0.01
$\Xi_b^0 \to P_{\Lambda^0}^{\{Y_2\}_{c_2}} \pi^0$	0.01	$\Omega_b^- \to P_{\Xi_{10}^-}^{\{Y_3\}_{c_5}} \pi^0$	0.01
$\Omega_b^- \to P_{\Xi_{10}^0}^{\{Y_3\}_{c_5}} \pi^-$	0.02		

- **We have used the pentaquark masses estimated in this work.**
- **$\Delta S = 0$ are suppressed by $|V_{cd}^* / V_{cs}^*|^2$ compared to $\Delta S = 1$.**

Estimates of the ratio of decay widths for $J^P = \frac{3}{2}^-$:

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$
$\Lambda_b \to P_p^{\{X_2\}_{c_1}} K^-$	1	$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \bar{K}^0$	1.38
$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \bar{K}^0$	1	$\Xi_b^0 \to P_{\Sigma^+}^{\{X_2\}_{c_2}} K^-$	1.38
$\Lambda_b \to P_{\Lambda^0}^{\{X_2\}_{c_3}} \eta'$	0.17	$\Lambda_b \to P_{\Lambda^0}^{\{X_2\}_{c_3}} \eta$	0.22
$\Xi_b^- \to P_{\Sigma^0}^{\{X_2\}_{c_2}} K^-$	0.69	$\Xi_b^- \to P_{\Lambda^0}^{\{X_2\}_{c_2}} K^-$	0.23
$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_3\}_{c_5}} \bar{K}^0$	0.24	$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_3\}_{c_5}} K^-$	0.24

Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$	Decay Process	$\Gamma/\Gamma(\Lambda_b^0 \to P_p^{\{X_2\}_{c_1}} K^-)$
$\boldsymbol{\Lambda_b \to P_p^{\{X_2\}_{c_1}} \pi^-}$ [1]	**0.06**	$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \pi^0$	0.03
$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \eta$	0.01	$\Lambda_b \to P_n^{\{X_2\}_{c_1}} \eta'$	0.01
$\Xi_b^- \to P_{\Xi^-}^{\{X_2\}_{c_4}} K^0$	0.02	$\Xi_b^- \to P_{\Sigma^0}^{\{X_2\}_{c_2}} \pi^-$	0.03
$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \eta$	0.02	$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \eta'$	0.01
$\Xi_b^- \to P_{\Sigma^-}^{\{X_2\}_{c_2}} \pi^0$	0.04	$\Xi_b^0 \to P_{\Sigma^0}^{\{X_2\}_{c_2}} \pi^0$	0.02
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\}_{c_2}} \eta$	0	$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\}_{c_2}} \eta'$	0
$\Xi_b^0 \to P_{\Lambda^0}^{\{X_2\}_{c_2}} \pi^0$	0.01	$\Omega_b^- \to P_{\Xi_{10}^-}^{\{X_3\}_{c_5}} \pi^0$	0.01
$\Omega_b^- \to P_{\Xi_{10}^0}^{\{X_3\}_{c_5}} \pi^-$	0.02		

- Neutron, η and η', and possibly π^0: only decays with K^-, or K^0, or π^-.

[1] First evidence of tetraquark- and pentaquark-structures in the Cabibbo-suppressed channel $\Lambda_b^0 \to J/\psi\, p\, \pi^-$ is reported recently by LHCb, [arXiv:1606.06999]

Summary

- The $P_c^+(4380)$ and $P_c^+(4450)$ correspond to $\mathcal{P}_{X_4}$ and $\mathcal{P}_{Y_2}$, respectively. However, $\Lambda_b^0 \to \mathcal{P}_{X_4} K^-$ suppressed due to HQS so disfavored.
- We anticipated fifty states having masses estimated to lie in the range 4100-5100 MeV in diquark-diquark-antiquark picture, $\bar{c}[cq][q'q'']$ with $q, q', q'' \in [u, d, s]$.
- $\mathcal{P}_{X_2}(4110 - 4130) = \{\bar{c}[cu]_{s=1}[ud]_{s=0}; L_{\mathcal{P}} =, J^P = \frac{3}{2}^- \}$
- Combining $SU(3)_F$-symmetry with HQS provided simplified predictive relations that might be helpful for future searches of pentaquarks.

Backup

Theoretical interpretations:

1. Diquark-diquark-antiquark picture L. Maiani *et al.* [arXiv:1507.04980]
2. Rescattering-induced kinematical effects F. K. Guo *et al.*, [arXiv:1507.04950]
3. Open charm-baryon and charm-meson bound states

   C. W. Xiao *et al.*, [arXiv:1508.00924]
4. Baryocharmonia V. Kubarovsky *et al.*, [arXiv:1508.00888]
5. Diquark-triquark R. F. Lebed, [arXiv:1507.05867]

States for $L_{\mathcal{P}} = 0$:

$$
\begin{aligned}
|0_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}; \frac{3}{2}\rangle_1 &= \frac{1}{\sqrt{2}}[(\uparrow)_c (\downarrow)_q - (\downarrow)_c (\uparrow)_q] (\uparrow)_{q'} (\uparrow)_{q''} (\uparrow)_{\bar{c}} \\
|1_{\mathcal{Q}}, 0_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}; \frac{3}{2}\rangle_2 &= \frac{1}{\sqrt{2}}[(\uparrow)_{q'} (\downarrow)_{q''} - (\downarrow)_{q'} (\uparrow)_{q''}] (\uparrow)_c (\uparrow)_q (\uparrow)_{\bar{c}} \\
|1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}; \frac{3}{2}\rangle_3 &= \frac{1}{\sqrt{6}} (\uparrow)_c (\uparrow)_q \{2 (\uparrow)_{q'} (\uparrow)_{q''} (\downarrow)_{\bar{c}} - [(\uparrow)_{q'} (\downarrow)_{q''} + (\downarrow)_{q'} (\uparrow)_{q''}] (\uparrow)_{\bar{c}}\} \\
|1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}; \frac{3}{2}\rangle_4 &= \sqrt{\frac{3}{10}}[(\uparrow)_c (\downarrow)_q + (\downarrow)_c (\uparrow)_q] (\uparrow)_{q'} (\uparrow)_{q''} (\uparrow)_{\bar{c}} - \sqrt{\frac{2}{15}} (\uparrow)_c (\uparrow)_q \{(\uparrow)_{q'} (\uparrow)_{q''} (\downarrow)_{\bar{c}} \\
&\quad + [(\uparrow)_{q'} (\downarrow)_{q''} + (\downarrow)_{q'} (\uparrow)_{q''}] (\uparrow)_{\bar{c}}\}, \\
|1_{\mathcal{Q}}, 1_{\mathcal{Q}'}, \frac{1}{2}_{\bar{c}}; \frac{5}{2}\rangle &= (\uparrow)_c (\uparrow)_q (\uparrow)_{q'} (\uparrow)_{q''} (\uparrow)_{\bar{c}}
\end{aligned}
$$

Backup

$$M_i = m_{\mathcal{Q}} + m_{\mathcal{Q}'} + m_c + \frac{B_{\mathcal{P}}}{2} L_{\mathcal{P}}(L_{\mathcal{P}}+1) + 2A_{\mathcal{P}} \frac{J_{\mathcal{P}}(J_{\mathcal{P}}+1) - L_{\mathcal{P}}(L_{\mathcal{P}}+1) - S_{\mathcal{P}}(S_{\mathcal{P}}+1)}{2} + \Delta M_i$$

$$\Delta M_5 = \frac{1}{2}(\mathcal{K}_{\bar{c}q} + \mathcal{K}_{\bar{c}c} + \mathcal{K}_{\bar{c}q'} + \mathcal{K}_{\bar{c}q''} + (\mathcal{K}_{cq'})_{\bar{3}} + (\mathcal{K}_{cq''})_{\bar{3}} + (\mathcal{K}_{qq'})_{\bar{3}} + (\mathcal{K}_{qq''})_{\bar{3}} + (\mathcal{K}_{cq})_{\bar{3}} + (\mathcal{K}_{q'q''})_{\bar{3}}).$$

$\Delta M_{i=1,\ldots,4}$: mass splitting terms that arise after the diagonalizing the 4×4 matrix.

Two-body decay rate:

The two-body decay rate in the center-of-mass frame can be expressed as

$$\Gamma \propto |q_{cm}||\mathcal{A}|^2 \propto |q_{cm}|^{2L+1},$$

where $|\mathcal{A}|$ is the amplitude of the respective decay mode, L is the relative orbital angular momentum of the final state particles, and q_{cm} is the center-of-mass momentum, defined as

$$\begin{aligned} |q_{cm}| &= q_{\mathcal{P}} = \sqrt{E_{\mathcal{P}}^2 - m_{\mathcal{P}}^2}, \\ E_{\mathcal{P}} &= \frac{m_{\mathcal{B}}^2 + m_{\mathcal{P}}^2 - m_{\mathcal{M}}^2}{2m_{\mathcal{B}}}, \end{aligned}$$

where, $m_{\mathcal{B}}$, $m_{\mathcal{P}}$ and $m_{\mathcal{M}}$ are the masses of the initial state b-baryon, final state pentaquark and pseudoscalar meson, respectively.