Ratios of Hidden-Charm Pentaquark Decay Widths in Compact Diquark Model

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based on the paper A. Ali et al., JHEP 10 (2019) 256 [arXiv:1907.06507]

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- Introduction
- Double well potential in hidden-charm tetraquarks
- Double well potential in hidden-charm pentaquarks
- Conclusions

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- At present, production, properties, and decays of heavy baryons are intensively studied both experimentally and theoretically
- Exotic resonances are found in $\Lambda_b \rightarrow p + K^- + J/\psi$ and $\Lambda_b \rightarrow p + \pi^- + J/\psi$ decays
- There is also the evidence of exotic resonance in $\Xi_b^- \to \Lambda + K^- + J/\psi$
- They are interpreted as pentaquarks

LHCb results on $\Lambda_b \rightarrow \rho + K^- + J/\psi$ decay

 In addition to the non-resonant channel, there are two different quasi-two-particle decay channels of Λ_b-baryon [LHCb Collab., Phys. Rev. Lett. 115 (2015) 072001]

Λ_b → Λ^{*} + J/ψ, where the Λ-hyperon or its excited states are produced and decay subsequently Λ^{*} → p + K⁻
 Λ_b → P^J_c + K⁻, where the P^J_c-pentaquark with spin J is produced and decays through the channel P^J_c → p + J/ψ



LHCb results on $\Lambda_b \rightarrow p + K^- + J/\psi$ decay

- In 2015, one narrow and one wide resonances interpreted as hidden-charm pentaquarks were found [LHCb Collab., Phys. Rev. Lett. 115 (2015) 072001]
- In 2019, three narrow pentaquark resonances were observed [LHCb Collab., Phys. Rev. Lett. 122 (2019) 222001]



Evidence of strange $P_{cs}(4459)$ pentaquark

- Resonance is found in $\Xi_b^- \to \Lambda^0 + J/\psi + K^-$ decay [LHCb Collab., Sci. Bull. 66 (2021) 1278]
- Its mass $M_{P_{cs}} = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV and decay width $\Gamma_{P_{cs}} = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV
- Two-resonance structure of the peak is not excluded
- Spin-parity is not defined
- Statistical significance is 3.1σ



Existing theoretical models of pentaquarks

- Several dynamical models of pentaquarks are suggested:
 - baryon-meson model (molecular pentaquark);
 - 2 triquark-diquark model;
 - 3 diquark-diquark-antiquark model;
 - 4 ..
- For example, in the diquark-diquark-antiquark model, dynamics is determined by interaction of light diquark [q₂q₃], heavy diquark [cq₁] and c-antiquark, where q_i is one of the light u-, d-or s-quarks [A. Ali et al., JHEP 10 (2019) 256]



- Hypothesis: tetraquark can plausibly be represented by two diquarks in double well potential separated by a barrier
 [L. Maiani, A.D. Polosa & V. Riquer, Phys. Lett. B778 (2018) 247]
- There are two length scales: diquark radius R_{Qq} & tetraquark radius R_{4q}
- Assumed to be well separated $\lambda = R_{4q}/R_{Qq} \ge 3$
- Tunneling transitions of quarks result into strong decays
- Diquark radius R_{Qq} in tetraquark can be different from diquark radius R^{baryon}_{Qa} in baryon
- Increase of experimental resolution and statistics is crucial to support or disprove this hypothesis



Hidden-Charm Tetraquark Decays to D-Mesons

- Diquark-antidiquark system can rearrange itself into a pair of color singlets by exchanging quarks through tunneling transition
- Small overlap between constituent quarks in different wells suppresses quark-antiquark direct annihilation
- Two stage process:
 - switch of quark and antiquark among two wells
 - evolution of quark-antiquark pairs into mesons
- Including diquark spins (subscripts), consider the states: $\Psi_{D}^{(1)} = [cu]_{0}(x) [\bar{c}\bar{u}]_{1}(y), \quad \Psi_{D}^{(2)} = C\Psi_{D}^{(1)} = [cu]_{1}(y) [\bar{c}\bar{u}]_{0}(x)$
- After Fierz rearrangements of color and spin indices, in evident meson notations

 $\Psi_{D}^{(1)} = A D^{0} \bar{D}^{*0} - B D^{*0} \bar{D}^{0} + iC D^{*0} \times \bar{D}^{*0}$ $\Psi_{D}^{(2)} = B D^{0} \bar{D}^{*0} - A D^{*0} \bar{D}^{0} - iC D^{*0} \times \bar{D}^{*0}$

A, B, and C are non-perturbative coefficients associated to barrier penetration amplitudes for different total spins of u and u

Hidden-Charm Tetraquark Decays to Charmonia

Tunneling transition of light quarks

$$X_u \sim rac{1}{\sqrt{2}} \left[\Psi_{\mathcal{D}}^{(1)} + \Psi_{\mathcal{D}}^{(2)}
ight] = rac{A+B}{\sqrt{2}} \left[D^0 ar{D}^{*0} - D^{*0} ar{D}^0
ight]$$

Tunneling transition of heavy quarks

 $X_u \sim a \, i J/\psi \times \left(\omega +
ho^0
ight)$

- Tunneling amplitude in leading semiclassical approximation, $\mathcal{A}_M \sim e^{-\sqrt{2ME}\ell}$, where *E* and ℓ are barrier height and extension
- For constituent quark masses, m_q and m_c , E = 100 MeV and $\ell = 2$ fm, the ratio of amplitides squared

 $R = \left[a/(A+B)
ight]^2 \sim \left(\mathcal{A}_{m_c}/\mathcal{A}_{m_q}
ight)^2 \sim 10^{-3}$

• With decay momenta $p_{
ho} \simeq 124 \text{ MeV}$ and $p_{DD^*} \simeq 2 \text{ MeV}$

$$rac{\Gamma(X(3872)
ightarrow J/\psi
ho)}{\Gamma(X(3872)
ightarrow Dar{D}^*)} = rac{p_
ho}{p_{DD^*}} R \sim 0.1$$

■ Experiment [PDG]: $B_{\exp}(X(3872) \rightarrow J/\psi \rho) = (3.8 \pm 1.2)\%$ $B_{\exp}(X(3872) \rightarrow D\bar{D}^*) = (37 \pm 9)\%$

- Hypothesis: pentaquark can be represented by heavy diquark and heavy triquark in double well potential separated by barrier [A. Ali et. al., JHEP 10 (2019) 256]
- There are two triquark-diquark representations

$$\Psi_{1}^{D} = \frac{1}{\sqrt{3}} \left[\frac{1}{\sqrt{2}} \epsilon_{ijk} \bar{c}^{i} \left[\frac{1}{\sqrt{2}} \epsilon^{jlm} c_{l} q_{m} \right] \right] \left[\frac{1}{\sqrt{2}} \epsilon^{knp} q_{n}^{\prime} q_{p}^{\prime \prime} \right] \equiv \left[\bar{c} \left[cq \right] \right] \left[q^{\prime} q^{\prime \prime} \right]$$
$$\Psi_{2}^{D} = \frac{1}{\sqrt{3}} \left[\frac{1}{\sqrt{2}} \epsilon_{ikj} \bar{c}^{i} \left[\frac{1}{\sqrt{2}} \epsilon^{knp} q_{n}^{\prime} q_{p}^{\prime \prime} \right] \right] \left[\frac{1}{\sqrt{2}} \epsilon^{jlm} c_{l} q_{m} \right] \equiv \left[\bar{c} \left[q^{\prime} q^{\prime \prime} \right] \right] \left[cq \right]$$

- From color algebra, these states are related, $\Psi_2^D = -\Psi_1^D$, but other internal dynamical properties can be different
- Ψ_2^D color structure is suitable for study strong decays

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Color-singlet combinations are meson-baryon alternatives

$$\begin{split} \Psi_{1}^{H} &= \left(\frac{1}{\sqrt{3}} \, \bar{c}^{i} c_{i}\right) \left[\frac{1}{\sqrt{6}} \, \epsilon^{jkl} q_{j} q_{k}^{\prime} q_{l}^{\prime\prime}\right] \equiv (\bar{c}c) \left[qq^{\prime} q^{\prime\prime}\right] \\ \Psi_{2}^{H} &= \left(\frac{1}{\sqrt{3}} \, \bar{c}^{i} q_{i}\right) \left[\frac{1}{\sqrt{6}} \, \epsilon^{jkl} c_{j} q_{k}^{\prime} q_{l}^{\prime\prime}\right] \equiv (\bar{c}q) \left[cq^{\prime} q^{\prime\prime}\right] \\ \Psi_{3}^{H} &= \left(\frac{1}{\sqrt{3}} \, \bar{c}^{i} q_{l}^{\prime}\right) \left[\frac{1}{\sqrt{6}} \, \epsilon^{jkl} c_{j} q_{k} q_{l}^{\prime\prime}\right] \equiv (\bar{c}q^{\prime}) \left[cqq^{\prime\prime}\right] \\ \Psi_{4}^{H} &= \left(\frac{1}{\sqrt{3}} \, \bar{c}^{i} q_{l}^{\prime\prime}\right) \left[\frac{1}{\sqrt{6}} \, \epsilon^{jkl} c_{j} q_{k} q_{l}^{\prime}\right] \equiv (\bar{c}q^{\prime\prime}) \left[cqq^{\prime}\right] \end{split}$$

- Ψ_1^H and Ψ_2^H only satisfy HQS condition
- Light [q'q'']-diquark is transmitted intact, retaining its spin quantum number, from b-baryon to pentaquark

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Keeping the color of the light diquark unchanged, convolution of two Levi-Civita tensors entering the triquark gives

$$\Psi^D_1 = -\frac{\sqrt{3}}{2}\left[\Psi^H_1 + \Psi^H_2\right],$$

- Color reconnection is not enough to reexpress pentaquark operator as direct product of the meson and baryon operators
- Spins of quarks and diquarks should be projected onto definite hadronic spin states
- One needs to know Dirac structure of pentaquark operators to undertake the Fierz transformations in Dirac space
- Exemplify this by considering $P_c(4312)$ pentaquark

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Mass Predictions for Unflavored Pentaquarks

J^P	AAAPR	AAAR	J ^P	AAAPR	AAAR
	$S_{ld} = 0, L$	= 0	$S_{ld} = 1, L = 1$		
1/2-	$\textbf{3830} \pm \textbf{34}$	4086 ± 42	1/2+	4144 ± 37	3970 ± 50
	4150 ± 29	4162 ± 38		4209 ± 37	4174 ± 44
3/2-	4240 ± 29	4133 ± 55		4465 ± 32	4198 ± 50
	$S_{ld} = 1, L = 0$			4530 ± 32	4221 ± 40
1/2-	4026 ± 31	4119 ± 42		4564 ± 33	4240 ± 50
	4346 ± 25	$\textbf{4166} \pm \textbf{38}$		4663 ± 32	$\textbf{4319} \pm \textbf{43}$
	4436 ± 25	4264 ± 41	3/2+	4187 ± 37	
3/2-	4026 ± 31	4072 ± 40		4250 ± 37	
	4346 ± 25	4300 ± 40		4508 ± 32	
	4436 ± 25	4342 ± 40		4570 ± 32	
5/2-	4436 ± 25	4409 ± 40		4511 ± 33	
	$S_{ld} = 0, L$	= 1		4566 ± 32	
1/2+	4030 ± 39	4030 ± 62		4656 ± 32	
	4351 ± 35	4141 ± 44	5/2+	4260 ± 37	4450 ± 44
	4430 ± 35	4217 ± 40		4581 ± 32	4524 ± 41
3/2+	4040 ± 39			4601 ± 32	4678 ± 44
	4361 ± 35			4656 ± 32	4720 ± 44
	4440 ± 35		7/2+	4672 ± 32	
5/2+	4457 ± 35	4510 ± 57			

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 Diquark-diquark-antiquark operators with spinless heavy and light diquarks

$$\Psi_{1}^{H(1)}(x,y) = \frac{1}{3} \left(\tilde{c}^{i}(x) \sigma_{2} \right) \left(c_{i}(y) \sigma_{2} q_{k}(y) \right) d_{0}^{k}(x)$$

$$\Psi_{2}^{H(1)}(x,y) = \frac{1}{3} \left(\tilde{c}^{i}(x) \sigma_{2} \right) \left(c_{k}(y) \sigma_{2} q_{i}(y) \right) d_{0}^{k}(x)$$

- For the lowest lying pentaquark, q = u and $d_0 = [u C \gamma_5 d]$, being scalar diquark
- Quarks are considered in the non-relativistic limit
- After Fierz transformation of Pauli matrices and suppressing position dependence, they can be rewritten in terms of hadrons

$$\Psi_{1}^{H(1)} = -\frac{i}{\sqrt{2}} \left[\boldsymbol{a} \eta_{c} + \boldsymbol{b} \left(\boldsymbol{\sigma} \, \boldsymbol{J} / \psi \right) \right] \boldsymbol{\rho}, \quad \Psi_{2}^{H(1)} = -\frac{i}{\sqrt{2}} \left[\boldsymbol{A} \, \bar{\boldsymbol{D}}^{0} + \boldsymbol{B} \left(\boldsymbol{\sigma} \, \bar{\boldsymbol{D}}^{*0} \right) \right] \Lambda_{c}^{+}$$

- A and B (a and b) are non-perturbative coefficients associated with barrier penetration amplitudes for light (heavy) quark
- They are equal in the limit of naive Fierz coupling

Similarly, diquark-diquark-antiquark operators containing heavy diquark with $S_{hd} = 1$ and light diquark $S_{ld} = 0$

$$\begin{split} \Psi_{1}^{H(2)}(x,y) &= \frac{1}{3} \left(\tilde{c}^{i}(x) \,\sigma_{2} \right) \left(c_{i}(y) \,\sigma_{2} \,\sigma \,q_{k}(y) \right) d_{0}^{k}(x) \\ \Psi_{2}^{H(2)}(x,y) &= \frac{1}{3} \left(\tilde{c}^{i}(x) \,\sigma_{2} \right) \left(c_{k}(y) \,\sigma_{2} \,\sigma \,q_{i}(y) \right) d_{0}^{k}(x) \end{split}$$

- Being direct product of spinor and vector, they need to be devided into two states with spins J = 1/2 and J = 3/2
- For $P_c(4312)$ interpreted as $J^P = 3/2^-$ pentaquark, decompositions in term of hadrons are as follows

$$\begin{split} \Psi_1^{H(3/2)} &= \frac{i\sqrt{2}}{3} \left\{ b' \, \boldsymbol{J}/\psi - 2ic' \left[\boldsymbol{\sigma} \times \boldsymbol{J}/\psi\right] \right\} \boldsymbol{\rho} \\ \Psi_2^{H(3/2)} &= -\frac{i\sqrt{2}}{3} \left\{ B' \, \bar{\boldsymbol{D}}^{*0} - 2iC' \left[\boldsymbol{\sigma} \times \bar{\boldsymbol{D}}^{*0}\right] \right\} \Lambda_c^+ \end{split}$$

P_c(4312) is mainly decaying either to *J*/ψ *p* final state, in which it was observed, or to Λ⁺_c *D*^{*0}

Hidden-Charm Pentaquark Decays

- Tunneling amplitude in leading semiclassical approximation, $A_M \sim e^{-\sqrt{2ME}\ell}$, where *E* and ℓ are barrier height and extension
- For constituent quark masses, m_u and m_c , E = 100 MeV and $\ell = 2$ fm, the ratio of amplitides squared

$$R_{
m penta} = rac{|b'|^2 + 4|c'|^2}{|B'|^2 + 4|C'|^2} \sim \left(rac{\mathcal{A}_{m_c}}{\mathcal{A}_{m_u}}
ight)^2 \sim 10^{-3} \sim R$$

• With decay momenta $p_p \simeq 660$ MeV and $p_{\Lambda_c} \simeq 200$ MeV

$$\frac{\Gamma(P_c(4312) \rightarrow J/\psi \ p)}{\Gamma(P_c(4312) \rightarrow \Lambda_c^+ \ \bar{D}^{*0})} = \frac{p_p}{p_{\Lambda_c}} \ R_{\text{penta}} \sim 10^{-3}$$

- If this approach is correct, $P_c(4312)$ should be searched in $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-$ decay
- This can also be applied to decays of *P_{cs}*(4459) pentaquark

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Summary

- Quark-Diquark-Diquark approach for pentaquarks is working quite successful in prediction of masses of heavy baryons and doubly-heavy exotic hadrons
- Decay width of tetraquarks with hidden charm or bottom can be explained within the diquark model by a presence of a barrier between heavy diquark and antidiquark
- Similarly, decay width of pentaquarks with hidden charm or bottom can be explained within the quark-diquark model by a presence of a barrier between heavy diquark and triquark
- If this approach is correct, $P_c(4312)$ -pentaquark should be also searched in $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-$ decay mode with good chances to be found

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 $\Lambda_b \rightarrow p + J/\psi + K^-$ Decay: 2019 Results by LHCb

Λ_b-baryon decay Λ_b → p + J/ψ + K⁻ was studied on
 9 times more data based on Run 1 and 2 than on Run 1

Three narrow peaks were observed in $m_{J/\psi p}$ distribution

State	Mass [MeV]	Width [MeV]	(95% CL)	\mathcal{R} [%]
$P_{c}(4312)^{+}$	$4311.9\pm0.7^{+6.8}_{-0.6}$	$9.8\pm2.7^{+3.7}_{-4.5}$	(< 27)	$0.30\pm0.07^{+0.34}_{-0.09}$
$P_{c}(4440)^{+}$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6\pm4.9^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_{c}(4457)^{+}$	$4457.3\pm0.6^{+4.1}_{-1.7}$	$6.4\pm2.0^{+5.7}_{-1.9}$	(< 20)	$0.53\pm0.16^{+0.15}_{-0.13}$



- $P_c(4312)$ is a new resonance
- $P_c(4450)$ splits into $P_c(4440)$ and $P_c(4457)$
- $P_c(4380)$ under question
- Spin-parities are unknown yet

Theoretical Interpretations of 3 Narrow Pentaquarks: Molecular, Hadrocharmonium & Compact Multiquark Pictures

 Hypothesis: tetraquark can plausibly be represented by two diquarks in double well potential separated by a barrier [L. Maiani, A.D. Polosa & V. Riquer, Phys. Lett. B778 (2018) 247]

Arguments in favor:

- At large distances, diquarks interact like QCD point charges
- Confining forces are the same as for quark and antiquark
- At shorter distances, forces among constituents in diquarks (e. g. attraction between quarks and antiquarks) reduce the diquark binding energies
- These effects increase at decreasing distance and produce repulsion among diquark and antidiquark, i. e. increasing component in potential at decreasing distance
- If this effect wins against the decrease due to the color attraction, the barrier is produced

