The hidden-charm pentaquark states in a mass splitting model

报告人：满自龙

山东大学

Based on

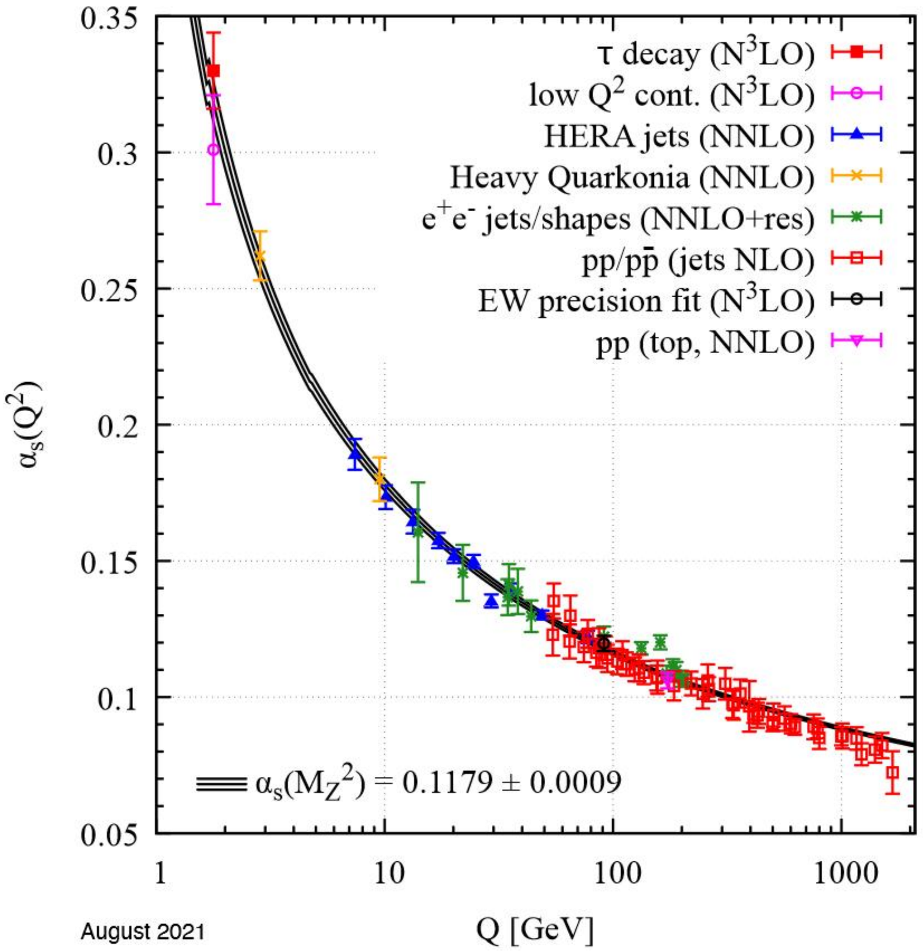
Shi-Yuan Li, Yan-Rui Liu, Zi-Long Man, Zong-Guo Si, and Jing Wu, arXiv:2307.00539

2023/7/27

CONTENTS|

QCD

- Asymptotic freedom
- Color confinement
- Chiral symmetry breaking



R.L.Workman,et.al PTEP, 083C01(2022)

High energy: asymptotic freedom

Low energy: non-perturbative important

Hadron properties difficult to derive from QCD

Methods: Lattice QCD、Quark Model、Effective field theory et.al .

Background

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

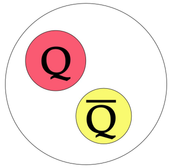
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

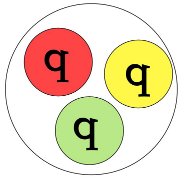
In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\overline{A}AAAA$, $\overline{AA}AAAAA$, etc., where $\overline{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\overline{A}A$, $\overline{AA}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\overline{A}A$ and AAA, that is, "deuces and treys".

Hadron

Conventional states:

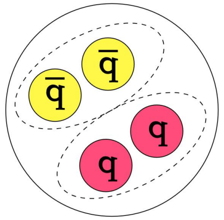


Meson

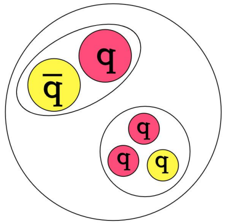


Baryon

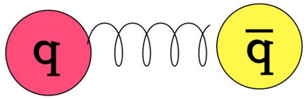
Exotic states:



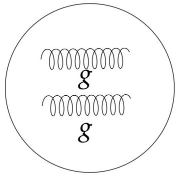
Compact multiquark states



Molecule states



Hybrid



Glueball

Background

- **History of pentaquark states** — Bing-Song Zou, Sci.Bull66, 1258(2021)

$\Lambda(1405)$

- $\overline{K}N$ **molecule state** $udsq\bar{q}$ — Dalitz and Tuan, PRL2, 425-428(1959)
- **1961** $\Lambda(1405) \to \Sigma\pi$
- **1964 Quark Model** → **an excited state** uds

one quark in an orbital p-wave excitation. After about 50 years' fighting on whether it is a (uds)-system or ($udsq\bar{q}$)-system (with q denoting light quark) of the $\bar{K}N$ type, until 2010, the Particle Data Group still claimed that "The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ – true 3-quark state or mere $\bar{K}N$ threshold effect? – unambiguously in favor of the first interpretation". A similar situ-

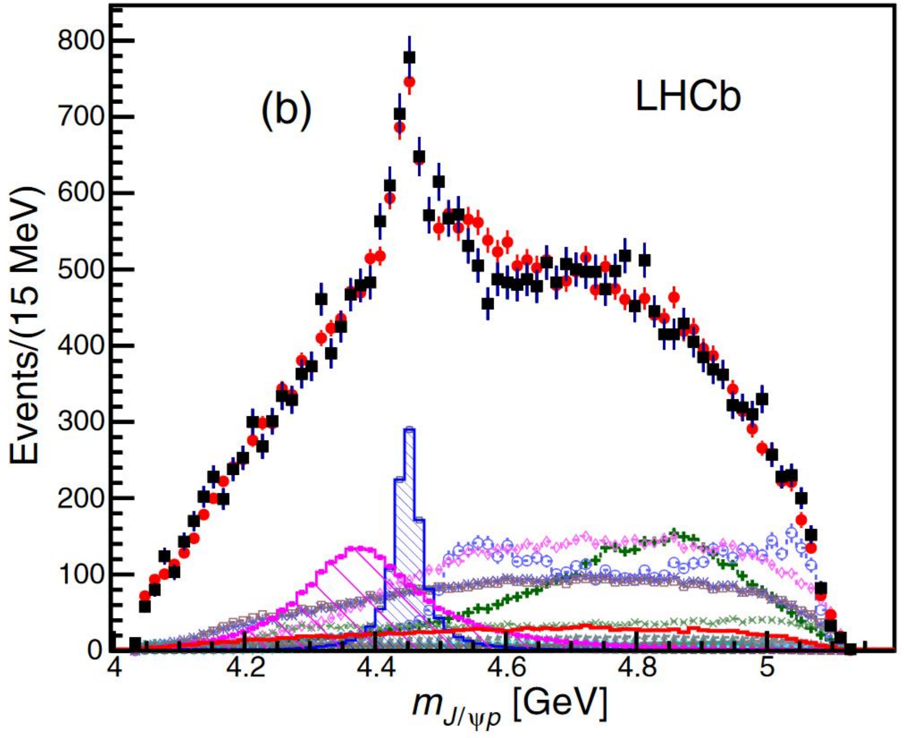
$N^*(1535)$

- $\overline{K}\Sigma - \overline{K}\Lambda$ **quasi-bound state** $qqqs\bar{s}$ — Kaiser,et.al, PLB362, 23-28(1995); Bo-Chao Liu,et.al PRL96, 042002(2006)
- **an excited state** qqq

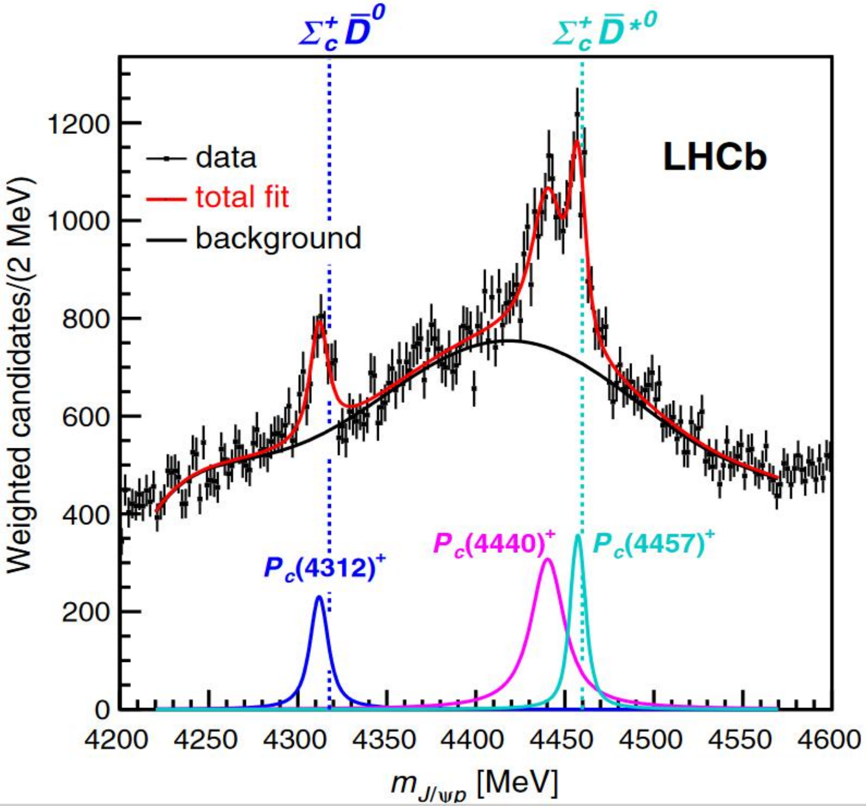
$\theta^+(1540)$ — Yan-Rui Liu,et.al PRC69, 035205(2004)

- $\overline{D}^{(*)}\Sigma_c$ **and** $\overline{D}^{(*)}\Xi_c$ **molecule states** —decay→ $J/\psi p$ **and** $J/\psi\Lambda$ **with mass above 4 GeV and width smaller than 100 MeV** — Jia-Jun Wu,et.al PRL105, 232001(2010)

In 2015, The LHCb Collboration observed two hidden-charm pentaquark states in $\Lambda_b^0 \to J/\Psi p K^-$ **channel**



$Pc(4380)^{+}, Pc(4450)^{+}$



$Pc(4312)^{+}, Pc(4440)^{+}, Pc(4457)^{+}$

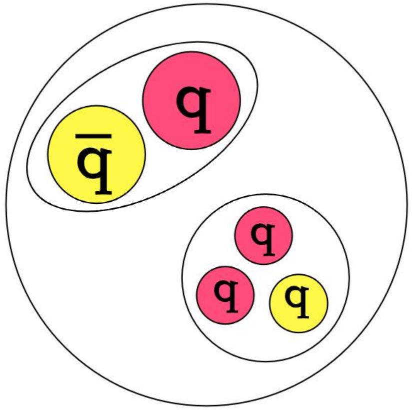
Minimal quark content $uudc\bar{c}$

R.Aaij et.al PRL115, 072001(2015)

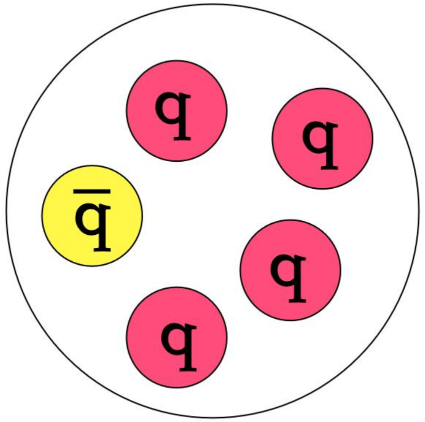
R.Aaij et.al PRL112, 222001(2019)

Background

Year		Mass(MeV)	Γ (MeV)	observed channels	
2015	$P_c(4380)^+$[1]	$4380 \pm 8 \pm 29$	$215 \pm 18 \pm 86$	$\Lambda_b^0 \to J/\psi p K^-$	$uudc\bar{c}$
2019	$P_c(4312)^+$[2]	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$\Lambda_b^0 \to J/\psi p K^-$	$uudc\bar{c}$
	$P_c(4440)^+$[2]	$4440 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.2}$	$\Lambda_b^0 \to J/\psi p K^-$	$uudc\bar{c}$
	$P_c(4457)^+$[2]	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Lambda_b^0 \to J/\psi p K^-$	$uudc\bar{c}$
2021	$P_{cs}(4459)^0$[4]	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$\Xi_b^- \to J/\psi \Lambda K^-$	$udsc\bar{c}$
2022	$P_c(4337)^+$[3]	$4337^{+7}_{-4}{}^{+2}_{-2}$	$29^{+26}_{-12}{}^{+14}_{-14}$	$B_s^0 \to J/\psi p\bar{p}$	$uudc\bar{c}$
2022	$P_{cs}(4338)^0$ [5]	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$	$B^- \to J/\psi \Lambda \bar{p}$	$udsc\bar{c}$



Molecular states are loosely bound states composed of meson-baryons by the long-range color-singlet meson exchange.



Compact pentaquark states are bound states of five quarks by the short-range one-gluon exchange

R.Aaij et.al PRL115, 072001(2015)
R.Aaij et.al PRL112, 222001(2019)
R.Aaij et.al Sci.Bull66, 1278 (2021)
R.Aaij et.al PRL 112, 063001(2022)
LHCb Collaboration arXiv:2210.10346

Guo,et.al Rev Mod Phys90, 015004(2018)
Liu,et.al Prog.Part.Nucl.Phys107, 237-320(2019)
Chen,et.al Rept.Prog.Phys86, 026201(2023)
Meng,et.al Phys Rept 1019, 1-149(2023)

Background

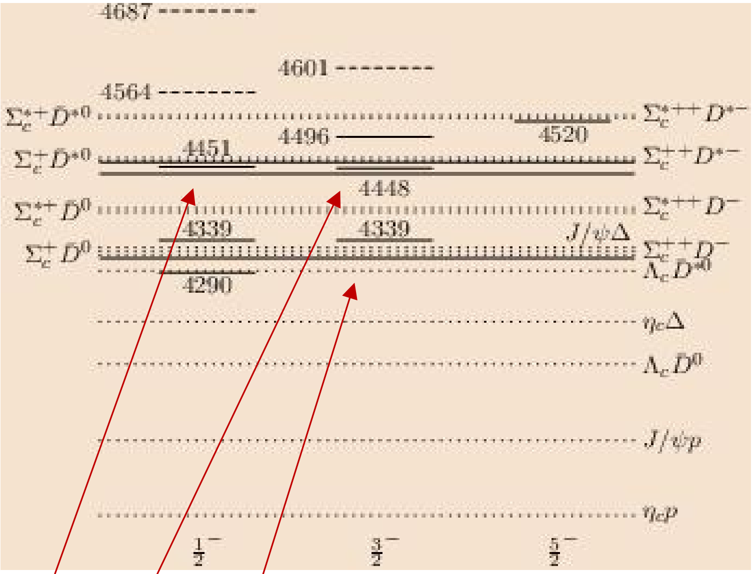
- Compact pentaquark states in chromomagnetic interaction (CMI) model.

Mass spectra are estimated by a reference
hadron-hadron channel

Jing Wu,et.al PRD95, 034002(2017)

Mass spectra and rearrangement decay properties of $(uud)_{8c}(c\bar{c})_{8c}$ **and** $(uus)_{8c}(c\bar{c})_{8c}$ **are studied**

Jian-Bo Cheng,et.al PRD100, 054002(2019)



$$P_c(4457)^+ : J^P = 3/2^-,$$
$$P_c(4440)^+ : J^P = 1/2^-,$$
$$P_c(4312)^+ : J^P = 3/2^-.$$

$Pc(4457), Pc(4440), Pc(4312)$ ➡ $J^P = 3/2^-, 1/2^-, 3/2^-$

1.Hadron-hadron threshold as reference scale
2. $(qqq)_{1c}(c\bar{c})_{1c}$ **component not considered**

➡

recontruct wave function
modify CMI model

Formalism| Mass splitting model

$$H=\sum_i m_i+\sum_i \frac{\vec{p}_i^{\,2}}{2m_i}+\sum_{i<j}\frac{\vec{\lambda}_i\vec{\lambda}_j}{4}\left(\frac{\alpha_s}{r_{ij}}-\frac{3}{4}br_{ij}-\frac{8\pi\alpha_s}{3m_im_j}S_i\cdot S_j e^{-\sigma^2r^2}\frac{\sigma^3}{\pi^{3/2}}\right)$$

$$H=\sum_i m_i-\sum C_{ij}\vec{\lambda}_i\cdot\vec{\lambda}_j\vec{\sigma}_i\cdot\vec{\sigma}_j=\sum_i m_i+H_{CMI}$$

m_i **is effctive quark mass, which contians the kinetic energy, color confinement , and so on.**

H_{CMI} **is color-magnetic interaction**

$$\mathrm{M}=\sum_i m_i+\langle H_{CMI}\rangle$$

$$M=\left[M_{ref}-\langle H_{CMI}\rangle_{ref}\right]+\langle H_{CMI}\rangle$$

Using hadron- hadron threshold as a reference

Choosing a compact state as a reference
Tetraquarks $X(4140)$ **:** $QQ\bar{Q}\bar{Q}, QQ\bar{q}\bar{q}, Qq\bar{q}\bar{q}\ldots$
Petanquarks $Pc(4312)$

Formalism| Mass splitting model

$$M = \left[M_{Pc(4312)} - \langle H_{CMI} \rangle_{Pc(4312)}\right] + \sum_{ij} \Delta_{ij} + \langle H_{CMI} \rangle$$

where $\Delta_{ij} = m_i - m_j$ **denotes the effective quark mass gap between i quark and j quark**

$$M_{nnnc\bar{c}} = (M_{P_c(4312)^+} - \langle H_{CMI} \rangle_{P_c(4312)^+}) + \langle H_{CMI} \rangle_{nnnc\bar{c}},$$
$$M_{nnsc\bar{c}} = (M_{P_c(4312)^+} - \langle H_{CMI} \rangle_{P_c(4312)^+}) + \Delta_{sn} + \langle H_{CMI} \rangle_{nnsc\bar{c}},$$
$$M_{ssnc\bar{c}} = (M_{P_c(4312)^+} - \langle H_{CMI} \rangle_{P_c(4312)^+}) + 2\Delta_{sn} + \langle H_{CMI} \rangle_{ssnc\bar{c}},$$
$$M_{sssc\bar{c}} = (M_{P_c(4312)^+} - \langle H_{CMI} \rangle_{P_c(4312)^+}) + 3\Delta_{sn} + \langle H_{CMI} \rangle_{sssc\bar{c}},$$

$(n = u, d)$

Quark mass differences (units: MeV) determined with various hadrons. The values from the extracted effective quark masses are $m_s - m_n = 178.6$ MeV and $m_b - m_c = 3328.2$ MeV.

Hadron	Hadron	$(m_s - m_n)$	Hadron	Hadron	$(m_b - m_c)$
D_s	D	103.5	B	D	3340.9
B_s	B	90.8	B_s	D_s	3328.2
Σ	N	187.1	η_b	η_c	3188.4
Λ	N	177.4	Λ_b	Λ_c	3333.1
Ω_c	Σ_c	158.8	Σ_b	Σ_c	3328.5
Ω_b	Σ_b	147.9	Ξ_b	Ξ_c	3326.2
Ξ_c	Λ_c	133.4	Ω_b	Ω_c	3315.7
Ξ_c	Σ_c	119.5			
Ξ_b	Λ_b	126.9			
Ξ_b	Σ_b	117.6			

Formalism| Wave function

$(I=\frac{3}{2},Y=1,J=\frac{5}{2})$	$[(F_S)^S_A(c\bar{c})^1_1]^{\frac{5}{2}}_1$
$(I=\frac{3}{2},Y=1,J=\frac{3}{2})$	$\frac{1}{\sqrt{2}}\{[(F_S)^{MS}_{MA}(c\bar{c})^1_8]^{\frac{3}{2}}_1-[(F_S)^{MA}_{MS}(c\bar{c})^1_8]^{\frac{3}{2}}_1\}$; $[(F_S)^S_A(c\bar{c})^0_1]^{\frac{3}{2}}_1$;$[(F_S)^S_A(c\bar{c})^1_1]^{\frac{3}{2}}_1$
$(I=\frac{3}{2},Y=1,J=\frac{1}{2})$	$\frac{1}{\sqrt{2}}\{[(F_S)^{MS}_{MA}(c\bar{c})^0_8]^{\frac{1}{2}}_1-[(F_S)^{MA}_{MS}(c\bar{c})^0_8]^{\frac{1}{2}}_1\}$; $\frac{1}{\sqrt{2}}\{[(F_S)^{MS}_{MA}(c\bar{c})^1_8]^{\frac{1}{2}}_1-[(F_S)^{MA}_{MS}(c\bar{c})^1_8]^{\frac{1}{2}}_1\}$; $[(F_S)^S_A(c\bar{c})^1_1]^{\frac{1}{2}}_1$
$(I=\frac{1}{2},Y=1,J=\frac{5}{2})$	$\frac{1}{\sqrt{2}}\{[(F_{MS})^S_{MA}(c\bar{c})^1_8]^{\frac{5}{2}}-[(F_{MA})^S_{MS}(c\bar{c})^1_8]^{\frac{5}{2}}\}$
$(I=\frac{1}{2},Y=1,J=\frac{3}{2})$	$\frac{1}{2}\{[(F_{MS})^{MA}_{MS}(c\bar{c})^1_8]^{\frac{3}{2}}+[(F_{MA})^{MS}_{MS}(c\bar{c})^1_8]^{\frac{3}{2}}+[(F_{MS})^{MS}_{MA}(c\bar{c})^1_8]^{\frac{3}{2}}-[(F_{MA})^{MA}_{MA}(c\bar{c})^1_8]^{\frac{3}{2}}\}$ $\frac{1}{\sqrt{2}}\{[(F_{MS})^S_{MA}(c\bar{c})^0_8]^{\frac{3}{2}}-[(F_{MA})^S_{MS}(c\bar{c})^0_8]^{\frac{3}{2}}\}$ $\frac{1}{\sqrt{2}}\{[(F_{MS})^S_{MA}(c\bar{c})^1_8]^{\frac{3}{2}}-[(F_{MA})^S_{MS}(c\bar{c})^1_8]^{\frac{3}{2}}\}$ $\frac{1}{\sqrt{2}}\{[(F_{MS})^{MS}_A(c\bar{c})^1_1]^{\frac{3}{2}}+[(F_{MA})^{MA}_A(c\bar{c})^1_1]^{\frac{3}{2}}\}$
$(I=0,Y=0,J=\frac{5}{2})$	$[(D_As)^S_{MS}(c\bar{c})^1_8]^{\frac{5}{2}}_1$
$(I=0,Y=0,J=\frac{3}{2})$	$[(D_As)^{MS}_{MS}(c\bar{c})^1_8]^{\frac{3}{2}}_1$; $[(D_As)^S_{MS}(c\bar{c})^0_8]^{\frac{3}{2}}_1$; $[(D_As)^S_{MS}(c\bar{c})^1_8]^{\frac{3}{2}}_1$; $[(D_As)^{MA}_{MA}(c\bar{c})^1_8]^{\frac{3}{2}}_1$; $[(D_As)^{MA}_A(c\bar{c})^1_1]^{\frac{3}{2}}_1$
$(I=0,Y=0,J=\frac{1}{2})$	$[(D_As)^{MS}_{MS}(c\bar{c})^0_8]^{\frac{1}{2}}_1$; $[(D_As)^{MS}_{MS}(c\bar{c})^1_8]^{\frac{1}{2}}_1$; $[(D_As)^S_{MS}(c\bar{c})^1_8]^{\frac{1}{2}}_1$; $[(D_As)^{MA}_{MA}(c\bar{c})^0_8]^{\frac{1}{2}}_1$ $[(D_As)^{MA}_{MA}(c\bar{c})^1_8]^{\frac{1}{2}}_1$ $[(D_As)^{MA}_A(c\bar{c})^0_1]^{\frac{1}{2}}_1$; $[(D_As)^{MA}_A(c\bar{c})^1_1]^{\frac{1}{2}}_1$

Flavor wave function

$$F_S = nnn$$

$$F_{MS} = \frac{1}{\sqrt{2}}(ud+du)u$$

$$F_{MA} = \frac{1}{\sqrt{2}}(ud-du)u$$

$$D_S = \frac{1}{\sqrt{2}}(ud+du)$$

$$D_A = \frac{1}{\sqrt{2}}(ud-du)$$

$$[(qqq_{flavor})^{spin}_{color}(c\bar{c})^{spin}_{color}]^{spin}_{color}(q=u,d,s)$$

$$[(F_S)^S_A(c\bar{c})^1_1]^{5/2}_1=(uuu)c\bar{c}\uparrow\uparrow\uparrow\uparrow\uparrow\phi_A$$

$$\langle H_{CMI}\rangle_{J=\frac{5}{2}}=8C_{12}+\frac{16}{3}C_{45}$$

Formalism| Rearrangement decay

A simple decay scheme

We assume that the Hamiltonian is a constant $H=\alpha$ and the sum of two-body rearrangement decay widths is equal to the measured width $\Gamma_{sum}=\Gamma_{total}$

$$
\begin{aligned}
(q_1q_2q_3)(c\bar{c}) &\to (q_1q_2c)_{1c} + (q_3\bar{c})_{1c},\\
(q_1q_2q_3)(c\bar{c}) &\to (q_1cq_3)_{1c} + (q_2\bar{c})_{1c},\\
(q_1q_2q_3)(c\bar{c}) &\to (cq_2q_3)_{1c} + (q_1\bar{c})_{1c},\\
(q_1q_2q_3)(c\bar{c}) &\to (q_1q_2q_3)_{1c} + (c\bar{c})_{1c}.
\end{aligned}
$$

$$\mathcal{M}^2 = \alpha^2 |\sum_i (x_i y_i)|^2$$

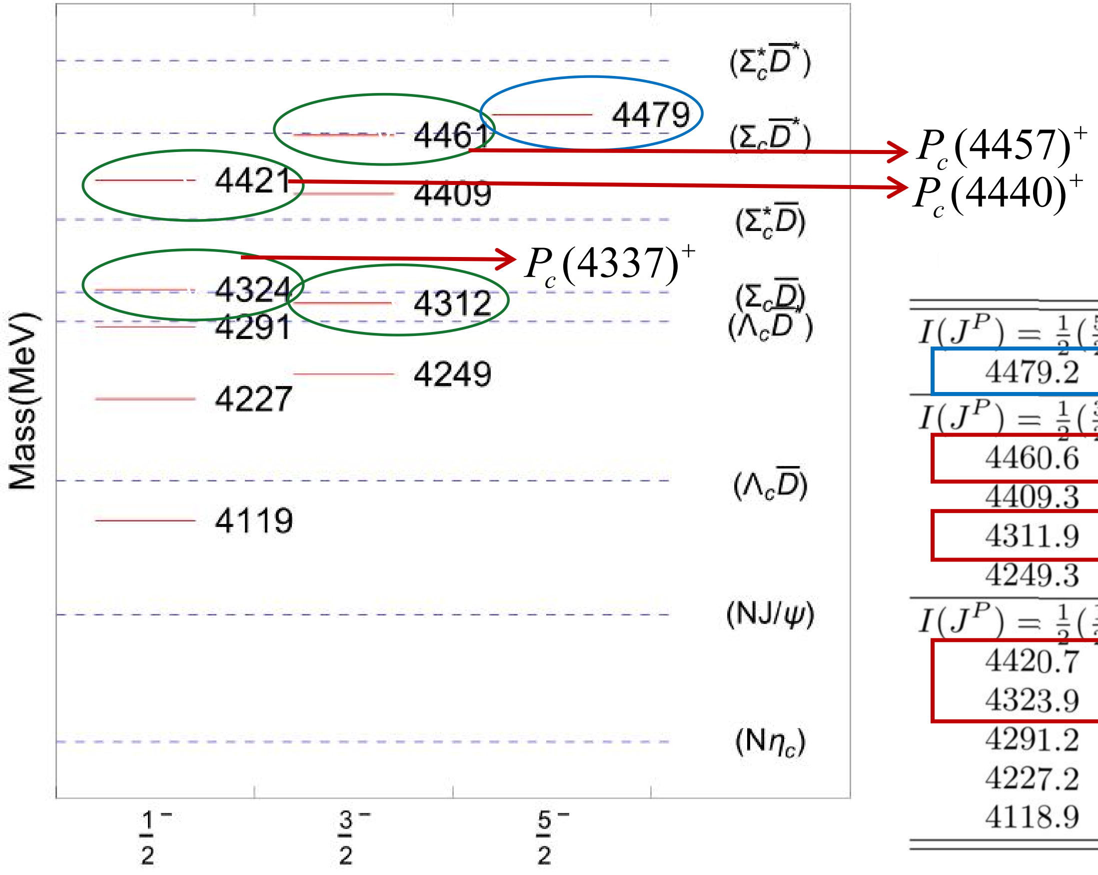
$$\Gamma = |\mathcal{M}|^2 \frac{|\vec{p}_1|}{8\pi M^2_{pentaquark}}.$$

J		$(I,Y)=(\frac{3}{2},1)$				
$\frac{5}{2}$		$\Sigma_c^* D^*$	$\Delta J/\psi$			
	$[(F_s)_1^{3/2}(c\bar{c})_1^1]_1^{5/2}$	$\frac{1}{3}$	1			
		$\Sigma_c^* D^*$	$\Sigma_c^* D$	$\Sigma_c D^*$	$\Delta J/\psi$	$\Delta\eta_c$
$\frac{3}{2}$	Ψ_1	$\frac{2\sqrt{5}}{9}$	$-\frac{2}{3\sqrt{3}}$	$\frac{2}{9}$	0	0
	$[(F_s)_1^{\frac{3}{2}}(c\bar{c})_1^0]_1^{\frac{3}{2}}$	$\frac{\sqrt{5}}{6\sqrt{3}}$	$\frac{1}{6}$	$-\frac{1}{3\sqrt{3}}$	1	0
	$[(F_s)_1^{\frac{3}{2}}(c\bar{c})_1^1]_1^{\frac{3}{2}}$	$\frac{1}{18}$	$\frac{\sqrt{5}}{6\sqrt{3}}$	$\frac{\sqrt{5}}{9}$	0	1
		$\Sigma_c^* D^*$	$\Sigma_c D^*$	$\Sigma_c D$	$\Delta J/\psi$	
$\frac{1}{2}$	Ψ_2	$\frac{2\sqrt{2}}{3\sqrt{3}}$	$-\frac{1}{3\sqrt{3}}$	$\frac{1}{3}$	0	
	Ψ_3	$\frac{2\sqrt{2}}{9}$	$\frac{5}{9}$	$-\frac{1}{3\sqrt{3}}$	0	
	$[(F_s)_1^{\frac{3}{2}}(c\bar{c})_1^1]_1^{\frac{1}{2}}$	$-\frac{1}{9}$	$\frac{\sqrt{2}}{9}$	$\frac{\sqrt{2}}{3\sqrt{3}}$	1	

Results for $nnnc\bar{c}$

We assum that the $P_c(4312)^+$ is the second lowest $I(J^P)=1/2(3/2^-)nnnc\bar{c}$ compact pentaquark and treat it as the reference state in studying other pentaquraks

Eigenvalue (MeV)	Eigenvector	Ratio
78.0	{0.264, -0.270, -0.224, 0.898}	0.980:0.020
26.8	{0.489, -0.324, 0.809, -0.040}	0.998:0.002
-70.7	{-0.686, 0.259, 0.539, 0.414}	0.829:0.171
-133.3	{0.264, -0.270, -0.224, 0.898}	0.193:0.807



$I=\frac{1}{2}$ $nnnc\bar{c}$ states

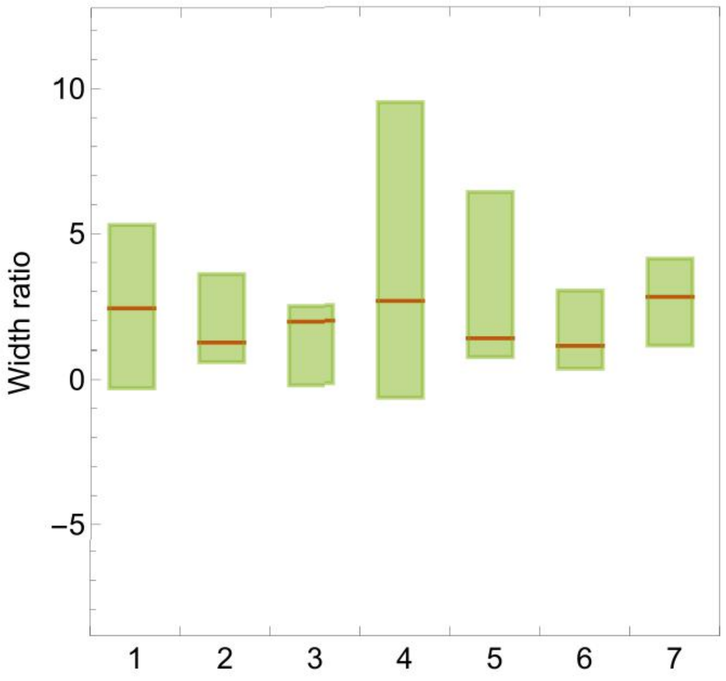
Rearrangement decay widths for the $I=\frac{1}{2}, Y=1$ $nnnc\bar{c}$ states in units of MeV.

$I(J^P)=\frac{1}{2}(\frac{5}{2}^-)$	$\Sigma_c^*\bar{D}^*$	Γ_{sum}
4479.2	(11.1,–)	0.0

$I(J^P)=\frac{1}{2}(\frac{3}{2}^-)$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}^*$	$\Lambda_c\bar{D}^*$	NJ/ψ	Γ_{sum}
4460.6	(32.7,–)	(3.0,1.6)	(4.6,–)	(3.5,2.8)	(2.0,0.7)	5.0
4409.3	(1.3,–)	(1.3,0.4)	(36.0,–)	(5.8,3.8)	(0.2,0.1)	4.2
4311.9	(0.0,–)	(20.2,–)	(0.9,–)	(17.7,4.6)	(17.1,5.2)	9.8
4249.3	(1.2,–)	(14.5,–)	(1.1,–)	(0.8,–)	(80.7,22.0)	22.0

$I(J^P)=\frac{1}{2}(\frac{1}{2}^-)$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c\bar{D}^*$	$\Sigma_c\bar{D}$	$\Lambda_c\bar{D}^*$	$\Lambda_c\bar{D}$	NJ/ψ	$N\eta_c$	Γ_{sum}
4420.7	(18.8,–)	(9.1,–)	(1.1,0.6)	(13.3,9.1)	(0.6,0.6)	(4.4,1.5)	(0.6,0.2)	12.1
4323.9	(7.9,–)	(20.5,–)	(0.8,0.1)	(0.7,0.2)	(8.2,6.8)	(16.9,5.2)	(2.3,0.9)	13.2
4291.2	(2.3,–)	(0.9,–)	(15.4,–)	(12.1,–)	(2.6,2.0)	(19.4,5.7)	(14.0,5.0)	12.7
4227.2	(0.1,–)	(0.2,–)	(10.5,–)	(1.0,–)	(12.3,6.9)	(59.3,15.4)	(1.7,0.6)	22.9
4118.9	(0.5,–)	(0.9,–)	(11.2,–)	(0.7,–)	(4.1,–)	(0.0,0.0)	(81.4,22.5)	22.5

Results for $nnnc\bar{c}$



Theoretical states

$$\Gamma(\tilde{P}_c(4421)^+):\Gamma(\tilde{P}_c(4461)^+) = 2.42,$$
$$\Gamma(\tilde{P}_c(4421)^+):\Gamma(\tilde{P}_c(4312)^+) = 1.24,$$
$$\Gamma(\tilde{P}_c(4312)^+):\Gamma(\tilde{P}_c(4461)^+) = 1.96,$$
$$\Gamma(\tilde{P}_c(4324)^+):\Gamma(\tilde{P}_c(4461)^+) = 2.64,$$
$$\Gamma(\tilde{P}_c(4324)^+):\Gamma(\tilde{P}_c(4312)^+) = 1.35,$$
$$\Gamma(\tilde{P}_c(4324)^+):\Gamma(\tilde{P}_c(4421)^+) = 1.09.$$

Experimental states

$$\Gamma(P_c(4440)^+):\Gamma(P_c(4457)^+) = 3.2^{+2.1}_{-3.5},$$
$$\Gamma(P_c(4440)^+):\Gamma(P_c(4312)^+) = 2.1^{+1.5}_{-1.5},$$
$$\Gamma(P_c(4312)^+):\Gamma(P_c(4457)^+) = 1.5^{+1.0}_{-1.7},$$
$$\Gamma(P_c(4337)^+):\Gamma(P_c(4457)^+) = 4.5^{+5.0}_{-5.2},$$
$$\Gamma(P_c(4337)^+):\Gamma(P_c(4312)^+) = 3.0^{+3.4}_{-2.3},$$
$$\Gamma(P_c(4337)^+):\Gamma(P_c(4440)^+) = 1.4^{+1.6}_{-1.1}.$$

Ratios between decay widths of different pentaquarks

$P_c(4457)^+, P_c(4440)^+, P_c(4337)^+$ **can be regarded as the J=3/2, J=1/2, and J=1/2 pentaquark states, respectively.**

For $P_c(4457)^+$ $\quad \Gamma(\Sigma_c^* \bar{D}):\Gamma(\Lambda_c \bar{D}^*):\Gamma(NJ/\Psi) = 2.3:4.0:1.0$

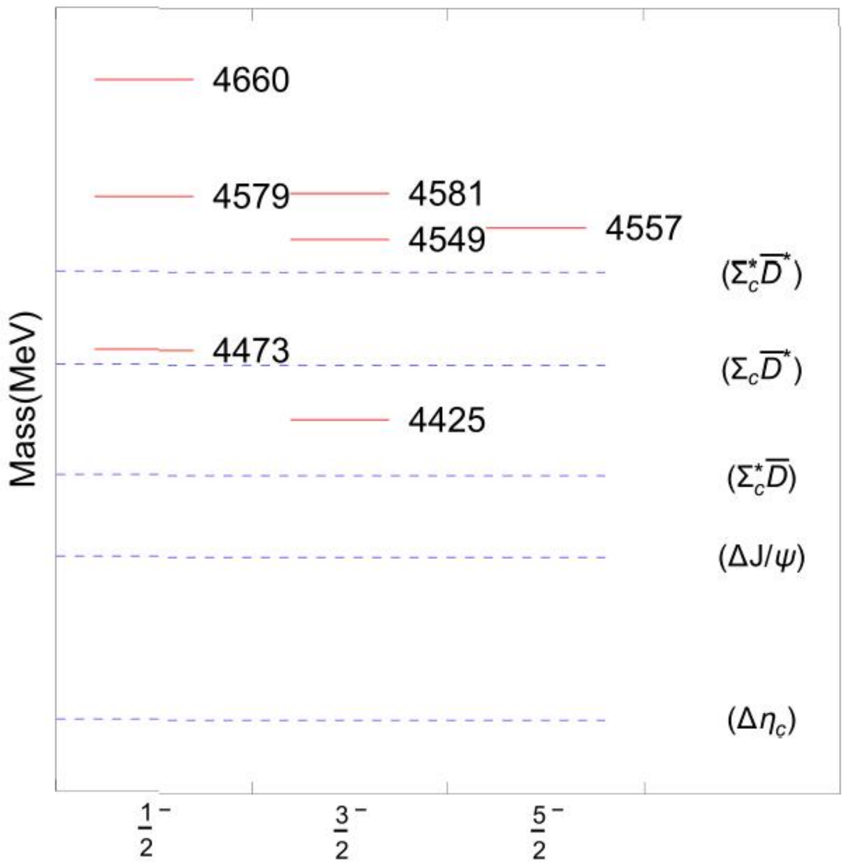
For $P_c(4440)^+$ $\quad \Gamma(\Lambda_c \bar{D}^*):\Gamma(\Sigma_c \bar{D}):\Gamma(\Lambda_c \bar{D}):\Gamma(NJ/\Psi):\Gamma(N\eta_c) = 45.5:3.0:3.0:7.5:1.0$

For $P_c(4312)^+$ $\quad \Gamma(NJ/\Psi):\Gamma(\Lambda_c \bar{D}^*) = 1.1$

For $P_c(4337)^+$ $\quad \Gamma(\Lambda_c \bar{D}):\Gamma(NJ/\Psi) = 1.3$

Prediction

Results for $nnnc\bar{c}$



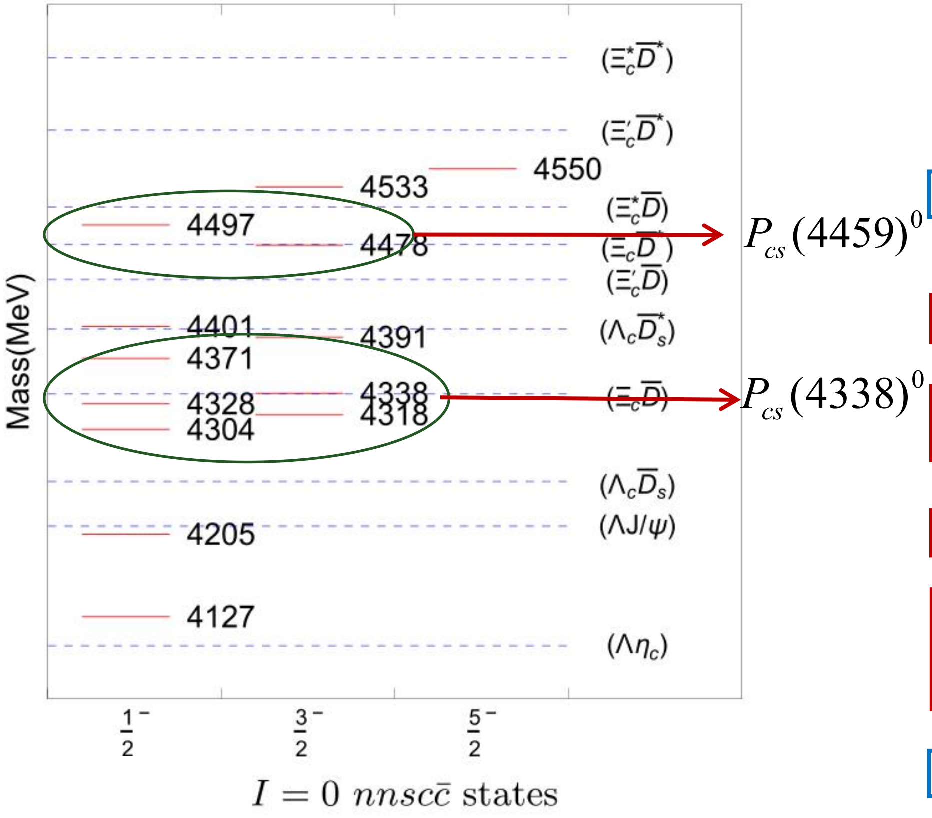
$I=\frac{3}{2}$ $nnnc\bar{c}$ states

Rearrangement decay widths for the $I=\frac{3}{2}, Y=1$ $nnnc\bar{c}$ states in units of MeV.

$I(J^P)=\frac{3}{2}(\frac{5}{2}^-)$	$\Sigma_c^*\bar{D}^*$	$\Delta J/\psi$				Γ_{sum}
4557.2	(11.1,3.6)	(100.0,26.9)				30.4
$I(J^P)=\frac{3}{2}(\frac{3}{2}^-)$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c^*\bar{D}$	$\Sigma_c\bar{D}^*$	$\Delta J/\psi$	$\Delta\eta_c$	Γ_{sum}
4581.0	(24.0,10.2)	(2.2,1.8)	(6.4,4.1)	(8.2,2.3)	(27.4,9.3)	27.6
4548.6	(5.6,1.5)	(10.8,8.0)	(2.2,1.2)	(5.0,1.3)	(72.4,23.7)	35.8
4425.2	(0.1,–)	(9.2,3.5)	(6.2,–)	(86.8,15.8)	(0.2,0.0)	19.4
$I(J^P)=\frac{3}{2}(\frac{1}{2}^-)$	$\Sigma_c^*\bar{D}^*$	$\Sigma_c\bar{D}^*$	$\Sigma_c\bar{D}$	$\Delta J/\psi$		Γ_{sum}
4660.1	(37.2,24.3)	(0.5,0.4)	(0.1,0.1)	(20.1,6.3)		31.0
4579.3	(1.0,0.4)	(28.8,18.1)	(0.0,0.0)	(43.7,12.2)		30.8
4473.3	(2.5,–)	(7.8,1.5)	(22.2,16.3)	(36.2,7.9)		25.8

Compared with the $I=1/2\,nnnc\bar{c}$ pentaquarks, the masses and rearrangement decay widths of $I=3/2$ states are overall larger.

Results for $nnsc\bar{c}$



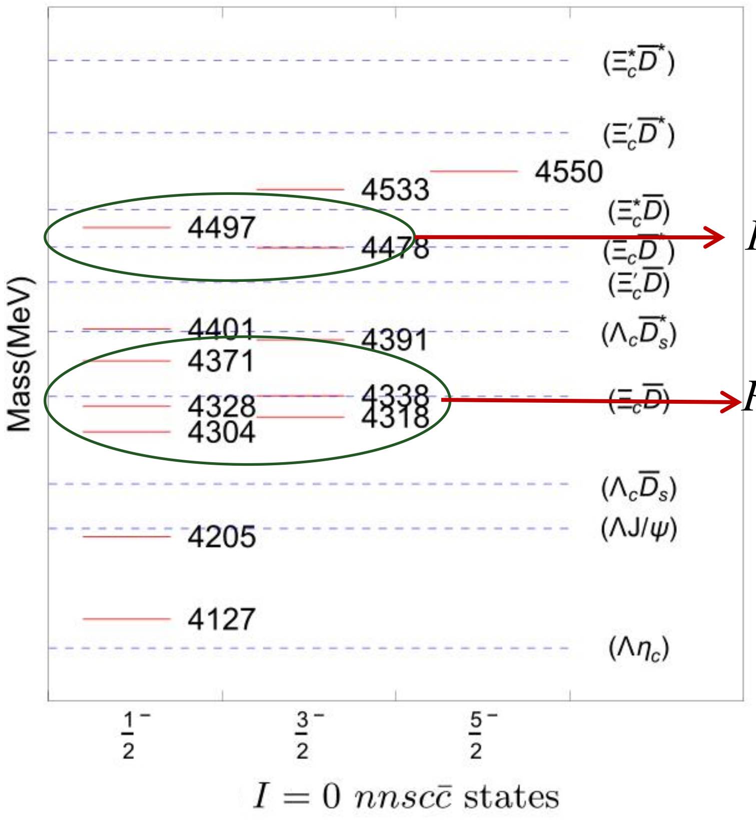
Rearrangement decay widths for the $I=0, Y=0$ $nnsc\bar{c}$ states in units of MeV.

$I(J^P)=0(\frac{5}{2}^-)$	$\Xi_c^*\bar{D}^*$									Γ_{sum}
4549.8	(66.7,–)									0.0
$I(J^P)=0(\frac{3}{2}^-)$	$\Lambda_c\bar{D}_s^*$	$\Xi_c^*\bar{D}^*$	$\Xi_c^*\bar{D}$	$\Xi_c'\bar{D}^*$	$\Xi_c\bar{D}^*$	$\Lambda J/\psi$				Γ_{sum}
4533.1	(6.0,1.4)	(49.9,–)	(4.2,0.7)	(5.4,–)	(3.0,0.9)	(2.3,0.7)				3.7
4478.2	(9.3,1.7)	(1.2,–)	(1.3,–)	(54.9,–)	(4.4,–)	(0.3,0.1)				1.8
4391.2	(20.0,–)	(0.1,–)	(24.8,–)	(2.1,–)	(17.5,–)	(24.3,6.0)				6.0
4337.9	(11.0,–)	(1.0,–)	(21.7,–)	(1.3,–)	(2.6,–)	(69.3,14.6)				14.6
4317.6	(53.7,–)	(0.6,–)	(6.3,–)	(0.2,–)	(30.9,–)	(3.8,0.7)				0.7
$I(J^P)=0(\frac{1}{2}^-)$	$\Lambda_c\bar{D}_s^*$	$\Lambda_c\bar{D}_s$	$\Xi_c^*\bar{D}^*$	$\Xi_c'\bar{D}^*$	$\Xi_c'\bar{D}$	$\Xi_c\bar{D}^*$	$\Xi_c\bar{D}$	$\Lambda J/\psi$	$\Lambda\eta_c$	Γ_{sum}
4497.0	(21.0,4.2)	(0.9,0.3)	(28.3,–)	(12.1,–)	(1.2,0.3)	(11.6,2.0)	(0.4,0.2)	(5.8,1.8)	(0.6,0.2)	8.9
4401.4	(0.8,0.0)	(10.6,2.6)	(10.8,–)	(31.2,–)	(0.6,–)	(1.0,–)	(4.9,1.6)	(20.5,5.2)	(3.0,1.0)	10.4
4371.4	(12.1,–)	(6.0,1.3)	(4.4,–)	(2.3,–)	(18.4,–)	(12.5,–)	(2.0,0.5)	(25.1,5.9)	(15.1,4.7)	12.4
4327.7	(40.7,–)	(4.2,0.8)	(0.1,–)	(0.2,–)	(2.4,–)	(30.0,–)	(3.1,–)	(12.1,2.4)	(0.0,0.0)	3.2
4304.3	(24.9,–)	(18.9,2.8)	(0.2,–)	(0.0,–)	(16.1,–)	(3.9,–)	(5.4,–)	(36.4,6.6)	(4.5,1.2)	10.7
4205.1	(0.4,–)	(4.9,–)	(0.6,–)	(1.2,–)	(19.5,–)	(0.5,–)	(3.9,–)	(0.1,–)	(76.5,15.6)	15.6
4127.0	(0.1,–)	(54.6,–)	(0.1,–)	(0.1,–)	(0.1,–)	(0.1,–)	(38.7,–)	(0.0,–)	(0.3,0.0)	0.0

I=0 case, five pentaquarks have masses around 4338 MeV and two pentaquarks have masses close to 4459 MeV.

Just from the spectrum, two J=3/2 pentaquark states are good candidates for the $P_{cs}(4338)^0$ and $P_{cs}(4459)^0$, but there are also other possibilities.

$$\Gamma(P_{cs}(4459)^0):\Gamma(P_{cs}(4338)^0)=2.5^{+1.6}_{-1.4}$$



$P_{cs}(4459)^0$

$P_{cs}(4338)^0$

If we assign the $P_{cs}(4459)^0, P_{cs}(4338)^0$ to be J=3/2 pentaquark states $\tilde{P}_{cs}(4478), \tilde{P}_{cs}(4338)$, respectively, $\Gamma(\tilde{P}_{cs}(4478)^0):\Gamma(\tilde{P}_{cs}(4338)^0)\sim 0.12$ which is contradicted with the experimantal value.

Other possible assignments:

$$\begin{aligned}
\Gamma(\tilde{P}_{cs}(4478)^0):\Gamma(\tilde{P}_{cs}(4371)^0) &= 0.15,\\
\Gamma(\tilde{P}_{cs}(4478)^0):\Gamma(\tilde{P}_{cs}(4328)^0) &= 0.56,\\
\boxed{\Gamma(\tilde{P}_{cs}(4478)^0):\Gamma(\tilde{P}_{cs}(4318)^0) = 2.57,}\\
\Gamma(\tilde{P}_{cs}(4478)^0):\Gamma(\tilde{P}_{cs}(4304)^0) &= 0.17,\\
\Gamma(\tilde{P}_{cs}(4497)^0):\Gamma(\tilde{P}_{cs}(4371)^0) &= 0.72,\\
\Gamma(\tilde{P}_{cs}(4497)^0):\Gamma(\tilde{P}_{cs}(4338)^0) &= 0.61,\\
\boxed{\Gamma(\tilde{P}_{cs}(4497)^0):\Gamma(\tilde{P}_{cs}(4328)^0) = 2.78,}\\
\Gamma(\tilde{P}_{cs}(4497)^0):\Gamma(\tilde{P}_{cs}(4318)^0) &= 12.71,\\
\Gamma(\tilde{P}_{cs}(4497)^0):\Gamma(\tilde{P}_{cs}(4304)^0) &= 0.83.
\end{aligned}$$

Theoretical widths are much smaller than the measured results.

$P_{cs}(4338)^0$ and $P_{cs}(4459)^0$ can be regarded as the $J^P=1/2^-$ pentaquark states, respectively.

For $P_{cs}(4338)^0$, $\boxed{\Gamma(\Lambda J/\Psi)}:\Gamma(\Lambda_c\bar{D}_s)=3.0$

For $P_{cs}(4457)^0$, $\Gamma(\Lambda_c\bar{D}_s^*):\Gamma(\Xi_c\bar{D}^*):\boxed{\Gamma(\Lambda J/\Psi)}=2.3:1.1:1.0$

Prediction

The widths of J=5/2 state, the lighest J=3/2 state, and the lighest J=1/2 state are narrow.

Results for $nns c\bar{c}$

Rearrangement decay widths for the $I=1, Y=0$ $nns c\bar{c}$ states in units of MeV.

$I(J^P)=1(\frac{5}{2}^-)$	$\Sigma_c^*\bar{D}_s^*$	$\Xi_c^*\bar{D}^*$	$\Sigma^* J/\psi$	Γ_{sum}
4614.2	(10.2,–)	(11.6,–)	(100.0,20.6)	20.6
4575.0	(89.8,–)	(21.8,–)	(0.0,0.0)	0.0

$I(J^P)=1(\frac{3}{2}^-)$	$\Sigma_c^*\bar{D}_s^*$	$\Sigma_c^*\bar{D}_s$	$\Sigma_c\bar{D}_s^*$	$\Xi_c^*\bar{D}^*$	$\Xi_c^*\bar{D}$	$\Xi_c'\bar{D}^*$	$\Xi_c\bar{D}^*$	$\Sigma^* J/\psi$	$\Sigma^*\eta_c$	$\Sigma J/\psi$	Γ_{sum}
4633.1	(18.8,0.6)	(1.3,0.3)	(6.9,1.1)	(23.4,–)	(1.3,0.5)	(6.7,1.8)	(0.0,0.0)	(35.5,7.8)	(8.0,2.3)	(0.0,0.0)	14.4
4604.2	(7.3,–)	(11.1,2.3)	(2.0,0.2)	(8.0,–)	(11.4,4.1)	(1.5,0.3)	(0.0,0.0)	(64.3,12.8)	(6.7,1.9)	(0.0,0.0)	21.6
4565.4	(72.4,–)	(3.9,0.7)	(3.1,–)	(15.5,–)	(1.1,0.3)	(0.9,–)	(7.9,2.9)	(0.0,0.0)	(0.1,0.0)	(3.2,0.9)	4.8
4512.5	(0.3,–)	(0.2,0.0)	(72.1,–)	(0.0,–)	(0.1,–)	(18.2,–)	(11.0,2.6)	(0.0,0.0)	(0.0,0.0)	(2.0,0.5)	3.1
4480.7	(0.0,–)	(7.5,–)	(7.1,–)	(0.0,–)	(10.7,–)	(5.9,–)	(0.0,0.0)	(0.2,–)	(85.0,16.9)	(0.0,0.0)	17.0
4436.6	(0.6,–)	(15.0,–)	(8.3,–)	(0.2,–)	(2.8,–)	(2.7,–)	(22.0,–)	(0.0,–)	(0.1,0.0)	(53.9,12.2)	12.2
4387.5	(0.6,–)	(61.1,–)	(0.5,–)	(0.1,–)	(14.3,–)	(0.1,–)	(0.7,–)	(0.0,–)	(0.0,0.0)	(40.8,7.7)	7.7

$I(J^P)=1(\frac{1}{2}^-)$	$\Sigma_c^*\bar{D}_s^*$	$\Sigma_c\bar{D}_s^*$	$\Sigma_c\bar{D}_s$	$\Xi_c^*\bar{D}^*$	$\Xi_c'\bar{D}^*$	$\Xi_c'\bar{D}$	$\Xi_c\bar{D}^*$	$\Xi_c\bar{D}$	$\Sigma^* J/\psi$	$\Sigma\eta_c$	$\Sigma J/\psi$	Γ_{sum}
4712.0	(35.2,5.9)	(0.3,0.1)	(0.0,0.0)	(37.1,10.4)	(0.3,0.1)	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(23.0,6.0)	(0.0,0.0)	(0.0,0.0)	22.6
4630.9	(1.3,0.0)	(27.9,4.3)	(0.0,0.0)	(1.8,–)	(28.1,7.1)	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(44.1,9.6)	(0.0,0.0)	(0.0,0.0)	21.1
4539.9	(36.0,–)	(8.3,–)	(2.1,0.5)	(10.6,–)	(5.0,–)	(0.1,0.0)	(21.4,6.6)	(0.9,0.5)	(0.7,0.1)	(0.6,0.2)	(9.2,2.6)	10.5
4523.0	(6.6,–)	(11.6,–)	(20.0,4.0)	(1.3,–)	(7.1,–)	(22.4,7.8)	(0.5,0.1)	(0.0,0.0)	(32.2,3.8)	(0.0,0.0)	(0.3,0.1)	15.8
4453.3	(9.8,–)	(47.3,–)	(0.4,0.1)	(2.4,–)	(11.1,–)	(0.1,0.0)	(2.8,–)	(6.9,3.0)	(0.0,–)	(2.9,0.9)	(25.5,6.0)	10.0
4420.2	(8.2,–)	(2.5,–)	(12.8,–)	(2.3,–)	(0.7,–)	(3.2,–)	(12.0,–)	(9.3,3.5)	(0.0,–)	(18.8,5.5)	(34.4,7.4)	16.3
4362.6	(0.2,–)	(1.0,–)	(30.0,–)	(0.0,–)	(0.3,–)	(7.1,–)	(4.7,–)	(19.0,4.0)	(0.0,–)	(9.6,2.5)	(30.5,5.0)	11.5
4262.8	(0.0,–)	(1.1,–)	(34.5,–)	(0.1,–)	(0.2,–)	(8.5,–)	(0.2,–)	(5.5,–)	(0.0,–)	(68.1,12.7)	(0.1,–)	12.7

The light J=5/2 should be a narrow one, which can be searched for in $\Lambda\pi J/\Psi$ channel.

Results for $ssnc\bar{c}$

Rearrangement decay widths for the $I=\frac{1}{2}, Y=-1$ $ssnc\bar{c}$ states in units of MeV.

$I(J^P)=\frac{1}{2}(\frac{5}{2}^-)$	$\Omega_c^*\bar{D}^*$	$\Xi_c^*\bar{D}_s^*$	$\Xi^* J/\psi$	Γ_{sum}
4671.2	(12.1,–)	(10.6,–)	(100.0,11.5)	11.5
4633.0	(87.9,–)	(22.7,–)	(0.0,0.0)	0.0

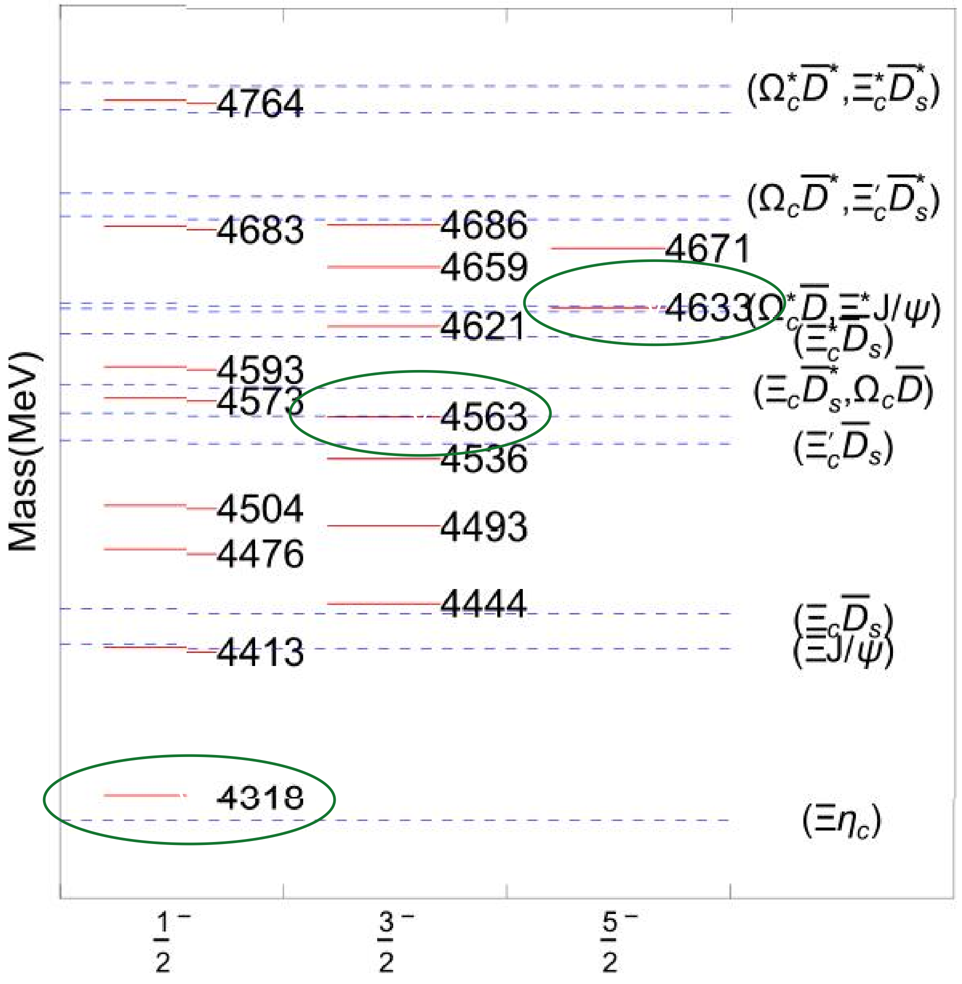
$I(J^P)=\frac{1}{2}(\frac{3}{2}^-)$	$\Omega_c^*\bar{D}^*$	$\Omega_c^*\bar{D}$	$\Omega_c\bar{D}^*$	$\Xi_c^*\bar{D}_s^*$	$\Xi_c^*\bar{D}_s$	$\Xi_c'\bar{D}_s^*$	$\Xi_c\bar{D}_s^*$	$\Xi^* J/\psi$	$\Xi^*\eta_c$	$\Xi J/\psi$	Γ_{sum}
4685.7	(21.8,–)	(0.5,0.1)	(7.0,–)	(17.5,–)	(0.5,0.2)	(7.3,–)	(0.0,0.0)	(46.0,6.1)	(7.3,1.7)	(0.0,0.0)	8.0
4659.3	(11.5,–)	(11.9,1.1)	(0.9,–)	(10.3,–)	(11.5,2.9)	(1.2,–)	(0.0,0.0)	(53.7,5.2)	(9.2,2.0)	(0.0,0.0)	11.2
4621.2	(65.0,–)	(4.7,–)	(4.5,–)	(19.0,–)	(1.1,0.1)	(1.0,–)	(6.8,1.7)	(0.0,–)	(0.1,0.0)	(3.4,0.9)	2.6
4563.3	(0.4,–)	(0.7,–)	(72.9,–)	(0.2,–)	(0.1,–)	(18.0,–)	(10.5,–)	(0.0,–)	(0.0,0.0)	(1.5,0.3)	0.3
4535.9	(0.0,–)	(12.5,–)	(5.8,–)	(0.0,–)	(8.9,–)	(6.9,–)	(0.0,–)	(0.2,–)	(83.2,6.8)	(0.1,0.0)	6.8
4492.7	(0.6,–)	(11.0,–)	(8.5,–)	(0.1,–)	(3.7,–)	(1.6,–)	(23.2,–)	(0.0,–)	(0.1,–)	(56.0,9.1)	9.1
4444.0	(0.6,–)	(58.7,–)	(0.5,–)	(0.2,–)	(15.8,–)	(0.2,–)	(1.0,–)	(0.0,–)	(0.0,–)	(39.0,3.9)	3.9

$I(J^P)=\frac{1}{2}(\frac{1}{2}^-)$	$\Omega_c^*\bar{D}^*$	$\Omega_c\bar{D}^*$	$\Omega_c\bar{D}$	$\Xi_c^*\bar{D}_s^*$	$\Xi_c'\bar{D}_s^*$	$\Xi_c'\bar{D}_s$	$\Xi_c\bar{D}_s^*$	$\Xi_c\bar{D}_s$	$\Xi^* J/\psi$	$\Xi\eta_c$	$\Xi J/\psi$	Γ_{sum}
4764.2	(36.8,–)	(0.1,0.0)	(0.0,0.0)	(34.9,3.2)	(0.1,0.0)	(0.0,0.0)	(0.0,0.0)	(0.0,0.0)	(26.1,5.2)	(0.0,0.0)	(0.0,0.0)	8.5
4682.5	(2.9,–)	(27.2,–)	(0.1,0.0)	(2.2,–)	(27.2,–)	(0.1,0.1)	(0.0,0.0)	(0.0,0.0)	(44.0,5.7)	(0.0,0.0)	(0.0,0.0)	5.7
4593.0	(39.6,–)	(15.0,–)	(0.1,0.0)	(9.0,–)	(1.5,–)	(1.0,0.3)	(21.1,2.8)	(0.8,0.4)	(0.4,–)	(0.6,0.2)	(10.3,2.4)	6.1
4573.0	(0.7,–)	(7.2,–)	(23.4,1.4)	(4.2,–)	(10.7,–)	(21.0,4.3)	(0.3,–)	(0.0,0.0)	(29.4,–)	(0.0,0.0)	(0.3,0.1)	5.7
4503.7	(7.7,–)	(46.3,–)	(0.8,–)	(2.2,–)	(12.3,–)	(0.2,–)	(2.4,–)	(5.0,1.6)	(0.0,–)	(2.6,0.7)	(31.2,5.4)	7.7
4476.4	(9.1,–)	(1.4,–)	(12.2,–)	(2.8,–)	(0.3,–)	(3.0,–)	(12.8,–)	(10.2,2.6)	(0.0,–)	(20.5,5.0)	(30.2,4.4)	12.0
4413.3	(0.4,–)	(1.5,–)	(28.6,–)	(0.1,–)	(0.3,–)	(7.6,–)	(4.9,–)	(20.0,–)	(0.0,–)	(9.4,1.9)	(28.0,–)	1.9
4318.1	(0.0,–)	(1.2,–)	(34.8,–)	(0.1,–)	(0.3,–)	(8.8,–)	(0.1,–)	(5.7,–)	(0.0,–)	(66.8,5.3)	(0.1,–)	5.3

The lighest state with spin 1/2 has mass around 4.3 GeV.

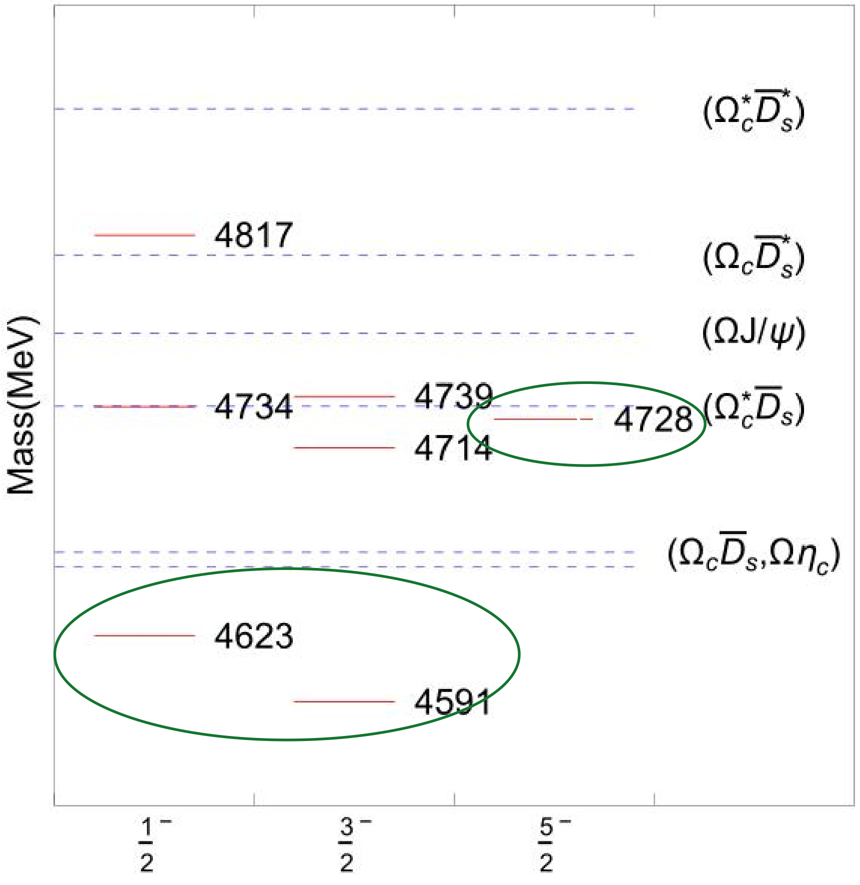
The widths of the light J=5/2 and the fourth highest J=3/2 state are narrow.

Results for $ssnc\bar{c}$



$I = \frac{1}{2}$ $ssnc\bar{c}$ states

Results for $sssc\bar{c}$



$I = 0$ $sssc\bar{c}$ states

Rearrangement decay widths for the $I = 0, Y = -2$ $sssc\bar{c}$ states in units of MeV.

$J = 0(\frac{5}{2}^-)$	$\Omega_c^*\bar{D}_s^*$	$\Omega J/\psi$				Γ_{sum}
4728.2	(11.1,−)	(100.0,−)				0.0
$J = 0(\frac{3}{2}^-)$	$\Omega_c^*\bar{D}_s^*$	$\Omega_c^*\bar{D}_s$	$\Omega_c\bar{D}_s^*$	$\Omega J/\psi$	$\Omega\eta_c$	Γ_{sum}
4738.9	(15.4,−)	(0.1,0.0)	(7.5,−)	(6.1,−)	(58.3,9.4)	9.4
4713.8	(14.2,−)	(11.6,−)	(0.6,−)	(12.4,−)	(41.5,5.7)	5.7
4590.8	(0.0,−)	(10.5,−)	(6.7,−)	(81.5,−)	(0.2,−)	0.0
$J = (\frac{1}{2}^-)$	$\Omega_c^*\bar{D}_s^*$	$\Omega_c\bar{D}_s^*$	$\Omega_c\bar{D}_s$	$\Omega J/\psi$		Γ_{sum}
4816.6	(34.5,−)	(0.0,0.0)	(0.0,0.0)	(29.5,3.5)		3.5
4734.0	(3.4,−)	(26.4,−)	(0.2,0.1)	(43.3,−)		0.1
4622.8	(2.8,−)	(10.6,−)	(22.0,−)	(27.1,−)		0.0

The lightest J=1/2 , the lightest J=3/2 , and the J=5/2 states should all be stable and can be searched for in the $\Xi^0\pi^- J/\psi$ channel.

Summary

- $P_c(4312)^+, P_c(4337)^+, P_c(4440)^+, P_c(4457)^+$ **can be assigned as the pantaquark states with** $I=1/2, J^P=3/2^-, 1/2^-, 1/2^-, 3/2^-$**, respectively .**
- $P_{cs}(4338)^0, P_{cs}(4459)^0$ **can be assigned as the** $I=0, J^P=1/2^-, 1/2^-$ **pantaquark states, respectively.**
- **There may also be two extremely narrow states in** $ssnc\bar{c}$ **case and three stable states in** $sssc\bar{c}$ **case, which can be searched for in future experiments.**

Thanks for your attention