Role of the tensor force in the heavy hadronic molecules

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in collaboration with

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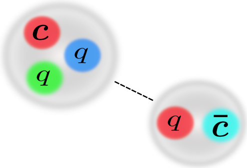
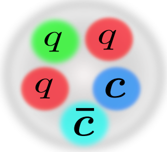
Outline

1. Introduction
   - Exotic hadrons - Hadronic molecules
   - Hidden-charm pentaquark *Pc*
2. Model setup
   - One Pion Exchange Potential
   - Compact 5-quark potential
3. Numerical results
   - Hidden-charm molecules
4. Summary



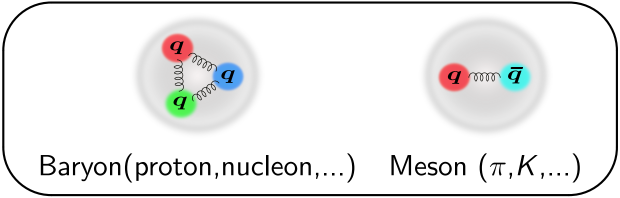
Hadronic molecule



Pentaquark (Compact)

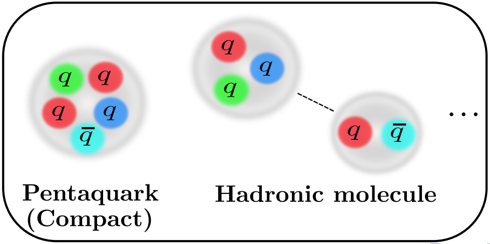
Hadron structure: Constituent quark model
Introduction

- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)

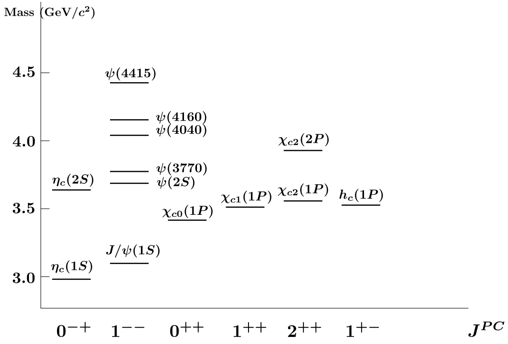


*q: "Constituent quark"

- Exotic Hadrons ($\neq qqq$, $q\bar{q}$): **Multiquark? Multihadron?**



▷ e.g. $c\bar{c}$ mesons (Charmonium)



N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534,

S. Godfrey and N. Isgur, PRD**32**(1985)189

one-g exchange

+

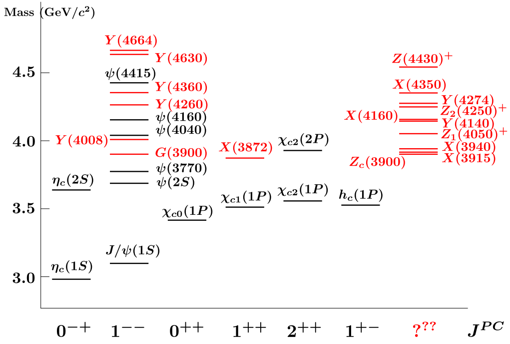
Confinement

⇓

$$V(r) = -\frac{\alpha_s}{r} + cr$$

$+\ldots$

▷ e.g. $c\bar{c}$ mesons (Charmonium) and **Unexpected *X*, *Y*, *Z***



N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534,

S. Godfrey and N. Isgur, PRD**32**(1985)189

one-g exchange

$+$

Confinement

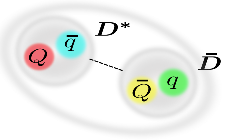
$\Downarrow$

$$V(r) = -\frac{\alpha_s}{r} + cr$$

$+ \ldots$

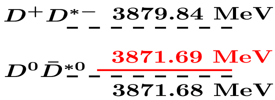
- Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) $\Rightarrow$ **Q. Structure? Physics?**

- Exotics as Hadronic molecule = Hadron composite system



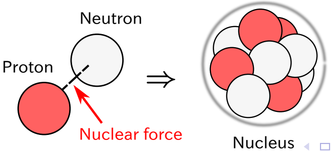
Hadronic molecule

$X(3872) = D\bar{D}^*$ molecule?

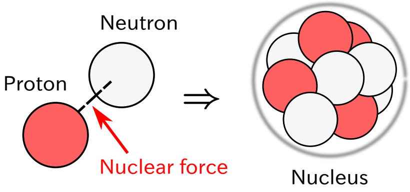


- Expected **near the thresholds**
  $\longrightarrow$ Hadron-hadron (quasi) bound state

$\Rightarrow$ Analogous to **Atomic Nuclei**
Deuteron $\sim$ pn bound state ($B = 2.2$ MeV)



- Driving force of Nuclei $\Rightarrow$ long range force: **π exchange**
  $\longrightarrow$ generating **the loosely bound state**



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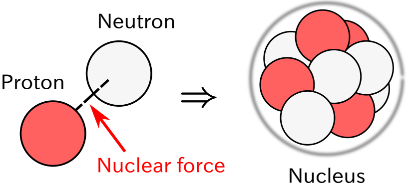

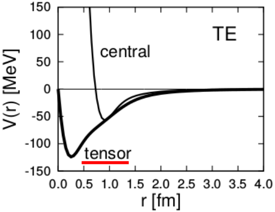

K.Ikeda *et al.*, Lect.Notes.Phys.**818**(2010)165

- Strong attraction from **Tensor term ($S - D$ mixing)**

- Driving force of Nuclei $\Rightarrow$ long range force: **π exchange**
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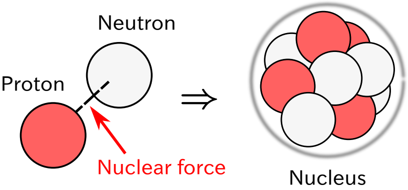
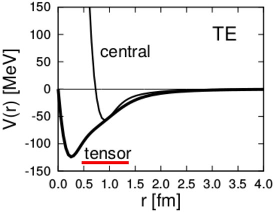
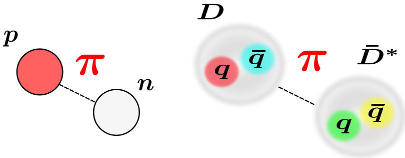




K.Ikeda *et al.*, Lect.Notes.Phys.**818**(2010)165

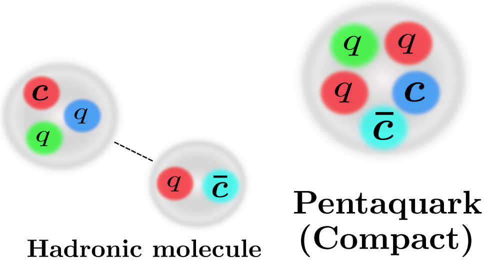
- Strong attraction from **Tensor term ($S - D$ mixing)**

$\Rightarrow$ Important role in the heavy hadronic moleucles?



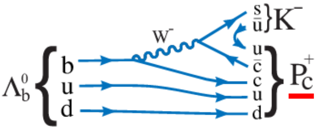
N.A.Tornqvist, Z.Phys.**C61**(1994)525

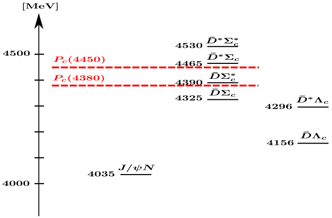
Hidden-charm pentaquarks



R.Aaij, *et al.* (LHCb collaboration) PRL**115**(2015)072001, PRL**122**(2019)222001

- Observation of the Hidden-charm Pentaquark ($c\bar{c}uud$) in $\Lambda_b^0 \to J/\psi K^- p$ Decay? R.Aaij, *et al.* (LHCb collaboration) PRL**115**(2015)072001



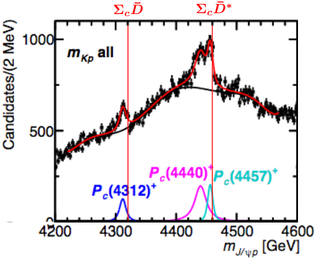


$P_c(4380)$: M =4380 MeV, Γ= 205 MeV $P_c(4450)$: M =4449.8 MeV, Γ = 39 MeV

- J^P? $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$, or $(5/2^+, 3/2^-)$
- There have been a lot of articles investigating the P_c states... Hadronic molecule? Compact state? Kinematical effect?

H.X.Chen, *et al.*, Phys.Rept.**639**(2016)1, A.Esposito, *et al.*,Phys.Rept.**668**(2016)1, A.Ali,*et al.*,PPNP**97**(2017)123

- R. Aaij, *et al.* Phys.Rev.Lett. 122 (2019) no.22, 222001



▷ $P_c(4450)$ in 2015 $\longrightarrow$ $P_c(4440)$ and $P_c(4457)$

$P_c(4440)$ M =4440.3 MeV, $\Gamma = 20.6$ $P_c(4457)$ $M = 4457.3$ MeV, $\Gamma = 6.4$ MeV

▷ Observation of **New state!** $P_c(4312)$ M =4311.9 MeV, $\Gamma = 9.8$ MeV

▷ $P_c(4380)$ in 2015? "these fits can neither confirm nor contradict the existence of the $P_c(4380)^+$"

- P_{c} states reported close to **the $\bar{D}^{(*)}\Sigma_c^{(*)}$ thresholds**
- π **exchange** in the heavy hadron system

- $P_{\rm c}$ states reported close to **the $\bar{D}^{(*)}\Sigma_c^{(*)}$ thresholds**
- **π exchange** in the heavy hadron system enhanced by **the heavy quark spin symmetry**!

N.Isgur,M.B.Wise,PLB**232**(1989)113

$\Rightarrow$ **$\bar{D}(0^-) - \bar{D}^*(1^-)$, $\Sigma_c(1/2^+) - \Sigma_c^*(3/2^-)$ mixing**

- P_c states reported close to **the $\bar{D}^{(*)}\Sigma_c^{(*)}$ thresholds**
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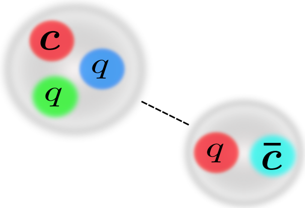
$\Rightarrow$ **$\bar{D}(0^-) - \bar{D}^*(1^-)$, $\Sigma_c(1/2^+) - \Sigma_c^*(3/2^-)$ mixing**

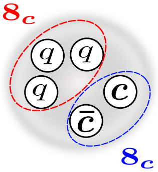
$\Rightarrow$ P_c states: $\bar{D}^{(*)}\Sigma_c^{(*)}$ molecules?

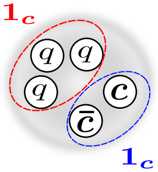


Hadronic molecule

Compact state: 5-quark configuration

- S. Takeuchi and M. Takizawa, PLB**764** (2017) 254-259.
  P_c states by the quark cluster model
- 5-quark configurations





$S_{q^3} = 1/2, 3/2,\ S_{c\bar{c}} = 0, 1$ $S_{q^3} = 1/2,\ S_{c\bar{c}} = 0, 1$

Compact state: 5-quark configuration

Introduction: pentaquark

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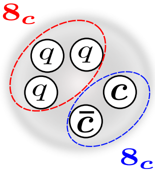

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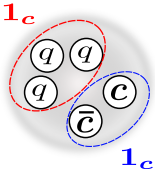

$S_{q^3} = 1/2,\ S_{c\bar{c}} = 0, 1$

- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

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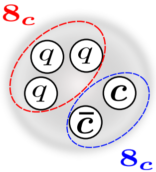
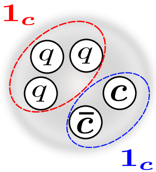




$S_{q^3} = 1/2, 3/2,\ S_{c\bar{c}} = 0, 1$ $\quad$ $S_{q^3} = 1/2,\ S_{c\bar{c}} = 0, 1$

- $[q^3\, 8_c\, 3/2]$: Color magnetic int. is attractive!

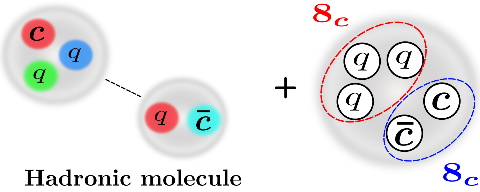
  $\Rightarrow$ Couplings to (qqc) baryon-$(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_{\rm c}$, are allowed!

Mixing of Compact state and Hadronic Molecule!

Model setup in this study

- **Hadronic molecule (MB) + Compact state ($5q$)**

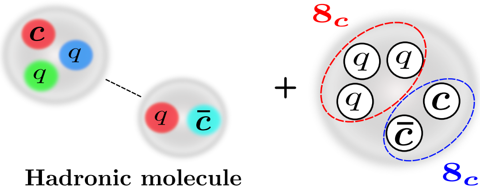
$MB + 5q$



Model setup in this study

- **Hadronic molecule** (MB) + **Compact state** ($5q$)
  $\Rightarrow$ MB coupled to $5q$ (Feshbach Projection)

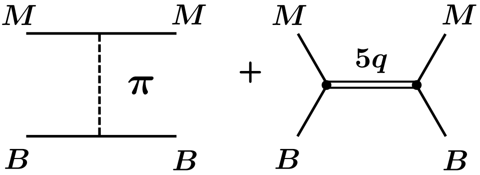
$MB + 5q$



Model setup in this study

- **Hadronic molecule** (*MB*) + **Compact state** ($5q$)
  $\Rightarrow$ *MB* coupled to $5q$ (Feshbach Projection)

Interaction of hadrons (M and B)



Long range int. Short range int.

▷ **Long range** interaction: One pion exchange potential (OPEP)
▷ **Short range** interaction: $5q$ potential

Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, PRD**96**(2017)114031
Y.Y, H.G-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, 1907.04684[hep-ph]

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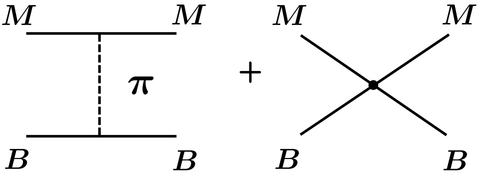


Long range int. Short range int.

▷ **Long range** interaction: One pion exchange potential (OPEP)

▷ **Short range** interaction: $5q$ potential **(→Local Gaussian)**

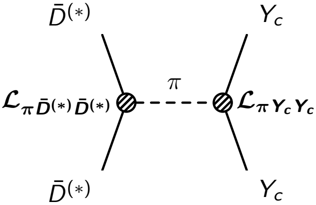
Spin dependence → Spin structure of $5q$

Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, PRD**96**(2017)114031

Y.Y, H.G-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, 1907.04684[hep-ph]

$\bar{D}^{(*)} Y_c$ Interaction: Long range force
HQS and OPEP

- One pion exchange potential



$\bar{D}^{(*)}$: $\bar{D}$ or $\bar{D}^*$

Y_c: Λ_c, Σ_c or Σ_c^*

$$V^{\pi}_{\bar{D}^{(*)} Y_c - \bar{D}^{(*)} Y_c} = \frac{g_{D^* D \pi} g_{Y_c Y_c \pi}}{f_\pi^2} \left[\vec{S}_1 \cdot \vec{S}_2 C(r) + S_{S_1 S_2} T(r) \right]$$

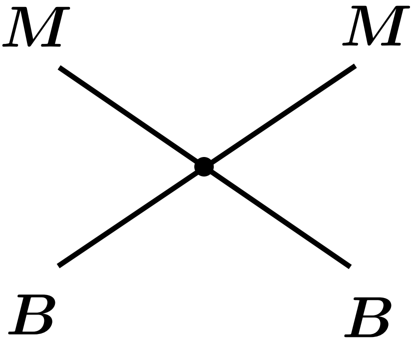
(Contact term is removed)

- Form factor with Cutoff Λ (determined by the hadron size)

$$F(q^2) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - q^2}, \quad \Lambda_{\bar{D}} \sim 1130 \text{ MeV}, \Lambda_{Y_c} \sim 840 \text{ MeV}$$

Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Phys.Rev. D**96** (2017), 114031

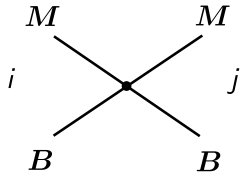
2. Short range force: 5-quark potential



Model: 5-quark potential

- 5-quark potential $\Rightarrow$ **Local Gaussian potential** is employed.

▷ Massive M_{5q} (few hundred MeV above $\bar{D}^*\Sigma_c^*$) $\to$ **Attractive**



$$\Rightarrow -f\, S_i S_j e^{-\alpha r^2}$$

Channel $i, j = \bar{D}^{(*)}\Lambda_c,\ \bar{D}^{(*)}\Sigma_c^{(*)}$ with $S-$wave

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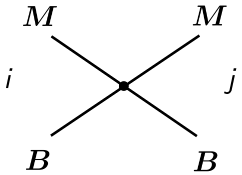


$$\Rightarrow -f\, S_i S_j e^{-\alpha r^2}$$

Channel $i, j = \bar{D}^{(*)}\Lambda_c,\ \bar{D}^{(*)}\Sigma_c^{(*)}$ with $S-$wave

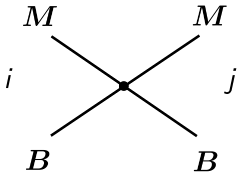
Free Parameters

Strength $\boldsymbol{f}$ and Gaussian para. $\boldsymbol{\alpha}$ ($\rightarrow$ may be fixed in the future)
($\boldsymbol{f}$ vs $\boldsymbol{E}$ will be shown latter. $\boldsymbol{\alpha = 1}$ fm$^{\boldsymbol{-2}}$ is fixed.)

Model: 5-quark potential

- 5-quark potential ⇒ **Local Gaussian potential** is employed.

▷ Massive M_{5q} (few hundred MeV above $\bar{D}^*\Sigma_c^*$) → **Attractive**



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Relative strength S_i

Spectroscopic factors ⇒ determined by **the spin structure** of $5q$

Model: 5-quark potential

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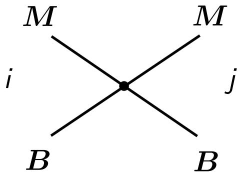

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Relative strength S_i

Spectroscopic factors $\Rightarrow$ determined by **the spin structure** of $5q$

Spectroscopic factor S_i (Spin structure)

$5q$ potential

- S-factor: $S_i = \left\langle (\bar{D} Y_c)_i \,\middle|\, 5q \right\rangle$

Table: Spectroscopic factors S_i for each meson-baryon channel.

J		$S_{c\bar{c}}$	S_{3q}	$\bar{D}\Lambda_c$	$\bar{D}^*\Lambda_c$	$\bar{D}\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Sigma_c^*$
1/2	(i)	0	1/2	0.4	0.6	−0.4	—	0.2	−0.6
	(ii)	1	1/2	0.6	−0.4	0.2	—	−0.6	−0.3
	(iii)	1	3/2	0.0	0.0	−0.8	—	−0.5	0.3
3/2	(i)	0	3/2	—	0.0	—	−0.5	0.6	−0.7
	(ii)	1	1/2	—	0.7	—	0.4	−0.2	−0.5
	(iii)	1	3/2	—	0.0	—	−0.7	−0.8	−0.2
5/2	(i)	1	3/2	—	—	—	—	—	−1.0

Spectroscopic factor S_i (Spin structure)

$5q$ potential

- S-factor: $S_i = \left\langle (\bar{D} Y_\mathrm{c})_i \,\middle|\, 5q \right\rangle$

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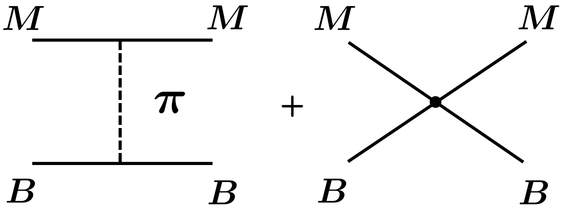
1/2	(i)	0	1/2	0.4	**0.6**	−0.4	—	0.2	**−0.6**
	(ii)	1	1/2	**0.6**	−0.4	0.2	—	**−0.6**	−0.3
	(iii)	1	3/2	0.0	0.0	**−0.8**	—	−0.5	0.3
3/2	(i)	0	3/2	—	0.0	—	**−0.5**	**0.6**	**−0.7**
	(ii)	1	1/2	—	**0.7**	—	0.4	−0.2	−0.5
	(iii)	1	3/2	—	0.0	—	**−0.7**	**−0.8**	−0.2
5/2	(i)	1	3/2	—	—	—	—	—	**−1.0**

- $\bar{D}Y_\mathrm{c}$ with **Large S_i** will play an important role.

Numerical Results for Hidden-charm sector



Long range int.

Short range int. (Gaussian)

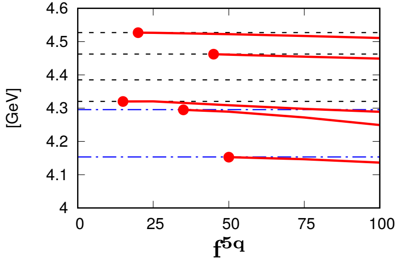
Bound state and Resonance

- Coupled-channel Schrödinger equation for $\bar{D}\Lambda_{\rm c}$, $\bar{D}^*\Lambda_{\rm c}$, $\bar{D}\Sigma_{\rm c}$, $\bar{D}\Sigma_{\rm c}^*$, $\bar{D}^*\Sigma_{\rm c}$, $\bar{D}^*\Sigma_{\rm c}^*$ (6 MB components).
- For $J^P = 1/2^-, 3/2^-, 5/2^-$ (Negative parity)

Results (f^{5q} vs E) of charm $\bar{D} Y_c$ for $J^P = 1/2^-$

- Energy with $V_\pi + V^{5q}(f^{5q})$. (Y.Yamaguchi *et al*, PRD**96** (2017), 114031)

$J^P = 1/2^-$

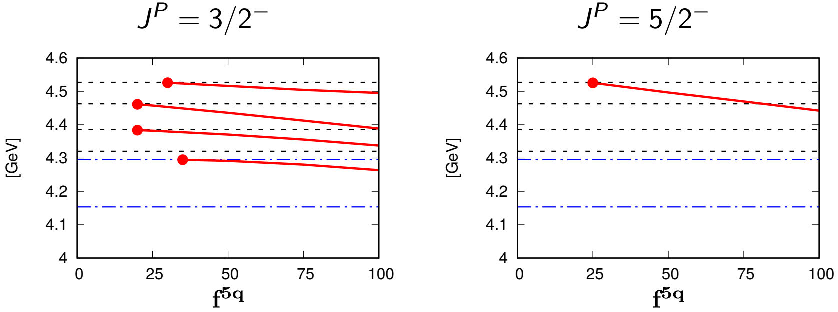


Dashed line: Thresholds, **Red line: Energy obtained**

- For small f^{5q}, **No bound state**
  $\Rightarrow$ The OPEP attraction is not enough to generate a state
- $5q$ potential helps to generate the states **near the thresholds**
  $\Leftrightarrow$ **Large S-factor** (Spin structure)

Results (f^{5q} vs E) for $J^P = 3/2^-, 5/2^-$

- Energy with $V_\pi + V^{5q}(f^{5q})$. (Y.Yamaguchi *et al*, PRD**96** (2017), 114031)



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In 2019, New P_c states by LHCb

- $f^{5q} = 45$ is fixed to reproduce new P_c's

Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, 1907.04684[hep-ph]

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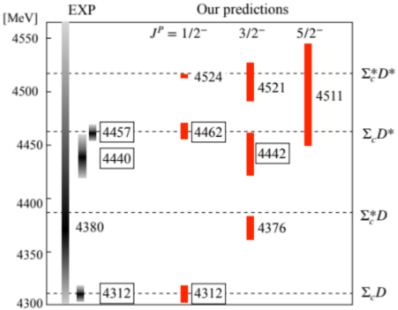

- (E, Γ) in our pred.
  $\leftrightarrow$ consistent with Exp for
  $P_c(4312)$, $P_c(4440)$, $P_c(4457)$

- Missing three $(1/2^-, 3/2^-, 5/2^-)$ states below $\bar{D}^*\Sigma_c^*$
- Broad $P_c(4380)$ $\leftrightarrow$ Our prediction with 4376 MeV
  $\rightarrow$ Further theoretical and experimental studies are necessary...

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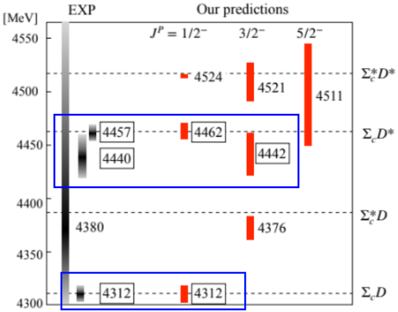

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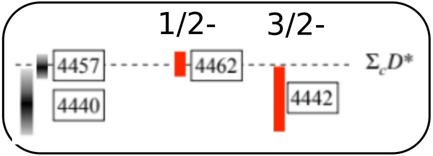
J^P assignment for $P_c(4440)$ and $P_c(4457)$



▷ J^P assignment

$P_c(4440) : 3/2^-$

$P_c(4457) : 1/2^-$

$\Rightarrow$ **$E(1/2^-) > E(3/2^-)$**

- OPEP of the $\bar{D}^*\Sigma_c$ channel

$1/2^-$: ^2S, ^4D

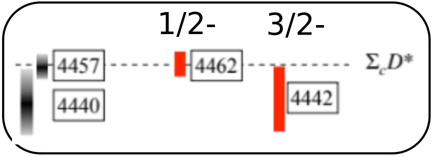
$$\begin{pmatrix} 4C & 2\sqrt{2}T \\ 2\sqrt{2}T & -2C + 4T \end{pmatrix}$$

$3/2^-$: ^4S, ^2D, ^4D

$$\begin{pmatrix} -2C & -2T & -4T \\ -2T & 4C & 2T \\ -4T & 2T & -2C \end{pmatrix}$$

$*$ C: Central force, T: Tensor force

J^P assignment for $P_c(4440)$ and $P_c(4457)$



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$3/2^- : {}^4S, \quad {}^2D, \quad {}^4D$

$$\begin{pmatrix} -2C & -\mathbf{2T} & -\mathbf{4T} \\ -\mathbf{2T} & 4C & \mathbf{2T} \\ -\mathbf{4T} & \mathbf{2T} & -2C \end{pmatrix}$$

$*$ C: Central force, T: Tensor force

- $S - D$, $D - D$ couplings producing the attraction from the tensor force

$\Rightarrow$ $1/2^-$: ${}^2S - {}^4D$
$3/2^-$: $\boldsymbol{{}^4S - {}^2D,\ {}^4S - {}^4D,\ {}^2D - {}^4D}$ $\leftarrow$ more attractive!

Summary

- Hidden-charm pentaquarks as Hadronic molecule + Compact multiquark
- $\bar{D}^{(*)} Y_c$ Interaction
  Long range force: OPEP with the tensor force, enhanced by the heavy quark symmetry
  Short range force: Coupling to Compact $5q$ states
- The OPEP is not enough to generate the bound state. $\rightarrow$ OPEP + $5q$ potential generates the states
- Applying this model to New hidden-charm pentaquarks by LHCb in 2019
  $\Rightarrow$ our prediction is consistent with EXP
- The J^P assignment $P_c(4440)$: $3/2^-$ and $P_c(4457)$: $1/2^-$ understood by the tensor force of the OPEP

Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Phys.Rev. D**96** (2017), 114031

Y.Y., H.Garcia-Tecocoatzi, A.Giachino, A.Hosaka, E.Santopinto, S.Takeuchi, M.Takizawa, 1907.04684[hep-ph]

Back up

Experimental mass and Our prediction

State	Mass	Width	Our pred. (M,Γ,J^P)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$(4312,\ 5,\ \frac{1}{2}^-)$
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$(4376{,}8,\ \frac{3}{2}^-)$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$(4442\ {,}26,\ \frac{3}{2}^-)$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$(4462{,}6.6,\ \frac{1}{2}^-)$
			$(4524{,}1.5,\ \frac{1}{2}^-)$
			$(4521,\ 23,\ \frac{3}{2}^-)$
			$(4511{,}55,\ \frac{5}{2}^-)$

(in units of MeV)

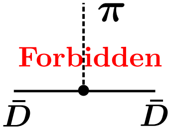
Coupled-channels

Channels	$\bar{D}Y_c(^{2S+1}L)$	
$1/2^-$	$\bar{D}\Lambda_c(^2S)$, $\bar{D}^*\Lambda_c(^2S)$, $\bar{D}\Sigma_c(^2S)$, $\bar{D}\Sigma_c^*(^4D)$, $\bar{D}^*\Sigma_c(^2S,^4D)$, $\bar{D}^*\Sigma_c^*(^2S,^4D,^6D)$	(10 ch)
$3/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^4S,^2D,^4D)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4S,^4D)$, $\bar{D}^*\Sigma_c(^4S,^2D,^4D)$, $\bar{D}^*\Sigma_c^*(^4S,^2D,^4D,^6D,^6G)$	(15 ch)
$5/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^2D,^4D,^4G)$, $\bar{D}\Sigma_c(^2D)$, $\bar{D}\Sigma_c^*(^4D,^4G)$, $\bar{D}^*\Sigma_c(^2D,^4D,^4G)$, $\bar{D}^*\Sigma_c^*(^6S,^2D,^4D,^6D,^4G,^6G)$	(16 ch)

- 6 $\bar{D}Y_c$ channels: $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$.
- $S-D$ mixing induced by the Tensor force (S_{12})

- Effective Lagrangians: Heavy hadron and π

R. Casalbuoni *et al.*, Phys.Rept.**281** (1997)145, T. M. Yan, *et al.*, PRD**46**(1992)1148
Y.-R.Liu and M.Oka, PRD**85**(2012)014015



▷ Heavy meson: $\bar{D}^{(*)}\bar{D}^{(*)}\pi$ **($DD\pi$: Parity violation)**

$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi}\mathrm{Tr}\left[H\gamma_\mu\gamma_5\partial^\mu\hat{\pi}\bar{H}\right], \quad H = \frac{1+\not{v}}{2}\left[D^*_\mu\gamma^\mu - D\gamma_5\right]$$

Heavy hadron-π coupling
HQS and OPEP

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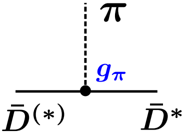

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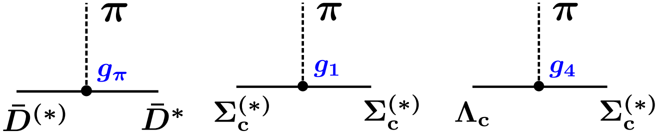

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▷ Heavy baryon: $\Sigma_c^{(*)}\Sigma_c^{(*)}\pi$, $\Lambda_c\Sigma_c^{(*)}\pi$ ($\Lambda_c\Lambda_c\pi$: Isospin breaking)

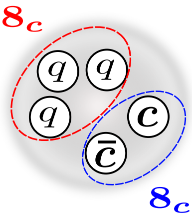
$$\mathcal{L}_{\pi BB} = -\frac{3}{4f_\pi}\mathbf{g_1}(iv_\kappa)\varepsilon^{\mu\nu\lambda\kappa}\mathrm{tr}\left[\bar{S}_\mu\partial_\nu\hat{\pi}S_\lambda\right] - \frac{g_4}{2f_\pi}\mathrm{tr}\left[\bar{S}^\mu\partial_\mu\hat{\pi}\Lambda_c\right] + \mathrm{H.c.},$$

$$\mathbf{S}_\mu = \mathbf{\Sigma}^*_{c\mu} - \frac{1}{\sqrt{3}}\left(\gamma_\mu + \mathbf{v}_\mu\right)\gamma_5\mathbf{\Sigma}_c, \quad g_\pi = 0.59, g_1 = 1.00, g_4 = 1.06$$

Spectroscopic factors S_i (Spin structure)

$5q$ potential

- Spin of $5q$ states $\rightarrow$ $S_{c\bar{c}}$ and S_{3q} configuration
  e.g. for $J^P = 1/2^-$, (i), (ii), (iii)



$J^P = 1/2^-$

	$S_{c\bar{c}}$	S_{3q}
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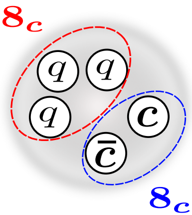

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type (i)	0	1/2
(ii)	1	1/2
(iii)	1	3/2

- **Overlap** of the spin wavefunctions of 5-quark state and $\bar{D}Y_{\rm c}$

$$S_i = \left\langle (\bar{D}Y_{\rm c})_i \,\middle|\, 5q \right\rangle$$

$\Rightarrow$ Relative strength of couplings to $\bar{D}Y_{\rm c}$ channel

Volume integrals of the potentials

- Bound and Resonant states appears for $\boldsymbol{f^{5q}} \gtrsim \mathbf{25}$
  $\Leftrightarrow$ Large? Small?

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▷ Volume integral $V(q=0) = \int V(r) dr^3$

Comparison with the NN interaction (Bonn potential)

R. Machleidt, K. Holinde and C. Elster, Phys. Rept. **149**, 1 (1987).

$$\left| V^{5q}_{f=25}(0) \right| = 1.1 \times 10^{-4}\ \mathrm{MeV} \sim 0.03 \left| C^{\sigma}_{NN}(0) \right|$$

(C^{σ}_{NN} : Central force of σ exchange)

- $\left| V^{5q}_{f=25}(0) \right|$ is **much smaller** than $|C^{\sigma}_{NN}(0)|$.

  However, the bound and resonant states are obtained!