Hadronic molecules with a short-range force by a quark model

Yasuhiro Yamaguchi[1]

in collaboration with

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[1]RIKEN, [2]INFN Genova, [3]RCNP, Osaka U., [4]Japan Coll. Social Work, [5]Showa Pharmaceutical U.

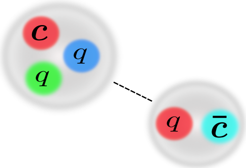
Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Phys.Rev. D96 (2017), 114031

Hadrons and Nuclear Physics meet ultracold atoms: a French Japanese workshop

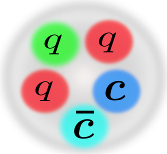
Outline

Hadronic molecules + Compact state

1. Introduction
   - Exotic hadron
   - Hidden-charm pentaquark
2. Model setup
   - Heavy Quark Spin Symmetry and OPEP
   - Compact 5-quark potential
3. Numerical results
   - Hidden-charm molecules
4. Summary



Hadronic molecule



Pentaquark (Compact)

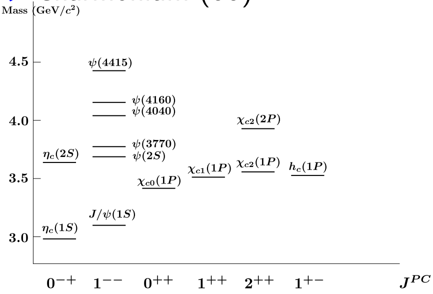
- Hadron: Composite particle of **Quarks** and **Gluons**
- Constituent quark model (Baryon(qqq) and Meson $q\bar{q}$) has been successfully applied to the hadron spectra!

Baryon(proton,nucleon,...) Meson (π,K,...)

▷ Quark potential (Coulomb type + Linear potential)

$$V_q(r) = -\frac{a}{r} + br + c + d\frac{\vec{S}_1 \cdot \vec{S}_2}{m_1 m_2}\delta^{(3)}(r) + \ldots$$

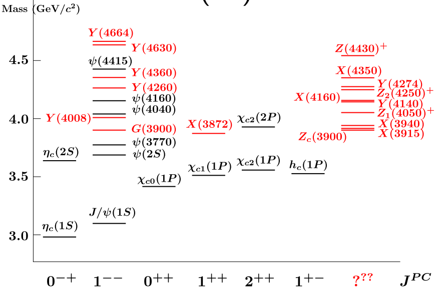
▷ Charmonium ($c\bar{c}$)



Charmonium $\boldsymbol{c\bar{c}}$

N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534
S. Godfrey and N. Isgur, PRD**32**(1985)189

▷ Charmonium ($c\bar{c}$) and **New Exotic hadrons *X*, *Y*, *Z***



Charmonium $c\bar{c}$

and

Exotic hadrons ($\neq c\bar{c}$)

$\boxed{X, Y, Z}$

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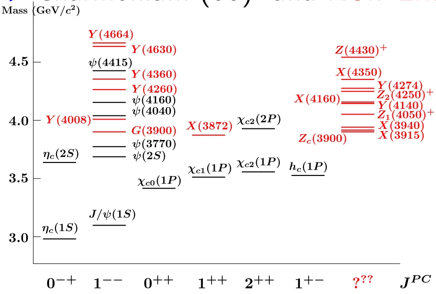

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▷ **What is the structure of exotic hadrons?**

⇒ Multiquark states?

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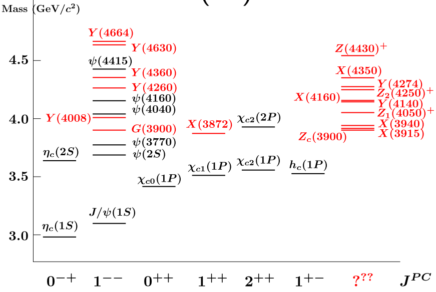

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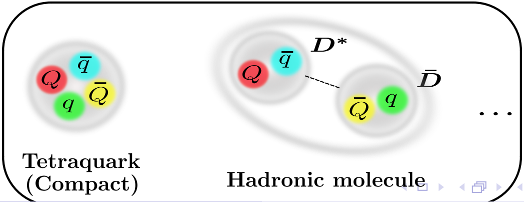
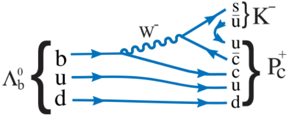


PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

R. Aaij *et al.**
(LHCb Collaboration)
(Received 13 July 2015; published 12 August 2015)

$\Lambda_\mathrm{b}^0 \to K^- P_\mathrm{c}^+$ decay



Two ($c\bar{c}uud$) Pentaquarks!

$P_c(4380)$: M=$4380 \pm 8 \pm 29$ MeV
$\Gamma = 205 \pm 18 \pm 86$ MeV

$P_c(4450)$: M=$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma = 39 \pm 5 \pm 19$ MeV

J^P: $(\frac{3}{2}^-, \frac{5}{2}^+)$, $(\frac{3}{2}^+, \frac{5}{2}^-)$ or $(\frac{5}{2}^+, \frac{3}{2}^-)$ *Opposite parity

best fit!

- $P_\mathrm{c}(4380)$ and $P_\mathrm{c}(4450)$ obtained near $\bar{D}\Sigma_\mathrm{c}^*$ and $\bar{D}^*\Sigma_\mathrm{c}$

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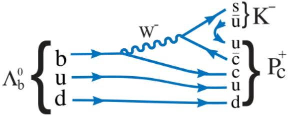

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best fit!

- $P_c(4380)$ and $P_c(4450)$ obtained near $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$

▷ Possible existence of Exotic baryons in the hidden-charm sector?

Proposals of various structures!

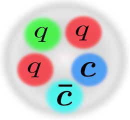
H.X.Chen, *et al.*, Phys.Rept.**639**(2016)1, A.Esposito, *et al.*,Phys.Rept.**668**(2016)1, A.Ali,*et al.*,PPNP**97**(2017)123

- Compact pentaquark ($c\bar{c}qqq$)?

  S.G.Yuan, *et al.* (2012), L.Maiani, *et al,* (2015),

  S.Takeuchi, *et al,* (2017), J. Wu, *et al.* (2017),

  …



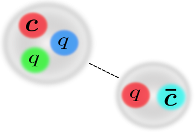
Pentaquark (Compact)

- Hadronic molecule ($\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$,...)?

  J.-J.Wu *et al.*, (2010) (2011), C. Garcia-Recio, *et al.* (2013),

  R. Chen, *et al.* (2015), Y.Shimizu, *et al.* (2016) (2017),

  …



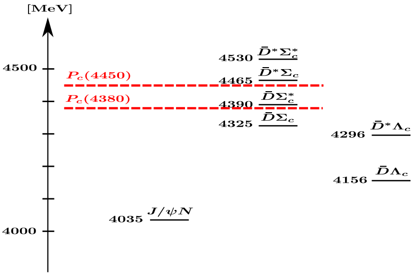
Hadronic molecule

- Kinematical effect? Cusp?
  (Non-resonant explanation)

  F.K.Guo, *et al.* (2015), X.H.Liu, *et al.* (2016),

  …

- e.g. $P_{\rm c}(4380)$, $P_{\rm c}(4450)$
  → close to **the meson-baryon thresholds**



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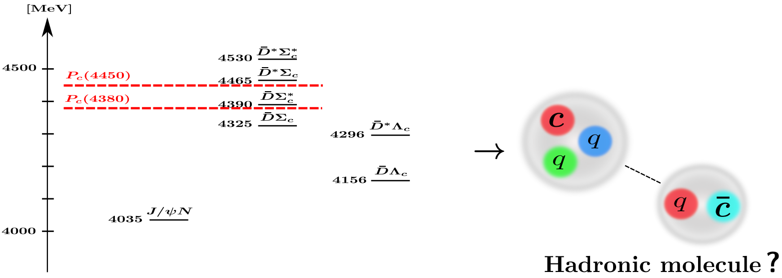
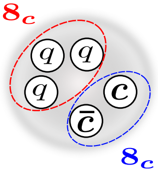


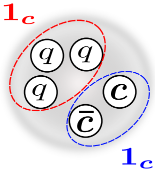
- Exotic state may be a loosely bound state of the meson-baryon.
  ⇒ Analogous to atomic nuclei (Deuteron: $B \sim$2.2 MeV)

Importance of Hadron-hadron interaction (not known...)

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



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



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

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

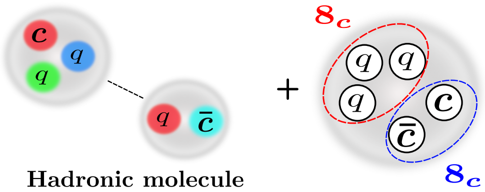
  $\Rightarrow$ Couplings to (qqc) baryon-$(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_{\rm c}$, are allowed!

Mixing of Compact state and Hadronic Molecule!

Model setup in this study

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

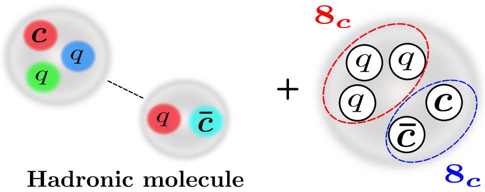
$MB + 5q$



Model setup in this study

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

$MB + 5q$



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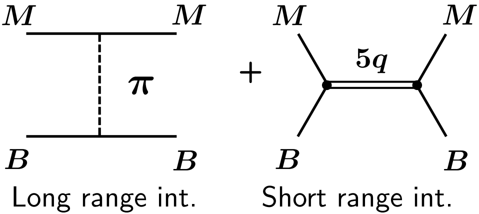
Interaction of hadrons (M and B)



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

▷ **Short range** interaction: $5q$ potential

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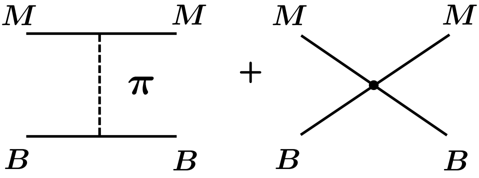
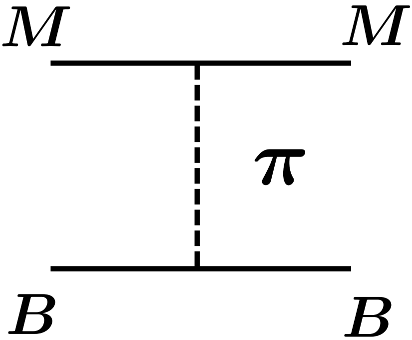


▷ **Long range** interaction: One pion exchange potential (OPEP)

▷ **Short range** interaction: $5q$ potential **(→Local Gaussian)**
(* Other int. **(double counting...)** → **Future work**)

MB bound states: Role of the $5q$ potential (Spin structure)

1. Long range force: One pion exchange potential



- Exchanging light meson π ($m_\pi \sim 140$ MeV)
- Driving force to bind Atomic nucleus

Heavy Quark Spin Symmetry

Heavy Quark Spin Symmetry

Charm (c), Bottom (b), Top (t)

Heavy Quark Spin Symmetry

Charm (c), Bottom (b), Top (t)

$\Downarrow$

1. Coupled channels of MB
2. Tensor force (OPEP)

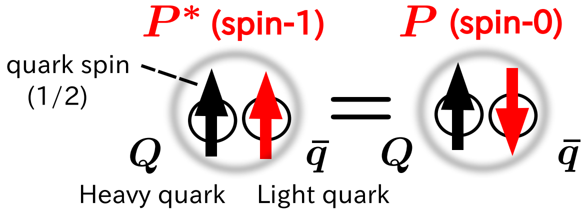
Heavy Quark Spin Symmetry (HQS)

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

- **Suppression of Spin-spin force** in $m_Q \to \infty$.

  $\Rightarrow$ **Mass degeneracy** of hadrons with the different J

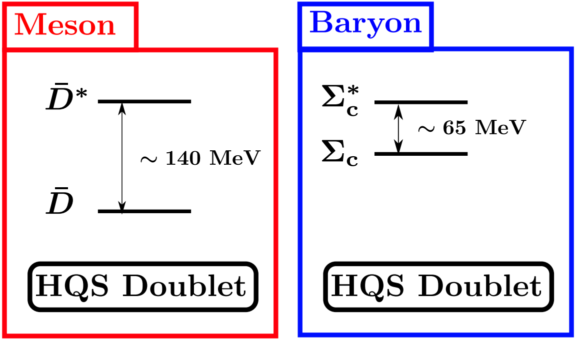
- e.g. $Q\bar{q}$ meson



$\Rightarrow$ Mass degeneracy of spin-0 and spin-1 states!

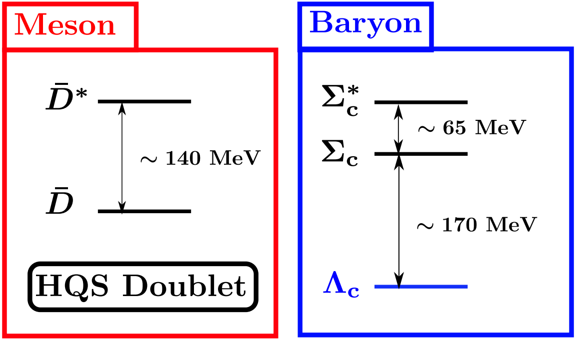
- Charm sector: $\bar{D}(0^-) - \bar{D}^*(1^-)$, $\Sigma_c(1/2^+) - \Sigma_c^*(3/2^+)$

- $\bar{D} - \bar{D}^*$ and $\Sigma_c - \Sigma_c^*$ mixing in the $\bar{D} Y_c$ system



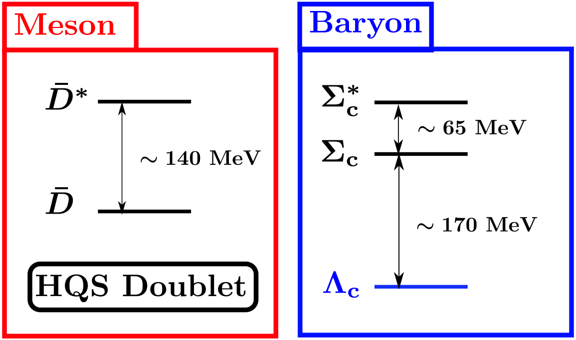
- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!

- $\bar{D}-\bar{D}^*$ and $\Sigma_c-\Sigma_c^*$ mixing in the $\bar{D}Y_c$ system



- Coupled channels of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$!
- In addition, **Λ_c (*cqq*)**: $\bar{D}^{(*)}\Lambda_c$ channel!?

- $\bar{D}-\bar{D}^*$ and $\Sigma_c-\Sigma_c^*$ mixing in the $\bar{D}Y_c$ system



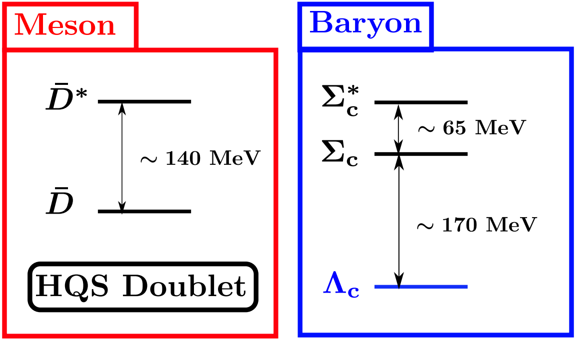
▷ 6 meson-baryon components

(1) $\bar{D}\Lambda_c$, (2) $\bar{D}^*\Lambda_c$, (3) $\bar{D}\Sigma_c$, (4) $\bar{D}\Sigma_c^*$,
(5) $\bar{D}^*\Sigma_c$, (6) $\bar{D}^*\Sigma_c^*$

Mass degeneracy $\to$ $\bar{D} - \bar{D}^*$, $\Sigma_c - \Sigma_c^*$ mixing!

HQS and OPEP

- $\bar{D} - \bar{D}^*$ and $\Sigma_c - \Sigma_c^*$ mixing in the $\bar{D}Y_c$ system



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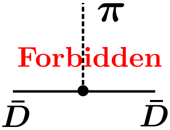
(5) $\bar{D}^*\Sigma_c$, (6) $\bar{D}^*\Sigma_c^*$ $\to$ Coupled by OPEP!

- Effective Lagrangians: Heavy hadron and $\boldsymbol{\pi}$

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)**

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

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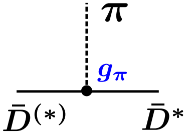

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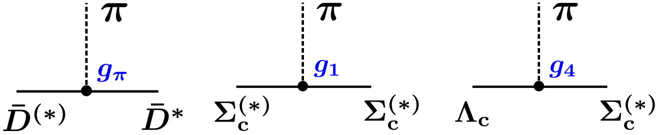

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▷ Heavy baryon: $\Sigma_c^{(*)}\Sigma_c^{(*)}\pi$, $\Lambda_c\Sigma_c^{(*)}\pi$ ($\Lambda_c\Lambda_c\pi$: Isospin breaking)

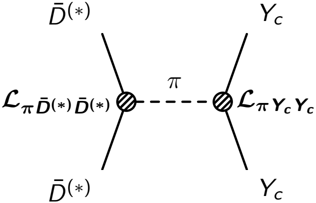
$$\mathcal{L}_{\pi BB} = -\frac{3}{4f_\pi}\mathbf{g_1}(iv_\kappa)\varepsilon^{\mu\nu\lambda\kappa}\mathrm{tr}\left[\bar{S}_\mu\partial_\nu\hat{\pi}S_\lambda\right] - \frac{g_4}{2f_\pi}\mathrm{tr}\left[\bar{S}^\mu\partial_\mu\hat{\pi}\Lambda_c\right] + \mathrm{H.c.},$$

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

$\bar{D}^{(*)} Y_c$ 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^*

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

(Contact term is removed)

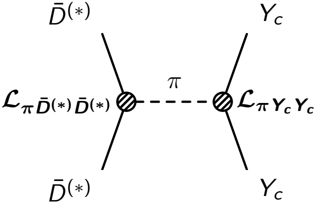
- Form factor with Cutoff Λ (determined by the hadron size)

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

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

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

- One pion exchange potential **with Tensor force!**



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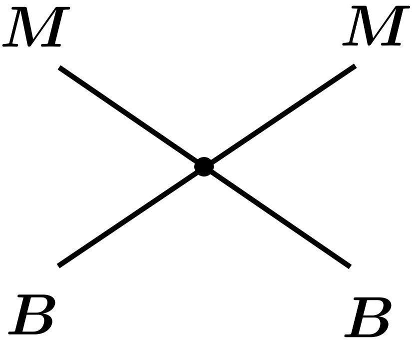
Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, Phys.Rev. D**96** (2017), 114031

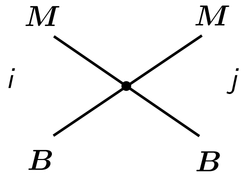
2. Short range force: 5-quark potential



Model: 5-quark potential

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

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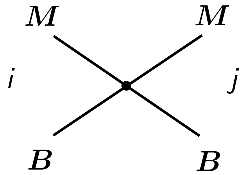

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Free Parameters

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^{-2} is fixed.)

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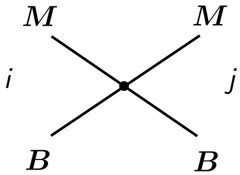

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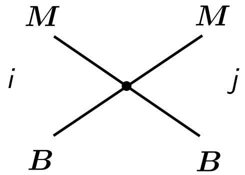

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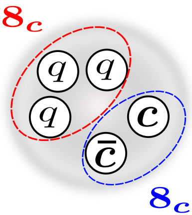
Spectroscopic factors S_i (Spin structure)
$5q$ potential

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



$J^P = 1/2^-$

	$S_{c\bar{c}}$	S_{3q}
type (i)	0	1/2
(ii)	1	1/2
(iii)	1	3/2

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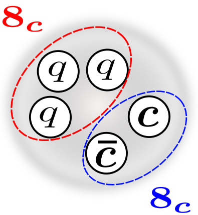

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- **Overlap** of the spin wavefunctions of 5-quark state and $\bar{D}Y_c$

$$S_i = \langle (\bar{D}Y_c)_i \,|\, 5q \rangle$$

⇒ Relative strength of couplings to $\bar{D}Y_c$ channel

Spectroscopic factor S_i (Spin structure)

$5q$ potential

- S-factor = Relative strength to $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$

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

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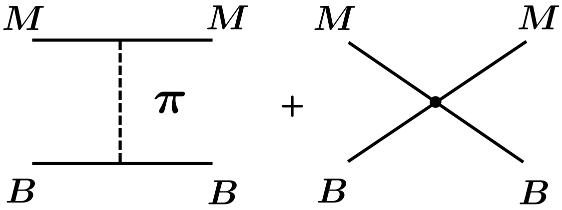
- $\bar{D}Y_c$ with **Large S_i** will play an important role.

Numerical Results for Hidden-charm sector



Long range int.

Short range int. (Gaussian)

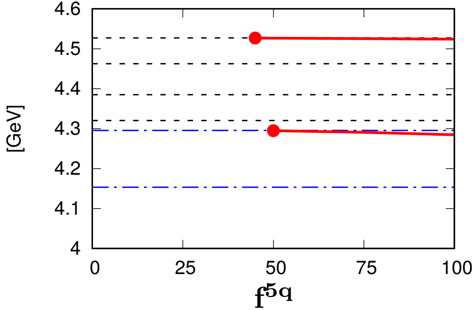
<u>Bound state and Resonance</u>

- 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 $J^P = 1/2^-$

- π exchange + V^{5q} [type (i)]

(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{1}{2})$



- No state in small f^{5q}

$\rightarrow$ π **exchange is not enough** to produce a bound state

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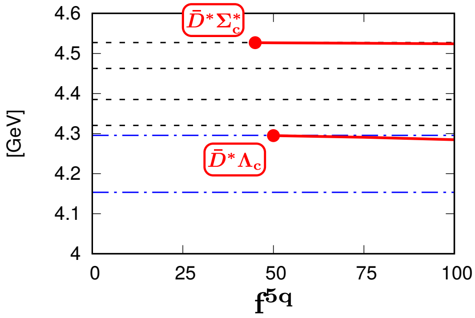

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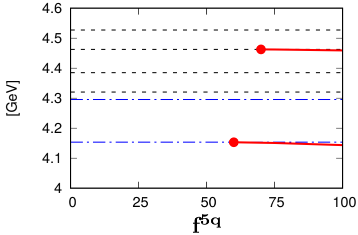
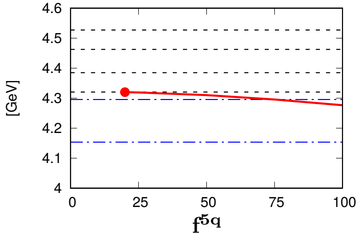


(iii) $(S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})$



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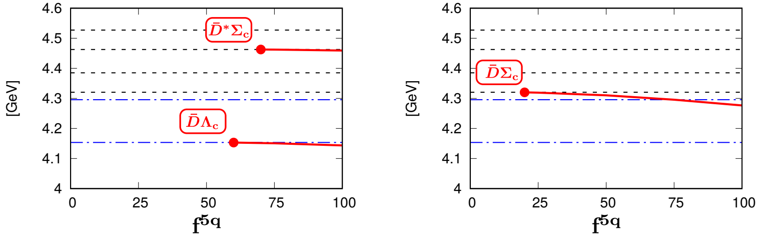

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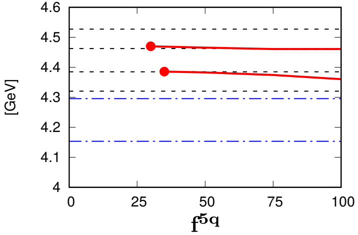

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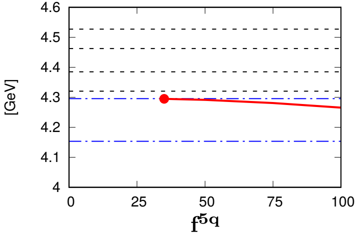

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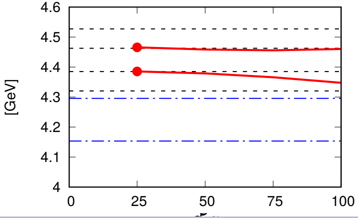

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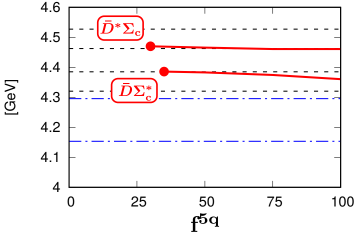

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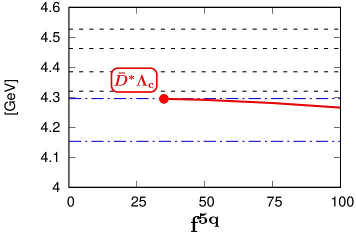

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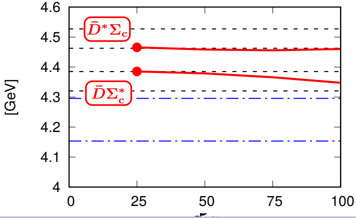

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Results (f^{5q} vs E) of charm $\bar{D}Y_c$ for $J^P = 5/2^-$

- Charm $\bar{D}Y_c$ for $\boldsymbol{J^P = 5/2^-}$, One $5q$ state

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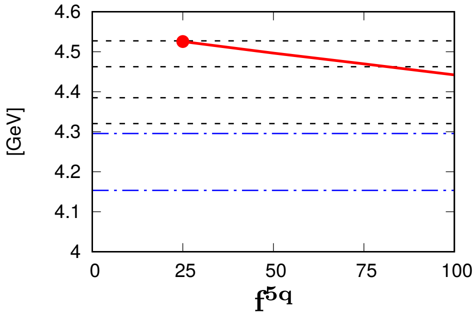

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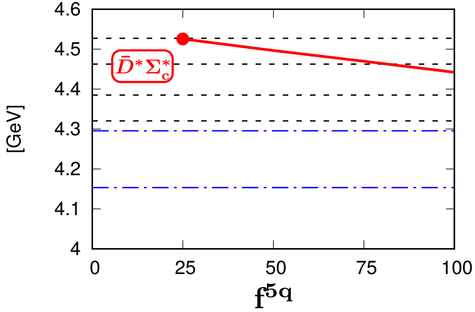
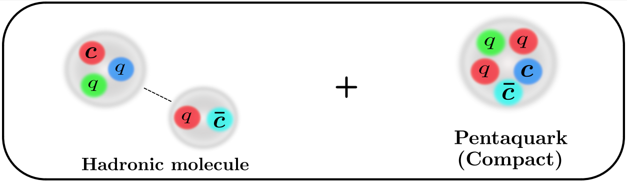


Summary of the hidden-charm sector

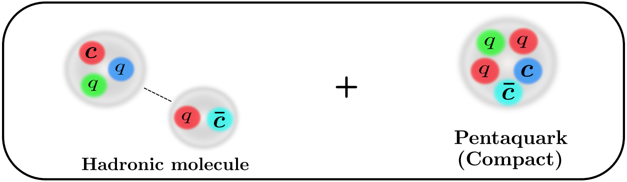
- OPEP is not strong enough to produce a state.
- The importance of the $5q$ potential
  $\Rightarrow$ States below the MB thresholds $\leftarrow$ **large S-factor**

Summary



- **Hadron interaction** is important in Hadronic molecules.
- Coupling to Compact $5q$ state is introduced as the short range interaction.
- Introducing **6 meson-baryon components**:
  Multiplet of the HQS, $\bar{D}\Sigma_{\rm c}, \bar{D}\Sigma_{\rm c}^{*}, \bar{D}^{*}\Sigma_{\rm c}, \bar{D}^{*}\Sigma_{\rm c}^{*} + \bar{D}\Lambda_c, \bar{D}^{*}\Lambda_c$
- Interaction: **π exchange** as a long range int., and **the compact 5-quark potential** as a short range int.
- For the hidden-charm, the π exchange is not enough to produce the states. **Importance of the $5q$ potential (Spin structure).**

Summary



- Future Works
  - ▷ Treatment of the $5q$ potential
  - **1.** Determining the strength f^{5q} (Quark model?)
  - **2.** Energy dependent $5q$ potential
  - **3.** Including the $J/\psi N$ channel
  - ▷ Other short range interaction (double counting)

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

Thank you for your kind attention.

Back up

Coupled-channels

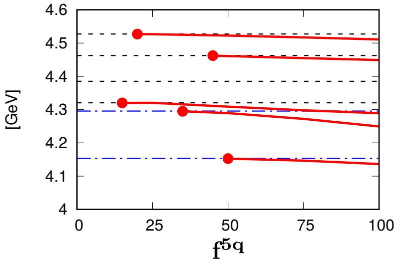
Channels	$\bar{D}Y_c(^{2S+1}L)$	
$1/2^-$	$\bar{D}\Lambda_c(^2S)$, $\bar{D}^*\Lambda_c(^2S)$, $\bar{D}\Sigma_c(^2S)$, $\bar{D}\Sigma_c^*(^4D)$, $\bar{D}^*\Sigma_c(^2S,^4D)$, $\bar{D}^*\Sigma_c^*(^2S,^4D,^6D)$	(10 ch)
$3/2^-$	$\bar{D}\Lambda_c(^2D)$, $\bar{D}^*\Lambda_c(^4S,^2D,^4D)$, $\bar{D}\Sigma_c(^2D)$,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

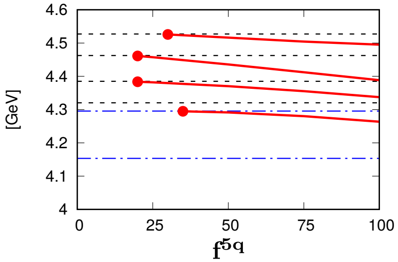
Result: V^{5q} (i) + (ii) + (iii)

- Hidden-charm: $V^{5q} = V^{5q}_{(i)} + V^{5q}_{(ii)} + V^{5q}_{(iii)}$

$J^P = 1/2^-$



$J^P = 3/2^-$



Volume integrals of the potentials

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

Volume integrals of the potentials

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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).

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

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

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

  However, the bound and resonant states are obtained!