ハドロン分子におけるコンパクトな5クォーク状態が作る近距離引力

山口康宏[1]

in collaboration with

Alessandro Giachino[2], 保坂淳[3], Elena Santopinto[2],
竹内幸子[4], 瀧澤誠[5]

[1] 理研, [2]INFN Genova, [3] 阪大 RCNP,
[4] 社会事業大, [5] 昭和薬科大

Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa,

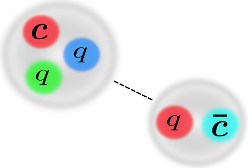
arXiv:1709.00819 [hep-ph]

KEK 理論センター研究会「ハドロン・原子核物理の理論研究最前線 2017」

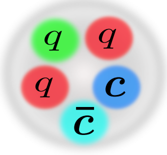
Outline

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
   - Hidden-bottom molecules
4. Summary



Hadronic molecule

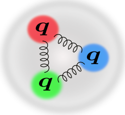


Pentaquark (Compact)

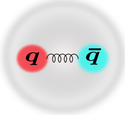
Conventional and Exotic hadrons

Introduction: Exotic hadron

- 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,...)

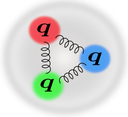


Meson (π,K,...)

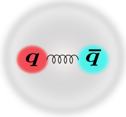
Conventional and Exotic hadrons

Introduction: Exotic hadron

- 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!

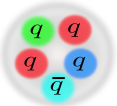


Baryon(proton,nucleon,...)

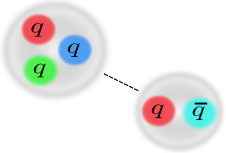


Meson (π,K,...)

- **Exotic hadrons?** $\rightarrow$ Multiquark state



Compact pentaquark



Hadronic molecule

...

Observation of two hidden-charm pentaquarks !!

Introduction: pentaquark

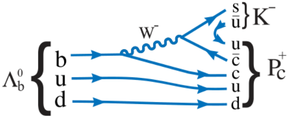
PRL 115, 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

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)

$\Lambda_b^0 \to K^- P_c^+$ decay



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

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

$P_c(4450)$: $\mathrm{M}=4449.8 \pm 1.7 \pm 2.5$ 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!

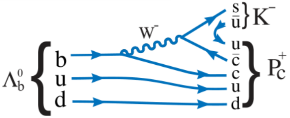
- $P_c(4380)$ and $P_c(4450)$ obtained near $\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$

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)

$\Lambda_b^0 \to K^- P_c^+$ decay



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

$P_c(4380)$: M=4380 ± 8 ± 29 MeV, Γ = 205 ± 18 ± 86 MeV

$P_c(4450)$: M=4449.8 ± 1.7 ± 2.5 MeV, Γ = 39 ± 5 ± 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!

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

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

Proposals of various structures!

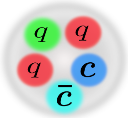
H.X.Chen, *et al.*, Phys.Rept.**639**(2016)1, A.Esposito, *et al.*,Phys.Rept.**668**(2016)1, A.Ali,*et al.*,PPNP**97**(2017)123

- 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),

  ...



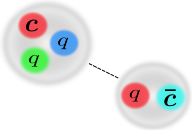
Pentaquark (Compact)

- 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),

  ...



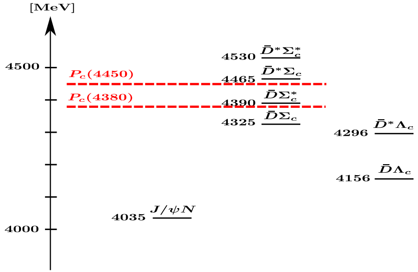
Hadronic molecule

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

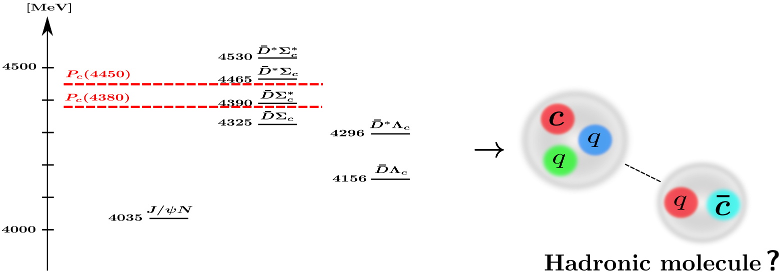
  F.K.Guo, *et al.* (2015), X.H.Liu, *et al.* (2016),

  ...

- e.g. $P_c(4380)$, $P_c(4450)$
  → close to **the meson-baryon thresholds**

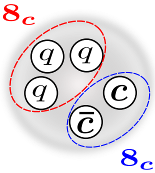


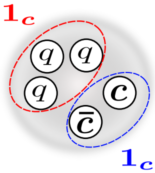
- e.g. $P_c(4380)$, $P_c(4450)$
  → close to **the meson-baryon thresholds**



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

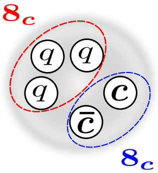
- S. Takeuchi and M. Takizawa, PLB**764** (2017) 254-259.
  P_c states by the quark cluster model
- 5-quark configurations

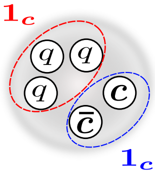




$S_{q^3} = 1/2, 3/2,\ S_{c\bar{c}} = 0, 1 \quad S_{q^3} = 1/2,\ S_{c\bar{c}} = 0, 1$

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

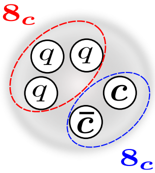


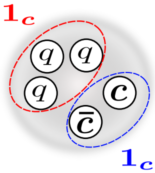


$S_{q^3} = 1/2, 3/2,\ S_{c\bar{c}} = 0, 1 \qquad S_{q^3} = 1/2,\ S_{c\bar{c}} = 0, 1$

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

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





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

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

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

Compact state $\Leftrightarrow$ Hadronic Molecule

Model setup in this study

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

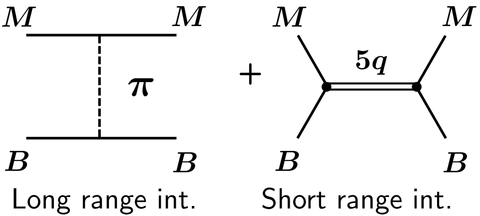
Model setup in this study

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

Model setup in this study

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

Interaction of hadrons (M and B)

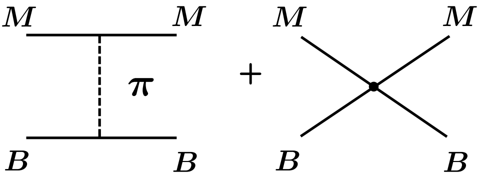


- **Long range** interaction: One pion exchange potential (OPEP)
- **Short range** interaction: $5q$ potential

Model setup in this study

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

Interaction of hadrons (M and B)



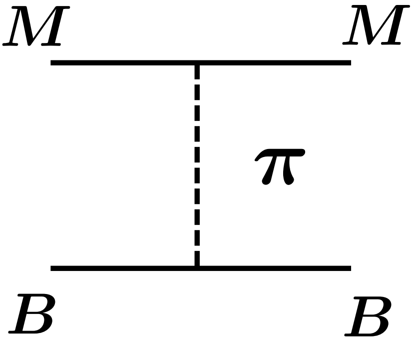
Long range int. Short range int.

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

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

***MB* bound states: Role of the $5q$ potential**

1. Long range force: One pion exchange potential



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)

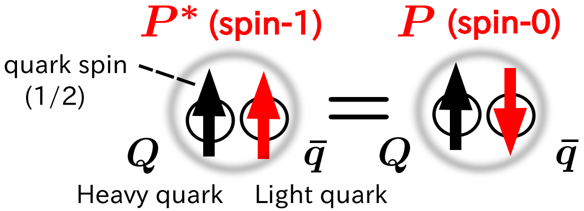
Heavy Quark Spin Symmetry (HQS)

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

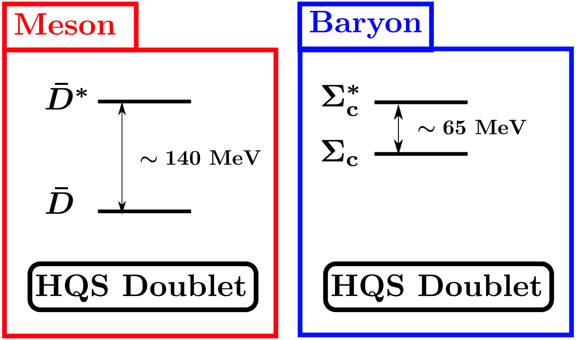
- e.g. $Q\bar{q}$ meson



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

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

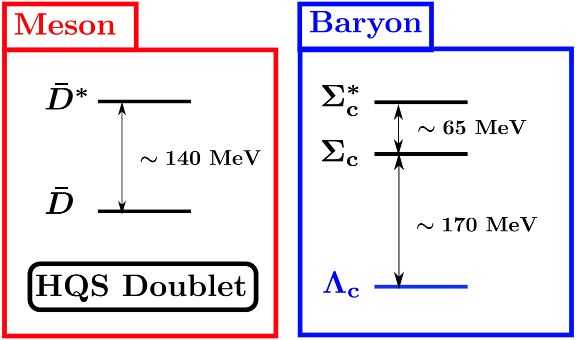
- $\bar{D}-\bar{D}^*$ and $\Sigma_c-\Sigma_c^*$ mixing in the $\bar{D}Y_c$ system



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

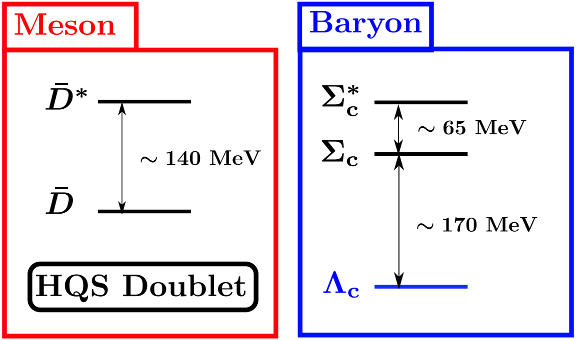
Mass degeneracy → $\bar{D} - \bar{D}^*$, $\Sigma_c - \Sigma_c^*$ mixing!
HQS and OPEP

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



- 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

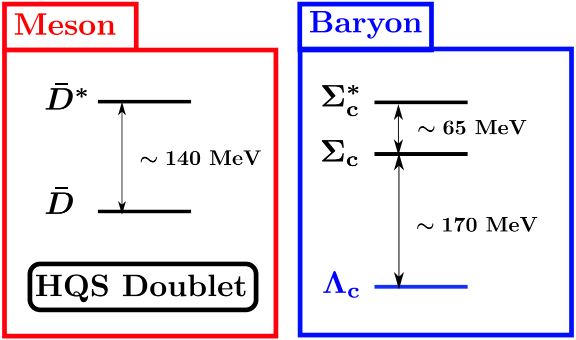


▷ 6 meson-baryon components

(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 → $\bar{D}-\bar{D}^*$, $\Sigma_c-\Sigma_c^*$ mixing!
HQS and OPEP

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



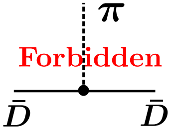
▷ 6 meson-baryon components

(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) $\bar{D}^*\Sigma_c^*$ → Coupled by OPEP!

Heavy hadron-π coupling
HQS and OPEP

- 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)**

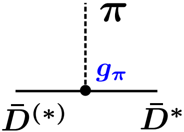
$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi}\mathrm{Tr}\left[H\gamma_\mu\gamma_5\partial^\mu\hat{\pi}\bar{H}\right], \quad H = \frac{1+\not{v}}{2}\left[D^*_\mu\gamma^\mu - D\gamma_5\right]$$

Heavy hadron-π coupling
HQS and OPEP

- 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



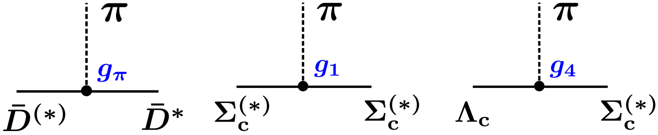
▷ Heavy meson: $\bar{D}^{(*)}\bar{D}^{(*)}\pi$ **($DD\pi$: Parity violation)**

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

Heavy hadron-π coupling
HQS and OPEP

- 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)**

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

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

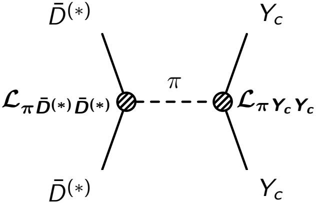
$$\mathcal{L}_{\pi BB} = -\frac{3}{4f_\pi}\mathbf{g_1}(iv_\kappa)\varepsilon^{\mu\nu\lambda\kappa}\mathrm{tr}\left[\bar{S}_\mu\partial_\nu\hat{\pi}S_\lambda\right] - \frac{g_4}{2f_\pi}\mathrm{tr}\left[\bar{S}^\mu\partial_\mu\hat{\pi}\Lambda_c\right] + \mathrm{H.c.},$$

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

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

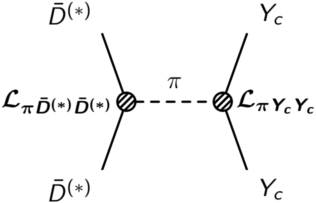
- Form factor with Cutoff Λ (determined by the hadron size)

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

Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, arXiv:1709.00819 [hep-ph]

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

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



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

Y_c: Λ_c, Σ_c or Σ_c^*

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

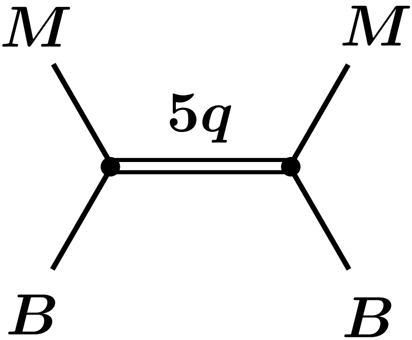
(Contact term is removed)

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

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

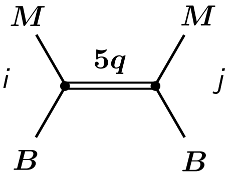
Y.Y, A. Giachino, A. Hosaka, E. Santopinto, S. Takeuchi, M. Takizawa, arXiv:1709.00819 [hep-ph]

2. Short range force: 5-quark potential



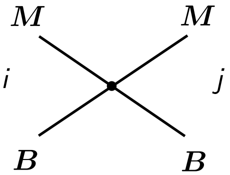
Model: 5-quark potential

- 5-quark potential ⇒ s-channel diagram...But



Model: 5-quark potential

- 5-quark potential ⇒ **Local Gaussian potential** is employed.
- Massive M_{5q} (few hundred MeV above $\bar{D}^*\Sigma_c^*$) → **Attractive**

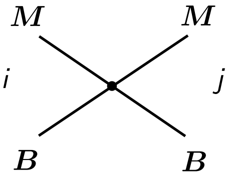


$$\Rightarrow -f\, S_i S_j e^{-\alpha r^2}$$

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

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**



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

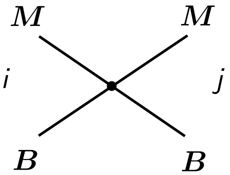
Channel $i, j = \bar{D}^{(*)}\Lambda_c,\ \bar{D}^{(*)}\Sigma_c^{(*)}$ with $S-$wave

Free Parameters

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

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

Free Parameters

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

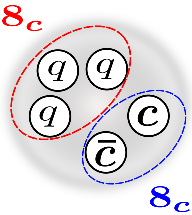
Relative strength S_i

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

Spectroscopic factors S_i

5q potential

- S-factor is determined by the spin structure of the 5q state
- Several 5q states with S_{3q} and $S_{c\bar{c}}$ configuration
  e.g. for $J^P = 1/2^-$, (i), (ii), (iii)

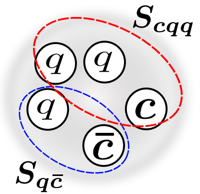


$J^P = 1/2^-$

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

Spectroscopic factors S_i
5q potential

- S-factor is determined by the spin structure of the 5q state
- Several 5q states with S_{3q} and $S_{c\bar{c}}$ configuration
  e.g. for $J^P = 1/2^-$, (i), (ii), (iii)



$J^P = 1/2^-$

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

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

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

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

- 5q−configuration: $8_c\ qqq$ and $8_c\ c\bar{c}$ with S−wave

$$V_{ij}^{5q}(r) = -f\mathbf{S_i}\mathbf{S_j}e^{-\alpha r^2}$$

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

- 5q−configuration: $8_c\,qqq$ and $8_c\,c\bar{c}$ with S−wave

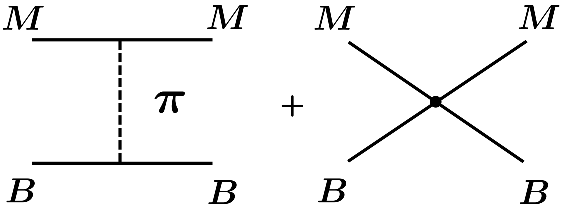
$$V^{5q}_{ij}(r) = -f\,\mathbf{S_i S_j}\,e^{-\alpha r^2}$$

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**

- **Large S_i** will play an important role.

Numerical Results for Hidden-charm sector



Long range int.

Short range int. (Gaussian)

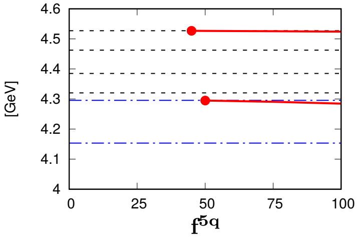
<u>Bound state and Resonance</u>

- Coupled-channel Schrödinger equation for $\bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$, $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ (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 $J^P = 1/2^-$

- OPEP + V^{5q} (i), (ii), (iii)

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



- No state in small f^{5q}

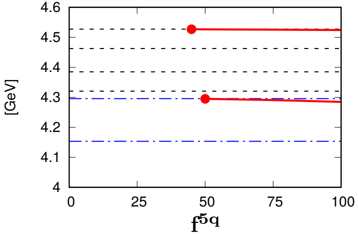
$\rightarrow$ OPEP is not enough to produce states

$\Rightarrow$ States appear **near the threshold**

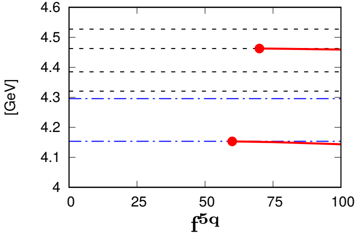
Results (f^{5q} vs E) of charm $\bar{D}Y_c$ for $J^P = 1/2^-$

- OPEP + V^{5q} (i), (ii), (iii)

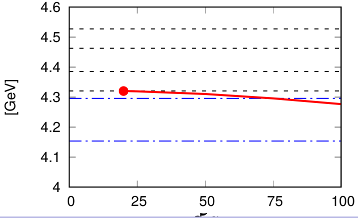
(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{1}{2})$



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



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



- No state in small f^{5q}

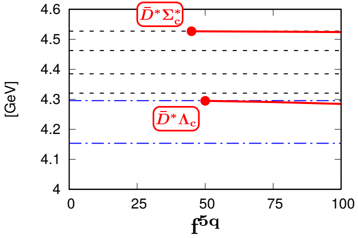
$\rightarrow$ OPEP is not enough to produce states

$\Rightarrow$ States appear **near the threshold**

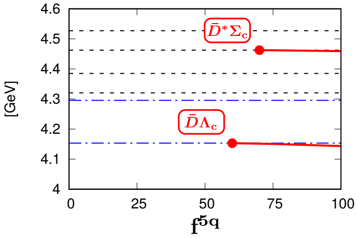
Results (f^{5q} vs E) of charm $\bar{D}Y_c$ for $J^P = 1/2^-$

- OPEP + V^{5q} (i), (ii), (iii)

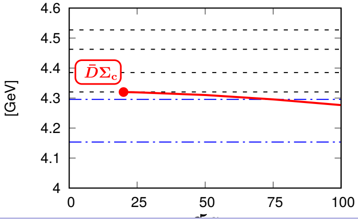
(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{1}{2})$



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



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



- No state in small f^{5q}

$\rightarrow$ OPEP is not enough to produce states

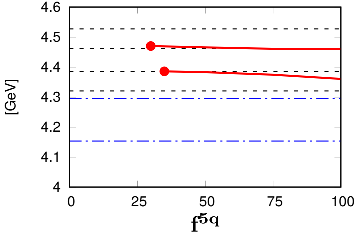
$\Rightarrow$ States appear **near the threshold**

$\Leftrightarrow$ **Large S-factor**

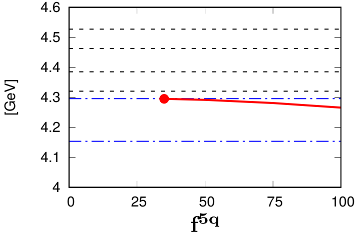
Results (f^{5q} vs E) of charm $\bar{D}Y_c$ for $J^P = 3/2^-$

- OPEP + V^{5q} (i), (ii), (iii)

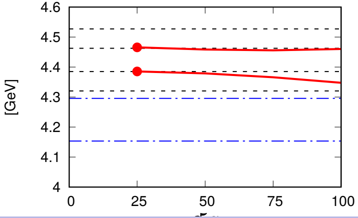
(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{3}{2})$



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



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



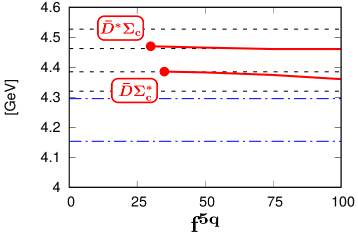
- No state in small f^{5q}

$\Rightarrow$ States appear near the thresholds

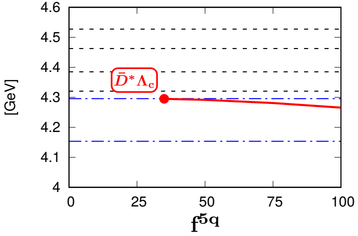
Results (f^{5q} vs E) of charm $\bar{D}Y_c$ for $J^P = 3/2^-$

- OPEP + V^{5q} (i), (ii), (iii)

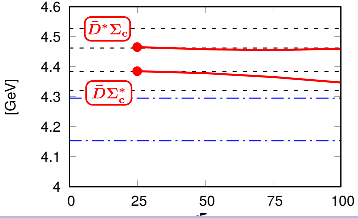
(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{3}{2})$



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



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



- No state in small f^{5q}

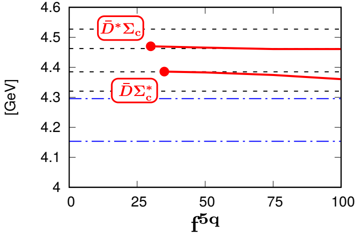
$\Rightarrow$ States appear near the thresholds

$\Leftrightarrow$ **Large S-factor**

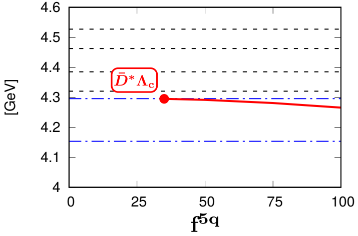
Results (f^{5q} vs E) of charm $\bar{D}Y_c$ for $J^P = 3/2^-$

- OPEP + V^{5q} (i), (ii), (iii)

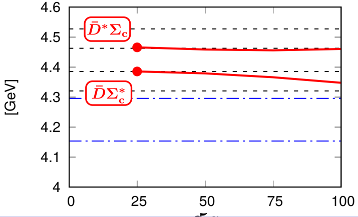
(i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{3}{2})$



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



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



- No state in small f^{5q}

$\Rightarrow$ States appear near the thresholds

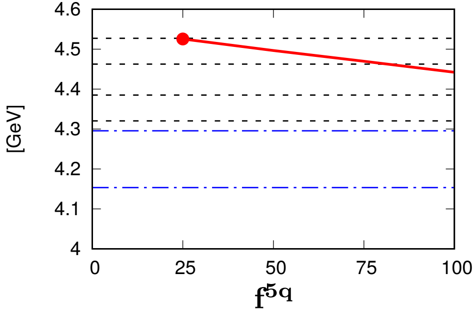
$\Leftrightarrow$ **Large S-factor**

- $P_c(4380)$? (below $\bar{D}\Sigma_c^*$)
  $P_c(4450)$? (below $\bar{D}^*\Sigma_c$)

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

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

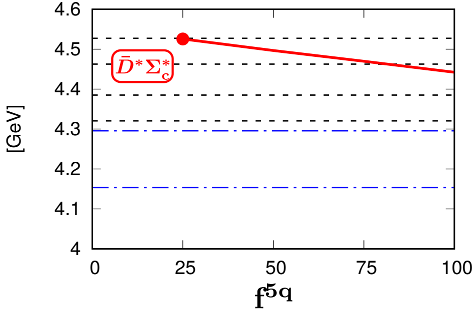
$$(S_{c\bar{c}}, S_{3q}) = (1, \tfrac{3}{2})$$



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

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



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**

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

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

▷ 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).

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

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

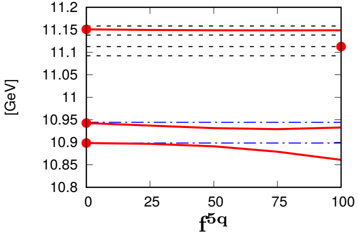
- $\left| V^{5q}_{f=25}(0) \right|$ is **much smaller** than $\left| C^{\sigma}_{NN}(0) \right|$.

  However, the bound and resonant states are obtained!

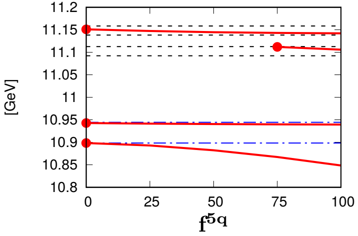
Results (f^{5q} vs E) of bottom BY_b for $J^P = 1/2^-$

- OPEP + V^{5q} (i), (ii), (iii)

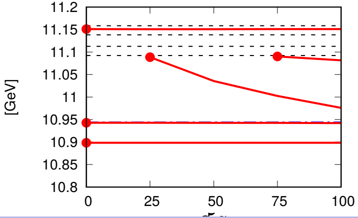
(i) $(S_{b\bar{b}}, S_{3q}) = (0, \frac{1}{2})$



(ii) $(S_{b\bar{b}}, S_{3q}) = (1, \frac{1}{2})$

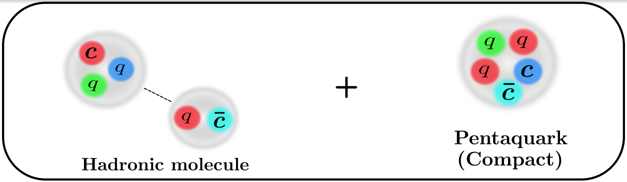


(iii) $(S_{b\bar{b}}, S_{3q}) = (1, \frac{3}{2})$



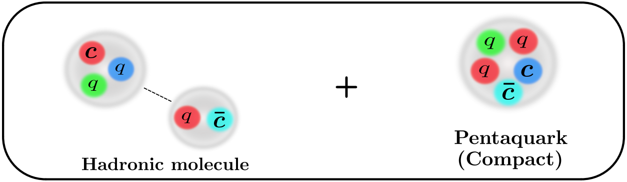
- OPEP produces **the states**!
- **Importance of OPEP**
  $B - B^*$, $\Sigma_b - \Sigma_b^*$ mixing
- **Many states** close to the thresholds

Summary



- 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: **OPEP** as a long range int., and
  the compact 5-quark potential as a short range int.
- By solving the coupled-channel Schrödinger equation for $\bar{D}Y_c$,
  the bound and resonant states are studied.
- For the hidden-charm, the OPEP is not enough to produce
  the states. **Importance of the 5q potential.**
- For the bottom sector, **the OPEP is enhanced** because of
  the mixing effect. OPEP + 5q potential produces many
  states.

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,

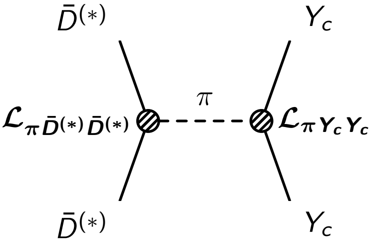
arXiv:1709.00819 [hep-ph]

Thank you for your kind attention.

Back up

Form factor

- To take into account the hadron structure, the form factor is introduced.



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

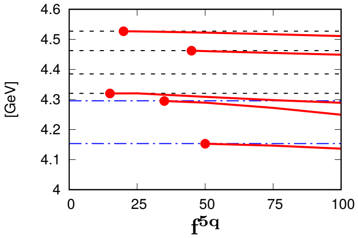
Y_c: $\Lambda_{\rm c}$, $\Sigma_{\rm c}$ or $\Sigma_{\rm c}^*$

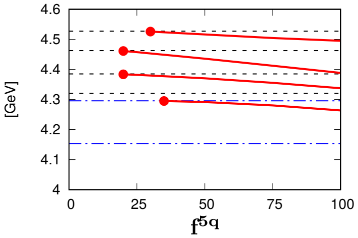
- Form factor with the cutoffs Λ_D, Λ_{Y_c}
  $\rightarrow$ Fixed by the hadron size ratio, $\Lambda_D = 1.35\Lambda_N$, $\Lambda_{Y_c} \sim \Lambda_N$

$$F(\Lambda, \vec{q}\,) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + |\vec{q}\,|^2}, \quad \frac{r}{r_N} = \frac{\Lambda_N}{\Lambda}, \Lambda_N = 837 \text{ MeV}.$$

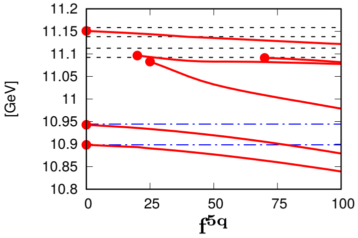
S.Yasui,K.Sudoh,PRD**80** (2009) 034008, Y.Yamaguchi,*et al.* PRD**84**(2011)014032

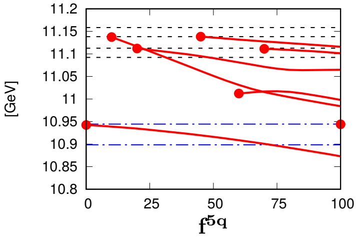
- Hidden-charm: $V^{5q} = V^{5q}_{(i)} + V^{5q}_{(ii)} + V^{5q}_{(iii)}$





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





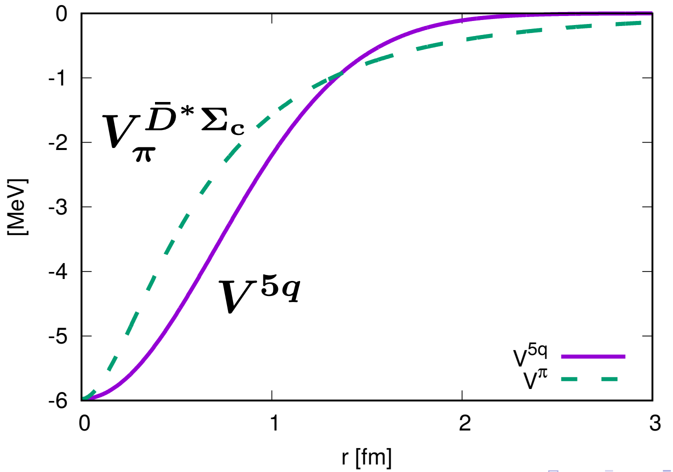
Model: Parameters f and α

- $V_{ij}^{5q}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1$ fm^{-2} (Assumption),

- $V^{5q}_{ij}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1$ fm^{-2} (Assumption),
$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**

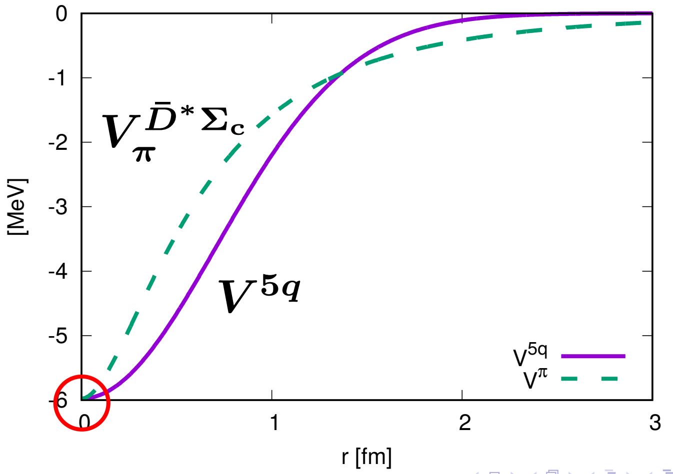


Model: Parameters f and α

- $V_{ij}^{5q}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1\ \mathrm{fm}^{-2}$ (Assumption),

$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**



Model: Parameters f and α

- $V_{ij}^{5q}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1\ \mathrm{fm}^{-2}$ (Assumption),
$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**

Volume integral $\mathcal{V}(q=0) = \int dr^3 V(r)$

$$\left|\mathcal{V}^{5q}(0)\right| \sim \frac{1}{4}\left|\mathcal{V}_\pi^{\bar{D}^*\Sigma_c}(0)\right|$$

Model: Parameters f and α

- $V_{ij}^{5q}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1$ fm^{-2} (Assumption),
$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**

Volume integral $\mathcal{V}(q=0) = \int dr^3 V(r)$

$$\left|\mathcal{V}^{5q}(0)\right| \sim \frac{1}{4}\left|\mathcal{V}_\pi^{\bar{D}^*\Sigma_c}(0)\right| \sim \frac{1}{15}\left|\mathcal{V}_\pi^{NN}(0)\right| \sim \frac{1}{880}\left|\mathcal{V}_\sigma^{NN}(0)\right|$$

($\mathcal{V}_\pi^{NN}$: Central force of OPEP in NN, $\mathcal{V}_\sigma^{NN}(0)$: σ exchange in NN)

Model: Parameters f and α

- $V_{ij}^{5q}(r) = -\mathbf{f_0} S_i S_j e^{-\alpha r^2}$

$\Rightarrow$ Parameters: $\alpha = 1$ fm^{-2} (Assumption),
$f_0 = V_\pi^{\bar{D}^*\Sigma_c}(r=0) \sim 6$ MeV. **(reference value)**

Volume integral $\mathcal{V}(q=0) = \int dr^3 V(r)$

$$\left|\mathcal{V}^{5q}(0)\right| \sim \frac{1}{4}\left|\mathcal{V}_\pi^{\bar{D}^*\Sigma_c}(0)\right| \sim \frac{1}{15}\left|\mathcal{V}_\pi^{NN}(0)\right| \sim \frac{1}{880}\left|\mathcal{V}_\sigma^{NN}(0)\right|$$

($\mathcal{V}_\pi^{NN}$: Central force of OPEP in NN, $\mathcal{V}_\sigma^{NN}(0)$: σ exchange in NN)

$\Rightarrow$ **Small contribution of V^{5q}**...
We will see the f dependence of the energy spectrum
($\boldsymbol{f_0}$: reference value)