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

Yasuhiro Yamaguchi

in collaboration with

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

30 Jan. 2018, Paris
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
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!

- Quark potential (Coulomb type + Linear potential)

\[
V_q(r) = -\frac{a}{r} + br + c + d\frac{\vec{S}_1 \cdot \vec{S}_2}{m_1 m_2} \delta^{(3)}(r) + ... 
\]
Exotic hadrons in the heavy quark region

Introduction: Exotic hadron

Charmonium ($c\bar{c}$)

- $\psi(4160)$
- $\psi(4040)$
- $\chi_{c2}(2P)$
- $\eta_c(2S)$
- $\psi(3770)$
- $\psi(2S)$
- $\chi_{c0}(1P)$
- $\chi_{c1}(1P)$
- $\chi_{c2}(1P)$
- $h_c(1P)$
- $J/\psi(1S)$

S. Godfrey and N. Isgur, PRD32(1985)189
Exotic hadrons in the heavy quark region

Introduction: Exotic hadron

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

<table>
<thead>
<tr>
<th>Mass (GeV/c^2)</th>
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<tbody>
<tr>
<td>4.5</td>
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<tr>
<td>(Y(4664))</td>
</tr>
<tr>
<td>(Y(4630))</td>
</tr>
<tr>
<td>(\psi(415))</td>
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<td>4.0</td>
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<tr>
<td>(Y(4360))</td>
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<td>3.5</td>
</tr>
<tr>
<td>(G(3390))</td>
</tr>
<tr>
<td>(\psi(3770))</td>
</tr>
<tr>
<td>(\eta_c(2S))</td>
</tr>
<tr>
<td>3.0</td>
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<tr>
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\(c\bar{c}\) and Exotic hadrons \((\neq c\bar{c})\)

Charmonium \(c\bar{c}\) and Exotic hadrons \(X, Y, Z\)

S. Godfrey and N. Isgur, PRD 32(1985)189
Exotic hadrons in the heavy quark region

Introduction: Exotic hadron

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

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</tr>
</tbody>
</table>

- \(Y(4664)\)
- \(Y(4630)\)
- \(\psi(4415)\)
- \(Y(4360)\)
- \(\psi(4160)\)
- \(Y(4360)\)
- \(\psi(4040)\)
- \(G(3900)\)
- \(\psi(3770)\)
- \(X(3872)\)
- \(\chi_{c1}(1P)\)
- \(\chi_{c2}(1P)\)
- \(\eta_c(1S)\)
- \(J/\psi(1S)\)
- \(h_c(1P)\)
- \(Z(4430)^+\)
- \(X(4350)\)
- \(X(4160)\)
- \(Y(4274)^+\)
- \(Z_2(4250)^+\)
- \(Y(4140)\)
- \(Z_1(4050)^+\)
- \(X(3940)\)
- \(X(3915)\)

**Charmonium** \(c\bar{c}\) and **Exotic hadrons** \(\neq c\bar{c}\)

\[X, Y, Z\]

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

⇒ **Multiquark states?**

S. Godfrey and N. Isgur, PRD32(1985)189
Exotic hadrons in the heavy quark region

Introduction: Exotic hadron

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

- Charmonium ($c\bar{c}$):
  - $Y(4664)$
  - $Y(4630)$
  - $\psi(4415)$
  - $\psi(4360)$
  - $Y(4260)$
  - $\psi(4160)$
  - $\psi(4040)$

- New Exotic hadrons ($\neq c\bar{c}$):
  - $X(3872)$
  - $\chi_{c2}(2P)$
  - $Z(4430)^+$
  - $X(4350)$
  - $X(4274)$
  - $Z_{c2}(4250)^+$
  - $Y(4140)$
  - $Z(4050)^+$
  - $X(3940)^+$
  - $Z_c(3900)$
  - $X(3915)$

What is the structure of exotic hadrons?

⇒ Multiquark states?

- Tetraquark (Compact)
- Hadronic molecule

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

30 Jan. 2018
Yasuhiro Yamaguchi (RIKEN)
Observation of two hidden-charm pentaquarks!!

Introduction: pentaquark

\[ \Lambda_b^0 \rightarrow K^- P_c^+ \] decay

Two (c\(\bar{c}uuud\)) Pentaquarks!

\[ P_c(4380): \quad M=4380 \pm 8 \pm 29 \text{ MeV} \]
\[ \Gamma = 205 \pm 18 \pm 86 \text{ MeV} \]

\[ P_c(4450): \quad M=4449.8 \pm 1.7 \pm 2.5 \text{ MeV} \]
\[ \Gamma = 39 \pm 5 \pm 19 \text{ MeV} \]

\( J^P: \ (3^-_2, \ 5^+_2), \ (3^+_2, \ 5^-_2) \) or \( (5^+_2, \ 3^-_2) \) *Opposite parity

*Best fit!

\( P_c(4380) \) and \( P_c(4450) \) obtained near \( \bar{D}\Sigma^*_c \) and \( \bar{D}^*\Sigma_c \)
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 $\Lambda^0_b \to J/\psi K^- p$ Decays

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

$\Lambda^0_b \to K^- P^+_c$ decay

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

- $P_c(4380)$: $M=4380 \pm 8 \pm 29$ MeV
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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?
Theoretical discussions of the hidden-charm baryons

Introduction: pentaquark

Proposals of various structures!

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

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

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

Exotic states near thresholds → Molecules?

Introduction: pentaquark

▷ e.g. $P_c(4380)$, $P_c(4450)$

→ close to the meson-baryon thresholds
Exotic states near thresholds → Molecules?

Introduction: pentaquark

▷ 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: $B \sim 2.2$ MeV)

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

Compact state: 5-quark configuration
Introduction: pentaquark

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

![Diagram of 5-quark configurations](image-url)

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

Couplings to (qqcq) baryon-(qcc) meson, e.g. $D_c$, are allowed!
Compact state: 5-quark configuration

Introduction: pentaquark

  $P_c$ states by the quark cluster model
- 5-quark configurations

\[ S_{q^3} = 1/2, 3/2, \quad S_{c\bar{c}} = 0, 1 \]
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- $[q^3 s_c 3/2]$: Color magnetic int. is attractive!
Compact state: 5-quark configuration
Introduction: pentaquark

  $P_c$ states by the quark cluster model
- 5-quark configurations

\[
\begin{align*}
S_{q^3} &= 1/2, 3/2, S_{c\bar{c}} = 0, 1 \\
S_{q^3} &= 1/2, S_{c\bar{c}} = 0, 1
\end{align*}
\]

- $[q^3 8_c 3/2]$: Color magnetic int. is attractive!
  \[\Rightarrow\] Couplings to $(qqc)$ baryon-$(q\bar{c})$ meson, e.g. $\bar{D}\Sigma_c$, are allowed!

Mixing of Compact state and Hadronic Molecule!
Model setup in this study

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

$MB + 5q$

Hadronic molecule
Model setup in this study

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

\[ MB + 5q \]

Hadronic molecule

\[ \text{hadronic molecule} \rightarrow \text{hadron} \]

\[ MB \rightarrow 5q \]

\[ MB + 5q \rightarrow \text{hadron} \]
Model setup in this study

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

**Interaction of hadrons** \((M \text{ and } B)\)

- **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** interaction: One pion exchange potential (OPEP)
- **Short range** interaction: $5q$ potential ($\rightarrow$ Local Gaussian)
  (* Other int. (double counting...) $\rightarrow$ Future work)

$MB$ bound states: Role of the $5q$ potential (Spin structure)
1. Long range force: One pion exchange potential

\[ M \quad \pi \quad M \]

- Exchanging light meson \( \pi \) (\( m_\pi \approx 140 \text{ MeV} \))
- Driving force to bind Atomic nucleus
Heavy Quark Spin Symmetry

Heavy Quark symmetry and OPEP
HQS and OPEP
Heavy Quark Spin Symmetry

Charm ($c$), Bottom ($b$), Top ($t$)
Heavy Quark Spin Symmetry

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

1. Coupled channels of MB
2. Tensor force (OPEP)
Heavy Quark Spin Symmetry and Mass degeneracy

Heavy Quark Spin Symmetry (HQS)  
N. Isgur, M. B. Wise, PLB232 (1989) 113

- Suppression of Spin-spin force in $m_Q \to \infty$.
  - Mass degeneracy of hadrons with the different $J$
- e.g. $Q\bar{q}$ meson

![Diagram showing quark spin (1/2) and mass degeneracy of spin-0 and spin-1 states]

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

HQS and OPEP

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

**Meson**

![Diagram showing the meson sector with $\bar{D}^*$ and $\bar{D}$ states connected by a ~140 MeV arrow.]

**Baryon**

![Diagram showing the baryon sector with $\Sigma_c^*$, $\Sigma_c$, and $\Lambda_c$ states connected by ~65 MeV and ~170 MeV arrows.]

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

- In addition, $\Lambda_c (cqq)$: $\bar{D}^{(*)}\Lambda_c$ channel!!
Mass degeneracy \( \rightarrow \bar{D} - \bar{D}^*, \Sigma_c - \Sigma_c^* \) 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

\[
(1) \quad \bar{D} \Lambda_c, \quad (2) \quad \bar{D}^* \Lambda_c, \quad (3) \quad \bar{D} \Sigma_c, \quad (4) \quad \bar{D} \Sigma_c^*, \\
(5) \quad \bar{D}^* \Sigma_c, \quad (6) \quad \bar{D}^* \Sigma_c^*
\]
Mass degeneracy $\rightarrow \bar{D} - \bar{D}^*, \Sigma_c - \Sigma_c^*$ mixing!

HQS and OPEP

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

- **Meson**
  - $\bar{D}^*$
  - $\bar{D}$
  - $\sim 140$ MeV

- **Baryon**
  - $\Sigma_c^*$
  - $\Sigma_c$
  - $\sim 65$ MeV
  - $\Lambda_c$
  - $\sim 170$ MeV

- 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) $\bar{D}^*\Sigma_c^*$ $\rightarrow$ Coupled by OPEP!
Heavy hadron-π coupling
HQS and OPEP

• Effective Lagrangians: Heavy hadron and π


\[ \mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi} \text{Tr} \left[ H \gamma_\mu \gamma_5 \partial^\mu \pi \bar{H} \right], \quad H = \frac{1+\nu}{2} \left[ D^*_\mu \gamma^\mu - D \gamma_5 \right] \]

⚠️ Heavy meson: \( \bar{D}(\ast) \bar{D}(\ast) \pi \) (\( \bar{D}D\pi \): Parity violation)
Effective Lagrangians: Heavy hadron and $\pi$


$\pi$

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

$g_\pi$

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

$$\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi} \text{Tr} \left[ H\gamma_\mu\gamma_5 \partial^\mu \hat{\pi} \bar{H} \right], \quad H = \frac{1+\gamma^\nu}{2} \left[ D^*_\mu \gamma^\mu - D\gamma_5 \right]$$
Heavy hadron-π coupling
HQS and OPEP

- Effective Lagrangians: Heavy hadron and π


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

\[
\mathcal{L}_{\pi HH} = -\frac{g_\pi}{2f_\pi} \text{Tr} \left[ H \gamma_\mu \gamma_5 \partial^\mu \hat{\pi} \hat{H} \right], \quad H = \frac{1+i\gamma_5}{2} \left[ D_\mu^* \gamma^\mu - D_\gamma^5 \right]
\]

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

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

\[
S_\mu = \Sigma_{c\mu}^* - \frac{1}{\sqrt{3}} (\gamma_\mu + v_\mu) \gamma_5 \Sigma_c,
\]

\( g_\pi = 0.59, g_1 = 1.00, g_4 = 1.06 \)
\( \bar{D}(\ast) Y_c \) Interaction: Long range force

HQS and OPEP

- One pion exchange potential

\[
\begin{align*}
\mathcal{L}_{\pi \bar{D}(\ast) \bar{D}(\ast)} \rightarrow & \quad \mathcal{L}_{\pi Y_c Y_c} \\
\bar{D}(\ast) & \quad \bar{D}(\ast) \\
\bar{D}(\ast) & \quad Y_c \\
Y_c & \quad Y_c
\end{align*}
\]

\[
V_{\pi \bar{D}(\ast) Y_c - \bar{D}(\ast) Y_c} = G \left[ \vec{S}_1 \cdot \vec{S}_2 C(r) + S_{S_1S_2} T(r) \right]
\]

(Contact term is removed)

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

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

One pion exchange potential with Tensor force!

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

(Contact term is removed)

Form factor with Cutoff \( \Lambda \) (determined by the hadron size)

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

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**

\[
M \quad M
\]

\[
\begin{array}{c}
\quad i \\
\downarrow & \quad M \\
\uparrow & \quad j \\
\quad B
\end{array}
\]

\[
\Rightarrow -f S_i S_j e^{-\alpha r^2}
\]

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 $D^*\Sigma_c^*$) $\Rightarrow$ Attractive

\[
\begin{align*}
&M &\quad M \\
&i &  \quad \quad \quad \quad \quad \quad \quad j &\Rightarrow -f S_i S_j e^{-\alpha r^2} \\
&B &\quad B
\end{align*}
\]

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

**Free Parameters**

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

\[
\begin{align*}
M_i & \quad M_j \\
B & \quad B
\end{align*}
\]

\[
(M_i - M_j) \quad \Rightarrow -f \ S_i S_j e^{-\alpha r^2}
\]

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

**Free Parameters**

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

**Relative strength $S_i$**

- Spectroscopic factors ⇒ determined by **the spin structure** of $5q$
5-quark potential ⇒ **Local Gaussian potential** is employed.

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

\[
M_i \rightarrow M_j \Rightarrow -f S_i S_j e^{-\alpha r^2}
\]

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

**Free Parameters**

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

**Relative strength $S_i$**

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

$$\begin{array}{c|c|c}
\text{type} & S_{c\bar{c}} & S_{3q} \\
\hline
\text{(i)} & 0 & 1/2 \\
\text{(ii)} & 1 & 1/2 \\
\text{(iii)} & 1 & 3/2 \\
\end{array}$$

$J^P = 1/2^-$
Spectroscopic factors $S_i$ (Spin structure)

5$q$ potential

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

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<th>Type</th>
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<th>$S_{3q}$</th>
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<tr>
<td>(i)</td>
<td>0</td>
<td>1/2</td>
</tr>
<tr>
<td>(ii)</td>
<td>1</td>
<td>1/2</td>
</tr>
<tr>
<td>(iii)</td>
<td>1</td>
<td>3/2</td>
</tr>
</tbody>
</table>

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

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

$\Rightarrow$ 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.

<table>
<thead>
<tr>
<th>$J$</th>
<th>$S_c\bar{c}$</th>
<th>$S_{3q}$</th>
<th>$\bar{D}\Lambda_c$</th>
<th>$\bar{D}^*\Lambda_c$</th>
<th>$\bar{D}\Sigma_c$</th>
<th>$\bar{D}\Sigma_c^{*}$</th>
<th>$\bar{D}^*\Sigma_c$</th>
<th>$\bar{D}^<em>\Sigma_c^{</em>}$</th>
</tr>
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<tbody>
<tr>
<td>1/2</td>
<td>(i) 0</td>
<td>1/2</td>
<td>0.4</td>
<td>0.6</td>
<td>−0.4</td>
<td>—</td>
<td>0.2</td>
<td>−0.6</td>
</tr>
<tr>
<td></td>
<td>(ii) 1</td>
<td>1/2</td>
<td>0.6</td>
<td>−0.4</td>
<td>0.2</td>
<td>—</td>
<td>−0.6</td>
<td>−0.3</td>
</tr>
<tr>
<td></td>
<td>(iii) 1</td>
<td>3/2</td>
<td>0.0</td>
<td>0.0</td>
<td>−0.8</td>
<td>—</td>
<td>−0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>3/2</td>
<td>(i) 0</td>
<td>3/2</td>
<td>—</td>
<td>0.0</td>
<td>—</td>
<td>−0.5</td>
<td>0.6</td>
<td>−0.7</td>
</tr>
<tr>
<td></td>
<td>(ii) 1</td>
<td>1/2</td>
<td>—</td>
<td>0.7</td>
<td>—</td>
<td>0.4</td>
<td>−0.2</td>
<td>−0.5</td>
</tr>
<tr>
<td></td>
<td>(iii) 1</td>
<td>3/2</td>
<td>—</td>
<td>0.0</td>
<td>—</td>
<td>−0.7</td>
<td>−0.8</td>
<td>−0.2</td>
</tr>
<tr>
<td>5/2</td>
<td>(i) 1</td>
<td>3/2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>−1.0</td>
</tr>
</tbody>
</table>

Spectroscopic factor $S_i$ (Spin structure)

$5q$ potential

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

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

<table>
<thead>
<tr>
<th>$J$</th>
<th>$S_{c\bar{c}}$</th>
<th>$S_{3q}$</th>
<th>$\bar{D}\Lambda_c$</th>
<th>$\bar{D}^*\Lambda_c$</th>
<th>$\bar{D}\Sigma_c$</th>
<th>$\bar{D}\Sigma_c^*$</th>
<th>$\bar{D}^*\Sigma_c$</th>
<th>$\bar{D}^<em>\Sigma_c^</em>$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>(i) 0</td>
<td>1/2</td>
<td>0.4</td>
<td>0.6</td>
<td>-0.4</td>
<td>-</td>
<td>0.2</td>
<td>-0.6</td>
</tr>
<tr>
<td></td>
<td>(ii) 1</td>
<td>1/2</td>
<td>0.6</td>
<td>-0.4</td>
<td>0.2</td>
<td>-</td>
<td>-0.6</td>
<td>-0.3</td>
</tr>
<tr>
<td></td>
<td>(iii) 1</td>
<td>3/2</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.8</td>
<td>-</td>
<td>-0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>3/2</td>
<td>(i) 0</td>
<td>3/2</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
<td>-0.5</td>
<td>0.6</td>
<td>-0.7</td>
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<td></td>
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<td>1/2</td>
<td>-</td>
<td>0.7</td>
<td>-</td>
<td>0.4</td>
<td>-0.2</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td>(iii) 1</td>
<td>3/2</td>
<td>-</td>
<td>0.0</td>
<td>-</td>
<td>-0.7</td>
<td>-0.8</td>
<td>-0.2</td>
</tr>
<tr>
<td>5/2</td>
<td>(i) 1</td>
<td>3/2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

$\bar{D}Y_c$ with Large $S_i$ will play an important role.
Numerical Results for Hidden-charm sector

**Bound state and Resonance**
- 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 \((f^5q \text{ vs } E)\) of charm \(\bar{D}Y_c\) for \(J^P = 1/2^-\)

- \(\pi\) exchange + \(V^5q\) [type (i)]
  \[(i) \ (S_{c\bar{c}}, S_{3q}) = (0, \frac{1}{2})\]

- No state in small \(f^5q\)
  \(\rightarrow\) \(\pi\) exchange is not enough to produce a bound state
  - 5q potential helps to appear the states near the thresholds
Results ($f_{5q}^5$ vs $E$) of charm $\bar{D} Y_c$ for $J^P = 1/2^-$

- $\pi$ exchange + $V_{5q}^5$ [type (i)]
  
  (i) $(S_{c\bar{c}}, S_{3q}) = (0, \frac{1}{2})$

No state in small $f_{5q}^5$

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

- $5q$ potential helps to appear the states near the thresholds
  $\Leftrightarrow$ Large $S$-factor (Spin structure)
Results ($f^{5q}$ vs $E$) of charm $\bar{D}Y_c$ for $J^P = 1/2^-$

- $\pi$ exchange + $V^{5q}$ [types (ii), (iii)]

  (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 $f^{5q}$

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

  - $5q$ potential helps to appear the states near the thresholds
Results ($f^5q$ vs $E$) of charm $\bar{D} Y_c$ for $J^P = 1/2^-$

- $\pi$ exchange + $V^5q$ [types (ii), (iii)]

(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 $f^5q$
  - $\pi$ exchange is not enough to produce a bound state
  - $5q$ potential helps to appear the states near the thresholds
  - Large $S$-factor (Spin structure)
Results ($f^{5q}$ vs $E$) of charm $\bar{D} Y_c$ for $J^P = 3/2^-$

- $\pi$ exchange + $V^{5q}$ (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 $f^{5q}$

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

- $\pi$ exchange + $V^{5q}$ (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 $J^P = 5/2^-$

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

$$(S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})$$
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 5$q$ state
  \[(S_{c\bar{c}}, S_{3q}) = (1, \frac{3}{2})\]

Summary of the hidden-charm sector

- OPEP is not strong enough to produce a state.
- The importance of the 5$q$ 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, $\bar{D}\Sigma_c$, $\bar{D}\Sigma^*_c$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma^*_c + \bar{D}\Lambda_c$, $\bar{D}^*\Lambda_c$
- Interaction: **$\pi$ exchange** as a long range int., and **the compact 5-quark potential** as a short range int.
- For the hidden-charm, the $\pi$ exchange is not enough to produce the states. **Importance of the $5q$ potential (Spin structure).**
Future Works

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. D96 (2017), 114031

Thank you for your kind attention.
Back up
## Coupled-channels

<table>
<thead>
<tr>
<th>Channels</th>
<th>$\bar{D}Y_c^{(2S+1L)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2$^-$</td>
<td>$\bar{D}\Lambda_c(2S)$, $\bar{D}^<em>\Lambda_c(2S)$, $\bar{D}\Sigma_c(2S)$, $\bar{D}\Sigma_c^</em>(4D)$, $\bar{D}^<em>\Sigma_c(2S, 4D)$, $\bar{D}^</em>\Sigma_c^*(2S, 4D, 6D)$ (10 ch)</td>
</tr>
<tr>
<td>3/2$^-$</td>
<td>$\bar{D}\Lambda_c(2D)$, $\bar{D}^<em>\Lambda_c(4S, 2D, 4D)$, $\bar{D}\Sigma_c(2D)$, $\bar{D}\Sigma_c^</em>(4S, 4D)$, $\bar{D}^<em>\Sigma_c(4S, 2D, 4D)$, $\bar{D}^</em>\Sigma_c^*(4S, 2D, 4D, 6D, 6G)$ (15 ch)</td>
</tr>
<tr>
<td>5/2$^-$</td>
<td>$\bar{D}\Lambda_c(2D)$, $\bar{D}^<em>\Lambda_c(2D, 4D, 4G)$, $\bar{D}\Sigma_c(2D)$, $\bar{D}\Sigma_c^</em>(4D, 4G)$, $\bar{D}^<em>\Sigma_c(2D, 4D, 4G)$, $\bar{D}^</em>\Sigma_c^*(6S, 2D, 4D, 6D, 4G, 6G)$ (16 ch)</td>
</tr>
</tbody>
</table>

- 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: $V_5^q (i) + (ii) + (iii)$

Hidden-charm: $V_5^q = V_5^q (i) + V_5^q (ii) + V_5^q (iii)$

$J^P = 1/2^-$

$J^P = 3/2^-$
Volume integrals of the potentials

- Bound and Resonant states appears for $f^{5q} \gtrsim 25$
  $\Leftrightarrow$ Large? Small?
Volume integrals of the potentials

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

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

Comparison with the $NN$ interaction (Bonn potential)


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

($C^\sigma_{NN}$ : Central force of $\sigma$ 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!