Exotic baryons as a hadronic molecule in the heavy quark region

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Hidden-charm pentaquarks as a molecules

1. Introduction
   - Exotic hadron in the heavy quark region
   - Observed Pentaquarks
   - Heavy Quark Spin Symmetry and Coupled channels

2. Meson-Baryon molecules:
   \[ \bar{D}(*) \Lambda_c(\gamma) - \bar{D}(*) \Sigma_c(\gamma) \]

3. Summary
Hidden-charm pentaquarks as *a* molecules

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   \( \bar{D}^{(*)} \Lambda_{c}^{(*)} - \bar{D}^{(*)} \Sigma_{c}^{(*)} \)

3. Summary
Hadrons in the heavy quark region

- 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!

\[
V(r) = -\frac{a}{r} + br + ... 
\]

▷ Quark-quark potential  
S. Godfrey and N. Isgur, PRD32(1985)189
Observation of the Exotic Hadron in the heavy quark (c, b) sectors!
Observation of the Exotic Hadron in the heavy quark (c, b) sectors!

e.g. Spectra of Charmonia

Charmonium $c\bar{c}$

- $\psi(4415)$
- $\psi(4120)$
- $\psi(4040)$
- $\chi_{c2}(2P)$
- $\eta_c(2S)$
- $\psi(3770)$
- $\psi(2S)$
- $\chi_{c0}(1P)$
- $\chi_{c1}(1P)$
- $\chi_{c2}(1P)$
- $h_c(1P)$
- $J/\psi(1S)$

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

Introduction

▷ Observation of the Exotic Hadron in the heavy quark (c, b) sectors!

e.g. Spectra of Charmonia

Charmonium c\c and Exotic hadrons (≠ c\c)

\( X, Y, Z \)

S. Godfrey and N. Isgur, PRD32(1985)189

▷ What is the structure of exotic hadrons?
▷ Why are many exotic hadrons found in the heavy quark region?
Exotic structure: Hadronic molecules

Introduction

Exotic hadrons ⟹ Multiquark states?

Tetraquark (Compact) Hadronic molecule

Loosely bound states (resonances) of hadrons appearing near the thresholds (M-M, M-B,...)

Analogous to Atomic Nuclei Molecules are formed by the Hadron-Hadron interaction dynamically.
Exotic structure: Hadronic molecules

Introduction

Loosely bound states (resonances) of hadrons

→ Appearing near the thresholds (M-M, M-B,...)

⇒ Analogous to Atomic Nuclei

Molecules are formed by the Hadron-Hadron interaction dynamically.
Exotic structure: Hadronic molecules

Introduction

Hadronic molecules

Meson-Meson (X, Y, Z?)

Meson-Baryon

X(3872), Z_b

Λ^*_c, Pentaquark???

Theoretical researches

- X(3872) as D\bar{D}^*,


- Λ(1405) as \bar{K}N, T. Hyodo and D. Jido, Prog. Part. Nucl. Phys. 67 (2012) 55

Hidden-charm pentaquarks as a molecules

1 Introduction
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2 Meson-Baryon molecules:
   $\bar{D}(*) \Lambda_c^{(*)} - \bar{D}(*) \Sigma_c^{(*)}$

3 Summary
Observation of two hidden-charm pentaquarks!!

Introduction

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

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

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb$^{-1}$ acquired with the LHCb detector from 7 and 8 TeV $pp$ collisions. An amplitude analysis of the three-body final state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass $14380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred $J^p$ assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

DOI: 10.1103/PhysRevLett.115.072001

PACS numbers: 14.40.Pq, 13.25.Gv
Observation of two hidden-charm pentaquarks!!

Introduction

1. $M = 4380 \pm 8 \pm 29$ MeV, $\Gamma = 205 \pm 18 \pm 86$ MeV (Broad)
2. $M = 4449.8 \pm 1.7 \pm 2.5$ MeV, $\Gamma = 39 \pm 5 \pm 19$ MeV (Narrow)
   - $J^P$ Assignment: $3/2^-, 5/2^+$; $3/2^+, 5/2^-$; $5/2^+, 3/2^-$
What is the structure of the pentaquarks?

**Introduction**

[Diagram: Pentaquark (Compact)]

- **Compact pentaquark?**
  - Quark model
    - W.L. Wang *et al.*, PRC **84**(2011)015203

- **Hadronic molecule?**
  - SU(4) flavor symmetry
    - J.-J. Wu *et al.*, PRL **105**(2010)232001
    - C.W. Xiao *et al.*, PRD **88**(2013)056012
Important issue of the heavy pentaquarks

**Introduction**

1. Pentaquarks are close to the **meson-baryon thresholds**
   \[ \Rightarrow \text{Hadronic molecules appears near the thresholds!} \]

2. **Heavy Quark Spin Symmetry**
   \[ \Rightarrow \text{SU(4) symmetry is broken in the charm quark sector.} \]
Hidden-charm pentaquarks as a molecules

1. Introduction
   - Exotic hadron in the heavy quark region
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   - Heavy Quark Spin Symmetry and Coupled channels

2. Meson-Baryon molecules:
   \( \bar{D}(\star)\Lambda_{c}^{\star} - \bar{D}(\star)\Sigma_{c}^{\star} \)

3. Summary
Heavy Quark Spin Symmetry (HQS)  

- **Suppression of Spin-spin force in** $m_Q \rightarrow \infty$.
  
  $\Rightarrow$ Decomposition of **Heavy quark spin and Light components**
  $$\vec{J} = \vec{L} + \vec{S} = \vec{S}_Q + \vec{j}$$

- **Mass degeneracy** of hadrons with the different $J$

- Mass degeneracy of \{\textit{D, D*}(Q\bar{q}) , \{\eta_c, J/\psi\}(Q\bar{Q}), \{\Sigma_c, \Sigma_c^*\}(Qqq) (baryons)\...
Mass degeneracy of heavy hadrons

**Introduction**

- Mass difference between vector and pseudoscalar mesons. ($Q\bar{q}$, $q = u, d$)
- $\Delta m$ decreases when the quark mass increases.
- Mass degeneracy of heavy hadrons appears!

![Diagram showing mass differences between vector and pseudoscalar mesons.](image)

**Vector meson ($J^P = 1^-$)**
- $\rho$: 770 MeV
- $K^*$: 890 MeV
- $D^*$: 2010 MeV
- $B^*$: 5325 MeV

**Pseudoscalar meson ($J^P = 0^-$)**
- $\pi$: 270 MeV
- $K$: 490 MeV

**Channel couplings**
- $\pi (q\bar{q})$ to $\rho$
- $\bar{K} (s\bar{q})$ to $K^*$
- $D (c\bar{q})$ to $D^*$
- $\bar{B} (b\bar{q})$ to $B^*$

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Mass degeneracy of heavy hadrons

Introduction

- Mass difference between $1/2^+$ and $3/2^+$ baryons. ($Qqq$, $q = u, d$)

- $\Delta m$ decreases when the quark mass increases.
- Mass degeneracy of heavy hadrons appears!

$\Rightarrow$ Small mass splitting leads to **Channel couplings**!
Interaction between $K$ (light meson) and $N$
$\Rightarrow$ Short range force ($\rho$, $\omega$ exchanges...) dominates.

\begin{itemize}
  \item Strange (Light)
  \item Charm (Heavy)
\end{itemize}
Interaction between $K$ (light meson) and $N$
$\Rightarrow$ Short range force ($\rho$, $\omega$ exchanges...) dominates.

![Strange (Light) \((KK\pi \times)\) vs. Charm (Heavy)]

- In the heavy ($c, b$) sector, the Heavy Quark Spin Symmetry induces the $\bar{D} - \bar{D}^*$ mixing.
  $m_{K^*} - m_K \sim 400$ MeV $\Leftrightarrow$ $m_{D^*} - m_D \sim 140$ MeV
- Appearance of the the one $\pi$ exchange potential.
Introduction

- OPEP is important to bind atomic nuclei.
- **Tensor force** of the OPEP generates a strong attraction.

![Diagram](image)

Tensor force $\Rightarrow ^3S_1 - ^3D_1$

$PN(^2S_{1/2}) - P^*N(^4D_{1/2})$
OPEP is important to bind atomic nuclei.

Tensor force of the OPEP generates a strong attraction.

\[ \begin{align*}
\text{Deuteron} & : & ^3S_1 & \rightarrow & ^3D_1 \\
\text{P}(*) \rightarrow N & : & ^2S_1/2 & \rightarrow & ^4D_1/2
\end{align*} \]

Tensor force \( \Rightarrow ^3S_1 - ^3D_1 \)

HQS: mixing of \( D - D^* \)

Tensor force: mixing of \( S - D \ (P - F) \)
Energy spectra of $\bar{D}$ meson-Nucleon ($\bar{D}N$) states

Introduction

One bound state, and resonances in charm and bottom sectors.

Many states near the thresholds.

No KN bound state

The tensor force from the $D\bar{D}$ mixing is important to produce a strong attraction.

$D^* N$ Threshold

$D N$ Threshold

Unit: MeV

Energy spectra of $\bar{D}$ meson-Nucleon ($\bar{D}N$) states

### Introduction

- One bound state

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**Diagram:**

- $\bar{D}^*N$ (2949 MeV)
- $\bar{D}N$ (2807 MeV)

---

Unit: MeV

Energy spectra of $\bar{D}$ meson-Nucleon ($\bar{D}N$) states

Introduction

- One bound state, and resonances in charm


Many states near the thresholds.

No $KN$ bound state

The tensor force from the $D\bar{D}$ mixing is important to produce a strong attraction!
Energy spectra of $\bar{D}$ meson-Nucleon ($\bar{D}N$) states

Introduction

- One bound state, and resonances in charm and bottom sectors!


Many states near the thresholds. ⇔ No KN bound state
Energy spectra of $\bar{D}$ meson-Nucleon ($\bar{D}N$) states

Introduction

- One bound state, and resonances in charm and bottom sectors!

![Energy spectrum diagram](image)

- Many states near the thresholds. ⇒ **No KN bound state**
- **The tensor force from the $\bar{D} - \bar{D}^*$ mixing** is important to produce a strong attraction!

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Channel coupling of Hidden-charm meson-baryon state

\[ \bar{c}q \quad \bar{D}^{(*)} \quad \Lambda_c \text{ or } \Sigma^*_c \]

Meson \quad \text{Baryon}
Coupled channels of the hidden-charm pentaquark

Introduction

- $\bar{D} - \bar{D}^*$ and $\Sigma_c - \Sigma_c^*$ mixings

Meson

\[ \bar{D}^* \quad \sim 140 \text{ MeV} \]

\[ \bar{D} \]

HQS Doublet

Baryon

\[ \Sigma_c^* \quad \sim 65 \text{ MeV} \]

\[ \Sigma_c \]

HQS Doublet

- Mass degeneracy of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$
Coupled channels of the hidden-charm pentaquark

Introduction

- $\bar{D} - \bar{D}^*$ and $\Sigma_c - \Sigma_c^*$ mixings

**Meson**

$\bar{D}^*$

$\sim 140$ MeV

$\bar{D}$

**Baryon**

$\Sigma_c^*$

$\sim 65$ MeV

$\Sigma_c$

$\sim 170$ MeV

$\Lambda_c$

- Mass degeneracy of $\bar{D}\Sigma_c$, $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ and $\bar{D}^*\Sigma_c^*$

- $\Lambda_c$ (cqq): $\bar{D}^{(*)}\Lambda_c$ channel?
Coupled channels of the hidden-charm pentaquark

Introduction

- $\bar{D}^*(\Lambda_c) - \bar{D}^*(\Sigma_c^*)$ mixing (analogous to $\Lambda N - \Sigma N$)
  $m_{\Sigma_c} - m_{\Lambda_c} \sim 170$ MeV

\[ \begin{array}{c|c}
\bar{D}^*(\Sigma_c^*) \text{ coupling} & \bar{D}^*(\Sigma_c^*) \text{ coupling} \\
\hline
\bar{D}^*(\Lambda_c) & \bar{D}^*(\Sigma_c^*) \\
\pi, \rho, \omega, \ldots & \pi, \rho \\
\bar{D}^*(\Sigma_c^*) & \bar{D}^*(\Sigma_c^*) \\
\Lambda_c & \Sigma_c^*
\end{array} \]

Tensor force producing a strong attraction!

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Coupled channels of the hidden-charm pentaquark

Introduction

- $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$ mixing (analogous to $\Lambda N - \Sigma N$)
  
  $m_{\Sigma_c} - m_{\Lambda_c} \sim 170$ MeV

\[
\begin{array}{c|c}
\bar{D}^{(*)} & \Sigma_c^{(*)} \\
\hline
\pi, \rho, \omega, \ldots & \\
\end{array}
\]

\[
\begin{array}{c|c}
\bar{D}^{(*)} & \Sigma_c^{(*)} \\
\hline
\pi, \rho & \\
\end{array}
\]

\[
\begin{array}{c|c|c}
\bar{D}^{(*)} & \Sigma_c^{(*)} & \Lambda_c \\
\hline
& & \\
\end{array}
\]

$\Rightarrow \bar{D}\Lambda_c, \bar{D}^*\Lambda_c, \bar{D}\Sigma_c, \bar{D}\Sigma_c^*, \bar{D}^*\Sigma_c, \bar{D}^*\Sigma_c^*$ (6 thresholds!)
Coupled channels of the hidden-charm pentaquark

**Introduction**

- $\bar{D}^*(\Lambda_c) - \bar{D}^*(\Sigma_c^*)$ mixing (analogous to $\Lambda N - \Sigma N$)
  
  $m_{\Sigma_c} - m_{\Lambda_c} \sim 170$ MeV

\[
\begin{array}{c|c|c}
\bar{D}^*(\Sigma_c^*) \text{ coupling} & \bar{D}^*(\Lambda_c^*) - \bar{D}^*(\Sigma_c^*) \text{ coupling} \\
\hline
\bar{D}^* & \Sigma_c^* & \bar{D}^* \\
\hline
\pi, \rho, \omega, \ldots & \Sigma_c^* & \pi, \rho \\
\hline
\bar{D}^* & \Sigma_c^* & \Lambda_c \\
\end{array}
\]

$\Rightarrow \bar{D} \Lambda_c, \bar{D}^* \Lambda_c, \bar{D} \Sigma_c, \bar{D} \Sigma_c^*, \bar{D}^* \Sigma_c, \bar{D}^* \Sigma_c^*$ (6 thresholds!)

- Coupling to a state with $\ell \neq 0$ ($D-$wave,...)
  
  $\Rightarrow$ Tensor force producing a strong attraction!
Coupled-Channels

- Allowed channels \((^{2S+1}L)\) for \(JP = 3/2^\pm, 5/2^\pm\)

<table>
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<tbody>
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- \(JP = 3/2^\pm:\)
- \(JP = 5/2^\pm:\)
Allowed channels \((2S+1L)\) for \(JP = 3/2^\pm, 5/2^\pm\)

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- \(JP = 3/2^\pm\): 15 channels!
- \(JP = 5/2^\pm\):
**Coupled-Channels**

- Allowed channels \((^{2S+1}L)\) for \(J^P = 3/2^\pm, 5/2^\pm\)

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- \(J^P = 3/2^\pm\): **15 channels!**
- \(J^P = 5/2^\pm\):
**Coupled-Channels**

- Allowed channels \((^{2S+1}L)\) for \(J^P = 3/2^\pm, 5/2^\pm\)

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- \(J^P = 3/2^\pm\): **15 channels**!
- \(J^P = 5/2^\pm\): **16 channels**!
Coupled-Channels

- Allowed channels \((2S+1L)\) for \(J^P = 3/2^\pm, 5/2^\pm\)

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- \(J^P = 3/2^\pm\): 15 channels!
- \(J^P = 5/2^\pm\): 16 channels!
Main Subject: Pentaquarks

- Hadronic molecules formed by hidden-charm meson-baryon.

- Bound and resonant states of $\bar{D}(*) \Lambda_c - \bar{D}(*) \Sigma_c^(*)$
  - Coupling to $\bar{D}(*) \Lambda_c$ and $\bar{D}(*) \Sigma_c^(*)$
  - Coupling to the state with $\ell \neq 0$
  - Negative and Positive parity states ($P = \pm$)
Main Subject: Pentaquarks

- Hadronic molecules formed by hidden-charm meson-baryon.

- Bound and resonant states of $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$
  - Coupling to $\bar{D}^{(*)}\Lambda_c$ and $\bar{D}^{(*)}\Sigma_c^{(*)}$
  - Coupling to the state with $\ell \neq 0$
  - Negative and Positive parity states ($P = \pm$)

The full-coupled channel analysis of $\bar{D}^{(*)}\Lambda_c - \bar{D}^{(*)}\Sigma_c^{(*)}$ has never performed so far!
Results of $\bar{D}^{(*)}B$ states (2-body)

Bound state and Resonance

- We solve the coupled-channel Schrödinger equations with $J^P = 3/2^\pm, 5/2^\pm$ and isospin $I = 1/2$.
- Interaction: $\pi\rho\omega\sigma$ exchange potentials
Effective Lagrangian with heavy quark symmetry


Meson: \[ \mathcal{L}_{\pi HH} = g_\pi \text{Tr} \left[ H_b \gamma_\mu \gamma_5 A_\mu^{ba} \bar{H}_a \right] \]

Baryon: \[ \mathcal{L}_{\pi BB} = \frac{3}{2} g_1 i \nu_\kappa \epsilon^{\mu\nu\lambda\kappa} \text{tr} \left[ \bar{S}_\mu A_\nu S_\lambda \right] + g_4 \text{tr} \left[ \bar{S}_\mu A_\mu \Lambda_c \right] \]

Heavy meson and baryon fields

\[ H_a = \frac{1+\gamma^\nu}{2} \left[ P_a^* \gamma^\mu - P_a \gamma^5 \right] \quad (1^- \text{ and } 0^-) \]

\[ S_\mu = \Sigma^*_\mu + \frac{\delta}{\sqrt{3}} \left( \gamma_\mu + \nu_\mu \right) \gamma_5 \Sigma \quad (3/2^+ \text{ and } 1/2^+) \]

\( \tilde{D} - \tilde{D}^* \) and \( \Sigma_c - \Sigma^*_c \) mixings
**D(*)B Interaction: Meson exchange potential**

- Effective Lagrangian with heavy quark symmetry


  \[ \mathcal{L}_{\pi HH} = g_\pi \text{Tr} \left[ H_b \gamma_\mu \gamma_5 A^\mu_{ba} \tilde{H}_a \right] \]

  **Baryon:**

  \[ \mathcal{L}_{\pi BB} = \frac{3}{2} g_1 i \nu_\kappa \varepsilon^{\mu \nu \lambda \kappa} \text{tr} \left[ \tilde{S}_\mu A_\nu S_\lambda \right] + g_4 \text{tr} \left[ \tilde{S}_\mu A_\mu \Lambda_c \right] \]

  **Heavy meson and baryon fields**

  \[ H_a = \frac{1 + \gamma_5}{2} \left[ P^*_{a\mu} \gamma_\mu - P_{a\mu} \gamma_5 \right] \quad (1^- \text{ and } 0^-) \]

  \[ S_\mu = \Sigma^*_{\mu} + \frac{\delta}{\sqrt{3}} (\gamma_\mu + \nu_\mu) \gamma_5 \Sigma \quad (3/2^+ \text{ and } 1/2^+) \]

- $\tilde{D} - \tilde{D}^*$ and $\Sigma_c - \Sigma_c^*$ mixings
**D(\*)B Interaction: Meson exchange potential**

- Effective Lagrangian with heavy quark symmetry


\[ \mathcal{L}_{mD(\*)D(\*)} \]

\[ \mathcal{L}_{mBB} \]

\[ V_{D(\*)B-D(\*)B} = G \left[ \vec{O}_1 \cdot \vec{O}_2 C(r) + S_{O_1O_2} T(r) \right] \]

- \( D(\*) \): \( \bar{D} \) or \( \bar{D}^* \)
- \( B \): \( \Lambda_c \), \( \Sigma_c \) or \( \Sigma_c^* \)
- \( m \): \( \pi \), \( \rho \), \( \omega \) or \( \sigma \)

- \( C(r) \): Central force, \( T(r) \): Tensor force

**Fig: Meson exchange diagram**
D(*)B Interaction: Meson exchange potential

- Effective Lagrangian with heavy quark symmetry


\[ V_{D(*)B-\bar{D}(*)B}^{\pi} = G \left[ \vec{O}_1 \cdot \vec{O}_2 C(r) + S_{O_1 O_2} T(r) \right] \]

\( C(r) \): Central force, \( T(r) \): Tensor force

- Form factor with common cutoff \( \Lambda \leftarrow \) Free parameter

\[ F(\Lambda, \vec{q}) = \frac{\Lambda^2 - m^2_\alpha}{\Lambda^2 + |\vec{q}|^2} \] (fixed by the observed mass of \( P_c \))

\[ \bar{D}(*) \]: \( \bar{D} \) or \( \bar{D}^* \)

\( B \): \( \Lambda_c, \Sigma_c \) or \( \Sigma^*_c \)

\( m \): \( \pi, \rho, \omega \) or \( \sigma \)
Determination of cutoff $\Lambda$ by observed $P_c^+$

- Narrow resonance $P_c^+(4450) \ (12\sigma)$
Narrow resonance $P_c^+(4450)$ (12σ)

→ In our results, only the $J^P = 5/2^-$ state appears above the $\bar{D}\Sigma_c^*$ threshold!
Narrow resonance $P_c^+(4450) (12\sigma)$

→ In our results, only the $J^P = 5/2^-$ state appears above the $\bar{D}\Sigma_c^*$ threshold!

$P_c^+(4450): \quad M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$

$J^P = 5/2^-$ state: \quad $M = 4428.6 \text{ MeV in } \Lambda = 1400 \text{ MeV}$
Narrow resonance $P_c^+(4450)$ (12σ)

→ In our results, only the $J^P = 5/2^-$ state appears above the $\bar{D}\Sigma_c^*$ threshold!

$P_c^+(4450)$: $M = 4449.8 \pm 1.7 \pm 2.5$ MeV
$J^P = 5/2^-$ state: $M = 4428.6$ MeV in $\Lambda = 1400$ MeV

Cutoff $\Lambda = 1400$ MeV, $J^P$ of $P_c^+(4450) = 5/2^-$
What is $J^P$ of $P_c^+(4380)$?

- $P_c^+(4450)$: $J^P = 5/2^-$ \Rightarrow $J^P$ of $P_c^+(4380)$ is $3/2^+$!
What is $J^P$ of $P_c^+(4380)$?

$P_c^+(4450)$: $J^P = 5/2^-$ ∴ $J^P$ of $P_c^+(4380)$ is $3/2^+$!
What is $J^P$ of $P^+_c(4380)$?

$P^+_c(4450)$: $J^P = 5/2^-$ $\Rightarrow$ $J^P$ of $P^+_c(4380)$ is $3/2^+$!

$P^+_c(4380)$: $M = 4380 \pm 8 \pm 29$ MeV

$J^P = 3/2^+$ state: $M = 4339.7$ MeV in $\Lambda = 1400$ MeV
What is $J^P$ of $P_c^+(4380)$?

- $P_c^+(4450): J^P = 5/2^-$ implies $J^P$ of $P_c^+(4380)$ is $3/2^+!$

$P_c^+(4380):$ $M = 4380 \pm 8 \pm 29 \text{ MeV}$

$J^P = 3/2^+$ state: $M = 4339.7 \text{ MeV}$ in $\Lambda = 1400 \text{ MeV}$

$P_c^+(4380):$ $J^P = 3/2^+$

Cutoff $\Lambda = 1400 \text{ MeV}$

$P_c^+(4450):$ $J^P = 5/2^-$
Other predicted states

(i) $J^P = 3/2^-$

(ii) $J^P = 3/2^+$

In $\Lambda = 1400$ MeV,

$J^P = 3/2^-$: 4136.0 MeV, 4307.9 MeV and 4348.7 MeV

$J^P = 3/2^+$: 4206.7 MeV

**New states** are predicted!

(can be decayed to $J/\psi p, \bar{D}^{(*)}\Lambda_c, ...$)
Other predicted states

(i) \( J^P = 3/2^- \)

(ii) \( J^P = 3/2^+ \)

- In \( \Lambda = 1400 \text{ MeV} \),
  - \( J^P = 3/2^- \): 4136.0 MeV, 4307.9 MeV and 4348.7 MeV
  - \( J^P = 3/2^+ \): 4206.7 MeV

New states are predicted!

(can be decayed to \( J/\psi p, \bar{D}^*(\Lambda_c), \ldots \))
Channel-coupling effects

- Obtained mass with **Full channel coupling**, without $\bar{D}(*)\Lambda_c$ and **without** $\ell > 0$ ($\ell > 1$)

```
\begin{align*}
\bar{D}\Sigma_c & \quad 4308 \\
\bar{D}\Sigma^* & \quad 4349 \\
\bar{D}\Lambda_c & \quad 4136 \\
\bar{D}^*\Sigma_c & \quad \text{Full} \\
\end{align*}
```

$J^P = 3/2^-$
Obtained mass with **Full channel coupling**, **without** $\bar{D}(\ast)\Lambda_c$ and **without** $\ell > 0$ ($\ell > 1$)
Obtained mass with **Full channel coupling**, without $\bar{D}(\ast)\Lambda_c$ and **without $\ell > 0$ ($\ell > 1$)**.

![Diagram](image-url)
Channel-coupling effects

- Obtained mass with **Full channel coupling**, without $\bar{D}^{(*)}\Lambda_c$ and without $\ell > 0$ ($\ell > 1$)

<table>
<thead>
<tr>
<th></th>
<th>$E$</th>
<th>$J^P = 3/2^-$</th>
<th></th>
<th>$E$</th>
<th>$J^P = 3/2^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{D}^*\Sigma_c$</td>
<td></td>
<td></td>
<td>$\bar{D}^*\Sigma_c$</td>
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<tr>
<td>$\bar{D}\Sigma^*_c$</td>
<td>4349</td>
<td>4400</td>
<td>$\bar{D}\Sigma^*_c$</td>
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<tr>
<td>$\bar{D}\Sigma_c$</td>
<td>4308</td>
<td>4278</td>
<td>$\bar{D}\Sigma_c$</td>
<td></td>
<td></td>
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<tr>
<td>$\bar{D}^*\Lambda_c$</td>
<td></td>
<td></td>
<td>$\bar{D}^*\Lambda_c$</td>
<td></td>
<td>4220</td>
</tr>
<tr>
<td>$\bar{D}\Lambda_c$</td>
<td>4136</td>
<td></td>
<td>$\bar{D}\Lambda_c$</td>
<td></td>
<td>4207</td>
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<tr>
<td><strong>Full</strong></td>
<td></td>
<td>$w/o$ $\bar{D}^{(*)}\Lambda_c$</td>
<td><strong>Full</strong></td>
<td></td>
<td>$w/o$ $\ell &gt; 0$</td>
</tr>
</tbody>
</table>
Channel-coupling effects

- Obtained mass with **Full channel coupling**, **without** $\bar{D}^{(*)}\Lambda_c$ and **without** $\ell > 0$ ($\ell > 1$)
Channel-coupling effects

- Obtained mass with **Full channel coupling, without $\bar{D}(\ast)\Lambda_c$** and **without $\ell > 0$ ($\ell > 1$)**

- $\bar{D}(\ast)\Lambda_c$ and $\ell > 0$ ($\ell > 1$) components are not negligible.
Obtained mass with Full channel coupling, without $\bar{D}(\ast)\Lambda_c$ and without $\ell > 0$.
Channel-coupling effects

Obtained mass with **Full channel coupling**, without $\bar{D}(\ast)\Lambda_c$ and **without** $\ell > 0$
Channel-coupling effects

- Obtained mass with **Full channel coupling**, without $\bar{D}(\ast)\Lambda_c$ and **without** $\ell > 0$

![Diagram showing energy (E) vs. states with identified states and labels for full and partial channel coupling.]

- $\bar{D}\Sigma_c$ and $\ell > 0$ components are important!

**Additional Notes:**

- **$\bar{D}(\ast)\Lambda_c$ and $\ell > 0$ components are important!**
Subject: Hidden-charm pentaquarks as a meson-baryon molecule

Coupled-channel analysis is performed, taking into account...

- Meson-baryon components $\bar{D}(\ast)\Lambda_c - \bar{D}(\ast)\Sigma_c(\ast)$
- Couplings to states with $\ell > 0$ ($S - D - G, P - F - H$)
  ⇒ Tensor force
- Negative and positive parity states with $J^P = 3/2^\pm, 5/2^\pm$

The meson exchange potential respecting to the heavy quark spin symmetry is employed.

The $J^P$ assignment of $P_c^+(4380)$ and $P_c^+(4450)$ is $3/2^+$ and $5/2^-$, respectively.

New states are predicted in $J^P = 3/2^\pm$.

Outlook

- Coupling to $J/\psi p$, cutoff $\Lambda$, $1/m_Q$ correction,...
Back up
(i) $J^P = 3/2^-$

(ii) $J^P = 3/2^+$

(iii) $J^P = 5/2^-$

(iv) $J^P = 5/2^+$
<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$E = E_{re} - i\Gamma/2$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2^-$</td>
<td>4136.0, 4307.9 $- i18.8$, 4348.7 $- i21.1$</td>
</tr>
<tr>
<td>$3/2^+$</td>
<td>4206.7 $- i41.2$, 4339.7 $- i26.8$</td>
</tr>
<tr>
<td>$5/2^-$</td>
<td>4428.6 $- i89.1$</td>
</tr>
</tbody>
</table>
Table: Obtained masses with full channel coupling (Full), without $\bar{D}^{(*)}\Lambda_c$ (w/o $\bar{D}^{(*)}\Lambda_c$) and without large orbital angular momentum $\ell$ (w/o $\ell > 0$ or w/o $\ell > 1$) in $\Lambda = 1400$ MeV.

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>Channels</th>
<th>Mass [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2^-$</td>
<td>Full</td>
<td>4136.0, 4307.9, 4348.7</td>
</tr>
<tr>
<td></td>
<td>w/o $\bar{D}^{(*)}\Lambda_c$</td>
<td>4278.4, 4400.4</td>
</tr>
<tr>
<td></td>
<td>w/o $\ell &gt; 0$</td>
<td>4220.4, 4376.6</td>
</tr>
<tr>
<td>$3/2^+$</td>
<td>Full</td>
<td>4206.7, 4339.7</td>
</tr>
<tr>
<td></td>
<td>w/o $\bar{D}^{(*)}\Lambda_c$</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>w/o $\ell &gt; 1$</td>
<td>4275.3</td>
</tr>
<tr>
<td>$5/2^-$</td>
<td>Full</td>
<td>4428.6</td>
</tr>
<tr>
<td></td>
<td>w/o $\bar{D}^{(*)}\Lambda_c$</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>w/o $\ell &gt; 0$</td>
<td>—</td>
</tr>
</tbody>
</table>
Table: Comparison of the lowest mass of hidden-charm meson-baryon molecules with $I(J^P) = 1/2(3/2^-)$ by this work with the early works. The obtained masses are shown in the second column in the unit of MeV. The value of this work is in $\Lambda = 1400$ MeV. The third column gives the channels which are considered in those works.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Mass [MeV]</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>4136.0</td>
<td>$D\Lambda_c, D^<em>\Lambda_c, D\Sigma_c, D\Sigma_c^</em>, D^<em>\Sigma_c, D^</em>\Sigma_c^*$</td>
</tr>
<tr>
<td>PRL105(2010)232001</td>
<td>4415</td>
<td>$D^<em>\Sigma_c, D^</em>\Sigma_c^*$ with only S-wave</td>
</tr>
<tr>
<td>PRC84(2010)015202</td>
<td>4454</td>
<td>$D^<em>\Sigma_c, D^</em>\Sigma_c^*$ with only S-wave</td>
</tr>
<tr>
<td>PRD88(2013)056012</td>
<td>4334.5</td>
<td>$J/\psi N, D^<em>\Lambda_c, D^</em>\Sigma_c, D\Sigma_c^<em>, D^</em>\Sigma_c^*$ with only S-wave</td>
</tr>
</tbody>
</table>