Exotic baryons from a heavy ($\bar{c}, \bar{b}$) meson and a nucleon

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in collaboration with

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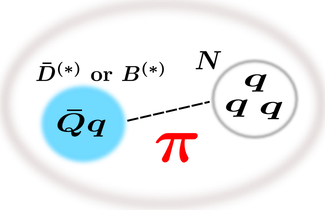
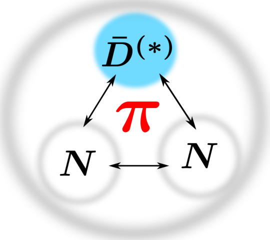
Nucleon Resonances: From Photoproduction to High Photon Virtualities
15 Oct. 2015, ECT*

Meson-Nucleon molecules with a heavy quark

1. Introduction
    - Hadronic molecule
    - Heavy Quark Spin Symmetry and one pion exchange potential
2. Meson-Nucleon molecules: $\bar{D}N$ and BN
3. $\bar{D}NN$ and BNN
4. Summary



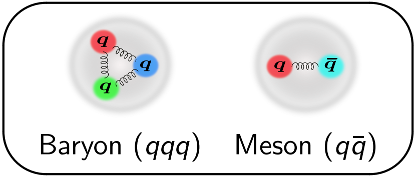
2-body system



Exotic hadrons in the heavy quark region
Introduction

- ▷ Constituent quark model (baryon(qqq), meson ($q\bar{q}$))

$\Rightarrow$ successfully applied to hadron spectra.



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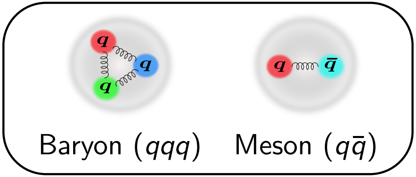
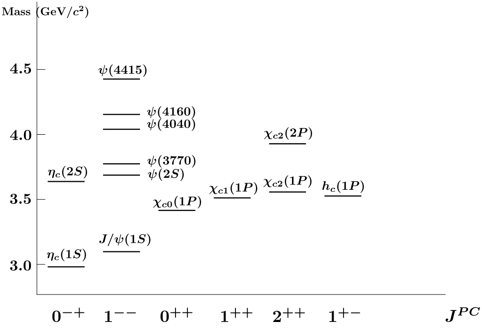




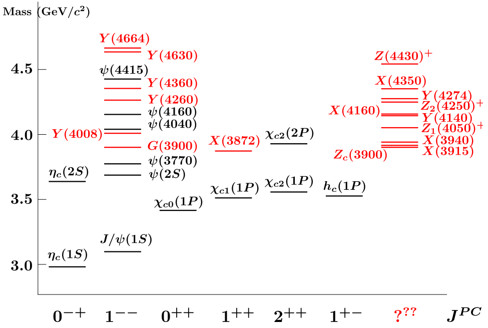
Charmonium **c$\bar{c}$**

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

- ▷ Constituent quark model (baryon(qqq), meson ($q\bar{q}$))
  ⇒ successfully applied to hadron spectra.

Baryon (qqq) Meson ($q\bar{q}$)

- ▷ **New Exotic hadrons X, Y, Z** in **the heavy quark (c, b)** sector



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

N. Brambilla, *et al.* Eur.Phys.J.C **71**(2011)1534
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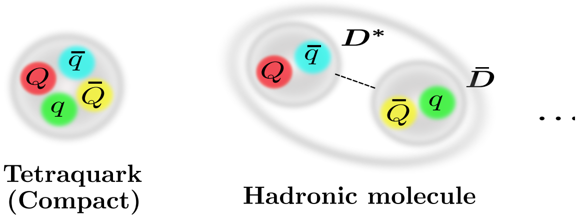
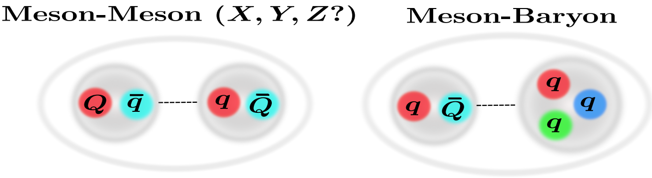
- ▷ **What is the structure of exotic hadrons?**

Exotic hadrons $\Rightarrow$ Multiquark states?



Hadronic molecules



X(3872), Z_b **Λ_c^*, Pentaquark???**

- Loosely bound states (resonances) of hadrons
  → Appearing **near the thresholds** (M-M, M-B,...)
- Molecules are formed by **the Hadron-Hadron interaction** dynamically.

Hadronic molecules

Meson-Meson $(X, Y, Z?)$ Meson-Baryon

X(3872), Z_b Λ_c^*, Pentaquark???

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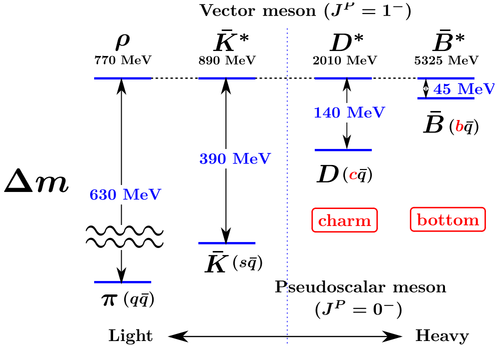
  → Appearing **near the thresholds** (M-M, M-B,...)
- Molecules are formed by **the Hadron-Hadron interaction** dynamically.

In the Heavy-hadron interaction,
the Heavy Quark Spin Symmetry plays an important role!

- Mass difference between vector and pseudoscalar mesons. $(Q\bar{q},\ q = u, d)$



- ▷ Δm decreases when the quark mass increases.
- ▷ Masses of $\{B, B^*\}$ ($\{D, D^*\}$) are almost degenerate.

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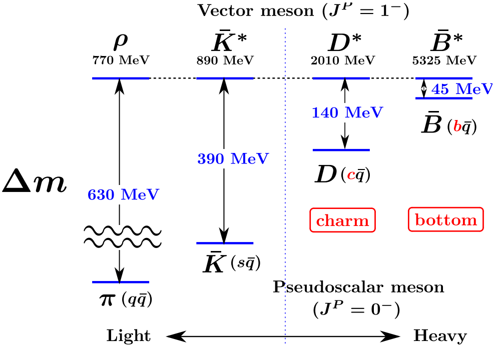


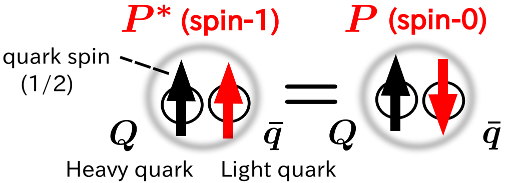
▷ Δm decreases when the quark mass increases.

▷ Masses of $\{B, B^*\}$ ($\{D, D^*\}$) are almost degenerate.
$\rightarrow$ **Heavy Quark Spin Symmetry!**

Heavy Quark Spin Symmetry (HQS)

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

- Spin-spin force between quarks is **suppressed in $m_Q \to \infty$.**
- e.g. Heavy-light mesons



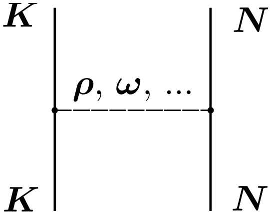
Δm_{P^*P} caused by the spin-spin force is small.

$\Rightarrow$ **Mass degeneracy** of hadrons with the different spins.

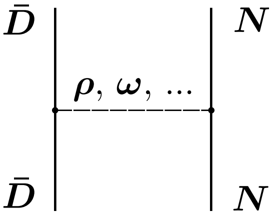
- Mass degeneracy of $\{D, D^*\}(Q\bar{q})$, $\{\eta_c, J/\psi\}(Q\bar{Q})$, $\{\Sigma_c, \Sigma_c^*\}(Qqq)$ (baryons)...
- **New symmetry** appearing in **the heavy quark region!**

- Interaction between K (light meson) and N
  $\Rightarrow$ Short range force (ρ, ω exchanges...) dominates.

Strange (Light)



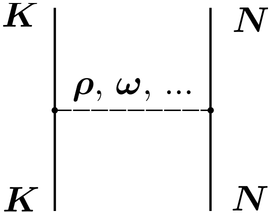
Charm (Heavy)

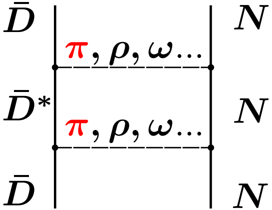


KN and $\bar{\text{D}}$N Interactions
Introduction

- Interaction between K (light meson) and N
  $\Rightarrow$ Short range force (ρ, ω exchanges...) dominates.

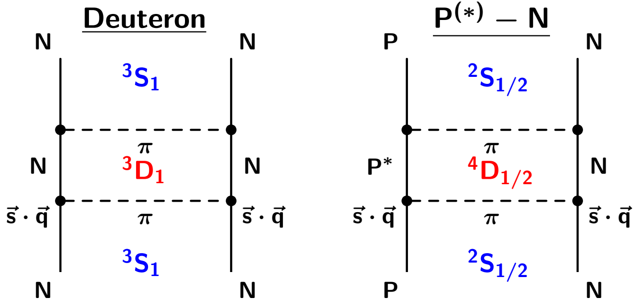
Strange (Light) (**KKπ** $\times$) **Charm (Heavy)**





- In the heavy (c, b) sector, the small Δm_{DD^*} due to **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
- The mixing enhances **the one π exchange potential (OPEP)**.

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



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

$PN(^2S_{1/2}) - P^*N(^4D_{1/2})$

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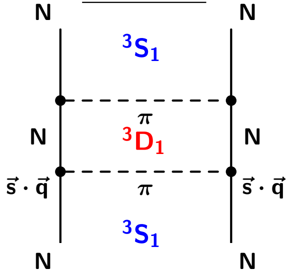
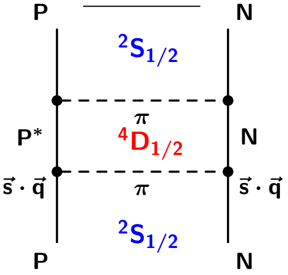
Deuteron



$P^{(*)} - N$



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

$PN(^2S_{1/2}) - P^*N(^4D_{1/2})$

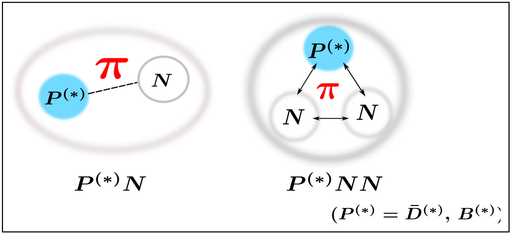
Hadronic molecule $\Rightarrow$ Nucleus-like state?

- Additional π exchange $\Rightarrow$ Meson-Meson (X, Y, Z), Meson-Baryon molecules (Meson Nuclei)

- Additional π exchange $\Rightarrow$ Meson-Meson (X, Y, Z), **Meson-Baryon molecules (Meson Nuclei)**

Main Subject

- Hadronic molecules formed by **Heavy meson-Nucleon with the π exchange potential**.



- $P = \bar{D}(\bar{c}q), B(\bar{b}q) \rightarrow$ No $q\bar{q}$ annihilation!

$\Rightarrow$ Bound states of $\bar{D}(B)$ nuclei are **stable against the strong decay! (Genuinely exotic states!)**

$\Leftrightarrow$ **K($\bar{s}$q) nuclei (Light sector) have not been found.** (KN interaction is repulsion.)

$\mathbf{P^{(*)}N}$ Interaction ($\mathbf{P^{(*)} = \bar{D}^{(*)}, B^{(*)}}$): OPEP

$$V^{\pi}_{PN-P^*N} = -\frac{g_\pi g_{\pi NN}}{\sqrt{2} m_N f_\pi}\frac{1}{3}\left[\vec{\varepsilon}^{\dagger}\cdot\vec{\sigma}C(r) + S_\varepsilon T(r)\right]\vec{\tau}_P\cdot\vec{\tau}_N$$

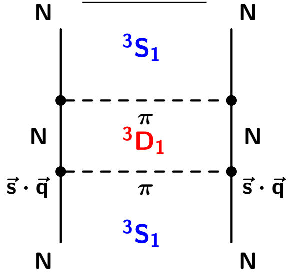
$$V^{\pi}_{P^*N-P^*N} = \frac{g_\pi g_{\pi NN}}{\sqrt{2} m_N f_\pi}\frac{1}{3}\left[\vec{T}\cdot\vec{\sigma}C(r) + S_T T(r)\right]\vec{\tau}_P\cdot\vec{\tau}_N$$

S.Yasui and K.Sudoh PRD**80**(2009)034008

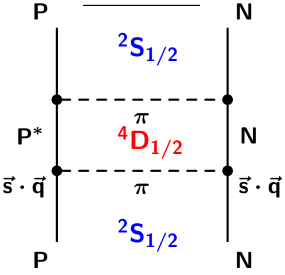
$C(r)$: Central force, $T(r)$: Tensor force

▷ $T(r)$ generates a strong attraction! ⇔ Deuteron

Deuteron



P(*) − N



Tensor force ⇒ $^3S_1 - {}^3D_1$

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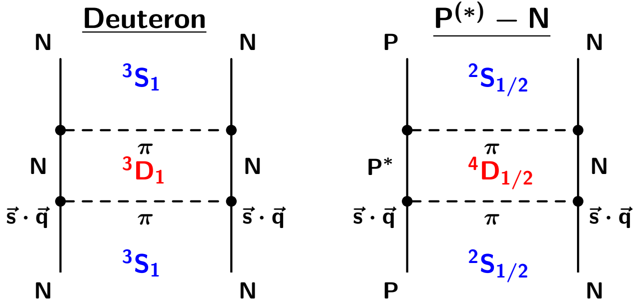
S.Yasui and K.Sudoh PRD**80**(2009)034008

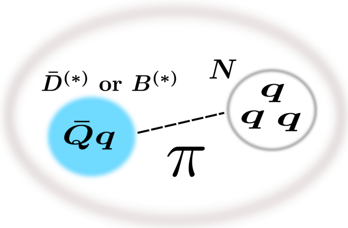
$C(r)$: Central force, $\mathbf{T}(\mathbf{r})$: **Tensor force**

▷ $\mathbf{T}(\mathbf{r})$ generates a **strong attraction!** ⇔ Deuteron



Tensor force ⇒ $^3S_1 - {}^3D_1$ $\qquad$ $PN(^2S_{1/2}) - P^*N(^4D_{1/2})$

Results of $\mathrm{P}^{(*)}\mathrm{N}$ states (2-body)

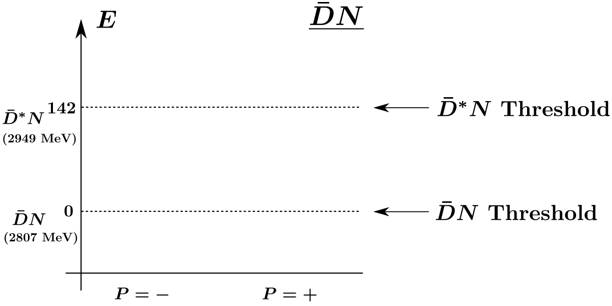


$\bar{D}N$, BN
Exotic states ($\bar{Q}q + qqq$)

<u>Bound state and Resonance</u>

- We solve the coupled-channel Schrödinger equations for PN and P^*N channels.
- Interaction: π, ρ, ω exchange potentials

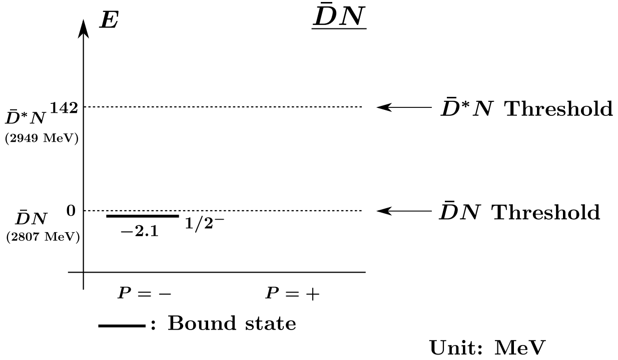
- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$ with $I = 0$



Unit: MeV

Y.Y., S.Ohkoda, S.Yasui and A.Hosaka, PRD**84** 014032 (2011) and PRD**85** 054003 (2012)

- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$ with $I = 0$
- One bound state

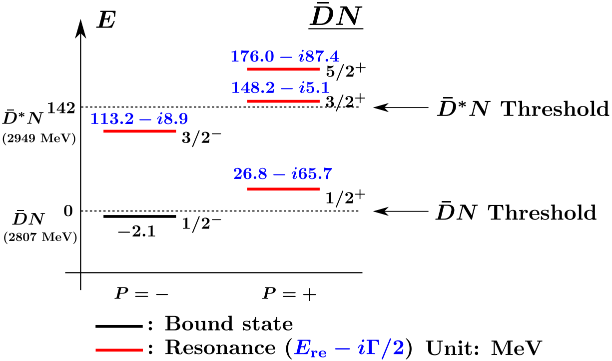


Y.Y., S.Ohkoda, S.Yasui and A.Hosaka, PRD**84** 014032 (2011) and PRD**85** 054003 (2012)

D̄N and BN for I = 0 (2-body)

D̄N and BN

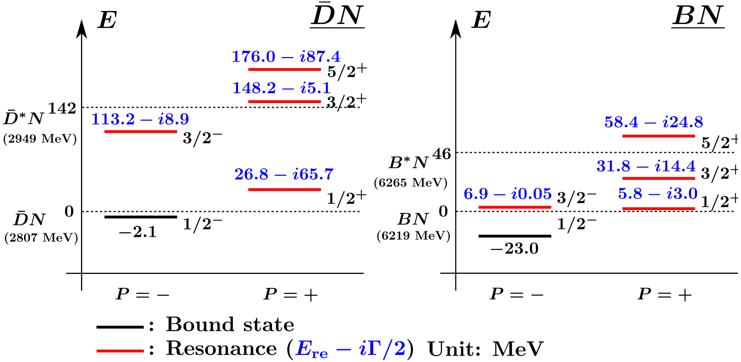
- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$ with $I = 0$
- One bound state, and resonances in charm



Y.Y., S.Ohkoda, S.Yasui and A.Hosaka, PRD**84** 014032 (2011) and PRD**85** 054003 (2012)

D̄N and BN for I = 0 (2-body)

- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$ with $I = 0$
- One bound state, and resonances in charm and bottom sectors!



Y.Y., S.Ohkoda, S.Yasui and A.Hosaka, PRD**84** 014032 (2011) and PRD**85** 054003 (2012)

- Many states near the thresholds. ⇔ **No KN bound state**

- Expectation values of OPEP in $\bar{D}N$

Table : Expectation values of V_π ([MeV])

$\bar{D}N$	$\langle V_{\bar{D}N-\bar{D}^*N} \rangle$	$\langle V_{\bar{D}^*N-\bar{D}^*N} \rangle$
Central	-2.5	1.6×10^{-1}
Tensor	-35.2	-1.1

- The tensor force of π exchange potential generates a strong attraction. Especially, $\bar{D}N - \bar{D}^*N$ mixing is important.

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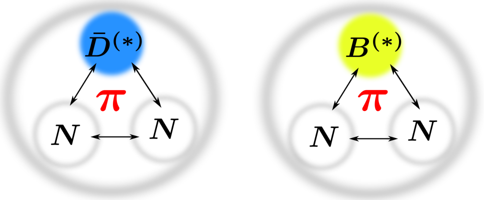
BN	$\langle V_{BN-B^*N} \rangle$	$\langle V_{B^*N-B^*N} \rangle$
Central	-8.2	1.3
Tensor	**-90.2**	-8.3

- Mixing effects are enhanced in BN due to small Δm_{BB^*}.

Results of $P^{(*)}NN$ states (3-body)

Exotic dibaryon states: $\bar{D}^{(*)}NN$, $B^{(*)}NN$



with $J^P = 0^-, 1^-$ and $I = 1/2$

Bound state and Resonance

- $P^{(*)}N$ interaction: $\pi\rho\omega$ exchanges
- NN interaction: AV8′ potential (B. S. Pudliner,*et.al.*, PRC**56**(1997)1720)

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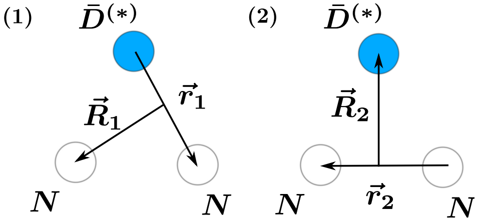

with $J^P = 0^-, 1^-$ and $I = 1/2$

Wave functions: Gaussian expansion methods

E. Hiyama, *et al.*, Prog.Part.Nucl.Phys.51(2003)223

Bound state and Resonance

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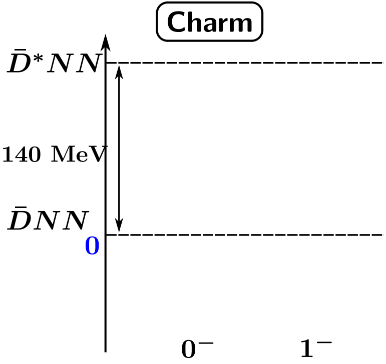
$\bar{D}^{(*)}NN$ and $B^{(*)}NN$ for $I = 1/2$ (3-body)

$\bar{D}NN$ and BNN

- Three-body systems: Bound state or Resonance?



Unit: MeV

YY, S. Yasui, and A. Hosaka, NPA **927** (2014) 110

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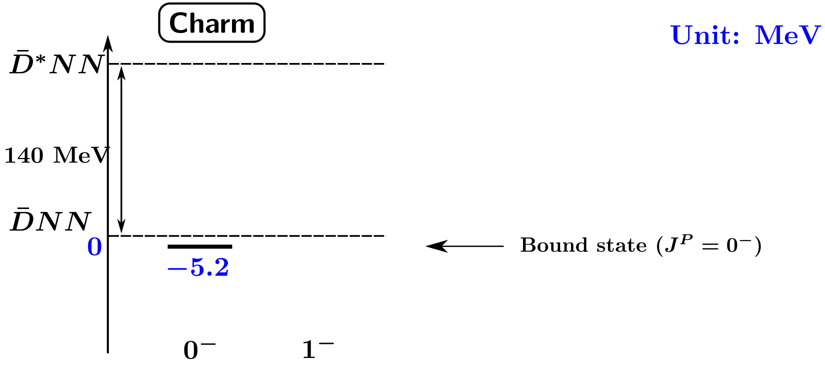

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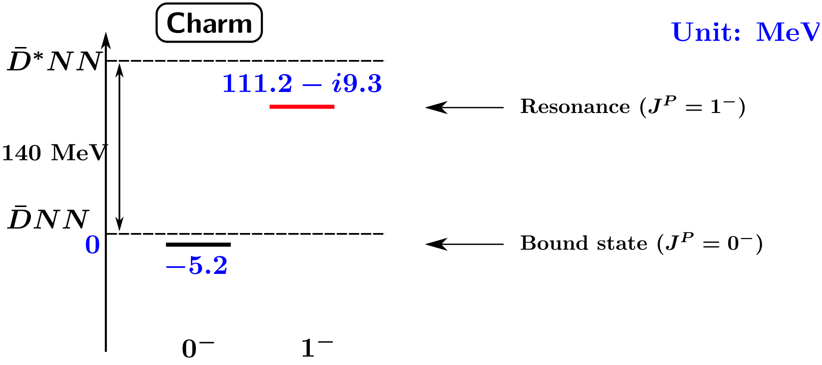
- **Bound states** for $J^P = 0^-$

- Three-body systems: Bound state or Resonance?



YY, S. Yasui, and A. Hosaka, NPA **927** (2014) 110

- **Bound states** for $J^P = 0^-$ and **Resonances** for $J^P = 1^-$ are found!

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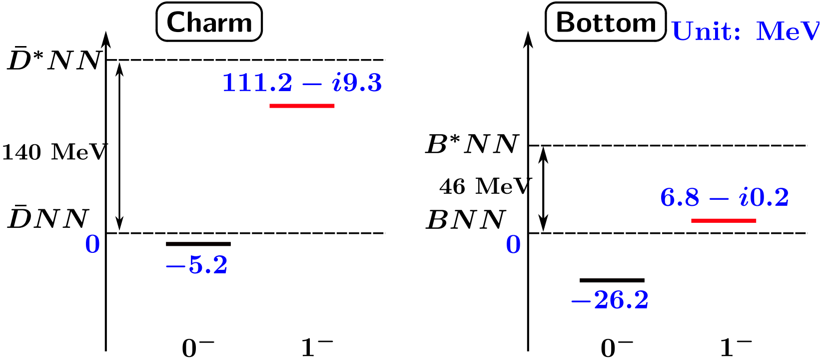

YY, S. Yasui, and A. Hosaka, NPA **927** (2014) 110

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New exotic states!

Q. How is the bound state formed?

$\Rightarrow$ Expectation values of the potentials $\langle\psi| V |\psi\rangle$

The bound state of $\bar{D}NN(0^-)$ (Unit: MeV)

$\bar{D}^{(*)}NN$	$\langle V_{\bar{D}N\text{–}\bar{D}^*N}\rangle$	$\langle V_{\bar{D}^*N\text{–}\bar{D}^*N}\rangle$	$\langle V_{NN}\rangle$
Central	-3.1	0.1	-9.2
Tensor	-45.6	-1.0	-0.3
LS	—	—	-0.5

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YY, S. Yasui, and A. Hosaka, NPA **927** (2014) 110

- **$\mathbf{V_{\bar{D}N\text{–}\bar{D}^*N}}$ (Tensor)** generates **the strong attraction**.

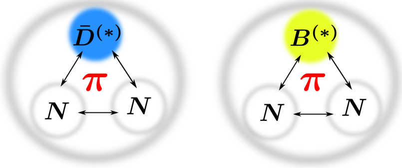
$\Leftrightarrow$ **the NN force ($\mathbf{V_{NN}}$)** plays a minor role, because **the Deuteron channel ($\mathbf{J^P_{NN} = 1^+}$) is suppressed**.
$(\bar{D}NN(J^P = 0^-))$

Summary

Subject: Hadronic molecules $P^{(*)}N$ and $P^{(*)}NN$
by introducing Heavy quark symmetry and OPEP

$\Downarrow$

- New Bound states and Resonances are found in $P^{(*)}N$ and $P^{(*)}NN$ in the heavy quark sectors.
- The Heavy quark symmetry enhances the OPEP between the heavy meson P and the nucleon N.
- **Tensor force of OPEP in PN – P*N mixing** plays a crucial role to produce the **New Exotic states**.



Thank you for your kind attention.