Hadronic molecular states and Heavy Quark Spin Symmetry

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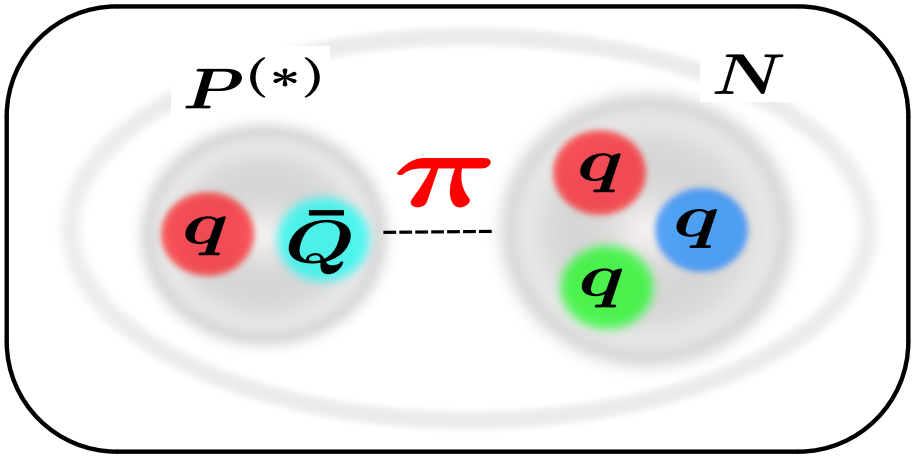
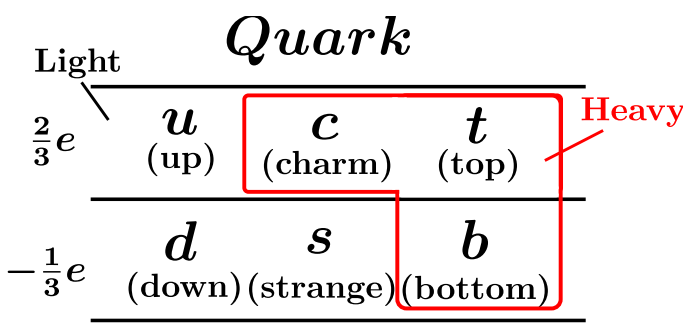


Lunch Seminar

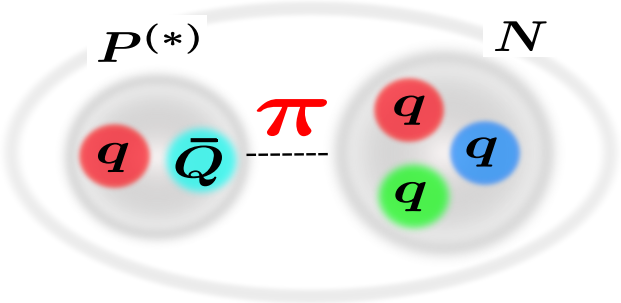
5/13 2015, YITP

Outline

1. Introduction
   - Hadronic molecules
   - 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

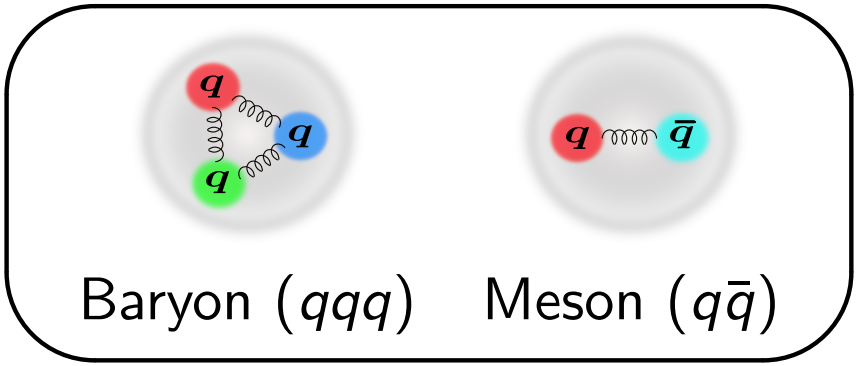


Hadronic molecules



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

$\Rightarrow$ successfully applied to hadron spectra.



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

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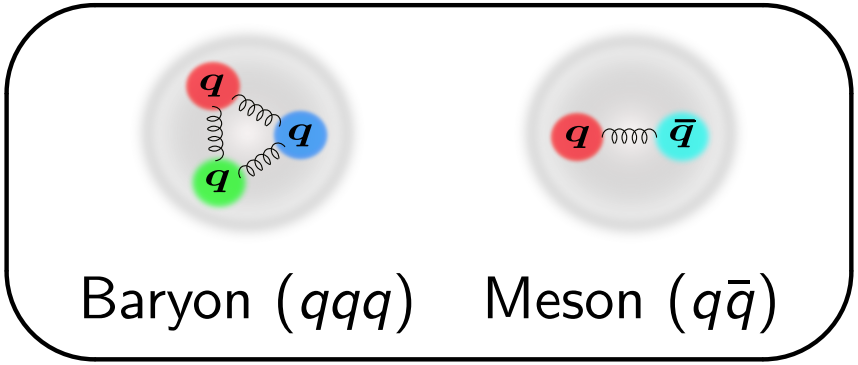

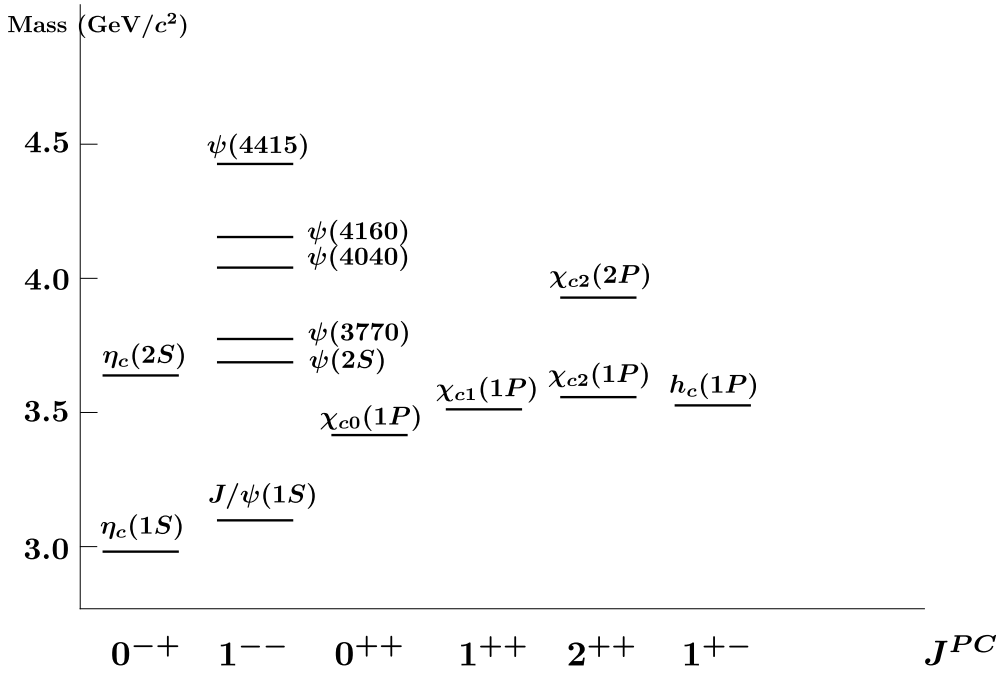

Charmonium $\mathbf{c\bar{c}}$

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

Exotic hadrons in the heavy quark region

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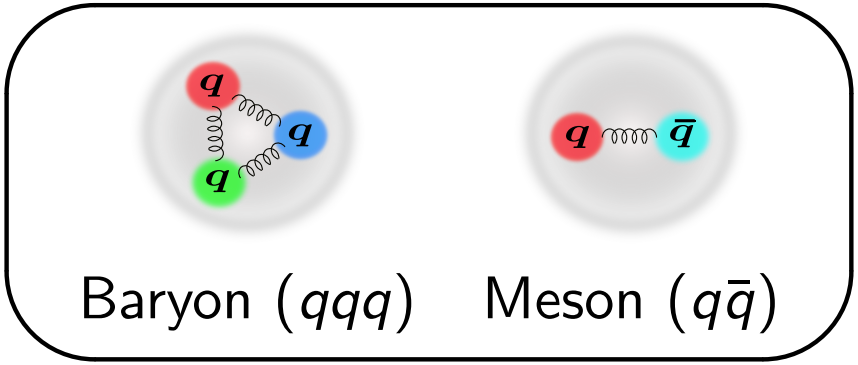
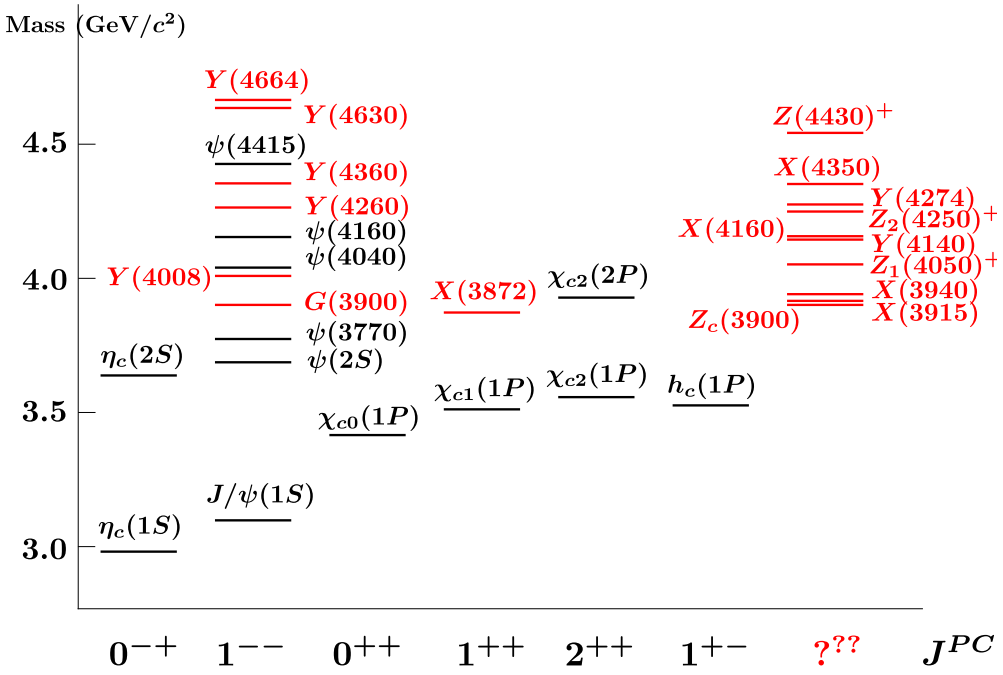


- **New Exotic hadrons X, Y, Z** in **the heavy quark (c, b)** sector



Charmonium $c\bar{c}$
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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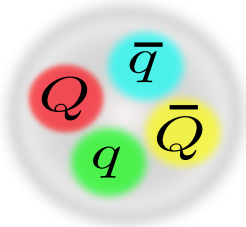
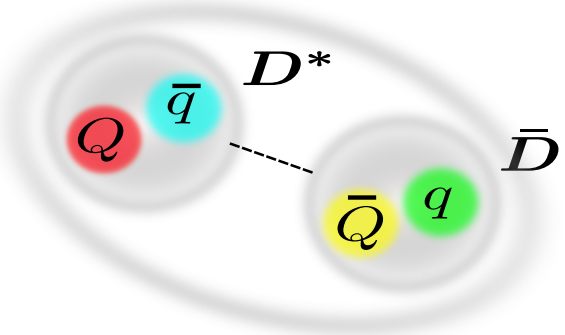
- **What is the structure of exotic hadrons?**

Exotic hadrons ⇒ Multiquark states?



Tetraquark
(Compact)

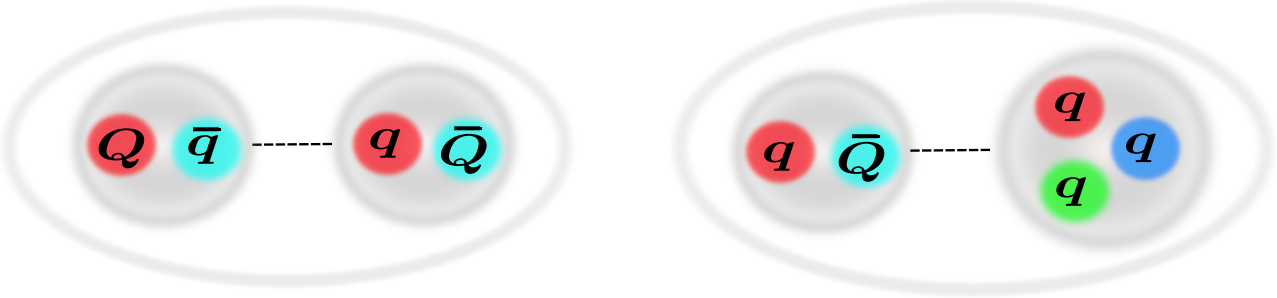


Hadronic molecule

$\cdots$

Hadronic molecules

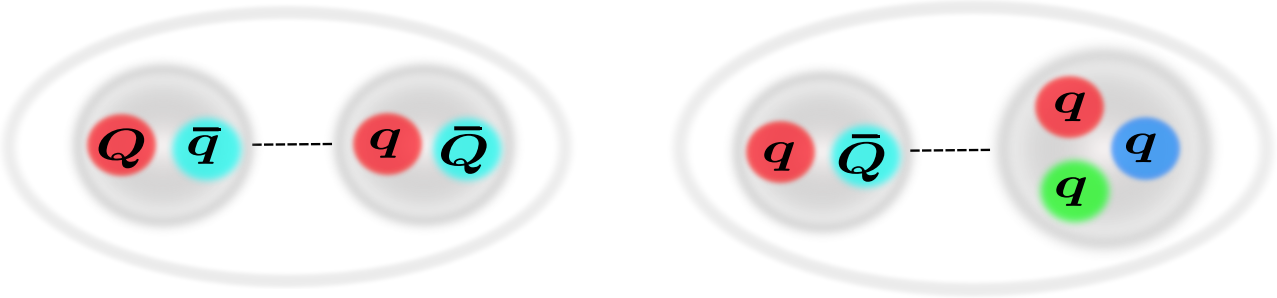
Meson-Meson (X, Y, Z?) **Meson-Baryon**



- Loosely bound states (resonances) of hadrons
  $\rightarrow$ 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**



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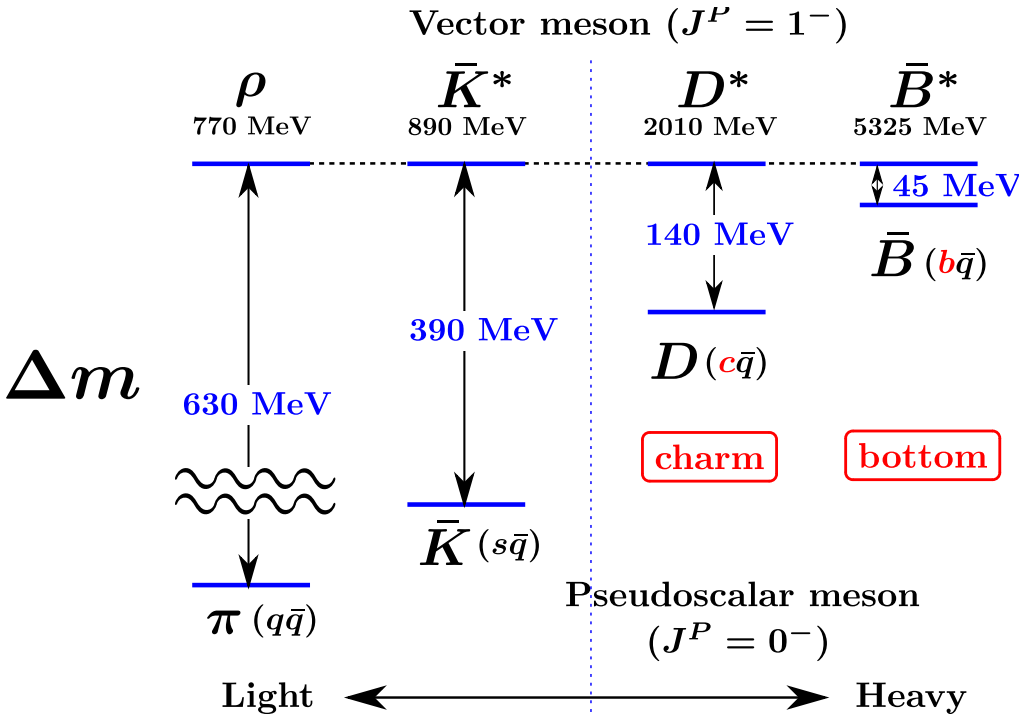
- Molecules are formed by **the Hadron-Hadron interaction** dynamically.

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

Mass degeneracy of heavy hadrons

Introduction

- 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.

Mass degeneracy of heavy hadrons

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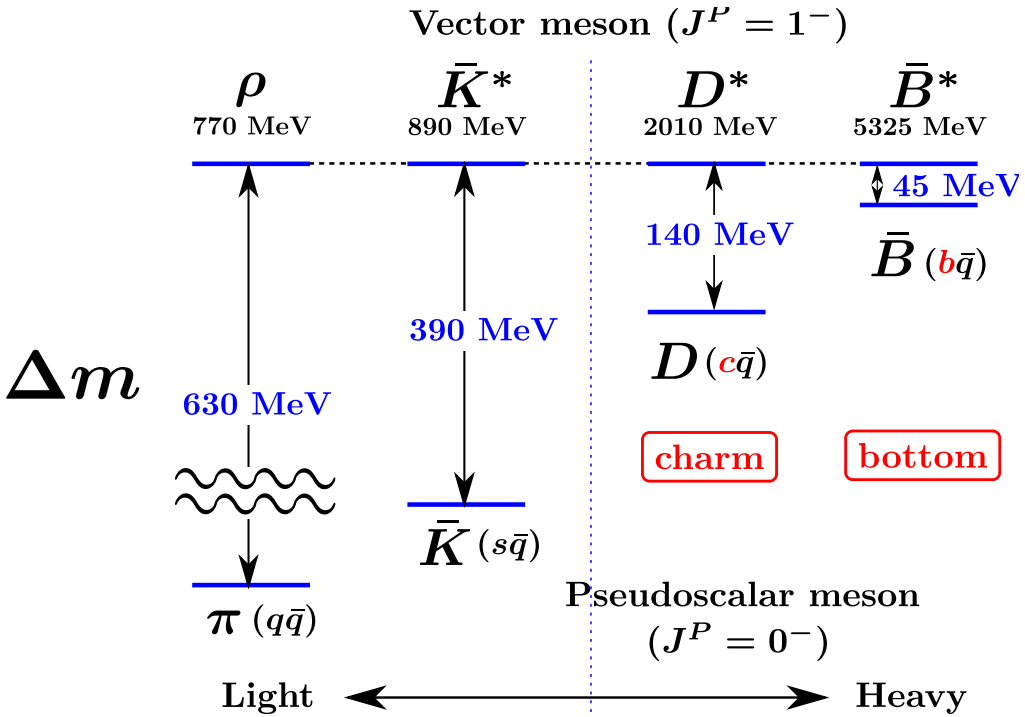
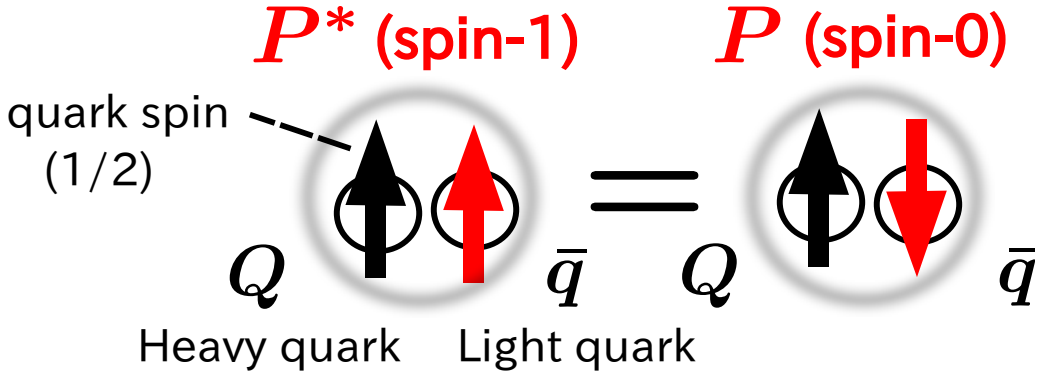


- ▷ Δm decreases when the quark mass increases.
- ▷ Masses of $\{B, B^*\}$ ($\{D, D^*\}$) are almost degenerate.
  $\rightarrow$ **Heavy Quark Spin Symmetry!**

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



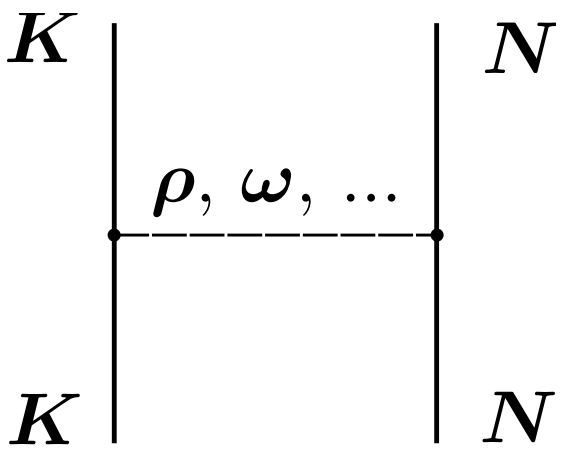
Δm_{P^*P} caused by the spin-spin force is small.

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

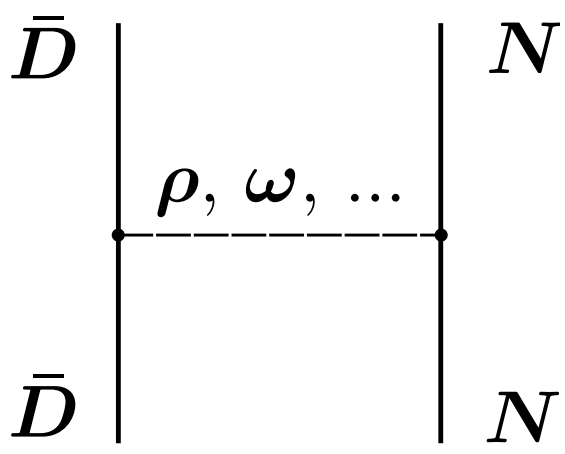
- Mass degeneracy of $\{D, D^*\}(Q\bar{q})$, $\{\eta_c, J/\psi\}(Q\bar{Q})$, $\{\Sigma_c, \Sigma_c^*\}(Qqq)$ (baryons)...
- **New symmetry** appearing in **the heavy quark region!**

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

Strange (Light)



Charm (Heavy)



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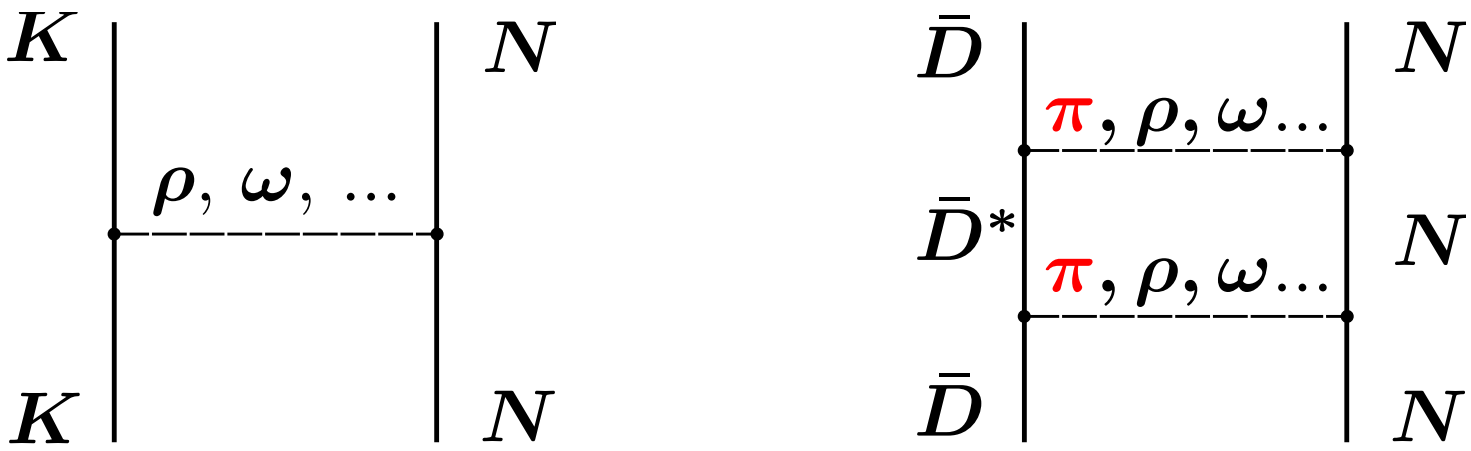
Strange (Light) (**KKπ** $\times$) **Charm (Heavy)**



- In the heavy sector, $\bar{D} - \bar{D}^*$ mixing caused by small $\Delta m_{\bar{D}\bar{D}^*}$ enhances **the one π exchange potential (OPEP)**.
- The small Δm_{DD^*} is induced by **the Heavy Quark Spin Symmetry**!

$$m_{K^*} - m_K \sim 400 \text{ MeV} \Leftrightarrow m_{D^*} - m_D \sim 140 \text{ MeV}$$

OPEP: Important role in the nuclei (H.Yukawa 1935)

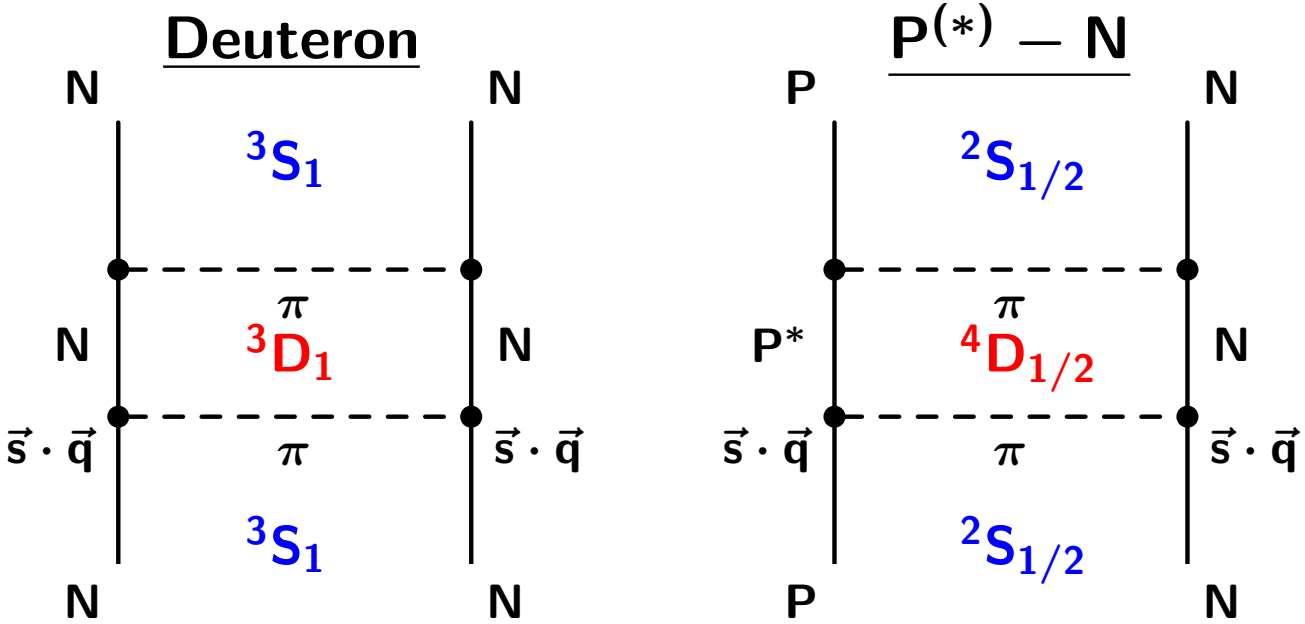
- One pion exchange potential

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

Spin-spin force **Tensor force**

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

- ▷ $T(r)$ generates **the strong attraction!** $\Leftrightarrow$ Deuteron



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

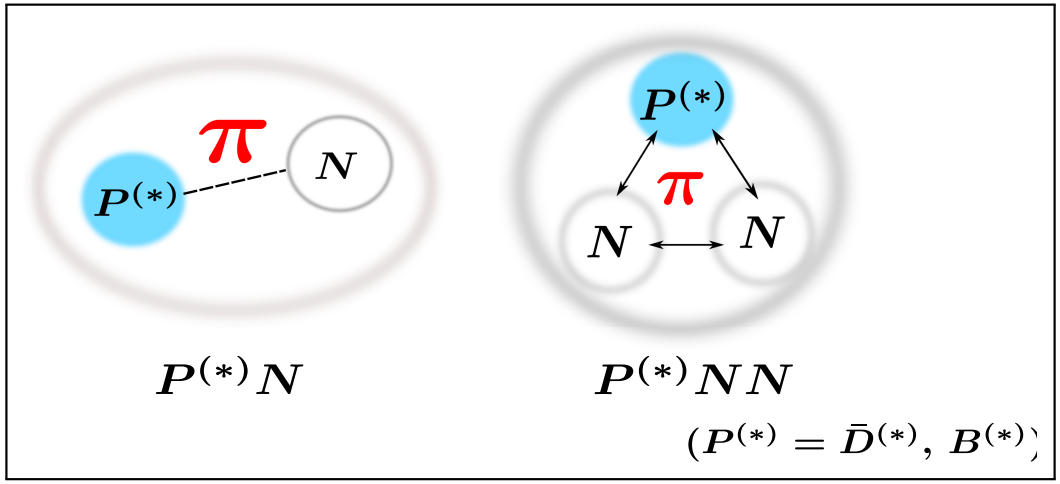
Hadronic molecule $\Rightarrow$ Nucleus-like state?

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

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

Main Subject

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



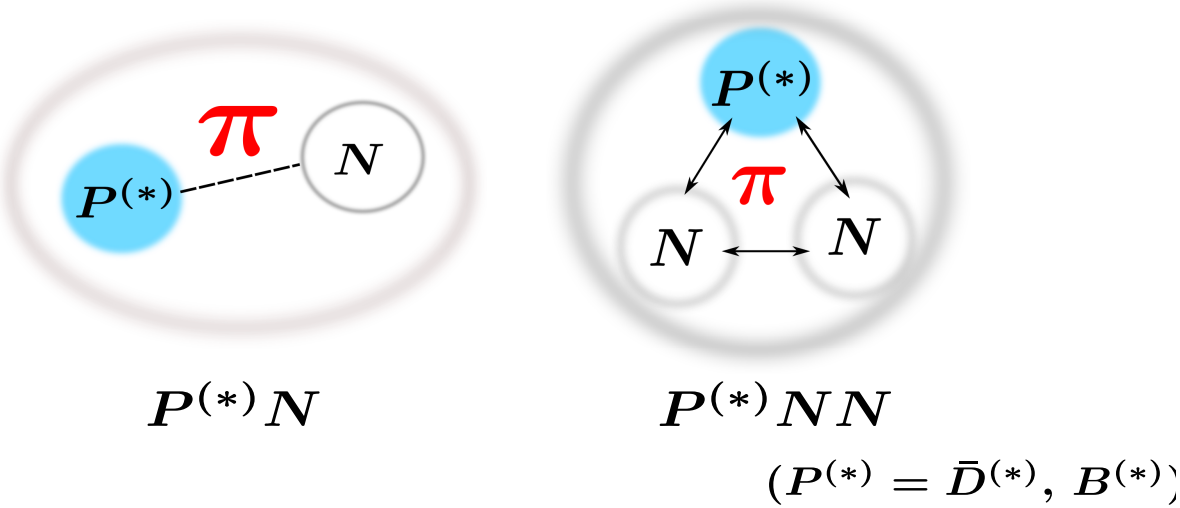
- $P = \bar{D}(\bar{c}q), B(\bar{b}q) \rightarrow$ No $q\bar{q}$ annihilation!

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

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

(KN interaction is repulsion.)

Results of $P^{(*)}N$ and $P^{(*)}NN$ states



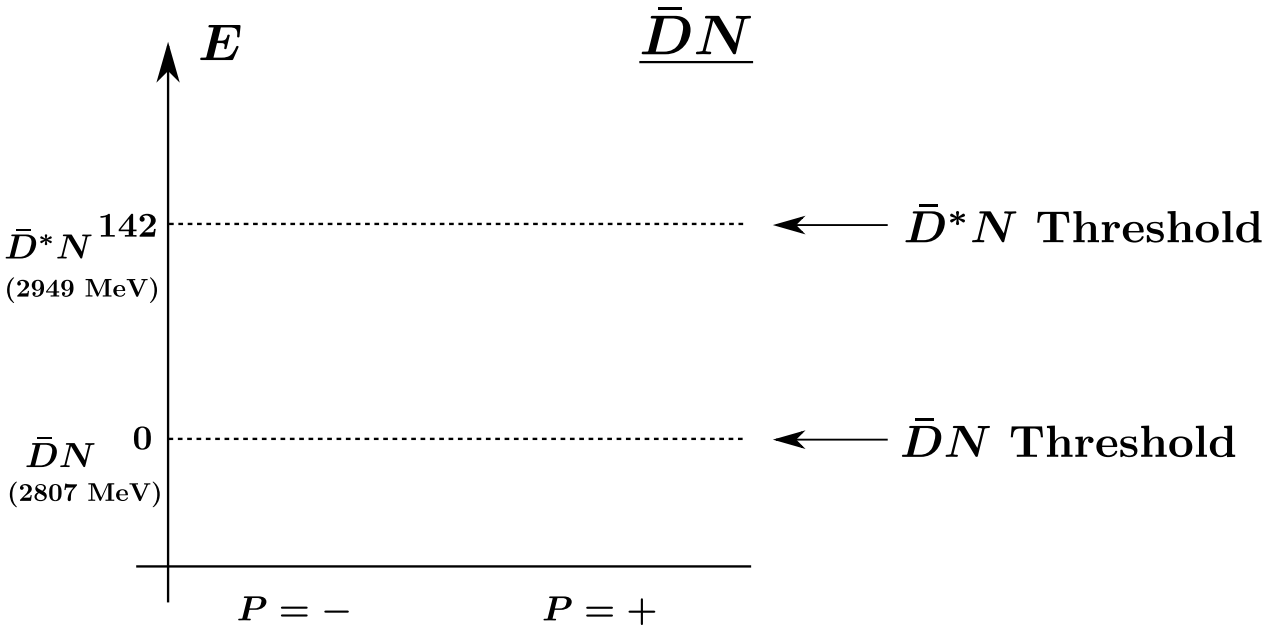
Bound state and Resonance

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

$\bar{D}N$ and BN for $I = 0$ (2-body)

$\bar{D}N$ and BN

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



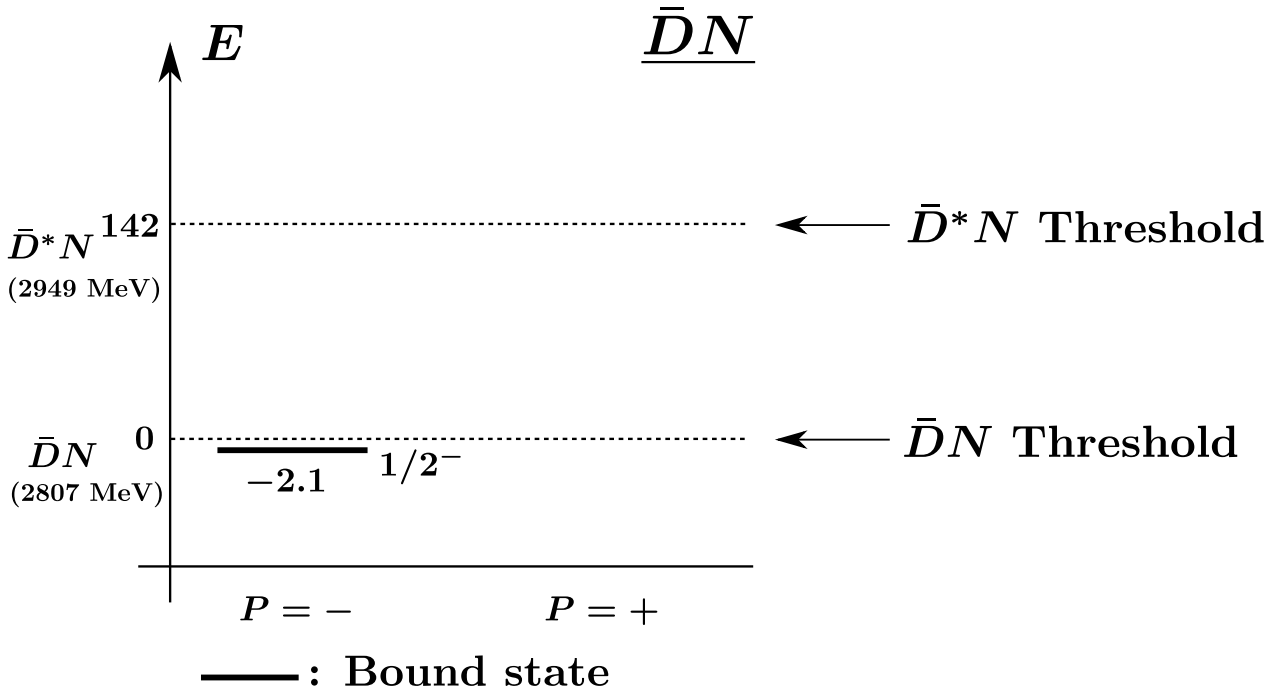
Unit: MeV

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

$\bar{D}N$ and BN for $I = 0$ (2-body)

$\bar{D}N$ and BN

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



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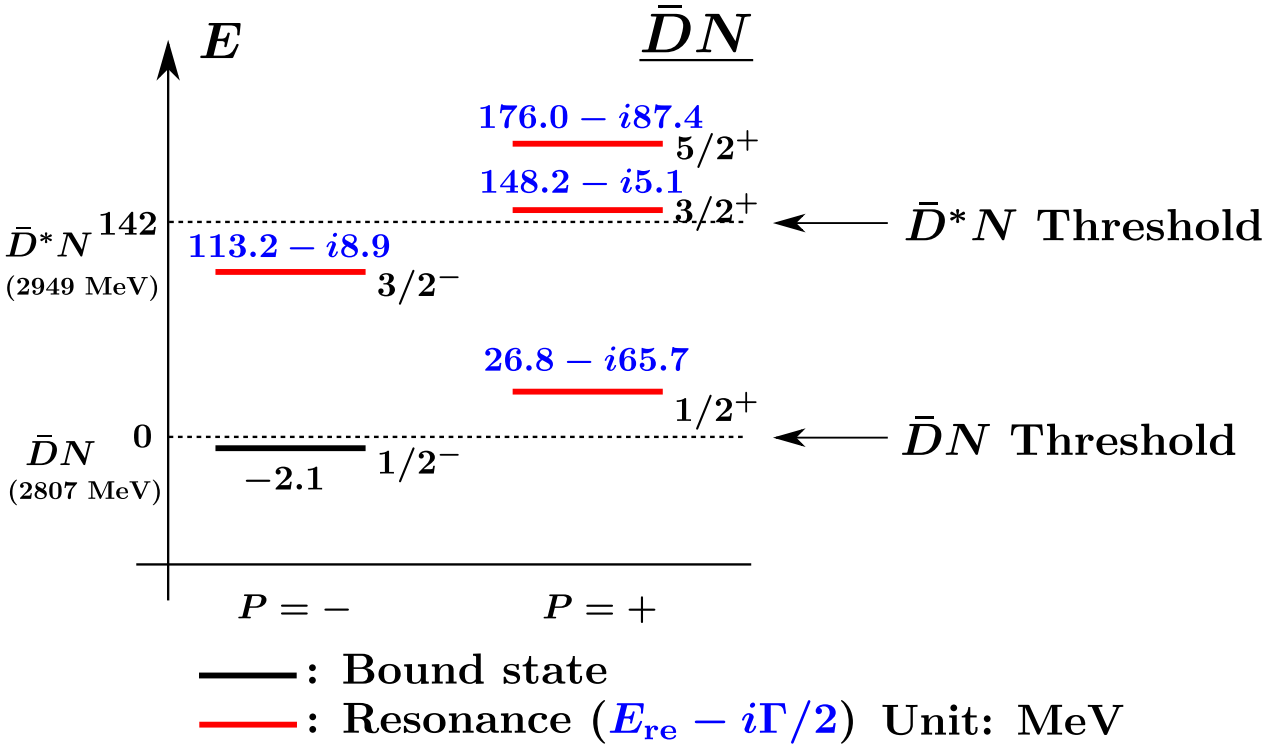
$\bar{D}N$ and BN for $I = 0$ (2-body)

$\bar{D}N$ and BN

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

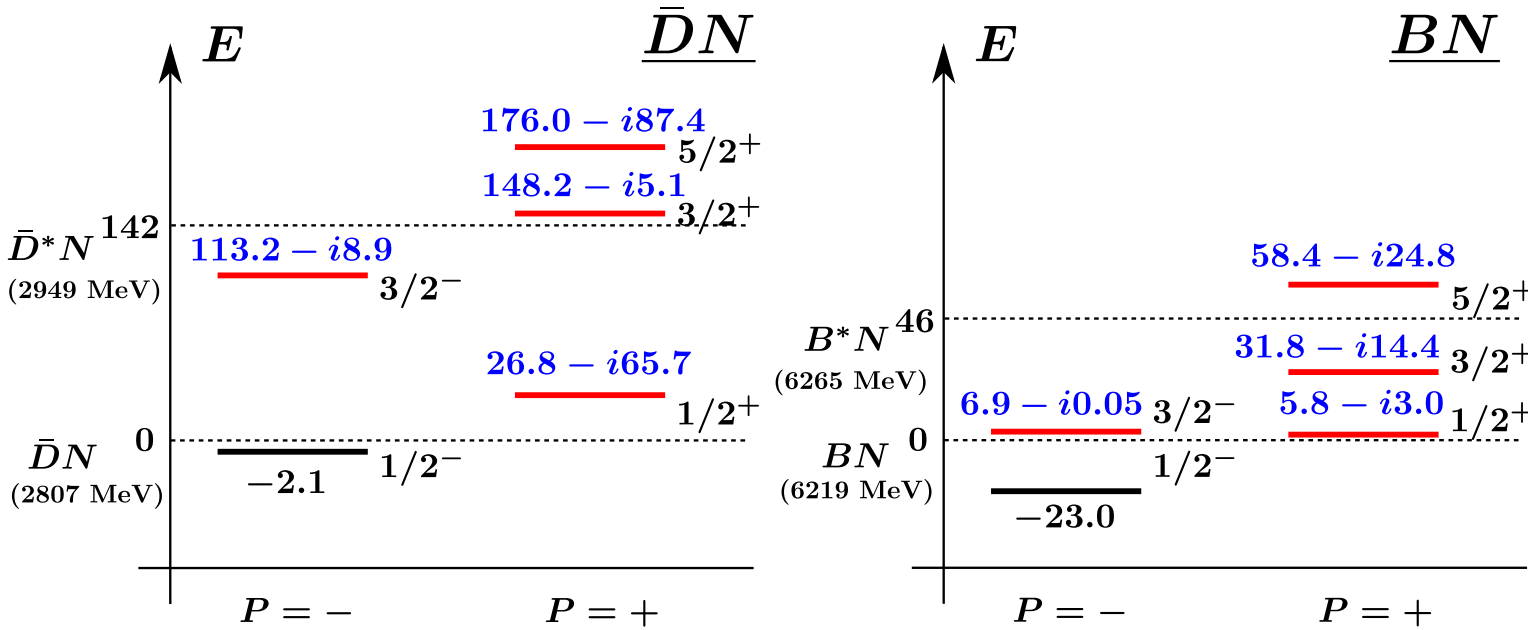


Y.Y., S.Ohkoda, S.Yasui and A.Hosaka, PRD**84** 014032 (2011) and PRD**85** 054003 (2012)

$\bar{D}N$ and BN for $I = 0$ (2-body)

$\bar{D}N$ and BN

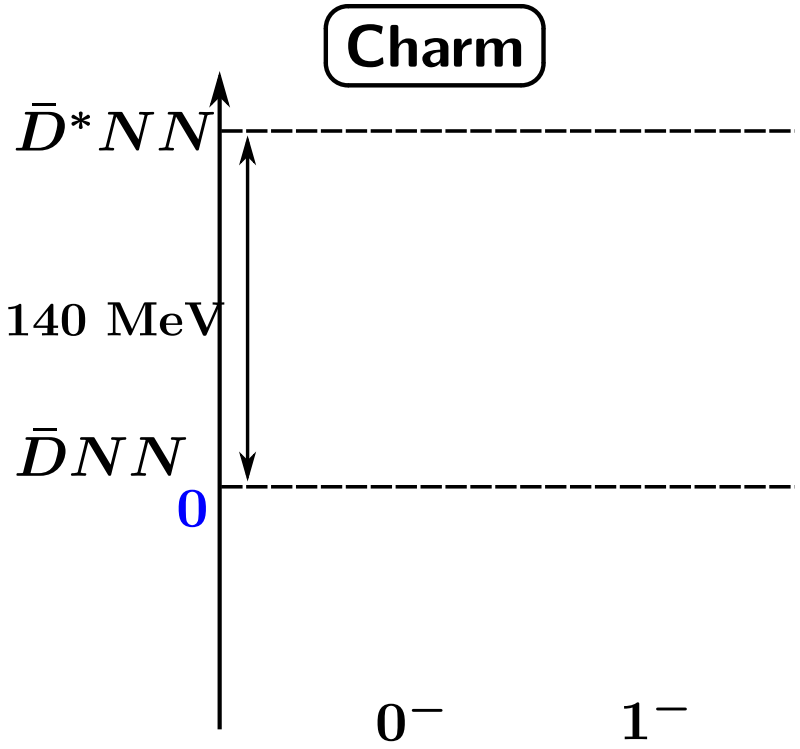
- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$ with $I = 0$
- One bound state, and resonances in charm and bottom sectors!



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

- Many states near the thresholds. $\Leftrightarrow$ **No KN bound state**

- Three-body systems: Bound state or Resonance?



Unit: MeV

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

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

$\bar{D}NN$ and BNN

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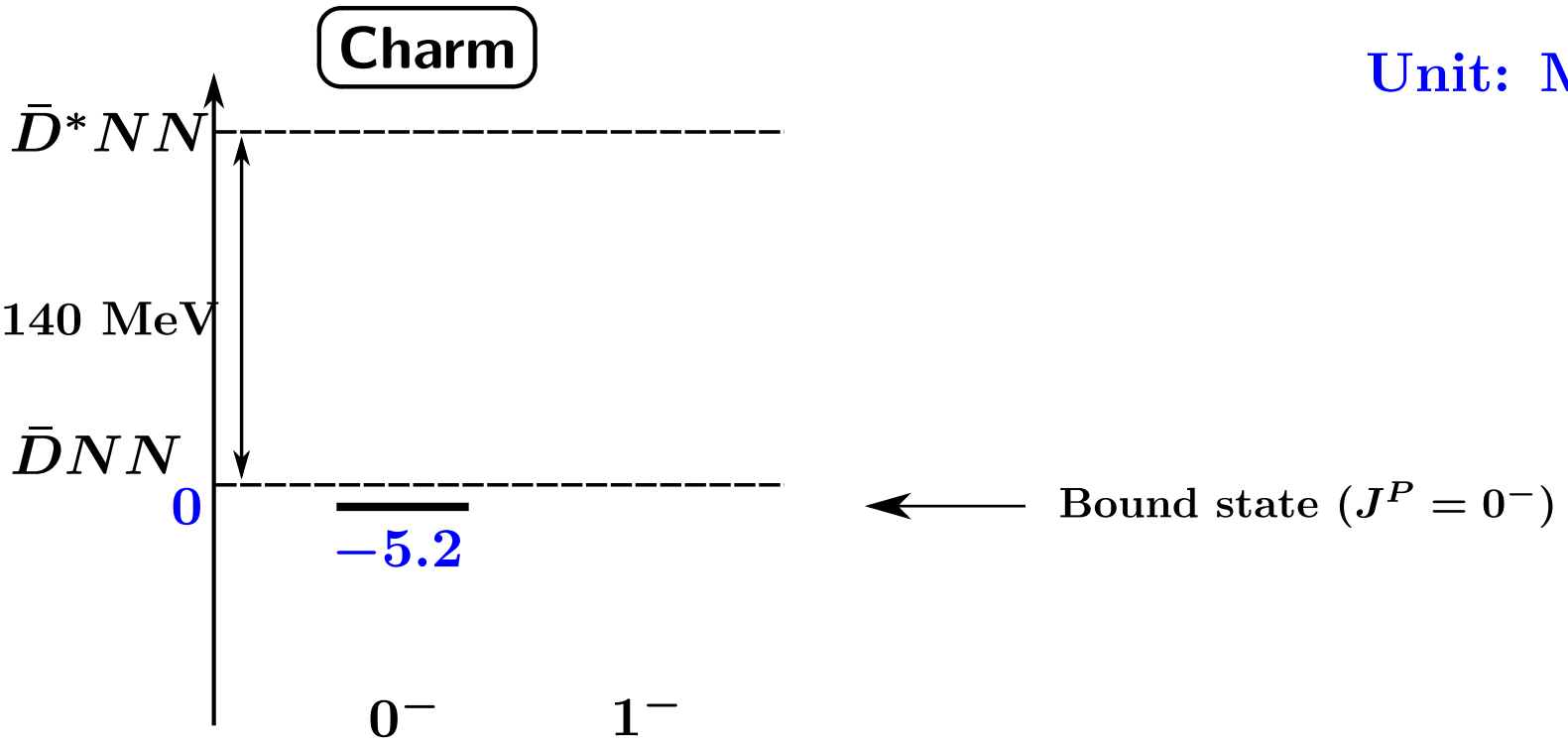

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- **Bound states** for $J^P = 0^-$

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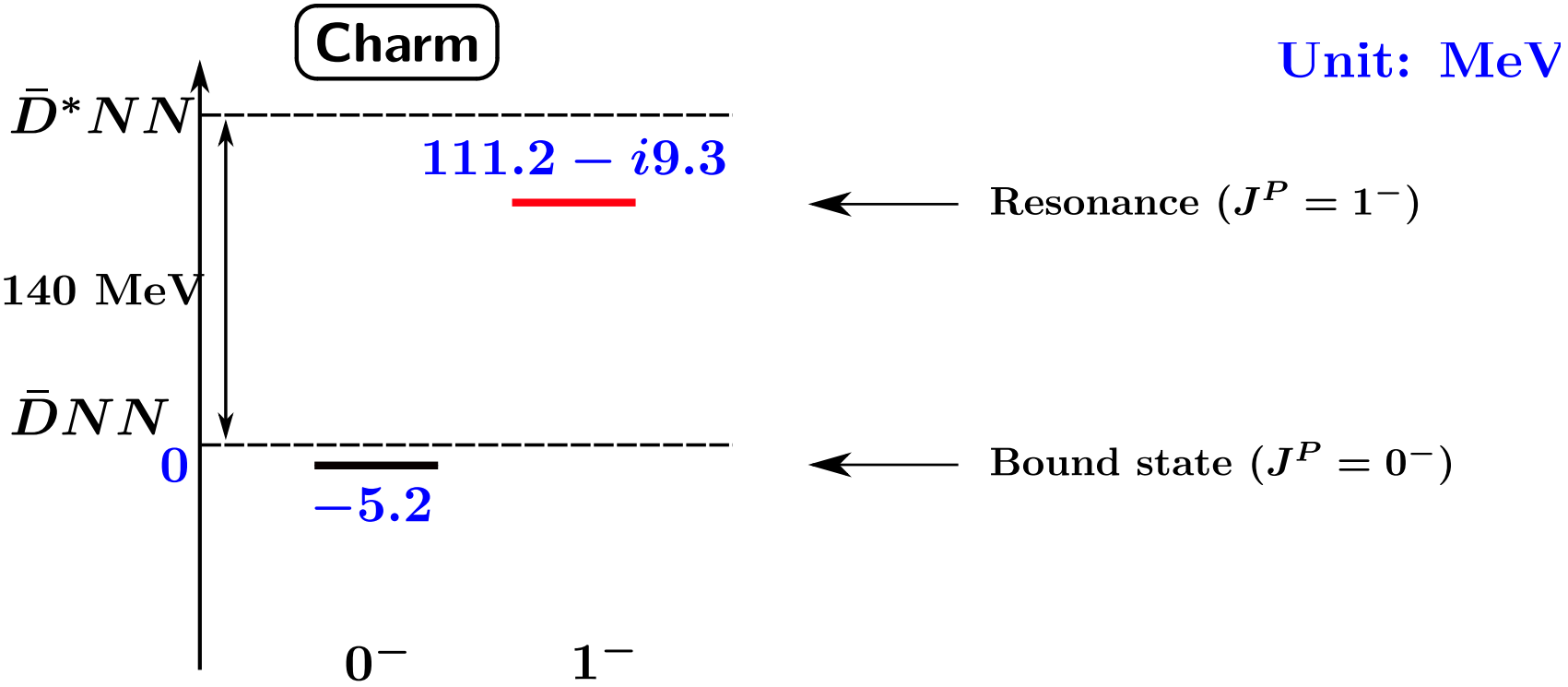

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- **Bound states** for $J^P = 0^-$ and **Resonances** for $J^P = 1^-$ are found!

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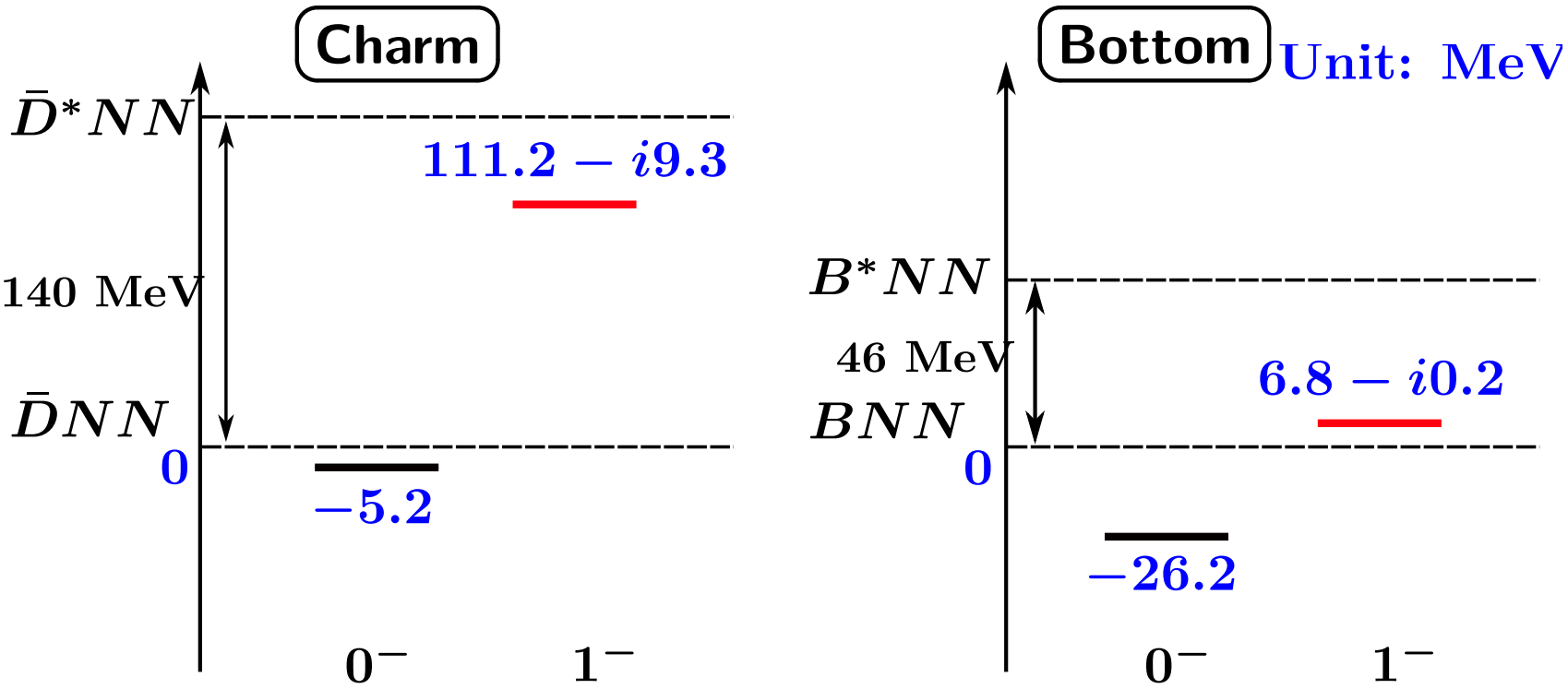
$\bar{D}NN$ and BNN

- Three-body systems: Bound state or Resonance?



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

New exotic states!

Energy expectation values of the bound states
$\bar{D}NN$ and BNN

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

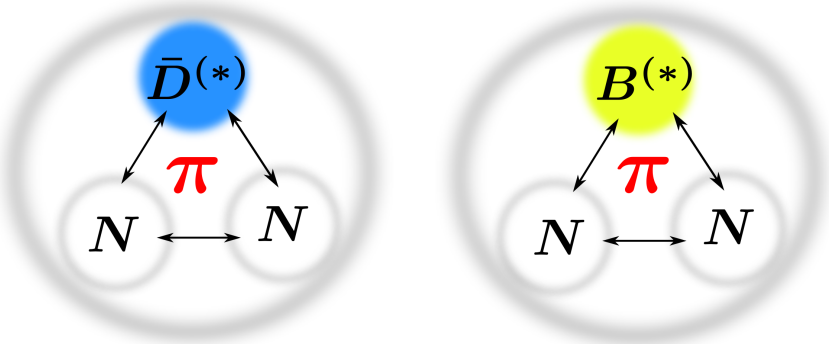
$\Leftrightarrow$ **the NN force (V_{NN})** plays a minor role, because **the Deuteron channel ($J^P_{NN} = 1^+$) is suppressed**.
($\bar{D}NN(J^P = 0^-)$)

Summary

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

$\Downarrow\Downarrow$

- 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.