Spin degeneracy of Hadronic molecules in the heavy quark region

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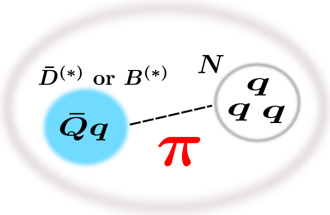
Outline

Hadronic systems containing 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. Heavy quark mass limit ($m_Q \to \infty$)
4. Summary



2-body system

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!

Baryon(proton,nucleon,...) Meson (π,K,...)

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

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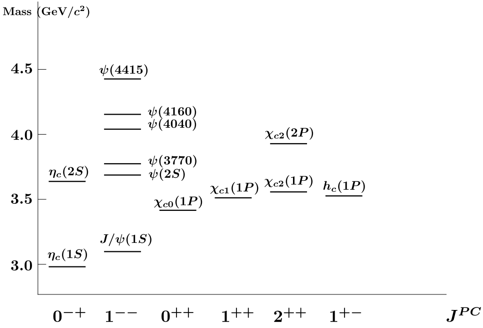
e.g. Spectra of Charmonia



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

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

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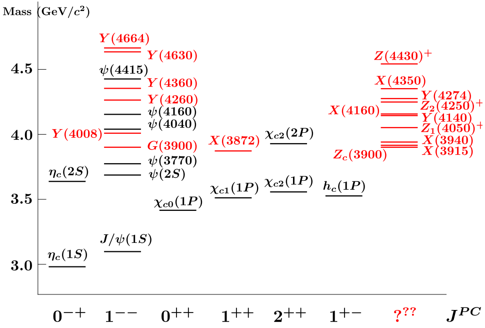
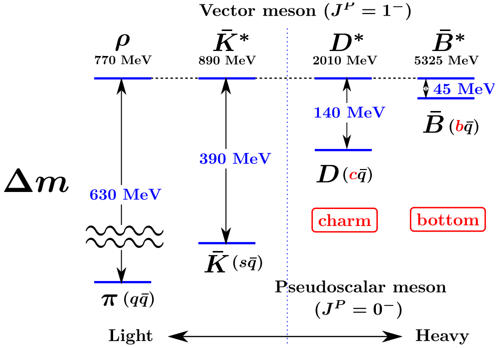


Charmonium **$c\bar{c}$**
and
Exotic hadrons ($\neq c\bar{c}$)
X, Y, Z

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

- What is **the structure of exotic hadrons** ?
- Why are many exotic hadrons found in **the heavy quark region**?

- 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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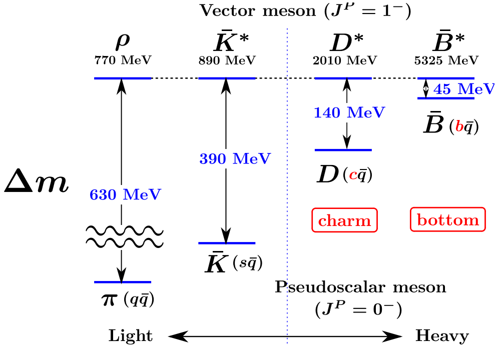


▷ Δm decreases when the quark mass increases.

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

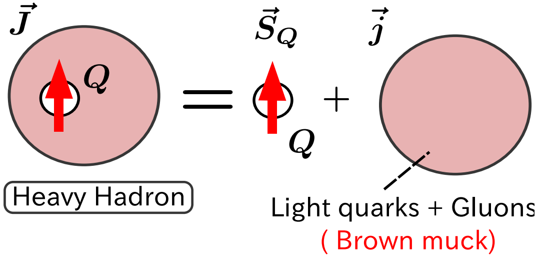
Heavy Quark Spin Symmetry (HQS)

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

- **Suppression of Spin-spin force** in $m_Q \to \infty$.

$\Rightarrow$ Decomposition of **Heavy quark spin** and **Light components**

$$\vec{\mathbf{J}} = \vec{\mathbf{L}} + \vec{\mathbf{S}} = \vec{\mathbf{S}}_{\mathbf{Q}} + \vec{\mathbf{j}}$$



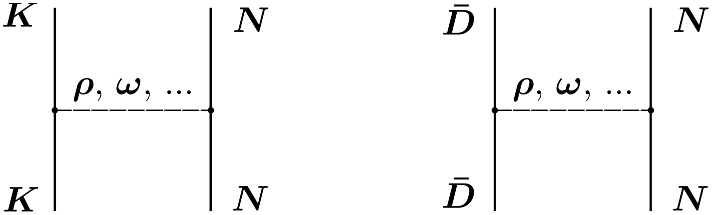
$\Rightarrow$ **Mass degeneracy** of hadrons with the different spins.

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

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

Strange (Light)

Charm (Heavy)



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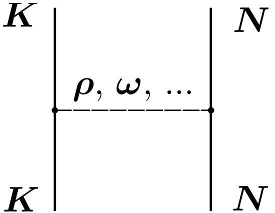
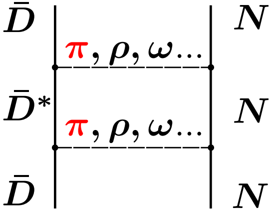
Strange (Light) (**KKπ** $\times$)

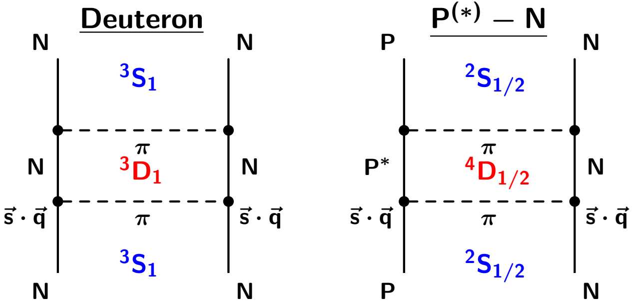


Charm (Heavy)



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

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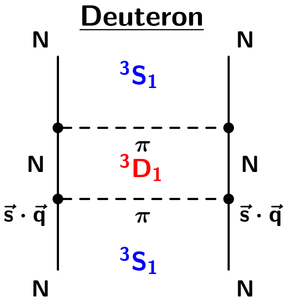
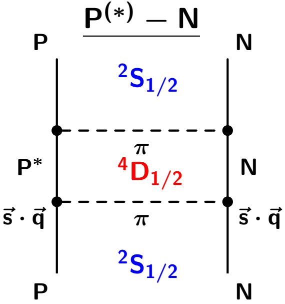




Tensor force $\Rightarrow$ $^3S_1 - {}^3D_1$

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

π exchange $\Rightarrow$ Nucleus-like state?

Hadronic molecules in the heavy quark region
Introduction

- Hadronic molecules (Hadron composite systems)
  $\to$ Appearing **near the thresholds** (M-M, M-B,...)

Exotic hadrons $\Rightarrow$ Hadronic molecules?

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

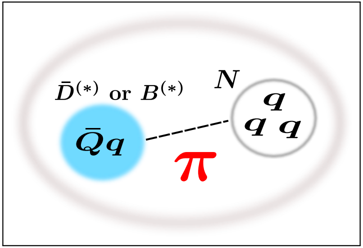
X(3872), Z_b **Λ_c^*, Pentaquark???**

▷ Theoretical researches

- $X(3872)$ as $D\bar{D}^*$,
  M. T. AlFiky, *et al.*,PLB**640**(2006)238,M. B. Voloshin, Prog.Part.Nucl.Phys.**61**(2008)455
- Z_b as $B\bar{B}^*$, J. R. Zhang, *et al.*, PLB**704**(2011)312,S.Ohkoda,*et al.*, PRD**86**(2012)014004
- Λ_c^* as DN, T.Mizutani, A.Ramos,PRC**74**(2006)065201,C. Garcia-Recio, *et al.*, PRD**79**(2009)054004

Main Subject: Heavy meson in nuclei

- Hadronic molecules formed by **Heavy meson-Nucleon with the π exchange potential**.
- Nature of the states containing heavy quarks



▷ New exotic states containing $\bar{Q}qqqq$

▷ **Strong attractions** of π exchange potential from the HQS.

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

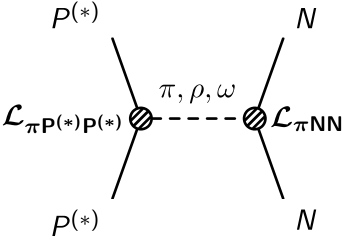


Fig: Meson exchange diagram

P: Pseudoscalar meson

P^*: Vector meson

N: Nucleon

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

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

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

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

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

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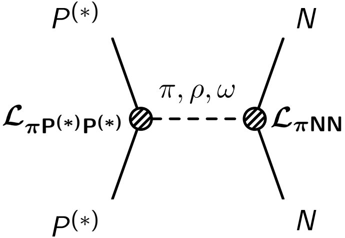

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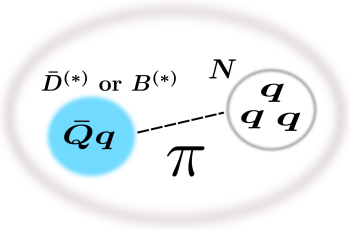
S.Yasui and K.Sudoh PRD**80**(2009)034008

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

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

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

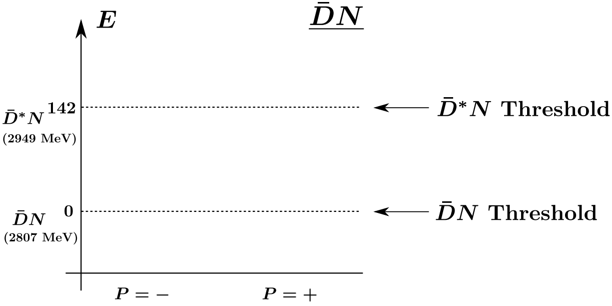


$\bar{D}N$, BN
Exotic states ($\bar{Q}q + qqq$)

Bound state and Resonance

- 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 $I = 0$

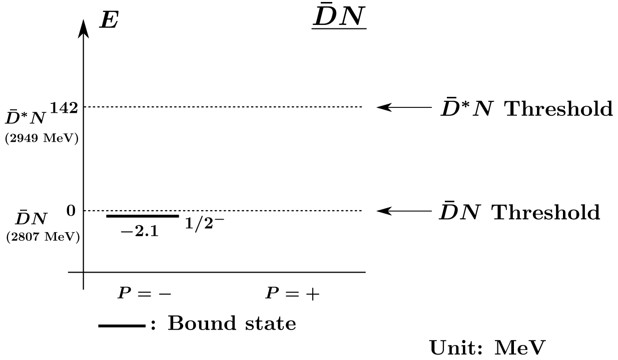


Unit: MeV

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

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

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



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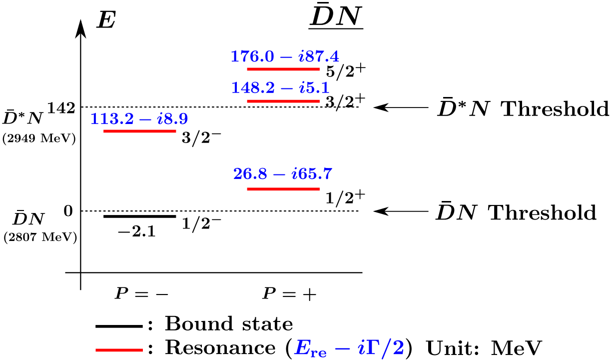
- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$ with $I = 0$
- One bound state, and resonances in charm



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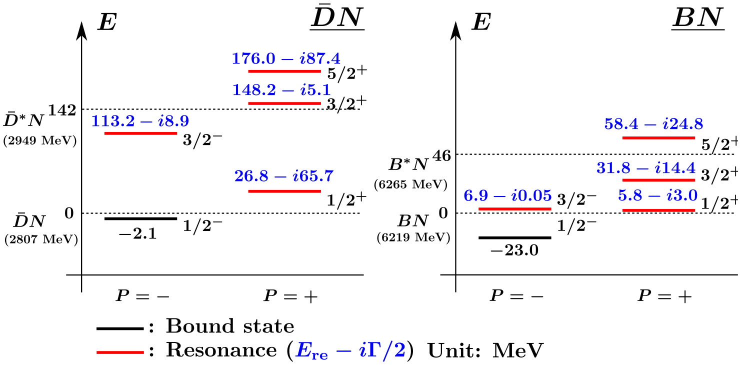
$\bar{\text{D}}$N and BN for I = 0 (2-body)

- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}$ 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 in Bound state of $J^P = 1/2^-$

$\bar{D}N$ and BN

- 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 the strong attraction. Especially, $\bar{D}N - \bar{D}^*N$ mixing is important.

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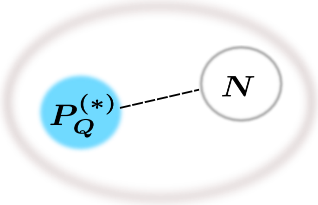
BN	$\langle V_{BN-B^*N} \rangle$	$\langle V_{B^*N-B^*N} \rangle$
Central	-8.2	1.3
Tensor	**-90.2**	-8.3

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

Results of $P_Q N$ states ($m_Q \to \infty$)

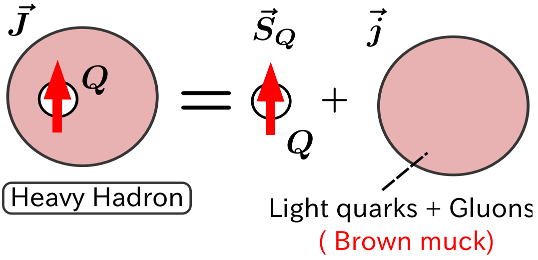


$P_Q^{(*)} N$ ($m_{P_Q^*} - m_{P_Q} = 0$)

Heavy quark mass limit

Heavy Quark Spin Symmetry (Again)

Heavy Quark Spin Symmetry (HQS) N.Isgur,M.B.Wise,PLB**232**(1989)113



$\Rightarrow$ **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)...

Mass degeneracy should appear not only in the ordinary states **but also in the hadronic molecules**!

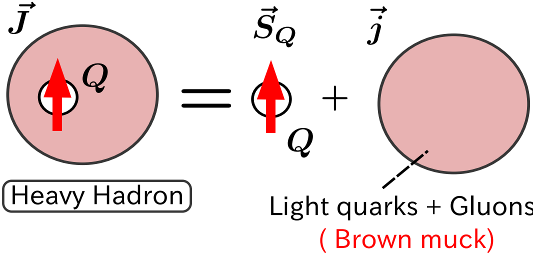
$P_Q N$ basis $\to$ Brown muck basis

- Mass degeneracy can be seen by introducing
  New basis ($\bar{Q} - [qN]$).

  S. Yasui, K. Sudoh, YY, S. Ohkoda, A. Hosaka and T. Hyodo, *et al.*,PLB**727**(2013)185,PRD**91**(2015)034034

Hadron basis $(P - N)$ $\Leftrightarrow$ Brown muck basis $(\bar{Q} - [qN])$

$$\left|[\ell,[S_P,S_N]_{S_{PN}}]_J\right\rangle \qquad \left|[S_Q,[\ell,[S_q,S_N]_{S_{qN}}]_j]_J\right\rangle$$



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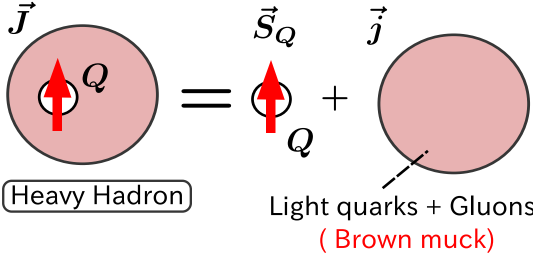

$$|PN\rangle = U|\bar{Q}\,[qN]\rangle$$

Unitary transformation

Comparing the Hamiltonians with different $\mathrm{J^P}$

- Hamiltonian $H_{J^P}(= K + V_\pi)$ of **Hadron basis (P − N)** in the heavy quark mass limit $(m_Q \to \infty)$

$$H_{1/2^-} = \begin{pmatrix} K_0 & \sqrt{3}C & -\sqrt{6}T \\ \sqrt{3}C & K_0 - 2C & -\sqrt{2}T \\ -\sqrt{6}T & -\sqrt{2}T & K_2 + C - 2T \end{pmatrix}$$

$$H_{3/2^-} = \begin{pmatrix} K_2 & \sqrt{3}T & -\sqrt{3}T & \sqrt{3}C \\ \sqrt{3}T & K_0 + C & 2T & T \\ -\sqrt{3}T & 2T & K_2 + C & -T \\ \sqrt{3}C & T & -T & K_2 - 2C \end{pmatrix}$$

$*$ K_l: Kinetic term, C: Central force, T: Tensor force

- **Can you expect they are degenerate?**

Comparing the Hamiltonians with different J^P

- Hamiltonian $H_{J^P}(= K + V_\pi)$ of **Brown muck basis ($\bar{Q}$[qN])** in the heavy quark mass limit ($m_Q \to \infty$)

$$\mathbf{H}^{\mathbf{BM}}_{\mathbf{1/2^-}} = \left(\begin{array}{c|cc} K_0 - 3C & 0 & 0 \\ \hline 0 & K_0 + C & 2\sqrt{2}T \\ 0 & 2\sqrt{2}T & K_2 + C - 2T \end{array}\right)$$

$$\mathbf{H}^{\mathbf{BM}}_{\mathbf{3/2^-}} = \left(\begin{array}{cc|cc} K_0 + C & 2\sqrt{2}T & 0 & 0 \\ 2\sqrt{2}T & K_2 + C - 2T & 0 & 0 \\ \hline 0 & 0 & K_2 - 3C & 0 \\ 0 & 0 & 0 & K_2 + C + 2T \end{array}\right)$$

$*$ K_l: Kinetic term, C: Central force, T: Tensor force

- In the Brawn muck basis, the Hamiltonians are **block diagonalized** in the heavy quark limit ($m_Q \to \infty$)!

Comparing the Hamiltonians with different J^P

- Hamiltonian $H_{J^P}(= K + V_\pi)$ of **Brown muck basis ($\bar{Q}$[qN])** in the heavy quark mass limit $(m_Q \to \infty)$

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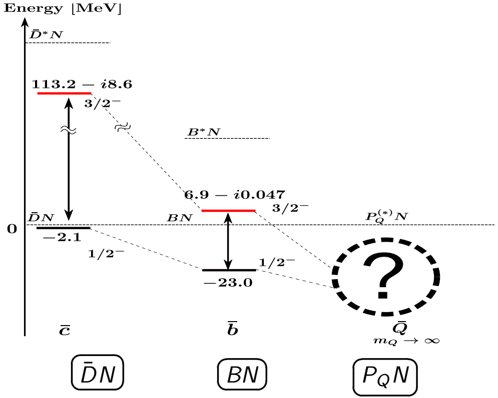
$*$ K_l: Kinetic term, C: Central force, T: Tensor force

- In the Brawn muck basis, the Hamiltonians are **block diagonalized** in the heavy quark limit $(m_Q \to \infty)$!
- **Blue components** produce **the degenerate states!**

Numerical Results: PN molecule in $m_Q \to \infty$

- In the $\bar{D}N$ and BN sectors (with finite heavy quark mass), **Bound states ($J^P = 1/2^-$)** and **resonances ($3/2^-$)** were found.



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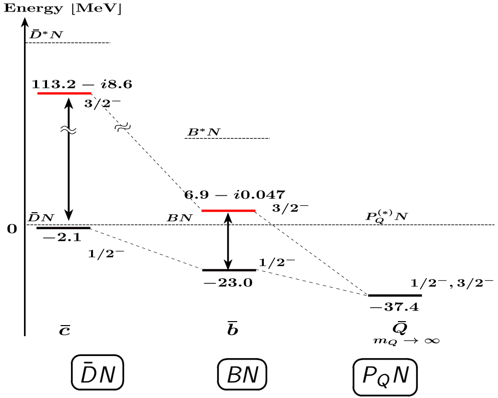

- **Degenerate states** are found! ($1/2^-$ and $3/2^-$)

YY, S. Ohkoda, A. Hosaka, T. Hyodo, S. Yasui, PRD**91**(2015)034034

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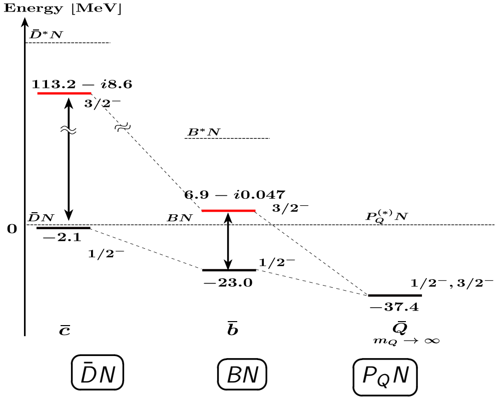

- **Degenerate states** are found! ($1/2^-$ and $3/2^-$)
  $\Rightarrow$ The molecules belong to the **HQS doublet**.

YY, S. Ohkoda, A. Hosaka, T. Hyodo, S. Yasui, PRD**91**(2015)034034

Summary

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

$\Downarrow$

- New Bound states and Resonances are found in $P^{(*)}N$ 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**.
- In $m_Q \to \infty$, we have obtained the degenerate states in the hadronic molecule.

Thank you for your kind attention.