

Spin degeneracy of Hadronic molecules in the heavy quark region

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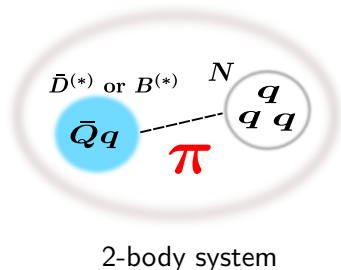
① Introduction

- Hadronic molecule
- Heavy Quark Spin Symmetry and one pion exchange potential

② Meson-Nucleon molecules: $\bar{D}N$ and BN

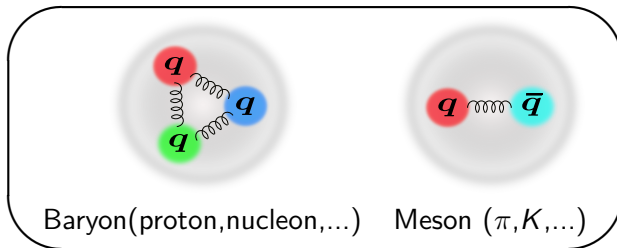
③ Heavy quark mass limit ($m_Q \rightarrow \infty$)

④ 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!



Exotic hadrons in the heavy quark region

Introduction

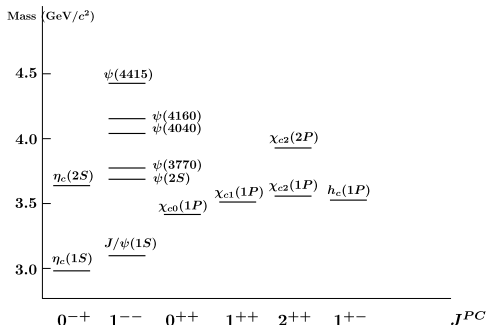
- ▶ Observation of **the Exotic Hadron** in **the heavy quark (c, b)** sectors!

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 $c\bar{c}$

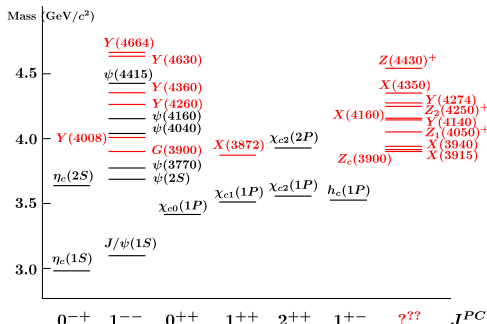
N. Brambilla, et al. Eur.Phys.J.C **71**(2011)1534
S. Godfrey and N. Isgur, PRD**32**(1985)189

Exotic hadrons in the heavy quark region

Introduction

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

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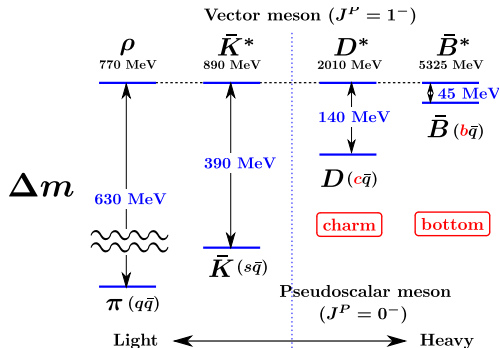
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- ▶ What is **the structure of exotic hadrons** ?
- ▶ Why are many exotic hadrons found in **the heavy quark region**?

Mass degeneracy of heavy hadrons

Introduction

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

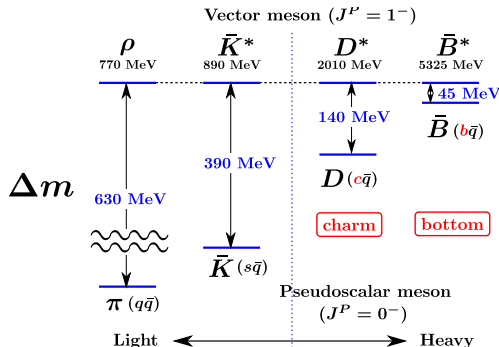


- Δm decreases when the quark mass increases.
- Masses of $\{B, B^*\}$ ($\{D, D^*\}$) are almost degenerate.

Mass degeneracy of heavy hadrons

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→ **Heavy Quark Spin Symmetry!**

Heavy Quark Spin Symmetry and Mass degeneracy

Introduction

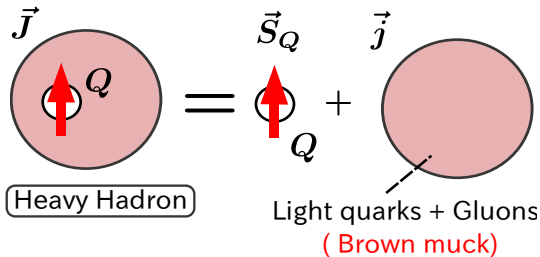
Heavy Quark Spin Symmetry (HQS)

N.Isgur, M.B.Wise, PLB232(1989)113

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

⇒ 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 spins.

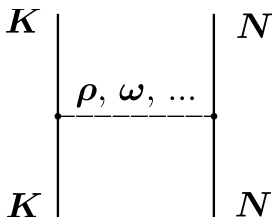
- Mass degeneracy of $\{D, D^*\}(Q\bar{q})$, $\{\eta_c, J/\psi\}(Q\bar{Q})$, $\{\Sigma_c, \Sigma_c^*\}(Qqq)$ (baryons)...

HQS and Interactions

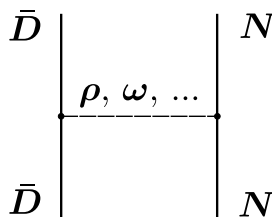
Introduction

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

Strange (Light)



Charm (Heavy)

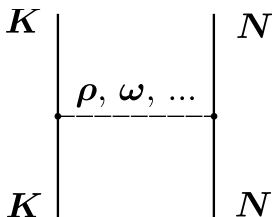


HQS and Interactions

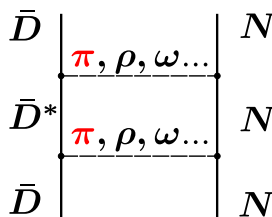
Introduction

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

Strange (Light) ($KK\pi \times$)



Charm (Heavy)



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

Introduction

- Deuteron

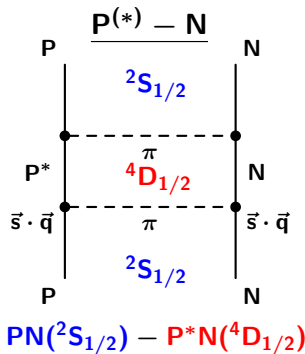
Tensor force $\Rightarrow {}^3S_1 - {}^3D_1$

$P^{(*)} - N$

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

Introduction

- ▷ **Tensor force** of the OPEP generates a strong attraction.



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

$$\text{PN}(^2\text{S}_{1/2}) - \text{P}^*\text{N}(^4\text{D}_{1/2})$$

π exchange $\Rightarrow$ Nucleus-like state?

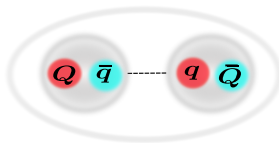
Hadronic molecules in the heavy quark region

Introduction

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

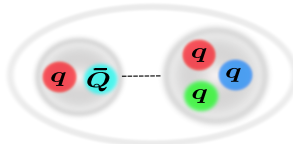
Exotic hadrons $\Rightarrow$ Hadronic molecules?

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



$X(3872), Z_b$

Meson-Baryon



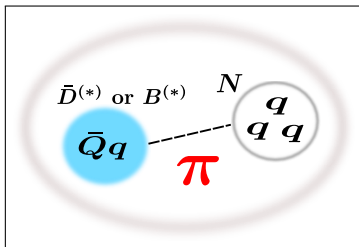
$\Lambda_c^*, \text{Pentaquark}???$

► 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

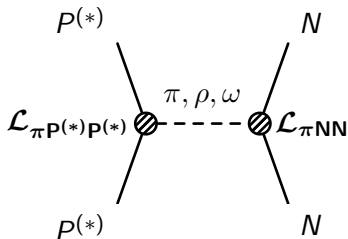
Main Subject: Heavy meson in nuclei

- 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.

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



P : Pseudoscalar meson

P^{*} : Vector meson

N : Nucleon

Fig: Meson exchange diagram

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

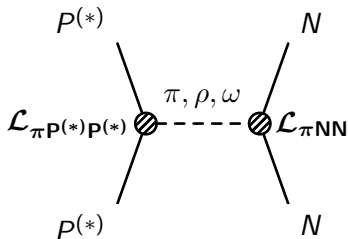
$$V_{P^{*}N-P^{*}N}^{\pi} = \frac{g_{\pi}g_{\pi NN}}{\sqrt{2}m_N f_{\pi}} \frac{1}{3} \left[\vec{T} \cdot \vec{\sigma} C(r) + S_T T(r) \right] \vec{\tau}_P \cdot \vec{\tau}_N$$

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

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

► $T(r)$ generates a strong attraction! $\Leftrightarrow$ Deuteron

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



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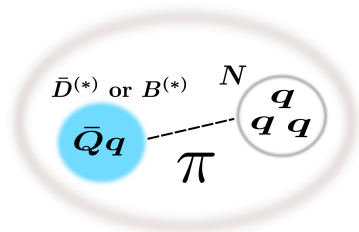
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S.Yasui and K.Sudoh PRD**80**(2009)034008

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

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

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



$\bar{D}N, BN$

Exotic states ($\bar{Q}q + qq$)

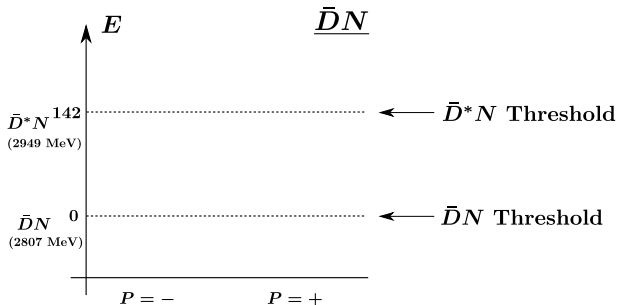
Bound state and Resonance

- 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 $I = 0$



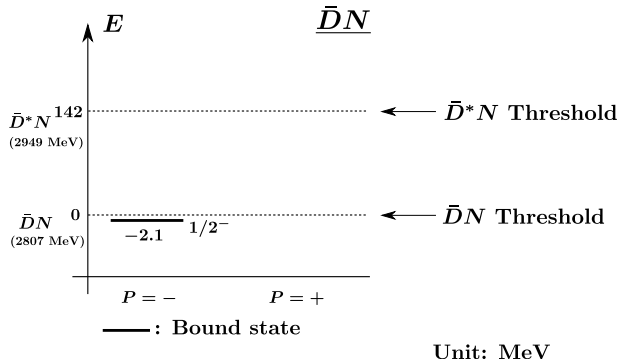
Unit: MeV

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

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- One bound state

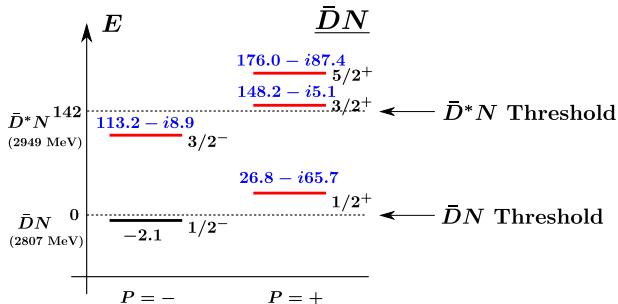


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$\bar{D}N$ and BN

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



—: Bound state

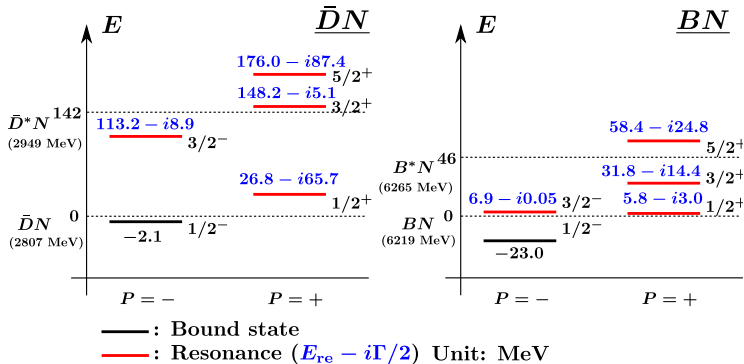
—: Resonance ($E_{\text{re}} - i\Gamma/2$) Unit: MeV

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, 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**

Expectation values in Bound state of $J^P = 1/2^-$ $\bar{D}N$ and $\bar{B}N$

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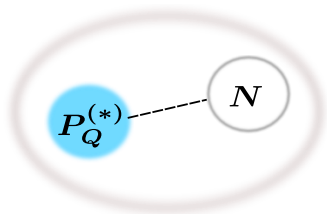
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The tensor force of π exchange potential generates **the strong attraction**. Especially, $\bar{D}N - \bar{D}^*N$ mixing is important.

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 ($m_Q \rightarrow \infty$)



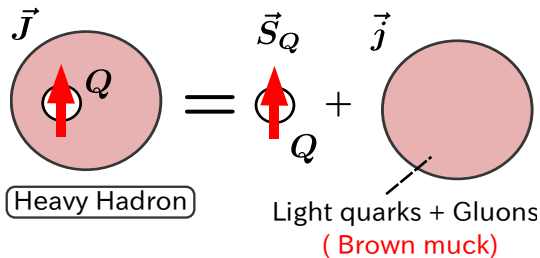
$$P_Q^{(*)} N \quad (m_{P_Q^{*}} - m_{P_Q} = 0)$$

Heavy quark mass limit

Heavy Quark Spin Symmetry (Again)

Heavy Quark Spin Symmetry (HQS)

N.Isgur, M.B.Wise, PLB232(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!

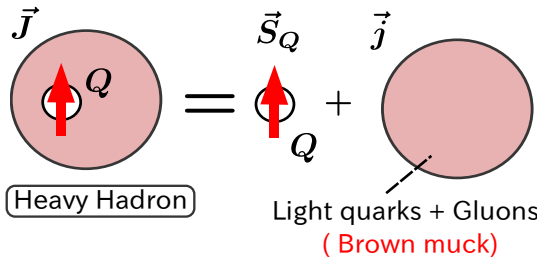
$P_Q N$ basis $\rightarrow$ Brown muck basis

- 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 ($\bar{Q} - [qN]$)

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



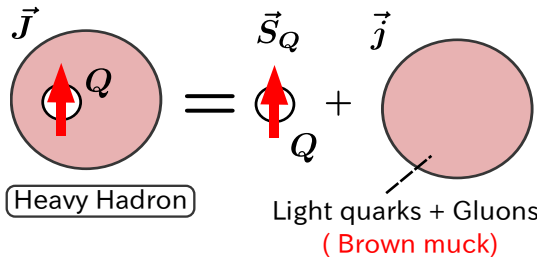
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$$|PN\rangle = U|\bar{Q}[qN]\rangle$$

Unitary transformation

Comparing the Hamiltonians with different J^P

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

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

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

* K_I : Kinetic term, C : Central force, T : Tensor force

- Can you expect they are degenerate?**

Comparing the Hamiltonians with different J^P

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

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

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

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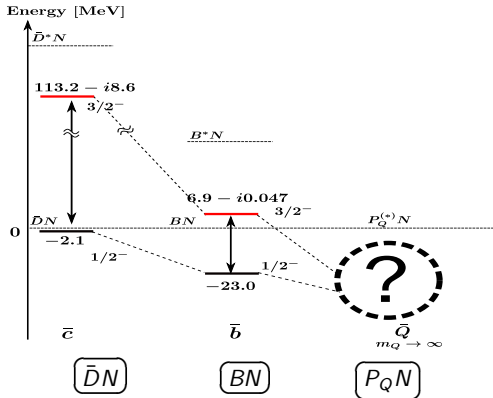
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* K_I : Kinetic term, C : Central force, T : Tensor force

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

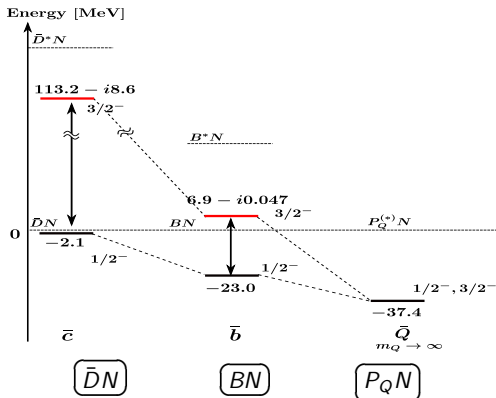
Numerical Results: PN molecule in $m_Q \rightarrow \infty$

- 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.



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

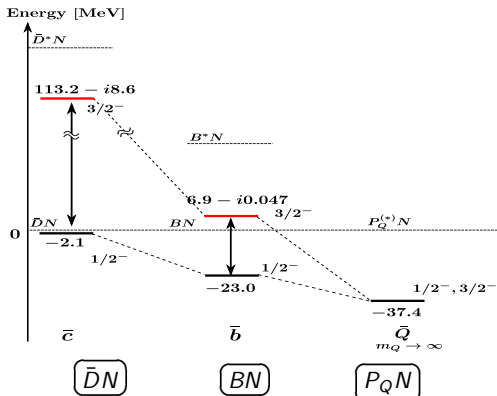
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- Degenerate states** are found! ($1/2^-$ and $3/2^-$)

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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

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



- 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 $m_Q \rightarrow \infty$, we have obtained the degenerate states in the hadronic molecule.

Thank you for your kind attention.