Exotic dibaryons with a heavy antiquark

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in collaboration with

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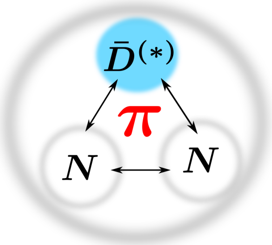
10/31-11/2 2013, Maskawa Hall in Kyoto University, Japan

Outline

1. Introduction
   - Heavy Quark Spin Symmetry
   - π exchange potential between heavy meson and nucleon.
2. Results of $\bar{D}^{(*)}NN$ and $B^{(*)}NN$
3. Results of $P^{(*)}NN$ in $m_Q \to \infty$
4. Summary



3-body system

Exotic hadrons in the heavy quark region

Introduction

- New particles (XYZ) with heavy quarks: Belle, BaBar...
- These states cannot be explained by **a simple quark model** (Baryons qqq, Meson $q\bar{q}$). $\rightarrow$ Exotic hadrons

In charm sector,

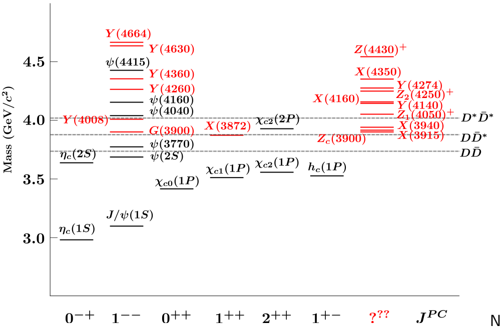


Fig.: Charmonium spectroscopy.

Charmonium $\mathbf{c\bar{c}}$
and
Exotic hadrons

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

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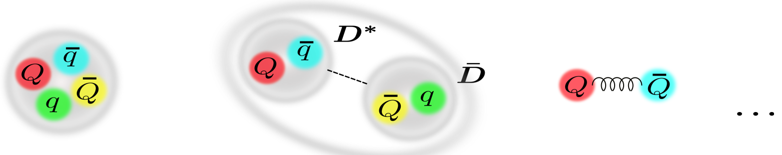
Structures of exotic hadrons. (Meson)



Tetraquark (Compact)

Hadronic molecule

$Q\bar{Q}g$ hybrid

Q: Heavy quark (c, b)、 q: Light quark (u, d)

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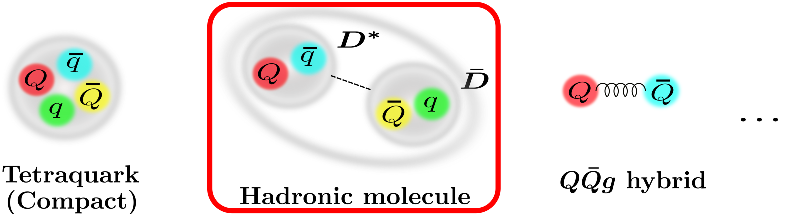
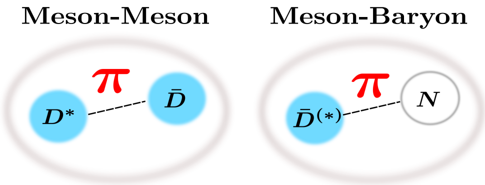


Q: Heavy quark (c, b)、 q: Light quark (u, d)

- Hadron molecules: Loosely bound state or resonance of two hadrons. Candidates? $X(3872)$, Z_b...

S.K.Choi *et al.*, PRL**91** (2003) 262001, A.Bondar, *et al.*, PRL**108**(2012)122001

Hadronic molecules



- Driving force to form molecules: π **exchange potential** ?
- In the heavy quark region,

Hadronic molecules

Meson-Meson Meson-Baryon

Heavy Quark Spin Symmetry

- Driving force to form molecules: **π exchange potential** ?
- In the heavy quark region, π exchange potential is enhanced by **the Heavy Quark Spin Symmetry**.
- Meson-Meson molecules: The importance of **the tensor force** in "Deuson" N. A. Törnqvist, Z. Phys. C **61** (1994) 525
- $\bar{D}N$ and BN ($\bar{Q}qqqq$) $\rightarrow$ **Genuinely Exotics!**

  T. D. Cohen, *et al.*,PRD**72**(2005)074010, S. Yasui and K. Sudoh,PRD**80**(2009)034008

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

  $\Leftrightarrow$ **KN ($\bar{s}qqqq$) doesn't exist due to a repulsive force.**

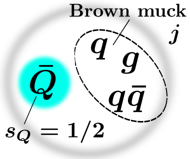
Heavy Quark Spin Symmetry   N.Isgur, M.B.Wise,PRL**66**,1130

- In the heavy quark limit ($m_Q \to \infty$),

$$\vec{J} = \vec{s}_Q + \vec{j}$$

s_Q: Heavy quark spin, j: the total angular momentum of the **brown muck**

(**Brown muck**: Everything other than the heavy quark in the hadron)



$\triangleright$ $s_Q = 1/2$ and j are decoupled

$\Rightarrow$ **Degenerate states** $\begin{cases} (j+1/2)^P \\ (j-1/2)^P \end{cases}$ $(j \neq 0)$

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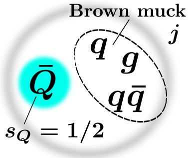

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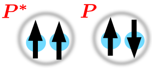
$\Rightarrow$ **Degenerate states** $\begin{cases} (j+1/2)^P \\ (j-1/2)^P \end{cases}$ $(j \neq 0)$

$\Downarrow$ Heavy meson

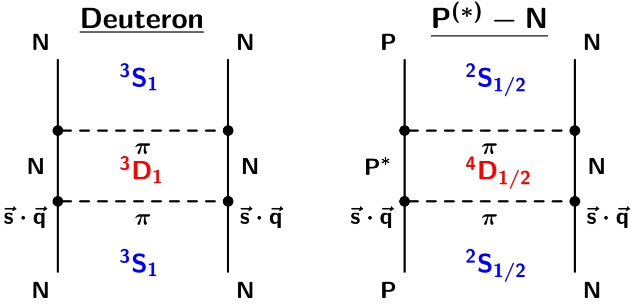


$\begin{cases} \text{Heavy pseudoscalar meson } \mathbf{P(0^-)} \text{ and} \\ \text{Heavy vector meson } \mathbf{P^*(1^-)} \text{ are } \textbf{degenerate}. \end{cases}$

Indeed, mass splitting between P and P^* is **small**.

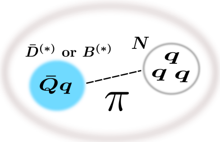
$\begin{cases} \mathbf{m_{B^*} - m_B \sim 45\,MeV} \\ \mathbf{m_{D^*} - m_D \sim 140\,MeV} \end{cases} \Leftrightarrow$ For strange sector $\mathbf{m_{K^*} - m_K \sim 400\,MeV}$

- The π exchange potential (OPEP) appears through **$PP^*\pi$ and $P^*P^*\pi$ vertices**. ($PP\pi$ is forbidden.)
  $\rightarrow$ The OPEP is enhanced when P and P^* are degenerate.
- The OPEP is important in the heavy meson system.
- The OPEP(**Tensor force**) generates a **strong attraction** in Analogy with Deuteron.



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

$P^{(*)}N$ molecule (2-body system) (previous works)

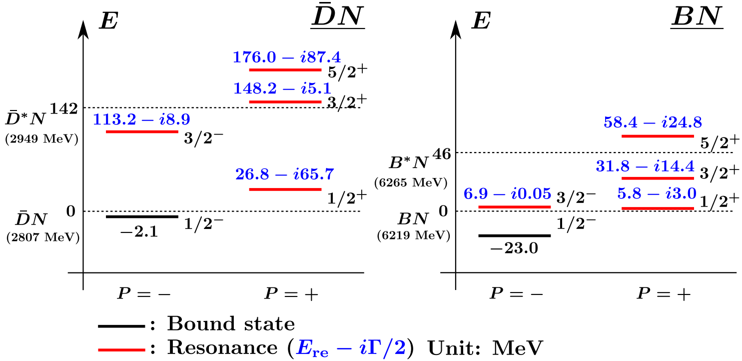


Exotic baryons!

▷ Bound and resonant states were obtained.

S. Yasui and K. Sudoh, PRD**80**(2009)034008
Y.Y., S.Ohkoda, S.Yasui and A.Hosaka, PRD**84**(2011)014032, PRD**85**(2012)054003

▷ **The tensor force of OPEP** plays an important role.



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

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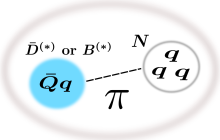

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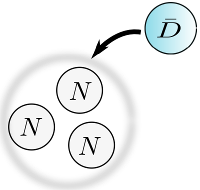
$\mathrm{P}^{(*)}$ nuclei (Few body or many body)?

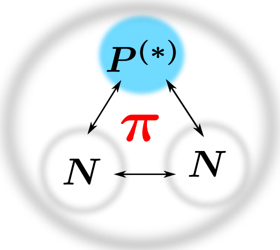


- $P^{(*)}$ nuclei ($P^{(*)} = \bar{D}^{(*)}, B^{(*)}$) $\rightarrow$ Exotics!
  - Impurity effects e.g. glue-like effect.
  - Heavy meson-nucleon interaction.
- several works for $\bar{D}(B)$ meson in nuclear matter and in ^{12}C, ^{208}Pb...

  e.g. C. Garcia-Recio, *et al.*, PRC**85** (2012)025203.
  S. Yasui and K. Sudoh, PRC**87**(2013)015202.
- However, there is **no study for few-body $\bar{\mathrm{D}}$(B) nuclei** in the literature so far.

Main Subject

- Exotic dibaryons with a heavy antiquark, $\bar{D}^{(*)}NN$ and $B^{(*)}NN$ (3-body system).



$$\boldsymbol{P^{(*)}NN}$$
$$(\boldsymbol{P^{(*)} = \bar{D}^{(*)},\ B^{(*)}})$$

- $P = \bar{D}(\bar{c}q), B(\bar{b}q) \to$ **Genuinely exotic states!**
  $\Leftrightarrow$ **KNN doesn't exist.** (KN interaction is repulsive force.)
- We study **bound and resonant states** by solving the coupled-channel Schrödinger equations for **PNN and P*NN channels**.
- We employ only OPEP. $(\rho, \omega ... \to$ Future Work)

▷ Lagrangian

- **Heavy-light chiral Lagrangian** R.Casalbuoni *et al.* PhysRept.**281**(1997)145

$$\mathcal{L}_{\pi HH} = ig_\pi \mathrm{Tr}\left[H_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba} \bar{H}_a\right], \quad g_\pi = 0.59 \text{ for } \bar{D} \text{ and } B$$

From $D^* \to D\pi$ decay

$$H_a = \frac{1+\not{v}}{2}\left[\mathbf{P}^*_{a\,\mu}\gamma^\mu - \mathbf{P}_a \gamma^5\right], \quad \bar{H}_a = \gamma^0 H_a \gamma^0$$

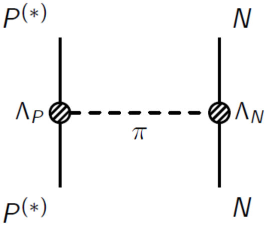
vector **pseudoscalar**

- **Bonn model** R.Machleidt *et al.* Phys Rept.**149**(1987)1

$$\mathcal{L}_{\pi NN} = ig_{\pi NN} \bar{N}_b \gamma^5 N_a \hat{\boldsymbol{\pi}}_{ba}, \quad g^2_{\pi NN}/4\pi = 13.6$$

From NN data

▷ Form factor ($P^{(*)}N$)



Lagrangian($P^{(*)}-N$) and Form factor

▷ Lagrangian

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From D* → Dπ decay

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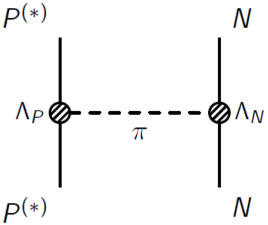
▷ Form factor ($P^{(*)}N$)

$$F(\vec{q}\,) = \frac{\Lambda_N^2 - m_\pi^2}{\Lambda_N^2 + |\vec{q}\,|^2}\frac{\Lambda_P^2 - m_\pi^2}{\Lambda_P^2 + |\vec{q}\,|^2}$$



1. Λ_N is fixed to reproduce the Deuteron. (NN system)
2. Λ_P; We assume $\Lambda_P/\Lambda_N = r_N/r_P$.

$$\begin{cases} \Lambda_D = 1.35\Lambda_N \\ \Lambda_B = 1.29\Lambda_N \end{cases} \Rightarrow \begin{array}{l} \Lambda_N = 830\,\mathrm{MeV} \\ \Lambda_D = 1121\,\mathrm{MeV} \quad \Lambda_B = 1070\,\mathrm{MeV} \end{array}$$

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

$\mathrm{P}^{(*)}\mathrm{N}$ ($\mathrm{P}^{(*)} = \bar{\mathrm{D}}^{(*)}, \mathrm{B}^{(*)}$) and NN interactions

- π exchange potential between $P^{(*)}(=\bar{D}^{(*)}, B^{(*)})$ and N

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

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

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

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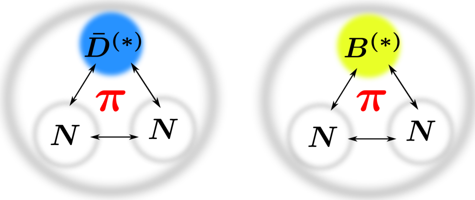
- NN int.: AV8$'$ potential B. S. Pudliner, *et.al.* ,PRC**56**(1997)1720

$$v_8'(r) = \sum_{p=1,8} v_p'(r)\mathcal{O}^p$$

$$\mathcal{O}^{p=1-8} = \begin{cases} \text{Central} & [1,\ \vec{\sigma}_1\cdot\vec{\sigma}_2]\otimes[1,\ \vec{\tau}_1\cdot\vec{\tau}_2] & \text{(4 operators)} \\ \text{Tensor} & S_{12}\otimes[1,\ \vec{\tau}_1\cdot\vec{\tau}_2] & (2) \\ \text{LS} & \vec{L}\cdot\vec{S}\otimes[1,\ \vec{\tau}_1\cdot\vec{\tau}_2] & (2) \end{cases}$$

Results of $\mathrm{P}^{(*)}$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

- Wave functions are expressed by the Gaussian expansion method. E. Hiyama, *et al.*, Prog.Part.Nucl.Phys.51(2003)223
- Resonances $\rightarrow$ Complex scaling method S.Aoyama,*et.al.*,PTP**116**,1(2006)

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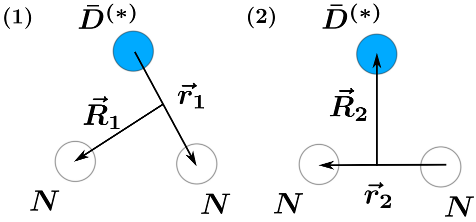

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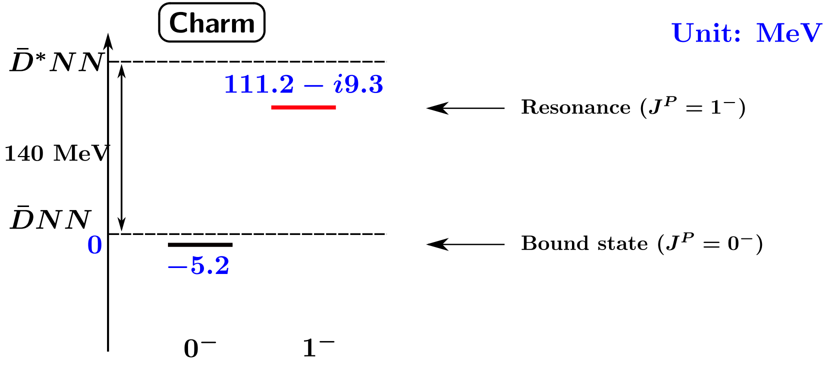
Results of $\bar{\mathrm{D}}^{(*)}$NN and $\mathrm{B}^{(*)}$NN with I = 1/2 (Exotic)
$\bar{\mathrm{D}}$NN and BNN

- **Bound states** for $J^P = 0^-$ and **Resonances** for $J^P = 1^-$ are found! YY, S. Yasui, and A. Hosaka, arXiv:1309.4324 [nucl-th]



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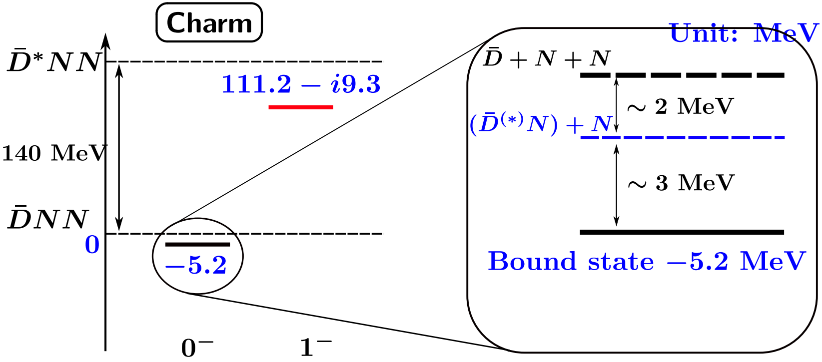

- $\bar{D}NN(0^-)$ locates below **$\bar{D}N(1/2^-) + N$ threshold**.

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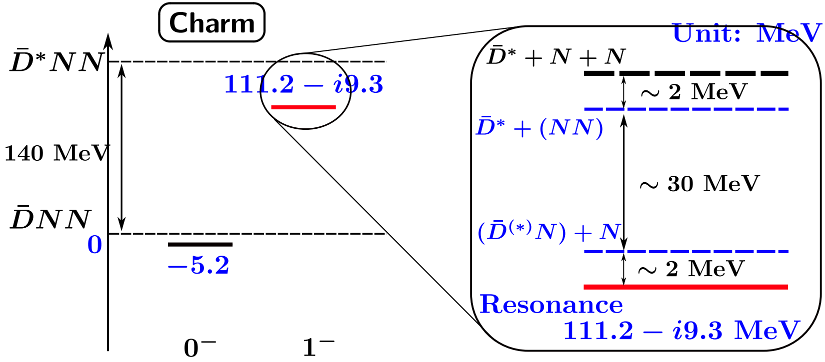

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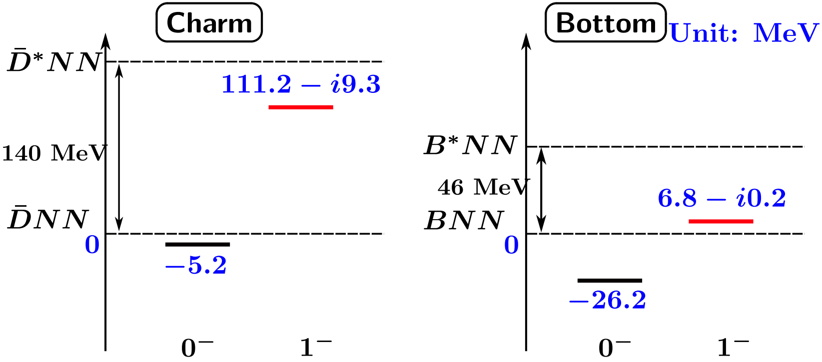

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- $\bar{D}NN(1^-)$ locates below **$\bar{D}^* + NN(1^+)$ and $\bar{D}N(3/2^-) + N$ thresholds**.
- $BNN > \bar{D}NN$ due to large reduced mass and small Δm_{BB^*}.

- Energy expectation values

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

$\bar{D}^{(*)}NN$	$\langle V_{\bar{D}N\text{–}\bar{D}^*N}\rangle$	$\langle V_{\bar{D}^*N\text{–}\bar{D}^*N}\rangle$	$\langle V_{NN}\rangle$
Central	-2.3	-0.1	-9.5
Tensor	-47.1	0.7	-0.2
LS	—	—	-0.03

YY, S. Yasui, and A. Hosaka, arXiv:1309.4324 [nucl-th]

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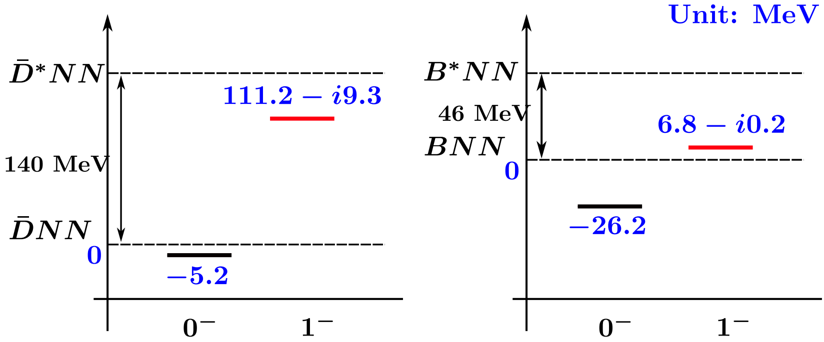
- Tensor force of **$\bar{\mathrm{D}}\mathrm{N} - \bar{\mathrm{D}}^*\mathrm{N}$ mixing** component generates **the strong attraction**.
- For V_{NN}, **central force** is stronger than **tensor force**.
  $\Rightarrow NN(0^+)$ subsystem dominates in the bound state,
  while $NN(1^+)$ (=Deuteron) is minor.

- If *PNN* channels are switched off...



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$\bar{D}NN$ and BNN

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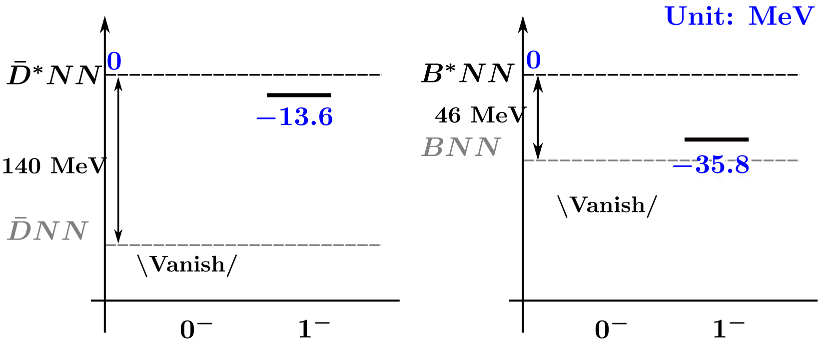
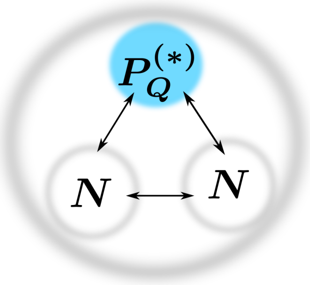


- The bound states for $J^P = 0^-$ vanish.
  $\Rightarrow$ $PN - P^*N$ mixing components are very important!
- For $J^P = 1^-$ channel, the bound states survive.
  $\Rightarrow$ **Feshbash resonance!**

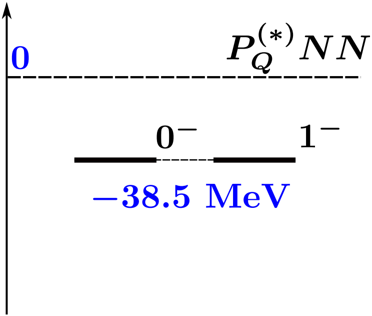
Results of $\mathrm{P_Q^{(*)}NN}$ states ($m_Q \to \infty$)



$\mathrm{P_Q^{(*)}NN}$ $(m_{P_Q^*} - m_{P_Q} = 0)$

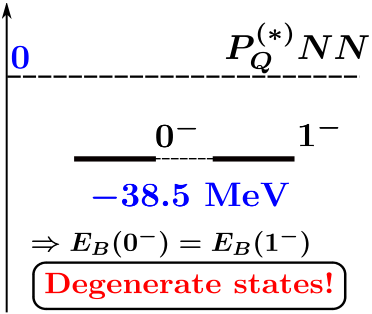
Results of $P_Q^{(*)}NN$ in $m_Q \to \infty$ (Exotic)

- We find bound states both for $J^P = 0^-$ and 1^-!



Results of $P_Q^{(*)}NN$ in $m_Q \to \infty$ (Exotic)

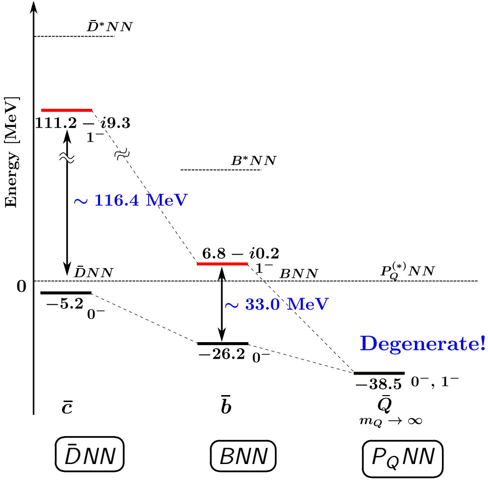
- We find bound states both for $J^P = 0^-$ and 1^-!



- $P^{(*)}NN$: Degenerate states $(j-1/2, j+1/2)^P = (0,1)^-$
  $\to$ Brown muck $[qNN]^{\mathcal{P}}$ has $j^{\mathcal{P}} = 1/2^+$.

Results of $P_Q^{(*)}NN$ in $m_Q \to \infty$ (Exotic)

- Energy-levels for $\bar{D}NN$, BNN and $P_Q NN(m_Q \to \infty)$



- Splitting between $E(1^-)$ and $E(0^-)$ decreases as m_Q increases.

Summary

- We have investigated genuinely exotic dibaryons formed by $P^{(*)}NN$.
- The π exchange potential was employed between a heavy meson $P^{(*)}$ and a nucleon N.
- For the $\bar{D}NN$ and BNN states, we have found the bound states with $J^P = 0^-$ and resonances with $J^P = 1^-$ for $I = 1/2$.
- **Tensor force of π exchange** plays a crucial role to produce a strong attraction.
- The **PN − P*N mixing** component is important to yield these states.
- In $m_Q \to \infty$, we have obtained the degenerate states of $J^P = 0^-$ and 1^-.

Back up

Central force and Tensor force

- Central force $C(r)$ and Tensor force $T(r)$

$$C(r) = \int \frac{d^3q}{(2\pi)^3} \frac{m_\pi^2}{\vec{q}^{\,2} + m_\pi^2} e^{i\vec{q}\cdot\vec{r}} F(\Lambda_P, \vec{q}) F(\Lambda_N, \vec{q})$$

$$S_T(\hat{r}) T(r) = \int \frac{d^3q}{(2\pi)^3} \frac{-\vec{q}^{\,2}}{\vec{q}^{\,2} + m_\pi^2} S_T(\hat{q}) e^{i\vec{q}\cdot\vec{r}} F(\Lambda_P, \vec{q}) F(\Lambda_N, \vec{q})$$

$$F(\Lambda, \vec{q}) = \frac{\Lambda^2 - m_\pi^2}{\Lambda^2 + \vec{q}^{\,2}}$$