Exotic few-body systems with a heavy meson

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in collaboration with

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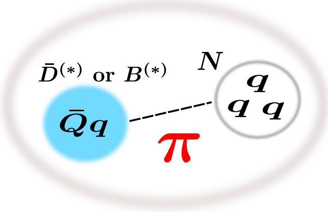
XIth Quark Confinement and the Hadron Spectrum

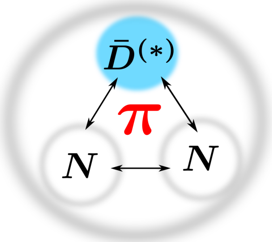
9/8-9/12 2014, Saint-Petersburg, Russia

Outline

1. Introduction
   - Hadronic molecule
   - Heavy Quark Spin Symmetry and one pion exchange potential
2. Results of $\bar{D}N$ and BN
3. Results of $\bar{D}NN$ and BNN
4. Results in the heavy quark limit ($m_Q \to \infty$)
5. Summary



2-body system



3-body system

- Constituent quark model has been successfully applied to hadron spectra. : qqq and $q\bar{q}$ **(Ordinary hadrons)**

  S. Godfrey and N. Isgur, PRD**32**(1985)189, S. Capstick and N. Isgur, PRD **34**(1986)2809

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  (in the heavy quark (c, b) sector)

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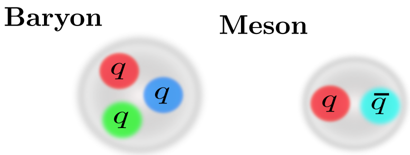

- **New Exotic hadron** X, Y, Z: KEK, SLAC, ... (in the heavy quark (c, b) sector)
- How can we understand structures of the exotic hadrons?

- Constituent quark model has been successfully applied to hadron spectra. : qqq and $q\bar{q}$ **(Ordinary hadrons)**

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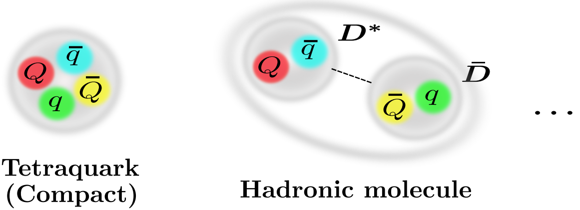
Multiquark states? (Meson)



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

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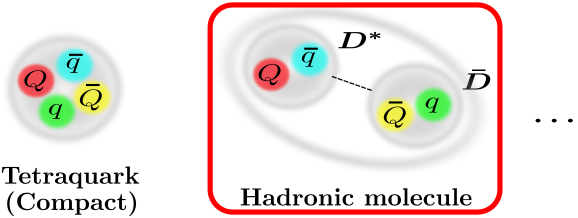
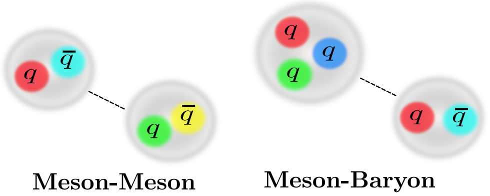


Q: Heavy quark (c, b)、 q: Light quark (u, d)

$\rightarrow$ Candidates? $X(3872)(D\bar{D}^*?)$, $Z_b(B\bar{B}^*?)$...

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

Hadronic molecules

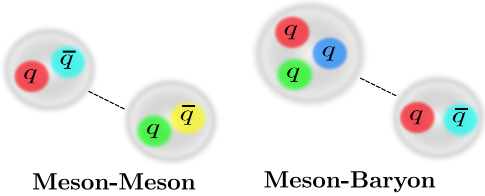


- Loosely bound states (resonances) of hadrons
  → Analogous to **Deuteron (proton-neutron)**

  N. A. Tornqvist,Z. Phys. C **61** (1994) 525

  ▷ near the threshold, $E_B \sim 2.2$ MeV
  ▷ spatially expanded, $\langle r^2 \rangle^{1/2} \sim 3.9$ fm
- In Hadron composite systems,

Hadronic molecules



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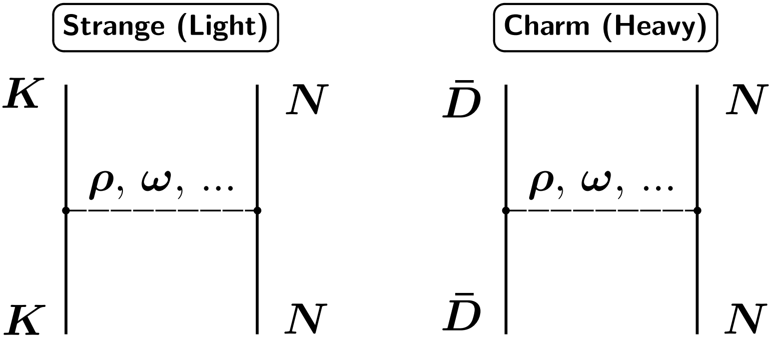
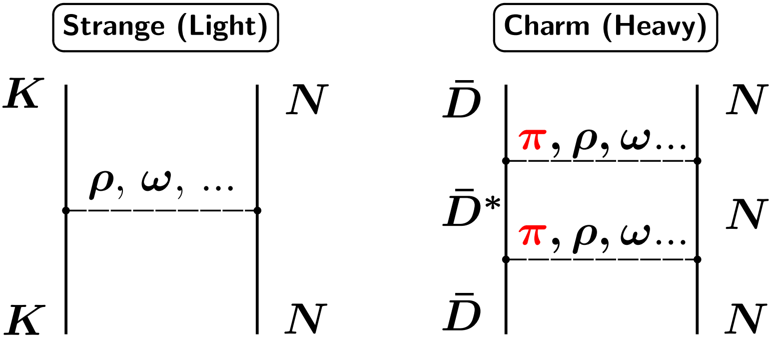
  ▷ near the threshold, $E_B \sim 2.2$ MeV
  ▷ spatially expanded, $\langle r^2 \rangle^{1/2} \sim 3.9$ fm
- In Hadron composite systems,
  Interactions between hadrons are important!



- Short range force (ρ, ω exchanges...) in KN.



- Short range force (ρ, ω exchanges...) in KN.
- In the heavy sector, **one π exchange potential (OPEP)** is enhanced by the $\bar{D} - \bar{D}^*$ mixing. ($\Delta m_{\bar{D}\bar{D}^*}$ is small)
- The small mass splitting is induced by **the Heavy Quark Spin Symmetry**!

  $\Rightarrow$ Interaction is different!

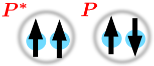
Heavy Quark Spin Symmetry and OPEP

Introduction

Heavy Quark Spin Symmetry (HQSS)

N.Isgur, M.B.Wise,PRL**66**,1130

- HQSS appears in the heavy quark mass limit ($m_Q \to \infty$).
- Spin-spin interaction $\longrightarrow 0$
  e.g. Heavy meson ($\bar{Q}q$)



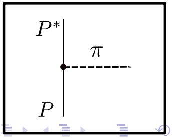
$\left\{ \begin{array}{l} \text{Heavy pseudoscalar meson } \mathbf{P(0^-)} \text{ and} \\ \text{Heavy vector meson } \mathbf{P^*(1^-)} \text{ are } \textbf{degenerate}. \end{array} \right.$

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

$\left\{ \begin{array}{l} \mathbf{m_{B^*} - m_B \sim 45\,MeV} \\ \mathbf{m_{D^*} - m_D \sim 140\,MeV} \end{array} \right. \Leftrightarrow$ For strangeness sector $\mathbf{m_{K^*} - m_K \sim 400\,MeV}$

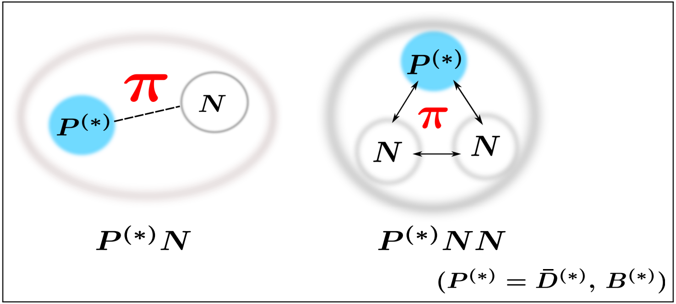
▷ OPEP appears through **$PP^*\pi$ and $P^*P^*\pi$ vertices**. ($PP\pi$ is forbidden.)

▷ Thanks to the degeneracy, **OPEP is enhanced**.



Main Subject

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



- $P = \bar{D}(\bar{c}q), B(\bar{b}q) \to$ No $q\bar{q}$ annihilation! **Genuinely exotic states!**

  $\Leftrightarrow$ **KN molecules have not been found.**

  (KN interaction is repulsion.)

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

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

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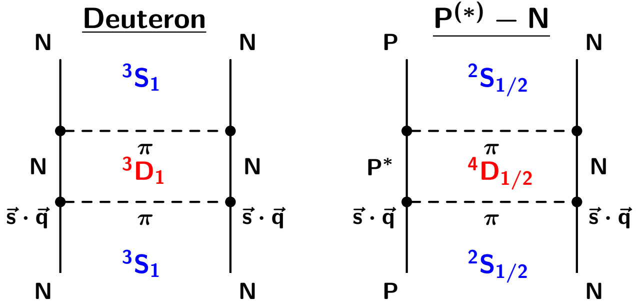
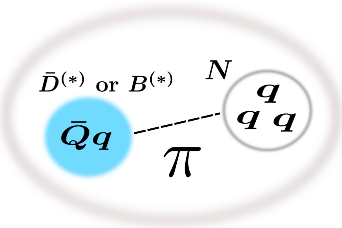


Tensor force ⇒ $^3S_1 - {}^3D_1$ $PN(^2S_{1/2}) - P^*N(^4D_{1/2})$

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

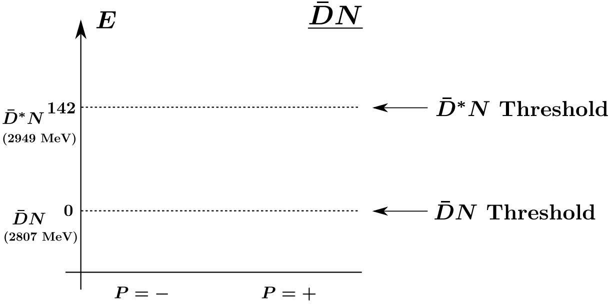


$\bar{D}N$, BN
Exotic states ($\bar{Q}q + qqq$)

<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 $I = 0$
- Bound and Resonant states.



Unit: MeV

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

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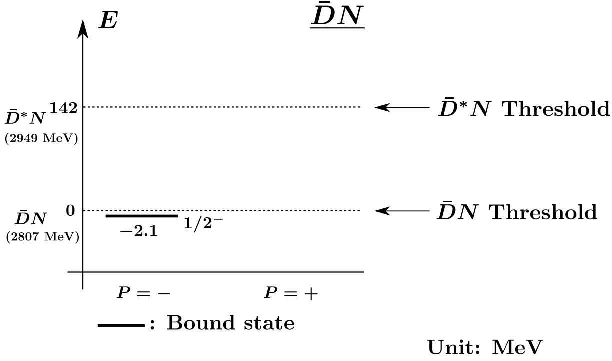

Y.Y., S.Ohkoda, S.Yasui and A.Hosaka, PRD**84** 014032 (2011) and PRD**85** 054003 (2012)

- One bound state

Numerical results: D̄N and BN for I = 0 (2-body)

D̄N and BN states

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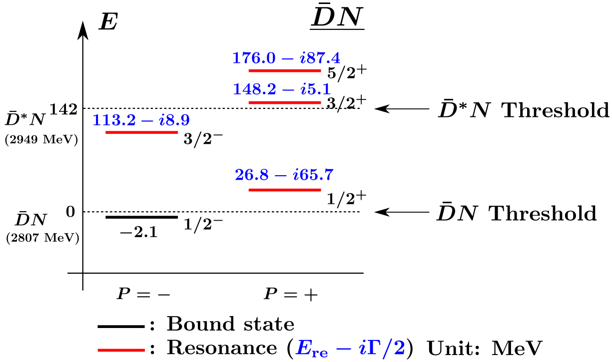

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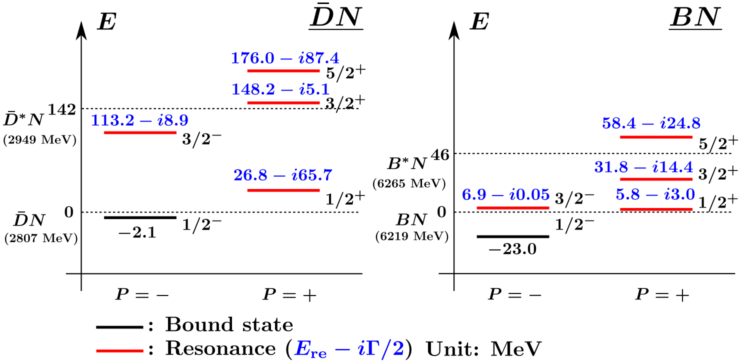

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- One bound state, and resonances!
- $E(BN) > E(\bar{D}N)$ due to large μ and small Δm_{BB^*}.

- Expectation values of OPEP

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	-1.8	-4.0×10^{-3}
Tensor	-32.8	0.1

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

Numerical results: Bound state in $I(J^P) = 0(1/2^-)$

$\bar{D}N$ and BN states

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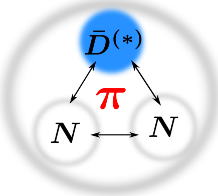
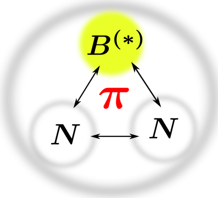
Comment:

- ρ, ω exchanges play **a minor role** due to the cancellation of them.

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

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



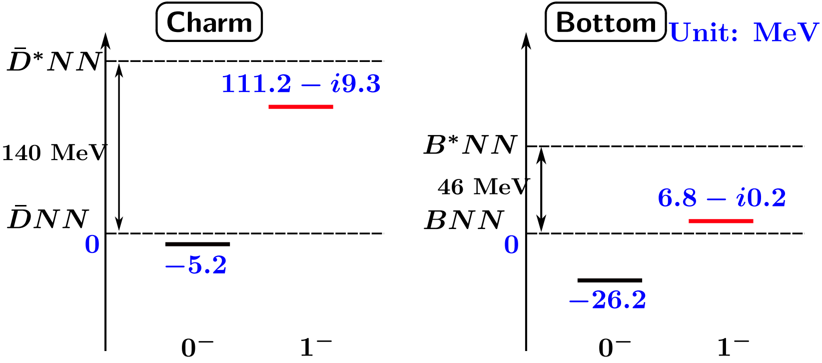


with $J^P = 0^-, 1^-$ and $I = 1/2$

Bound state and Resonance

- $P^{(*)}N$ interaction: OPEP
- NN interaction: AV8$'$ potential (B. S. Pudliner,*et.al.*, PRC**56**(1997)1720)

- **Bound states** for $J^P = 0^-$ and **Resonances** for $J^P = 1^-$ are found! YY, S. Yasui, and A. Hosaka, NPA **927** (2014) 110



- 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, NPA **927** (2014) 110

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

- Tensor force of $\mathbf{V_{\bar{D}N\text{–}\bar{D}^*N}}$ generates **the strongest attraction**.
  $\Rightarrow$ It dominates in the bound state.

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- For V_{NN}, **Central force** is stronger than **Tensor force**.
  In the bound states, $NN(0^+)$ subsystem dominates,
  while $NN(1^+)$ (=Deuteron) is minor.

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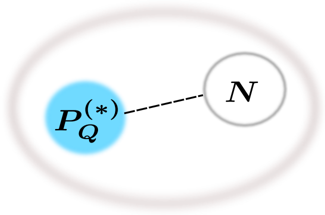
$J^P = 0^-$、$\bar{D}(0^-) \Rightarrow NN(0^+)$ is major.

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

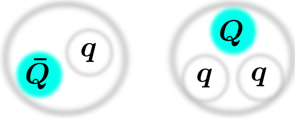


$P_Q^{(*)}N$ ($m_{P_Q^*} - m_{P_Q} = 0$)

Heavy quark mass limit

Heavy Quark Spin Symmetry (Again)

- In the ordinary heavy hadrons, the mass degeneracy is found.



$$\begin{cases} J = j - 1/2 \\ J' = j + 1/2 \end{cases}$$
$$(j \neq 0,\ s_Q = 1/2)$$

(j: Total angular momentum of Everything other than the heavy quark (Brown muck) $\Leftrightarrow \vec{J} = \vec{j} + \vec{s}_Q = \vec{L} + \vec{S}$)
e.g. $D(0^-) \sim D^*(1^-)$, $\Sigma_c(1/2^+) \sim \Sigma_c(3/2^+)$

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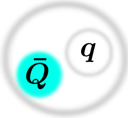

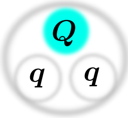

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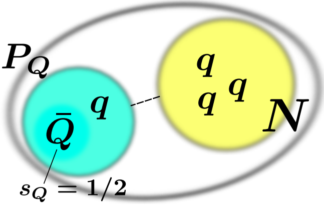
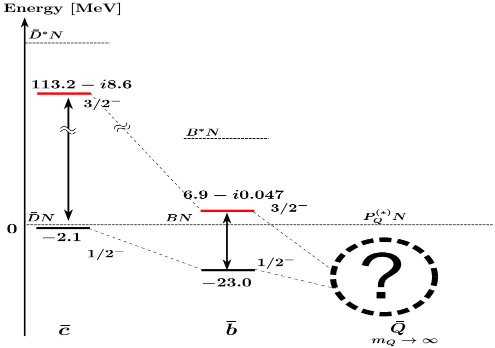
- Hadronic molecule (Multi-hadron system)



  - Is a mass degeneracy realized?

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



PN molecule in $m_Q \to \infty$

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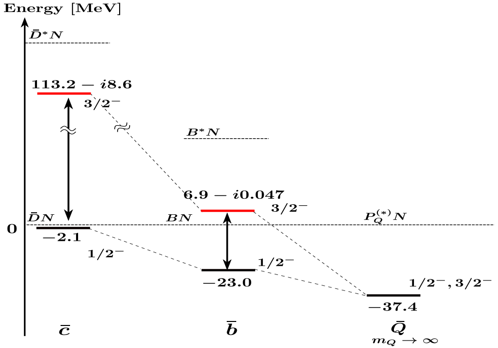

- **Degenerate states** are found! ($1/2^-$ and $3/2^-$)

YY, S. Ohkoda, A. Hosaka, T. Hyodo, S. Yasui, arXiv:1402.5222 [hep-ph]

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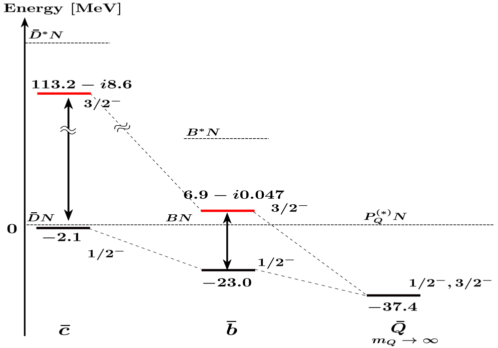
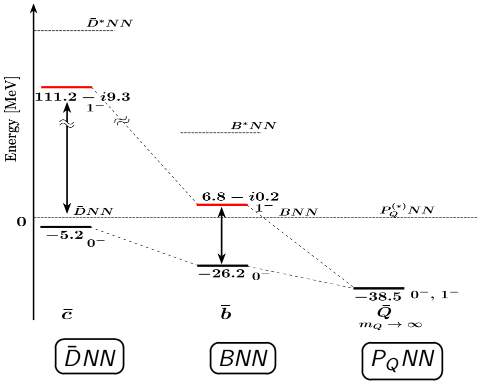


- **Degenerate states** are found! ($1/2^-$ and $3/2^-$)
  $\Rightarrow$ They belong to the **HQS doublet**.

YY, S. Ohkoda, A. Hosaka, T. Hyodo, S. Yasui, arXiv:1402.5222 [hep-ph]

Degenerate states in $P^{(*)}NN$ states ($m_Q \to \infty$)

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



- PNN states with $J^P = 0^-$ and 1^- are **degenerate**!

Summary

- We have investigated exotic baryons formed by $P^{(*)}N$ and $P^{(*)}NN$ with respecting the Heavy Quark Symmetry.
- For $\bar{D}^{(*)}N$ and $B^{(*)}N$, many bound states and resonances are found in $I = 0$.
- 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 in hadronic molecular states.

Thank you for your kind attention.

Back up

Lagrangian($P^{(*)} - N$) ; π , ρ and ω exchanges

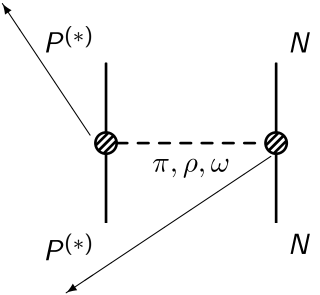
Heavy-light chiral lagrangian R.Casalbuoni *et al.* PhysRept.**281**(1997)145

- $\mathcal{L}_{\pi HH} = -\frac{g_\pi}{\sqrt{2}f_\pi}\mathrm{Tr}\left[H_b\gamma_\mu\gamma_5\vec{\tau}\cdot\partial^\mu\vec{\pi}_{ba}\bar{H}_a\right]$
- $\mathcal{L}_{vHH} = -i\beta\mathrm{Tr}\left[H_b v^\mu(\rho_\mu)_{ba}\bar{H}_a\right] + i\lambda\mathrm{Tr}\left[H_b\sigma^{\mu\nu}F_{\mu\nu}(\rho)_{ba}\bar{H}_a\right]$

Heavy meson field

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

vector pseudoscalar



Bonn model R. Machleidt, PRC**63**(2001)024001

- $\mathcal{L}_{\pi NN} = ig_{\pi NN}\bar{N}_b\gamma^5 N_a\vec{\tau}\cdot\vec{\pi}_{ba}$
- $\mathcal{L}_{vNN} = g_{vNN}\bar{N}_b\left(\gamma^\mu(\hat{\boldsymbol{\rho}}_\mu)_{ba} + \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu(\hat{\boldsymbol{\rho}}^\mu)_{ba}\right)N_a$

Lagrangian($P^{(*)} - N$) ; π , ρ and ω exchanges

Heavy-light chiral lagrangian

R.Casalbuoni *et al.* PhysRept.**281**(1997)145

- $\mathcal{L}_{\pi HH} = -\frac{\mathbf{g_\pi}}{\sqrt{2}f_\pi}\mathrm{Tr}\left[H_b\gamma_\mu\gamma_5\vec{\tau}\cdot\partial^\mu\vec{\pi}_{ba}\bar{H}_a\right]$

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

- $\mathcal{L}_{vHH} = -i\boldsymbol{\beta}\mathrm{Tr}\left[H_b v^\mu(\rho_\mu)_{ba}\bar{H}_a\right] + i\boldsymbol{\lambda}\mathrm{Tr}\left[H_b\sigma^{\mu\nu}F_{\mu\nu}(\rho)_{ba}\bar{H}_a\right]$

  From radiative and semileptonic decays of heavy meson

  Isola *et al.* PRD**68**,114001(2003)

Heavy meson field

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

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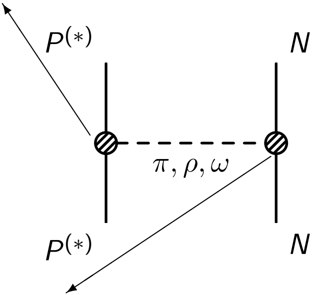


Bonn model

R. Machleidt, PRC**63**(2001)024001

From NN data

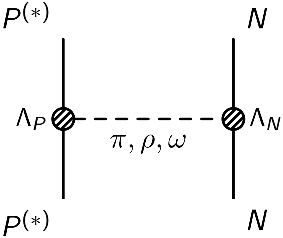
- $\mathcal{L}_{\pi NN} = i\mathbf{g_{\pi NN}}\bar{N}_b\gamma^5 N_a\vec{\tau}\cdot\vec{\pi}_{ba}$
- $\mathcal{L}_{vNN} = \mathbf{g_{vNN}}\bar{N}_b\left(\gamma^\mu(\hat{\boldsymbol{\rho}}_\mu)_{ba} + \frac{\boldsymbol{\kappa}}{2m_N}\sigma_{\mu\nu}\partial^\nu(\hat{\boldsymbol{\rho}}^\mu)_{ba}\right)N_a$

These coupling constants are fixed!

Form factor and Cut-off parameter Λ

- Form factor F with cutoff $\Lambda = \Lambda_N, \Lambda_P$

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



Form factor and Cut-off parameter Λ

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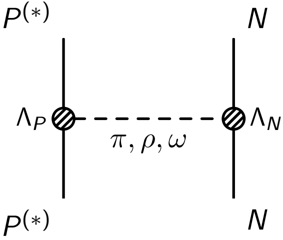
1. Λ_N is fixed to reproduce the properties of Deuteron. (NN system with Bonn potential)
   $\Rightarrow \Lambda_N = 830\ (\pi),\ 846\ (\pi\rho\omega)$ MeV



2. Λ_P is determined by the ratios of radii of P and N. We assume $\Lambda_P/\Lambda_N = r_N/r_P$.

$$\begin{cases} \Lambda_D = 1.35\Lambda_N \\ \Lambda_B = 1.29\Lambda_N \end{cases}$$

S.Yasui and K.Sudoh PRD**80**,034008

$$\Rightarrow \Lambda_D = 1121\,\text{MeV}(\pi),\ 1142\,\text{MeV}(\pi\rho\omega)$$

$$\Lambda_B = 1070\,\text{MeV}(\pi),\ 1091\,\text{MeV}(\pi\rho\omega)$$

Cut-off parameters are also fixed!

Central force and Tensor force

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

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

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

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

- Spin operators

$$\vec{\varepsilon}^{\,\pm} = (\mp 1/\sqrt{2}, \pm i\sqrt{2}, 0), \quad \vec{\varepsilon}^{\,(0)} = (0, 0, 1)$$

$$T^i = i\varepsilon^{ijk} \varepsilon_j^\dagger \varepsilon_k$$

- Coupling constants

$$g_\pi = 0.59 \text{ for } \bar{D} \text{ and } B, \; g_{\pi NN}^2/4\pi = 13.6$$

$$(g_{D^* D\pi} = 2\sqrt{m_D m_{D^*}} g_\pi / f_\pi = 17.9)$$

- Expectation values of meson exchange potentials
- $\bar{D}^{(*)}N(1/2^-)$: $\bar{D}N(^2S_{1/2})$, $\bar{D}^*N(^2S_{1/2}, ^4D_{1/2})$

The bound state of $\bar{D}N(1/2^-)$

Components	V_π	V_ρ	V_ω
$\langle \bar{D}N(S)\|V\|\bar{D}N(S)\rangle$	0.0	−2.7	3.6
$\langle \bar{D}N(S)\|V\|\bar{D}^*N(S)\rangle$	−2.4	−5.2	1.0
$\langle \bar{D}N(S)\|V\|\bar{D}^*N(D)\rangle$	−35.2	3.4	−0.6
$\langle \bar{D}^*N(S)\|V\|\bar{D}^*N(S)\rangle$	0.4	0.7	0.1
$\langle \bar{D}^*N(S)\|V\|\bar{D}^*N(D)\rangle$	−5.0	0.6	−0.1
$\langle \bar{D}^*N(D)\|V\|\bar{D}^*N(D)\rangle$	3.7	−0.9	0.4
Total	−38.6	−4.4	4.4

- The tensor force of π exchange potential generates **a strong attraction**. Especially, $\bar{D}N - \bar{D}^*N$ mixing is important.
- ρ, ω exchanges play **a minor role** due to the cancellation of them.