Exotic baryons from a heavy meson and a nucleon

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in collaboration with

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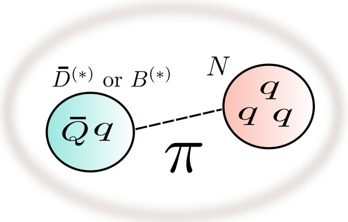
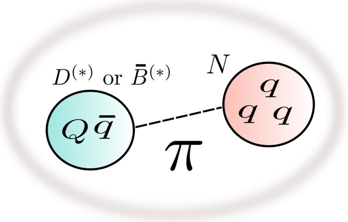


$\bar{D}N(BN)$ molecule.



$DN(\bar{B}N)$ molecule.

Exotic hadron

- They have an **exotic quantum number** which cannot be reached by quark model.
- **Multiquark component** is essential.

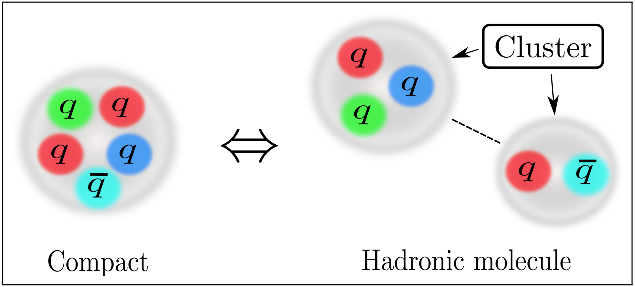
Pentaquark Θ^+ D.Diakonov *et al.*Z.Phys.A**359**,305, T.Nakano*et al.*Phys.Lett.**91**,012002

- Observation of Θ^+ triggered the study of exotic hadrons.
- Because Θ^+ has $\boldsymbol{S=+1}$,
  it cannot be described by simple baryon. $\Rightarrow$ $\boldsymbol{uudd\bar{s}}$?

$Z_b(10608), Z_b(10653)$ I.Adachi *et al.*,arXiv:1105.4583, Phys.Rev.Lett.**108**,122001

- They have **electric charge**. $\Rightarrow$ Not simple $b\bar{b}$.
- $\boldsymbol{b\bar{b}q\bar{q}}$**?**, $\boldsymbol{B-\bar{B}^*\ (B^*-\bar{B}^*)}$ **molecular state?**

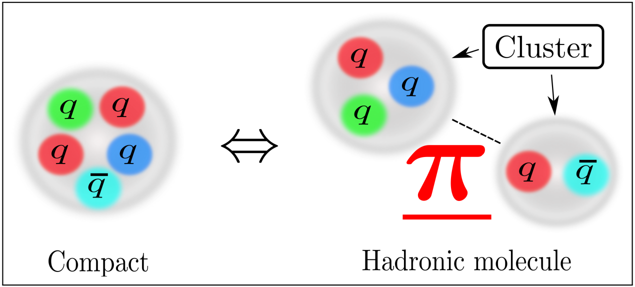
Multiquark system($qqqq\bar{q}$, $qq\bar{q}\bar{q}$,...) may form various structures.



- Multiquark system may compose partial **cluster** structures ($qqq + q\bar{q}$) and they form **hadronic molecule**.

Question: **Molecular state really exists?**

To investigate **meson-baryon** (present talk) and **meson-meson** (**Ohkoda's talk**) systems, we find molecules.



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Question: **Molecular state really exists?**

To investigate **meson-baryon** (present talk) and **meson-meson** (**Ohkoda's talk**) systems, we find molecules.

We focus on π **exchange interaction** to make a hadronic molecule.

Heavy meson and Heavy Quark Symmetry
Introduction

We consider heavy meson(D, B) and Nucleon molecular state because D, B can be coupled with π due to Heavy Quark Symmetry.

- **Heavy Quark Symmetry (HQS)** N.Isgur, M.B.Wise,PRL**66**,1130

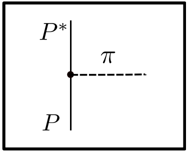
  This symmetry appears in the heavy quark mass limit ($m_Q \to \infty$).

  Spin-spin interaction $\longrightarrow 0$

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

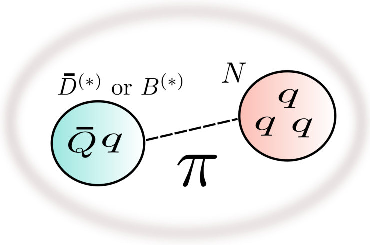
  Indeed, mass splitting between P and P^* is very small.

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



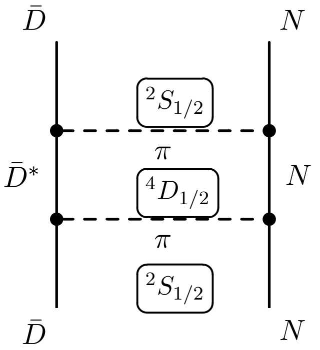
$\longrightarrow$ This degenerate provides ***$PP^*\pi$* vertex**.

Tensor force



Hadronic molecule?

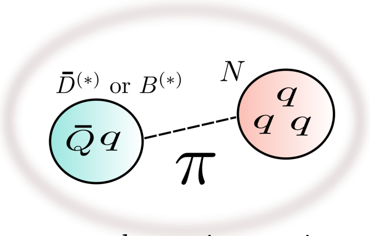
$\Rightarrow$



- π exchange(**Tensor force**) mixes $\bar{D}N$ and $\bar{D}^*N$ and generates a **strong attractive force**.
- This mechanism is similar to Deuteron system($^3S_1 -^3 D_1$).
  Binding energy~2.2 MeV, Relative radii~4 fm
- Tensor force makes $\bar{D}N$ loosely bound states?

Purpose

- Searching for **exotic baryons** formed by Heavy meson-Nucleon molecule with **OPEP**



- We employ π, ρ, ω exchange interactions.
  $\rightarrow$ comparing the result when π exchange is used with the result when $\pi\rho\omega$ exchange is used.
- We study **bound** and **scattering** states.
- To obtain **binding energies** and **properties of resonance**, we solve the coupled-channel Schrödinger equations for PN and P^*N systems.

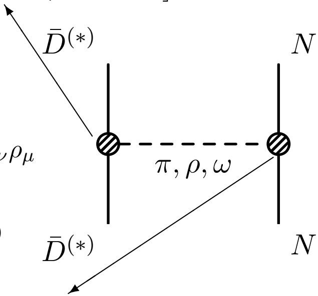
Heavy quark effective theory R.Casalbuoni *et al.* PhysRept.**281**,145(1997)

- $\mathcal{L}_{\pi HH} = ig_\pi \mathrm{Tr}\left[H_b \gamma_\mu \gamma_5 \mathcal{A}^\mu_{ba} \bar{H}_a\right]$
- $\mathcal{L}_{vHH} = -i\beta \mathrm{Tr}\left[H_b v^\mu (\rho_\mu)_{ba} \bar{H}_a\right] + i\lambda \mathrm{Tr}\left[H_b \sigma^{\mu\nu} F_{\mu\nu}(\rho)_{ba} \bar{H}_a\right]$

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

vector pseudoscalar

$$\mathcal{A}^\nu = \frac{i}{f_\pi}\partial^\nu \hat{\boldsymbol{\pi}},\ \rho_\mu = \frac{i g_v}{\sqrt{2}}\hat{\boldsymbol{\rho}}_\mu,\ F_{\mu\nu}(\rho) = \partial_\mu \rho_\nu - \partial_\nu \rho_\mu$$



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

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

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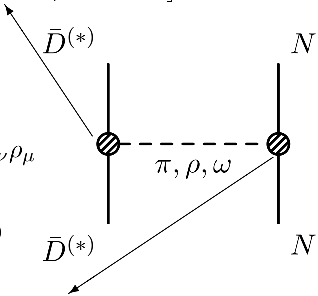

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These coupling constants are not free parameter!

($D^* \to D\pi$, leptonic decay of B, NN data...)

Form factor and Cut-off parameter Λ
$\bar{D}N$ and BN states

- Form factor at each vertex
$$F_\alpha(\Lambda, \vec{q}) = \frac{\Lambda^2 - m_\alpha^2}{\Lambda^2 + |\vec{q}|^2}$$
- Λ_N is determined to reproduce the properties of deuteron.
- For Λ_P, we assume $\Lambda_P/\Lambda_N = r_N/r_P$. r_N/r_P is obtained from quark model.

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

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

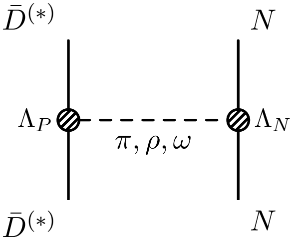


Table: Cutoff parameters.

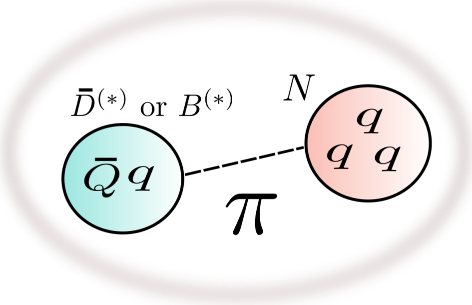
Potential	Λ_N [MeV]	Λ_D [MeV]	Λ_B [MeV]
π	830	1121	1070
π, ρ, ω	846	1142	1091

We investigate $J^P = 1/2^{\pm}, \cdots, 7/2^{\pm}$ states with $I = 0, 1$.

J^P	channels
$1/2^-$	$\bar{D}N(^2S_{1/2})$ $\bar{D}^*N(^2S_{1/2}, {}^4D_{1/2})$
$1/2^+$	$\bar{D}N(^2P_{1/2})$ $\bar{D}^*N(^2P_{1/2}, {}^4P_{1/2})$
$3/2^-$	$\bar{D}N(^2D_{3/2})$ $\bar{D}^*N(^4S_{3/2}, {}^4D_{3/2}, {}^2D_{3/2})$
$3/2^+$	$\bar{D}N(^2P_{3/2})$ $\bar{D}^*N(^2P_{3/2}, {}^4P_{3/2}, {}^4F_{3/2})$
$5/2^-$	$\bar{D}N(^2D_{5/2})$ $\bar{D}^*N\ (^2D_{5/2}, {}^4D_{5/2}, {}^4G_{5/2})$
$5/2^+$	$\bar{D}N(^2F_{5/2})$ $\bar{D}^*N\ (^4P_{5/2}, {}^2F_{5/2}, {}^4F_{5/2})$
$7/2^-$	$\bar{D}N(^2G_{7/2})$ $\bar{D}^*N\ (^4D_{7/2}, {}^2G_{7/2}, {}^4G_{7/2})$
$7/2^+$	$\bar{D}N(^2F_{7/2})$ $\bar{D}^*N\ (^2F_{7/2}, {}^4F_{7/2}, {}^4H_{7/2})$

- Tensor force, mixing these channels with $\Delta l = 2$, leads to **coupled-channel equations**.

Results of $\bar{D}N$ and BN states



Truly exotic state

Bound state and Resonance

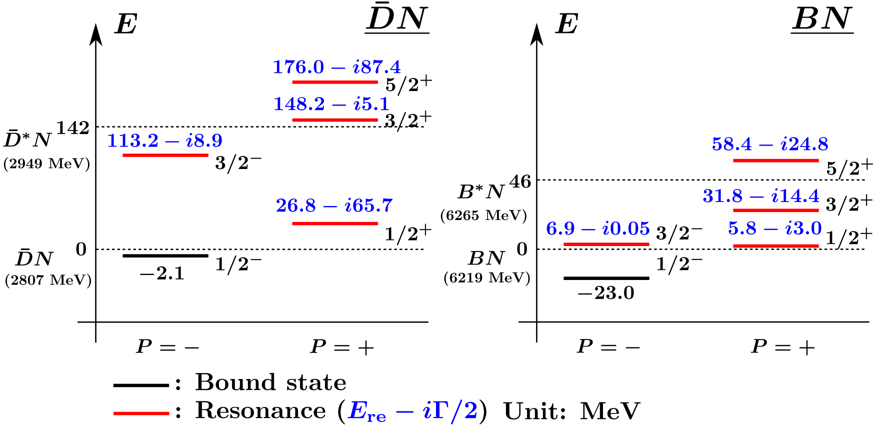
We found **loosely bound states** with $I(J^P) = 0(1/2^-)$.

Table: Binding energies and relative distance in $I(J^P) = 0(1/2^-)$ state.

	$\bar{D}N(\pi)$	$\bar{D}N(\pi\rho\omega)$	$BN(\pi)$	$BN(\pi\rho\omega)$
E_B [MeV]	1.60	2.13	19.50	23.04
$\langle r^2 \rangle^{1/2}$ [fm]	3.5	3.2	1.3	1.2

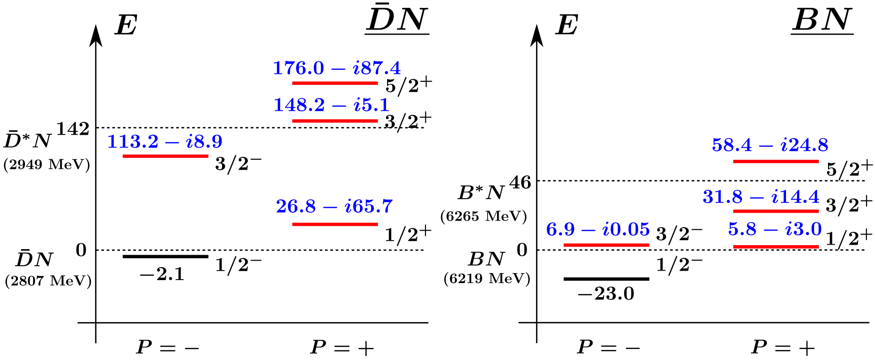
- The results of $\pi\rho\omega$ interaction are close to that of π exchange interaction.
  $\rightarrow$ The π exchange plays an important role and **dominates** this system.
- $E_B(BN) > E_B(\bar{D}N)$ because BB^* strong mixing (small ΔM_{BB^*}) yields **a strong attraction** (Tensor force).

- We found many resonances.
- If $PN - P^*N$ mixing is ignored, bound states and resonances vanish.



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

PN-P^*N mixing plays an important role!

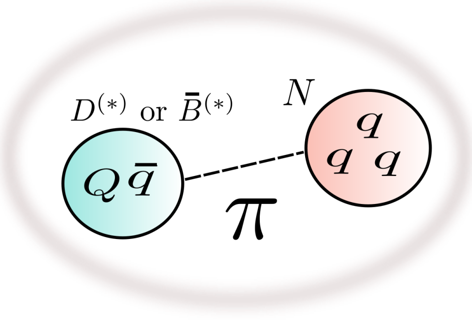


—— : Bound state

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

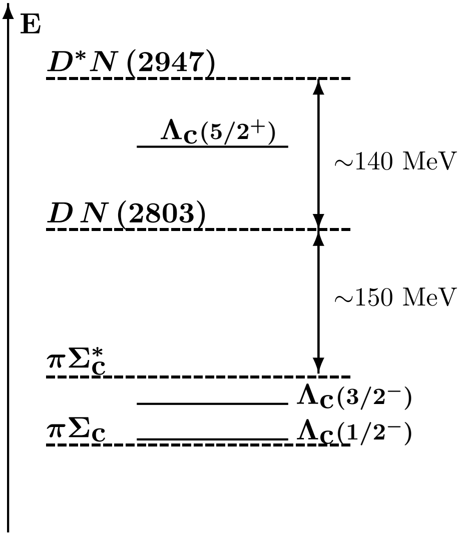
Y.Y, S.Ohkoda, S.Yasui and A.Hosaka, PRD**84** 014032 (2011) and PRD**85** 054003 (2012)

DN and $\bar{B}N$ states



$$\bar{D} \to D$$

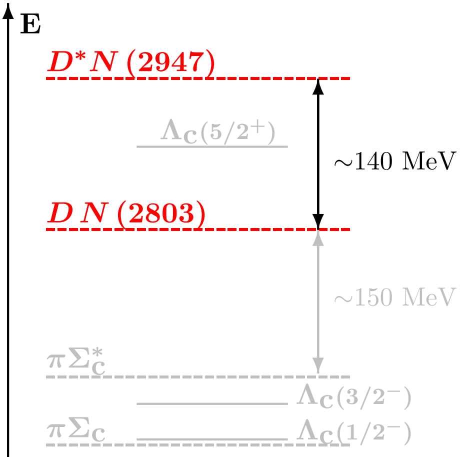
DN state + $\Lambda_c, \pi\Sigma_c$



DN is more complex than $\bar{D}N$.

$$\begin{pmatrix} \Lambda_c & \cdots & \cdots \\ \cdots & \pi\Sigma_c,\ \pi\Sigma_c^* & \cdots \\ \cdots & \cdots\ \cdots & DN,\ D^*N \end{pmatrix}$$

We have to consider
not only $D^{(*)}N$
but also Λ_c, $\pi\Sigma_c^{(*)}$,
$\Lambda_c - DN$, $\pi\Sigma_c - DN$...



DN is more complex than $\bar{D}N$.

Λ_c	$\cdots$	$\cdots$
$\cdots$	$\pi\Sigma_c, \pi\Sigma_c^*$	$\cdots$
$\cdots$		DN, D^*N

We have to consider
not only $D^{(*)}N$
but also Λ_c, $\pi\Sigma_c^{(*)}$,
$\Lambda_c - DN$, $\pi\Sigma_c - DN$...
$\Rightarrow$ Future work

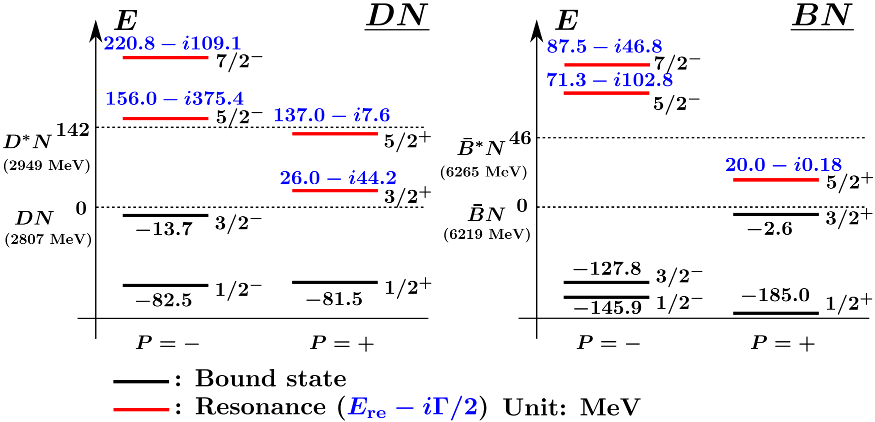
We consider only $DN - D^*N$.

$D^{(*)}N$ molecular state due to π exchange

Results of DN and $\bar{B}N$ in $I = 0$

DN and $\bar{B}N$ states

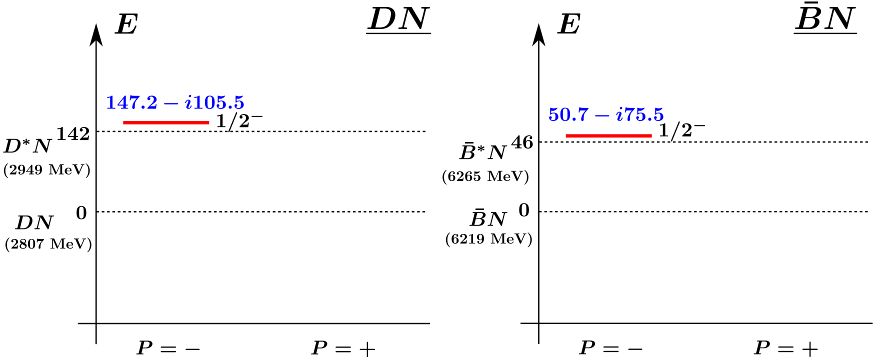
- DN state is calculated in analogy with $\bar{D}N$.
- But $V_\pi \to -V_\pi$, $V_\omega \to -V_\omega$ due to G-parity.



We found many bound states and resonances!

But deeply bound state may be coupled with Λ_c, $\pi\Sigma_c$ strongly.

- We found a resonance only in $J^P = 1/2^-$.
- Attraction is not strong because Isospin factor is small.
- $\vec{\tau}_D \cdot \vec{\tau}_N = 1$. For $I=0$, $\vec{\tau}_D \cdot \vec{\tau}_N = -3$



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

Summary

- We investigate exotic baryons from a heavy meson and a nucleon with respecting the Heavy Quark Symmetry.
- We Solve coupled-channel Schrödinger equations and bound states and Resonances are found.
- π exchange dominates this system while vector meson exchange plays a minor role.
- For $\bar{D}N$ state, loosely bound states and resonances are found.
- For DN state, deeply bound states are found. They are coupled with Λ_{C}, $\pi\Sigma_{\mathrm{C}}$... $\Rightarrow$ Future work
- Tensor force plays a crucial role to produce these molecular states.