重い中間子と核子による
エキゾチックハドロンの解析

山口　康宏[1]

共同研究者

大古田俊介 [1], 安井繁宏 [2], 菊地右馬 [1], 保坂淳 [1]

RCNP[1], KEK[2]

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   - Heavy Quark Symmetry
2. Interactions
3. $\bar{D}N$ and BN molecules
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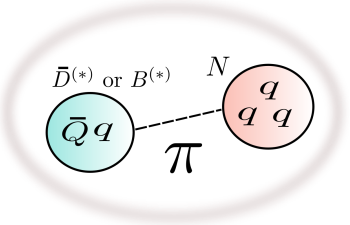
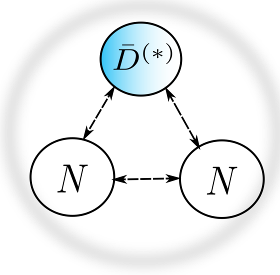
4. DN and $\bar{B}N$ molecules
   — Non-Exotic state ($Q\bar{q}qqq$)
5. $\bar{D}NN$ and BNN
   — Three body system
6. Summary

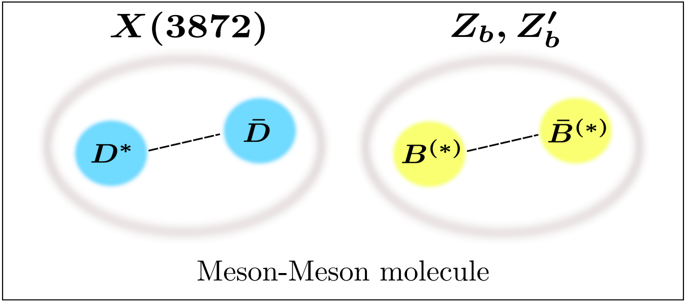


$\bar{D}N(BN)$ molecule.



$\bar{D}NN$, BNN

- ハドロン分子状態: エキゾチックハドロンの構造を説明する新たな形態
- 閾値近傍で分子状態の候補が見つかっている
- *e.g.*



- ヘビークォーク領域では、**Heavy Quark Symmetry による One pion exchange potential** が重要な働きをする

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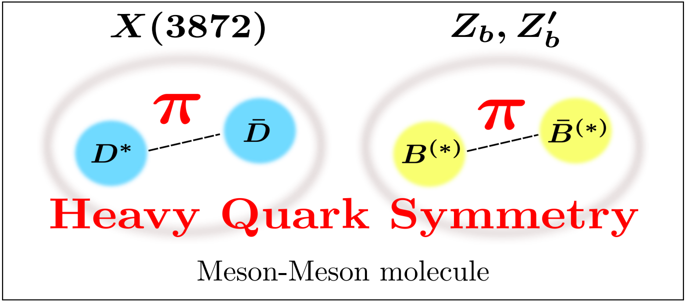

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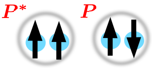
Heavy meson and Heavy Quark Symmetry
Introduction

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

- This symmetry appears in the heavy quark mass limit $(m_Q \to \infty)$.
- Spin-spin interaction $\longrightarrow 0$



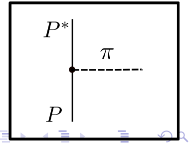
$\begin{cases} \text{Heavy pseudoscalar meson } \boldsymbol{P(0^-)} \text{ and} \\ \text{Heavy vector meson } \boldsymbol{P^*(1^-)} \text{ are } \textbf{degenerate}. \end{cases}$

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

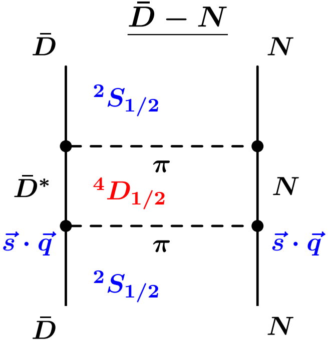
$$\begin{cases} m_{B^*} - m_B \sim 45\,\text{MeV} \\ m_{D^*} - m_D \sim 140\,\text{MeV} \\ m_{K^*} - m_K \sim 400\,\text{MeV} \end{cases}$$

This degeneracy induces **$PP^*\pi$ vertex**.

$\begin{cases} PP\pi \text{ is forbidden due to parity violation.} \\ KK^*\pi \text{ is suppressed by large } \Delta m_{KK^*}. \end{cases}$



- π exchange(**Tensor force**) generates a **strong attraction**.
- Tensor force appears through **the mixing $\bar{D}N$ and $\bar{D}^*N$**.



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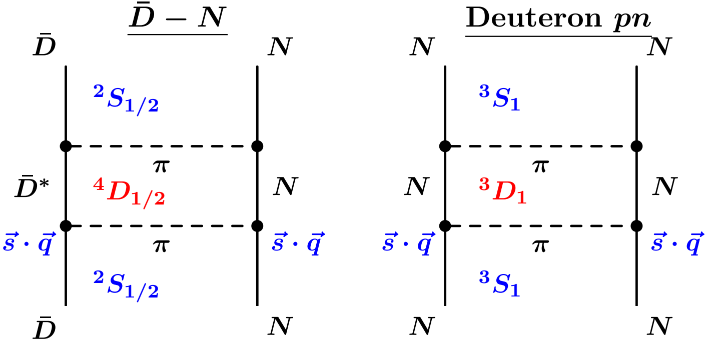
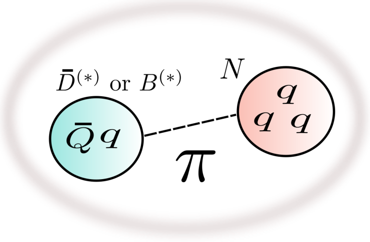


- Deuteron: $^3D_1$ induces large kinetic term.
  $\rightarrow$ **Loosely bound state** with small E_B and large $\sqrt{\langle r^2 \rangle}$.
- Tensor force constructs **$\bar{D}N$ hadronic molecule**?

Purpose

- Searching for exotic hadrons formed by **Heavy meson-Nucleon molecule with π exchange**.

Meson-Baryon



- We employ π, ρ, ω exchange potentials.
- We study **bound and resonant states** by solving the coupled-channel Schrödinger equations for PN and P^*N channels.

Interactions

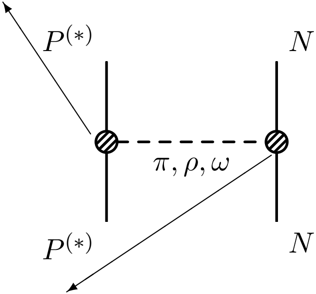
Heavy quark effective theory R.Casalbuoni *et al.* PhysRept.**281**,145(1997)

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

Heavy meson field

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

vector pseudoscalar



Bonn model R.Machleidt *et al.* Phys Rept.**149**,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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  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 leptonic and radiative decay of B
  Isola *et al.* PRD**68**,114001(2003)

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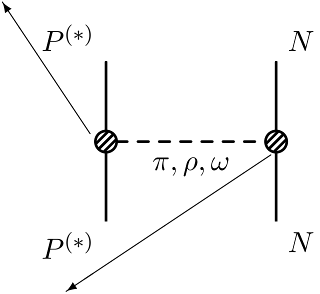

Bonn model

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From NN data

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

These coupling constants are fixed!

Form factor and Cut-off parameter Λ

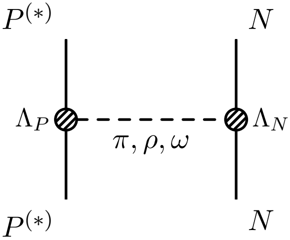
- Form factor at each vertex

$$F_\alpha(\Lambda, \vec{q}) = \frac{\Lambda^2 - m_\alpha^2}{\Lambda^2 + |\vec{q}|^2}$$

1. Λ_N is fixed to reproduce the properties of Deuteron. (NN system with Bonn potential)
2. 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



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

Coupling constants and Cut-off are not free parameters!

Various coupled channels for a given J^P

We investigate $J^P = 1/2^{\pm}, \cdots, 7/2^{\pm}$ states with $I = 0, 1$ in full channel couplings of PN and P^*N.

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

- **Higher L state** plays a crucial role to produce attraction through **the tensor force**.

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$7/2^-$	$PN(^2G_{7/2})$ P^*N $(^4D_{7/2}, {}^2G_{7/2}, \mathbf{^4G_{7/2}})$	4
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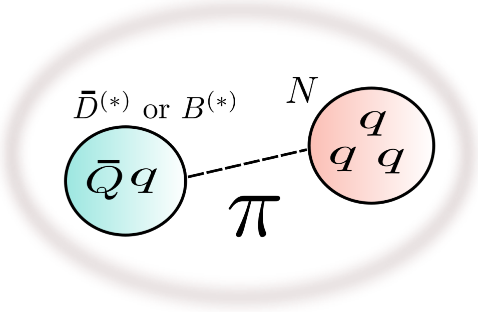
Results of $\bar{D}N$ and BN states



Truly exotic state

Bound state and Resonance

- We find bound states in $I(J^P) = 0(1/2^-)$.
- We compare results of two potentials:
  (1) Only π exchange potential
  (2) $\pi\rho\omega$ exchange potential

Table: Binding energies E_B and relative distance $\sqrt{\langle r^2 \rangle}$.

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

(π): Only π exchange is used. $(\pi\rho\omega)$: $\pi\rho\omega$ exchanges are used.

- Small E_B (near the threshold) and large $\sqrt{\langle r^2 \rangle}$
  $\Rightarrow$ **Loosely bound states**
- The result of (π) is close to that of $(\pi\rho\omega)$.
  $\Rightarrow$ π exchange dominates?

- Expectation values of meson exchange potentials

$\bar{D}N$ expectation values (Unit: MeV)

Component	V_π	V_ρ	V_ω
$\langle \bar{D}N(S)\| V \|\bar{D}N(S)\rangle$	0	−2.72	3.56
$\langle \bar{D}N(S)\| V \|\bar{D}^*N(S)\rangle$	−1.24	−2.59	0.49
$\langle \bar{D}N(S)\| V \|\bar{D}^*N(D)\rangle$	**−17.60**	1.66	−0.31
$\langle \bar{D}^*N(S)\| V \|\bar{D}^*N(S)\rangle$	0.37	0.65	0.13
$\langle \bar{D}^*N(S)\| V \|\bar{D}^*N(D)\rangle$	−2.50	0.26	-4.85×10^{-2}
$\langle \bar{D}^*N(D)\| V \|\bar{D}^*N(D)\rangle$	3.69	−0.94	0.39
total	**−38.63**	−4.36	4.35

$\Leftarrow$ $\bar{D}N(S) - \bar{D}^*N(D)$ component with Tensor

Strong attraction!

- **Tensor force of π exchange plays a dominant role** while ρ, ω exchanges are minor.

- Expectation values of meson exchange potentials

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BN expectation values (Unit: MeV)

Component	V_π	V_ρ	V_ω
$\langle BN(S)\| V \|BN(S)\rangle$	0	−5.38	7.02
$\langle BN(S)\| V \|B^*N(S)\rangle$	−4.09	−8.21	1.56
$\langle BN(S)\| V \|B^*N(D)\rangle$	**−45.12**	4.15	−0.77
$\langle B^*N(S)\| V \|B^*N(S)\rangle$	2.03	3.19	0.62
$\langle B^*N(S)\| V \|B^*N(D)\rangle$	−11.17	1.06	-0.20×10^{-2}
$\langle B^*N(D)\| V \|B^*N(D)\rangle$	13.24	−3.24	1.36
total	**−105.49**	−11.42	10.17

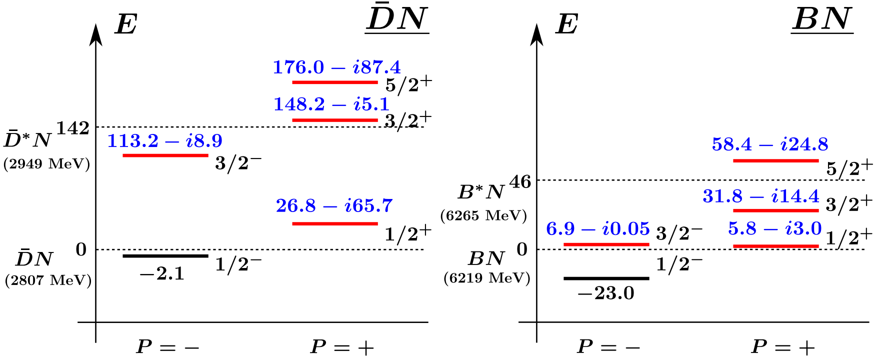
- **Tensor force of π exchange plays a dominant role** while ρ, ω exchanges are minor.
- Small Δm_{BB^*} induces strong BB^* mixing and tensor force. Therefore, **BN state is more bound** than $\bar{D}N$.

- Bound states and Resonances

Results of $\bar{D}N$ and BN in $I = 0$

$\bar{D}N$ and BN states

- Bound states and Resonances



—— : 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)

- Without $\bar{D}^*N(B^*N)$ channels. **(π exchange is absent.)**

  $\Rightarrow$ **No bound state and resonance.**

  The π exchange potential is important!

- Result of $\bar{D}N$ and BN in $I = 1$.

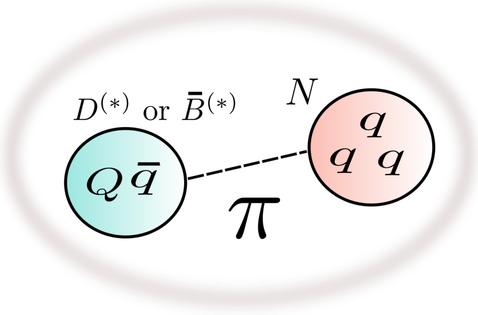
  $\Rightarrow$ **No bound state and resonance.**

  This state doesn't obtain **a sufficient attraction.**

$$\vec{\tau}_P \cdot \vec{\tau}_N = \begin{cases} -3 & (I=0) \quad \text{Strong attraction} \\ 1 & (I=1) \quad \textbf{Weak attraction} \end{cases}$$

The contribution from Tensor force is small.

DN and $\bar{B}N$ states



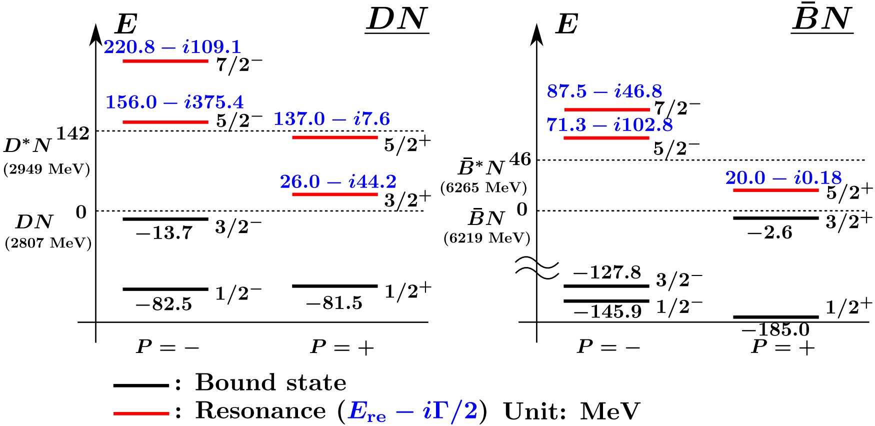
$$\bar{D} \rightarrow D$$

Heavy baryon と結合する

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

DN and $\bar{B}N$ states

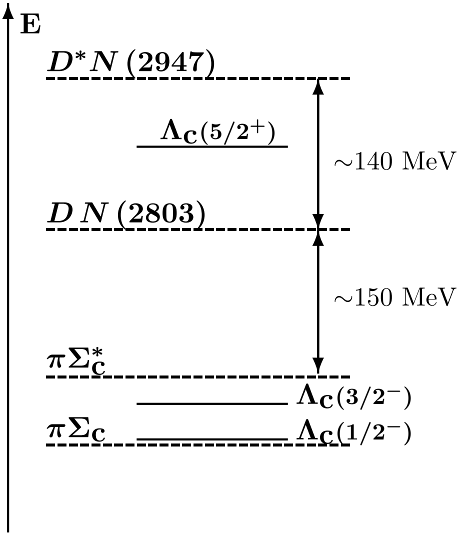
- DN state is calculated in analogy with $\bar{D}N$.
- But $V_\pi \to -V_\pi$, $V_\omega \to -V_\omega$ due to G-parity.



We found many bound states and resonances in $I = 0$.

Compared to $\bar{D}N$ states, DN states are more bound.

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



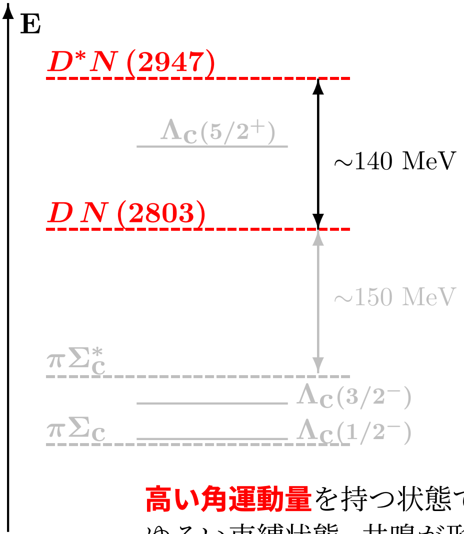
DN is more complex than $\bar{D}N$.

$$\left(\begin{array}{c|c|c} \Lambda_c & \cdots & \cdots \\ \hline \cdots & \pi\Sigma_c,\, \pi\Sigma_c^* & \cdots \\ \hline \cdots & \cdots & DN,\, D^*N \end{array}\right)$$

$q\bar{q}$ 消滅を通して
Qqq や $\pi\Sigma_c$ とも結合する

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

DN and $\bar{B}N$ states



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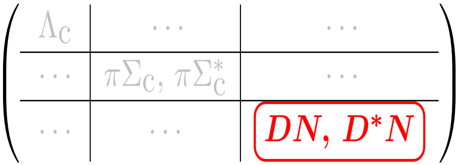


$q\bar{q}$ 消滅を通して
Qqq や $\pi\Sigma_c$ とも結合する

高い角運動量を持つ状態では、**π 交換力**が重要になり、
ゆるい束縛状態 · 共鳴が形成される。
$\rightarrow DN - D^*N$ が支配的になる。

ここまでのまとめ

- ヘビークォーク領域では、**Heavy Quark Symmetry** による π **交換力**が働く。
- $I = 0$ 状態に多くの束縛共鳴を見つけた。

$$J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}, 7/2^{\pm}$$

	Exotic $\bar{D}N, BN$	Non-exotic $DN, \bar{B}N$
$I = 0$	Some states	Many states
$I = 1$	None	Only one

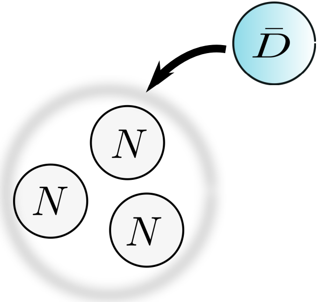
- ヘビーメソン-バリオン分子状態の生成に、**テンソル力**が重要な働きをする。
- Non-exotic: 低い角運動量を持つ状態では、$DN - D^*N$ 以外の効果を取り入れる必要がある。

$\bar{D}N$ molecule (2-body system)

- Tensor force plays an important role.

$$\Downarrow$$

$\bar{D}NN$ (Few-body system)?

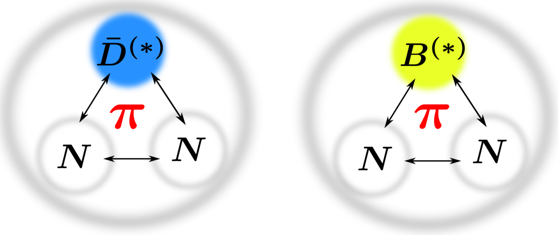


- $\bar{D}$ 中間子原子核
  - ヘビーメソンと核子間の相互作用の解明
  - ヘビーメソン内の構成クォークの性質
  - 原子核中でのヘビーメソンの性質の変化
  - ヘビーメソンを入れたことによる原子核の構造の変化
- π 交換力によって $\bar{D}NN$ **bound state** は形成されるか?

Heavy meson in nuclear matter: Bound state

$\bar{D}NN$ and BNN

- $\bar{D}^{(*)}NN$, $B^{(*)}NN$ (3-body system) $J^P = 0^-, 1^-, I = 1/2$



- $P^{(*)}N$ interaction: **One pion exchange potential**
- NN interaction: Minnesota potential

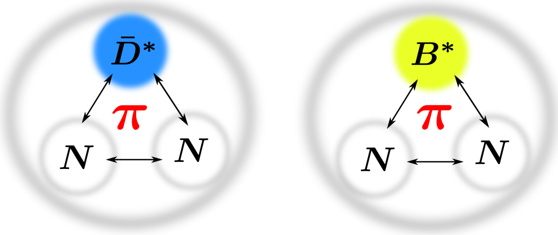
  D. R. Thompson,*et.al.*,Nucl.Phys.A**286**(1977)53.

2 体系 $(\bar{D}^{(*)}N)$ のときと同様に、$\bar{D}N - \bar{D}^*N$ **mixing** が重要な働きをすると期待するが...

Heavy meson in nuclear matter: Bound state

$\bar{D}NN$ and BNN

- $\bar{D}^*NN$, B^*NN (3-body system) $J^P = 0^-, 1^-, I = 1/2$



- $P^{(*)}N$ interaction: **One pion exchange potential**
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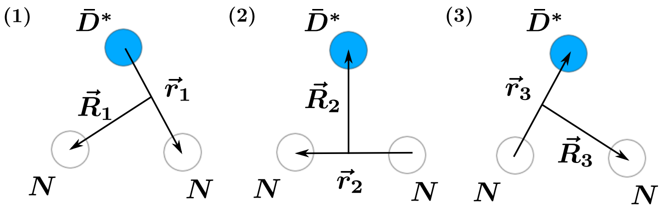
D. R. Thompson, *et. al.*, Nucl.Phys.A**286**(1977)53.

まずは $\bar{D}^*NN$、B^*NN について解析を行う。

Method

- Variational method を用いてシュレディンガー方程式を解き、束縛エネルギーを求める。
- Jacobi coordinates



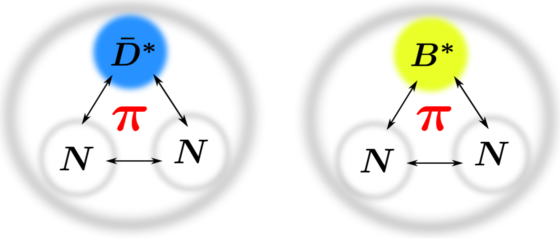
- Wave functions: Gaussian expansion method

$$\psi_{i,l}(r) = r^l \exp\left(-\frac{r^2}{2b_i^2}\right)$$

$$b_i = b_1 a^{i-1} \ (i = 1, \cdots, 10), \ b_1 = 0.3 \text{ fm}, b_{10} = 10.0 \text{ fm}$$

E. Hiyama, *et. al.*, Prog.Part.Nucl.Phys.**51**(2003)223

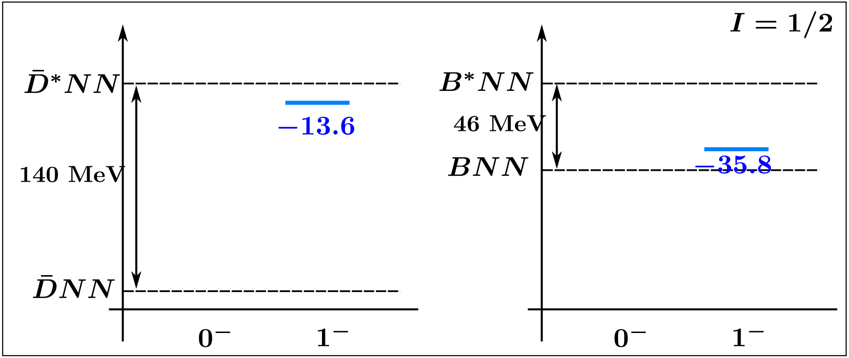
Results of $\bar{D}^*NN$ and B^*NN states



$$J^P = 0^-, 1^-、I = 1/2$$

Results of $\bar{D}^*NN, B^*NN$ bound states ($I = 1/2$)
$\bar{D}NN$ and BNN

- $J^P = 0^-$: No bound state
- $J^P = 1^-$: $\bar{D}^*NN$ (**−13.6 MeV**), B^*NN (**−35.8 MeV**)



- テンソル力を無視して計算すると、束縛状態は消失する。
- これらの状態が Feshbach 共鳴として $\bar{D}^{(*)}NN$, $B^{(*)}NN$ 状態に寄与する可能性がある。

Summary

- ヘビーメソンと核子による $P^{(*)}N$、P^*NN の束縛・共鳴状態について解析を行った。
- $P^{(*)}N$ では、$I = 0$ で多くの束縛状態・共鳴が得られた。
- P^*NN では、$(I, J^P) = (1/2, 1^-)$ で束縛状態が得られた。
- これらの状態の形成に π 交換ポテンシャルのテンソル力が重要な働きをしている。

- $PNN - P^*NN$ mixing を取り入れる。
- 3 体系での束縛状態・共鳴について解析を行う。

Back up

Interactions: Minnesota potential

$$V_{NN}(r) = \left(V_{0R}\, e^{-\kappa_R r^2} - \frac{1}{2}(1+P^\sigma)V_{0t}\, e^{-\kappa_t r^2} - \frac{1}{2}(1-P^\sigma)V_{0s}\, e^{-\kappa_s r^2}\right)$$
$$\times \left(\frac{1}{2}u + \frac{1}{2}(2-u)P^r\right),$$
$$V_{0R} = 200\,\mathrm{MeV}, \quad \kappa_R = 1.487\,\mathrm{fm}^{-2},$$
$$V_{0t} = 178\,\mathrm{MeV}, \quad \kappa_t = 0.639\,\mathrm{fm}^{-2},$$
$$V_{0s} = 91.85\,\mathrm{MeV}, \quad \kappa_R = 0.465\,\mathrm{fm}^{-2},$$
$$u = 0.95$$

D. R. Thompson,*et.al.*,Nucl.Phys.A**286**(1977)53.