Exotic dibaryons with a heavy antiquark

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in collaboration with

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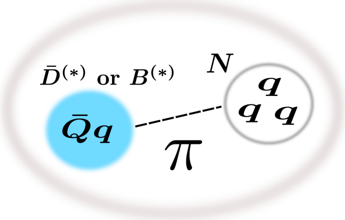
ミニ滞在型研究検討会
「チャームバリオンの構造と生成」

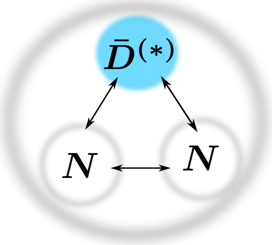
9/10-13 2013, KEK Tokai Campus

Outline

1. Introduction
   - π exchange potential between heavy meson and nucleon.
2. Results of $\bar{D}N$ and BN
   — Exotic states $(\bar{Q}q + qqq)$
3. Results of $\bar{D}NN$ and BNN
4. Summary



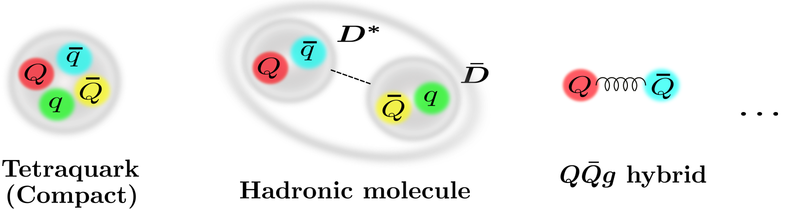
2-body system



3-body system

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

Structures of exotic hadrons. (Meson)



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

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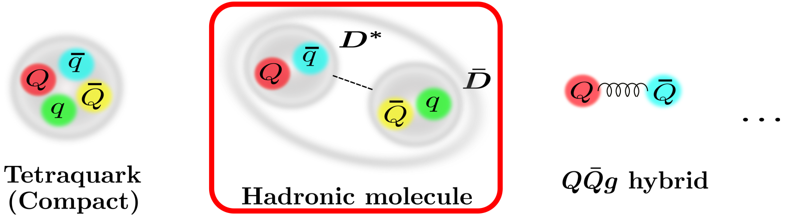
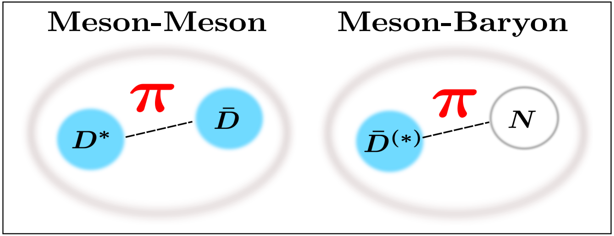


Q: Heavy quark (c, b)、 q: Light quark (u, d)

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

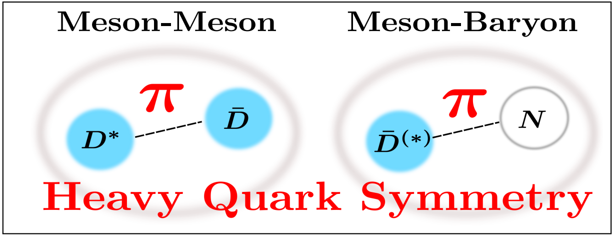
S.K.Choi *et al.*, PRL**91** (2003) 262001, A.Bondar, *et al.*, PRL**108**(2012)122001

- What is a driving force to form a molecules?: **π exchange potential**



- In the heavy quark region,

- What is a driving force to form a molecules?: **π exchange potential**



- In the heavy quark region, π exchange potential is enhanced by **the Heavy Quark Symmetry**.
- Meson-Meson molecules: The importance of the tensor force in "Deuson" (= **Deuteron-like** two mesons bound states)

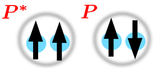
  N. A. Tornqvist,Z. Phys. C **61** (1994) 525
- Meson-Nucleon molecules, $\bar{D}N$ and BN.

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

Heavy meson and Heavy Quark Symmetry

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 $\longrightarrow 0$

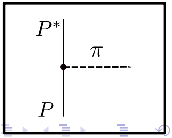


{ Heavy pseudoscalar meson **$P(0^-)$** and
Heavy vector meson **$P^*(1^-)$** are **degenerate**.

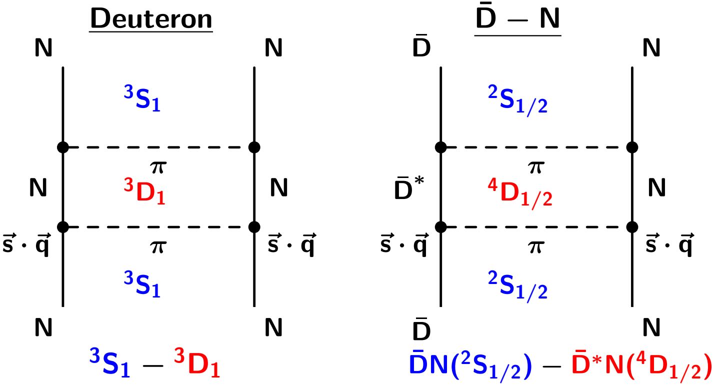
Indeed, mass splitting between P and P^* is **small**.

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

- The π exchange potential appears through **$PP^*\pi$ and $P^*P^*\pi$ vertices**. ($PP\pi$ is forbidden.)
- Thanks to the degeneracy, **π exchange potential is enhanced**.



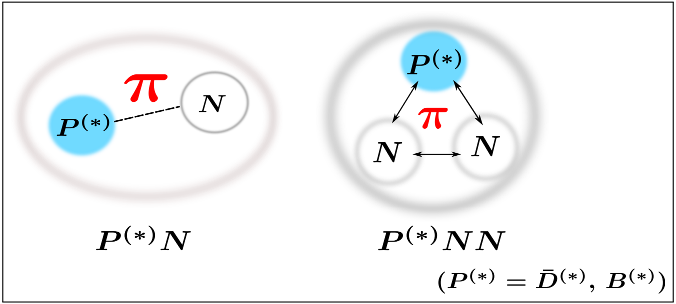
- π exchange(**Tensor force**) generates a **strong attraction**.



- Deuteron: $^3S_1 -^3 D_1$ mixing
- The tensor force comes from $\underline{\bar{D}N - \bar{D}^*N}$ and $\underline{\bar{D}^*N - \bar{D}^*N}$ mixings.

Purpose

- Searching for exotic baryons formed by **Heavy meson-Nucleon with π exchange potential**.



- We study **bound and resonant states** by solving the coupled-channel Schrödinger equations for **PN and P*N channels**.
- $P = \bar{D}(\bar{c}q), B(\bar{b}q) \rightarrow$ **Genuine exotic states!**
  $\Leftrightarrow$ **KN and KNN don't exist.** (KN interaction is repulsive.)

Interactions: π, ρ and ω exchange potentials

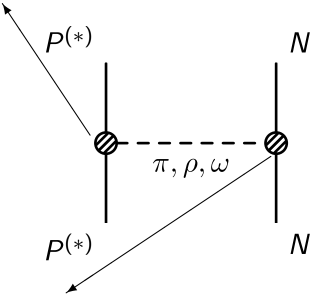
Heavy-light chiral lagrangian R.Casalbuoni *et al.* PhysRept.**281**,145(1997)

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

Heavy meson field

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

vector pseudoscalar



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

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

Heavy-light chiral lagrangian

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From D* → Dπ 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)

Heavy meson field

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

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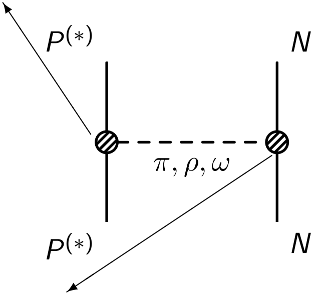


Bonn model

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

From NN data

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

These coupling constants are fixed!

Form factor and Cut-off parameter Λ

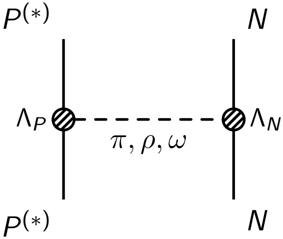
- Form factor F with cutoff Λ at each vertex

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

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



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

Cut-off parameters are also fixed!

$P^{(*)}N$ Interaction

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

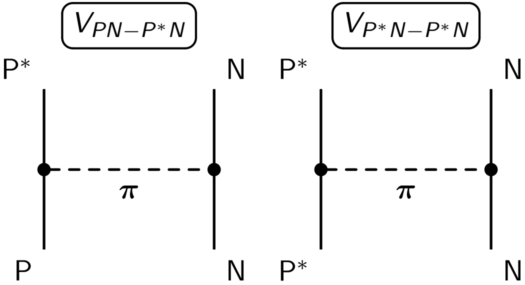
$$V_{PN-P^*N} = -\frac{g g_{\pi NN}}{\sqrt{2} m_N f_\pi} \frac{1}{3} \left[\vec{\varepsilon}^\dagger \cdot \vec{\sigma} C(r) + S_\varepsilon T(r) \right] \vec{\tau}_P \cdot \vec{\tau}_N$$

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

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

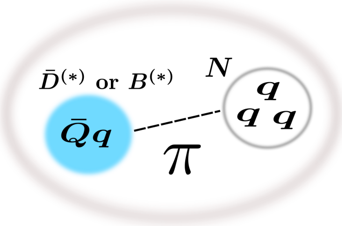
$C(r)$: Central force, $T(r)$: Tensor force

$g = 0.59$ for $\bar{D}$ and B, $g^2_{\pi NN}/4\pi = 13.6$



Both V_{PN-P^*N} and $V_{P^*N-P^*N}$ have **Tensor Force T(r)**.

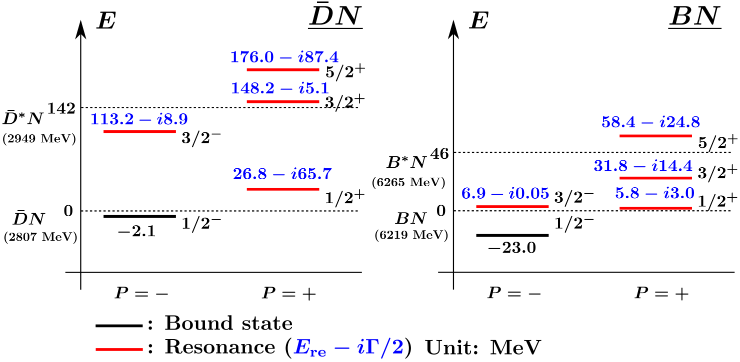
Results of PN states (2-body)



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

Bound state and Resonance

- Bound and Resonant states are found near the thresholds.



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

- Loosely Bound states ($1/2^-$):
  $\langle r^2 \rangle^{1/2}$ is 3.2 fm ($\bar{D}N$) and 1.2 fm (BN).
- BN is more bound than $\bar{D}N$ due to heavier μ and small Δm_{BB^*}.

The bound state in $I(J^P) = 0(1/2^-)$

- 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.

The bound state in $I(J^P) = 0(1/2^-)$

$\bar{D}N$ and BN states

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$\langle \bar{D}N(S) \| V \| \bar{D}^*N(D) \rangle$	**−35.2**	3.4	−0.6
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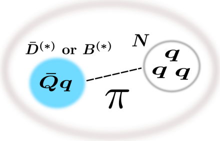
PN molecule (2-body system)



▷ Tensor force plays an important role.

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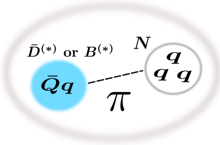
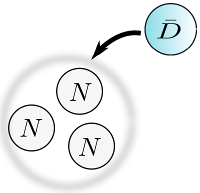


▷ Tensor force plays an important role.

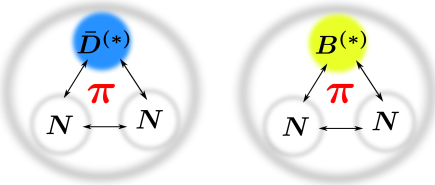
P nuclei (Few body or many body)?



- There have been several works for $\bar{D}(B)$ meson in nuclear matter and in ^{12}C, ^{208}Pb.
  C. Garcia-Recio, *et al.*, Phys. Rev. C **85** (2012) 025203.
  S. Yasui and K. Sudoh, Phys. Rev. C **87** (2013) 015202.
- However, there is **no study for few-body $\bar{\text{D}}$(B) nuclei** in the literature so far.

Tensor force yields a bound state of $\bar{\text{D}}$NN and/or BNN?

- Exotic dibaryon states ($P = \bar{Q}q$). No $q\bar{q}$ annihilation!



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

Method

- We study bound and resonant states.

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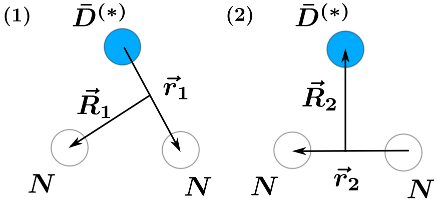
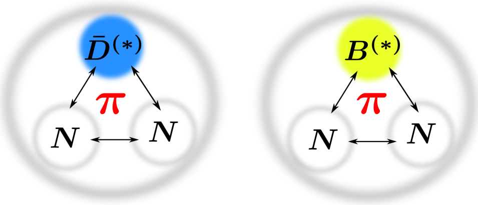


$J^P = 0^-, 1^-, I = 1/2$

Method

- We study bound and resonant states.
- Wave functions are expressed by the Gaussian expansion method. E. Hiyama, *et al.*, Prog.Part.Nucl.Phys.51(2003)223
- Resonances → Complex scaling method S.Aoyama,*et.al.*,PTP**116**,1(2006)
- Interactions
  - $P^{(*)}N$ int. : **π exchange potential** ($\rho, \omega \to$ Future Work)
  - NN int.: AV8′ potential B. S. Pudliner,*et.al.* ,Phys.Rev.C**56**(1997)1720

Results of PNN states (3-body)

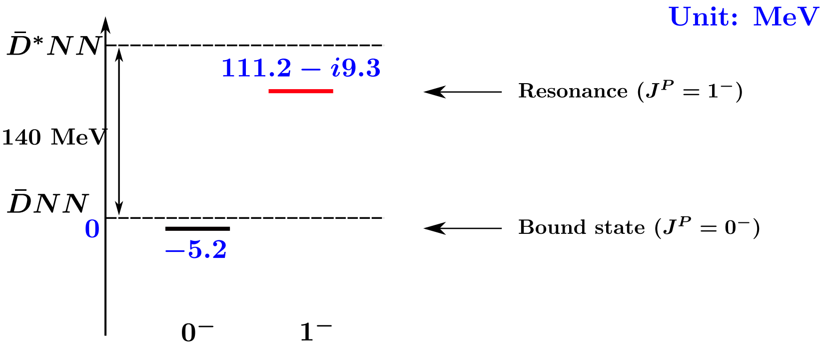


$\bar{D}NN$, BNN

Exotic dibaryon states

<u>Bound state and Resonance</u>

- **Bound states** for $J^P = 0^-$ and **Resonances** for $J^P = 1^-$ are found! Y.Y., S. Yasui, and A. Hosaka, in preparation



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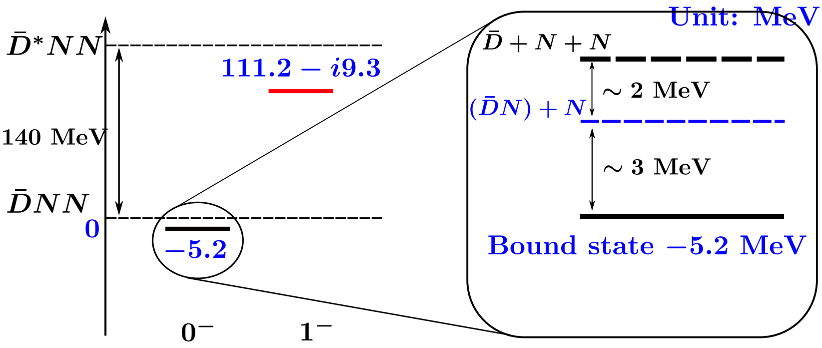

- $\bar{D}NN(0^-)$ locates below **$\bar{D}N(1/2^-)$ + N threshold**.

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

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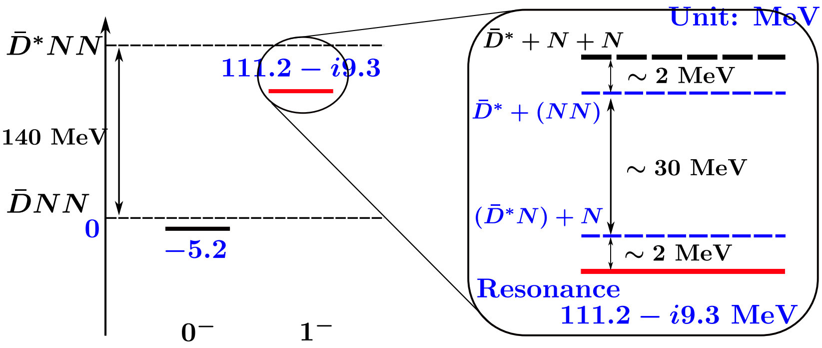

- $\bar{D}NN(0^-)$ locates below **$\bar{D}N(1/2^-) + N$ threshold**.
- $\bar{D}NN(1^-)$ locates below **$\bar{D}^* + NN(1^+)$ and $\bar{D}N(3/2^-) + N$ thresholds**.

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

$\bar{\mathrm{D}}$NN and BNN

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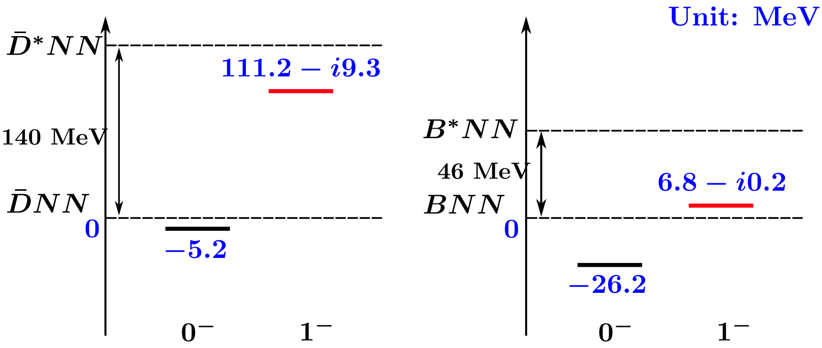

- $\bar{D}NN(0^-)$ locates below **$\bar{\mathrm{D}}\mathrm{N}(1/2^-) + \mathrm{N}$ threshold**.
- $\bar{D}NN(1^-)$ locates below **$\bar{\mathrm{D}}^* + \mathrm{NN}(1^+)$ and $\bar{\mathrm{D}}\mathrm{N}(3/2^-) + \mathrm{N}$ thresholds**.
- $BNN > \bar{D}NN$ due to large reduced mass and small Δm_{BB^*}.

- 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

Y.Y, S. Yasui, and A. Hosaka, in preparation

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Y.Y, S. Yasui, and A. Hosaka, in preparation

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- Energy expectation values

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

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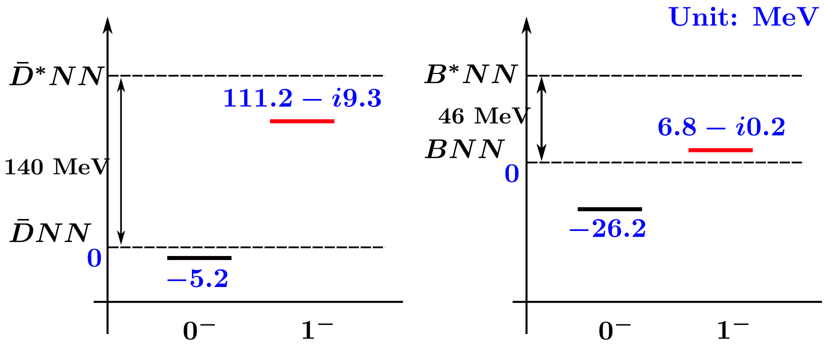
Y.Y, S. Yasui, and A. Hosaka, in preparation

- Tensor force of **$\bar{D}N - \bar{D}^*N$ 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 $NN(1^+)$ is minor.

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



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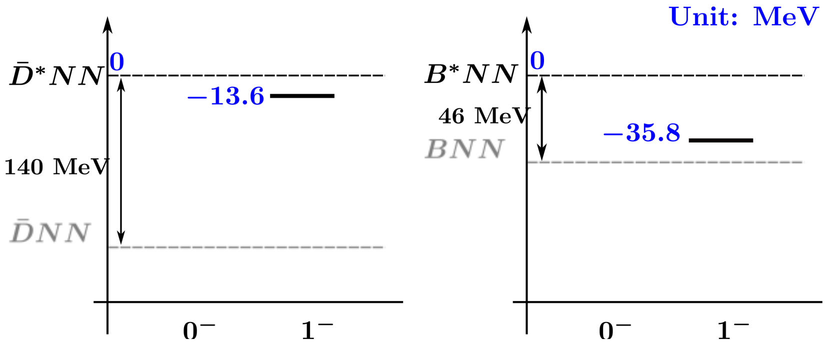
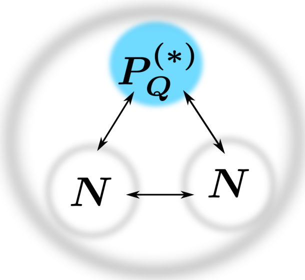


- For $J^P = 1^-$ channel, the bound states survive.
  $\Rightarrow$ **Feshbash resonance!**
- The bound states of $J^P = 0^-$ vanish.
  $\Rightarrow$ $PN - P^*N$ mixing components are very important!

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

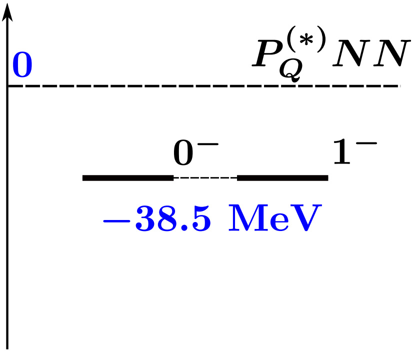


$P_Q^{(*)}NN$ ($m_{P_Q^*} - m_{P_Q} = 0$)

Bound state and Resonance

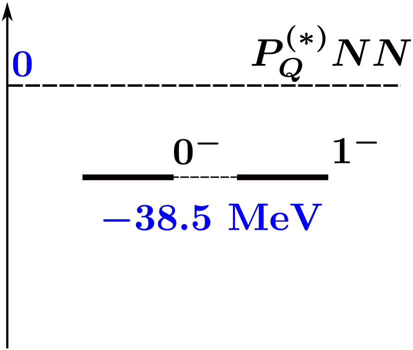
Results of $P_Q^{(*)}NN$ with $m_Q \to \infty$ (Exotic)

- Bound states for $J^P = 0^-$ and 1^- are found.



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

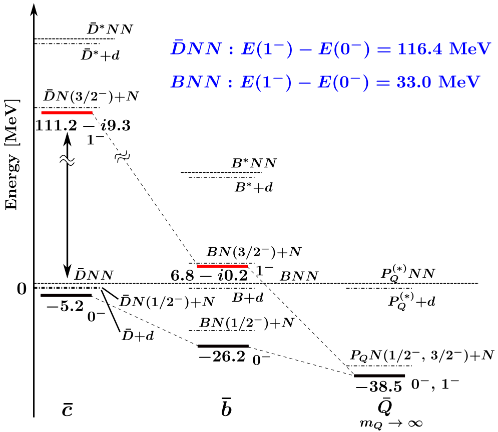
- Bound states for $J^P = 0^-$ and 1^- are found.



Degenerate states!

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

- Bound states for $J^P = 0^-$ and 1^- are found.



We also find the degenerate state for $P_Q^{(*)}N$ with $E_b = -34.1$ MeV.

S. Yasui, K. Sudoh, YY, S. Ohkoda, A. Hosaka and T. Hyodo, arXiv:1304.5293 [hep-ph]

Spin degeneracy

- In the heavy quark limit ($m_Q \to \infty$), the heavy quark spin s_Q is separated from the total spin of the brown muck j_l.

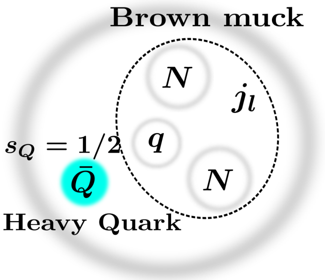
$$J = s_Q + j_l$$

J : Total angular momentum, s_Q : Heavy quark spin, j_l : Brown muck spin

- **The spin degenerate states** appear in a system with single heavy quark.

W. Roberts and M. Pervin, Int. J. Mod. Phys. A **23**, 2817 (2008)

S. Yasui, K. Sudoh, YY, S. Ohkoda, A. Hosaka and T. Hyodo, arXiv:1304.5293 [hep-ph]



- Doublet
  $J = j_l - 1/2, j_l + 1/2$ ($j_l \neq 0$)
- Singlet $J = 1/2$ ($j_l = 0$)

Light spin-complex: $[qNN]_{j_l}$

Spin degeneracy in $P^{(*)}N$ states ($m_Q \to \infty$)

PN basis

$1/2^- : |PN(^2S_{1/2})\rangle, |P^*N(^2S_{1/2})\rangle, |P^*N(^4D_{1/2})\rangle$

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

$3/2^- : |PN(^2D_{3/2})\rangle, |P^*N(^4S_{3/2})\rangle, |P^*N(^4D_{3/2})\rangle, |P^*N(^2D_{3/2})\rangle$

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

S. Yasui, K. Sudoh, YY, S. Ohkoda, A. Hosaka and T. Hyodo, arXiv:1304.5293 [hep-ph]

Spin degeneracy in $P^{(*)}N$ states ($m_Q \to \infty$)

Spin-complex basis

$$1/2^- : |[Nq(^1S_0)]\bar{Q}\rangle_{1/2}, |[Nq(^3S_1)]\bar{Q}\rangle_{1/2}, |[Nq(^3D_1)]\bar{Q}\rangle_{1/2}$$

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

$$3/2^- : |[Nq(^3S_1)]\bar{Q}\rangle_{3/2}, |[Nq(^3D_1)]\bar{Q}\rangle_{3/2}, |[Nq(^1D_2)]\bar{Q}\rangle_{3/2}, |[Nq(^3D_2)]\bar{Q}\rangle_{3/2}$$

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

S. Yasui, K. Sudoh, YY, S. Ohkoda, A. Hosaka and T. Hyodo, arXiv:1304.5293 [hep-ph]

Spin degeneracy in $P^{(*)}N$ states ($m_Q \to \infty$)

Spin-complex basis

$$1/2^- : |[Nq(^1S_0)]\bar{Q}\rangle_{1/2}, |[Nq(^3S_1)]\bar{Q}\rangle_{1/2}, |[Nq(^3D_1)]\bar{Q}\rangle_{1/2}$$

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

$$3/2^- : |[Nq(^3S_1)]\bar{Q}\rangle_{3/2}, |[Nq(^3D_1)]\bar{Q}\rangle_{3/2}, |[Nq(^1D_2)]\bar{Q}\rangle_{3/2}, |[Nq(^3D_2)]\bar{Q}\rangle_{3/2}$$

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

S. Yasui, K. Sudoh, YY, S. Ohkoda, A. Hosaka and T. Hyodo, arXiv:1304.5293 [hep-ph]

Spin degeneracy in $P^{(*)}N$ states ($m_Q \to \infty$)

Spin-complex basis

$1/2^-$: $|[Nq(^1S_0)]\bar{Q}\rangle_{1/2}$, $|[\mathbf{Nq(^3S_1)]\bar{Q}}\rangle_{1/2}$, $|[\mathbf{Nq(^3D_1)]\bar{Q}}\rangle_{1/2}$

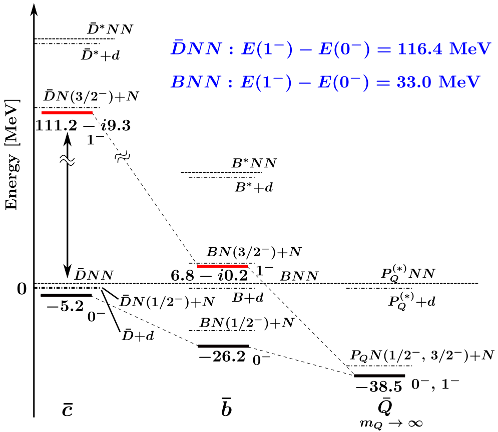
$$H^{\rm SC}_{1/2^-} = \left(\begin{array}{c|cc} K_0 - 3C & 0 & 0 \\ \hline 0 & \mathbf{K_0 + C} & \mathbf{-2\sqrt{2}T} \\ 0 & \mathbf{-2\sqrt{2}T} & \mathbf{K_2 + C - 2T} \end{array}\right)$$

$3/2^-$: $|[\mathbf{Nq(^3S_1)]\bar{Q}}\rangle_{3/2}$, $|[\mathbf{Nq(^3D_1)]\bar{Q}}\rangle_{3/2}$, $|[Nq(^1D_2)]\bar{Q}\rangle_{3/2}$, $|[Nq(^3D_2)]\bar{Q}\rangle_{3/2}$

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

S. Yasui, K. Sudoh, YY, S. Ohkoda, A. Hosaka and T. Hyodo, arXiv:1304.5293 [hep-ph]

- $P^{(*)}N$ (2-body):
  $E_b = -34.1$ MeV for $J^P = 1/2^-$ and $3/2^-$ (**with $\mathbf{j_l^{\mathcal{P}} = 1^+}$**).



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

$[qNN]_{j_l^{\mathcal{P}}}$

$\mathbf{j_l^{\mathcal{P}} = 1/2^+}$

- Spin singlet state doesn't appear in this case, because **j_l cannot be zero**.
  $P^{(*)}N$, $P^{(*)}NNN$, $P^{(*)}NNNNN$... (Odd N's) $j_l = 0$ OK
  $P^{(*)}NN$, $P^{(*)}NNNN$, $P^{(*)}NNNNNN$... (Even N's) $j_l \neq 0$

Summary

- We have investigated exotic baryons formed by $P^{(*)}N$ and $P^{(*)}NN$ with respecting the Heavy Quark Symmetry.
- The π exchange potential was employed between a heavy meson $P^{(*)}$ and a nucleon N.
- We have found many bound states and resonances in $P^{(*)}N$ (2-body system).
- For the $\bar{D}NN$ and BNN states (3-body system), we have found the bound states with $J^P = 0^-$ and resonances with $J^P = 1^-$ for $I = 1/2$.
- **Tensor force of PN – P*N mixing component** plays a crucial role to produce a strong attraction.
- The degenerate states of $P_Q^{(*)}NN$ with $J^P = 0^-$ and 1^-, and $j_l^{\mathcal{P}} = 1/2^+$ is found in the heavy quark limit.

Back up

Central force and Tensor force

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

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

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

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

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.

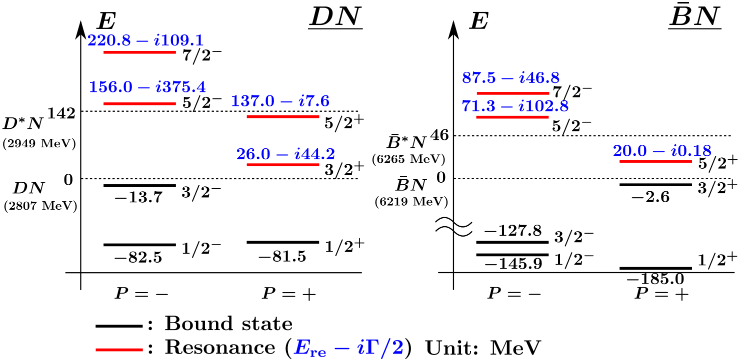
J^P	channels	# of channels
$1/2^-$	$PN(^2S_{1/2})$ $P^*N(^2S_{1/2}, {}^4D_{1/2})$	3
$1/2^+$	$PN(^2P_{1/2})$ $P^*N(^2P_{1/2}, {}^4P_{1/2})$	3
$3/2^-$	$PN(^2D_{3/2})$ $P^*N(^4S_{3/2}, {}^2D_{3/2}, {}^4D_{3/2})$	4
$3/2^+$	$PN(^2P_{3/2})$ $P^*N(^2P_{3/2}, {}^4P_{3/2}, {}^4F_{3/2})$	4
$5/2^-$	$PN(^2D_{5/2})$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

Results of DN and B̄N with I = 0 ($Q\bar{q}$ + qqq states)

DN and B̄N states

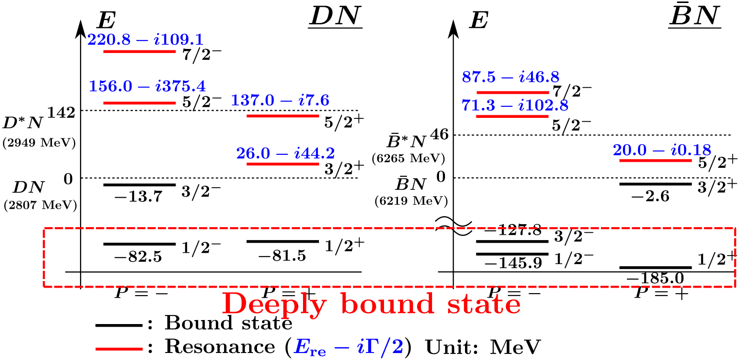
- $J^P = 1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}, 7/2^{\pm}$ with $I = 0$



Y.Y, S.Ohkoda, S.Yasui and A.Hosaka, PRD**87**,074019 (2013)

- Both ρ and ω exchanges are attractive in DN ($\bar{B}N$).
  $\Rightarrow$ DN ($\bar{B}N$) states are **more bound**.
- Excited Λ_c's and Λ_b's? $\Rightarrow$ But $\pi\Sigma_c$ ($\pi\Sigma_b$) is not considered.

- $J^P = 1/2^\pm, 3/2^\pm, 5/2^\pm, 7/2^\pm$ with $I = 0$



Y.Y, S.Ohkoda, S.Yasui and A.Hosaka, PRD**87**,074019 (2013)

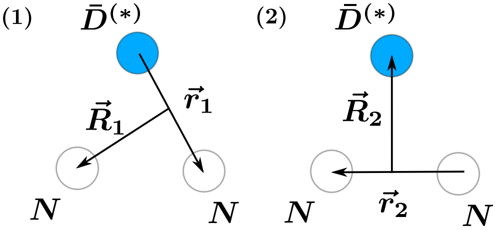
Deeply bound states: Small radius < 1 fm

There are couplings not only to $\pi\Sigma_c$ ($\pi\Sigma_b$), but also to Qqq.

Large L states: π exchange is important. $DN - D^*N$ dominance?

Method

- Jacobi coordinate



- Wave function

$$\Phi_L^{(c)}(r_c, R_c) = \sum_{n_1,n_2,l_1,l_2} C\left[\phi_{n_1,l_1}^{(c)}(r_c)\psi_{n_2,l_2}^{(c)}(R_c)\right]_L$$

$$\phi_{n_1,l_1}(r) = \exp\left(-r^2/2b_n^2\right)\mathcal{Y}_{l_1}(\hat{r})$$

$$b_n = b_1 a^{n-1}(n = 1, \cdots, 10),\ b_1 = 0.3\,\mathrm{fm},\ b_{10} = 10.0\,\mathrm{fm}$$