Exotic baryons from a heavy meson and a nucleon

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in collaboration with
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Related talk
S. Yasui, Anti-D and B meson in nuclear medium at zero temperature, 2/18
Recent progress in hadron physics -From hadrons to quark and gluon-
February 18-22, 2013, Yonsei University
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Hadronic molecule in the heavy quark region

Introduction

- Hadronic molecule gives us new aspect for Exotic states.
- Candidates in the heavy quark region
  - Quarkonium-like states; $X(3872)$, $Z_b$, ...
  - Baryon states; No evidence so far... However

Meson-Meson

($X(3872)$, $Z_b$, ...)

Belle Collaboration PRL91(2003)262001,PRL108(2012)122001

Loosely bound state near the threshold.
Hadronic molecule in the heavy quark region

Introduction

- Hadronic molecule gives us new aspect for Exotic states.
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Meson-Baryon molecules are expected near the thresholds!
→ New Excited baryons ($\Lambda_c, \Sigma_c$)?, Pentaquark states?

Meson-Meson (X(3872), $Z_b$, ...)

Meson-Baryon

$D^*$ $\to$ $\bar{D}$

$D$ $\to$ $N$

Loosely bound state near the threshold.

Belle Collaboration PRL91(2003)262001,PRL108(2012)122001
In the heavy quark region,
Hadronic molecule in the heavy quark region

Introduction

In the heavy quark region, \( \pi \) exchange potential with the Heavy Quark Symmetry produces a strong attraction.

S. Yasui and K. Sudoh, PRD 80 (2009) 034008
T. D. Cohen, P. M. Hohler and R. F. Lebed, PRD 72 (2005) 074010

It is expected that this attraction plays a crucial role to yield hadronic molecule.
Heavy meson and Heavy Quark Symmetry

Introduction

Heavy Quark Symmetry  N.Isgur, M.B.Wise,PRL66,1130

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

\[ P^* \quad P \]

\[
\begin{align*}
\text{Heavy pseudoscalar meson } P(0^-) \text{ and } \\
\text{Heavy vector meson } P^*(1^-) \text{ are degenerate. }
\end{align*}
\]

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

\[
\begin{align*}
m_{B^*} - m_B & \sim 45 \text{ MeV} \\
m_{D^*} - m_D & \sim 140 \text{ MeV} \\
m_{K^*} - m_K & \sim 400 \text{ MeV}
\end{align*}
\]

This degeneracy induces \( PP^*\pi \) vertex.

\[
\begin{align*}
PP\pi & \text{ is forbidden due to parity violation. } \\
KK^*\pi & \text{ is suppressed by large } \Delta m_{KK^*}.
\end{align*}
\]
**π exchange potential**: Analogy with Deuteron

**Introduction**

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

**Deuteron**

\[
\begin{align*}
\left(3S_1\right) & \quad \left(3D_1\right) \\
\left(\bar{s}\cdot\bar{q}\right) & \quad \left(\bar{s}\cdot\bar{q}\right) \\
N & \quad N
\end{align*}
\]

- **For** \(\bar{D}N\), **Tensor force mixes** \(\bar{D}N(2S_{1/2})\) **and** \(\bar{D}^*N(4D_{1/2})\).

- **Tensor force yields** \(\bar{D}N\) (\(\bar{D}NN\)) **bound states?**
Searching for exotic baryons formed by Heavy meson-Nucleon with $\pi$ exchange potential.

We study bound and resonant states by solving the coupled-channel Schrödinger equations for $PN$ and $P^*N$ channels.
Interactions: $\pi$, $\rho$ and $\omega$ exchanges

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

- $\mathcal{L}_{\pi HH} = ig_{\pi} \text{Tr} \left[ H_b \gamma_\mu \gamma_5 A_{ba}^\mu \bar{H}_a \right]$

- $\mathcal{L}_{\nu HH} = -i \beta \text{Tr} \left[ H_b \nu^\mu (\rho_\mu)_{ba} \bar{H}_a \right] + i \chi \text{Tr} \left[ H_b \sigma^{\mu\nu} F_{\mu\nu} (\rho)_{ba} \bar{H}_a \right]$

**Heavy meson field**

$H_a = \frac{1+\varphi}{2} \left[ P_{a \mu} \gamma^\mu - P_a \gamma^5 \right]$, \hspace{1cm} $\bar{H}_a = \gamma^0 H_a \gamma^0$

- vector
- pseudoscalar

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

- $\mathcal{L}_{\pi NN} = ig_{\pi NN} \bar{N}_b \gamma^5 N_a \hat{\pi}_{ba}$

- $\mathcal{L}_{\nu NN} = g_{\nu NN} \bar{N}_b \left( \gamma^\mu (\hat{\rho}_\mu)_{ba} + \frac{\kappa}{2m_N} \sigma_{\mu\nu} \partial^\nu (\hat{\rho}^\mu)_{ba} \right) N_a$
Heavy quark effective theory

- $\mathcal{L}_{\pi HH} = ig_\pi \text{Tr} \left[ H_b \gamma_\mu \gamma_5 A^\mu_{ba} \tilde{H}_a \right]$ 

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

- $\mathcal{L}_{\nu HH} = -i\beta \text{Tr} \left[ H_b \nu^\mu (\rho_\mu)_{ba} \tilde{H}_a \right] + i\lambda \text{Tr} \left[ H_b \sigma^{\mu\nu} F_{\mu\nu} (\rho)_{ba} \tilde{H}_a \right]$ 

  From leptonic and radiative decay of $B$

  Isola et al. PRD68,114001(2003)

Heavy meson field

- $H_a = \frac{1+\gamma'}{2} \left[ P^*_a \gamma^\mu - P^a \gamma^5 \right], \quad \tilde{H}_a = \gamma^0 H_a \gamma^0$

  - vector  pseudoscalar

Bonn model

- $\mathcal{L}_{\pi NN} = ig_\pi NN \tilde{N}_b \gamma^5 N_a \hat{\pi}_{ba}$

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

These coupling constants are fixed!
Form factor and Cut-off parameter $\Lambda$

- Form factor at each vertex
  \[
  F_\alpha(\Lambda, \vec{q}) = \frac{\Lambda^2 - m_\alpha^2}{\Lambda^2 + |\vec{q}|^2}
  \]

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

2. For $\Lambda_P$, we assume $\Lambda_P/\Lambda_N = r_N/r_P$. $r_N/r_P$ is obtained from quark model.

\[
\begin{aligned}
\Lambda_D &= 1.35\Lambda_N \\
\Lambda_B &= 1.29\Lambda_N
\end{aligned}
\]

S. Yasui and K. Sudoh PRD80,034008

| Potential | $\Lambda_N$ [MeV] | $\Lambda_D$ [MeV] | $\Lambda_B$ [MeV] |
|-----------|-------------------|-------------------|-------------------|
| $\pi$     | 830               | 1121              | 1070              |
| $\pi, \rho, \omega$ | 846               | 1142              | 1091              |

Coupling constants and Cut-off are not free parameters!
Results of $\bar{D}N$ and $BN$ states

Truly exotic state

Bound state and Resonance
Various coupled channels for a given $J^P$ (2-body)

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

| $J^P$ | 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 |

- Tensor force mixes $PN$ and $P^*N$. 

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Various coupled channels for a given $J^P$ (2-body)

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

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

- Tensor force mixes $PN$ and $P^*N$.
- Large $L$ channel plays a crucial role to produce attraction.
The bound states of $\bar{D}N$ and $BN$ (Exotic state)

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

- We find bound states of $\bar{D}N$ and $BN$ with $I(J^P) = 0(1/2^-)$. Y.Y., et al., PRD 84, 014032 (2011)
- We compare results of two potentials:
  1. Only $\pi$ 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               |

($\pi$): Only $\pi$ 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 ($\pi$) is close to that of ($\pi\rho\omega$).
  $\Rightarrow$ **$\pi$ exchange dominates?**
Expectation values of $I(J^P) = 0(1/2^-)$ states
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\tilde D N$ and $B N$ states
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- Expectation values of meson exchange potentials

| \tilde D N expectation values (Unit: MeV) | $V_\pi$ | $V_\rho$ | $V_\omega$ |
|-----------------------------------------|--------|----------|-----------|
| $\langle \tilde D N(S) | V | \tilde D N(S) \rangle$ | 0      | -2.72    | 3.56      |
| $\langle \tilde D N(S) | V | \tilde D^* N(S) \rangle$ | -2.48  | -5.18    | 0.90      |
| $\langle \tilde D N(S) | V | \tilde D^* N(D) \rangle$ | -35.20 | 3.32     | -0.62     |
| $\langle \tilde D^* N(S) | V | \tilde D^* N(S) \rangle$ | 0.37   | 0.65     | 0.13      |
| $\langle \tilde D^* N(S) | V | \tilde D^* N(D) \rangle$ | -5.00  | 0.52     | -9.70 × 10^{-2} |
| $\langle \tilde D^* N(D) | V | \tilde D^* N(D) \rangle$ | 3.69   | -0.94    | 0.39      |
| total | -38.63 | -4.36    | 4.35      |

$\Leftrightarrow \tilde D N(S) - \tilde D^* N(D)$ component with Tensor

Strong attraction!

- Tensor force of $\pi$ exchange plays a dominant role
  while $\rho$, $\omega$ exchanges are minor due to the cancellation of them.
Expectation values of $I(J^P) = 0(1/2^-)$ states

**$\bar{D}N$ and $BN$ states**

- Expectation values of meson exchange potentials

| $\bar{D}N$ expectation values (Unit: MeV) | $BN$ expectation values (Unit: MeV) |
|-----------------------------------------|----------------------------------|
| Component             | $V_\pi$ | $V_\rho$ | $V_\omega$ | Component             | $V_\pi$ | $V_\rho$ | $V_\omega$ |
|-----------------------|---------|----------|------------|-----------------------|---------|----------|------------|
| $\langle \bar{D}N(S)|V|\bar{D}N(S)\rangle$ | 0       | -2.72    | 3.56       | $\langle BN(S)|V|BN(S)\rangle$ | 0       | -5.38    | 7.02       |
| $\langle \bar{D}N(S)|V|\bar{D}^*N(S)\rangle$ | -2.48   | -5.18    | 0.90       | $\langle BN(S)|V|B^*N(S)\rangle$ | -8.18   | -16.42   | 3.12       |
| $\langle \bar{D}N(S)|V|\bar{D}^*N(D)\rangle$ | -35.20  | 3.32     | -0.62      | $\langle BN(S)|V|B^*N(D)\rangle$ | -90.24  | 8.30     | -1.54      |
| $\langle \bar{D}^*N(S)|V|\bar{D}^*N(S)\rangle$ | 0.37    | 0.65     | 0.13       | $\langle B^*N(S)|V|B^*N(S)\rangle$ | 2.03    | 3.19     | 0.62       |
| $\langle \bar{D}^*N(S)|V|\bar{D}^*N(D)\rangle$ | -5.00   | 0.52     | -9.70 $\times 10^{-2}$ | $\langle B^*N(S)|V|B^*N(D)\rangle$ | -22.34  | 2.12     | -0.40 $\times 10^{-2}$ |
| $\langle \bar{D}^*N(D)|V|\bar{D}^*N(D)\rangle$ | 3.69    | -0.94    | 0.39       | $\langle B^*N(D)|V|B^*N(D)\rangle$ | 13.24   | -3.24    | 1.36       |
| total                | $-38.63$  | $-4.36$  | 4.35       | total                | $-105.49$ | $-11.42$ | 10.17      |

- $BN$ is similar to $\bar{D}N$.
- Small $\Delta m_{BB^*}$ induces strong $BB^*$ mixing and tensor force.
  Therefore, $BN$ state is more bound than $\bar{D}N$. 

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Results of $\bar{D}N$ and $BN$ with $I = 0$ (Exotic states)

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

- $J^P = 1/2^\pm, 3/2^\pm, 5/2^\pm, 7/2^\pm$ with $I = 0$ ($\pi\rho\omega$ potential)

- Resonant states with large $L$ are also found.
- Tensor force provides a strong attraction for resonances.
- The $PN - P*N$ mixing is important.

Y. Y., S. Ohkoda, S. Yasui and A. Hosaka, PRD 84 014032 (2011) and PRD 85 054003 (2012)
Results of $\bar{D}N$ and $BN$ with $I = 1$ (Exotic states)

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

No Bound state and Resonance with $I = 1$.

$\bar{D}N^* \quad ^{142}$
(2949 MeV)

$\bar{D}N \quad ^0$
(2807 MeV)

$B^*N ^{46}$
(6265 MeV)

$BN ^0$
(6219 MeV)

$P = -$ $P = +$

: Bound state

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

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

The attraction is weak due to small isospin factor.

$$\vec{r}_P \cdot \vec{r}_N = \begin{cases} -3 & (I = 0) \\ 1 & (I = 1) \end{cases}$$

Strong attraction

Weak attraction
Results of $DN$ and $\bar{B}N$ states

$D^{(*)}$ or $\bar{B}^{(*)}$

$Q\bar{q}$

$N$

$qqq$

$\pi$

Ordinary state

$\bar{D} \rightarrow D$
Results of $DN$ and $\bar{B}N$ with $I = 0$ (Ordinary states)
$DN$ and $\bar{B}N$ states

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

| Energy | $DN$ | $\bar{B}N$ |
|--------|------|-------------|
| $E$    |       |             |
| 220.8  | $7/2^-$ | 87.5       |
| -13.7  | $3/2^-$ | 5/2-$^-$    |
| -82.5  | $1/2^-$ | 20.0-$^+$   |
| -145.9 | $1/2^-$ | $-185.0$   |

$DN$ (2807 MeV) and $\bar{B}N$ (6219 MeV) states are more bound.

Tensor force provides a strong attraction.
Both $\rho$ and $\omega$ exchanges are attractive in $DN$ ($\bar{B}N$).
$\Rightarrow$ $DN$ ($\bar{B}N$) states are more bound.
Excited $\Lambda_c$'s and $\Lambda_b$'s? $\Rightarrow$ But $\pi\Sigma_c$ ($\pi\Sigma_b$) is not considered.

Y.Y, S.Ohkoda, S.Yasui and A.Hosaka, arXiv:1301.4557 [hep-ph]

18-22 February, 2013 Y. Yamaguchi(RCNP) Recent progress in hadron physics @ Yonsei Univ. 16
Results of $DN$ and $\bar{B}N$ with $I = 0$ (Ordinary states)

$DN$ and $\bar{B}N$ states

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

Deeply bound states: Small radius $< 1$ fm

- There are couplings not only to $\pi \Sigma_c$ ($\pi \Sigma_b$), but also to $Qqq$.
- They are difficult to be described as simple $PN$ molecule.

Y.Y, S.Ohkoda, S.Yasui and A.Hosaka, arXiv:1301.4557 [hep-ph]
Results of $DN$ and $\bar{B}N$ with $I = 0$ (Ordinary states)

$DN$ and $\bar{B}N$ states

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

Near $PN$ and $P^*N$ thresholds

- $\pi$ exchange potential dominates and the size becomes large.
- Molecular structure is expected.

Y.Y, S. Ohkoda, S. Yasui and A. Hosaka, arXiv:1301.4557 [hep-ph]
Results of $DN$ and $\bar{B}N$ with $I = 1$ (Ordinary states) $DN$ and $\bar{B}N$ states

- Resonance with $J^P = 1/2^-$. 

\[147.2 - i105.5 \quad 1/2^-\]
\[50.7 - i75.5 \quad 1/2^-\]

$DN$ (2949 MeV) $\bar{B}N$ (6265 MeV)

$DN$ (2807 MeV) $\bar{B}N$ (6219 MeV)

- The attraction is weak due to small isospin factor.
**$PN$ molecule (2-body system)**

- Tensor force plays an important role.

\[\Downarrow\]

**$PNN$ (3-body system)**

Does Tensor force produce $\bar{DNN}$ and $BNN$ bound states?
Three-body system: $\bar{D}^(*)NN$ and $B^(*)NN$ (Exotic states) $\bar{D}NN$ and $BNN$

- Exotic states (No $q\bar{q}$ annihilation!)
- Bound and resonant states are studied.

Method

- Variational calculation with Complex scaling method.
- Interactions
  - $P^(*)N$ int. : $\pi$ exchange potential
  - $NN$ int.: AV8' potential

S. Aoyama, et.al., PTP116, 1(2006)
Results of $\bar{D}^{(*)}NN$ and $B^{(*)}NN$ with $I = 1/2$ (Exotic) $\bar{D}NN$ and $BNN$

- $J^P = 0^-$: Bound states
- $J^P = 1^-$: Resonances

Unit: MeV

Tensor force plays an important role to produce an attraction. (Especially, $PN - P^*N$ components)

When it is switched off, these states disappear.
Results of $\bar{D}^\ast NN$ and $B^\ast NN$ with $I = 1/2$ (Exotic) $\bar{D}NN$ and $BNN$

- $J^P = 0^-$: Bound states
- $J^P = 1^-$: Resonances

Tensor force plays an important role to produce an attraction. (Especially, $PN - P^*N$ components)
- When it is switched off, these states disappear.
- Binding energy: $\bar{D}NN > \bar{D}N$
Results of $\bar{D}^{(*)}NN$ and $B^{(*)}NN$ with $I = 1/2$ (Exotic) 

- $J^P = 0^-$: Bound states
- $J^P = 1^-$: Resonances

Tensor force plays an important role to produce an attraction. (Especially, $PN - P^*N$ components)
- When it is switched off, these states disappear.
- Binding energy: $\bar{D}NN > \bar{D}N$
Results of $\bar{D}^{(*)}NN$ and $B^{(*)}NN$ with $I = 1/2$ (Exotic)

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

- $J^P = 0^-$: Bound states
- $J^P = 1^-$: Resonances

$\bar{D}^*NN$

140 MeV

$\bar{D}NN$

0

111.2 $- i9.3$

46 MeV

$B^*NN$

6.8 $- i0.2$

$BNN$

0

$\bar{D}NN$ is more bound than $BNN$.

We predict $\bar{D}NN$ and $BNN$ bound states (Resonances) with $\pi$ exchange potential.
Summary

- We have investigated exotic baryons formed by $P(*)N$ and $P(*)NN$ with respecting the Heavy Quark Symmetry.

- Two-body system: $\bar{D}N$, $BN$ and $DN$, $\bar{B}N$
  We have found many bound states and resonances.

| 2-body | Exotic  | Ordinary |
|--------|---------|----------|
|        | $\bar{D}N$, $BN$ | $DN$, $\bar{B}N$ |
| $I = 0$ | Some states | Many states |
| $I = 1$ | None | Only one |

- Three-body system: $\bar{D}NN$ and $BNN$

| 3-body | $\bar{D}NN$, $BNN$ |
|--------|------------------|
| $J^P = 0^-$ | Bound state |
| $J^P = 1^-$ | Resonance |

- **Tensor force of $\pi$ exchange** plays a crucial role to produce a strong attraction in $P(*)N$ and $P(*)NN$. 

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