反 D 中間子と核子のエキゾチックな束縛状態と散乱状態の解析

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in collaboration with

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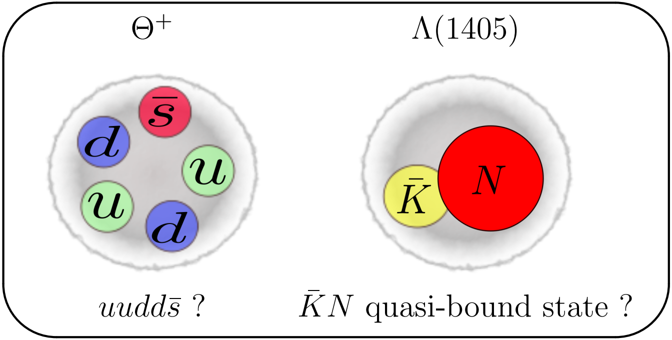
RCNP[1], KEK[2]

Exotic hadron

エキゾチックハドロンは "風変わりな" 構造を持っている。
qqq や $q\bar{q}$ では説明することができない。



etc.

- ハドロン物理で盛んに研究されているテーマの一つ。

$\bar{D}(B)$-N bound state

$$\bar{D} = \begin{cases} \bar{D}^0\,(\bar{c}u) \\ D^-(\bar{c}d) \end{cases}, \quad B = \begin{cases} B^+(\bar{b}u) \\ B^0\,(\bar{b}d) \end{cases}$$

- $\bar{D}(B)$-N bound state

$\bar{Q}q + qqq$ で構成されたのエキゾチックハドロン
$*$ 対消滅が起きない

Previous work

- $\bar{D}N$ 系に対する実験データが不足している
- Yasui,Sudoh[1] によって π 交換力による $\bar{D}N$,BN 束縛状態の存在が示唆された

[1] S.Yasui and K.Sudoh, Phys Rev. D **80**, 034008 (2009)

Heavy meson and Heavy quark symmetry

- Heavy quark symmetry[2] (HQS)
  Isuger と Wise が導入[2]、$m_Q \to \infty$ の極限で現れる。
  - Heavy quark spin symmetry

Spin-spin interaction $\longrightarrow 0$

$$\begin{cases} \text{Heavy pseudoscalar meson } \bar{D}(0^-) \text{ と} \\ \text{Heavy vector meson } \bar{D}^*(1^-) \text{ の縮退が起こる} \end{cases}$$

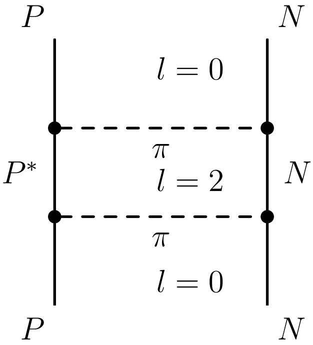
実験でも、P と P^* の質量差は小さい

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

$\longrightarrow$ P^*N mixing が現れる

[2] N.Isuger and M.B.Wise, Phys. Rev. Lett. **66**,1130(1990)

P^*N mixing and π exchange interaction



$m_{K^*} - m_K \sim 400$ MeV $\times$

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

Couple P^*N channel with PN system

P^*N mixing が π 交換相互作用をもたらす
$\Rightarrow$ 束縛状態の期待

目的

- ヘビーメソンと核子の束縛状態としてのエキゾチックな状態を探す

- 相互作用として HQS に基づいた π, ρ, ω 交換を用いる
- 非相対論近似のもとでシュレディンガー方程式を解き、束縛エネルギーと S 行列を求める

Interactions

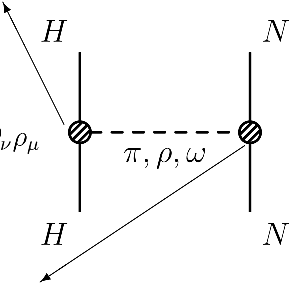
Heavy quark effective theory[3]

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

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

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[4]

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

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[3] R.Casalbuoni ,*et al.* Phys Rept. ,281 (1997) 145

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

PN and P^*N system

We investigate $J^P = 1/2^-$ and $3/2^-$ state.

- Various coupled channels for $J^P = 1/2^-, 3/2^-$ state.

(1) $J^P = 1/2^-$ state $\begin{cases} PN & {}^2S_{1/2} \\ P^*N & {}^2S_{1/2}, {}^4D_{1/2} \end{cases}$ 3-channels

(2) $J^P = 3/2^-$ state $\begin{cases} PN & {}^2D_{3/2} \\ P^*N & {}^4S_{3/2}, {}^4D_{3/2}, {}^2D_{3/2} \end{cases}$ 4-channels

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$\rightarrow$ **bound state** $(I = 0)$

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$\rightarrow$ no bound state

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$\rightarrow$ resonance?

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$\rightarrow$ resonance?

Solve coupled channel equation!

Result for $J^P = 1/2^-$ state

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

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

Table: Binding energy and root mean square radii 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

- π 交換のみの場合と π, ρ, ω 交換がある場合を比較
  $\rightarrow$ π 交換相互作用が支配的に働いている
- $\bar{D}^* N$ mixing よりも $B^* N$ mixing の方が強い

Result for $J^P = 3/2^-$ state

The scattering state with $(I, J^P) = (0, 3/2^-)$

- $J^P = 3/2^-$ 状態には束縛状態はなかった $\cdots$
- Phase shift をみると

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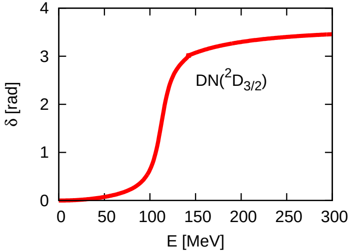
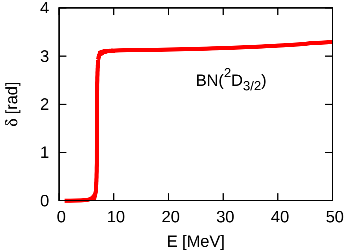
Phase shift for $\bar{D}N(^2D_{3/2})$



Phase shift for $BN(^2D_{3/2})$



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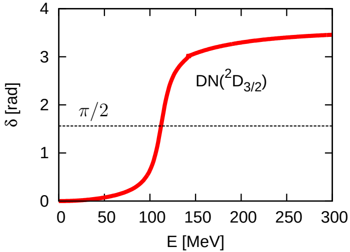

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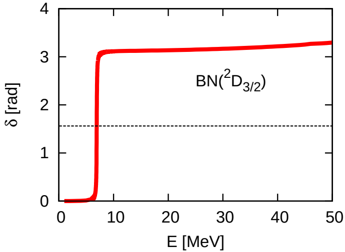
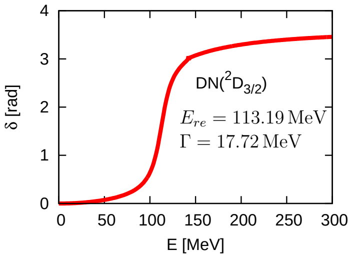


Phase shifts cross $\pi/2 \rightarrow$ **Resonant state**

The scattering state with $(I, J^P) = (0, 3/2^-)$

新たなエキゾチックな状態を予言!

Phase shift for $\bar{D}N(^2D_{3/2})$



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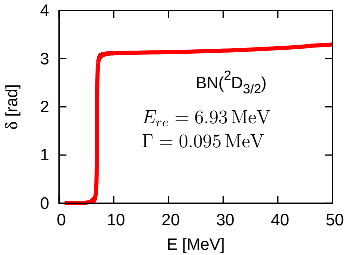

Phase shifts cross $\pi/2 \rightarrow$ **Resonant state**

The resonance in $(I, J^P) = (0, 3/2^-)$ channel

PN と P^*N のチャンネル結合を切る

$$J^P = 3/2^- \text{ state} \begin{cases} PN & {}^2D_{3/2} \leftarrow \text{Ignored} \\ P^*N & {}^4S_{3/2}, {}^4D_{3/2}, {}^2D_{3/2} \end{cases} \quad \text{3-channels}$$

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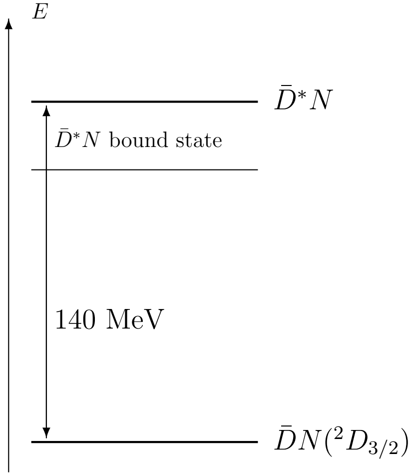
⇒ P^*N チャンネル単独で束縛

Table: Bounding energy for P^*N system

	Binding energy [MeV]
$\bar{D}^*N$	11.50
B^*N	21.67

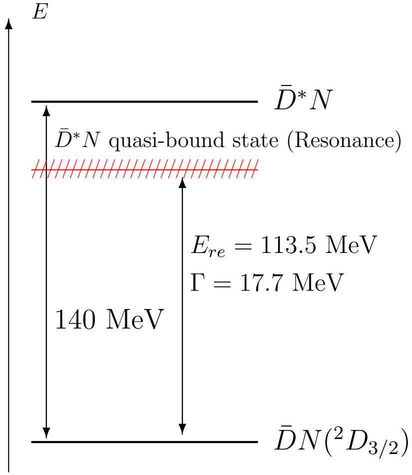
この共鳴は **Feshbach 共鳴** である

The resonance in $(I, J^P) = (0, 3/2^-)$ channel



Feshbach resonance

The resonance in $(I, J^P) = (0, 3/2^-)$ channel



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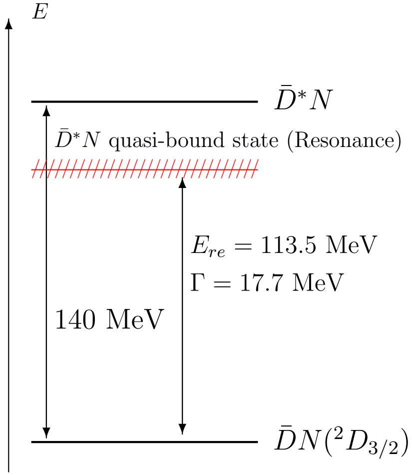
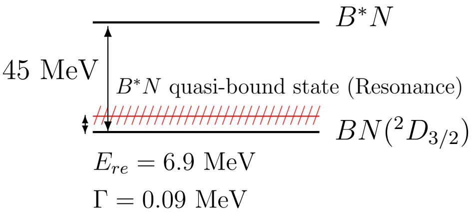


Feshbach resonance

$\bar{D}^* N$ mixing $<$ $B^* N$ mixing



Summary

- Heavy quark symmetry に基づいた相互作用を用いて $\bar{D}N$，BN 系の束縛状態、散乱状態の解析を行った。
- $(I, J^P) = (0, 3/2^-)$ 状態に新たな共鳴状態があることを予言した。
- 共鳴は Feshbach 共鳴であった。
- 束縛状態、共鳴状態の形成には P^*N チャンネルの結合と π 交換相互作用が重要な役割を果たしている。

形状因子 F とカットオフ Λ

- vertex の形状因子

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

- 核子の vertex のカットオフ Λ_N は Bonn potential で Deuteron の束縛エネルギーを再現するように決定する
- ヘビーメソンの vertex のカットオフ Λ_P は

$$\Lambda_D = 1.35\Lambda_N$$
$$\Lambda_B = 1.29\Lambda_N$$

Table: Cutoff parameter.

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