Heavy exotic hadrons as meson-baryon molecules

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in collaboration with

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Hadron structure: Constituent quark model

- Hadron = Quark composite system
- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)

Baryon(proton,nucleon,...) Meson (ρ,$K^{(*)}$,...)

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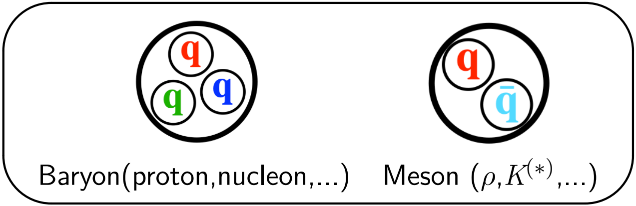
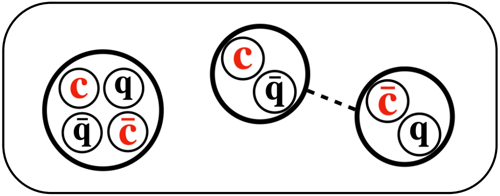


- Exotic Hadrons ($\neq qqq,\ q\bar{q}$): **Multiquark? Multihadron?**



Hadronic molecules of $D^{(*)}$ mesons

- **Hadronic moleule** as an exotic hadron
  $=$ Hadron-hadron bound state near thresholds?

Reviews: Y.Y *et.al.*,J.Phys.G**47**(2020)053001, H.-X. Chen, *et.al.*, Rept. Prog. Phys. **86** (2023), 026201 ,...

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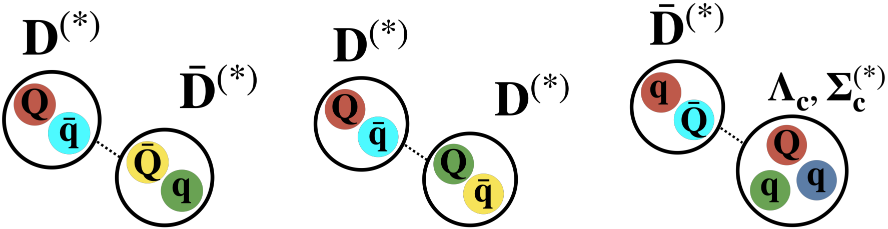

Hidden-charm tetraquark XYZ | **Doubly-charmed tetraquark** T_{cc} | **Hidden-charm pentaquark** P_c, P_{cs}

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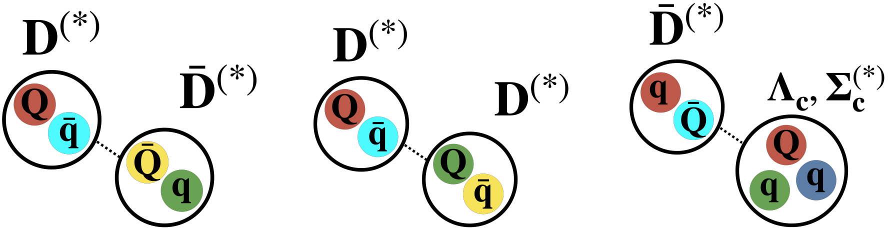

Hidden-charm tetraquark	**Doubly-charmed tetraquark**	**Hidden-charm pentaquark**
XYZ	T_{cc}	P_c, P_{cs}

- **Importance of the D meson interactions!**

  $\Leftrightarrow$ K interactions, Hyperon interactions,... **in the strangeness sector**

Hadron interactions

Problem Hadron interactions are **NOT established** yet...
due to the lack of the hadron-scattering data
($\leftrightarrow$ Lattice QCD, Femtoscopy, etc near future!)

How can we describe hadron interactions?

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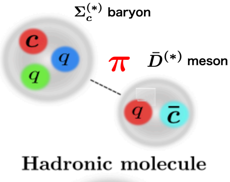
- Long-range int. known in the nuclear force !
- Chiral and Heavy quark spin symmetries



OPEP

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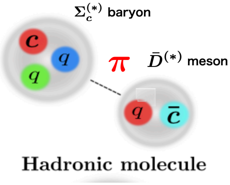
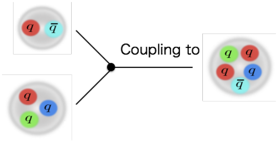
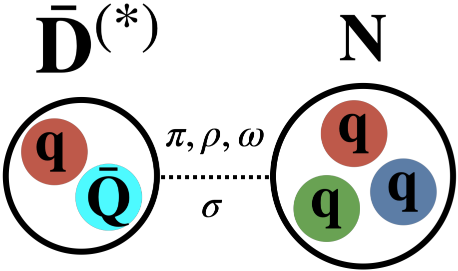
Short-range int. Many models

- ρ, ω, σ meson exchanges (analogy to Nuclear force)
- Quark exchanges, Mixing of Compact state, etc.





$\bar{D}$ meson-Nucleon systems



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- **Genuine Exotic pentaquark channel**

  $\bar{D}(\bar{c}q) + N(qqq) \Rightarrow$ Minimal quark content $\boldsymbol{\bar{c}qqqq}$ (No $q\bar{q}$ annihilation)

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  H1 Collaboration, Phys.Lett.B 588 (2004) 17

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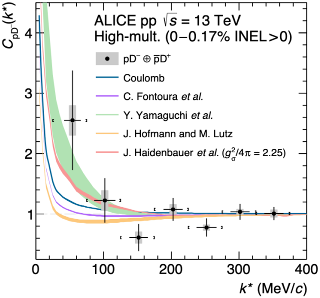

S. Acharya *et al.* [ALICE], Phys.Rev.D 106 (2022) 052010

Model	$a(I=0)$ [fm]	$a(I=1)$ [fm]	
Yamaguchi et al.	-4.38	-0.07	**Bound state**
Haidenbauer et al.	0.67	0.04	**Attractive**
Fontoura et al.	0.16	-0.25	**Attractive**
Hofmann and Lutz	-0.16	-0.26	**Repulsive**

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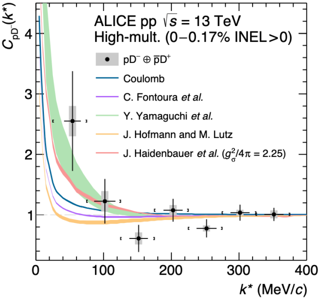

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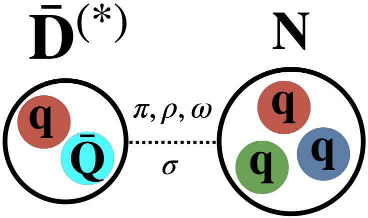
- Recent Lattice QCD: $\bar{D}N$ potential by HALQCD

  W. Yamada *et al.*, arXiv:2603.12251 [hep-lat]

Construction of the $\bar{D}N$ interaction



- Heavy quark spin symmetry ($\bar{D} - \bar{D}^*$ mixing) + Realistic NN interaction
  Y.Y, Shigehiro Yasui, Atsushi Hosaka, Phys. Rev. D 106, 094001 (2022)
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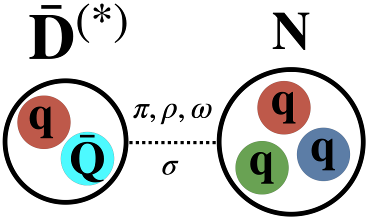

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  - $\pi + \rho, \omega, \sigma$ exchanges are introduced

    - **The π exchange (Tensor)** is the driving force to bind Deuteron

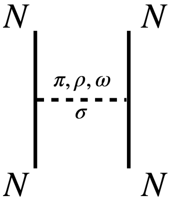
    - **The σ exchange** also generates the attraction $\rightarrow$ important to explain both $I = 0, 1$ NN scattering data simultaneously,

    while there is **ambiguity in V_σ.**

CD-Bonn potential → Simplified CD-Bonn

R. Machleidt, PRC**63**(2001)024001

- Realistic NN potential having the meson exchanges $\pi, \rho, \omega, \sigma$
- Complicated structures of the CD-Bonn, introducing light and heavy "σ_I's", Non-locality,...
  σ_0 for $I = 0$ and σ_1 for $I = 1$



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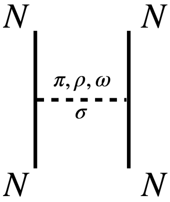

⇒ Obtaining a simplified NN potential in this work,

- employing the light "σ" and the local approximation
- Keeping the coupling constants, but rescaling the cutoffs $\Lambda_N \to \kappa_I \Lambda_N$

CD-Bonn parameters

Mesons	Masses [MeV]	$\frac{g^2_{\alpha NN}}{4\pi}$	$\frac{f_{\alpha NN}}{g_{\alpha NN}}$	Λ_N [MeV] $I=0$	Λ_N [MeV] $I=1$
π	138.04	13.6	—	1384	1330
ρ	769.68	0.84	6.1	1054	1013
ω	781.94	20	0.0	1207	1159
σ_0	350	0.51673	—	2011	—
σ_1	452	3.96451	—	—	1932

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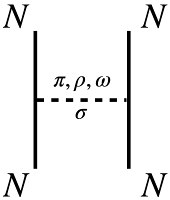

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$$\boldsymbol{\kappa_{I=0} = 0.80,\ \kappa_{I=1} = 0.77}$$

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Results of the Simplified CD-Bonn

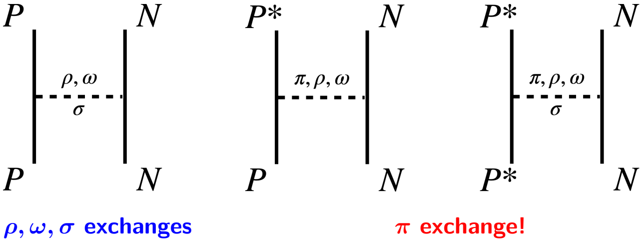
	Simplified CD-Bonn	Exp
B_d [MeV]	2.23 (input)	2.23
a_0 [fm]	5.30	5.42
r_{e0} [fm]	1.56	1.75
a_1 [fm]	-23.7 (input)	-23.7
r_{e1} [fm]	2.34	2.77

The NN properties are reproduced!

Heavy meson-Nucleon interactions

- $DD\pi$ vertex is forbidden due to the parity conservation. $\rightarrow$ No OPEP in the $\bar{D}N$ int.
- Small $\Delta m_{\bar{D}\bar{D}^*} \sim 140$ MeV (Heavy quark spin symmetry) induces the $\bar{D}N - \bar{D}^*N$ channel-coupling interactions $\rightarrow$ enhancing the **π exchange**

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



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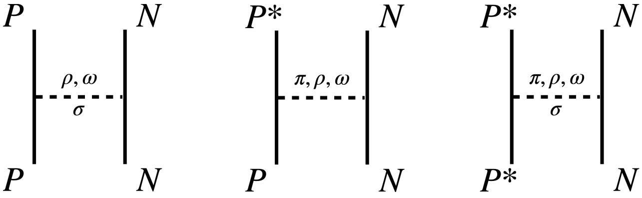
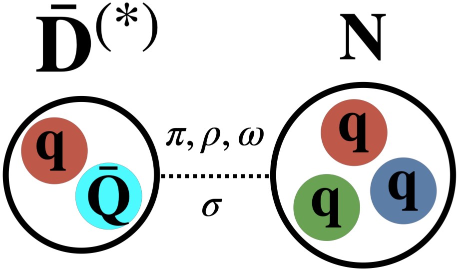


ρ, ω, σ exchanges **π exchange!**

- Parameters
  - $g_{\pi D} = 0.59$ ($D^* \rightarrow D\pi$), $\beta_v = 0.9$, $\lambda = 0.56$ [GeV^{-1}] (B decay)
  - $\boldsymbol{g_{\sigma D} = g_{\sigma NN}/3}$ (σ couples to q in $P(\bar{Q}q)$) $\rightarrow$ We will see the $g_{\sigma D}$ dependence
  - Cuttoff: $\Lambda_D = 1.35\Lambda_N$ from the hadron size

Numerical results



- Solving the coupled-channel Schrödinger equations with the constructed meson exchange potentials.

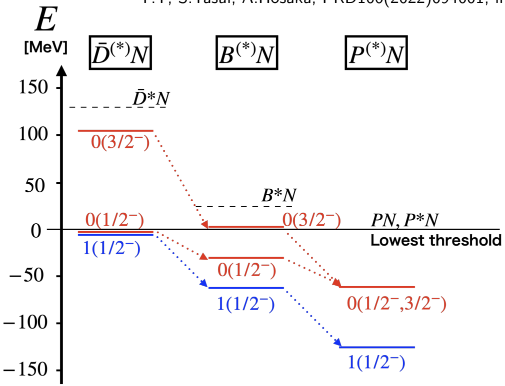
  $J^P = 1/2^-$: $\bar{D}N(^2S_{1/2}), \bar{D}^*N(^2S_{1/2}, ^4D_{1/2})$ **3 channels**

  $J^P = 3/2^-$: $\bar{D}N(^2D_{3/2}), \bar{D}^*N(^4S_{3/2}, ^4D_{3/2}, ^2D_{3/2})$ **4 channels**

- Studying Bound and Resonant states for $\bar{D}N$, BN and PN (heavy quark limit) systems

Summary of numerical results for $\bar{D}N$, BN and PN

Y.Y, S.Yasui, A.Hosaka, PRD106(2022)094001, in preparation



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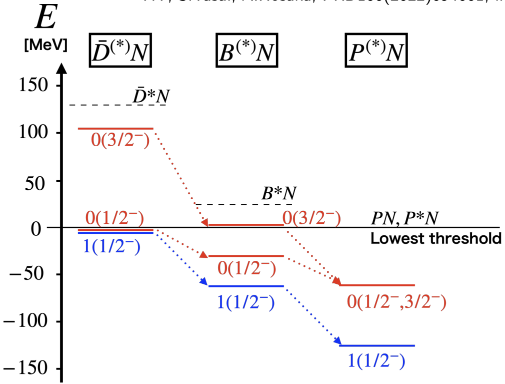

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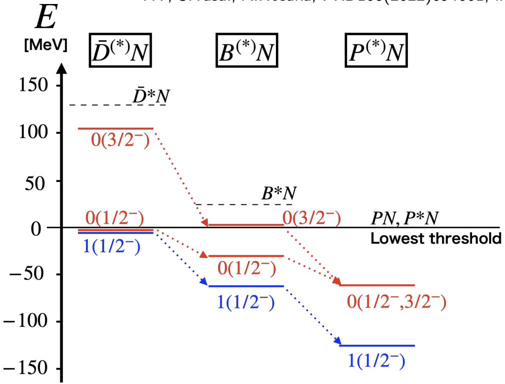

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(j_ℓ: the total angular momentum of the light cloud)

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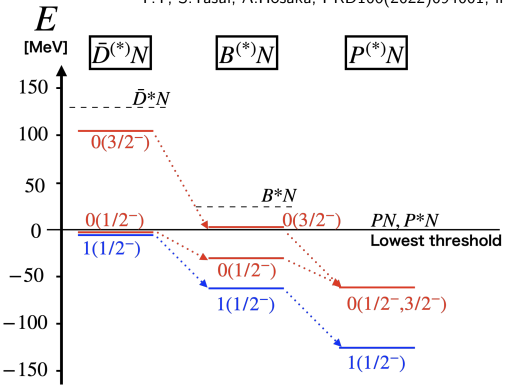

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- For $I = 1$, **$1/2^-$ bound states** ⇒ **HQS singlet** with $j_\ell = 0$

Numerical results of the $\bar{D}^{(*)}N$ state for $I(J^P) = 0(1/2^-)$

- Bound state

Numerical results of the $\bar{D}^{(*)}N$ state for $I(J^P) = 0(1/2^-)$

- Bound state **is found!** $\rightarrow$ Binding energy $=$ **1.38 MeV**
- Mixing ratio
  $\Rightarrow$ $\bar{D}N(^2S_{1/2})$: 96.1%, $\bar{D}^*N(^2S_{1/2})$: 1.94%, $\bar{D}^*N(^4D_{1/2})$: 1.93%
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- Potential energy expectation values $\langle \boldsymbol{V} \rangle$

$\langle V_\pi \rangle$ (−38.61)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	0.0	−0.79	−17.35
$\bar{D}^*N(^2S_{1/2})$	−0.79	0.28	−3.20
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$\langle V_{\rho+\omega} \rangle$ (7.34)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	7.05	−3.89	2.62
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$\langle V_\sigma \rangle$ (−5.25)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	−4.46	—	—
$\bar{D}^*N(^2S_{1/2})$	—	−0.48	—
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V_π tensor

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$\langle V_\pi \rangle$ (**−38.61**)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
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$\bar{D}^*N(^2S_{1/2})$	−0.79	0.28	**−3.20**
$\bar{D}^*N(^4D_{1/2})$	**−17.35**	**−3.20**	3.79

V_π tensor

$\langle V_{\rho+\omega} \rangle$ (7.34)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	7.05	**−3.89**	2.62
$\bar{D}^*N(^2S_{1/2})$	**−3.89**	2.44	0.49
$\bar{D}^*N(^4D_{1/2})$	2.62	0.49	−0.58

V_ρ spin-spin

$\langle V_\sigma \rangle$ (−5.25)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	**−4.46**	—	—
$\bar{D}^*N(^2S_{1/2})$	—	−0.48	—
$\bar{D}^*N(^4D_{1/2})$	—	—	−0.31

V_σ

Phase shifts of the $J^P = 3/2^-$ states with $I = 0$

- $J^P = 3/2^-$: $\bar{D}N(^2D)$, $\bar{D}^*N(^4S)$, $\bar{D}^*N(^2D)$, $\bar{D}^*N(^4D)$

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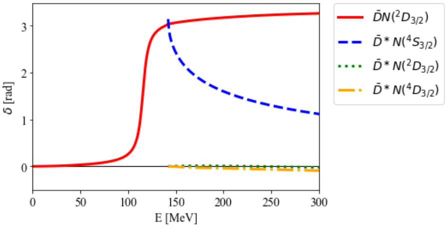
$\bar{D}^{(*)}N$ phase shifts



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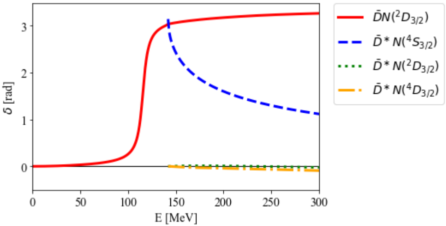
$\bar{D}^{(*)}N$ **phase shifts**



- $\bar{D}N(^2S)$ increasing beyond $\pi/2$

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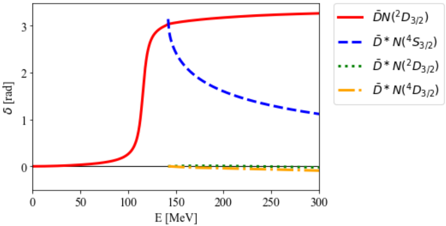

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$\Rightarrow$ **Resonance**
$(E_{re}, \Gamma) = (115.6, 8.42)$ MeV

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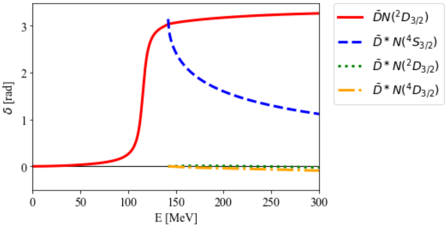

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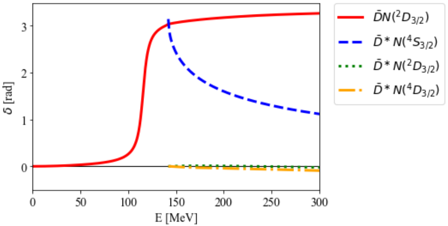

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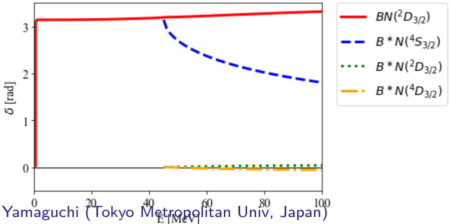
$B^{(*)}N$ phase shifts



- $BN(^2D)$ resonance slightly above the BN threshold

  $(E_{re}, \Gamma) = (0.515, 5.09 \times 10^{-5})$ MeV

- Quasi bound state in $B^*N(^4S)$

Numerical results for $I = 1$ ($J^P = 1/2^-$)

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- Mixing ratio
  $\Rightarrow$ $\bar{D}N(^2S_{1/2})$: 88.9%, $\bar{D}^*N(^2S_{1/2})$: 10.9%, $\bar{D}^*N(^4D_{1/2})$: 0.106%
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$\langle V_\pi \rangle$ (-4.81)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	0.0	-0.95	-1.60
$\bar{D}^*N(^2S_{1/2})$	-0.95	-0.66	0.51
$\bar{D}^*N(^4D_{1/2})$	-1.60	0.51	-5.04×10^{-2}

$\langle V_{\rho+\omega} \rangle$ (2.02)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	29.45	-14.85	0.75
$\bar{D}^*N(^2S_{1/2})$	-14.85	1.18	-0.25
$\bar{D}^*N(^4D_{1/2})$	0.75	-0.25	8.10×10^{-2}

$\langle V_\sigma \rangle$ (-79.32)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	-55.59	—	—
$\bar{D}^*N(^2S_{1/2})$	—	-23.66	—
$\bar{D}^*N(^4D_{1/2})$	—	—	-7.21×10^{-2}

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$\vec{\tau}_1 \cdot \vec{\tau}_2 = +1$

$\leftrightarrow I = 0 : \vec{\tau}_1 \cdot \vec{\tau}_2 = -3$

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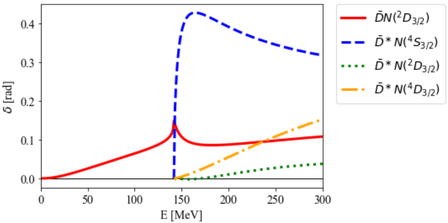
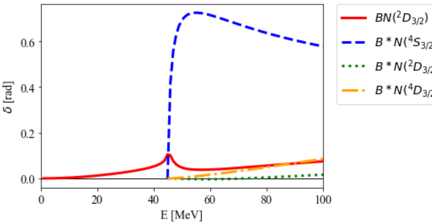
$\bar{D}^{(*)}N$



$B^{(*)}N$



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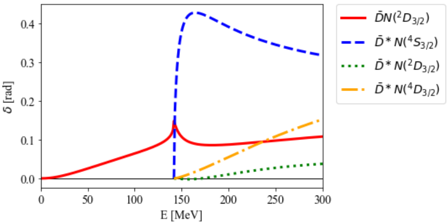

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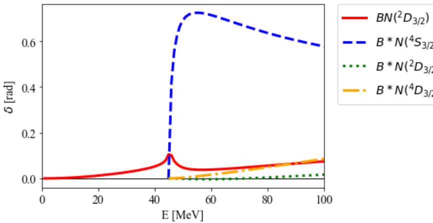
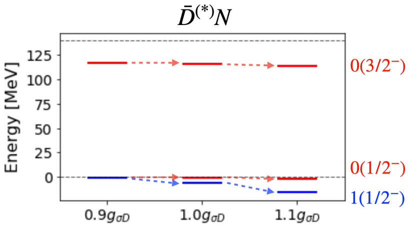


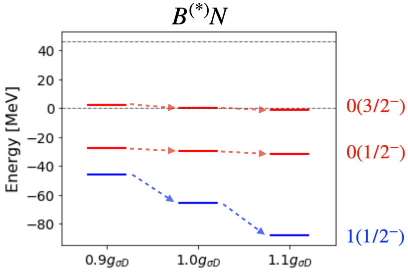
- No (quasi) bound state

⇔ **Bound states for $I(J^P) = 1(1/2^-)$**

  - $\rho + \omega$ produce a strong repulsion
  - The $1(1/2^-)$ bound state is in the HQS singlet (with $j_\ell = 0$), while $1(3/2^-)$ belongs to another HQS multiplet (with $j_\ell = 1$ **or** 2)

Sensitivity to the σ coupling ($g_{\sigma D}$ vs E)





$I = 0$:

Stable against g_σ changing

$I = 1$:

Strongly depending on g_σ

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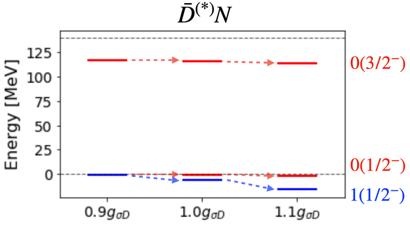

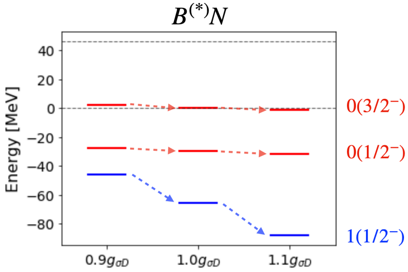

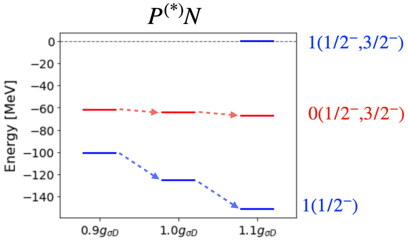

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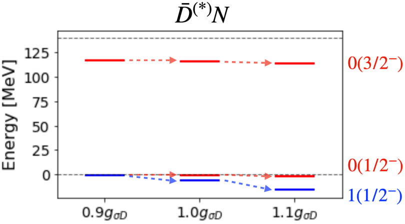

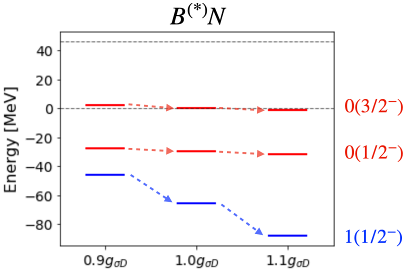

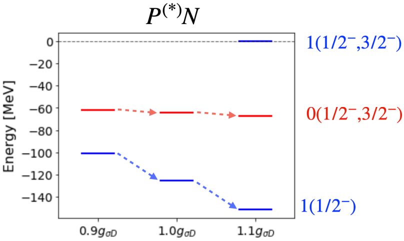

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For PN, Another **HQS doublet** $\boldsymbol{(1(1/2^-, 3/2^-))}$ appears with the strong attraction

Summary

- Investigation of the $\bar{D}N$ interactions
  - Genuine open-charm pentaquark
  - Correlation function obtained by ALICE
- Constructing Meson exchange potentials based on CD-Bonn and Heavy quark symmetry
- Studying $J^P = 1/2^-, 3/2^-$ states
  - Bound states and Resonances are found
  - For $I = 0$, the $1/2^-$ bound states and the $3/2^-$ resonances, belonging to the HQS doublet
    $\rightarrow$ The OPEP tensor force is dominant. The states are stable against the g_σ changing.
  - For $I = 1$, the $1/2^-$ bound state, being the HQS singlet
    $\rightarrow$The σ exchange is dominant. The states strongly depend on $g_{\sigma D}$

Y.Y, Shigehiro Yasui, Atsushi Hosaka, Phys. Rev. D 106, 094001 (2022), in preparation

Thank you for your kind attention.