A narrow quasi-bound state of the DNN system

1. Introduction

2. Setup for the variational calculation
   I. DN potential
   II. NN potential

3. Result
   I. Variational calculation
      • DNN bound state with $S_{NN}=0$
      • DNN state with $S_{NN}=1$
   II. Faddeev-FCA calculation

4. Summary

Variational part:
A. Doté (KEK theory center)
T. Hyodo, M. Oka (TITech)

Faddeev-FCA part:
M. Bayar, C. W. Xiao,
E. Oset (Valencia univ.)

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Hyp 2012 @ Barcelona, Spain, 1st Oct., 2012
1. Introduction
**D mesic nuclei**

= *Charm analog system of \(K^{\bar{b}ar}\) nuclei?*

**Strangeness**

\[K^{\bar{b}ar} = s \, q^{\bar{b}ar}\]

\[\Lambda(1405) = K^{\bar{b}ar}N \, Q.B.S.\]

**Charm**

\[D = c \, q^{\bar{b}ar}\]

\[\Lambda_c(2595) = DN \, Q.B.S?\]
**D mesic nuclei**

= **Charm analog system of K\(^{\bar{\text{bar}}}\) nuclei?**

If \(\Lambda_c(2595)\) is a quasi-bound state of \(I=0\) DN system, ...

- **D nuclei may be a narrow state.**
  \[ \Gamma(\Lambda_c^*) = 1.8 \text{ MeV} \ll \Gamma(\Lambda^*) = 50 \text{ MeV} \]

- **Non-rela. treatment is justified.**
  \[ M_D = 1867 \text{ MeV} \gg M_K = 494 \text{ MeV} \]

**Physics of D mesic nuclei is more clear than that of K\(^{\bar{\text{bar}}}\) nuclei.**

**D nuclei may help the study of K\(^{\bar{\text{bar}}}\) nuclei.**
**Essential D mesic nucleus = DNN**

\[ K^-pp \sim K^{\text{bar}}NN-\piYN \]

- \( M_K = 494\text{MeV} \)
- \( J^{\pi}=0^-, T=1/2 \)

- \( J^{\pi}=0^- \) \( (S_{NN}=0, L=0), T=1/2 \)
Essential D mesic nucleus = DNN

$\text{DNN-}\pi Y_\zeta N$

$M_D = 1867 \text{MeV}$

$J^\pi = 0^-, T=1/2$

- $J^\pi = 0^- \ (S_{NN}=0, L=0), T=1/2$
- $J^\pi = 1^- \ (S_{NN}=1, L=0), T=1/2$
Complementary study
... Variational and Faddeev-FCA calc.

- **Variational calculation**
  - Single channel calculation
    - ... partially take into account the coupled channel effect
  - Treat DNN three-body dynamics
  - Perturbatively estimate the decay width
    (mesonic/non-mesonic decay)
  - Structure of the DNN system by analysis of wave function

- **Faddeev calculation**
  - (Fixed Center Approximation)
    - Fully coupled channel
    - Killed 2N dynamics
    - Directly treat the decay width including 2N absorption
    - No information on the structure

† M. Bayar, J. Yamagata-Sekihara and E. Oset, PRC84, 015209 (2011)
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Dr. Bayar’s talk
“The $K^{\text{bar}}\text{NN}$ revisited including absorption”
Parallel IV, 15:45 - on 4th Oct.

† M. Bayer, J. Yamagata-Sekihara and E. Oset,
PRC84, 015209 (2011)
2. Set up
2. Set up ... same as $K^-pp$ study


- Effective $DN$ potential
  
  Vector meson exchange picture potential
  
  ... Coupled-channel potential ($DN$, $\pi\Sigma_c$, $\pi\Lambda_c$, ...)

  \textbf{Generate dynamically the }$I=0$\textbf{ resonance }$\Lambda_c(2595)$

\textbf{DN single-channel potential} ... equivalent as for $DN$ scattering amplitude
**DN potential**

Based on Mizutani-Ramos study†

Coupled-channel calculation in $DN, \pi\Sigma_c, \pi\Lambda_c, \ldots$ etc with WT-type interaction

\[
v_{ij}^{(1)}(W) = -\frac{\kappa C_{ij}^{(1)}}{4f^2} (2W - M_i - M_j) \sqrt{\frac{M_i + E_i}{2M_i}} \sqrt{\frac{M_j + E_j}{2M_j}}
\]

- WT interaction $\approx$ Vector meson exchange potential
- Due to KSRF relation

- $\kappa=1/4$ for charm exchange process
- $\ldots$ $DN \longleftrightarrow \pi Y_c$
- $\kappa=1$ for other cases

---

Effective $DN$ potential

**Similar way to the $K^{\bar{\text{b}}arN}$ study**††

- Eliminate other channels than $DN$.
- Reproduce the original $DN$ scattering amplitude.
- Single-range Gaussian form

† T. Mizutani and A. Ramos, PRC74, 065201 (2006)
†† T. Hyodo and W. Weise, PRC77, 035204 (2007)
**DN potential**

\[ v_{DN}(r; W) = \frac{M_N}{2\pi^{3/2}a_s^3\tilde{\omega}(W)} \]
\[ \times [v_{\text{eff}}(W) + \Delta v(W)] \exp[-(r/a_s)^2] \]

- **Energy-dependent pot.**
- \( a_s = 0.40 \text{fm} \)

- **DN scattering amplitude**

- \( \Lambda_c(2595) \) dynamically generated

- Resonance @ 2766 MeV
2. Set up ... same as $K^{-}pp$ study


- **Effective $DN$ potential**

  Vector meson exchange picture potential

  ... Coupled-channel potential ($DN$, $\pi\Sigma_c$, $\pi\Lambda_c$, ...)

  *Generate dynamically the $l=0$ resonance $\Lambda_c(2595)$*

- **$NN$ potential** ... $NN$ phase shift respected

  - Av18\(^1\)
  - Hasegawa-Nagata No.1\(^2\) Revised
  - Minnesota\(^3\)

  Repulsive core  ~ 3 GeV

  ~ 1 GeV

  ~ 0.1 GeV

2) A. Hasegawa and S. Nagata, PTP45, 1786 (1971)
**NN potentials = Minnesota, HN1R, Av18**

Potential (\(^1E\) channel)

- Minnesota (\(u=1\))
- HN1R
- Av18 (C+SS)

Phase shift (\(^1S_0\))

\[
\begin{align*}
0.25 \times V_1 + 0.95 \times V_2 + 1.00 \times V_3 \\
\text{Long-range} & \quad \text{Middle-range} & \quad \text{Short-range}
\end{align*}
\]

**HN1R = slightly modified Hasegawa-Nagata No.1**

- \(^3E\) channel: Reproduce B. E. of deuteron
- \(^1E\) channel: No bound state in \(^1S_0\) channel

\(r [\text{fm}]\)

\(E_{cm} [\text{MeV}]\)

\(\delta [\text{deg.}]\)
2. Set up ... same as \textit{K-pp} study


- Effective \textit{DN} potential = \textit{Complex potential}

  Vector meson exchange picture potential
  ... Coupled-channel potential (\textit{DN}, \pi\Sigma_c, \pi\Lambda_c, ...)

- \textit{DN single-channel potential} ... equivalent as for \textit{DN} scattering amplitude

- \textit{NN} potential ... \textit{NN} phase shift respected
  - Av18
  - Hasegawa-Nagata No.1 Revised
  - Minnesota

- Repulsive core \sim 3 \text{ GeV}
- \sim 1 \text{ GeV}
- \sim 0.1 \text{ GeV}

- \textbf{Variational calculation}
  - Use the \textit{real part} of the effective \textit{DN} potential
  - Expand the trial wave function with Gaussian base
3. Result

\[ \text{DNN bound state with } S_{NN} = 0 \]

\[ J^\pi = 0^- , \ T = 1/2 \]

\[ L = 0 \]
**DNN(S=0) : Minnesota, HN1R, Av18**

**B. E. and size of DNN (S=0)**

<table>
<thead>
<tr>
<th>Potential</th>
<th>B.E. (MeV)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Minnesota</td>
<td>250.9</td>
<td>250.9</td>
<td>209.4</td>
</tr>
<tr>
<td>HN1R</td>
<td>225.4</td>
<td>225.4</td>
<td>209.4</td>
</tr>
<tr>
<td>Av18 (C+SS)</td>
<td>209.4</td>
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**NN**

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**R_{rms}**

<table>
<thead>
<tr>
<th>Potential</th>
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<th>B.E. (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minnesota</td>
<td>0.5</td>
<td>0.5</td>
<td>0.75</td>
</tr>
<tr>
<td>HN1R</td>
<td>0.75</td>
<td>0.75</td>
<td>1.26</td>
</tr>
<tr>
<td>Av18 (C+SS)</td>
<td>1.26</td>
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</tr>
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**DNN (S=0)**

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<tr>
<td>Minnesota</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
<tr>
<td>HN1R</td>
<td>16.5</td>
<td>16.5</td>
<td>16.5</td>
</tr>
<tr>
<td>Av18 (C+SS)</td>
<td>0.5</td>
<td>0.5</td>
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**\(\Lambda_{c^*} - N\)**

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<tbody>
<tr>
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**\(\Gamma(\pi Y_c)\)**

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<td>26</td>
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**DN pot.**

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</table>
Structure of DNN ($S=0$)

One-body density

$D$ meson distributes compactly inside of the system.

NN pot: HN1R
DN pot. : $b=0.40\,\text{fm}$, $B(D)=208.9\,\text{MeV}$
**Structure of DNN (S=0)**

**DN correlation density**

Isospin-decomposed

\[ \rho_{DN,I}(r), \rho_{\Lambda_c^*}(r) \ [fm^{-3}] \]

\[ r^2 \rho_{DN,I}^{\text{Normalized}}(r) \ [fm^{-1}] \]

\[ r^2 \rho_{\Lambda_c^*}(r) \ [fm^{-1}] \]

- The distribution of the I=0 DN component in DNN (S=0) system is similar to that of the DN forms \( \Lambda_c^* \).
  
  (Similar to \( K^{bar}NN \) case)

**Notations:**

- DNN (I=0)
- DNN (I=1)

**Parameters:**

- NN pot: HN1R
- DN pot.: \( b=0.40\text{fm} \), \( B(D)=208.9\text{MeV} \)
3. Result

DNN bound state with $S_{NN}=1$

$J^\pi=1^-, T=1/2$

$L=0$
$S=1$ state of DNN

Total energy vs $1/\sqrt{\mu}$

- Increase $1/\sqrt{\mu}$
  - $\Rightarrow$ DNN $(S=1)$ energy $\rightarrow \Lambda_c^* - N$ threshold energy

$\Lambda_c^* - N$ scattering state!
3. Result

Faddeev-FCA calculation

\[ J^\pi=0^-, \ T=1/2 \]

\[ J^\pi=1^-, \ T=1/2 \]
DNN with Faddeev-FCA calculation

Result (with 2N absorption)

\[ J^{\pi}=0^{-}, \ T=1/2 \]

Total mass \( \sim 3490 \text{ MeV} \)

\[ J^{\pi}=1^{-}, \ T=1/2 \]

Total mass \( \sim 3500 \text{ MeV} \)

- \( \sim 250 \text{ MeV} \) below DNN threshold
- both states are below \( \Lambda_c^*N \) threshold
- Full decay width \( \sim 20-25 \text{ MeV} \)
4. Summary
4. Summary

The DNN system studied with two approaches: Variational and Faddeec-FCA approaches

- Charm analog state of $K^{\text{bar}}NN$
- $J^{\pi}=0^- (S_{NN}=0)$ and $1^- (S_{NN}=1), T=1/2$

DN potential

- Based on vector-meson exchange picture
- $\Lambda_c(2595)$ ... described as a DN resonance of $I=0$
- [Variational] Effective DN potential reproducing $I=0$ scattering amplitude with single Gaussian form

NN potentials [Variational]

- Minnesota ... Soft core (0.1GeV)
- Hasegawa Nagata No.1 (R) ... Mild core (1GeV)
- Av18 (Gaussian fitted) ... Hard core (3GeV)
4. Summary

As a result of variational calculation, ...

\[ DNN \ (J^{\pi}=0^-) \ ... \ bound \ below \ \Lambda_c(2595)-N \ threshold \]

- Total B. E. \( \sim 225 \) MeV
  \( (\sim 15\) MeV below \( \Lambda_c(2595)-N \) threshold
  Total mass \( \sim 3520 \) MeV)
- Decay width \( (\pi Y_c) \sim 25\) MeV
  ... narrow compared with total B.E.

\[ D \ meson \ stays \ at \ center \ of \ the \ system, \ I=0 \ DN \ component \ \cong \ \Lambda_c(2595) \]

\[ DNN \ (J^{\pi}=1^-) \ ... \ scattering \ state \ of \ \Lambda_c(2595)-N \]

Faddeev-FCA calculation gives ...

- Both \( J^{\pi}=0^- \) and \( 1^- \) states are bound below \( \Lambda_c(2595)-N \) threshold.
  Total mass \( \sim 3500 \) MeV
- Narrow decay width, even including \( 2N \) absorption
  Full width \( \sim 20 – 25 \) MeV