DN interaction, $\Lambda_c(2595)$, and DNN quasi-bound state

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Contents

- Introduction
- DN interaction and $\Lambda_c(2595)$
- DNN quasi-bound state
  - Variational calculation with DN potential
  - FCA to Faddeev equation
- Summary
Conventions for heavy mesons

Convention of quantum number of quarks

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<thead>
<tr>
<th></th>
<th>strange</th>
<th>charm</th>
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<tbody>
<tr>
<td>S</td>
<td>-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>-1</td>
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Heavy-light mesons: bar for negative flavor-ness (q~u,d)

<table>
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<tr>
<th></th>
<th>with (\bar{q})</th>
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<tbody>
<tr>
<td></td>
<td>(\bar{K}) (s(\bar{q}))</td>
<td>D (c(\bar{q}))</td>
<td>(\bar{B}) (b(\bar{q}))</td>
</tr>
<tr>
<td></td>
<td>(K) (s(q))</td>
<td>(\bar{D}) (c(q))</td>
<td>(B) (b(q))</td>
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\(\text{DN} \leftrightarrow \bar{K}N\) : non-exotic light quark annihilation

\(\bar{D}N \leftrightarrow KN\) : exotic \(\Theta^+\), Yasui-Sudoh
Why DN and DNN?

Comparison with $\bar{K}N$ system in l=0 channel

- Large mass splitting between DN and $\pi\Sigma_c$
- Narrow negative parity $\Lambda_c^*$, analogous to $\Lambda(1405)$?

$\Lambda^*$: a $\bar{K}N$ bound state in the $\pi\Sigma$ continuum --> $\bar{K}$ nuclei
$\Lambda_c^*$: a DN bound state in the $\pi\Sigma_c$ continuum --> D nuclei? (c.f. conventionally, $\Lambda_c^* \sim 3$-quark state)
Can $\Lambda_c^*$ (with large binding) be a DN quasi-bound state?

- D (1867 MeV) is heavier than $\bar{K}$ (496 MeV). Kinetic energy is suppressed. If the DN interaction were the same with $\bar{K}N$, system would develop a deeper quasi-bound state.

- Vector meson exchange picture leads to a stronger DN interaction than $\bar{K}N$ at threshold

$$\frac{V_D}{V_K} = \frac{m_D}{m_K} \sim 3.8$$

DN system can generate a strongly bound state: $\Lambda_c^*$. 

DN interaction and $\Lambda_c(2595)$
Vector meson exchange for DN

DN (KN) interaction in vector meson exchange (low energy)

\[ V \sim g \bar{u} \gamma^\mu u \times \frac{1}{k^2 - m_v^2} \left[ g_{\mu\nu} - \frac{k_\mu k_\nu}{m_v^2} \right] \times g(q + q')^\nu \]

\[ \rightarrow -\bar{u} \gamma^\mu u \frac{g^2}{m_v^2} g_{\mu\nu} (q + q')^\nu \quad (k \ll m_v) \]

\[ \rightarrow -\frac{1}{2f^2} \bar{u}(\psi + \psi') u \quad \text{(KSRF relation)} \]

\[ \rightarrow -\frac{1}{2f^2} (q^0 + q^{0'}) \quad \text{(nonrel. leading)} \]

\[ \rightarrow -\frac{m}{f^2} \quad \text{(at threshold)} \]

Interaction in DN-πΣ_c system

\[ V \sim \left( \begin{array}{c} -3m_D \\ \sqrt{\frac{3}{2}} \kappa_c \frac{m_D + m_\pi}{2} \\ \frac{3}{2} \kappa_c \frac{m_D + m_\pi}{2} \\ -4m_\pi \end{array} \right) \]

- strong DN interaction --> large binding energy
- suppressed off-diagonal coupling --> narrow width of Λ_c^*
Coupled-channel DN ($\pi\Sigma_c$, $\eta\Lambda_c$, $K\Xi_c$, $K\Xi_c'$, $D_s\Lambda$, $\eta'\Lambda_c$) scattering see T. Mizutani, A. Ramos, Phys. Rev. C74, 065201 (2006)

Subtraction constants (cutoff parameters) are chosen to reproduce $\Lambda_c^*$ in $I=0$. Apply the same constants to $I=1$.

A resonance at ~ 2760 MeV is generated in $I=1$ channel.
c.f. PDG 1*: $\Lambda_c^*(2765)$ or $\Sigma_c^*(2765)$ ??
DN local potential

**Equivalent single-channel local potential**


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

- reproduces the coupled channel amplitude

This potential reproduces the DN amplitude in CC model.

Larger (smaller) real (imaginary) part than \(\bar{K}N\)
Our model space: meson-baryon channels. No bare field.

- Is the quasi-bound state a DN molecule?

No. Pole contribution can be hidden in the cutoff.


\[
T = \frac{1}{(V^{(1)})^{-1} - G(a)}
\]

\[
T = \frac{1}{(V^{(1)} + V^{(2)})^{-1} - G(a')}
\]

↑ pole

Once the cutoff parameter is chosen to reproduce data, it can play a role of bare field as well as other coupled channels (πΣ_c^*, D*N, etc.), which are not included in the model space.
Strategy for DNN bound state

Coupled-channel model
DN amplitude, $\Lambda_c(2595)$

DN single-channel potential

real part

Three-body variational calculation
- Structure from wave function
- NN dynamics is dynamically solved.

Fixed-center approximation to Faddeev equation
- Two-body absorption
- Imaginary part of the amplitude is treated.

Assume NN distribution

Coupled-channel ($\pi Y_c N$) effect is partly included.
DNN quasi-bound state

Variational calculation: setup

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

- $J^P=0^-$ “D$^+$nn”
  
  $S_{NN}=0$
  
  $I_{NN}=1$ (s-wave) --> $\text{DN}(I=0) : \text{DN}(I=1) = 3:1$

- $J^P=1^-$ “D$^+$d”
  
  $S_{NN}=1$
  
  $I_{NN}=0$ (s-wave) --> $\text{DN}(I=0) : \text{DN}(I=1) = 1:3$

Two-body interactions

- DN imaginary part is neglected
- energy dependence is fixed at $\Lambda_c^*$ ($I=1$ QBS disappears)
- three kinds of NN forces (Av18, HN1R, Minnesota)
Results of the DNN system

- J=0 bound, J=1 unbound w.r.t. [DN]N
- mesonic decay width is small
- softer the core, larger the binding

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<th>HN1R</th>
<th>Minnesota</th>
<th>Av18</th>
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<tr>
<td></td>
<td>(J=1)</td>
<td>(J=0)</td>
<td>(J=0)</td>
</tr>
<tr>
<td>(B)</td>
<td>bound</td>
<td>bound</td>
<td>bound</td>
</tr>
<tr>
<td>(B)</td>
<td>208</td>
<td>225</td>
<td>251</td>
</tr>
<tr>
<td>(M_B)</td>
<td>3537</td>
<td>3520</td>
<td>3494</td>
</tr>
<tr>
<td>(\Gamma_{\pi Y_c N})</td>
<td>-</td>
<td>26</td>
<td>38</td>
</tr>
<tr>
<td>(E_{\text{kin}})</td>
<td>338</td>
<td>352</td>
<td>438</td>
</tr>
<tr>
<td>(V(\text{NN}))</td>
<td>0</td>
<td>-2</td>
<td>19</td>
</tr>
<tr>
<td>(V(\text{DN}))</td>
<td>-546</td>
<td>-575</td>
<td>-708</td>
</tr>
<tr>
<td>(T_{\text{nuc}})</td>
<td>113</td>
<td>126</td>
<td>162</td>
</tr>
<tr>
<td>(E_{NN})</td>
<td>113</td>
<td>124</td>
<td>181</td>
</tr>
<tr>
<td>(P(\text{Odd}))</td>
<td>75.0 %</td>
<td>14.4 %</td>
<td>7.4 %</td>
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Variational calculation: results

DNN quasi-bound state

209-251 MeV

209-251 MeV

1-4.3 MeV
DNN quasi-bound state

Variational calculation: DN correlation

Isospin decomposition of DN two-body correlation

$$\rho_{DN}(r) = \langle \Psi \mid \sum_{i=1,2} \delta^3(\mid r_D - r_i \mid - r) \mid \Psi \rangle$$

DN (I=0) correlation is similar to $\Lambda_c^*$
Fixed-center approximation to Faddeev equation

- Complex DN amplitude
- all two-body pairs are in s-wave
- NN distribution is assumed
  (chosen to be smaller than the deuteron)
FCA calculation: two-body absorption

Two-body absorption --> imaginary part of DN amplitude

\[ g_{DN} \rightarrow g_{DN} + i \text{Im} \delta \tilde{g} \]

DN loop

two-body absorption contribution

DNN quasi-bound state

Re

Im

FIG. 4. Form factor of the deuteron, and the one correspond-

Fig. 5 (other mechanisms and decay channels will be dis-

instrumenting the

system. Yet, there are limits

system more compact,

\[ s_{1/2}^2 \approx 0 \] t he wave function \( \tilde{\Lambda} \)

accounted for at the end of the formalism.

 integrating, and make a change of the spatial variables

Defining of

\[ \alpha \]

for the

amplitude,

\[ \tilde{\Lambda} \]

inspecting of Fig. 8, together with the values of

This leads to the expression of the coupling of the reso-

For a narrow resonance, we can approximate the am-

\[ \delta \tilde{g} \]

two-body

\[ \text{Im} \delta \tilde{g} \]

\[ g_{DN} \rightarrow g_{DN} + i \text{Im} \delta \tilde{g} \]

two-body absorption contribution

\[ s_{1/2}^2 \approx 0 \] t he wave function \( \tilde{\Lambda} \)

accounted for at the end of the formalism.

 integrating, and make a change of the spatial variables

Defining of

\[ \alpha \]

for the

amplitude,
DNN quasi-bound state

FCA calculation: result

Magnitude of the three-body amplitude square

\[ |T| \]

**J=0 channel:** \( M \sim 3500 \text{ MeV} \)
- strong signal, **consistent with the variational calculation**

**J=1 channel:** \( M \sim 3500 \text{ MeV} \) and \( M \sim 3700 \text{ MeV} \)?
- week signal, not found in the variational calculation??
- \( I=1 \) DN interaction is important for this channel.
Possible experiments

Antiproton beam

\[ \bar{p} + ^3\text{He} \rightarrow \bar{D}^0 D^0 pn \rightarrow \bar{D}^0 [DNN] \]

- PANDA?

Pion beam

\[ \pi^- + d \rightarrow D^- D^+ np \rightarrow D^- [DNN] \]

\[ \pi^- + d \rightarrow D^- \Lambda_c^+ n \rightarrow D^- [DNN] \]

- J-PARC high momentum beamline?

Heavy Ion collision

Coalescence DNN (large binding), \( \Lambda_c^* N \) (small binding)

- RHIC, LHC,...

We study DN interaction and DNN system

DN interaction is constructed by regarding $\Lambda_c^*$ as “DN quasi-bound state”.

A narrow DNN quasi-bound state in spin $J=0$ channel.

$B_{\text{DNN}} \sim 250 \text{ MeV}, \quad B_{\Lambda_c^*N} \sim 40 \text{ MeV}$

$\Gamma \sim 20-40 \text{ MeV}$

DN forms a compact cluster, but $\Lambda_c^*N$ bounds loosely.

M. Bayar et al., arXiv:1205.2275 [hep-ph]