D-meson-nucleon interaction and DNN systems

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Introduction

Conventions for heavy mesons

Convention of quantum number of quarks

<table>
<thead>
<tr>
<th></th>
<th>strange</th>
<th>charm</th>
<th>bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>$-1$</td>
<td>$+1$</td>
<td>$-1$</td>
</tr>
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Heavy-light mesons: bar for negative flavor-ness ($q \sim u,d$)

<table>
<thead>
<tr>
<th></th>
<th>with $\bar{q}$</th>
<th>with $q$</th>
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</thead>
<tbody>
<tr>
<td>with $\bar{q}$</td>
<td>$\bar{K}$ ($s\bar{q}$)</td>
<td>$K$ ($s\bar{q}$)</td>
</tr>
<tr>
<td>with $q$</td>
<td>$D$ ($c\bar{q}$)</td>
<td>$\bar{D}$ ($c\bar{q}$)</td>
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$\bar{D}N \leftrightarrow KN$ : exotic $\Theta^+$, Ikeda’s talk

$DN \leftrightarrow \bar{K}N$ : non-exotic light quark annihilation
Why DN and DNN?

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

$\bar{K}N$ vs. $\pi\Sigma_c$

$\Lambda^*(1405)$

$\sim 100$ MeV

$\sim 15-30$ MeV

$\sim 210$ MeV

$\sim 200$ MeV

- 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?
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

  \[
  \frac{V_D}{V_K} = \frac{m_D}{m_K} \sim 3.8 \quad \text{(next slide)}
  \]

DN system can generate a **strongly bound state**: $\Lambda_c^*$. 
Vector meson exchange for DN

DN ($\bar{K}N$) interaction in vector meson exchange (low energy)

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

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

\[
\rightarrow -\frac{1}{2f^2} \bar{u}(\not{q} + \not{q'}) u \quad \text{(KSRF relation)}
\]

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

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

Interaction in DN-$\pi\Sigma_c$ system

\[
V \sim \begin{pmatrix}
-3m_D \\
\sqrt{\frac{3}{2} \kappa_c \frac{m_D + m_\pi}{2}} \\
\sqrt{\frac{3}{2} \kappa_c \frac{m_D + m_\pi}{2}} - 4m_\pi
\end{pmatrix}
\]

- strong DN interaction $\rightarrow$ large binding energy
- suppressed off-diagonal coupling $\rightarrow$ narrow width of $\Lambda_c^*$
Coupled-channel DN (πΣ_c, ηΛ_c, KΞ_c, KΞ_c', D_sΛ, η'Λ_c) scattering

Subtraction constants (cutoff parameters) are chosen to reproduce Λ_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*: Λ_c*(2765) or Σ_c*(2765) ??
DN interaction and \( \Lambda_c(2595) \)

**DN local potential**

**Equivalent single-channel local potential**


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

- reproduces the coupled channel amplitude

This potential reproduces the DN amplitude in CC model.
Larger (smaller) real (imaginary) part than \( \bar{K}N \)
Strategy for DNN bound state

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

DN single-channel potential

- 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) --> DN(I=0):DN(I=1) = 3:1

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

Two-body interactions

- DN imaginary part is neglected
- energy dependence is fixed at Λ_c* (I=1 QBS disappears)
- three kinds of NN forces (Av18, HN1R, Minnesota)
DNN quasi-bound state

Variational calculation: results

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

<table>
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<tr>
<th></th>
<th>HN1R</th>
<th>Minnesota</th>
<th>Av18</th>
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<tbody>
<tr>
<td>( J = 1 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unbound</td>
<td>208</td>
<td>225</td>
<td>251</td>
</tr>
<tr>
<td>bound</td>
<td>3537</td>
<td>3520</td>
<td>3494</td>
</tr>
<tr>
<td>( J = 0 )</td>
<td></td>
<td></td>
<td></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(NN) )</td>
<td>0</td>
<td>-2</td>
<td>19</td>
</tr>
<tr>
<td>( V(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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209-251 MeV

1-43 MeV

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Isospin decomposition of DN two-body correlation

\[ \rho_{DN}(x) = \langle \Psi | \sum_{i=1,2} \delta^3(|\mathbf{r}_D - \mathbf{r}_i| - x) | \Psi \rangle \]

DN (I=0) correlation is similar to \( \Lambda_c^* \)
DNN quasi-bound state

FCA calculation

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)
DNN quasi-bound state

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

\[
\text{ Re } \quad \text{ Im }
\]

\[
\text{s}_{1/2} \text{[MeV]}
\]

\[
2200 \quad 2300 \quad 2400 \quad 2500 \quad 2600 \quad 2700 \quad 2800 \quad 2900 \quad 3000
\]
DNN quasi-bound state

FCA calculation: result

Magnitude of the three-body amplitude square

\[ J=0 \]

\[ J=1 \]

**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??
- \( l=1 \) 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, \( \Lambda_c^* N \)

- 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.

$B_{\text{DNN}} \sim 250$ MeV, $B_{\Lambda_{c}^{*}N} \sim 40$ MeV

$\Gamma \sim 20$-40 MeV

DN interaction in $I=1$ channel (negative parity $\Sigma_{c}^{*}$) is important for $J=1$ result.

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