Energy and width of a narrow $|\frac{1}{2}\rangle$ DNN quasibound state

Tetsuo Hyodo

Tokyo Institute of Technology

with M. Bayar, C.W. Xiao, A. Dote, M. Oka, E. Oset

supported by Global Center of Excellence Program
“Nanoscience and Quantum Physics”
Contents

Introduction

DN interaction and $\Lambda_c(2595)$

DNN quasi-bound state

- Variational calculation with DN potential
- FCA to Faddeev equation

Summary
Why DN and DNN?

$ar{K}$ nuclei $\leftarrow \Lambda^*$: a $\bar{K}N$ bound state in the $\pi\Sigma$ continuum

$D$ nuclei? $\leftarrow \Lambda_c^*$: a DN bound state in the $\pi\Sigma_c$ continuum

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

- narrow negative parity $\Lambda_c^*$, analogous to $\Lambda(1405)$?

(conventional view: $\Lambda_c^* \sim 3$-quark state 200 MeV binding: too large?)
Can $\Lambda_c^*$ (with large binding) be a $DN$ quasi-bound state?

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

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

(next slide)

- $D$ (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.

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

$$B_{DN} > B_{\bar{K}N} = 15-30 \text{ MeV}$$
**Vector meson exchange for DN**

**DN (K̅N) interaction in vector meson exchange (low energy)**

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

- \( k \ll m_v \) + KSRF relation

\[ \rightarrow -\frac{1}{2f^2}(q^0 + q'^0) \]  
(Weinberg-Tomozawa)

- at threshold

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

**Interaction in DN-πΣ_c system (J/Ψ exchange ignored)**

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

\[ \kappa_c \sim \frac{m_{K^*}^2}{m_{D^*}^2} \sim \frac{1}{4} \]

- strong DN interaction --> large binding energy

- suppressed off-diagonal coupling --> narrow width of \( \Lambda_c^* \)
Coupled-channel $DN (\pi \Sigma_c, \eta \Lambda_c, K \Xi_c, K \Xi_c', D_s \Lambda, \eta' \Lambda_c)$ scattering

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

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

Equivalent single-channel local potential


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

- reproduces the coupled channel amplitude

- This potential reproduces the \( \text{DN} \) amplitude in CC model.

- Larger (smaller) real (imaginary) part than \( \bar{\text{KN}} \)
Strategy for DNN bound state

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

DNN 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 ($\pi Y_0^c N$) effect is partly included.
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>
<thead>
<tr>
<th></th>
<th>HN1R</th>
<th>Minnesota</th>
<th>Av18</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( J = 1 )</td>
<td>( J = 0 )</td>
<td>( J = 0 )</td>
</tr>
<tr>
<td>( B )</td>
<td>unbound</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 YcN} )</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_{\text{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>
</tr>
</tbody>
</table>
Variational calculation: \( \text{DN} \) correlation

Isospin decomposition of \( \text{DN} \) two-body correlation

\[
\rho_{\text{DN}}(r) = \langle \Psi | \sum_{i=1,2} \delta^3(|r_D - r_i| - r) \rangle \Psi
\]

\( \text{DN (I}=0) \) correlation is similar to \( \Lambda_C^\ast \)
DNN quasi-bound state

**FCA calculation**

Fixed-center approximation to Faddeev equation

- Complex $DNN$ amplitude
- All two-body pairs are in s-wave
- $NN$ distribution is assumed
  (checked with the variational calculation result)
FCA calculation: two-body absorption

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

$g_{DN} \rightarrow g_{DN} + i \text{Im} \delta g$

$DN$ loop
two-body absorption contribution
In Figs. 9 and 10 we show the results for one-body and two-body densities, respectively. The results are summarized in Table I, together with the uncertainties. The novelty, which is welcome, is that we can see the strong signal, consistent with the variational calculation.

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

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

Antiproton beam

\[ \bar{p} + ^3\text{He} \to \bar{D}^0D^0np \to \bar{D}^0[DNN]^+ \]

- PANDA?

Pion beam

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

\[ \pi^- + d \to D^-\Lambda_c^{*+}n \to D^-[DNN]^+ \]

- 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 $J=0$ and isospin $I=1/2$ channel.

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

$\Gamma \sim 20-40$ MeV

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