Structure of the $\Lambda(1405)$ and kaon-nucleon dynamics

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Contents

Chiral unitary approach

Structure of Λ(1405)

• Dynamical or CDD pole (genuine quark state)?

• Nc Behavior and quark structure

• Electromagnetic properties

Effective single-channel KN interaction


On the KNN (strange dibaryon) system
Description of $S = -1$, $\bar{K}N$ s-wave scattering: $\Lambda(1405)$ in $I=0$

- Interaction $\leftrightarrow$ chiral symmetry
  

- Amplitude $\leftrightarrow$ unitarity (coupled channel)
  
  R.H. Dalitz, T.C. Wong, G. Rajasekaran, PR153, 1617 (1967)

\[
T = \frac{1}{1 - VG} V
\]

\[= \text{chiral}\]


works successfully, also in $S=0$ sector, meson-meson scattering sectors, systems including heavy quarks, ...
Chiral unitary approach

How it works? vs experimental data

Total cross sections

threshold ratios

<table>
<thead>
<tr>
<th></th>
<th>( \gamma )</th>
<th>( R_c )</th>
<th>( R_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp.</td>
<td>2.36</td>
<td>0.664</td>
<td>0.189</td>
</tr>
<tr>
<td>theo.</td>
<td>1.80</td>
<td>0.624</td>
<td>0.225</td>
</tr>
</tbody>
</table>

\[ \pi \Sigma \] spectrum

**πΣ** spectrum

**πΣ** mass distribution


\( \Rightarrow \) \( \bar{K}N \) interaction in this framework
Two poles for one resonance

Poles of the amplitude in the complex plane: resonance

\[ T_{ij}(\sqrt{s}) \sim \frac{g_ig_j}{\sqrt{s - M_R + i\Gamma_R/2}} \]

\[ \sim \]

Real part

Imaginary part

Residues

Mass

Width/2

Couplings

Physical state: superposition

\[ |\Lambda(1405)\rangle = a|\Lambda_1^*\rangle + b|\Lambda_2^*\rangle \]

Dynamical state and CDD pole

Resonances in two-body scattering

- Knowledge of interaction (potential)
- Experimental data (cross section, phase shift,...)

(a) dynamical state: molecule, quasi-bound, ...

\[ \begin{array}{c}
\text{M} \\
\text{B}
\end{array} \]

e.g.) Deuteron in NN, positronium in $e^+e^-$, ($\sigma$ in $\pi\pi$), ...

(b) CDD pole: elementary, independent, ...

\[ \begin{array}{c}
\text{M} \\
\text{B}
\end{array} \]

e.g.) J/$\Psi$ in $e^+e^-$, ($\rho$ in $\pi\pi$), ...

Resonances in chiral unitary approach $\rightarrow$ (a) dynamical?

CDD pole contribution in chiral unitary approach

Amplitude in chiral unitary model

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

- \( V \): interaction kernel (potential)
- \( G \): loop integral (Green’s function)

Known CDD pole contribution

1. Explicit resonance field in \( V \)
2. Contracted resonance propagator in \( V \)

Defining “natural renormalization scheme”, we find CDD pole contribution in \( G \) (subtraction constant).

Structure of \( \Lambda(1405) \) resonance


\[ N(1535) \text{ in } \pi N \text{ scattering} \]
\[ \rightarrow \text{dynamical} + \text{CDD pole} \]

\[ \Lambda(1405) \text{ in } \bar{K}N \text{ scattering} \]
\[ \rightarrow \text{mostly dynamical} \]
Nc scaling in the model

Nc : number of color in QCD
Hadron effective theory / quark structure

The Nc behavior is known from the general argument.
 <-- introducing Nc dependence in the model,
analyze the resonance properties with respect to Nc


Nc scaling of (excited) qqq baryon

\[ M_R \sim \mathcal{O}(N_c), \quad \Gamma_R \sim \mathcal{O}(1) \]

Result : \( \Gamma_R \neq \mathcal{O}(1) \)
~ non-qqq (i.e. dynamical) structure

Electromagnetic properties

Attaching photon to resonance

--> em properties : rms, form factors,...

Structure of Λ(1405) resonance

result of mean squared radii :

\[ |\langle r^2 \rangle_E | = 0.33 \text{ [fm}^2\text{]} \]

large (em) size of the Λ(1405) : c.f. -0.12 [fm^2] for neutron

--> meson-baryon picture

We study the structure of the $\Lambda(1405)$ resonance.

Summary 1: Structure of $\Lambda(1405)$

- Dynamical or CDD?
  - $\Rightarrow$ dominance of the MB components

- Analysis of Nc scaling
  - $\Rightarrow$ non-qqq structure

- Electromagnetic properties
  - $\Rightarrow$ large e.m. size
We study the structure of the $\Lambda(1405)$ resonance.

**Dynamical or CDD?**
- Dominance of the MB components

**Analysis of Nc scaling**
- Non-qqq structure

**Electromagnetic properties**
- Large e.m. size

Independent analyses consistently support the **meson-baryon molecule picture** of the $\Lambda(1405)$.
Effective single-channel KN interaction

Effective interaction based on chiral SU(3) dynamics

Result of chiral dynamics --\(\rightarrow\) single channel potential

Coupled-channel BS eq. + real valued interaction
\[ T_{ij}(\sqrt{s}) \]
\[ V_{ij}(\sqrt{s}) \]

few-body K-nuclei

(exact transformation)

Single-channel BS eq. + complex interaction
\[ T_{\text{eff}}(\sqrt{s}) = T_{ii}(\sqrt{s}) \]
\[ V_{\text{eff}}(\sqrt{s}) \]

(with approximation)

Schrödinger equation + local, complex, and energy-dependent potential
\[ f_{\text{eff}}(\sqrt{s}) \sim T_{\text{eff}}(\sqrt{s}) \]
\[ U_{\text{eff}}(r, \sqrt{s}) \]
Effective single-channel $KN$ interaction

(Diagonal) scattering amplitude in $\bar{K}N$ and $\pi\Sigma$

Resonance in $\bar{K}N$ channel: at around 1420 MeV

$\sim 1420$ MeV

$\sim 1405$ MeV

Binding energy: $B = 15$ MeV $\leftrightarrow 30$ MeV
Effective single-channel KN interaction

**Origin of the two-pole structure**

**Chiral interaction**

\[
V_{ij} = -C_{ij} \frac{\omega_i + \omega_j}{4f^2}
\]

\[
C_{ij} = \begin{pmatrix}
3 & -\sqrt{3/2} \\
-\sqrt{3/2} & 4
\end{pmatrix}
\]

\[
\omega_i \sim m_i, \quad 3.3m_\pi \sim m_K
\]

Very strong attraction in $\bar{K}N$ (higher energy) \(\rightarrow\) bound state

Strong attraction in $\pi\Sigma$ (lower energy) \(\rightarrow\) resonance

Two poles : natural consequence of chiral interaction (pole position is model dependent)
Effective single-channel $\bar{K}N$ interaction

**Schematic illustration : AY vs Chiral**

**AY**

$\bar{K}N$ | **bound state**

$\pi\Sigma$ | **continuum**

**Chiral** *(Dalitz’s coupled-channel model)*

$\bar{K}N$ | **bound state**

$\pi\Sigma$ | **resonance**

**Feshbach resonance**

$\Lambda(1405)$ experiment

**Feshbach resonance on resonating continuum**
Summary 1: \( \bar{K}N \) interaction

We study the consequence of chiral SU(3) dynamics in \( \bar{K}N \) phenomenology.

- Resonance structure in \( \bar{K}N \) appears at around 1420 MeV via strong \( \pi \Sigma \) dynamics.
- Two attractive interactions in \( \bar{K}N \) and \( \pi \Sigma \) lead to a weaker effective \( \bar{K}N \) interaction.
- This results in two poles for the \( \Lambda(1405) \).


Application to K-pp system (without \( \pi \Sigma \bar{N} \))

Doté-san’s talk
On the KNN (strange dibaryon) system

Which channel is relevant?

Theoretical studies
KNN - (πΣN) channels

Experimental candidates
- energy ≤ πΣN

observed in ΛN inv. mass
effect of decay channel coupling
The KNN (strange dibaryon) system

Λ*N state in chiral dynamics

Chiral dynamics --> two Λ* states: Λ*₁, Λ*₂

|Λ(1405)⟩ = a|Λ*₁⟩ + b|Λ*₂⟩

B=2 system: Λ*₁N, Λ*₂N?

|B = 2, S = −1⟩ = a'|Λ*₁N⟩ + b'|Λ*₂N⟩

Y. Ikeda, RCNP workshop, Dec. 25, 2008

mixing of Λ*₁N <-> Λ*₂N

KNN

No mixing

With mixing

Λ*₁N

Λ*₂N

K-pp (DHW)?

level repulsion --> Λ*₁N becomes light?

T. Uchino, T. Hyodo, M. Oka, in preparation
On the KNN (strange dibaryon) system

Summary 2: KNN system

KNN or strange dibaryon system

To compare with observed candidates, we should choose relevant channel(s).

importance of $\pi\Sigma N$ channel?

actual decay into $\Lambda N$ channel

--> change the spectrum?

If there are two states for $\Lambda^*(1405)$, there could be two states in KNN-$\pi\Sigma N$ system

Mixing of two $\Lambda^*$

--> level repulsion?