Chiral dynamics, structure of Λ(1405), and ΛN phenomenology

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**Introduction**

### $\Lambda(1405)$ and $\bar{K}N$ dynamics

**$\Lambda(1405)$**: $J^P = 1/2^-, I = 0$

- **Mass**: $1406.5 \pm 4.0$ MeV
- **Width**: $50 \pm 2$ MeV
- **Decay mode**: $\Lambda(1405) \rightarrow \left(\pi \Sigma\right)_{I=0}$ 100%

**“naive” quark model**

- p-wave
- $\sim 1600$ MeV?

N. Isgur, G. Karl, PRD18, 4187 (1978)

**Coupled channel multi-scattering**

$\leftarrow$ strong $\bar{K}N$ int.

R.H. Dalitz, T.C. Wong, G. Rajasekaran, PR153, 1617 (1967)

**$\bar{K}N$ int. below threshold**

$\bar{K}N$ scatt.

exp. @ J-PARC

kaonic nuclei, $\Lambda(1405), ...$

$\Lambda(1405)$
Chiral dynamics

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

- Interaction <-- chiral symmetry <-- kaon as NG boson


- Amplitude <-- unitarity (coupled channel) <-- strong int.

  R.H. Dalitz, T.C. Wong, G. Rajasekaran, PR153, 1617 (1967)

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

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

How it works? vs experimental data

Introduction

Good agreement in wide energy region (E >, =, < threshold).


Total cross sections

Threshold ratios

\( \gamma \) \( R_c \) \( R_n \)

exp. 2.36 0.664 0.189

theo. 1.80 0.624 0.225

\( \pi \Sigma \) spectrum

\( \pi \Sigma \) mass distribution
Two poles for one resonance

Poles of the amplitude in the complex plane: resonance

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

Real part

Imaginary part

Mass

Width/2

Residues

Couplings

Physical state: superposition

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

Analysis of Hemingway data by $I=0$ model. Spectrum $(\pi^{-}\Sigma^+)$ is not in $I=0$.

\[ \sigma(\pi^-\Sigma^+) \propto \frac{1}{3} |T^{I=0}|^2 \]

\[ + \frac{1}{2} |T^{I=1}|^2 - \frac{2}{\sqrt{6}} \text{Re}(T^{I=0} \cdot T^{I=1}) \]

$I=1$ interference

$\Sigma(1385)$


アイソスピンの正しい状態（l=0）を選ぶにはπΣの3つの荷電状態（π⁰Σ⁰, π±Σ∓）を全て同時に測定する必要がある（未達成）。
（現実的にはπ⁰Σ⁰はl=1がないので理想的か？）
ポールが2つある効果は、スペクトルが反応によって変化することを調べる必要がある。⇒ 1つの実験で検証／排除は不可能

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

ただし反応計算は模型依存。
1ポールでも干渉でピーク位置が変化。
**Structure of \( \Lambda(1405) \) resonance** (Bグループ)

- Dynamical or CDD (genuine quark state)?

- Nc Behavior and quark structure

- Electromagnetic properties

**Phenomenology of \( \bar{K}N \) interaction** (Cグループ)

- Construction of local \( \bar{K}N \) potential

- Application to three-body \( \bar{K}NN \) system
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, ...

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


Resonances in chiral unitary approach -> (a) dynamical?

e.g.) Deuteron in NN, positronium in e^+e^-, (σ in π π), ...

e.g.) J/Ψ in e^+e^-, (ρ in π π), ...
CDD pole contribution in chiral unitary approach

Amplitude in chiral unitary model

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

- \( V \): 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).

N(1535) in \( \pi N \) scattering

--> dynamical + CDD pole

\( \Lambda(1405) \) in \( \bar{K}N \) scattering

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

Electromagnetic properties

Attaching photon to resonance

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

result of mean squared radii :

$$< r^2 >_E = -2.193 \text{ fm}^2$$

large (em) size of the $\Lambda(1405)$

--> meson-baryon picture

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

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

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

- Electromagnetic properties
  - $\Rightarrow$ large e.m. size
Summary 1: Structure of $\Lambda(1405)$

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

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

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

- Electromagnetic properties
  - $\Rightarrow$ large e.m. size

- Independent analyses consistently support the meson-baryon molecule picture of the $\Lambda(1405)$
Deeply bound (few-body) kaonic nuclei?

Potential is purely phenomenological. What does chiral dynamics tell us about it?

Effective interaction based on chiral SU(3) dynamics

Few-body kaonic nuclei in chiral dynamics
- single-channel \(\bar{K}N\) potential

Construction of effective single-channel potential


1) Coupled-channel --> single \(\bar{K}N\) channel BS equation
   incorporation of \(\pi\Sigma\) channel (exact)

2) Local potential in Schrödinger equation (approximate)

--> \(\bar{K}N\) interaction : attractive, but weaker than the
phenomenological potential.

Application to K-pp system : bound, but \(B \sim 20\) MeV


Why the interaction is weaker? --> structure of the \(\Lambda(1405)\)
Phenomenology of $\bar{K}N$ interaction

Scattering amplitude in $\bar{K}N$ and $\pi\Sigma$

Resonance in $\bar{K}N$ : around 1420 MeV
<-- strong $\pi\Sigma$ dynamics (coupled-channel)

Binding energy : $B = 15$ MeV $\leftrightarrow 30$ MeV

Two poles with same quantum numbers
Different weights of the pole residues $\rightarrow$ different spectra

Phenomenology of KN interaction

**Origin of the two-pole structure**

**Chiral interaction**

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

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

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

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

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

**Two attractive interactions \( \rightarrow \) Two states**

\( \pi\Sigma \rightarrow \pi\Sigma \) attraction : chiral SU(3) symmetry
Schematic illustration: AY vs Chiral

**AY**

\[ \bar{K}N \]

**continuum**

\[ \pi\Sigma \]

**bound state**

**Feshbach resonance**

**Λ(1405) experiment**

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

\[ \bar{K}N \]

**resonance**

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

Single-channel effective $\bar{K}N$ interaction is attractive and forms $K$-pp bound system, about 20 MeV binding.

Resonance structure in $\bar{K}N$ appears at around $1420\,\text{MeV}$ \(<--\) strong $\pi\Sigma$ dynamics

Two attractive interactions in $\bar{K}N$ and $\pi\Sigma$ --> weaker effective $\bar{K}N$ interaction.

Phenomenology of KN interaction + α

Three-body calculations for $\overline{K}NN$

Single-channel variational calculation (DHW)

B.E. = 20 ± 3 MeV, $\Gamma(\piYN) = 40 \sim 70$ MeV

Coupled-channel Faddeev calculation (IS) using chiral interaction


B.E. ~ 79 MeV, $\Gamma(\piYN) \sim 74$ MeV

Why are they so different?
Inconsistency in theoretical calculations?

- $\pi\Sigma N$ dynamics?
  (existence of another N when eliminating $\pi\Sigma$ channel)

Two-pole structure for $\bar{K}NN$

Y. Ikeda, H. Kamano, T. Sato

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

“Chiral unitary like” model
: two poles in $\bar{K}N-\pi\Sigma$ amplitude

Solving Faddeev equation, they find
two poles in $\bar{K}NN-\pi\Sigma N$ amplitude

<table>
<thead>
<tr>
<th>Pole I</th>
<th>Pole II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{K}$- and $N$-exchanges in $Z$</td>
<td>$-14.5 - i28.7$ $-36.7 - i109.3$</td>
</tr>
<tr>
<td>$\bar{K}$-, $N$- and $\pi$-exchanges in $Z$</td>
<td>$-13.6 - i27.8$ $-45.8 - i104.0$</td>
</tr>
<tr>
<td>Full mechanism</td>
<td>$-13.7 - i29.0$ $-37.2 - i93.3$</td>
</tr>
</tbody>
</table>

--> Two poles for three-body system?
Two poles in two-body scattering:

higher energy pole --> $\bar{K}N$ bound state
lower energy pole --> $\pi\Sigma$ resonance

If there are two poles in three-body system, “single-channel” approach of DHW focuses on the higher energy pole of $\bar{K}NN$, since the $\pi\Sigma N$ channel has been eliminated.

Then, where is the lower energy state in three-body system?
---> Schematic model calculation
Treating $\Lambda(1405)$ as an elementary field, construct “$\Lambda^*N$ potential” through meson exchange


This approach may be justified by the observation that the $\Lambda^*$ seems to be surviving in K-pp system.

Attractive interaction (mainly from $\sigma$ exchange) --> bound $\Lambda^*N$, $\Lambda^*NN$ systems

$\Lambda^*$ coupling constant: unknown (← FINUDA data).
Λ*N state in chiral model

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

With sufficient attraction (σ exchange),
--> two Λ*N bound states in B=2 system : Λ*₁N, Λ*₂N

In addition, mixing of Λ*₁N <--> Λ*₂N : level repulsion

Λ* coupling constant : unknown

We consider this model simulates the thee-body calculation
--> DHW result = Λ*₁N
Phenomenology of KN interaction \(+\alpha\)

\(\Lambda^*N\) state in chiral model: result would be...

Assume \(B=B, M=M\),

\[ E_{\Lambda_2^*N} = 47 + 2M \quad [\text{MeV}] \]
Phenomenology of KN interaction +α

**Λ* N state in chiral model**

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

\[
|\Lambda(1405)\rangle = a|\Lambda^*_1\rangle + b|\Lambda^*_2\rangle
\]

\(\bar{K}N\)

\(\pi\Sigma\)

**B=2 system : Λ*₁N, Λ*₂N**

\[
|B = 2, S = -1\rangle = a'|\Lambda^*_1 N\rangle + b'|\Lambda^*_2 N\rangle
\]

Summary 3: $\overline{\text{KNN}}$ system

$B=2$ and $S=-1$ system in chiral dynamics

Possibility of two poles for three-body $\overline{\text{KNN}}$ state in Faddeev approach.

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

If this is the case, DHW result may corresponds to higher energy $\Lambda^*_{1N}$ state.

estimate of $\Lambda^*_{2N} \sim 47 + 2M$ MeV?

T. Uchino, T. Hyodo, M. Oka, in preparation

When the lower energy channel is strongly interacting, coupled-channel approach would be mandatory.