Status of $\Lambda(1405)$ in chiral dynamics

Tetsuo Hyodo
Yukawa Institute for Theoretical Physics, Kyoto Univ.

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Λ(1405) in chiral SU(3) dynamics
- Precise experimental constraint
- Determination of pole positions
  Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

Kaonic nuclei
- Local $\bar{K}N$ potential and $\Lambda(1405)$ wave function
  K. Miyahara, T. Hyodo, PRC93, 015201 (2016)
- Density of kaonic nuclei
- $\bar{K}N$ v.s. $NN$ correlations
  S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara, T. Hyodo,
  PRC95, 065202 (2017)
Two aspects of $K(\bar{K})$ meson

- **NG boson** of chiral $SU(3)_R \otimes SU(3)_L \rightarrow SU(3)_V$
- **Massive** by strange quark: $m_K \sim 496$ MeV

$\rightarrow$ **Spontaneous/explicit** symmetry breaking

$K\bar{N}$ interaction ...


- is coupled with $\pi\Sigma$ channel
- generates $\Lambda(1405)$ below threshold

- is fundamental building block for $\bar{K}$-nuclei, $\bar{K}$ in medium, ...
Precise measurement of the kaonic hydrogen X-rays

M. Bazzi, et al., PLB 704, 113 (2011); NPA 881, 88 (2012)

- Shift and width of atomic state $\leftrightarrow$ $K-p$ scattering length


Quantitative constraint on the $\bar{K}N$ interaction at fixed energy
Strategy for $\bar{K}N$ interaction

Above the $\bar{K}N$ threshold: direct constraints
- $K-p$ total cross sections (old data)
- $\bar{K}N$ threshold branching ratios (old data)
- $K-p$ scattering length (new data: SIDDHARTA)

Below the $\bar{K}N$ threshold: indirect constraints
- $\pi\Sigma$ mass spectra (new data: LEPS, CLAS, HADES,...)
Construction of the realistic amplitude in chiral SU(3) dynamics

Chiral coupled-channel approach with systematic $\chi^2$ fitting

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

\[
\mathcal{K}N = \mathcal{T}W + \mathcal{V} + \mathcal{V}T
\]

Chiral perturbation theory

1) TW term
\[\mathcal{O}(p)\]
6 cutoffs
TW model

2) Born terms
\[\mathcal{O}(p)\]
TWB model

3) NLO terms
\[\mathcal{O}(p^2)\]
7 LECs
NLO model
**Best-fit results**

<table>
<thead>
<tr>
<th></th>
<th>TW</th>
<th>TWB</th>
<th>NLO</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E$ [eV]</td>
<td>373</td>
<td>377</td>
<td>306</td>
<td>$283 \pm 36 \pm 6$ [10]</td>
</tr>
<tr>
<td>$\Gamma$ [eV]</td>
<td>495</td>
<td>514</td>
<td>591</td>
<td>$541 \pm 89 \pm 22$ [10]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>2.36</td>
<td>2.36</td>
<td>2.37</td>
<td>$2.36 \pm 0.04$ [11]</td>
</tr>
<tr>
<td>$R_n$</td>
<td>0.20</td>
<td>0.19</td>
<td>0.19</td>
<td>$0.189 \pm 0.015$ [11]</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.66</td>
<td>0.66</td>
<td>0.66</td>
<td>$0.664 \pm 0.011$ [11]</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f</td>
<td>1.12</td>
<td>1.15</td>
<td>0.96</td>
<td></td>
</tr>
</tbody>
</table>

**SIDDHARTA**

**Branching ratios**

**Cross sections**

**Accurate description of all existing data ($\chi^2$/d.o.f. $\sim 1$)**
**Comparison with SIDDHARTA**

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<td>$\chi^2$/d.o.f.</td>
<td>1.12</td>
<td>1.15</td>
<td>0.957</td>
</tr>
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</table>

$\bar{K}N$ interaction in chiral SU(3) dynamics

**TW and TWB are reasonable, while best-fit requires NLO.**
Subthreshold extrapolation

Uncertainty of $\bar{K}N \rightarrow \bar{K}N$ ($l=0$) amplitude below threshold

![Graph showing real and imaginary parts of $\bar{K}N$ and $\pi\Sigma$ amplitudes in the full approach.](image)


- c.f. without SIDDHARTA


SIDDHARTA is essential for subthreshold extrapolation.
Extrapolation to complex energy: two poles

Two poles: superposition of two states

J.A. Oller, U.G. Meissner, PLB 500, 263 (2001);

- Higher energy pole at 1420 MeV, not at 1405 MeV
- Attractions of TW in 1 and 8 (\(\bar{K}N\) and \(\pi\Sigma\)) channels

NLO analysis confirms the two-pole structure.
105. Pole Structure of the Λ(1405) Region

Written November 2015 by Ulf-G. Meißner (Bonn Univ. / FZ Jülich) and Tetsuo Hyodo (YITP, Kyoto Univ.).

The Λ(1405) resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and versatile formalism to describe these resonances is the one-boson-exchange model (OBEP) [2]. It was first used to describe the Λ(1405) in Ref. 3 of the chiral-unitary community 400-MeV region. ZYCHOR 08 inst the two-pole model, but this REVAl 09, which finds little basis in pole models; and IKEDA 12, 1405) fits nicely into a $J^P = 1/2^-$ pole, solution number 2. Fig. 1 of our note on “Charmed

- Our analysis (+ 2 other groups) included
- Pole positions are now tabulated, prior to mass/width.
Construction of $\bar{K}N$ potential

Local $\bar{K}N$ potential is useful for

- extraction of the wave function of $\Lambda(1405)$
- application to few-body Kaonic nuclei/atoms

Strategy

Fit to experimental data (chiral SU(3) EFT)

equivalent amplitude

Single-channel complex $\bar{K}N$ potential [1] (used in $\bar{K}$-nuclei calculation)

Coupled-channel real $\bar{K}N-\pi\Sigma-\pi\Lambda$ potential [2]

[1] K. Miyahara, T. Hyodo, PRC 93, 015201 (2016);
Structure of $\Lambda(1405)$

$\bar{K}N$ wave function at $\Lambda(1405)$ pole

K. Miyahara, T. Hyodo, PRC93, 015201 (2016)

- substantial distribution at $r > 1$ fm
- root mean squared radius $\sqrt{\langle r^2 \rangle} = 1.44$ fm

The size of $\Lambda(1405)$ is much larger than ordinary hadrons.
Kaonic nuclei : current status

Recent experiment for $\bar{K}NN$ (J-PARC E15, $^3\text{He}(K-,\Lambda p)n$)


$B = 47 \pm 3^{+3}_{-6}$ MeV, $\Gamma = 115 \pm 7^{+10}_{-9}$ MeV

Theoretical calculation with realistic $\bar{K}N$ interaction
- Fit to $K-p$ cross sections and branching ratios
- SIDDHARTRA constraint of Kaonic hydrogen


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<tbody>
<tr>
<td>$B$ [MeV]</td>
<td>53.3</td>
<td>47.4</td>
<td>32.2</td>
<td>25-28</td>
</tr>
<tr>
<td>$\Gamma_{\piYN}$ [MeV]</td>
<td>64.8</td>
<td>49.8</td>
<td>48.6</td>
<td>31-59</td>
</tr>
</tbody>
</table>

- $2\text{N}$ absorption ($\Gamma_{YN}$) is NOT included.
Kaonic nuclei

Rigorous few-body approach to $\bar{K}$ nuclear systems


Applications

- Stochastic variational method with correlated gaussians

$$\hat{V} = \hat{V}^{KN}(\text{Kyoto } \bar{K}N) + \hat{V}^{NN}(\text{AV4}')$$

(single channel)

Results for $A = 2, 3, 4, 6$

<table>
<thead>
<tr>
<th></th>
<th>$\bar{K}NN$</th>
<th>$\bar{K}N\bar{N}$</th>
<th>$\bar{K}NN\bar{N}$</th>
<th>$\bar{K}NNNN\bar{N}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$ [MeV]</td>
<td>25-28</td>
<td>45-50</td>
<td>68-76</td>
<td>70-81</td>
</tr>
<tr>
<td>$\Gamma$ [MeV]</td>
<td>31-59</td>
<td>26-70</td>
<td>28-74</td>
<td>24-76</td>
</tr>
</tbody>
</table>

- quasi-bound state below the lowest threshold
- decay width (without multi-$\bar{N}$ absorption) $\sim$ binding energy
Applications

High density?

Nucleon density distribution in four-nucleon system

- central density increases (not substantially $\leftarrow$ NN core)

- $B = 68$-$76$ MeV (Kyoto $\overline{KN}$)

- $B = 85$-$87$ MeV (AY)

Central density is not always proportional to $B \leftarrow$ tail of w.f.
Interplay between $^{\text{NN}}$ and $^{\text{KN}}$ correlations 

Two-nucleon system

$^{1S_0}$ ($l_{^\text{NN}}=1$)

\begin{align*}
\text{unbound} \\
\text{(quasi-)bound} \\
\overline{KN}(I=0):\overline{KN}(I=1) = 3:1
\end{align*}

$^{3S_1}$ ($l_{^\text{NN}}=0$)

\begin{align*}
\text{bound (d)} \\
\Lambda(1405) \\
\text{unbound} \\
\overline{KN}(I=0):\overline{KN}(I=1) = 1:3
\end{align*}

$^{\text{NN}}$ correlation $<^{\text{KN}}$ correlation (also in A=6)
Interplay between $NN$ and $\bar{K}N$ correlations 2

Four-nucleon system with $J^\pi=0^-, l=1/2, l_3=+1/2$

\[
|\bar{K}NNNN\rangle = C_1 \left( \begin{array}{c} p \\ p \\ p \\ n \\ \end{array} \right) + C_2 \left( \begin{array}{c} p \\ p \\ n \end{array} \right)
\]

- $\bar{K}N$ correlation
  
  \(l=0\) pair in $K-p$ (3 pairs) or $\bar{K}^0n$ (2 pairs) : $C_1 > C_2$

- $NN$ correlation
  
  $ppnn$ forms $\alpha$ : $C_1 < C_2$

- Numerical result
  
  $|C_1|^2 = 0.08$, $|C_2|^2 = 0.92$

$NN$ correlation $> \bar{K}N$ correlation
Summary: $\Lambda(1405)$

- SIDDHARTA measurement of kaonic hydrogen reduces the ambiguity of $\bar{K}N$ amplitude.

- Pole positions of $\Lambda(1405)$ are determined by fitting all existing data with $\chi^2/d.o.f. \sim 1$.

$$z_1 = (1424^{+7}_{-23} - i26^{+3}_{-14}) \text{ MeV}, \quad z_2 = (1381^{+18}_{-6} - i81^{+19}_{-8}) \text{ MeV}$$

- Realistic $\bar{K}N$ potential is constructed.

- Structure of few-body kaonic nuclei reflects the interplay between $NN$ and $\bar{K}N$ correlations.

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)

K. Miyahara. T. Hyodo, PRC93, 015201 (2016)