$\bar{K}N$ interaction and Kaonic nuclei

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$ar{K}N$ interaction

- Systematic analysis in chiral SU(3) dynamics

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

- Realistic $ar{K}N$ potential

K. Miyahara, T. Hyodo, PRC 93, 015201 (2016)

(Selected topics of) Kaonic nuclei

- Few-body systems up to A=6

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

$\bar{K}N$ 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


- Shift and width of atomic state \( \rightarrow \) K-p scattering length


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

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

Below the $\bar{K}N$ threshold: indirect constraints
- $\pi\Sigma$ mass spectra (new data: LEPS, CLAS, HADES, …)
Systematic analysis in chiral SU(3) dynamics

Construction of the realistic amplitude

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


Chiral perturbation theory

1) TW term

2) Born terms

3) NLO terms

$O(p)$

$O(p^2)$

6 cutoffs

7 LECs

TW model

TWB model

NLO model
Systematic analysis in chiral SU(3) dynamics

**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 ± 36 ± 6 [10]</td>
</tr>
<tr>
<td>$\Gamma$ [eV]</td>
<td>495</td>
<td>514</td>
<td>591</td>
<td>541 ± 89 ± 22 [10]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>2.36</td>
<td>2.36</td>
<td>2.37</td>
<td>2.36 ± 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 ± 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 ± 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>

**Branching ratios**

**SIDDHARTA**

**$K$-hydrogen and cross sections are consistent (c.f. DEAR).**
Comparison with SIDDHARTA

<table>
<thead>
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<tr>
<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>

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

Systematic analysis in chiral SU(3) dynamics

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

Y. Kamiya, K. Miyahara, S. Ohnishi, Y. Ikeda, T. Hyodo, E. Oset, W. Weise,

- c.f. without SIDDHARTA


SIDDHARTA is essential for subthreshold extrapolation.
Local $\bar{K}N$ potential is useful for
- extraction of the wave function of $\Lambda(1405)$
- application to few-body Kaonic nuclei

Single-channel energy-dependent $\bar{K}N$ potential

- Chiral dynamics (thin)
  \[ T(W) = V(W) + V(W)G(W)T(W) \]

- Potential (thick)
  \[ U(W, r) + \text{Schrödinger eq.} \]

- Reasonable on-shell scattering amplitude on real axis
Issues to be improved:

- Amplitude was not constrained by SIDDHARTA
- Pole structure of the amplitude was not reproduced.

<table>
<thead>
<tr>
<th>Model</th>
<th>Original Pole position (MeV)</th>
<th>Potential Pole position (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORB [68]</td>
<td>1427 – 17i, 1389 – 64i</td>
<td>1419 – 42i</td>
</tr>
<tr>
<td>HNJH [66,67]</td>
<td>1428 – 17i, 1400 – 76i</td>
<td>1421 – 35i</td>
</tr>
<tr>
<td>BNW [57,59]</td>
<td>1434 – 18i, 1388 – 49i</td>
<td>1404 – 46i</td>
</tr>
<tr>
<td>BMN [58]</td>
<td>1421 – 20i, 1440 – 76i</td>
<td>1416 – 27i</td>
</tr>
</tbody>
</table>

Construction of realistic potential


- Chiral SU(3) at NLO with SIDDHARTA
- Equivalent amplitude in the complex energy plane

Kyoto $\bar{K}N$ potential reproduces data $\chi^2/dof \sim 1$: realistic
Kaonic nuclei

Few-body $\bar{K}$ nuclear systems


- Stochastic variational method with correlated gaussians
- $\bar{K}N$ : Kyoto $\bar{K}N$ potential, $NN$ : AV4' (hard core)

<table>
<thead>
<tr>
<th></th>
<th>$\bar{K}NN$</th>
<th>$\bar{K}NNN$</th>
<th>$\bar{K}NNNN$</th>
<th>$\bar{K}NNNNN$</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>

- **bound** below the lowest threshold
- **decay** width (without multi-N absorption) $\sim$ binding energy
High density?

Nucleon density distribution in four-nucleon system

- central density increases (not substantially $\rightarrow$ NN core)
- $B = 68$-$76$ MeV (Kyoto $\overline{K}N$)
- $B = 85$-$87$ MeV (AY)

Central density is not always proportional to $B \rightarrow$ tail of w.f.
Interplay between $NN$ and $\bar{K}N$ correlations

Two-nucleon system

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

- Unbound

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

- Bound (d)

$K\bar{N}(I=0)$: $K\bar{N}(I=1) = 3:1$

$\Lambda(1405)$

$K\bar{N}(I=0):K\bar{N}(I=1) = 1:3$

$NN$ correlation < $\bar{K}N$ correlation (also in $A=6$)
(Selected topics of) Kaonic nuclei

**Interplay between $NN$ and $\bar{K}N$ correlations 2**

Four-nucleon system with $J^π=0^-, I=1/2, I_3=+1/2$

\[
|\bar{K}NNNN\rangle = C_1 \begin{pmatrix} p \\ p \\ p \\ n \end{pmatrix} + C_2 \begin{pmatrix} p \\ p \\ n \\ n \end{pmatrix}
\]

- $\bar{K}N$ correlation
  - $I=0$ 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
$\bar{K}N$ scattering is quantitatively described ($\chi^2$/d.o.f. $\sim 1$) by NLO chiral coupled-channel approach with accurate $K$-$p$ scattering length. Realistic $\bar{K}N$ potential is now available. Few-body kaonic nuclei exist as quasi-bound states. Structure is determined by the interplay between $NN$ and $\bar{K}N$ correlations.

$\bar{K}N$ amplitude $\Lambda(1405)$ $\bar{K}$ nuclei