In-medium $\bar{K}$ mesons
from atoms to strange dibaryons
MESON 2014, Kraków, May-June 2014
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- $\bar{K}N - \pi Y$ chiral dynamics and its consequences
- $\bar{K}$ nuclear clusters; strange dibaryons
- $\bar{K}$-nucleus potentials from $K^-$ atoms
- No $\bar{K}$ condensation on earth

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Acta Physica Polonica B 45 (2014) 673-687
$\bar{K}N - \pi Y$ Chiral Dynamics
$K^-p$ scattering amplitude from NLO chiral SU(3) dynamics


Threshold amplitude constrained by SIDDHARTA exp.

Strong subthreshold $K^-p$ attraction; $\Lambda(1405)$ physics;
consequences for kaonic atoms & nuclear clusters

$K^-NN \toYN$ absorption not accounted for by this model.
T. Hyodo, W. Weise, PRC 77 (2008) 035204 $I = 0$ coupled-channel amplitudes

Location of ‘resonances’: $\bar{K}N \approx 1420$ MeV, $\pi\Sigma \approx 1405$ MeV

$\bar{K}N$ pole relatively narrow, and stable to fit variations. $\pi\Sigma$ pole broader, unstable, and affects subthreshold.

IHW (2012): $z_{\bar{K}N}=1424-i26$ MeV, $z_{\pi\Sigma}=1381-i81$ MeV
$K^{-}p$ subthreshold ambiguity

Two NLO chiral-model fits by Guo-Oller, PRC 87 (2013) 035202

- **Fit I:** meson-independent $f = 125.7 \pm 1.1$ MeV.
- **Fit II:** physical values for $f_\pi$, $f_K$, $f_\eta$.
  Will create problems when confronted with $K^-$-atom data.
- Amplitudes constrained at threshold by SIDDHARTA.
  $\bar{K}N$ pole robust, $\pi\Sigma$ pole correlated with fit.
K nuclear few-body systems
Energy dependence in $\bar{K}$ nuclear few-body systems

• $\Lambda(1405)$ induces strong energy dependence of the scattering amplitudes $f_{\bar{K}N}(\sqrt{s})$ and the underlying effective single-channel input potentials $v_{\bar{K}N}(\sqrt{s})$.

• $s = (\sqrt{s_{\text{th}}} - B_K - B_N)^2 - (\vec{p}_K + \vec{p}_N)^2 \leq s_{\text{th}}$

• Expanding nonrelativistically near $\sqrt{s_{\text{th}}} \equiv m_K + m_N$:
  $$\delta \sqrt{s} = -\frac{B}{A} - \frac{A-1}{A} B_K - \xi_N \frac{A-1}{A} \langle T_{N:N} \rangle - \xi_K \left( \frac{A-1}{A} \right)^2 \langle T_K \rangle,$$
  $$\delta \sqrt{s} \equiv \sqrt{s} - \sqrt{s_{\text{th}}}, \quad B_K = -E_K, \quad \xi_N(K) \equiv \frac{m_{N(K)}}{(m_N + m_K)}.$$

• Self-consistency: output $\sqrt{s}$ from solving the Schroedinger equation identical with input $\sqrt{s}$. 

3– & 4–body $B$ & $\Gamma$ calculated self-consistently


- Variational calculation in hyperspherical basis controlled by $K_{\text{max}}$
- $\bar{K}N$ energy dependence [Hyodo–Weise, PRC 77 (2008) 035204] restrains $B$ & $\Gamma$ by treating $\delta \sqrt{s_{\bar{K}N}}$ self-consistently
- $B(4\text{-body})$ small w.r.t. non-chiral estimates of over 100 MeV
• $\bar{K}NN$: is there an excited $I = 1/2$ quasibound state ($\bar{K}d$, dominantly $I_{NN} = 0$) on top of “$K^-pp$” g.s.?

• Barnea, Gal & Liverts do not find such a bound state below the $\Lambda^*N$ threshold at $B = 11.4$ MeV.

• Bayar & Oset [NPA 881 (2012) 127]: **YES**, bound by about 9 MeV, from a peak in $|T_{\bar{K}NN}|^2$ calculated in a fixed-scatterer approximation to Faddeev equations.

• Shevchenko [NPA 890-1 (2012) 50]: **UNLIKELY**, judging from the $K^-d$ scattering length and effective range deduced from a $\bar{K}NN$ Faddeev calculation.

• Shevchenko & Revai [PRC, arXiv:1402.3935]: **NO**, searching for poles in a $\bar{K}NN$ Faddeev calculation.
### \( K^-pp \) calculated binding energies & widths

<table>
<thead>
<tr>
<th>(MeV)</th>
<th>chiral, energy dep. calculations</th>
<th>non-chiral, static calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>16</td>
<td>17–23</td>
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<tr>
<td>( \Gamma )</td>
<td>41</td>
<td>40–70</td>
</tr>
</tbody>
</table>

Robust binding & large widths; chiral models give weak binding

5. T. Yamazaki, Y. Akaishi, PLB \textbf{535} (2002) 70
8. S. Wycech, A.M. Green, PRC \textbf{79} (2009) 014001 (including \( p \) waves)
Yamazaki et al. PRL 104 (2010) 132502, DISTO data reanalysis at 2.85 GeV

Broad $K^-pp$ structure in $pp \to \Lambda pK^+$ at $\pi N\Sigma$ threshold

Forthcoming experiments: $pp \to (K^-pp) + K^+$ at GSI
$K^-^3\text{He} \to (K^-pp) + n$ (E15) & $\pi^+d \to (K^-pp) + K^+$ (E27) at J-PARC
from $\Lambda(1405)N$ to $\Sigma(1385)N$

- $\Lambda(1405)N$ is in a way a doorway to the quasibound $I = 1/2, J^P = 0^- \bar{K}NN$ dibaryon. Lower $S = -1$ components are $\pi\Lambda N$ and $\pi\Sigma N$, the lowest of which is $\pi\Lambda N$, but it cannot support any strongly attractive meson-baryon $s$-wave interaction.

- The $\pi\Lambda N$ system can benefit from strong meson-baryon $p$-wave interactions fitted to the $\Delta(1232) \rightarrow \pi N$ and $\Sigma(1385) \rightarrow \pi\Lambda$ form factors. Maximize isospin and angular momentum couplings by full alignment: $I = 3/2, J^P = 2^+$. In particular, $\Lambda N$ is in $^3S_1$. This is a Pion Assisted Dibaryon, see Gal & Garcilazo, PRD 78 (2008) 014013.
- Add the $\pi\Sigma N$ channel [PRC 81 (2010) 055205, and finalized in NPA 897 (2013) 167].
A $\pi\Lambda N$ resonance about 10–20 MeV below the $\pi\Sigma N$ threshold is found by solving coupled-channel Faddeev equations. Results are sensitive to the pion-baryon $p$-wave form factors.

- This resonance is a pion assisted quasibound dibaryon, suggesting doorway states of the type $\Sigma(1385)N$ and $\Delta(1232)Y$, the lower of which is $\Sigma(1385)N$ with $I = 3/2$ and $^5S_2$, $J^P = 2^+$. These are different labels from the $I = 1/2$ and $^1S_0$, $J^P = 0^-$ for $\Lambda(1405)N$ viewed as a doorway to $K^-pp$. 
• Adding a $\bar{K}NN$ channel does not help, because the leading $^3S_1\,NN$ configuration is Pauli forbidden.

• Search for this $\Upsilon$ dibaryon at GSI & J-PARC in:
  
  $p + p \rightarrow \Upsilon^{++} + K^0, \quad \Upsilon^{++} \rightarrow \Sigma^+ + p,$
  
or $\pi^+ + d \rightarrow \Upsilon^{++} + K^0, \quad \Upsilon^{++} \rightarrow \Sigma^+ + p.$

• A $(\pi^+, K^+)$ reaction as in E27 would lead to $YN$ decay states similar to those anticipated in searches of $K^- pp$. Another possibility at J-PARC or GSI is:
  
  $\pi^- + d \rightarrow \Upsilon^- + K^+, \quad \Upsilon^- \rightarrow \Sigma^- + n.$

• **Nonstrange $D_{IS}$ pion assisted dibaryons**

  $\pi NN$: $D_{12}(2150) \& D_{21}(?)$

  $\pi N\Delta$: $D_{03}(2370) \& D_{30}(?)$
Pion-assisted $D_{03}(2370)$ $\Delta\Delta$ dibaryon

- Approximate $\pi\pi NN$ problem by $\pi N\Delta'$ problem.
- Separable pair interactions: $\pi N$ $\Delta$-isobar form factor by fitting $\delta(P_{33})$; $N\Delta'$ $D_{12}(2150)$-isobar form factor by fitting $NN(1D_2)$ scattering.
- 3-body $S$-matrix pole equation reduces to effective $\Delta\Delta'$ diagram:
• $P_{33}$ form factors of size 0.9 & 1.3 fm: 
  $M = 2363 \pm 20$, $\Gamma = 65 \pm 17$ MeV,
in good agreement with WASA@COSY (Clement’s & Workman’s talks here).

• Although bound w.r.t. $\Delta\Delta$, $\mathcal{D}_{03}(2370)$ is resonating w.r.t. the $\pi - \mathcal{D}_{12}(2150)$ threshold.  
The subsequent decay $\mathcal{D}_{12}(2150) \rightarrow \pi d$ is seen in the $\pi d$ Dalitz plot projection.

• $NN$-decoupled dibaryon resonances $\mathcal{D}_{21}$ & $\mathcal{D}_{30}$ predicted 10–30 MeV higher, respectively; 
  see also Bashkanov-Brodsky-Clement “Novel 6q Hidden-Color Dibaryons in QCD” 
  PLB 727 (2013) 438 (Bashkanov’s poster here).
What do $K^-$ atoms tell us?
$K_{\text{atom}}^-$ widths across the periodic table in model F (deep pot.)

Lowest $\chi^2$ phenom. model, $\chi^2 = 84$ per 65 data points,

Left: $K^{-}$-Ni 4f atomic wavefunction overlap with nuclear density for deep potential, revealing a nuclear $\ell = 3$ quasibound state.

Right: FINUDA $1s_\Lambda$ formation rates in $K_{\text{stop}}$ capture in nuclei [Cieplý-Friedman-Gal-Krejčiřík, PLB 698 (2011) 226]. Deep $K^{-}$ nuclear potential is favored.
Self-consistency requirement imposed in recent $K^-$ atom calculations [Cieplý-Friedman-Gal-Gazda-Mareš, PLB 702 (2011) 402]:

$$\sqrt{s_{K^-N}} \rightarrow E_{th} - B_N - B_K - \xi_N \frac{p_N^2}{2m_N} - \xi_K \frac{p_K^2}{2m_K}$$

$$\xi_{N(K)} = \frac{m_{N(K)}}{(m_N + m_K)}$$

$$\frac{p_K^2}{2m_K} \sim -V_{K^-} \approx 100 \text{ MeV}$$

$K^-$ is not at rest!

Friedman-Gal, NPA 899 (2013) 60

$K^-N$ subthreshold energy vs nuclear density in $K^-$ atoms.

A dominant in-medium effect
**Left:** IHW free-space input $f_{K^-N}$  
**Right:** atomic-fit output $F^\text{eff}_{\text{tot}}$

- Subthreshold energy shift is applied self consistently to in-medium 1N amplitude plus $(2+...)N$ phenomenological amplitude.
- Multiple-scattering inclusion of in-medium correlations.
- $K^-$-atom best-fit: $\chi^2/N_{\text{data}} = 118/65$  [Friedman-Gal, NPA 899 (2013) 60].
**Full and reduced data set fits** \( [b(\rho_0) \text{ in fm}] \)

<table>
<thead>
<tr>
<th>N</th>
<th>shallow potential</th>
<th>deep potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \chi^2 )</td>
<td>Re ( b(\rho_0) )</td>
</tr>
<tr>
<td>65</td>
<td>130</td>
<td>0.62±0.05</td>
</tr>
<tr>
<td>15</td>
<td>44</td>
<td>0.78±0.13</td>
</tr>
</tbody>
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Reduced sets, C(2p) Si(3d) Ni(4f) Sn(5g) Pb(7i), with upper-level yield & lower-level width & shift, preserve features obtained from fits to full data. Need more accurate measurements in a few atoms. [E. Friedman, in MESON 2010, IJMPA 26 (2011) 468]
Feasibility of upper-level width measurements, on top of lower-level, vs. detector resolution for superconducting microcalorimeter detectors, normalized at 53 eV width for 100 keV x-ray.

condensation on earth?
RMF quasibound spectra calculated self-consistently (NLO30 ‘+ SE’)

D. Gazda, J. Mareˇ s, NPA 881 (2012) 159

- NLO30 is a chirally motivated coupled channel separable model with in-medium versions [A. Ciepl´ y, J. Smejkal, NPA 881 (2012) 115]
- $\Gamma_K$ due only to $K^-N \rightarrow \pi Y$ (no $K^-NN \rightarrow YN$) decay modes
- Self consistency: deep $K^-$ levels are narrower than shallow ones
Saturation of $B_{\bar{K}}(\kappa)$ in RMF for multi-$K^-$ $^{40}$Ca nuclei.

Vector-meson repulsion among $\bar{K}$ mesons.

$B_{\bar{K}}(\kappa \to \infty) << (m_K + M_N - M_\Lambda) \approx 320$ MeV.

Saturation of $B_{\bar{K}}(\kappa)$ in RMF for $^{208}$Pb + $\eta$Λ + $\kappa$K$^-$.

$\bar{K}$ mesons do not replace hyperons in stable self-bound strange matter.
Summary

- Large widths, $\Gamma_\bar{K} > 50$ MeV, expected for single-$\bar{K}$ quasibound nuclear states. Focus on light systems. $K^-pp$ searches are underway in GSI and J-PARC.

- Look for $(I = \frac{3}{2}, J^P = 2^+)\ YN\pi$ dibaryon.

- Major issues: (i) how deep is $\bar{K}$ nuclear spectrum? (ii) how big is $\Gamma(\bar{K}NN \rightarrow YN)$ w.r.t. $\Gamma(\bar{K}N \rightarrow \pi Y)$? Do $K^-d$ atom (SIDDHARTA-II at DAΦNE) & selective $K^-$ atom measurements (JPARC?)

- $B_{\bar{K}}$ saturates in multi-$\bar{K}$ nuclei and hypernuclei. $\bar{K}$ condensation is unlikely in self-bound matter.

- Thanks to my collaborators N. Barnea, A. Cieplý, E. Friedman, D. Gazda, J. Mareš