Kaon-nucleus interaction and Deeply bound kaonic nuclei

Unique Feature and Perspectives of Nuclear $K$ Bound Systems
The low-energy interactions of the lightest pseudoscalar mesons (pions and kaons) with nuclear systems are largely dictated by the spontaneously broken chiral symmetry of QCD. In the limit of massless up, down and strange quarks, pions and kaons would emerge as massless Goldstone bosons. The small explicit symmetry breaking induced by the $u$– and $d$–quarks masses, $m_{u,d} < 10$ MeV, moves the pion mass to its empirical (small) value. Likewise, the strange quark mass, $m_s \sim 0.1$ GeV, can still (with caution) be considered small compared to the spontaneous chiral symmetry breaking scale, $\Lambda_{\chi} = 4\pi f_\pi \sim 1$ GeV, expressed in terms of the pion decay constant $f_\pi \approx 0.09$ GeV.

![Graph of QCD mass and Higgs mass](image)

**FIG. 1:** Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale.
Origin of barion masses, structure of QCD vacuum, Chiral Symmetry
How to study all this?

**chiral symmetry (X.S.)**
- Symmetry of (light q. sector) QCD Lagrangian in the limit $m_u = m_d = 0$
  (invariant under transformations acting separately on left and right handed quarks; explicit breaking small: $m_{ud} \approx 7\text{MeV}$)
- **Spontaneously broken** in the QCD vacuum
  (Ground state not symmetric, Absence of parity doublets, Almost massless pion, Large quark condensate)
- **Fundamental symmetry of QCD**
  - Dictates low energy interactions;
  - Origin of major part of (dynamical) hadron mass
- **X.S. restored** at high temperature (big bang, heavy ions collision) and density (neutron stars) nuclear matter
  - Partially restored at normal nuclear matter density

Change of Hadronic masses and interactions expected if XS restored

Use of the nucleus as a laboratory to study low energy QCD phenomena, phases of nuclear matter, phase transitions (FINUDA, ALICE experiments)
Low energy KN interactions

Test our understanding of the strong interaction in the confinement region.

Strangeness conservation → \( K^+ N(A) \) and \( K^- N(A) \) interactions very different

\( K^- N \): dominated by low en. resonances (\([\Sigma(1385)], \Lambda(1405), \Lambda(1520)\)…)
- large cross section (~40mb at \( E_k \leq 500 \text{MeV} \))

→ importance of many body effects; propagation and modification of resonances in nuclear medium difficult/intriguing problem

Important role of under thresh. res.es

\( K^+ N \) : no low energy resonances (no ubar, dbar quarks). No inelastic channels (but CX). Smaller and ~constant cross section (~10mb at \( p_k \leq 800 \text{MeV/c} \))
→ mostly related to QCD predictions

\[
\begin{align*}
\Sigma & \quad \Lambda(1405) \\
1300 & \quad 1400 \\
\bar{K}N & \quad \text{MeV}
\end{align*}
\]

\[
\begin{align*}
\Sigma & \quad \Lambda(1405) \\
1300 & \quad 1400 \\
\bar{K}N & \quad \text{Thr.}
\end{align*}
\]
The $\bar{K}N$ interaction

$K^-p$ (I=0) channel: difficult to study because of presence of resonances.

At low energy (and below thresh) the K-p interaction is believed to be attractive, but…
apparently, from experiments:

- **S-wave $K^-$ nucleon scattering length is negative at threshold**
  → “repulsive type” interaction

- **$K_\alpha$ line shift of kaonic hydrogen is negative**
  → “repulsive type” interaction
**Results on the shift and width for kaonic hydrogen**

**DEAR results:**
\[ \varepsilon_{1s} = -193 \pm 37(\text{stat}) \pm 6(\text{syst}) \text{ eV} \]
\[ \Gamma_{1s} = 249 \pm 111(\text{stat}) \pm 30(\text{syst}) \text{ eV} \]
The behavior of the $K^-p$ potential is a phenomenon well known in nuclear physics.

- Simple arguments from low-energy scattering show that the existence of a bound state below threshold always leads to a repulsive scattering length. M.A. Preston and R.K. Badhuri, *Structure of the nucleus*, Addison-Wesley

- Analogy between the $K^-p$ scattering in the $I=0$ channel and the proton-neutron (p-n) scattering in the deuteron channel ($I=0, S=1$): the interaction between the proton and neutron is attractive, but the scattering length in the deuteron channel ($I=0, S=1$) is repulsive, due to the existence of the deuteron as a bound state. [In nuclear matter, however, the deuteron disappears, largely due to Pauli blocking, and the true attractive nature of the p-n interaction emerges.]
If the \( s \)-wave, isospin \( I=0 \) \( \Lambda(1405) \) resonance is dominantly a \( KN \) bound state \( \rightarrow \) the actual \( K\cdot p \) interaction is **attractive** although it appears repulsive in the scattering length and the \( K_{\alpha} \) energy shift of kaonic hydrogen.
In-medium effects on the dynamics of the $\Lambda$ (1405)

Influence of the nuclear medium on $\Lambda$(1405) formation

Strong non-linear density dependence of optical potential:
- **Repulsion** in free space
- **Attraction** in nuclear matter

- This comes from experiments:
  - Result of a systematic phenomenological re-analysis of kaonic atoms data
    

- Mechanism: **Pauli principle** on proton weakening of binding $\rightarrow \Lambda$(1405) mass shift up to threshold
Influence of the nuclear medium (Pauli blocking) on the formation of the $\Lambda(1405)$


In free space, at threshold, point A, $a_{K^-p}<0$ → repulsive interaction

In nuclear matter at rather low density ($\sim 0.2 \rho_0$), at threshold, point B, $a_{K^-p}>0$ → attractive interaction

Fig. 1. Real (dashed lines) and imaginary parts (solid lines) of the $K^-p$ scattering amplitude in nuclear matter at different values of the Fermi momentum $p_F = (3\pi^2 \rho/2)^{1/3}$, as a function of the total c.m. energy $\sqrt{s}$.

- **a) free space, $p_F = 0$**;
- **b) $\sim 0.2 \rho_0$, $p_F = 150$ MeV/c**;
- **c) $\sim 1.4 \rho_0$, $p_F = 300$ MeV/c**; $\rho_0 = 0.17 \text{ fm}^{-3}$
Role of a bound state below threshold

The behavior of the $K^-p$ potential is a phenomenon well known in nuclear physics.

- Simple arguments from low-energy scattering show that the existence of a bound state below threshold always leads to a repulsive scattering length.  

- Analogy between the $K^-p$ scattering in the $I=0$ channel and the proton-neutron (p-n) scattering in the deuteron channel ($I=0$, $S=1$):  
  the interaction between the proton and neutron is attractive, but the scattering length in the deuteron channel ($I=0$, $S=1$) is repulsive, due to the existence of the deuteron as a bound state. In nuclear matter, however, the deuteron disappears, largely due to Pauli blocking, and the true attractive nature of the p-n interaction emerges.
Kaon-nucleus interaction and the formation of deeply bound \( K^- \)-nuclear states

Bound states. Binding a negatively charged s-wave pion at the surface of a heavy nucleus is a matter of subtle balance between Coulomb attraction and the repulsion resulting from the pion-nuclear strong interaction. In case of a negatively charged (anti)kaon, the driving \( K^- \)-nucleon interaction is attractive. It is sufficiently strong to generate the \( \Lambda(1405) \) just below \( KN \) threshold. In the region of this resonance, the coupling to the \( \pi\Sigma \) channel prohibits the formation of long-lived, narrow \( K^- \)-nuclear states. However, if the \( KN \) attraction is still active below the \( \pi\Sigma \) threshold, then there is a chance to form narrow \( K^- \)-nuclear bound states. This is the hypothesis introduced by Akaishi and Yamazaki [1]. The present status of data and phenomenology regarding this important issue is reported elsewhere in these Proceedings. The basic question we wish to address here is the following: to what extent does our present knowledge of low-energy \( KN \) interactions support such expectations? This study is guided by chiral \( SU(3) \) effective field theory, representing QCD with strange quarks in the low-energy limit.

Before turning to this central theme it is useful to give a brief summary of the s-wave pion-nucleus interaction and its detailed energy dependence, driven by the spontaneously broken chiral symmetry of low-energy QCD. This energy dependence is generic to the interaction of Goldstone bosons with matter. The interactions of pions and kaons with nucleons and nuclei are nonetheless quite different in comparison. The reason is the different degree of explicit chiral symmetry breaking, induced by the \( u, d- \) and \( s \)-quark masses as they transform into the mass difference between pion and kaon.
Problem

How the spontaneous and explicit chiral symmetry breaking pattern of low energy QCD changes in the nuclear environment

How the hadron masses and interactions change in the nuclear medium

Method

Producing deeply bound states from which to deduce the hadron-nucleus potential and the in-medium hadron mass

Deeply bound states of pions and kaons in the Coulomb and strong fields of a nucleus represent ideal conditions for investigating the way in which the spontaneous and explicit chiral symmetry breaking pattern of low-energy QCD changes in a nuclear environment. Such systems offer a high-precision testing ground for the detailed behavior of the (energy and momentum dependent) interactions of Goldstone bosons in a varying density.
Deeply bound kaonic nuclei

The s quark plays a leading role in forming a dense and cold nucleus.

A new paradigm of Nuclear Physics
T. Yamazaki et al.

Nuclei of 2nd generation

Excitation energy (MeV)

\[
\begin{align*}
\Sigma^0 \otimes A^{-1}[Z] &\quad \Sigma^+ \otimes A^{-1}[Z - 1] \\
\Xi^- \otimes A^{-1}[Z + 1] &\quad \Sigma^0 \otimes A^{-1}[Z] \\
\Lambda\Lambda \otimes A^{-2}[Z] &\quad \Sigma^+ \otimes A^{-1}[Z - 1] \\
\Lambda\Lambda \otimes A^{-2}[Z] &\quad \Sigma^0 \otimes A^{-1}[Z] \\
K^0 \otimes A^1[Z] &\quad K^- \otimes A^1[Z + 1] \\
\Lambda \otimes A^{-1}[Z] &\quad \pi^- \otimes A^1[Z + 1] \\
\end{align*}
\]

- (K^-, K^+)
- (K^-, \pi^+), (\pi^-, K^+)
- (K^-, \pi^-), (\pi^+, K^+)
- (K^-, N)

S=0 nuclei

S=-1

S=-2

FINUDA @ DAΦNE
-1959: $\Lambda(1405)$ proposed by Dalitz
-1985: deeply bound kaonic nuclear states proposed by Wycech
-Investigations on $\bar{K}$-Nucleon interaction both in vacuum and in nuclear matter still very intense today.

- $\bar{K}$-N in nuclear matter
  Ideal testing ground for studying nuclear density dependence of (spont. and expl.) chiral symmetry breaking (Kaon mass shift, $\Lambda(1405)$ in NM, kaon condensation…)

- $\bar{K}$-nucleus deeply bound states
  Sensitive tool to study $\bar{K}$-N interaction in nuclear matter:
  Energy Deeply b. state → $\bar{K}$-Nucleus potential → in medium kaon mass
  "In-medium mass spectroscopy" (Yamazaki)
Nuclear deeply bound $\bar{K}$ states

- Study of deeply bound atomic states successful with pions
  Similar approach with Kaons?

- DB pionic states: interplay between attractive coulomb
  and repulsive nuclear interaction at nuclear surface

- $\bar{K}$- N interaction: attractive $\rightarrow$ strong absorption ($\pi\Sigma$ channel)
  forbids narrow bound states ($\Gamma\sim100\text{MeV}$)
  Unless $\bar{K}$-N attraction survives below $\Sigma\pi$ threshold

- If $\bar{K}$-nucleus opt. potential deep enough possibility of narrow states

No unique solution from exp. data (atomic data not selective,
No consensus on $\bar{K}\pi$ below thr. & role of $\Lambda(1405)$)
Shallow ($\sim50\text{ MeV}$) [1] $\rightarrow$ no narrow DBKN state,
$\Gamma\sim100\text{MeV}$ (yes DB atomic states)
Deep($\geq100$-$200\text{MeV}$)[2] $\rightarrow$ narrow DBKN states

Nuclear deeply bound $\bar{K}$ states

Akaishi, Yamazaki (PRC 65 (2002) 044005) \( \Lambda(1405) = \bar{K}N \) bound state. Strong I=0 $\bar{K}N$ attraction

- Very deep potential
- Few body systems ($K^{-}p p$, $K^{-}n p p$, …) studied:
  - **Strong binding** ($\geq 100$ MeV), **Narrow width** (down to 20 MeV-pionic)
  - Strong nuclear density enhancement $\rho \sim 4-9\rho_0$ and nuclear shrinkage
  - Information on $\bar{K}N$ interaction in high density cold N.M., Partial C.S.R, kaon condensation,…

- Several other studies on DBKN clusters both on few-body systems and in heavier systems [#]. Some common features
  - Narrowing of width with increasing binding energy
  - Local (central) density increase

[#] Mares, Friedman, Gal (nucl-th/0601009; NPA in press); Ivanov, Kienle, Marton, Widmann (nucl-th/0512037), Zhong et al, nucl-th/0601009; Wycech et al, nucl-th/0501019
No unique solution for $\bar{K}$ optical potential from exp. data ($\bar{K}N$ interaction below thr., role of $\Lambda(1405)$, atomic data …)

**Shallow** (~50 MeV) [1] $\rightarrow$ no narrow DBKN state, $\Gamma \sim 100$ MeV (yes DB atomic states)

**Deep** ($\geq 100$-200 MeV)[2] $\rightarrow$ narrow DBKN states can exist

Akaishi, Yamazaki (PRC 65 (2002) 044005)
Construct very deep potential from $\Lambda(1405) = \bar{K}N$ bound state
Strong $I=0$ $\bar{K}$-N attraction

---


Summary of predicted $\bar{K}$ clusters. $M$: total mass [MeV]. $E_K$: total binding energy [MeV]. $\Gamma_K$: decay width [MeV]. $\rho(0)$: nucleon density at the center of the system [fm$^{-3}$]. $R_{\text{rms}}$: root-mean-square radius of the nucleon system [fm]. $k_p$ and $k_K$: rms internal momenta [fm$^{-1}$] of p and K$^-$, respectively. The calculated binding energies are subject to an increase by $\approx 10$ MeV, when the relativistic effect on K$^-$ is taken into account.

<table>
<thead>
<tr>
<th>$\bar{K}$ cluster</th>
<th>$M c^2$</th>
<th>$E_K$</th>
<th>$\Gamma_K$</th>
<th>$\rho(0)$</th>
<th>$R_{\text{rms}}$</th>
<th>$k_p$</th>
<th>$k_K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pK$^-$</td>
<td>1407</td>
<td>27</td>
<td>40</td>
<td>0.59</td>
<td>0.45</td>
<td>1.37</td>
<td>1.37</td>
</tr>
<tr>
<td>ppK$^-$</td>
<td>2322</td>
<td>48</td>
<td>61</td>
<td>0.52</td>
<td>0.99</td>
<td>1.49</td>
<td>1.18</td>
</tr>
<tr>
<td>pppK$^-$</td>
<td>3211</td>
<td>97</td>
<td>13</td>
<td>1.56</td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ppnK$^-$</td>
<td>3192</td>
<td>118</td>
<td>21</td>
<td>1.50</td>
<td>0.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ppppK$^-$</td>
<td>4171</td>
<td>75</td>
<td>162</td>
<td>1.68</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pppnK$^-$</td>
<td>4135</td>
<td>113</td>
<td>26</td>
<td>1.29</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ppnnK$^-$</td>
<td>4135</td>
<td>114</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ppK$^-K^-$</td>
<td>2747</td>
<td>117</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ppnK$^-K^-$</td>
<td>3582</td>
<td>221</td>
<td>37</td>
<td>2.97</td>
<td>0.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pppnK$^-K^-$</td>
<td>4511</td>
<td>230</td>
<td>61</td>
<td>2.33</td>
<td>0.73</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Theoretical calculations of K-pp

<table>
<thead>
<tr>
<th></th>
<th>Binding Energy</th>
<th>Decay Width</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ivanov, Kienle, Marton and Widdman</td>
<td>118MeV</td>
<td>58MeV**</td>
<td>Phenomenological model</td>
<td>nucl-th/0512037</td>
</tr>
<tr>
<td>Shevchenko, Gal and Mares</td>
<td>55—70MeV</td>
<td>90—110MeV*</td>
<td>Coupled channel Faddeev equation</td>
<td>nucl-th/0610022</td>
</tr>
<tr>
<td>Ikeda and Sato</td>
<td>76MeV</td>
<td>54MeV*</td>
<td>Coupled channel Faddeev equation</td>
<td>nucl-th/0701001</td>
</tr>
<tr>
<td>Doté and Weise</td>
<td>&lt;50MeV</td>
<td></td>
<td>Antisymmetrized Molecular Dynamics</td>
<td>nucl-th/0701050</td>
</tr>
<tr>
<td>cf. Λ(1405)</td>
<td>25±4MeV</td>
<td>50±2MeV</td>
<td></td>
<td>PDG</td>
</tr>
</tbody>
</table>

* pionic decay only
** non-pionic decay only

Recent theoretical predictions for K-pp
Experimental data

**Missing mass experiments**

\[ ^4\text{He}(\text{stopped } K^-, n): K^- np \]

\[ S^1(3140), \Gamma < 25 \text{ MeV}, T=0 \]

\[ B=169 \text{ MeV} \]

\[ ^4\text{He}(\text{stopped } K^-, p): K^- npn \]

\[ S^0(3115), \Gamma < 25 \text{ MeV}, T=1 \]

\[ B \sim 194 \text{ MeV} \]


Iwasaki et al, nucl-ex/0310018
FOPI-GSI Ni-Ni @1.9GeV

Experimental data

Possible decay channel: $ppnK^- \rightarrow \Lambda + d$

d-Cuts:
- $HM3MIN$
- $DM3MIN$
- $M3LOW$
- $M3HIGH$
- $DML$
- $DPHLM3MIN$
- $YDLMAX$
- $PTDLMIN$
- $PTDLMAX$
- $CCNT$
- $EM3MIN$
- $F_{10}$

Additional cuts:
- $|\Delta\phi| > 30^\circ$
- $y_{\text{pair}} < 0.65$

Properties:
- $M \approx M(\text{KEK}) = 3.14$ GeV
- $\Gamma >> 20$ MeV > $\Gamma(\text{KEK})$

Signal-MC
Background-MC

Exotic hadronic atoms, ECT*, June 05
M. Herrmann, Uni-HD
The search for (deeply) bound antikaon nuclear states
Experimental activity

• **Missing mass spectroscopy**
  - **Energy** measurement of recoiling particles in the \( A(K^-,N)X \) reaction
    - KEK-PS E471 (\( K^-_{\text{stop}},N \))
    - AGS E930 (\( K^-_{\text{in-flight}},n \))
    - KEK-PS E549 (\( K^-_{\text{stop}} \))

• **Invariant mass spectroscopy**
  - Detection of **decay products** of kaonic nuclear clusters (easier for light systems..)
    - \( (K^-pp) \rightarrow \Lambda + p \)
    - \( (K^-ppn) \rightarrow \Lambda + d \)
    - Typically (for stopped \( K^- \))
      - \( p_{p(\Lambda)} \sim 500 \text{ MeV/c} \)
      - \( p_{\pi(\Lambda)} < 200 \text{ MeV/c} \)
      - \( p_p \sim 500 \text{ MeV/c} \)

  - Full event reconstruction desirable (necessary)
  - Angular correlation between the emitted pairs necessary (desirable)

• **FOPI** (Ni-Ni heavy ion collisions@**GSI**)  
• **FINUDA** (\( K^-_{\text{stop}} \))
• **OBELIX** (p He)
• **KEK-PS E471-E549 \( ^4\text{He} \) (\( K^-_{\text{stop}},YN \))

Several experimental searches going on but no clear evidence yet

Study of multinucleon absorption backgrounds crucial
Experimental search for DBKS

How to study DBKN?
Missing mass expts $\rightarrow$ ambiguous results;
Inv. Mass expts NEEDED (exclusive measurements):
still extremely difficult task because of presence of
• Competing reactions
• Strong correlated and uncorrelated backgrounds
• FSI distortions
• Feeble signal ...
• ….details later

END OF PART II