Studies of low-energy K- hadronic interactions with light nuclei by AMADEUS

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On the behalf of the AMADEUS collaboration

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Plan

1. Motivation and scientific case
2. AMADEUS @ DAΦNE
3. Analysis results
4. Conclusions & perspectives
Motivation and Scientific Case

The investigation of the **in-medium modification of the $\bar{K}N$ interaction** is of **fundamental** for the low-energy QCD in the non perturbative regime.

**Chiral perturbation theory (ChPT):** effective field theory where mesons and baryons represent the effective degrees of freedom instead of the fundamental quark and gluon fields.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{mesons}}(\Phi) + \mathcal{L}_B(\Phi, \Psi_B)$$

- The chiral symmetry is **spontaneously broken** → the existence of massless and spinless Nambu-Goldstone bosons which are identified with the pions. Explicitly broken by $q$ masses.
- **Very successful** in describing the $\pi N$, $\pi \pi$ and $NN$ interactions in the low-energy regime and is considered as the theory of the low-energy strong interaction in the $SU(2)$ flavour sector.

The extension of the theory to the sector with the **quark s** turns out to be more problematic since it is not directly applicable to the $\bar{K}N$ channel.
The $\chi$PT is not applicable to the $\bar{K}N$ channel due to the emerging of the $\Lambda(1405)$ and the $\Sigma(1385)$ resonances just below the $\bar{K}N$ mass threshold.

$\Sigma(1385)$ $\Lambda(1405)$

$\Lambda(1405)$ I=0 $J^P = \frac{1}{2}^-$

$M = (1405.1^{+1.3}_{-1.0})$ MeV $\Gamma = (50.5 \pm 2.0)$ MeV

decay modes: $\Sigma\pi$ (I=0) 100%

$\Sigma(1385)$ I=1 $J^P = \frac{3}{2}^+$

decay modes: $\Lambda\pi$ (I=1) $(87.0 \pm 1.5)$ %

$\Sigma\pi$ (I=1) $(11.7 \pm 1.5)$ %

Possible solutions:

- Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics
- Phenomenological $\bar{K}N$ and NN potentials

The parameters of the models are constrained by the existing scattering data.


Chiral


and by the SIDDHARTA measurement of $K_\alpha$ transition in Kaonic hydrogen at threshold

M. Bazzi et al., 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113
The $\chi$PT is not applicable to the $\bar{K}N$ channel due to the emerging of the $\Lambda(1405)$ and the $\Sigma(1385)$ resonances just below the $\bar{K}N$ mass threshold.

$$\Sigma(1385) \quad \Lambda(1405)$$

$\Lambda(1405)$ $I=0$ $J^P = \frac{1}{2}^-$

$M = (1405.1^{+1.3}_{-1.0})$ MeV $\Gamma = (50.5 \pm 2.0)$ MeV
decay modes: $\Sigma\pi$ ($I=0$) $100\%$

$\Sigma(1385)$ $I=1$ $J^P = \frac{3}{2}^+$
decay modes: $\Lambda\pi$ ($I=1$) $(87.0 \pm 1.5)\%$
$\Sigma\pi$ ($I=1$) $(11.7 \pm 1.5)\%$

Possible solutions:

- **Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics**
- **Phenomenological $\bar{K}N$ and NN potentials**

...but... large differences in the subthreshold extrapolations! **Significantly weaker attraction in chiral SU(3) models** than in phenomenological potential models.

**Re** Im

|-------|----------------------------------------------------------|

New experimental constraints!!!

The controversial nature of the $\Lambda(1405)$

The $\Lambda(1405)$ state does not fit with the simple three quarks model ($uds$) and it is commonly accepted that it is, at least partially, a $\bar{K}N$ bound state.

- **Chiral SU(3) coupled channel dynamics:**
  the state is given by the superpositions of two poles of the $\bar{K}N$ scattering amplitude.

  \[ M = 1425 \text{ MeV} \rightarrow \text{mainly coupled to the } \bar{K}N \text{ channel} \]

  \[ M = 1380 \text{ MeV} \rightarrow \text{mainly coupled to the } \Sigma\pi \text{ channel} \]

- **Phenomenological potentials models:** the $\Lambda(1405)$ is a pure $\bar{K}N$ bound state with mass $M=1405 \text{ MeV}$, binding energy $BE = 27 \text{ MeV}$ and width $\Gamma = 50 \text{ MeV}$. 
Possible existence of kaonic bound states


Predicted in the $\bar{K}N$ interaction in the $I=0$ channel due to the strong interaction

Essential impact on the EoS of Neutron Stars

gravitational waves signal emitted by binary system of Neutron Stars

Theory

Dote, Hyodo, Weisse
Barnea, Gal, Liverts
Ikeda, Kamano, Sato
Bicudo
Bayar, Oset
Dote, Inoue, Myo
Sekihara, Oset, Ramos

Chiral models| BE [MeV]| $\Gamma$ [MeV]| Reference
---|---|---|---

Phen. approach| BE [MeV]| $\Gamma$ [MeV]| Reference
---|---|---|---
Reva, Shevchenko| 32| 49| Phys. Rev. C 90 no. 3 (2014) 034004

Experiments

| Experiment | BE [MeV]| $\Gamma$ [MeV]| Reference |
---|---|---|---|
FINUDA| $115^{+8}_{-5}$\,(stat.)$^{+5}_{-4}$\,(syst.)| $67^{+14}_{-11}$\,(stat.)$^{+3}_{-4}$\,(syst.)| PRL 94 (2005), 212303 |
OBELIX| 160.9±4.9| <24.4±8.0| NPA 789 (2007), 222 |
E549| -| -| MPLA 23 (2008), 2520 |
DISTO| 103±3\,(stat.)±5\,(syst.)| 118±8\,(stat.)±10\,(syst.)| PRL 104 (2010), 132502 |
LEPS/SPring-8| Upper limit| -| PLB 728 (2014), 616 |
HADES| Upper limit| -| PLB 742 (2015), 242 |
E27| $95^{+18}_{-17}$\,(stat.)$^{+30}_{-21}$\,(syst.)| $162^{+87}_{-45}$\,(stat.)$^{+66}_{-78}$\,(syst.)| PTEP (2015), 021D01 |
AMADEUS| Upper limit| -| PLB 758 (2016), 134 |
E15 1st run| $15^{+5}_{-4}$\,(stat.)$^{+12}_{-12}$\,(syst.)| $110^{+10}_{-17}$\,(stat.)$^{+27}_{-27}$\,(syst.)| PTEP (2016), 051D01 |
E15 2nd run| $47^{+3}_{-4}$\,(stat.)$^{+4}_{-6}$\,(syst.)| $115^{+7}_{-15}$\,(stat.)$^{+10}_{-20}$\,(syst.)| PLB 789 (2019), 612 |
Possible existence of kaonic bound states

FINUDA, E549, E15, AMADEUS: K⁻ induced reactions
DISTO, HADES: p-p collisions
OBELIX: anti-p annihilations
E27: π induced reactions
LEPS/SPring-8: photoproduction
AMADEUS: KLOE 2004-2005 dataset analysis ($\mathcal{L} = 1.74 \text{ pb}^{-1}$)

Possibility to use KLOE materials as an active target
- DC wall (750 $\mu$m C foil, 150 $\mu$m Al foil);
- DC gas (90% He, 10% $\text{C}_4\text{H}_{10}$).

KLOE
- Cylindrical DC with $4\pi$ geometry & electromagnetic calorimeter
- 96% acceptance
- high efficiency and resolution for charged and neutral particles
- exclusive measurement of the considered

AMADEUS @ DAΦNE
- $\phi \rightarrow K^- K^+$ (49.2%), $\approx 1000 \phi/s$
- monochromatic low momentum Kaons $\approx 127 \text{ Mev/c}$
- back to back $K^- K^+$ topology
- small hadronic background due to the beam

DAΦNE

Entries 431010
Mean 25.02
Std Dev 18.67
**Λπ⁻ analysis: K⁻n non-resonant transition amplitude**

**Λ(1405) case**

**Goal:** how much comes from resonance in $K^−N → Y\pi$

**Non-resonant transition amplitude never measured before below threshold**

IN FLIGHT $K^-^{12}C$ opens window between 1416 MeV and KN threshold

rest –

rest+flight –

resonant and non-resonant $K^-p$ (I=0) components are to be disentangled


$K^-"n" → Λ\pi^-$ direct formation in $^4He$


Simulations for resonant and non-resonant processes performed based on calculations for both S-state and P-state K- capture AT REST and IN FLIGHT.
**Σ^0p analysis: K^- multi-nucleon absorptions in ^{12}C**

K^-^{12}C → Σ^0 p R → (p π^-) γ p R

detected particles

No statistically significant bound state emerges at 2σ level

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**Final fit**

- data
- π^0 background
- 4NA+Uncorr.
- 3NA
- 2NA FSI
- 2NA QF
- Total QF

χ^2 = 0.85

2NA-QF clearly separated
From other processes

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<table>
<thead>
<tr>
<th>Process</th>
<th>( \text{yield} / K_{\text{stop}} \cdot 10^{-2} )</th>
<th>( \text{σ}_{\text{stat}} \cdot 10^{-2} )</th>
<th>( \text{σ}_{\text{syst}} \cdot 10^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2NA-QF</td>
<td>0.127</td>
<td>± 0.019</td>
<td>+0.004</td>
</tr>
<tr>
<td>2NA-FSI</td>
<td>0.272</td>
<td>± 0.028</td>
<td>+0.002</td>
</tr>
<tr>
<td>Tot 2NA</td>
<td>0.376</td>
<td>± 0.033</td>
<td>+0.003</td>
</tr>
<tr>
<td>3NA</td>
<td>0.274</td>
<td>± 0.069</td>
<td>+0.044</td>
</tr>
<tr>
<td>Tot 3body</td>
<td>0.546</td>
<td>± 0.074</td>
<td>+0.048</td>
</tr>
<tr>
<td>4NA + bkg.</td>
<td>0.773</td>
<td>± 0.053</td>
<td>+0.025</td>
</tr>
</tbody>
</table>

Simultaneous fit of:
- \( \Lambda p \) invariant mass;
- angular correlation;
- proton momentum;
- \( \Lambda \) momentum.

Total reduced \( \chi^2 \): \( \chi^2/{d.o.f} = 0.94 \)

The ratio between the branching ratios of the 2NA-QF in the \( \Lambda p \) channel and in the \( \Sigma^0 p \) is measured to be:

\[
\mathcal{R} = \frac{BR(K^- pp \to \Lambda p)}{BR(K^- pp \to \Sigma^0 p)} = 0.7 \pm 0.2 \text{(stat.)}^{+0.2}_{-0.3} \text{(syst.)}
\]

and the ratio between the corresponding phase spaces is \( \mathcal{R}' \approx 1.22 \).

According to the pion exchange model:

\[
\frac{BR(K^- pp \to \Lambda p)}{BR(K^- pp \to \Sigma^0 p)} = \frac{BR(K^- p \to \Lambda^0 p)}{BR(K^- p \to \Sigma^0 \pi^0)}
\]

Using BE and $\Gamma$ from experiments:

**FINUDA at DAΦNE**

- $^{2}\Lambda$N: Fixing BE and moving $\Gamma$

**AMADEUS at DAΦNE**

- BRs evaluation

Using $\Delta p$ analysis:

- $K_{pp}$ bound state search

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**Table:**

<table>
<thead>
<tr>
<th>Process</th>
<th>Branching Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{2}\Lambda$N-QF $\Delta p$</td>
<td>$0.20 \pm 0.04$ (stat.) $\pm 0.02$ (syst.)</td>
</tr>
<tr>
<td>$^{2}\Lambda$N-FSI $\Delta p$</td>
<td>$3.8 \pm 2.3$ (stat.) $\pm 1.1$ (syst.)</td>
</tr>
<tr>
<td>$^{2}\Lambda$N-QF $\Sigma^0 p$</td>
<td>$0.54 \pm 0.20$ (stat.) $^{+0.20}_{-0.10}$ (syst.)</td>
</tr>
<tr>
<td>$^{2}\Lambda$N-FSI $\Sigma^0 p$</td>
<td>$5.4 \pm 1.5$ (stat.) $^{+1.0}_{-2.5}$ (syst.)</td>
</tr>
<tr>
<td>$^{2}\Lambda$N-CONV $\Sigma/\Lambda$</td>
<td>$22 \pm 4$ (stat.) $^{+1}_{-12}$ (syst.)</td>
</tr>
<tr>
<td>$^{3}\Lambda$ $\Delta p$</td>
<td>$1.1 \pm 0.3$ (stat.) $\pm 0.2$ (syst.)</td>
</tr>
<tr>
<td>$^{3}\Lambda$ $\Sigma^0 p$</td>
<td>$1.9 \pm 0.7$ (stat.) $^{+0.5}_{-0.4}$ (syst.)</td>
</tr>
</tbody>
</table>
**Λt analysis: Cross section and BR for 4NA in K⁻⁺⁴He → Λt process**

**Previous data:**

- in $^4$He: bubble chamber experiment
  only 3 events compatible with Λt kinematics found
  \[ \text{BR}(K^{-}\text{He} \rightarrow \Lambda t) = (3 \pm 2) \times 10^{-4}/K_{\text{stop}} \]  → global, no 4NA

- in solid targets: $^6,^7\text{Li}$, $^9\text{Be}$ (FINUDA)
  40 events, only back-to-back data
  \[ \Lambda t \text{ emission yield} \rightarrow 10^{-3} - 10^{-4} / K_{\text{stop}} \]  → global, no 4NA

**AMADEUS analysis**

We measure the triton mass by TOF

\[ \text{BR}(K^{-}\text{He(4NA) \rightarrow \Lambda t}) < 2.0 \times 10^{-4}/K_{\text{stop}} \]  (95% c. l.)

\[ \sigma(100 \pm 19 \text{ MeV/c}) (K^{-}\text{He(4NA) \rightarrow \Lambda t}) = (0.81 \pm 0.21 \text{ (stat)} +0.03_{-0.04} \text{ (syst)}) \text{ mb} \]

**Final fit**

- carbon data from DC wall
- $4\text{NA} K^{-}\text{He \rightarrow \Lambda t}$ in flight MC
- $4\text{NA} K^{-}\text{He \rightarrow \Lambda t}$ at rest MC
- $4\text{NA} K^{-}\text{He \rightarrow \Sigma^0_t}$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC
- $4\text{NA} K^{-}\text{He \rightarrow \Sigma^0_t}$, $\Sigma^0 \rightarrow \Lambda\gamma$ MC

Entries 150

**Paper in preparation**
**Goal:** measurement of the $K^- H \rightarrow \Sigma^0 \pi^0$ cross sections for $p_K = 98\pm10$ MeV/c


Low momentum $K^-$ scattering cross sections in this Isospin $I = 0$ channel represent a fundamental input for the non-perturbative low energy QCD models
Thank you for attention!
How deep can be bound antikaon in nucleus?

Experimental search in $K^{-}$ induced reactions

$E549$ at KEK: $K^{-}_\text{stop} + ^4\text{He} \rightarrow \Lambda + p + X'$

$FINUDA$ at DAΦNE: $K^{-}_\text{stop} + X \rightarrow \Lambda + p + X'$

$BE = (115^{+6}_{-5}\text{ (stat.)}^{+3}_{-4}\text{ (syst.)}) \text{ MeV}$

$\Gamma = (67^{+14}_{-11}\text{ (stat.)}^{+2}_{-3}\text{ (syst.)}) \text{ eV/c}^2$
AMADEUS: KLOE 2004-2005 dataset analysis ($\mathcal{L} = 1.74$ pb$^{-1}$)

AMADEUS scientific case
- nature of $\Lambda(1405)$ and $K^-N$ amplitude below threshold
- $K^-$ multiN absorption
- kaonic nuclear clusters
- $YN$ correlation studies ($\Lambda p, \Sigma^0 p, \Lambda t$)
- low-energy charged $K$ cross section (for $p=100$ MeV)
$K^-$ $^{12}\text{C} \rightarrow \Lambda/\Sigma^0 \ p$ (2NA) 

$K^-$ $^4\text{He} \rightarrow \Lambda/\Sigma^0 \ t$ (4NA)

$\Lambda$ decay vertex

hadronic vertex

$\rho > 170\text{MeV/c}$

$L_p > 30\text{cm} \ & \ L_\pi > 50\text{cm}$

Proton/triton mass measured by TOF

$1112 < M_{\rho\pi} < 1118 \text{MeV/c}^2$
Essential impact on the EoS of Neutron Stars

Role of strangeness in dense baryonic matter, kaon condensation? Strange quark matter? Hyperons in Neutron Stars?

The central densities are expected to be large enough to activate the strangeness production:

\[ p + e^- \rightarrow n + \nu_e \]
\[ n \rightarrow p + K^- \]

HOT TOPIC after the measurement of the gravitational waves signal emitted by binary system of Neutron Stars (GW170817)
YN/NN scatterings

Y-N/NN interaction essential impact on the case of NEUTRON STARS

Microscopic approach to hyperonic matter EOS

2BF: nucleon-nucleon (NN), nucleon-hyperon (NY), hyperon-hyperon (YY)
e.g. Nijmegen, Julich models

3BF: NNN, NNY, NYY, YYY

Hyperonic sector: experimental data
1. YN scattering (very few data)
2. Hypernuclei
No experimental information on $\Sigma^0$-N/NN interaction

Drastic role played by $\Lambda NN$. Calculations can be compatible with neutron star observations.

Note: no $\nu_\Lambda$, no protons, and no other hyperons included yet...

Figure 2: "Total" cross section $\sigma_T$ (as defined in Eq. (24)) as a function of $p_{\text{lab}}$. The experimental cross sections are taken from Refs. [52] (dilled circles), [53] (open squares), [65] (open circles), and [66] (dilled squares) ($\Lambda p \to \Lambda p$), from [54] ($\Sigma^+ p \to \Lambda n$, $\Sigma^- p \to \Sigma^0 n$) and from [55] ($\Sigma^+ p \to \Sigma^+ n$, $\Sigma^- p \to \Sigma^- n$). The red/dark band shows the chiral EFT results to NLO for variations of the cutoff in the range $\Lambda = 500, \ldots, 850$ MeV, while the green/light band are results to LO for $\Lambda = 550, \ldots, 700$ MeV. The dashed curve is the result of the Itakura '04 meson-exchange potential [56].