Low Energy antikaon-nucleon/nuclei interaction studies by AMADEUS

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Investigation of in-medium modification of the $\bar{K}N$ interaction 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.

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

- Chiral symmetry is **spontaneously broken** → existence of massless and spinless Nambu-Goldstone bosons which are identified with the pions (SU(2)). Explicitly broken by quark masses.
- **Very successful** in describing the $\pi N$, $\pi \pi$ and NN interactions in the low-energy regime.

**Problematic extension of the theory to the s sector, not directly applicable to the KN channel.** See talk by A. Ramos
Low-energy QCD in the u-d-s sector

ChPT not applicable to the KN channel due to the emerging of the \( \Lambda(1405) \) and the \( \Sigma(1385) \) resonances just below the KN mass threshold (~1432 MeV)

\[ \begin{align*}
\Sigma(1385) \quad & \Lambda(1405) \\
\text{decay modes: } & \Sigma \pi (I=0) \quad 100\% \\
\text{decay modes: } & \Lambda \pi (I=1) \quad (87.0 \pm 1.5) \% \\
& \Sigma \pi (I=1) \quad (11.7 \pm 1.5) \% \\
\end{align*} \]

Possible solutions:

➢ Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics
➢ Phenomenological \( \bar{K}N \) and NN potentials
Low-energy QCD in the u-d-s sector

The parameters of the models are constrained by the existing scattering data → above the threshold

Low-energy QCD in the u-d-s sector

...but... large differences in the subthreshold extrapolations!

**Significantly weaker attraction in chiral SU(3) models** than in phenomenological potential models. See talk by J. Mares

**Figure:**

- Phenomenological potential model
- Chiral SU(3) dynamics

**Graphs:**

- Re and Im for Phen. and Chiral
- KN threshold region
- s^{1/2} [MeV]
- F_{KN} [fm]
The $\Lambda(1405)$ case

- Chiral unitary models: $\Lambda(1405)$ is an $I = 0$ quasibound state emerging from the coupling between the $KN$ and the $\Sigma\pi$ channels. Two poles in the neighborhood of the $\Lambda(1405)$:


- Akaishi-Esmaili-Yamazaki phenomenological potential


  Confirmation of single pole ansatz?

- Chiral dynamics predicts significantly **weaker attraction** than AY (local, energy independent) potential in **far-subthreshold** region
The $\Lambda(1405)$ case

BBUBBLE CHAMBER search of the $\Lambda(1405)$:

- O. Braun et al. Nucl. Phys. B129 (1977) 1
  
  $K$- induced reactions on $d \to \Sigma^{-}\pi^{+} n$ the resonance is found & 1420 MeV

- D. W. Thomas et al., Nucl. Phys. B56 (1973) 15
  
  pion induced reaction $\pi^{-} p \to K^{+}\pi^{-}\Sigma^{0}$ the resonance is found & 1405 MeV

  
  $K^{-} p \to \pi^{-} \Sigma^{+}(1660) \to \pi^{-} (\pi^{+} \Lambda(1405)) \to \pi^{-} \pi^{+}(\pi\Sigma)$ & 4.2 GeV
  
  analysed by Dalitz and Deloff $M = 1406.5 \pm 4.0$ MeV, $\Gamma = 50 \pm 2$ MeV

  
  $p p \to p K^{+} \pi^{0}$ the resonance is found & 1390 MeV
The $\Lambda(1405)$ case

THE “LINE-SHAPE” OF THE $\Lambda(1405)$ DEPENDS ON THE OBSERVED CHANNEL!!

\[
\frac{d\sigma(\Sigma^{-}\pi^{+})}{dM} \propto \frac{1}{3} |T^0|^2 + \frac{1}{2} |T^1|^2 + \frac{2}{\sqrt{6}} \text{Re}(T^0 T^{1*})
\]

\[
\frac{d\sigma(\Sigma^{+}\pi^{-})}{dM} \propto \frac{1}{3} |T^0|^2 + \frac{1}{2} |T^1|^2 - \frac{2}{\sqrt{6}} \text{Re}(T^0 T^{1*})
\]

\[
\frac{d\sigma(\Sigma^{0}\pi^{0})}{dM} \propto \frac{1}{3} |T^0|^2
\]
The $\Lambda(1405)$ case

THE “LINE-SHAPE” OF THE $\Lambda(1405)$ DEPENDS ON THE OBSERVED CHANNEL!!

\[
\frac{d\sigma(\Sigma^+\pi^-)}{dM} \propto \frac{1}{3} |T^0|^2 + \frac{1}{2} |T^1|^2 + \frac{2}{\sqrt{6}} \Re(T^0T^1*)
\]

\[
\frac{d\sigma(\Sigma^-\pi^+)}{dM} \propto \frac{1}{3} |T^0|^2 + \frac{1}{2} |T^1|^2 - \frac{2}{\sqrt{6}} \Re(T^0T^1*)
\]

\[
\frac{d\sigma(\Sigma^0\pi^0)}{dM} \propto \frac{1}{3} |T^0|^2
\]

IS DIFFERENT IN $\Sigma^+\pi^-$ VS $\Sigma^-\pi^+$ DUE TO ISOSPIN INTERFERENCE
The \( \Lambda(1405) \) case

The "line-shape" of the \( \Lambda(1405) \) depends on the observed channel!!

\[
\frac{d\sigma}{dM}((\Sigma^{-}\pi^{+})) \propto \frac{1}{3}|T^{0}|^2 + \frac{1}{2}|T^{1}|^2 + \frac{2}{\sqrt{6}}Re(T^{0}\overline{T}^{1*})
\]

\[
\frac{d\sigma}{dM}((\Sigma^{+}\pi^{-})) \propto \frac{1}{3}|T^{0}|^2 + \frac{1}{2}|T^{1}|^2 - \frac{2}{\sqrt{6}}Re(T^{0}\overline{T}^{1*})
\]

\[
\frac{d\sigma}{dM}(\Sigma^{0}\pi^{0}) \propto \frac{1}{3}|T^{0}|^2
\]

Is different in \( \Sigma^{+}\pi^{-} \) vs \( \Sigma^{-}\pi^{+} \) due to isospin interference.

The cleanest signature of the \( \Lambda(1405) \) is given by the neutral channel:

- is free from isospin interference
- is purely \( I = 0 \), no \( \Sigma(1385) \) contamination.
\( \Lambda(1405) \) .. the golden channel

Crystall Ball: \( Kp \rightarrow \Sigma^0\pi\pi^0 \) for kaon momentum in the range (514-750 MeV/c). S. Prakhov et al. Phys Rev. C70 (2004) 03465 (interpreted by Magas et al. PRL 95, 052301 (2005))

CLAS: \( \gamma p \rightarrow K^+ \Sigma\pi \)

COSY julich: \( pp \rightarrow pK^+ \Sigma^0\pi^0 \)
The \( \Lambda(1405) \) .. the golden channel

Crystall Ball: \( Kp \rightarrow \Sigma^0\pi^0 \) for kaon momentum in the range (514-750 MeV/c). S. Prakhov et al. Phys Rev. C70 (2004) 03465
(Magas et al. PRL 95, 052301 (2005))

Even in the same \( \Sigma^0\pi^0 \) the "line-shape" of the \( \Lambda(1405) \) changes.

It must also depend on the production mechanism.

COSY julich: \( pp \rightarrow pK^+ \Sigma^0\pi^0 \)

Fig. 4. a) Missing-mass \( MM(p_{K^+}K^+) \) distribution for the \( pp \rightarrow pK^+p\pi^-X^0 \) reaction for events with \( M(p_{\Sigma^0}\pi^-) \approx m(\Lambda) \) and \( MM(pK^+p\pi^-) > 190 \text{MeV/c}^2 \). Exper-
The $\Lambda(1405)$ case

Two main biases:

- the kinematical energy threshold 1412 MeV
  
  $$(MK + Mp - |BEp|) \text{ the high pole energy region is closed},$$

- The shape and the amplitude of the NON-RESONANT
  
  $\Sigma\pi$ production below KbarN threshold never measured.

An ideal experiment:

- $\Lambda(1405)$ is produced in K- p absorption $\rightarrow$ mainly coupled to the high
  mass pole,

- $\Lambda(1405)$ is observed in the $\Sigma^0\pi^0$ decay channel (almost pure isospin 0),

- K- is absorbed in-flight on a bound proton with $p_K \sim 100$ MeV, $\Sigma\pi$
  invariant mass gain of $\sim 10$ MeV to open an energy window to the
  high mass pole.

- Knowledge of the $\Sigma\pi$ NON-RESONANT production amplitude.
How deep can an antikaon be bound in a nucleus?

Possible Bound States:

\[(\bar{K}^- \text{ pp}) \rightarrow \Lambda \text{ p} \]
\[\rightarrow \Sigma^0 \text{ p} \]
\[\text{(K}^- \text{ ppn}) \rightarrow \Lambda \text{ d} \]
\[\rightarrow \Sigma^0 \text{ d} \]

predicted if strong \(\bar{K}N\) interaction in the \(I=0\) channel.

[Wycech (1986) - Akaishi & Yamazaki (2002)]

\(\bar{K}^-\text{pp} \) bound state

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<table>
<thead>
<tr>
<th>Experiments reporting DBKNS</th>
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<tbody>
<tr>
<td><strong>FINUDA</strong></td>
</tr>
<tr>
<td><strong>DISTO</strong></td>
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<tr>
<td><strong>OBELIX</strong></td>
</tr>
<tr>
<td><strong>LEPS/SPRING-8</strong></td>
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</tbody>
</table>
How deep can an antikaon be bound in a nucleus?

interpreted in

[from the talk of T. Nagae at HYP2015, Sep. 10, 2015]
Bound state search in K- induced reactions

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

detected particles

Measurement of yields and shapes of the K- multi-nucleon yields is mandatory to solve the puzzle!

They are the counterpart of the non-resonant single nucleon capture

- **1NA**: K- single nucleon absorption
- **2NA**: K- two nucleon absorption
- **2NA + conversion**, multi-nucleon, or **Bound State**?
and K- multi-nucleon cross section?

Transport models and collision calculations need the measurement of the K- multi-nucleon cross sections at low energy...

In medium K̅ properties investigated in heavy-ion & proton nuclei collisions, K- mass modification extrapolated from the K- production yield still missing!
AMADEUS scientific case

- Nature of the $\Lambda(1405)$ & K-N amplitude below threshold → $\gamma \pi$ CORRELATION STUDIES

- K- multi-nucleons absorptions cross sections

- kaonic nuclear clusters

→ $\gamma \pi$ CORRELATION STUDIES  (i.e. $\Lambda p, \Sigma^0 p$, and $\Lambda t$ final states)

- Low-energy charged kaon cross sections for low momenta (100 MeV/c)

- YN scattering → extremely poor experimental information from scattering data (strong impact on the EoS of Neutron Stars Related to NS merging radiation + GW emission)
AMADEUS & DAΦNE

DAΦNE
- double ring e^+ e^- collider working at C.M. energy of $\phi$, producing $\approx 1000 \phi /s$
  - low momentum Kaons
  - $\approx 127$ Mev/c
- back to back $K^+ K^-$ topology

AMADEUS step 0 → KLOE 2004-2005 dataset analysis ($\mathcal{L} = 1.74$ fb$^{-1}$)

KLOE
- Cilindrical drift chamber with a $4\pi$ geometry and electromagnetic calorimeter
  - 96% acceptance
  - optimized in the energy range of all charged particles involved
- good performance in detecting photons and neutrons checked by kloNe group
  [M. Anelli et al., Nucl Inst. Meth. A 581, 368 (2007)]
K⁻ absorption on light nuclei

from the materials of the KLOE detector
DC gas (90% He, 10% C₄H₁₀) & DC wall (C + H)

**AT-REST** (K⁻ absorbed from atomic orbit) or **IN-FLIGHT** (p_K ~ 100MeV)

**Advantage:**
excellent resolution ..
\[ \sigma_{p\Lambda} = 0.49 \pm 0.01 \text{ MeV/c in DC gas} \]
\[ \sigma_{m_{yy}} = 18.3 \pm 0.6 \text{ MeV/c}^2 \]

**Disadvantage:**
Not dedicated target → **different nuclei contamination** → complex interpretation .. but → new features ..
K⁻ in flight absorption.
At-rest VS in-flight $K^-$ captures

**AT-REST**
$K^-$ absorbed from atomic orbit
$(p_K \sim 0 \text{ MeV})$

**IN-FLIGHT**
$(p_K \sim 100 \text{ MeV})$
Pure graphite Carbon target

Advantages:

- gain in statistics
- pure K$^-$ Carbon absorptions
- pure absorptions at-rest.

- MC simulation: 26% of K$^-$ stopped in $^{12}$C

- Thickness optimized to maximize the number of stopping K$^-$ in the target (minimizing energy loss)

(\sim 90 \text{ pb}^{-1}; \text{ analyzed } 37 \text{ pb}^{-1}, \times 1.5 \text{ statistics})
K⁻ - N single nucleon absorption resonant and non-resonant amplitudes
**\(\Lambda(1405)\) case**

![Graph](image)

**FIG. 4:** Theoretical \((\pi^0\Sigma^0)\) invariant mass distribution for an initial kaon lab momenta of 687 MeV. The non-symmetrized distribution also contains the factor 1/2 in the cross section.

**FIG. 5:** Two experimental shapes of \(\Lambda(1405)\) resonance. See text for more details.

\[ p_{\pi^0} \text{ resolution: } \sigma_p \approx 12 \text{ MeV/c} \]

**Counts/(10\text{MeV/c})**

**IN-FLIGHT**

K- 12C opens a window between 1416 MeV and K-Nth

**At rest**

**In flight**
Λ(1405) : extracting the resonant I = 0 contribution

PID optimised, data fit is ongoing necessary the input of the Λπ⁻ measurement

- K. Piscicchia et al., APP B48 (2017) 10, 1875
- C. Curceanu, K. Piscicchia et al., APP B46 (2015) 1, 203

rest —
rest+flight —

resonant and non-resonant

K⁻ p (I=0) components are to be disentangled

IN-FLIGHT
K⁻ 12C
opens a window between 1416 MeV and K-Nth
Resonant VS non-resonant

\[ K^- N \rightarrow (Y^* ?) \rightarrow Y \pi \]

how much comes from resonance?

Non resonant transition amplitude
never measured before below threshold
can be obtained exploiting \( K^- N \) in-medium absorption,

chosen target \(^4\)He

- \( K^- \) angular momentum at the capture
- absorbing nucleon wave function \}

known quantities
Resonant VS non-resonant

Investigated using:

\[ K^- \rightarrow n \rightarrow \Lambda \pi^- \] direct formation in \( ^4\text{He} \)

the goal is to measure \( |f_{N-R}^{\Lambda \pi^-(I=1)}| \)
Resonant VS non-resonant

Investigated using:

\( K^- \rightarrow \Lambda \pi^- \) to extract \(|f^{N-R}_{\Lambda \pi} (I=1)|\) below threshold

K$^-$ $^4$He $\rightarrow$ $\Lambda p$ $^3$He resonant and non-resonant processes

Theoretical shapes for:

- total $\Lambda\pi^-$ momentum spectra for the resonant ($\Sigma^*$) and non-resonant ($l = 1$) processes were calculated, for both S-state and P-state K$^-$ capture at-rest and in-flight.
- Corrections to the amplitudes due to $\Lambda/\pi$ final state interactions were estimated.
Simultaneous fit: \((p_{\Lambda\pi^-} - m_{\Lambda\pi^-} - \cos(\theta_{\Lambda\pi^-}))\)
Comparison

$m_{\Lambda\pi}$ fit
Light band sys err.
Dark band stat. Err.
Outcome of the measurement

From the well known $\Sigma^*$ transition probability:

$$\frac{N_{R} - a_{r}}{R_{E} - a_{r}} = \frac{\int_{0}^{p_{\text{max}}} P_{r_{i}}(p_{\Lambda_{\pi}}) \, dp_{\Lambda_{\pi}}}{\int_{0}^{p_{\text{max}}} P_{r_{j}}(p_{\Lambda_{\pi}}) \, dp_{\Lambda_{\pi}}} = |f_{ar}^{s}|^2 \cdot 8,94 \cdot 10^5 \text{MeV}^2.$$

$$|f_{ar}^{nr}| = |A_{K-n\rightarrow\Lambda\pi^-}| = (0.334 \pm 0.018 \text{stat}^{+0.034}_{-0.058} \text{syst}) \text{fin}$$

compatible with $K^- p \rightarrow \Lambda \pi^0$ scattering above threshold

J. K. Kim, Columbia University Report, Nevis 149 (1966),

J. K. Kim, Phys Rev Lett, 19 (1977) 1074:

<table>
<thead>
<tr>
<th>$E = -33$ MeV</th>
<th>$p_{lab} = 120$ MeV</th>
<th>160 MeV</th>
<th>200 MeV</th>
<th>245 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.334 \pm 0.018 \text{stat}^{+0.034}_{-0.058} \text{syst}$</td>
<td>0.33(11)</td>
<td>0.29(10)</td>
<td>0.24 (6)</td>
<td>0.28(2)</td>
</tr>
</tbody>
</table>
To compare with theoretical calculations:

1) extract the amplitude for each model .. \( A_{K-n} = (\text{Re} F_{K-n}^2 + \text{Im} F_{K-n}^2)^{1/2} \)

2) scale the amplitudes for the \( K \cdot n \) couplings to the \( \Sigma \pi^0 \) and \( \Sigma^0 \pi^- \) channels:

\[
\frac{Prob_{K-n \to \Lambda \pi^-}}{Prob_{K-n \to \Sigma\pi^0}} = \frac{Ph_{K-n \to \Lambda \pi^-}}{c_1 Ph_{K-n \to \Sigma\pi^0}}
\]

Isospin \((I, I_z) = (1, -1)\) component

\[
\frac{Prob_{K-n \to \Lambda \pi^-}}{Prob_{K-n \to \Sigma^0 \pi^-}} = \frac{Ph_{K-n \to \Lambda \pi^-}}{c_2 Ph_{K-n \to \Sigma^0 \pi^-}}
\]

Phase spaces ratios
comparison with th. models

\[ |f_{ar}^s| = (0.334 \pm 0.018 \text{ stat}^{+0.034}_{-0.058 \text{ syst}}) \text{ fm}. \]

\[ A_{K^-n \to \Lambda \pi^0} \left( s^{1/2} \sim 1400 \text{ MeV} \right)^{1/2} \]

\[ E_{K_n} = -|B_n| - \frac{p_3^2}{2\mu_{\pi\Lambda}} H_\epsilon \]

Nucl. Phys. A954 (2016) 75-93

comparison with th. models

See talk by A. Ramos


$K^- \text{- multiN absorption and search for bound states}$
AMADEUS contribution from low energy $K^-\,^{12}C$ absorption $\Sigma^0p / \Lambda p$ final states


no significant bound state emerges at the level of 2σ

- $\Lambda p$ analogous analysis finalized
- $K$-multi-nucleon yields & cross sections obtained for $pK \sim 100$ MeV/c
- disappearance of the bound state in $K^-\,^{12}C$ induced reaction explained

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Yield / $K^-_{stop} \cdot 10^{-2}$</th>
<th>$\sigma_{stat} \cdot 10^{-2}$</th>
<th>$\sigma_{syst} \cdot 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2NA-QF</td>
<td>0.127</td>
<td>$\pm 0.019$</td>
<td>$+0.004$ \quad $-0.008$</td>
</tr>
<tr>
<td>2NA-FSI</td>
<td>0.272</td>
<td>$\pm 0.028$</td>
<td>$+0.022$ \quad $-0.023$</td>
</tr>
<tr>
<td>Tot 2NA</td>
<td>0.376</td>
<td>$\pm 0.033$</td>
<td>$+0.023$ \quad $-0.032$</td>
</tr>
<tr>
<td>3NA</td>
<td>0.274</td>
<td>$\pm 0.069$</td>
<td>$+0.044$ \quad $-0.021$</td>
</tr>
<tr>
<td>Tot 3body</td>
<td>0.546</td>
<td>$\pm 0.074$</td>
<td>$+0.048$ \quad $-0.033$</td>
</tr>
<tr>
<td>4NA + bkg.</td>
<td>0.773</td>
<td>$\pm 0.053$</td>
<td>$+0.025$ \quad $-0.076$</td>
</tr>
</tbody>
</table>
AMADEUS contribution from low energy $K^-^{12}C$ absorption $\Sigma^0 p / \Lambda p$ final states

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

Total reduced $\chi^2$:

$$\frac{\chi^2}{dof} = 0.94$$
AMADEUS contribution from low energy $K^-\,^{12}C$ absorption $\Sigma^0 p / \Lambda p$ final states

Table 1 Branching ratios and cross sections of the $K^-$ multi-nucleon absorption processes. The statistical and systematic errors are also shown.

<table>
<thead>
<tr>
<th>Process</th>
<th>Branching Ratio (%)</th>
<th>$\sigma$ (mb) @ $p_K$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2NA-QF $\Lambda p$</td>
<td>$0.25 \pm 0.02$ (stat.) $^{+0.01}_{-0.02}$ (syst.)</td>
<td>$2.8 \pm 0.3$ (stat.) $^{+0.1}_{-0.2}$ (syst.) @ $128 \pm 29$</td>
</tr>
<tr>
<td>2NA-FSI $\Lambda p$</td>
<td>$6.2 \pm 1.4$ (stat.) $^{+0.8}_{-0.6}$ (syst.)</td>
<td>$69 \pm 15$ (stat.) $^{+6}_{-6}$ (syst.) @ $128 \pm 29$</td>
</tr>
<tr>
<td>2NA-QF $\Sigma^0 p$</td>
<td>$0.35 \pm 0.09$ (stat.) $^{+0.13}_{-0.06}$ (syst.)</td>
<td>$3.9 \pm 1.0$ (stat.) $^{+1.4}_{-0.7}$ (syst.) @ $128 \pm 29$</td>
</tr>
<tr>
<td>2NA-FSI $\Sigma^0 p$</td>
<td>$7.2 \pm 2.2$ (stat.) $^{+4.2}_{-5.4}$ (syst.)</td>
<td>$80 \pm 25$ (stat.) $^{+46}_{-60}$ (syst.) @ $128 \pm 29$</td>
</tr>
<tr>
<td>3NA $\Lambda pn$</td>
<td>$1.4 \pm 0.2$ (stat.) $^{+0.1}_{-0.2}$ (syst.)</td>
<td>$15 \pm 2$ (stat.) $^{+2}_{-60}$ (syst.) @ $117 \pm 23$</td>
</tr>
<tr>
<td>3NA $\Sigma^0 pn$</td>
<td>$3.7 \pm 0.4$ (stat.) $^{+0.2}_{-0.4}$ (syst.)</td>
<td>$41 \pm 4$ (stat.) $^{+2}_{-5}$ (syst.) @ $117 \pm 23$</td>
</tr>
<tr>
<td>4NA $\Lambda pn$</td>
<td>$0.13 \pm 0.09$ (stat.) $^{+0.08}_{-0.07}$ (syst.)</td>
<td>-</td>
</tr>
<tr>
<td>2NA-$\Sigma / \Lambda$ conv.</td>
<td>$2.1 \pm 1.2$ (stat.) $^{+0.9}_{-0.8}$ (syst.)</td>
<td>-</td>
</tr>
</tbody>
</table>

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:

$$\mathcal{R} = 0.7 \pm 0.2 \text{(stat.)}^{+0.2}_{-0.3} \text{(syst.)}$$

and the ratio between the corresponding phase spaces is $1.22$.

According to the pion exchange model:

$$\mathcal{R} = \frac{\text{BR}(K^-pp \rightarrow \Lambda p)}{\text{BR}(K^-pp \rightarrow \Sigma^0 p)} = \frac{\text{BR}(K^-p \rightarrow \Lambda\pi^0)}{\text{BR}(K^-p \rightarrow \Sigma^0\pi^0)}$$
AMADEUS contribution from low energy $K^- \cdot ^{12}\text{C}$ absorption $\Sigma^0p / \Lambda p$ final states

**FINUDA:**

\[ K^-_{stop} + X \rightarrow \Lambda + p + X' \]

1. But...the large number of events originates from $K^-$ absorption on $^{12}\text{C}$
2. only back-to-back $\Lambda p$ pairs ($\cos\theta_{Ap} < -0.8$)

\[ K^- + ^{12}\text{C} \rightarrow \Lambda + p + R \]

Measured spectra but only back-to-back $\Lambda p$ events a la FINUDA ($\cos\theta_{Ap} < -0.8$)

$\rightarrow$ the shape of the $\Lambda p$ invariant mass spectrum is compatible with the spectrum reported by FINUDA

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

Total reduced $\chi^2$:

$\chi^2/dof = 0.94$

<table>
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<tr>
<th>Process</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2NA-QF $\Lambda p$</td>
<td>$0.20 \pm 0.04$</td>
</tr>
<tr>
<td>2NA-FSI $\Lambda p$</td>
<td>$3.8 \pm 2.3$</td>
</tr>
<tr>
<td>2NA-QF $\Sigma^0 p$</td>
<td>$0.54 \pm 0.20$</td>
</tr>
<tr>
<td>2NA-FSI $\Sigma^0 p$</td>
<td>$5.4 \pm 1.5$</td>
</tr>
<tr>
<td>3NA $\Lambda p n$</td>
<td>$1.1 \pm 0.3$</td>
</tr>
<tr>
<td>3NA $\Sigma^0 p n$</td>
<td>$1.9 \pm 0.7$</td>
</tr>
<tr>
<td>2NA-$\Sigma/\Lambda$conv</td>
<td>$22 \pm 4$</td>
</tr>
</tbody>
</table>
AMADEUS contribution from low energy $K^-^{12}C$ absorption $\Sigma^0p/\Lambda p$ final states

**FINUDA:**

$K^-_{stop} + X \rightarrow \Lambda + p + X'$

- 6 targets: 3 of $^{12}C$ (50%)
  - 2 of $^6Li$ (35%)
  - 1 of $^7Li$ (15%)

Interpreted as the signal of:

$K^-pp \rightarrow \Lambda + p$

1. But...the large number of events originates from $K^-$ absorption on $^{12}C$
2. only back-to-back $\Lambda p$ pairs ($\cos\theta_{\Lambda p} < -0.8$)

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

Total reduced $\chi^2$:

$$\chi^2/dof = 0.94$$

**Process** | **Branching Ratio (%)**
--- | ---
2NA-QF $\Lambda p$ | $0.20 \pm 0.04\text{(stat.)} \pm 0.02\text{(syst.)}$
2NA-FSI $\Lambda p$ | $3.8 \pm 2.3\text{(stat.)} \pm 1.1\text{(syst.)}$
2NA-QF $\Sigma^0p$ | $0.54 \pm 0.20\text{(stat.)} \pm 0.20\text{(syst.)}$
2NA-FSI $\Sigma^0p$ | $5.4 \pm 1.5\text{(stat.)} \pm 2.7\text{(syst.)}$
3NA $\Lambda pn$ | $1.1 \pm 0.3\text{(stat.)} \pm 0.2\text{(syst.)}$
3NA $\Sigma^0pn$ | $1.9 \pm 0.7\text{(stat.)} \pm 0.8\text{(syst.)}$
2NA-$\Sigma/\Lambda$conv | $22 \pm 4\text{(stat.)} \pm 1\text{(syst.)}$

The shape of the $\Lambda p$ invariant mass spectrum is not consistent with the spectrum reported by FINUDA.
$K^- - 4NA$ cross section & BR
**Λt available data**

Available data:

- **in Helium:**
  - bubble chamber experiment
  - $K^-$ stopped in liquid helium, $\Lambda$ dn/t search. **3 events** compatible with the $\Lambda t$ kinematics were found

\[ \text{BR}(K^-\text{He} \rightarrow \Lambda t) = (3 \pm 2) \times 10^{-4}/K_{\text{stop}} \quad \text{global, no 4NA} \]

- **Solid targets**
    - **(40 events** in different solid targets)
Λt available data


- a study of Λ vs t momentum correlation and an opening angle distribution
- 40 events collected and added together coming from different targets (\(^6\text{Li}, \(^7\text{Li}, \(^9\text{Be}\))

Filled histogram= data
Open histogram = Phase space simulation

\[ \text{K- } \Lambda \rightarrow \Lambda t \Lambda' \]

Unclear back to back topology

Λt emission yield \( \rightarrow 10^{-3} - 10^{-4} / K_{\text{stop}} \)

global, no 4NA

Experimental data only back-to-back
\(K^- \, ^4\text{He} \rightarrow \Lambda t\) cross section,  DC gas sample

Contributing processes:

- Single nucleon absorption (1NA)
  \[K^- \, ^4\text{He} \rightarrow \Lambda \pi^0 t_{\text{res}}\]
  \[K^- \, ^4\text{He} \rightarrow \Sigma^0 \pi^0 t_{\text{res}}, \quad \Sigma^0 \rightarrow \Lambda \gamma\]

Spectator tritons have low momentum:

\(p_t \sim\) Fermi momentum

4NA processes – \(K^-\) absorbed on FREE \(\alpha\):
- \(K^- \, ^4\text{He} \rightarrow \Lambda t\)
- \(K^- \, ^4\text{He} \rightarrow \Sigma^0 t, \quad \Sigma^0 \rightarrow \Lambda \gamma\)
$K^- \ ^4\text{He} \rightarrow \Lambda t$ cross section, DC gas sample contributing processes:

Main background: $K^-$ absorption on $^{12}\text{C}$ (isobutane contamination)

$$4\text{NA}: \ K^- \ ^{12}\text{C} \rightarrow K^- (\alpha)^\text{bound} \ ^8\text{Be} \rightarrow \Lambda/\Sigma^0 \ t \ ^8\text{Be}$$

7 MeV/c$^2$ lower invariant mass threshold respect to:

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

+ all possible elastic/inelastic FSI processes with primary $\Lambda/\Sigma$ formation

uncorrelated $\Delta t$ low invariant mass:

Calculated $\Sigma$ conversion:

$$K^- \ ^{12}\text{C} \rightarrow \Sigma^0 \pi^0 \ ^{11}\text{B} \rightarrow \Lambda i \pi^0 \ ^8\text{Be}$$

Measured $K^- \ ^{12}\text{C}$ sample from $K^-$ captures in wall:

- Entries 428
- Kinematic limit in $^{12}\text{C}$

K- captures in gas:

- Entries 150
$K^- \, ^4\text{He} \rightarrow \Lambda t \, \, \, 4\text{NA \, fit}$

--- carbon data from DC wall

--- $4\text{NA} \, K^- \, ^4\text{He} \rightarrow \Lambda t \, \, \, \text{in flight \, MC}$

--- $4\text{NA} \, K^- \, ^4\text{He} \rightarrow \Lambda t \, \, \, \text{at rest \, MC}$

--- $4\text{NA} \, K^- \, ^4\text{He} \rightarrow \Sigma^0 t \, \, , \, \Sigma^0 \rightarrow \Lambda \gamma \, \, \, \text{MC}$

--- $4\text{NA} \, K^- \, ^4\text{He} \rightarrow \Sigma^0 t \, \, , \, \Sigma^0 \rightarrow \Lambda \gamma \, \, \, \text{MC}$
$K^- {^4}\text{He} \rightarrow \Lambda t \ 4\text{NA} \ \text{fit}$

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

$\sigma(100 \pm 19 \ \text{MeV/c}) \ (K^-{^4}\text{He}(4\text{NA}) \rightarrow \Lambda t) =$

$= (0.81 \pm 0.21 \ \text{(stat)} ^{+0.03}_{-0.04} \ \text{(syst)}) \ \text{mb}$

![Graphs showing distribution of counts](image)
The reaction $K^{-}{}^{12}\text{C} \rightarrow \Lambda/\Sigma^{0}t^{8}\text{Be}$ was studied without FSI. The branching ratio (BR) is given by:

$$BR(K^{-}\text{He}(4\text{NA}) \rightarrow \Lambda t) = 1.5 \pm 0.5 \times 10^{-4} \text{ (stat)} \pm 0.7 \times 10^{-4} \text{ (syst)} /K_{\text{stop}}$$

The cross sections $\sigma$ are:

$$\sigma( K^{12}\text{C} (4\text{NA}) \rightarrow \Lambda t^{8}\text{Be}) = 0.58 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ mb}$$

$$\sigma( K^{12}\text{C} (4\text{NA}) \rightarrow \Sigma^{0}t^{8}\text{Be}) = 1.88 \pm 0.35 \text{ (stat)} \pm 0.21 \text{ (syst)} \text{ mb}$$
Perspective:

Measurement of the

$$K^- H \rightarrow \Sigma^0 \pi^0$$ cross section for $$p_K = 97 \pm 10$$ MeV/c

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881 98 (2012)
Low momentum $p_{\Sigma^+}$ structure in $\Sigma^+\pi^-$ formation

Fig. 5. Momentum distributions of sigmas from the $^6Li(K^-_{stop}, \pi^\pm\Sigma^\mp)A'$ reactions. The grey-filled histograms are the measured distributions. The distributions of Monte-Carlo generated sigmas are depicted by full dots, and with open diagrams are represented the M-C generated sigmas being reconstructed by FINUDA.


$K^- ~ ^6Li ~ \rightarrow ~ \Sigma^+\pi^- ~ A'$
Gamov state formation of a $\Sigma^+$ in light nuclei?


\[ K^- \, ^9\text{Be} \rightarrow \Sigma^+\pi^- + \alpha + n + t \]

no structure at low momentum

\[ K^- \, ^{12}\text{C} \rightarrow \Sigma^+\pi^- A' \]

structure at low momentum

can not be explained by energy loss, the target is much thinner
Low momentum pΣ structure in Σ+π− formation


K− 9Be → Σ+π− + α + n + t

no structure at low momentum

K− 12C → Σ+π− A'

structure at low momentum

amounts some % of the total yield

also in thiner targets

(not explained by energy loss)

Hypothesis: Σ+ trapped in a Gamov state, interplay of the attractive nuclear potential & repulsive Coulomb barrier

S. Wycech, K. P., EPJ Web. Conf. 130 (2016) 02011


Gamov state formation of a $\Sigma^+$ in light nuclei?

... work in progress

Gamov peak following in-flight capture

$K^- \, ^{12}\text{C} \rightarrow \Sigma^+\pi^- \, ^{11}\text{Be}$

about 3\% of the large peak

Breit – Wigner - $\mathbf{(E, \Gamma)} = (1405,40); (1410,40); (1420,40)$

Position $p_{\Sigma^+} = 15 \text{ MeV}/c$

peculiar structure due to the limitation of the phase space
ThanK you
$K^-$ decay vtx radial position
W.O. target

$\Lambda$ decay vtx radial position
W. target
Figure 26. $\Lambda$-t reconstructed invariant mass for the MC simulated processes: $K^{-4}He \to \Lambda t 4NA$ at-rest (blue), $K^{-4}He \to \Lambda t 4NA$ in-flight (red), $K^{-4}He \to \Sigma^{0}t \to \Lambda\gamma t$ at-rest (cyan), $K^{-4}He \to \Sigma^{0}t \to \Lambda\gamma t$ in-flight (magenta).
Figure 22. Measured total $\Sigma^+\pi^-$ momentum distribution ($p_{\Sigma^+\pi^-}$) for the selected $K^- H \rightarrow \Sigma^+\pi^-$ events in-flight.
The shapes of the three distributions for the two samples of $\Lambda\pi - p$ events are compatible, evidencing that the gas and the wall samples do not suffer, for the $\Lambda\pi$ channel, severe efficiency or acceptance differences. Moreover the ratios: $(\Lambda\pi - p$ events$)/(total\ \Lambda\pi$ events) for the gas and wall samples are 45/150 and 150/428 respectively, evidencing compatible detection efficiencies for the two samples.
\[ \Sigma^0 \ p \text{ correlated production,} \]
 goals of this analysis

**K- Absorption**

- Pin down the contribution of the process:
  \[ K^- + NN \rightarrow \Sigma^0 + p \]

  with respect to processes as:
  \[ K^- + NN \rightarrow \Sigma^0 + p \rightarrow p'' + \Sigma^{0''} \ (FSI) \]
  \[ K^- + NNN \rightarrow \Sigma^0 + p + X \]
  \[ K^- + NNNN \rightarrow \Sigma^0 + p + X \]

**Kaonic Bound States**

\[ ppK^- \rightarrow \Sigma^0 + p \]

- Yield Extraction and Significance
Absorption results

O. Vazquez Doce et al., Physics Letters B 758 (2016) 134

...is there room for the signal of a ppK- bound state?
Fit with $ppK^-$

Best solution:

- B.E. = 45 MeV/c²
- Width = 30 MeV/c²

$$\chi^2 = 0.807$$
Evaluation of the significance of the ppK- signal

For B.E. = 45 MeV/c^2, Width = 30 MeV/c^2

\[ \frac{Yield}{K_{stop}} = (0.044 \pm 0.009 \text{stat}^{+0.004}_{-0.005 \text{syst}}) \cdot 10^{-2} \]

F-test to evaluate the addition of an extra parameter to the fit:

Significance of “signal” hypothesis w.r.t “Null-Hypothesis” (no bound state)

No significant detection of ppK- bound state