Low energy interaction studies of negative kaons in light nuclear targets by AMADEUS

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

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

- Chiral perturbation theory: interacting systems of N-G bosons (pions, kaons) coupled to baryons works well for \( \pi\pi, \pi N, K^+N \) .. NOT for \( K^-N \) !!

- \( K^- = (s\bar{u}) \) strangeness = -1, \( K^+ = (\bar{u}s) \) strangeness = +1

strange baryons stable respect to strong interaction all have s = -1

- the sub-threshold region is dominated by resonances \( \rightarrow \) complex multichannel dynamics
\( \Lambda(1405) \) just below \( KN \) threshold (1432 MeV)

Possible solutions:
- Non-perturbative Coupled Channels approach: Chiral Unitary SU(3) Dynamics
- phenomenological \( KN \) and NN potentials
The $\Lambda(1405)$ case

**Theoretical prediction** Dalitz-Tuan (1959)

**First experimental evidence:**

$K \cdot p \rightarrow \pi \pi \pi \Sigma$

- $\Lambda(1405)$
- $\Lambda(1116)$

- $3$ quark?
- molecular?
- $\bar{K}N$ bound state?
- pentaquark?

**Mass** = 1405.1$^{+1.3}_{-1.0}$ MeV,

**Width** = 50.5 ± 2.0 MeV

$I = 0$, $S = -1$, $J^p = 1/2^-$,

Status: ****,

strong decay into $\Sigma \pi$
The $\Lambda(1405)$ case

$\Lambda(1405)$ is located slightly below the $\bar{K}N$ threshold (1432 MeV)

Three quark model picture difficulties to reproduce the $\Lambda(1405)$:

- According to its negative parity, one of the quarks has to be excited to $l = 1$
- Nucleon sector, we find the $N(1535) \rightarrow$ the expected mass of the $\Lambda^*$ is around 1700 MeV
- Too big energy splitting observed between the $\Lambda(1405)$ and the $\Lambda(1520)$ interpreted as the spin-orbit partner ($J^p = 3/2^-$).
- Pentaquark (4q + qbar in $l = 0$), but also predicts other, unobserved, excited baryons,

R. Dalitz and collaborators first suggested to interpret $\Lambda(1405)$ as an $\bar{K}N$ quasibound state.

The $\Lambda(1405)$ case

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

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

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

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

  
  $p p \rightarrow p K^+ \pi \Sigma$ the resonance is found & 1390 MeV
The $\Lambda(1405)$ case

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

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

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

$$\frac{d\sigma(\Sigma^{0}\pi^{0})}{dM} \propto \frac{1}{3} |T^0|^2$$
THE “LINE-SHAPE” OF THE $\Lambda(1405)$ DEPENDS ON THE OBSERVED CHANNEL!!

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

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

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

IS DIFFERENT IN $\Sigma^+\pi^-$ VS $\Sigma^-\pi^+$

DUE TO ISOSPIN INTERFERENCE
The "LINE-SHAPE" of the Λ(1405) depends on the observed channel!!

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

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

The clearest signature of the Λ(1405) is given by the neutral channel:

- is free from isospin interference
- is purely I = 0, no Σ(1385) contamination.
**Λ(1405) .. the golden channel**

Crystall Ball: \( Kp \rightarrow \Sigma^0 \pi^0 \pi^0 \) 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))

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


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

\( \Lambda(1405) \) .. the golden channel

Crystall Ball: \( Kp \rightarrow \Sigma^0 \pi^0 \pi^0 \) 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 jilich: \( pp \rightarrow pK^+ \Sigma^0 \pi^0 \n(\text{I. Zychor et al., Phys. Lett. B 660 (2008) 167})\)

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

- Chiral unitary models: $\Lambda(1405)$ is an $I = 0$ quasibound state emerging from the coupling between the $\bar{K}N$ and the $\Sigma\pi$ channels. Two poles in the neighborhood of the $\Lambda(1405)$:
  
  **two poles**: about 1420; about 1380 MeV

- Akaishi-Esmaili-Yamazaki phenomenological potential


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

Two main biases:

- The kinematical energy threshold 1412 MeV 
  \( (M_{\bar{K}} + M_p - |BE_p|) \) the high pole energy region is closed,
- The shape and the amplitude of the NON-RESONANT \( \Sigma \pi \) production below KbarN threshold is unknown.

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 (pure isospin 0),
- K- is absorbed in-flight on a bound proton with \( p_{\bar{K}} \sim 100 \text{ MeV} \), \( \Sigma \pi \) invariant mass gain of \( \sim 10 \text{ MeV} \) to open an energy window to the high mass pole.
- Knowledge of the \( \Sigma \pi \) NON-RESONANT production amplitude.
AMADEUS & DAΦNE

DAΦNE
- double ring $e^+e^-$ collider working at C.M. energy of $\phi$
  - producing $\approx 1000 \phi /s$
  - $\phi \rightarrow K^+K^- \ (BR = (49.2 \pm 0.6)\%)$
  - **low momentum** Kaons
    - $\approx 127 \text{ Mev/c}$
  - **back to back** $K^+K^-$ topology

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

KLOE
- Cylindrical 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**
(pₖ~100MeV)

![Diagram of the KLOE detector](image)

**Advantage:**
excellent resolution ..

\[ \sigma_{p\Lambda} = 0.49 \pm 0.01 \text{ MeV/c in DC gas} \]
\[ \sigma_{myy} = 18.3 \pm 0.6 \text{ MeV/c}^2 \]

**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**  
($p_K \sim 100 \text{ MeV}$)
The scientific goal of AMADEUS

Low energy QCD in strangeness sector is still waiting for experimental conclusive constrains on:

1) $\bar{K}$-N potential $\rightarrow$ how deep can an antikaon be bound in a nucleus?

   - $U_{\bar{K}N}$ strongly affects the position of the $\Lambda(1405)$ state $\rightarrow$ we investigate it through $(\Sigma-\pi)^0$ decay $\rightarrow$ Y $\pi$ CORRELATION

   - if $U_{\bar{K}N}$ is strongly attractive then $K^-$ NN bound states should appear $\rightarrow$ we investigate through $(\Lambda/\Sigma$-N) decay $\rightarrow$ Y N CORRELATION

2) Y-N potential $\rightarrow$ extremely poor experimental information from scattering data

   - $U_{YN}$ determines the strength of the final state YN (elastic & inelastic) scattering in nuclear environment $\rightarrow$ could be tested by Y N CORRELATION
The scientific goal of AMADEUS

Low energy QCD in strangeness sector is still waiting for experimental conclusive constrains on:

1) \( \bar{K} \)-N potential \( \rightarrow \) how deep can an antikaon be bound in a nucleus?

- \( U_{\bar{K}N} \) strongly affects the position of the \( \Lambda(1405) \) state \( \rightarrow \) we investigate it through \( (\Sigma-\pi)^0 \) decay \( \cdots \) \( Y\pi\) CORRELATION

- if \( U_{\bar{K}N} \) is strongly attractive then \( K^-NN \) bound states should appear \( \rightarrow \) we investigate through \( (\Lambda/\Sigma-N) \) decay \( \cdots \) \( YN \) CORRELATION

2) \( Y-N \) potential \( \rightarrow \) extremely poor experimental information from scattering data

- \( U_{YN} \) determines the strength of the final state \( YN \) (elastic & inelastic) scattering in nuclear environment \( \rightarrow \) could be tested by \( YN \) CORRELATION
$K^{-} - N$ single nucleon absorption
the case of the $\Lambda(1405)$
**$\Lambda(1405)$ case**

IN-FLIGHT $K^- 12C$ opens a window between 1416 MeV and K-Nth

**p$_{\pi^0}$ resolution: $\sigma_p \approx 12$ MeV/c**

![Theoretical invariant mass distribution](image1)

![Two experimental shapes of $\Lambda(1405)$ resonance](image2)

**Text:**

At rest

In flight

Counts/(10MeV/c)

$M^*_\pi$ (MeV/c$^2$)

$M^*_K$ (MeV/c$^2$)
Resonant VS non-resonant

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

in medium, how much comes from resonance?

Non resonant transition amplitude:
- Never measured before below threshold
  (33 MeV below threshold):

\[ E_{Kn} = -|B_n| - \frac{p_3^2}{2\mu_{\pi,N,3H_e}}, \]

- few, old theoretical calculations
Resonant VS non-resonant

Investigated using:

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

the goal is to measure \(|f^{N-R}_{\Lambda \pi} (I=1)|\)

to get information on \(|f^{N-R}_{\Sigma \pi} (I=0)|\)
Theoretical shapes for:

total $\Lambda\pi^-$ momentum spectra for the resonant ($\Sigma^-$) and non-resonant ($I = 1$) 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.

Collaboration with S. Wycech
How to extract the $K^- n \rightarrow \Lambda \pi^-$ non resonant transition amplitude

simultaneous fit ($p_{\Lambda\pi^-} - m_{\Lambda\pi^-} - \cos(\theta_{\Lambda\pi^-})$) with signal and background processes:

- non resonant $K^-$ capture at-rest from $S$ states in $^4$He
- resonant $K^-$ capture at-rest from $S$ states in $^4$He
- non resonant $K^-\Lambda^-\pi^-\Lambda^-\pi^-$ capture in-flight in $^4$He
- resonant $K^-\Lambda^-\pi^-\Lambda^-\pi^-$ capture in-flight in $^4$He

- primary $\Sigma\pi^-\Lambda$ production followed by the $\Sigma N \rightarrow \Lambda N'$ conversion process
- $K^-$ capture processes in $^{12}$C giving rise to $\Lambda\pi^-$ in the final state

In order to extract: NR-ar/RES-ar & NR-if/RES-if
Results for the $K^- n \rightarrow \Lambda \pi^-$ non resonant transition amplitude

<table>
<thead>
<tr>
<th>Channels</th>
<th>Ratio/Amplitude</th>
<th>$\sigma_{\text{stat}}$</th>
<th>$\sigma_{\text{syst}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RES-ar/NR-ar</td>
<td>0.39</td>
<td>$\pm 0.04$</td>
<td>$+0.18$ $-0.07$</td>
</tr>
<tr>
<td>RES-if/NR-if</td>
<td>0.23</td>
<td>$\pm 0.03$</td>
<td>$+0.23$ $-0.22$</td>
</tr>
<tr>
<td>NR-ar</td>
<td>12.00 %</td>
<td>$\pm 1.66$ %</td>
<td>$+1.96$ $-2.77$ %</td>
</tr>
<tr>
<td>NR-if</td>
<td>19.24 %</td>
<td>$\pm 4.38$ %</td>
<td>$+5.90$ $-3.33$ %</td>
</tr>
<tr>
<td>$\Sigma \rightarrow \Lambda$ conv.</td>
<td>2.16 %</td>
<td>$\pm 0.30$ %</td>
<td>$+1.62$ $-0.83$ %</td>
</tr>
<tr>
<td>$K^{-12C}$ capture</td>
<td>57.00 %</td>
<td>$\pm 1.23$ %</td>
<td>$+2.21$ $-3.19$ %</td>
</tr>
</tbody>
</table>

TABLE I. Resonant to non-resonant ratios and amplitude of the different channels extracted from the fit of the $\Lambda \pi^-$ sample. The statistical and systematic errors are also shown. See text for details.

extracted:

$NR$-$ar/RES$-$ar$ & $NR$-$if/RES$-$if$
Simultaneous momentum–angle–mass fit

Preliminary
Comparison

\[ m_{\Lambda\pi} \text{ fit} \]

Light band sys err.

Dark band stat. Err.
Outcome of the measurement

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

\[
\frac{N_R - a_r}{R_{ES} - a_r} = \frac{\int_0^{p_{max}} P_{nr}^a(p_{\Lambda\pi}) \, dp_{\Lambda\pi}}{\int_0^{p_{max}} P_{res}^a(p_{\Lambda\pi}) \, dp_{\Lambda\pi}} = \Rightarrow |f_{ar}^s| = (0.334 \pm 0.018 \text{ stat}^{+0.034}_{-0.058} \text{ syst}) \text{ fm}.
\]

\[= |f_{ar}^s|^2 \cdot 8.94 \cdot 10^5 \text{ MeV}^2.\]

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>
Outcome of the measurement

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

$$\frac{\text{NR} - \text{ar}}{\text{RES} - \text{ar}} = \frac{\int_0^{p_{\text{max}}} P_{ar}^{nr}(p_{\Lambda\pi}) \, dp_{\Lambda\pi}}{\int_0^{p_{\text{max}}} P_{ar}^{res}(p_{\Lambda\pi}) \, dp_{\Lambda\pi}} =$$

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

$$= |f_{ar}^s|^2 \cdot 8.94 \cdot 10^5 \text{ MeV}^2.$$

Good agreement with chiral calculation:

Y. Ikeda, T. Hyodo and W. Weise,

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.


$K^-\ ^6Li \rightarrow \Sigma^+\pi^- A'$
Low momentum $p_{\Sigma^+}$ structure in $\Sigma^+\pi^-$ formation


$K^-\,^9\text{Be} \rightarrow \Sigma^+\pi^- + 2\alpha$

no structure at low momentum

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

structure at low momentum

amounts some % of the total yield

also in thinner targets

(not explained by energy loss)

Hypothesis: $\Sigma^+$ trapped in a Gamov state, interplay of the attractive nuclear potential & repulsive Coulomb barrier

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

R. Del Grande, K. Piscicchia and S. Wycech, Formation of $\Sigma^+\pi^-$ pairs in nuclear captures of $K^-\Sigma$ mesons, accepted in Acta. Phys. Polon B

S. Wycech, K. Piscicchia, On Gamov states of $\Sigma^+$ hyperons, accepted in Acta. Phys. Polon B
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 - $(E, \Gamma) = (1405, 40); (1410, 40); (1420, 40)$

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

peculiar structure due to

the limitation of the phase space
$K^- \text{ multiN absorption and search for bound states}$
How deep can an antikaon be bound in a nucleus?

Possible Bound States:

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

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

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

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

....at the end of 2015

<table>
<thead>
<tr>
<th>Experiments reporting DBKNS</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>FINUDA</td>
<td>M. Agnello et al. PRL94, 212303 (2005)</td>
</tr>
<tr>
<td>DISTO</td>
<td>T. Yamazaki et al. PRL104 (2010)</td>
</tr>
<tr>
<td>OBELIX</td>
<td>G. Bendiscioli et al. NPA789, 222 (2007)</td>
</tr>
<tr>
<td>LEPS/SPring-8</td>
<td>A.O. Tokiyasu et al. PLB728, 616-621 (2014)</td>
</tr>
<tr>
<td>J-PARC E27</td>
<td>Y. Ichikawa et al. PTEP, 021D01 (2015)</td>
</tr>
</tbody>
</table>

Extraction of a signal
Upper limit
Upper limit
Extraction of a signal
Extraction of a signal
Extraction of a signal
Extraction of a signal
How deep can an antikaon be bound in a nucleus?

interpreted in

[from the talk of T. Nagae at HYP2015, Sep. 10, 2015]
J-PARC E15

\[ K^- + ^3\text{He} \rightarrow \Lambda + p + n \]

Invariant mass spectroscopy

\[ M = 2355 \pm 6^{\text{(stat.)}} \pm 8^{\text{(syst.)}} \text{ MeV/c}^2 \]
\[ \Gamma = 110 \pm 19^{\text{(stat.)}} \pm 17^{\text{(syst.)}} \text{ MeV/c}^2 \]

\[ \text{BE} = 15 \text{ MeV} \]

**Σ0 p 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:

\[ K^- + NN \rightarrow \Sigma^0 + p \rightarrow p^\prime + \Sigma^0 (FSI) \]

\[ K^- + NNNN \rightarrow \Sigma^0 + p + X \]

\[ K^- + NNNNN \rightarrow \Sigma^0 + p + X \]

**Kaonic Bound States**

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

Yield Extraction and Significance
Final fit

\[ \chi^2 = 0.85 \]

2NA-QF clearly separated
From other processes

From the contributions to the fit, the yields are extracted for K- stop
Absorption results

<table>
<thead>
<tr>
<th></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>± 0.019</td>
<td>+0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−0.008</td>
</tr>
<tr>
<td>2NA-FSI</td>
<td>0.272</td>
<td>± 0.028</td>
<td>+0.022</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−0.023</td>
</tr>
<tr>
<td>Tot 2NA</td>
<td>0.376</td>
<td>± 0.033</td>
<td>+0.023</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−0.032</td>
</tr>
<tr>
<td>3NA</td>
<td>0.274</td>
<td>± 0.069</td>
<td>+0.044</td>
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<td></td>
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<td></td>
<td>−0.021</td>
</tr>
<tr>
<td>Tot 3body</td>
<td>0.546</td>
<td>± 0.074</td>
<td>+0.048</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−0.033</td>
</tr>
<tr>
<td>4NA + bkg.</td>
<td>0.773</td>
<td>± 0.053</td>
<td>+0.025</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−0.076</td>
</tr>
</tbody>
</table>

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

...is there room for the signal of a \text{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/c², Width = 30 MeV/c²

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

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
\( \kappa^{-4}\text{He} \rightarrow \Lambda t \)

4NA cross section and yield
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)
At available data


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

Filled histogram = data
Open histogram = Phase space simulation

$K^{-} \Lambda \rightarrow \Lambda t \Lambda'$

Unclear back to back topology

$\Lambda t$ emission yield $\rightarrow 10^{-3} - 10^{-4} / K^{-}$

global, no 4NA

Experimental data only back-to-back
\( \Lambda t \) correlation studies in \(^4\)He from the DC gas:

- **Contributing processes**
  - Single nucleon absorption (1NA):
    \[
    K^- \, ^4\text{He} \rightarrow \Lambda \, \pi^0 \, t_{\text{res}}
    \]
    \[
    K^- \, ^4\text{He} \rightarrow \Sigma^0 \pi^0 \, t_{\text{res}}, \quad \Sigma^0 \rightarrow \Lambda \gamma
    \]
  - Conversion on triton:
    \[
    K^- \, ^4\text{He} \rightarrow \Sigma^0 \pi^0 \, t, \quad \Sigma^0 t / \Lambda t
    \]

- **Tritons are spectators, too low momentum:**
  - Too low momentum:
    - \( p_t \sim \text{Fermi momentum} \)
    - Lower than the calorimeter threshold (\( p_t \sim 500 \text{ MeV/c} \))
  - Checked by MC simulations

**4NA processes** – \( K^- \) absorbed by the \( \alpha \) particle:

- Conversion is suppressed by the \( \Sigma^0 - t \)
  - Back to back topology!
  \[
  K^- \, ^4\text{He} \rightarrow \Lambda t
  \]
  \[
  K^- \, ^4\text{He} \rightarrow \Sigma^0 t, \quad \Sigma^0 \rightarrow \Lambda \gamma
  \]
MC simulations: efficiency & resolution

mass threshold at-rest

\[ M_\Lambda_t \text{ invariant mass resolution } = 2.2 \text{ MeV/c}^2 \]

overall detection + reconstruction efficiency for 4NA direct \( \Lambda_t \) production:

\[ \epsilon_{4NA,ar,\Lambda_t} = 0.0493 \pm 0.0006 \quad ; \quad \epsilon_{4NA,if,\Lambda_t} = 0.0578 \pm 0.0006, \]

at-rest \hspace{2cm} in-flight
K$^{-}$ $^{4}$He $\rightarrow$ $\Lambda t$ 4NA cross section

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

Total number of events = 136
4NA K- $^4$He $\rightarrow$ Λt at rest $\rightarrow$ 1 ± 1 events
4NA K- $^4$He $\rightarrow$ Λt in flight $\rightarrow$ 12 ± 3 events

BR(K- $^4$He(4NA) $\rightarrow$ Λt) $< 1.3 \times 10^{-4}$/K$_{stop}$

$\sigma$(100 ± 19 MeV/c) (K- $^4$He(4NA) $\rightarrow$ Λt) $=$
= (0.42 ± 0.13(stat) $^+0.01_{-0.02}$ (syst)) mb

<table>
<thead>
<tr>
<th>Contribution to the spectra</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{-4}$He $\rightarrow$Λt at rest</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>$K^{-4}$He $\rightarrow$Λt in-flight</td>
<td>0.09 ± 0.02</td>
</tr>
<tr>
<td>$K^{-4}$He $\rightarrow$Σ$^0$t in-flight</td>
<td>0.05 ± 0.03</td>
</tr>
<tr>
<td>$K^{-12}$C $\rightarrow$Λt experimental distribution from the carbon DC wall</td>
<td>0.85 ± 0.06</td>
</tr>
</tbody>
</table>

$\chi^2$ / ndf = 0.654

--- carbon data from DC wall
--- 4NA K- $^4$He $\rightarrow$ Λt in flight MC
--- 4NA K- $^4$He $\rightarrow$ Λt at rest MC
--- 4NA K$^{-}$ $^4$He $\rightarrow$ Σ$^0$t , Σ$^0$ $\rightarrow$ Λγ MC
--- 4NA K$^{-}$ $^4$He $\rightarrow$ Σ$^0$t , Σ$^0$ $\rightarrow$ Λγ MC

--- data
perspectives:

- Sub-threshold $K^-$ n $\rightarrow$ $\Lambda \pi^-$ non resonant amplitude
  
  Nucl. Phys. A954 (2016) 75-93

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

  experimental paper finalised

  next step extract the same info in I = 0 to interpret the $\Sigma^0 \pi^0$ spectra

- $K^-$ multiN absoption yields in $\Sigma^0$ p  
  Physics Letters B 758 (2016) 134

<table>
<thead>
<tr>
<th></th>
<th>yield / $K_{\text{stop}}^{-}$ $\cdot 10^{-2}$</th>
<th>$\sigma_{\text{stat}}$ $\cdot 10^{-2}$</th>
<th>$\sigma_{\text{syst}}$ $\cdot 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2NA-QF</td>
<td>0.127</td>
<td>$\pm 0.019$</td>
<td>$^{+0.004}_{-0.008}$</td>
</tr>
</tbody>
</table>

  Same analysis is ongoing in $\Lambda$ p (R. Del Grande PhD thesis)

- interpretation of the $p\Sigma^+$ spectra

- $K^- {^4}\text{He} \rightarrow \Lambda t$ 4NA cross section  
  $\sigma (100 \pm 19 \text{ MeV/c}) (K^-{^4}\text{He}(4\text{NA}) \rightarrow \Lambda t) = (0.42 \pm 0.13\text{(stat)}^{+0.01}_{-0.02} \text{ (syst)}) \text{ mb}$  
  paper in preparation

- feasibility study of the $\Sigma^0$ - N/NN two and three body forces  
  measurement from K-absorption in $^4$He
\[(K^{-} \text{ ppn}) + n \rightarrow \Sigma^{0} d + n\]
\&
\[(K^{-} \text{ pn}) + d \rightarrow \Sigma^{0} n + d\]

3NA & 2NA in \(^{4}\text{He}\)

for the investigation of the

\(\Sigma^{0}\)-N & \(\Sigma^{0}\)-(NN) two and three body interaction
No experimental information on $\Sigma^0$-N/NN interaction


Figure 2: "Total" cross section $\sigma$ (as defined in Eq. (24)) as a function of $p_{thb}$. The experimental cross sections are taken from Refs. [32] (filled circles), [33] (open squares), [65] (open circles), and [66] (filled squares) ($\Lambda p \to \Lambda p$), from [54] ($\Sigma^+ p \to \Lambda n$, $\Sigma^- p \to \Sigma^0 n$) and from [55] ($\Sigma^+ p \to \Sigma^- p$, $\Sigma^+ p \to \Sigma^0 p$). The red/dark band shows the chiral EFT results to NLO for variations of the cutoff in the range $\Lambda = 500, \ldots, 650$ MeV, while the green/light band are results to LO for $\Lambda = 550, \ldots, 700$ MeV. The dashed curve is the result of the Jülich '04 meson-exchange potential [36].
Y-N/NN interaction essential impact on the case of NEUTRON STARS

ECT*, Trento (Italy), 27 – 31 October 2014

Strangeness in Neutron Stars

Ignazio Bombaci
Dipartimento di Fisica “E. Fermi”, Università di Pisa
INFN Sezione di Pisa

Microscopic approach to hyperonic matter EOS

input

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
Involved reactions:

$$3\text{NA} - (K^-\text{ppn}) + n \rightarrow \Sigma^0\text{d} + n$$

- The $\Sigma^0$ identification (with respect to $\Lambda$) enables to avoid the dominant internal conversion background. Moreover there is presently no available $\Sigma^0$-N interaction data.

- $^4\text{He}$ good target no nuclear fragmentation can follow the $3\text{NA}$ primary process.

---

IF F.S.I. IS MORE PROBABLE AMONG $\Sigma^0\text{-}\Lambda$ (THEN $\Sigma^0\text{-n}$ OR $\Lambda\text{-n}$) THE RELATIVE YIELDS:

$$\frac{Y_{3\text{NA},1}}{Y_{3\text{NA},2}}$$

GIVE INFORMATION ON $\Sigma^0\text{NN}$ 3-body INTERACTION

BACKGROUND: $2\text{NA} (K^-\text{ppn}) + d \rightarrow (\Lambda\text{ n}) + d$
Comparison with available data

\[ 3\text{NA} - (K^- \, \text{ppn}) + n \rightarrow \Sigma^0 \, d + n \]

Data correspond to K- captures in \(^{12}\text{C}\) solid target.

The most energetic part of the \(m_{\Sigma^0 d}\) invariant mass spectrum, correlated with high \(p_{\Sigma^0}\) and \(p_d\) momenta, corresponds to the \(3\text{NA} - (K^- \, \text{ppn})\) process.

The \(\Sigma^0\) \(d\) statistics corresponding to the sample of K- captures in the gas (\(^4\text{He}\)) from the KLOE DC is too small.

A dedicated measurement with pure \(^4\text{He}\) target is mandatory!!
3NA

(K- ppn) + n → Σ⁰ d + n

without FSI

Corresponds to the highest part of the invariant mass spectrum

the blue region is populated by:

free 3NA + 3NA followed FSI.

Lower energies (below 3220 MeV) involve 2NA and complex FSI processes with fragmentation of the residual.
3NA

$(K^-\text{ ppn}) + n \rightarrow \Sigma^0 d + n$

without FSI

Corresponds to the highest part of the $\Sigma^0$ momentum spectrum.

The narrow $\Sigma^0$ momentum distribution will enable to $\Sigma^0$-NN cross section at $550 \pm 50$ MeV/c.
3NA - (K- ppn) + n → Σ0 d + n signature:

- Highest Σ0 - d angular correlation
- low Fermi momentum neutron

\[ \cos(\theta_{\Sigma_0 d}) \]
Using the same data set ...

The competing process

\[ 2\text{NA} - (K^+ p n) + d \rightarrow \Sigma^0 n + d \]

can be used to extract the complementary information:

TWO simultaneous fits \((\Sigma^0 n \& \Sigma^0 d)\) of the same data set with the constraint

\[ \frac{Y_{2\text{NA},1}}{Y_{2\text{NA},2}} \]

give information on the \(\Sigma^0 n\) 2-body interaction.

CONTRAINT: GLOBAL 2NA @ 3NA YIELDS MUST BE COMPATIBLE!
Background reactions:

\[
\begin{align*}
1\text{NA} & \rightarrow (K^- p) + pnn \rightarrow \Sigma^0 \pi^0 n d \\
(K^- n) + ppn & \rightarrow \Sigma^0 \pi^- p d
\end{align*}
\]

- low energy (took away by the pion) not correlated \( \Sigma^0 d \) pairs.

It is easy to be disentangled (similar to the \( \Sigma^0 p \) analysis).
Thank you
Gamov state formation of a $\Sigma^+$ in light nuclei?


$K^{-}{}^{9}\text{Be} \rightarrow \Sigma^{+}\pi^{-} + 2\alpha$

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
Hypothesis: $\Sigma^+$ trapped in a Gamov state, interplay of the attractive nuclear potential & repulsive Coulomb barrier

See: S. Wycech, K. Piscicchia, EPJ Web. Conf. 130 (2016) 02011
R. Del Grande, K. Piscicchia and S. Wycech, Formation of $\Sigma^+\pi^-$ pairs in nuclear captures of K$^-$ mesons, accepted in Acta. Phys. Polon B
S. Wycech, K. Piscicchia, On Gamov states of $\Sigma^+$ hyperons, accepted in Acta. Phys. Polon B