Low energy Kaon-nucleon/nuclei interaction studies at DAΦNE by AMADEUS

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AMADEUS at the DAΦNE e⁺e⁻ collider

DAΦNE

• Double ring e⁺ e⁻ collider working in C.M. energy of \( \Phi \) (≈ 500 MeV/c)
• \( \Phi \rightarrow K^+ K^- (49.1\%) \) (≈ 600 \( K^+ K^- /s \))
• low momentum Kaons (≈ 127 MeV/c)
• back to back \( K^+ K^- \) topology (about 1000/second)

AMADEUS using KLOE

• 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)))
Experimental program of **AMADEUS**

Unprecedented studies of the **low-energy charged kaons interactions in nuclear matter**: solid and gaseous targets (d, $^3\text{He}$, $^4\text{He}$, $^8\text{Be}$, $^{12}\text{C}$ …) in order to obtain unique quality information about:

- possible existence of **kaonic nuclear clusters** (deeply bound kaonic nuclear states – DBKNS) * search in the $\Lambda p$, $\Lambda d$, and $\Lambda t$ final channels

- Interaction of $K^-$ with **one and more nucleons** (single and multi – nucleon $K^-$ absorption)

- $\Lambda(1405)$ in all 3 decay channels (which is its nature?)

- Low-energy charged kaon **cross sections** for momenta lower than 100 MeV/c (missing today)

- Many other processes of interest in the low-energy QCD in strangeness sector → implications from particle and nuclear physics to astrophysics (dense baryonic matter in **neutron stars**)

* **DBKNS**: $\Lambda p$ channel - Kpp bound by about 60-90 MeV!!! (in a normal nucleus the BE/nucleon is about 6-7 MeV) – a role in neutron stars?
Investigation of K⁻ absorption on light nuclei

(AT REST) (K absorbed from atomic orbit) or

(IN FLIGHT) (pK~100 MeV)

Reactions we investigate:

- Λp, Λd and Λt final state channels from single or multi-nucleon absorption processes

- \( K^- 'p' \rightarrow \Sigma^0\pi^0 \)

- \( K^- 'p' \rightarrow \Sigma^+\pi^- \)

- \( K^- 'n' \rightarrow \Lambda\pi^- \) (direct formation) or

- \( K^- N \rightarrow \Sigma^0\pi^0/\Sigma^+\pi^- \); \( \Sigma N \rightarrow \Lambda\pi \) (internal conversion processes)

R&D for more refined setup: ScFi + SiPM (trigger system) TPC – GEM (inner tracker)

Experimental tests of the trigger prototype for the AMADEUS experiment based on SciFi read by MPPC, Nucl.Instrum.Meth. A671 (2012) 125128

Step 0: Low energy $K^-$ hadronic interaction studies with KLOE existent data

The Drift Chamber (DC) of KLOE contains mainly $^4$He (90%, 10% isobutane $C_4H_{10}$)

Monte Carlo simulations show:
- ~ 0.1% of $K^-$ stop in the DC volume
- ~ 2% stop in the Carbon entrance wall of the DC
  = thousands of events with $K^-$ hadronic interactions

Possibility to use KLOE materials as an active target

Advantage:
  excellent resolution ..
  $\sigma_{p\Lambda} = 0.49 \pm 0.01$ MeV/c in DC gas
  $\sigma_{m\gamma\gamma} = 18.3 \pm 0.6$ MeV/c$^2$

Disadvantage:
  Non dedicated target $\rightarrow$ different nuclei contamination $\rightarrow$ complex interpretation ..
  but $\rightarrow$ new features .. $K$ in flight absorption
Data samples analysed

- **2004/2005 KLOE data**: K⁻ absorption in light nuclei of KLOE materials (H, ⁹Be, ¹²C, ⁴He) ~ 2.2 fb⁻¹ in total analysed luminosity

- Dedicated **2012** run with pure graphite **Carbon target** inside KLOE 4/6 mm of thickness (~90 pb⁻¹ collected; at disposition with good calibration and analyzed 37 pb⁻¹)

  → K⁻ ¹²C absorptions AT - REST
Data samples analysed

- **2004/2005 KLOE data**: $K^{-}$ absorption in light nuclei of KLOE materials ($H, ^{9}Be, ^{12}C, ^{4}He$) $\sim 2.2$ fb$^{-1}$ in total analysed luminosity

- Dedicated **2012** run with pure graphite **Carbon target** inside KLOE 4/6 mm of thickness (~90 pb$^{-1}$ collected; at disposition with good calibration and analyzed 37 pb$^{-1}$)

$\rightarrow$ $K^{-}$$^{12}C$ absorptions AT - REST
**Λp / Λd / Λt** scientific case

- study important for the further understanding of aspects of **low-energy QCD in strangeness sector**

- possibility to gain information on the modification of the hadron mass and interaction in nuclear medium

- possibility to study very interesting and in this moment hot topic of **kaonic nuclear clusters** also called …

- **Deeply Bound Kaonic Nuclear States** (as for ex. $K^-pp$ in $Λp$ channel and $K^-ppn$ in $Λd$ channel are predicted due to the strong KN interaction in the $I=0$ channel by Wycech (1986) and Akaishi & Yamazaki (2002))

- interpretation strongly depends on **single and multi – nucleon absorption process** which can be studied in this channels
Theoretical and experimental studies

Theoretical work on $K^{pp}$ - It does exist

... a $K^{pp}$ puzzle

Experiments:

<table>
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<th>(MeV)</th>
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<th>Faddeev</th>
<th>Faddeev</th>
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<td>B</td>
<td>48</td>
<td>17-23</td>
<td>50-70</td>
<td>45-80</td>
<td>40-80</td>
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<tr>
<td>$\Gamma$</td>
<td>61</td>
<td>40-70</td>
<td>90-110</td>
<td>45-75</td>
<td>40-85</td>
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Production via $pp \rightarrow pK^+\Lambda$ (2.85 GeV)

$B = 105 \pm 2 \pm 5$ MeV
$\Gamma = 118 \pm 8 \pm 10$ MeV

DISTO

LEPS-Spring8

E27 @ J-Parc

Contributions from $N^*$, interferences using PWA

HADES
\( \Lambda p/d/t \) channel:
brief info about event selection

Analysis of events in the DC gas volume:

\[ N_n \rightarrow \text{higher mass particle} = p, d \text{ or } t \]

Particle identification via:

- \( dE/dx \) information in the DC wires
- \( E \) deposited in the EMC

Mass by TOF

\[ \Lambda \rightarrow p + \pi^- \]
Analysis of events in the DC gas volume:

\[ N_n - \text{higher mass particle} = p, d \text{ or } t \]

Particle identification via:

- \(dE/dx\) information in the DC wires
- \(E\) deposited in the EMC

Mass by TOF

\[ \Lambda \to p + \pi^- \]

PDG: \( M_\Lambda = 1115.683 \pm 0.006 \pm 0.006 \)
$\Lambda p/d/t$ channel:
brief info about event selection – particle ID

Selection in masses obtained by Time of Flight

![Mass distribution graph](attachment:mass_graph.png)

- Protons are associated with EMC cluster, or if no cluster associated
- Track reaching the calorimeter region + “proton signature” in the dE/dx of DC gas is requested
KLOE is the highest acceptance apparatus for these type of studies:

Excellent acceptance of the KLOE detector:

Acceptance study done with phase space $K^- + ^4\text{He} \to \Lambda p n n$
MC simulation

1NA
$\Sigma N/\Lambda N$ –DBKS
2NA

KEK-E549
The presence of a pion is the characteristic signal of a single nucleon absorption:

$$K·n \rightarrow \Sigma \pi^- + \text{conversion process } \Sigma p/\Lambda p$$
Simulated contributing channels

1NA with $\Sigma/\Lambda$ conversion:

$$K^+ N \rightarrow \Sigma \pi \ + \ \Sigma p/\Lambda p \text{ conversion in } ^4\text{He}$$

$$K^+ H \rightarrow \Sigma \pi \ + \ \Sigma p/\Lambda p \text{ conversion in } ^{12}\text{C (molecular!)}$$

2NA processes:

$$K^+ NN \rightarrow \Lambda p$$

$$K^+ NN \rightarrow \Sigma^0 p \text{ (lost photon)}$$

$$K^+ NN \rightarrow \Sigma^0 p \ + \ \Sigma p/\Lambda p \text{ conversion in } ^4\text{He}$$

Pionic 2NA modes: $K^+ NN \rightarrow Y \pi N$

Uncorrelated processes:

Simulation based in «spectator» protons from $\Lambda d$ correlated events in $^{12}\text{C}$
**Λp preliminary fit**

2D fit ($M_{Λp}, \cos θ_{Λp}$)

---

**Conversion**

- $K-N → Σπ + Σ/p/Λp$ conversion in $^4$He
- $K-H → Σπ + Σ/p/Λp$ conversion in $^{12}$C
  - No fragmentation (higher mass)
  - Residual fragmented (lower mass)
- $K-NN → Λπp$ (higher mass)
- $K-NN → Σπp$ (lower mass)
- $K-NN → Σ^0p$ (lower mass)

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Uncorrelated background

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**Data**

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**Global fit**

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**Conversion**

- Conversion in $^{12}$C
- Conversion in $^4$He
- Conversion after 1NA
- Conversion after 2NA: more energetic
- 2NA direct production
KLOE data $\Lambda d$ analysis

Events with $\cos\theta_{\Lambda d} < -0.75$

572 $\Lambda d$ events in the DC gas

Structures at high mass clearly correlated with back-to-back events
Previous experiments on $\Lambda t$ channel

Only FINUDA and an old bubble chamber experiment [ M. Roosen, J.H. Wickens, Il Nuovo Cimento 66, (1981), 101 ] (with only 3 events!) have published $\Lambda t$ spectra from $K^-$ absorption

FINUDA presented:
• a study of $\Lambda$ vs $t$ momentum correlation and an opening angle distribution
• 40 events collected and added together coming from different targets (Li, Be, C, $D_2O$)

Filled histogram = data
Open histogram = Phase space simulation

Experimental data showing only back-to-back events
Λτ channel analyses with KLOE

Invariant mass spectrum and opening angle distribution of Λτ pairs in DC gas

Red line – events in the gas with $\cos(\theta_{\Lambda\tau}) < -0.97$

= BACK-TO-BACK events

High energy tritons expected to come from the rare 4 NA process

<table>
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<table>
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<tbody>
<tr>
<td>135</td>
<td>-0.6073</td>
<td>0.5286</td>
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</table>

Clear back-to-back enhancement of the Λτ events

135 events in gas - highest statistics ever
Λt channel analyses

Processes contributing the Λt spectrum

\[ \text{K}^{-} \, ^{4}\text{He} \rightarrow \Lambda t \, \pi^{0} \]
\[ \text{K}^{-} \, ^{4}\text{He} \rightarrow \Sigma^{0}\pi^{0} \, t \, \, , \, \Sigma^{0} \rightarrow \Lambda \gamma \]

Most probable processes to contribute the spectra, but…

have too low momentum to be observed
(tritons are required to have a cluster in EMC (i.e. P>500 MeV))

exclusive pionless 4NA processes:

\[ \text{K}^{-} \, ^{4}\text{He} \rightarrow \Lambda t \]
\[ \text{K}^{-} \, ^{4}\text{He} \rightarrow \Sigma^{0} \, t \, \, , \, \Sigma^{0} \rightarrow \Lambda \gamma \]

Conversion on triton:

\[ \text{K}^{-} \, ^{4}\text{He} \rightarrow \Sigma^{0}\pi^{-0} \, t \, \, , \, \Sigma^{0}t / \Lambda t \]

When the spectra will be fitted we shall see if there is still room for a possible

K\text{-ppnn} kaon nuclear cluster signal
**Λ(1405) scientific case**

**Λ(1405)**: mass = 1405.1$^{+1.3}_{-1.0}$ MeV, width = 50 ± 2 MeV

$I = 0$, $S = 1$, $J^P = \frac{1}{2}^-$, Status: ****, strong decay into $\Sigma\pi$

Its nature has been a puzzle for decades: three quark state, unstable KN bound state, pentaquark, two poles??

Chiral unitary models: Λ(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 Λ(1405):

two poles: (z1 = 1424+7-23− i 26+3-14 ; z2 = 1381+18-6− i 81+19-8 ) MeV

mainly coupled to KN  \hspace{1cm} mainly coupled to $\Sigma\pi$  \hspace{1cm} line-shape depends on production mechanism

\[
\frac{d\sigma(\Sigma^-\pi^+)}{dM} \propto \frac{1}{3} |T^0|^2 + \frac{1}{2} |T^1|^2 \hspace{0.5cm} + \frac{2}{\sqrt{6}} Re(T^0T^{1*})
\]

\[
\frac{d\sigma(\Sigma^+\pi^-)}{dM} \propto \frac{1}{3} |T^0|^2 + \frac{1}{2} |T^1|^2 \hspace{0.5cm} - \frac{2}{\sqrt{6}} Re(T^0T^{1*})
\]

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

Line-shape also depends on the decay channel

observed in only 3 experiments ... with different line-shapes!

Pure $I=0$ (free from $\Sigma(1385)$ background)
Latest results: CLAS & HADES

First parallel measurement of $\Lambda(1405)$ lineshape in all 3 $\Sigma\pi$ channels

different reactions and higher momentum

Measurement of the Isospin interference contribution via the $\Sigma^+\pi^- / \Sigma^-\pi^+$ ratio and of the $\Sigma^*/\Lambda^*$ ratio
Λ(1405) signal searched by K⁻ interaction with a bound proton in Carbon
K⁻ p → Σ⁰π⁰ detected via: (Λγ)(γγ)
Strategy: K⁻ absorption in the DC entrance wall, mainly ¹²C with H contamination (epoxy)

\[ \sigma_m \approx 32 \text{ MeV/c}^2 ; \quad p_{\pi^0\Sigma^0} \text{ resolution: } \sigma_p \approx 20 \text{ MeV/c}. \]

Negligible (Λπ⁰ + internal conversion) background = (3±1) % → no I=1 contamination
Comparison with K⁻ absorption in emulsion

A higher invariant mass region is opened

<table>
<thead>
<tr>
<th>Invariant Mass (MeV/c²)</th>
<th>Momentum (MeV/c)</th>
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<tbody>
<tr>
<td>Mass limit on ¹²C at rest</td>
<td>Number of events / 20 MeV/c</td>
</tr>
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</table>

2005 data
2012 data

N.U.
$\Sigma^0 \pi^0$ channel: the $\pi^0$ momentum

$P(\pi^0)$ resolution: $\sigma_p \approx 12$ MeV/c

$P(\pi^0)$ could be used for in-flight/at-rest separation
The $\Sigma^+ \pi^-$ channel

$K^- H \rightarrow \Sigma \pi$

The $K^- H$ interaction probability estimate based on $K^-$ interaction AT REST in hydrocarbons mixture data (Lett. Nuovo Cimento, C 1099 (1972))

= order of 1%

Thanks to the excellent $p_{\pi^-}$ resolution < 1 MeV

...
\( \Sigma^+ \pi^- \) channel

\( K^- H \) contribution \( \sim 20\% \)

... in flight absorption is extremely different!
$\Sigma^+ \pi^- \text{ invariant mass spectra: at rest / in flight}$

Removing the H component is fundamental since it behaves like a high mass pole.

Possibility to disentagle: Hydrogen, in-flight, at-rest, K-capture

If resonant component is important a high mass component appears.
Conclusions and perspectives

• Search for the kaonic nuclear clusters:
  fit of the $\Lambda p$ spectrum close to conclusive, refinement in the analyses in $\Lambda d$ channel ongoing, $\Lambda t$ channel – highest statistic ever

• Excellent possibility to make a **study of single and multi nucleon absorption processes** in these channels

• **Quantitative information that can be extracted:**
  • 1NA/2NA absolute rate per stopped kaon in $^4$He
  • 1NA/2NA $\Sigma$-$\Lambda$ conversion rates

• **Qualitative information:**
  1NA shape
  • $m(\Sigma\pi)$ spectra show a high invariant mass component $\rightarrow$ associated to in-flight $K^-$ capture
  • Preliminary $\Lambda\pi^-$ first measurement of RES/NON-RES ratio in nuclear $K^-$ absorption
Conclusions and perspectives

AMADEUS experiment:

Implementation of dedicated solid targets & cryogenic gaseous targets (H, d, $^3$He, $^4$He) inside the KLOE DC

The AMADEUS setup will be implemented in the 50 cm. gap in KLOE DC around the beam pipe:

- **Target**: A gaseous He target for a first phase of study
- **Trigger**: 1 or 2 layers of ScFi surrounding the interaction point

R&D activity ongoing:
more refined setup: ScFi + SiPM (trigger system) TPC – GEM (inner tracker)
Thank you
Spare slides
Resonant vs non-resonant issue:

How much comes from resonance: \( KN \rightarrow (Y^* \ ?) \rightarrow Y\pi \)

Channel: \( K^- \ ^4\text{He} \rightarrow \Lambda \pi^- \ ^3\text{He} \ ... \text{the idea} \)

Bubble chamber experiments exhibit two components:

- Low momentum \( \Lambda \pi^- \) pair \( \rightarrow \) S-wave, \( I=1 \), non-resonant transition amplitude.
- High momentum \( \Lambda \pi^- \) pair \( \rightarrow \) P-wave resonant formation ?

Also exists in S-state K-mesic atom as a result of the three body structure of the system

\( (K = 1, \ n=2, \ ^3\text{He} = 3) \)

Channel: $K^- \, ^4\text{He} \rightarrow \Lambda \, \pi^- \, ^3\text{He} \ldots \text{the idea}$

$K^-(s=0) \, ^4\text{He}(s=0) \, n(s=1/2) \, \Sigma^-(s=3/2) \rightarrow \text{resonance p-wave only}$

atomic s-state capture:

- $(K^- \, ^4\text{He} \rightarrow \Lambda \, \pi^- \, ^3\text{He})$ absorptions from $(n \, s)$ - atomic states are assumed $\rightarrow$
- $^4\text{He}$ bubble chamber data  (Fetkovich, Riley interpreted by Uretsky, Wienke)

- Coordinates recoupling enables for P-wave resonance formation
Channel: $K^- + ^4\text{He} \rightarrow \Lambda + \pi^- + ^3\text{He}$ ... the strategy

- Fit of the $p_{\Lambda\pi^-}$ observed distribution using calculated distributions:

$$P_{s^p} (p_{\Lambda\pi}) = |\Psi_N (p_{\Lambda\pi})|^2 |f_{s^p} (p_{\Lambda\pi})|^2 \rho$$

non-resonant

$$P_{s^p} (p_{\Lambda\pi}) = |\Psi_N (p_{\Lambda\pi})|^2 c^2 |2f_{\Sigma^*} (p_{\Lambda\pi})|^2 \rho/3 (kp_{\Lambda\pi})^2$$

resonant

- To determine for the first time the ratio resonant/non-res.

$$|f_{N^-R_{\Lambda\pi}}|$$ given the fairly well known $$|f_{\Sigma^*_{\Lambda\pi}}|$$
Channel: \( K^- \ ^4\text{He} \rightarrow \Lambda \pi^- \ ^3\text{He} \) ... calculated reactions

Calculated primary hadronic interactions:

\[ K^- \ ^4\text{He} \rightarrow \Lambda \pi^- \ ^3\text{He} \]
- At-rest: S-wave non-Res / P-wave \( \Sigma(1385) \) Res
- In-flight: S-wave non-Res / P-wave \( \Sigma(1385) \) Res

\[ K^- \ ^4\text{He} \rightarrow \Sigma^0 \pi^- \ ^3\text{He} \]
- At-rest: S-wave non-Res / P-wave \( \Sigma(1385) \) Res
- In-flight: S-wave non-Res / P-wave \( \Sigma(1385) \) Res

\[ K^- \ ^4\text{He} \rightarrow (\Sigma \pi)^0 \ ^3\text{H} \]
- At-rest: S-wave non-Res / S-wave \( \Lambda(1405) \) Res / P-wave \( \Sigma(1385) \) Res
- In-flight: S-wave non-Res / S-wave \( \Lambda(1405) \) Res / P-wave \( \Sigma(1385) \) Res
$K^- \, ^4\text{He} \rightarrow \Lambda \, \pi^- \, ^3\text{He}$  preliminary fit

Simultaneous fit ($p_{\Lambda\pi^-} - m_{\Lambda\pi^-} - \theta_{\Lambda\pi^-}$) leaving the ratio At-rest/In-flight and $^{12}\text{C}$ contamination to vary around the estimated values within errors:

Global fit
- $\Lambda \, \pi^-$ At-rest N-R
- $\Lambda \, \pi^-$ At-rest RES
- $\Lambda \, \pi^-$ In-flight N-R
- $\Lambda \, \pi^-$ In-flight RES
- $\Lambda \, \pi^-$ events from $K^- \, ^{12}\text{C}$
- $\Sigma \, p/n \rightarrow \Lambda \, p/n$ conversion

![Histogram with data points and fit parameters]

<table>
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<tr>
<th>data_p</th>
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<tbody>
<tr>
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$K^- \ ^4\text{He} \rightarrow \Lambda\pi^- \ ^3\text{He}$ preliminary fit

Simultaneous fit $(p_{\Lambda\pi^-} - m_{\Lambda\pi^-} - \theta_{\Lambda\pi^-})$ leaving the ratio At-rest / In-flight and $^{12}\text{C}$ contamination to vary around the estimated values within errors:

- $\chi^2/ (\text{ndf} - \text{np}) = 1.2$
- $(\text{At-rest RES})/(\text{At-rest N-R}) = 0.6 \pm 0.06$
- $(\text{In-flight RES})/(\text{In-flight N-R}) = 0.6 \pm 0.3$

- $(\text{In-flight}) / (\text{At-rest}) = 1.9 \pm 0.5$
- $\Sigma \ p/n \rightarrow \Lambda \ p/n$ conversion $= (9.6 \pm 0.8)\%$
- $\Lambda\pi^-$ events from $K^- \ ^{12}\text{C} = (57 \pm 1)\%$
Ongoing

Is there room for a 2NA pionic mode?

\[ K^-NN \rightarrow Y\pi N \]

The preliminary fits find possible contribution for this processes (~ 5%)

\[ \Sigma^0p \text{ – signature of the 2NA process} \]

\[ \Lambda\gamma \text{ invariant mass spectra} \]

\[ \text{\Lambda}_p\text{ events in }^1\text{2C} \]

\[ M_{\Lambda\gamma}(\text{MeV/c}^2) \]

\[ \text{\Lambda}_{p\pi^-}\text{ events in }^1\text{2C} \]

\[ M_{\Lambda\gamma}(\text{MeV/c}^2) \]
Acceptance study with phase space
\( K^- + ^4\text{He} \rightarrow \Lambda \, p \, n \, n \) MC simulation

\[ A = A(P_{\Lambda p}, \theta_{\Lambda p}, M_{\Lambda p}) \]

where \( P_{\Lambda p} \) is the added momentum for the Lambda and the proton, \( \theta_{\Lambda p} \) is the angle between the two particles, and \( M_{\Lambda p} \) is its invariant mass. A sample of \( 5 \times 10^6 \) MC events has been produced and reconstructed in order to obtain the acceptance function, that is evaluated in 8 intervals of \( P_{\Lambda p} \) (between 0 and 800 MeV/c) and \( \theta_{\Lambda p} \) (between 0 and 180 degrees), and 40 intervals for \( M_{\Lambda p} \).

\[ A^{i,j,k} = MC(P^i_{\Lambda p}, \theta^j_{\Lambda p}, M^k_{\Lambda p})/REC(P^i_{\Lambda p}, \theta^j_{\Lambda p}, M^k_{\Lambda p}) \]

with \( i, j = 1, 8 \) and \( k = 1, 40 \).
Acceptance study with phase space
$K^- + ^4\text{He} \rightarrow \Lambda p nn$ MC simulation

Projection of acceptance function depending on $(P_\Lambda, P_p, M_{\text{inv}} \Lambda p)$ on the Invariant mass plane

- **Red**: True phase space MC
- **Black**: Reconstructed MC

Normalization 1:1
(no efficiency evaluation)
Calculation of the $K^- 4He \rightarrow \Lambda\pi^- 3He$

resonant and non-resonant production

Figura 1: Left: $\Lambda\pi^-$ momentum distributions $P^x(p_{\Lambda\pi})$ black, $P^y(p_{\Lambda\pi})$ blue. Right: $\Lambda\pi^-$ mass distributions $P^x(m_{\Lambda\pi})$ black, $P^y(m_{\Lambda\pi})$ blue.

At rest

Performed by Kristian Piscicchia
in collaboration with prof. Wycech

RESONANT
NON-RESONANT

In flight

Figura 1: Left: $\Lambda\pi^-$ momentum distributions $P^x(p_{\Lambda\pi})$ black, $P^y(p_{\Lambda\pi})$ blue. Right: $\Lambda\pi^-$ mass distributions $P^x(m_{\Lambda\pi})$ black, $P^y(m_{\Lambda\pi})$ blue.
Simulations made and data to be studied for the following processes:
(gas of the DC $^4$He 90%, 10% isobutane $C_4H_{10}$)

**Single nuclear absorption (1NA)**

1) $K^- H \rightarrow \Sigma^+ \pi^- \theta^+ n/\Lambda p$ (conversion on neutron from $C$)

2) $K^- n \rightarrow \Sigma^0 \pi^- \theta^0 p/\Lambda p$ ($^4$He ; 1NA)

3) $K^- p \rightarrow \Sigma^+ \pi^- \theta^+ n/\Lambda p$ ($^4$He ; 1NA)

4) $K^- n \rightarrow \Sigma^0 \pi^- \theta^0 n/\Lambda n$ ($^4$He ; 1NA)
Λp and Λpπ⁻ samples

- All Λp events
- Λpπ⁻ selection (x2)

The presence of a pion is the characteristic signal of an absorption by a single nucleon:

Absorption: \( K^-N \rightarrow \Sigma\pi \) + conversion process: \( \Sigma p/\Lambda p \)

- detected particles
Previous experiments on $\Lambda d$ channel

- Observed spectra from FINUDA and KEK showing possible bound states in the high invariant mass region – a “bump” around 3250 MeV/c$^2$

KEK

FINUDA
DATA

2 NA with conversion
2NA direct formation of $\Sigma^0$ or $\Lambda$ with $p$
DATA

1NA with conversion
\[ \Lambda p \text{ analysis} \]

Simulations made and data to be studied for the following processes:
(gas of the DC \(^4\)He 90\%, 10\% isobutane \(C_4H_{10}\))

Double nuclear absorption (2NA)
(all on \(^4\)He)

5) \(K^- pp \rightarrow \Lambda p(n)(n)\)

6) \(K^- pp \rightarrow \Sigma^0 p(n)(n)\)

7) \(K^- pn \rightarrow \Sigma^0 n \quad \Sigma^0 p/\Lambda p \rightarrow \Lambda p(n)\)

8) \(K^- pp \rightarrow \Sigma^0 p \quad \Sigma^0 n/\Lambda n \rightarrow \Lambda n(n)\)

9) \(K^- pn \rightarrow \Sigma^0 n \quad \Sigma^0 n/\Lambda n \rightarrow \Lambda n(p)\)

10) \(K^- pn \rightarrow \Lambda \pi^- p(d)\) (mesonic)

11) \(K^- pn \rightarrow \Sigma^0 \pi^- p(d)\) (mesonic)
**Λp analysis**

**quantitative output: 2NA absorption rate per stopped Kaon**

  
  $0.16 \pm 0.03$ (in He)

  
  $0.19 \pm 0.03$ (in C) ← No $\Sigma-\Lambda$ rate

FINUDA and KEK has not published this number

**Description of $\Sigma N \rightarrow \Lambda N$ in medium**

- High quality experimental data challenges available models
- New detailed theoretical models for YN interaction
- Very important astrophysical implications: presence of hyperons in neutron stars
Λp analysis

The 2 peaks:
- hydrogen absorption + 12C conversion
- 4He conversion

Still to discuss

$M_{\Lambda p} \text{ (MeV/c}^2\text{)}$
Another process to take into account:

- Low momentum proton process: ‘**double nucleon conversion**’
\[ \cos(\theta_{\Lambda p}) \]

\[ KE_{\Sigma\pi} \text{ (MeV/c)} \]

\[ P_{\Sigma\pi} \text{ (MeV/c)} \]
Scientific case for the $\Lambda p / \Lambda d / \Lambda t$ and $\Lambda p + \pi^-$ channels:
Scientific case for the $\Lambda p$ / $\Lambda d$ / $\Lambda t$ and $\Lambda p + \pi^-$ channels:

How hadron masses and interactions change in nuclear medium .. approach by means of kaonic nuclear clusters. 

Deeply Bound Kaonic Nuclear States:

- $K^-pp \rightarrow \Lambda p$
- $K^-ppn \rightarrow \Lambda d$
- $K^-ppnn \rightarrow \Lambda t$

predicted due to the strong KN interaction in the I=0 channel.

Interpretation strongly depends on single and multi – nucleon absorption processes - they can be well studied in this channels
Absorptions in the DC gas

\[ \Lambda \rightarrow p + \pi^- \]

**Λ(1116) mass measurement**

**KLOE: statistical error 0.003 MeV/c^2**

PDG: \[ M_\Lambda = 1115.683 \pm 0.006 \text{ stat} \pm 0.006 \text{ syst (MeV/c^2)} \]

\[ \sigma = 0.289 \pm 0.003 \text{ MeV/c^2} \]

PDG measurement: *PhysRevLett.72.1322 (1994)*

- pp collisions. 6 DC’s. B=1.17 Tm.
- Momentum resolution: \( \Delta p / p = 0.01 \)
- Callibrated with \( K_s^{0} \rightarrow \pi^+ \pi^- \) decay
- 60K events

Momentum Calibration of the KLOE Drift Chamber

A. Antonelli, M. Antonelli, L. Passalacqua

- Using K+ decays for calibration in KLOE the systematic error in the \( \Lambda \) mass can be reduced down to \(~0.013\) MeV (optimistic...)
$\Sigma^0 \pi^0$ channel

Invariant mass spectra with mass hypothesis on $\Sigma^0$ and $\pi^0$ non resonant misidentification background subtracted (left)

$\sigma_m \approx 17 \text{ MeV/c}^2 \quad (^{12}\text{C}) \quad \sigma_m \approx 15 \text{ MeV/c}^2 \quad (^{4}\text{He})$

Similar $m(\Sigma^0\pi^0)$ shapes due to the similar kinematical thresholds for $^{4}\text{He}$ and $^{12}\text{C}$.
Λ(1405) scientific case

Long history of K⁻ nuclear absorption experiments

1) $m_{\Sigma n}$ spectra cut at the energy limit at-rest

2) $(\Sigma^\pm \pi^\mp)$ with $\Sigma(1385)$ contamination

To test the higher mass pole:
- production in $KN$ reactions (only chance to observe it)
- decaying in $\Sigma^0\pi^0$ (free from $\Sigma(1385)$ background $I=1$)