Investigation of the low-energy kaons hadronic interactions in light nuclei by AMADEUS

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Framework:
Low-Energy QCD with Strange Quarks

Strangeness in baryonic matter:

• role of strangeness in EoS of neutron stars

• hyperon-nucleon and hyperon-hyperon interactions role in the investigation of dense baryonic matter

• new constraints from 2 solar masses neutron stars, very stiff Equation of State required!

But

• the basic ingredient .. namely $\bar{K}N$ interaction still unclear and mysterious from the experimental point of view.
Framework: Low-Energy QCD with Strange Quarks

Approached by the investigation of the antikaon-nucleon interaction

Important constraints:

- $K^-N$ threshold physics (shift and width of kaonic atoms levels measured by SIDDHARTA)
- $\Sigma\pi$ mass spectra
- Nature and properties of the $\Lambda(1405)$ considered as $K^-N$ quasibound state embedded in the $\Sigma\pi$ continuum
Framework:
Low-Energy QCD
with Strange Quarks

CHIRAL PERTURBATION THEORY
Interacting systems of NAMBU-GOLDSTONE BOSONS (pions, kaons) coupled to BARYONS

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

works well for low-energy pion-pion and pion-nucleon interactions

... but NOT for systems with strangeness \( S = -1 \)

BECAUSE \( \Lambda(1405) \) just below \( K^-N \) threshold (1432 MeV)

Solutions:
• Non-perturbative Coupled Channels approach based on Chiral SU(3) Dynamics
• phenomenological \( \bar{K}N \) and NN potentials
**Scientific case Λ(1405)**

\[ \Lambda(1405) : \text{mass} = 1405.1^{+1.3}_{-1.0} \text{ MeV}, \quad \text{width} = 50 \pm 2 \text{ MeV} \]

\[ I = 0, \quad S = -1, \quad J^p = 1/2^-, \quad \text{Status: ****, strong decay into } \Sigma \pi \]

Its nature has been a puzzle for decades: three quark state, unstable \( K \bar{N} \) bound state, penta-quark, two poles??

**First experimental evidence:**


\[ K^- p \rightarrow \pi \pi \pi \Sigma \]

![Graph of baryons](image)
Scientific case $\Lambda(1405)$

$\Lambda(1405)$ is a negative parity baryon resonance (spin = 1/2, isospin = 0, strangeness = -1) located slightly below the KN threshold, decaying into the $\Sigma\pi$ channel through the strong interaction.

The three quark model picture has some difficulties to reproduce the $\Lambda(1405)$. According to its negative parity, one of the quarks has to be excited to the $l = 1$ orbit. Similar to the nucleon sector, where one of the lowest negative parity baryon is the N(1535), the expected mass of the $\Lambda^*$ is around 1700 MeV (since it contains one strange quark). Another difficulty is the energy splitting observed between the $\Lambda(1405)$ and the $\Lambda(1520)$, if is interpreted as the spin-orbit partner ($J^p = 3/2^-$).

R. Dalitz and collaborators first suggested to interpret $\Lambda(1405)$ as an KN quasibound state.

**Scientific case \( \Lambda(1405) \)**

- **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 \( \Lambda(1405) \):

  4) **two poles:** \( z_1 = 1424^{+7}_{-23} - i 26^{+3}_{-14} \); \( z_1 = 1381^{+18}_{-6} - i 81^{+19}_{-8} \) MeV (Nucl. Phys. A881, 98 (2012))

mainly coupled to \( \bar{K}N \)  \[ \rightarrow \] mainly coupled to \( \Sigma \pi \)  \[ \rightarrow \] line-shape depends on production mechanism

- **Akaishi-Esmaili-Yamazaki phenomenological potential**


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

TO TEST THE HIGHER POLE:

- production in $\bar{K}N$ reactions (only chance to observe the high mass pole)
- decaying in $\Sigma^0\pi^0$ (free from $\Sigma(1385)$ background $I=1$)

Chiral dynamics predicts significantly weaker attraction than AY (local, energy independent) potential in far-subthreshold region.

Distribution shape depends on the decay channel:

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

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

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

$K^-$ nuclear absorption experiments .. long history .. BUT

1) $m_{\pi\Sigma}$ spectra CUT AT THE ENERGY LIMIT AT-REST

2) $(\Sigma\pm\pi\mp) \Sigma(1385)$ CONTAMINATION

"A study of $K^-\ ^4He \to (\Sigma\pm\pi\mp) + \ ^3H$ using slow instead of stopping $K^-$ would be very useful in eliminating some of the uncertainties in interpretation”


The $\Sigma^0\pi^0$ spectrum was only observed in 3 experiments ... with different line-shapes!


P. J. Carlson, et al. Nucl. Phys. 74 642

Magas et al. PRL 95, 052301 (2005) 034605 S.

TWO SAMPLES OF DATA:

- **2004-2005** KLOE data (Analyzed luminosity of \(~1.5 \text{ fb}^{-1}\))

  K\(^-\) absorbed in KLOE materials (H, \(^4\)He, \(^9\)Be, \(^{12}\)C)  
  At-rest + In-flight

- Dedicated **2012** run with pure graphite Carbon target inside KLOE  
  (~90 pb\(^{-1}\); analyzed 37 pb\(^{-1}\), x1.5 statistics)

  K\(^-\) \(^{12}\)C absorptions At-rest
AMADEUS & DAΦNE with KLOE

DAΦNE
Double ring $e^+e^-$ collider working in C. M. energy of $\phi$, producing $\approx 600 \, K^+K^- /s$
$\phi \rightarrow K^+K^- \, (BR = (49.2 \pm 0.6)\%)$
- low momentum Kaons
  $\approx 127 \, \text{Mev/c}$
- back to back $K^+K^-$ topology

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)))
Low-energy $K^-$ hadronic interactions studies with KLOE, why?

MC simulations show that:
- $\sim 0.1$ of $K^-$ stopped in the DC gas (90% He, 10% $C_4H_{10}$)
- $\sim 2\%$ of $K^-$ stopped in the DC wall (750 $\mu$m c. f., 150 $\mu$m Al foil).

Possibility to use KLOE materials as an active target

Advantage: excellent resolution ..

$\sigma_{p\Lambda} = 0.49\pm0.01$ MeV/c in DC gas

$\sigma_{m\gamma} = 18.3\pm0.6$ MeV/c$^2$

Disadvantage: Non dedicated target $\rightarrow$ different nuclei contamination $\rightarrow$ complex interpretation ..
but $\rightarrow$ new features .. $K^-$ in flight absorption.
Carbon target inside KLOE

Advantages:

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

• MC simulation: 26% of $K^-$ stopped in C, 2% of $K^-$ stopped in Al hence aluminium contamination from 19% $\rightarrow$ 7%!

• Thickness optimized (based on MC simulations) to maximize the number of stopping $K^-$ in the target, minimizing the charged particles energy loss.

($\sim 90 \text{ pb}^{-1}$; analyzed $37 \text{ pb}^{-1}$, $x1.5$ statistics)
Carbon target inside KLOE

Advantages:

- gain in statistics
- K⁻ absorptions occur in Carbon
- absorptions at-rest.
K^{-} \rightarrow \Sigma^{0} \pi^{0}

bound proton in $^4$He / $^{12}$C
**Σ⁰ π⁰ channel**

K⁻ 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)

Negligible (Λπ⁰ + internal conversion) background = (3±1) % → no I=1 contamination
$\Sigma^0 \pi^0$ channel

$K^-$ nuclear absorption experiments .. long history .. BUT

1) $m_{\Sigma^0 \pi^0}$ spectra always cut at the at-rest limit

2) $(\Sigma \pm \pi \mp)$ spectra suffer $\Sigma(1385)$ contamination

P. J. Carlson, et al. Nucl. Phys. 74 642


Fig. 6. Detailed differences in $M_{\Sigma^0 \pi^0}$ spectra among the Hyodo–Weise prediction and the present model predictions.
\( \Sigma^0 \pi^0 \) channel

In-flight component ... FIRST EVIDENCE IN K- ABSORPTION MASS SPECTROSCOPY

\[ m_{\text{lim}}^{12}\text{C} \quad \text{at-rest} \]
\[ m_{\text{lim}}^{12}\text{C} \quad \text{in-flight} \]

open a higher invariant mass region

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

2005 DATA

Counts/(10 MeV/c)

2012 DATA

Counts/(10 MeV/c)

in-flight component

\[ m_{2\pi^0}^{2050} \quad \text{(MeV/c)} \]

\[ p_{\pi^0} \quad \text{(MeV/c)} \]

\[ m_{2\pi^0}^{2012} \quad \text{(MeV/c)} \]

\[ p_{\pi^0} \quad \text{(MeV/c)} \]
**Σ⁰ π⁰ channel**

Invariant mass spectra with mass hypothesis on Σ⁰ and π⁰ non resonant misidentification background subtracted (right)

\[ \sigma_m \approx 17 \text{ MeV}/c^2 \quad ^{12}\text{C} \quad \sigma_m \approx 15 \text{ MeV}/c^2 \quad ^{4}\text{He} \]

Similar \( m_{π^0Σ^0} \) shapes due to the similar kinematical thresholds for \(^4\text{He}\) and \(^{12}\text{C}\).

**2005 DATA**
$\Sigma^0\pi^0$ channel

Acceptance corrected $m_{\pi^0\Sigma^0}$ spectra, DC wall (left) DC gas (right)

Acceptance function evaluated in 8 intervals of $p_{\pi^0\Sigma^0}$ (between 0 and 700 MeV/c) 8 intervals of $\theta_{\pi^0\Sigma^0}$ (between 0 and 3.15 rad) 30 intervals of $m_{\pi^0\Sigma^0}$ (between 1300 and 1600 MeV/c$^2$)
Fit of $\Sigma^0\pi^0$ spectrum in C

8 component fit, simultaneously $m_{\Sigma^0\pi^0}$ & $p_{\Sigma^0\pi^0}$:

- Breit-Wigner resonant component $K^-C$ at-rest/in-flight. $(M,\Gamma) = (1405 \div 1430, 5 \div 52)$

- Non resonant $\Sigma^0\pi^0$ $K^-H$ production at-rest/in-flight

- Non resonant $\Sigma^0\pi^0$ $K^-C$ production at-rest/in-flight

- $\Lambda\pi^0$ background ($\Sigma(1385) + $ I.C.)

- non resonant misidentification ($n.r.m.$) background

$K^- {^{12}C} \rightarrow \Sigma^0\pi^0 + {^{11}}B$ (Boron spectator, left in ground state)

secondary interactions not taken into account.
Fit of $\Sigma^0\pi^0$ spectrum in $C$

$\chi^2_{\text{min}} / \text{ndf} \sim 1.7$ corresponding to $(M_{\text{min}}, \Gamma_{\text{min}}) = (1426, 52) \text{ MeV}/c^2$

- Global fit
- Resonant component $K^{-}C$ at-rest
- n. r. $K^{-}C$ at-rest
- n. r. $K^{-}C$ in-flight
- n. r. $K^{-}H$ in-flight
- $\Lambda^0\pi^0$ background + n. r. m.

Preliminary more next weeks
$K^- \rightarrow \Sigma^+ \pi^-$

bound proton in $^4\text{He} / ^{12}\text{C}$
$\Sigma^+\pi^-$ invariant mass spectra

$K^- p \rightarrow \Sigma^+\pi^-$ detected via: $(p\pi^0)\pi^-$

The excellent momentum resolution for $\pi^-$ enables to disentangle in-flight from at-rest $K^-$ capture

Hint: if resonant production contribution is important a high mass pole appears!
Resonant VS non-resonant

Another unsolved question..

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

how much comes from resonance?

Investigated using:

\[ K^- "n" \rightarrow \Lambda \pi^- \]  
direct formation in \(^4\)He
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 → ^4\text{He} bubble chamber data (Fetkovich, Riley interpreted by Uretsky, Wienke)

- Coordinates recupling 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:

\[
P_{s^p}(p_{\Lambda\pi}) = |\Psi_N(p_{\Lambda\pi})|^2 |f_{s}(p_{\Lambda\pi})|^2 \rho \quad \text{resonant}
\]

\[
P_{s^p}(p_{\Lambda\pi}) = |\Psi_N(p_{\Lambda\pi})|^2 c^2 |2f^{\Sigma^*}(p_{\Lambda\pi})|^2 \rho/3 (kp_{\Lambda\pi})^2 \quad \text{non-resonant}
\]

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

\[
|f^{N-R}_{\Lambda\pi}| \quad \text{given the fairly well known} \quad |f^{\Sigma^*}_{\Lambda\pi}|
\]
$K^- \, ^4He \rightarrow \Lambda \, \pi^- \, ^3He \text{ fit}$

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
K\(^-\) \ ^4\text{He} \rightarrow \Lambda \pi^- \ ^3\text{He} \quad \text{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:

- \(\chi^2 / (\text{ndf} - \text{np}) = 1.2\)
- \((\text{At-rest RES}) / (\text{At-rest N-R}) = 1.26 \pm 0.06\)
- \((\text{In-flight RES}) / (\text{In-flight N-R}) = 2.59 \pm 0.3\)

- \((\text{In-flight}) / (\text{At-rest}) = 2.9 \pm 0.5 \rightarrow \text{consistent with the estimate in } \Sigma^+\pi^-\)
- \(\Sigma \ p/n \rightarrow \Lambda \ p/n \ \text{conversion} = (12.2 \pm 0.8)\%\)
- \(\Lambda \pi^- \ \text{events from } K^- \ ^{12}\text{C} = (38 \pm 1)\%\)
Kaonic nuclei

Deeply bound kaonic nuclear states
Kaonic nuclei

How deeply is bound a kaon in a nucleus?

Different theoretical approaches:
- Few-body calculations solving Faddeev equations
- Variational calculations with phenomenological KN potential
- KN effective interactions based on Chiral SU(3) dynamics

Experimental studies in the $\Lambda p$ decay channel
- $pp$ collisions: DISTO (published), FOPI, HADES (ongoing analysis)
- Absorption experiments:

**FINUDA**
$K^-$ stopped + $X$ -> $\Lambda p X'$

- 6Li
- $X = 7Li$
- 9Be

**Strong attractive l=0 KN interaction** favors discrete nuclear states high $B$ and small $\Gamma$.
Kaonic nuclei

How deeply is bound a kaon in a nucleus?

**Strong attractive I=0 KN interaction** favors discrete nuclear states **high B and small Γ**.

Different theoretical approaches:
- Few-body calculations solving Faddeev equations
- Variational calculations with phenomenological KN potential
- KN effective interactions based on Chiral SU(3) dynamics

**Experimental studies in the Λp decay channel**
- pp collisions: DISTO (published), FOPI, HADES (ongoing analysis)
- Absorption experiments

@KEK E-549

K- stopped + 4He -> Λp X

[arXiv:0711.4943v1]
Kaonic nuclei

How deeply is bound a kaon in a nucleus?

Different theoretical approaches:
- Few-body calculations solving Faddeev equations
- Variational calculations with phenomenological KN potential
- KN effective interactions based on Chiral SU(3) dynamics

Experimental studies:
- pp collisions
  - K+ + p -> Λ + p
- Absorption experiments:
  - @KEK E-549
    - K- stopped + 4He -> Λ + p X

Oton Vázquez Doce
Kaonic nuclei

- Deeply bound state by strong interaction.
- Strong attraction of the $l=0$ $\bar{K}N$ interaction ($\bar{K}N^{l=0}$) plays an important role in kaonic nuclei.

K$^-\pi p$ bound state

- The simplest kaonic nuclei.
- Theoretical prediction of B.E. and $\Gamma$ depend on the $\bar{K}N$ interaction and the calculation method.

<table>
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<th>B.E (MeV)</th>
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<td>Y. Ikeda and T. Sato</td>
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<td>A. Dote, T. Hyodo, W. Weise</td>
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<td>15.7</td>
<td>41.2</td>
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KLOE data: $\Lambda p$ analysis

Analysis of events in the DC gas volume

$K^-$ stopped + 4He $\rightarrow \Lambda p \ X$  
\[ \rightarrow p \pi^- \]
KLOE data: Λp analysis

Λp events (inclusive)
Λπ-ρ events (x2.5)

1NA: K-N → Λπ- (N from residual nucleus)
2NA: K-NN → ΛN (pionless)

alternative process: ΣN/ΛN conversion

1NA: K-N → Σπ → ΣN → ΛN
KLOE data: $\Lambda p$ analysis

$\Lambda p$ events (inclusive)

\[1 \text{NA} + \text{conversion } \Sigma^+ n \rightarrow \Lambda p \quad K^- p \rightarrow \Sigma^+ \pi^- \rightarrow \Lambda p \pi^-\]

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

Simulations:
KLOE data: $\Lambda p$ analysis

Fit 3D ($P_\Lambda$, $P_p$, $\theta_\Lambda p$) for $\Lambda p$ inclusive selection with proton mass calculated by TOF (calorimeter hit)

DATA
Total simulation
1NA simulation
2NA (in absorption or conversion) sim.
Conclusions and perspectives ..

- $m_{\Sigma^\pm}$ spectra show a high invariant mass component → associated to in-flight $K^-$ capture.

- PRELIMINARY $\Lambda\pi^-$ first measurement of RES/N-R ratio in nuclear $K^-$ absorption. Next steps …

- Same analysis is ongoing for $\Sigma^0\pi^-$ → extraction of $|f^{N-R}_{\Sigma^0\pi^-}(I=1)|$.

- Similar description of $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ production → extraction of $|f^{N-R}_{\Sigma^+\pi^-}|$ and $|f^{N-R}_{\Sigma^-\pi^+}|$, a comparison of these could give an estimate of $|f^{N-R}_{\Sigma^+\pi^-}(I=0) + f^{N-R}_{\Sigma^+\pi^-}(I=1)|$ against $|f^{N-R}_{\Sigma^+\pi^-}(I=0) - f^{N-R}_{\Sigma^+\pi^-}(I=1)|$.


Sheding light on the nature of the $\Lambda(1405)$ and its behaviour in nuclear matter is crucial to understand the role of strangeness in our universe.
SPARE SLIDES...
Completely neutral channel: 
\[ \Lambda \rightarrow n \pi^0 \]
Possibility to detect neutrons!

black MC \hspace{1cm} \text{red data}

Perspective: \[ \Sigma^- \pi^+ \rightarrow (n\pi^-) \pi^+ \]

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)))
KLOE data on $K^-$ nuclear absorption

Use of two different data samples:

- KLOE data from 2004/2005 (2.2 fb$^{-1}$ total, 1.5 fb$^{-1}$ analyzed)
- Dedicated run in november/december 2012 with a Carbon target 4/6 mm thickness (~90 pb$^{-1}$; analyzed 37 pb$^{-1}$, x1.5 statistics)

Position of the $K^-$ hadronic interaction inside KLOE:
Photon clusters identification

\[ K^- \rightarrow \Sigma^0 \pi^0 \rightarrow (\Lambda(1116) \gamma_3) (\gamma_1 \gamma_2) \rightarrow (p \pi^-) 3\gamma \]

1) 3 neutral clusters selection \((E_{cl} > 20 \text{ MeV})\) not from \(K^+\) decay \((K^+ \rightarrow \pi^+ \pi^0)\)

2) photon clusters selection: \(\chi^2 = t^2/\sigma^2\) where \(t = t_i - t_j\) time of flights in light speed hypothesis.

Three photons in time from the \(\Lambda\) decay vertex \(r_\Lambda\)

3) photon clusters identification: \(\gamma_3\) from \(\pi^0 \rightarrow \gamma_1 \gamma_2\)

4) Cuts on \(\chi^2_i\) and \(\chi^2_{i\Sigma}\) optimized on MC simulations & splitted clusters rejection

Efficiency \((98\pm1)\%\) to identify photons and \((78\pm2)\%\) to select the correct triple of neutral clusters.
Resolution for neutral clusters

DATA 2004/2005

MC

DATA 2004/2005

Resolution for neutrals!

$\sigma_{\gamma\gamma} = 18.3 \pm 0.6 \text{ MeV}/c^2$
$\Sigma^+ \pi^-$ channel ... A NEW POWERFUL TOOL (A. Scordo)!

$K^- p \rightarrow \Sigma^+ \pi^-$ detected via: $(p\pi^0) \pi^-$

BEFORE ...

$K^- H$ interaction probability estimate based on $K^-H$ interaction AT-REST in hydrocarbons mixture data (Lett. Nuovo Cimento, C 1099 (1972)) order of 1% !!!

NOW

Thanks to the excellent $p_{\pi^-}$ resolution ...
\[ \Sigma^+ \pi^- \text{ channel ... A NEW POWERFUL TOOL (A. Scordo)!} \]

\[ K^- p \to \Sigma^+ \pi^- \text{ detected via: } (p\pi^0) \pi^- \]

**2005 DATA**

- Complete understanding of different nuclear targets in different KLOE materials
- \( K^- \text{ H contribution } \sim 20\% \)

**2012 DATA**

- \( K^- \text{ H absorption in-flight (MC)}\)
- \( K^- \text{ H absorption at-rest (MC)}\)
- \( K^- \text{ }^{12}\text{C absorption in-flight (MC)}\)
- \( K^- \text{ }^{12}\text{C absorption at-rest (MC)}\)

**ONLY!**
Concluding, a fit of $\Sigma^0\pi^0$ spectrum requires ...

9 components:

- Resonant component $K^- C$ at-rest/in-flight.
- Non resonant $\Sigma^0\pi^0$ $K^- H$ production at-rest/in-flight
- Non resonant $\Sigma^0\pi^0$ $K^- C$ production at-rest/in-flight
- $\Lambda\pi^0$ background ($\Sigma(1385) + I.C.$)
- non resonant misidentification ($n.r.m.$) background

A careful model of $K^-$ - nuclear interaction is required in Helium and Carbon!
Channel: $K^- \,^4\text{He} \rightarrow \Lambda \,\pi^- \,^3\text{He}$ … 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: \( K^- \ {^4}\text{He} \rightarrow \Lambda \ {^3}\text{He} \) … the strategy

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

\[
P_s^s (p_{\Lambda\pi}) = |\Psi_N (p_{\Lambda\pi})|^2 |f^s (p_{\Lambda\pi})|^2 \rho \\
P_s^p (p_{\Lambda\pi}) = |\Psi_N (p_{\Lambda\pi})|^2 c^2 |2f^{*} (p_{\Lambda\pi})|^2 \rho/3 (kp_{\Lambda\pi})^2
\]

where \( \rho = k p_{\Lambda\pi}^2 \)

The constant \( c = M_K/(M_K+M_n) = 0.345 \) re-couples the S x S waves to P x P waves.

- To determine the ratio resonant/non-res.

\[
|f^{N-R}_{\Lambda\pi}| \text{ given the fairly well known } |f^{*}_{\Lambda\pi}|
\]
Channel: $K^- \; ^4\text{He} \rightarrow \Lambda \; \pi^- \; ^3\text{He} \; \ldots \; \text{calculated reactions}$

Calculated primary hadronic interactions:

$K^- \; ^4\text{He} \rightarrow \Lambda \; \pi^- \; ^3\text{He}$

\begin{align*}
\text{At-rest:} & \quad \text{S-wave non-Res} / \quad \text{P-wave } \Sigma(1385) \text{ Res} \\
\text{In-flight:} & \quad \text{S-wave non-Res} / \quad \text{P-wave } \Sigma(1385) \text{ Res}
\end{align*}

$K^- \; ^4\text{He} \rightarrow \Sigma^0 \; \pi^- \; ^3\text{He}$

\begin{align*}
\text{At-rest:} & \quad \text{S-wave non-Res} / \quad \text{P-wave } \Sigma(1385) \text{ Res} \\
\text{In-flight:} & \quad \text{S-wave non-Res} / \quad \text{P-wave } \Sigma(1385) \text{ Res}
\end{align*}

$K^- \; ^4\text{He} \rightarrow (\Sigma \; \pi)^0 \; ^3\text{He}$

\begin{align*}
\text{At-rest:} & \quad \text{S-wave non-Res} / \quad \text{S-wave } \Lambda(1405) \text{ Res} / \quad \text{P-wave } \Sigma(1385) \text{ Res} \\
\text{In-flight:} & \quad \text{S-wave non-Res} / \quad \text{S-wave } \Lambda(1405) \text{ Res} / \quad \text{P-wave } \Sigma(1385) \text{ Res}
\end{align*}
Channel: $K^- \, ^4\text{He} \rightarrow \Lambda \, \pi^- \, ^3\text{He}$ … calculated reactions

Calculated secondary hadronic interactions:

EACH INTERNAL CONVERSION PROCESS:

$$\Sigma \, p/n \rightarrow \Lambda \, p/n$$

was calculated for both P-wave and S-wave produced $\Sigma$s.
Channel: \( \text{K}^{-} \ 4\text{He} \rightarrow \Lambda \pi^{-} \ 3\text{He} \ ... \) calculated reactions

Calculated secondary hadronic interactions:

**EACH INTERNAL CONVERSION PROCESS:**

\[ \Sigma \ p/n \rightarrow \Lambda \ p/n \]

was calculated for both P-wave and S-wave produced \( \Sigma \)s.

Some Carbon from Isobutane

\[ \Lambda \pi^{-} \text{ direct production} \]

\[ \text{In-flight} \]

\[ \text{At-rest} \]

\[ \Sigma^{0} \ p \text{ conversion} \]

\[ \Sigma^{0} \ n \text{ conversion} \]

\[ \Sigma^{+} \ n \text{ conversion} \]
$K^- \ ^4\text{He} \rightarrow \Lambda \pi^- \ ^3\text{He}$ events selection
\[ \text{K}^{-} \text{ } ^{4}\text{He} \rightarrow \Lambda \pi^{-} \text{ } ^{3}\text{He} \text{ events selection} \]

- **CUT** based on MC simulations used to select \( \Lambda \pi^{-} \) direct production events
- At-rest CAN NOT be separated from In-flight \( \rightarrow \) global fit performed
- Background sources:
  - \( \Lambda \pi^{-} \) events from \( \Sigma \text{ p/n} \rightarrow \Lambda \text{ p/n} \) conversion
  - \( \Lambda \pi^{-} \) events from \( K^{-} {^{12}}\text{C} \) absorptions in Isobutane
**K^- 4He → Λ π^- 3He background**

- **Σ p/n → Λ p/n conversion:**
  
  Each possible conversion channel was simulated:
  
  \[ \Sigma^0 p / \Sigma^0 n / \Sigma^+ n / \text{At-rest} / \text{In-flight} / \text{from RES and N-R produced Σs} \]

- **Λ π^- events from K^- 12C absorptions in Isobutane (90% He, 10% C_4H_{10}):**
  
  K^- 12C DATA in the KLOE DC wall are used

  estimated contribution:
  
  \[ \frac{N_{KHe}}{N_{KC}} = \left( \frac{n_{KHe}}{n_{KC}} \right) \cdot \left( \frac{\sigma_{KHe}}{\sigma_{KC}} \right) \cdot \left( \frac{\text{BR}_{KHe}(Λ π^-)}{\text{BR}_{KC}(Λ π^-)} \right) \sim 1.3 ± 0.3 \]


  **K^- 12C still not calculated:**
  
  - uncertain initial state of K meson \( l_K = 1, 2, 3 \)
  
  - 4 nucleons in s-orbit, 8 nucleons in p-orbit
  
  - final state hyperon interactions
Study of the background

The main background sources for this channel are (example in $^{12}$C):

- $K^- \, ^{12}C \rightarrow \Sigma^0(1385) + ^{11}B \rightarrow \Lambda\pi^0 + ^{11}B$

$\Sigma^0(1385)$ can not decay in $\Sigma^0\pi^0$ for isospin conservation.

- Internal conversion $K^- \, ^{12}C \rightarrow \Lambda(1405) + ^{11}B \rightarrow \Sigma^0\pi^0 + ^{11}B$, $\Sigma^0 N \rightarrow \Lambda N$ competes with the decay $\Sigma^0 \rightarrow \Lambda\gamma$.

Both background sources were analyzed by different methods:

- $\gamma_1/\gamma_2$ DATA
- $\gamma_3$ DATA
- $\gamma_3$ MC

photon energy distribution

$\Lambda$ momentum in the $\Sigma^0$ rest frame
Study of the background

In both cases $\gamma_3$ is not present, if a contamination is present, the neutral cluster which is associated to $\gamma_3$ by reconstruction should show differences.

- Right: the energy distribution of $\gamma_3$ (green) is in perfect agreement with MC simulations of pure signal events (blue) (energy spectrum of $\gamma_1\gamma_2$ is shown in black).
- Left: the time distribution of $\gamma_3$ (green) is in agreement with the time distributions of the two photons coming from $\pi^0$ decay (black).
Study of the background

The numbers of pure background $\Sigma(1385)$ and $\Sigma^0 N \rightarrow \Lambda N$ events passing the analysis cuts are normalized to pure signal $\Lambda(1405)$ events, then weighted to the BRs for $\Lambda \pi^0$ direct production (D), internal conversion (IC) and $\Sigma^0 \pi^0$ production due to $K^-$ interaction in $^4$He and C respectively:


The percentages of background events entering the final selected samples are:

$$\frac{n_{\Lambda \pi^0 \text{ D norm}} + n_{\Lambda \pi^0 \text{ IC norm}}}{n_{\Sigma^0 \pi^0} + n_{\Lambda \pi^0 \text{ D norm}} + n_{\Lambda \pi^0 \text{ IC norm}}} = 0.03 \pm 0.01 \text{ in DC wall (0.03 \pm 0.02 in DC gas)}$$
\( p^{\Sigma^0} \) spectrum for boost and anti-boost events

\( p^{\Sigma^0\pi^0} \) distribution for lower (black) and higher (red) \( p_k \) values
$\Sigma^0\pi^0$ channel

Mass momentum correlatation

Top $m_{\Sigma^0\pi^0}$ vs $p_{\Sigma^0\pi^0}$, bottom $\theta_{\Sigma^0\pi^0}$ vs $p_{\Sigma^0\pi^0}$.
Fit of $\Sigma^0\pi^0$ spectrum in C

8 component fit, simultaneously $m_{\Sigma^0\pi^0}$ & $p_{\Sigma^0\pi^0}$:

- Breit-Wigner resonant component $K^-$ C at-rest/in-flight. $(M,\Gamma) = (1405 \div 1430, 5 \div 52)$
- Non resonant $\Sigma^0\pi^0$ $K^-$ H production at-rest/in-flight
- Non resonant $\Sigma^0\pi^0$ $K^-$ C production at-rest/in-flight
  - $\Lambda\pi^0$ background ($\Sigma(1385) + \text{I.C.}$)
  - non resonant misidentification ($n.r.m.$) background

$K^- ^{\text{12C}} \rightarrow \Sigma^0\pi^0 + ^{\text{11B}}$ (Boron spectator, left in ground state)

secondary interactions not taken into account.
Fit of $\Sigma^0\pi^0$ spectrum in C

$\chi^2_{\text{min}} / \text{ndf} \sim 1.7$ corresponding to $(M_{\text{min}}, \Gamma_{\text{min}}) = (1426, 52)$ MeV/c²

- Global fit
- Resonant component $K^- C$ at-rest
- n. r. $K^- C$ at-rest
- n. r. $K^- C$ in-flight
- n. r. $K^- H$ in-flight
- $\Lambda^0\pi^0$ background + n. r. m.

Preliminary: more next weeks
$\Lambda\pi^-$ + extra-proton

The extra-$p$ indicates fragmentation of the residual nucleus
($\Sigma / \Lambda$ conversion, $\Sigma / \Lambda / \pi$ secondary interactions, multi-nucleon absorption)
but ...

- if ($\Lambda\pi^-$ direct production) then 3% extra-$p$
- if ($\Lambda\pi^-$ in-direct production) then 25% extra-$p$