STUDY OF THE $\Sigma^0 p$ CORRELATIONS FROM K$^-$ ABSORPTIONS WITH KLOE

Otón Vázquez Doce (Excellence Cluster Universe - TUM)
on behalf of the AMADEUS Collaboration

CONF12 – Thessaloniki – Tuesday 6 September 2016
K⁻ in nuclear matter and the ¯K N potential

- K⁻ - nucleon interaction is attractive (kaonic atoms)
- **Absorption processes** have a large cross-section and should be taken into account

### Kaonic Clusters

- K⁻ acting as glue between two or more nucleons → molecular state is formed
- It is predicted by most theories in the field but with very different **Binding Energy** and **Width**

<table>
<thead>
<tr>
<th>Method</th>
<th>Variation</th>
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<th>Faddeev-AGS</th>
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<th>Faddeev-Yakubovsky</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (MeV)</td>
<td>17-23</td>
<td>48</td>
<td>16</td>
<td>60-95</td>
<td>9-16</td>
<td>50-70</td>
<td>32</td>
<td>51.5</td>
</tr>
<tr>
<td>Γ (MeV)</td>
<td>40-70</td>
<td>61</td>
<td>41</td>
<td>45-80</td>
<td>34-46</td>
<td>90-110</td>
<td>49</td>
<td>61</td>
</tr>
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</table>

Prof. Nagae, HYP2015, Sep. 10, 2015
**KN interactions**

- Models for neutron stars with K⁻ condensate inside, depending on the strength of the K⁻ - nucleon potential (**at large densities**)

- Measurements of 2 solar masses constrain the neutron star EOS to be **stiff**

- New precise experimental data is needed: KN(s) interactions, bound states,...
Experiments:

**K^- Absorption**

<table>
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<tr>
<th>FINUDA</th>
<th>K^- + A</th>
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<td>KEK-PS: E549</td>
<td>K^- + 4 He → Λ + N + X</td>
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B(ppK^-) = 115 MeV
Γ(ppK^-) = 67 MeVc^-2


Selection of the different mechanisms only on the base of the ΛN missing mass.
A: associated to 2N absorption
Experiments:

**K⁻ Absorption**

**FINUDA**  
\( K⁻ + Δ \)

**KEK-PS: E549**  
\( K⁻ + ^4He \rightarrow \Lambda + N + X \)

**pp collisions**

**DISTO:** deviation spectra, Extraction of a signal

**HADES:** PWA analysis of the final state including all \( N^* \) decaying into KL pairs  
Extraction of upper limit

---


**DISTO pp → p K⁺\( \Lambda \) @ \( \Tp = 2.85 \) GeV**

\[ B(ppK⁻) = 103 \text{ MeVc}^{-2} \]
\[ \Gamma(ppK⁻) = 118 \text{ MeVc}^{-2} \]

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**HADES pp → pK⁺\( \Lambda \) @ \( p = 2.85 \) GeV**

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Coherent Upper-Limit for the ppK⁻

<table>
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<th>Wave</th>
<th>Cross Section (μb)</th>
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<tbody>
<tr>
<td>0⁺</td>
<td>1.9 – 3.9</td>
</tr>
<tr>
<td>1⁻</td>
<td>2.1 – 4.2</td>
</tr>
<tr>
<td>2⁺</td>
<td>0.7 – 2.1</td>
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K⁺ Absorptions with KLOE

Otón Vázquez Doce

Experiments:

K⁺ Absorption

FINUDA
K⁺ + N

KEK-PS: E549
K⁻ + ⁴He → Λ + N + X

pp collisions

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Recent results

LEPS/SPring-8
d(γ,K⁺π⁻ )
J-PARC E27
d(π⁺, K⁺)
J-PARC E15
³He(K⁺,n)

T. Hashimoto et al., PTEP (2015) 061D01

J-PARC E15: ³He(K⁺,n) @ 1 GeV/c


LEPS/SPring-8: d(γ,K⁺π⁻ ) @ Eγ=1.5-2.4 GeV

Y. Ichikawa et al., PTEP 2015, 021D01

J-PARC E27: d(π⁺, K⁺) @ 1.69 GeV/c

B =95 +18 −17 (stat.) +30 −21 (syst.) MeV
Γ = 162 +87 −45 (stat.) +66 −78 (syst.) MeV
**K^- absorptions with KLOE**

- 1.74 fb^{-1} analyzed from 2004/2005 data

\[ K^- \text{ stopped in-flight.} + {}^{12}\text{C} \rightarrow \Sigma^0 \text{p A} \]

**Absorptions in Inner Wall**: \(^{12}\text{C} + {}^{27}\text{Al}\)

~ 1% of K^- stop (650μm + 100μm Al coating in both sides)

**KLOE detector**:  
- Momentum resolution: \(\sigma_p/p \sim 0.4\)  
- 4\(\pi\)-geometry with ~ 96% acceptance  
- Calorimeter optimized for γ: \(\sigma(m_\gamma) \sim 18\text{ MeV/c}^2\)  
- Vertex position resolution ~ 1 mm (in DC)
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**
- Search for the formation of the \( ppK^- \) and its decay in:
  \[ ppK^- \rightarrow \Sigma^0 + p \]

  Yield Extraction and significance
Analysis Steps

1) Lambda PID

proton pion Inv. M.

\[ M_{p\pi^-} \]

M. Inv. Resolution \( \sigma = 0.5 \text{ MeV} \)

2) Primary proton ID

\[ p\Lambda \quad 0.49 \pm 0.01 \text{ MeV}/c \]

\[ pp \quad 2.63 \pm 0.07 \text{ MeV}/c \]

\[ M_{\Lambda p} \quad 1.10 \pm 0.03 \text{ MeV}/c^2 \]

\[ r_{\text{vertex}} \quad 0.12 \pm 0.01 \text{ cm} \]

\( \Lambda p \) common vertex
(contamination of \( \Lambda d, \Lambda t \) below 2%)

Relative accept. (a.u.)
Analysis Steps

3) $\gamma$ identification (from $\Sigma^0 \rightarrow \Lambda \gamma$) in the EMC

Time coincidence after the correction for the $\Lambda$ path

Background under the single-photon signal
Analysis Steps

4) Background evaluation and extraction of the $\Sigma^0$ signal

**Machine background**
- Obtained from sideband analysis
- fixed via this fit and subtracted after normalization of the yield due to additional cut on the $\Sigma^0$ mass

**$\Lambda\pi^0$ Background**
- From $\Lambda\pi^0$ experimental sample
- With one or two $\gamma$’s detected
- Component used for the following fit but with Yield constrained with $2\sigma$ of prefit
Analysis Steps

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Cut around $\Lambda\gamma$ mass:
- keep $\Sigma^0\ p$ signal + $\Lambda\pi^0$ background
- subtract machine background
Analysis Steps

5) Interpretation of the $\Sigma^0 p$ signal

Considered processes:

**Data**

\[ K^- + A \rightarrow \Lambda p \, \pi^0 \]  \hspace{1cm} $\pi^0$ background

\[ K^- + A \rightarrow \Sigma^0(\pi)p(A') \]  \hspace{1cm} Uncorrelated background (low mom. protons)

**Simulations**

\[ K^- + pp \rightarrow \Sigma^0 p \]  \hspace{1cm} 2NA

\[ K^- + ppn \rightarrow \Sigma^0 p n \]  \hspace{1cm} 3NA

\[ K^- + ppnn \rightarrow \Sigma^0 p n n \]  \hspace{1cm} 4NA
Absorption simulation

\[ K^- + pp \rightarrow \Sigma^0 p \quad 2\text{NA} \]
\[ K^- + ppn \rightarrow \Sigma^0 p n \quad 3\text{NA} \]
\[ K^- + ppnn \rightarrow \Sigma^0 p n n \quad 4\text{NA} \]

**Ingredients:**

- Nucleons momenta according to Fermi Distribution in \(^{12}\text{C}\)
- Energy and momentum conservation
- Difference of mass between the initial and residual
- K- in-flight (p ~ 120 MeV/c) and at-rest 50%-50%
Absorption simulation

\[ K^- + pp \rightarrow \Sigma^0 p \quad \text{2NA} \]
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- Nucleons momenta according to Fermi Distribution in $^{12}$C
- Energy and momentum conservation
- Difference of mass between the initial and residual
- $K$- in-flight ($p \sim 120$ MeV/c) and at-rest 50%-50%
- Final state interaction of $\Sigma^0$ or $p$ with other nucleons (1 or 2 collisions for $\Sigma^0$ and $p$ with 50% probability)
- For 2NA different fragmentation scenarios for the rest-nucleus $A'$ have been considered (modification only in $\Sigma^0p$ invariant mass)
Analysis Steps

6) Fit of the experimental data with the cocktail and extraction of the absorption yields.

Simultaneous fit of signal components and pi0 bkg to:

- \text{Inv. M. } \Sigma^0 p
- \text{Cos}\theta(\Sigma^0 p)
- p_{\Sigma 0}
- p_{\text{proton}}
Final fit

From the contributions to the fit, the yields are extracted for $K^-$ stop

$\chi^2 = 0.85$

2NA-QF clearly separated from other processes
Absorption results

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<tr>
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<th>yield / $K_{stop} \cdot 10^{-2}$</th>
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**2NA-QF**: hyperon-nucleon production involving only 2 nucleons
- comprehends all possible fragmented states of the residual nucleus
Absorption results

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...is there room for the signal of a \texttt{ppK^-} bound state?  

Repeat the fit with the inclusion of a simulated bound state (Breit-Wigner) in a grid with different values for the \textbf{Binding Energy} and \textbf{Width}:

- B.E.: 15-75 MeV/c\textsuperscript{2} (15 MeV/c\textsuperscript{2} steps)
- Width: 30-70 MeV/c\textsuperscript{2} (20 MeV/c\textsuperscript{2} steps)
**Fit with ppK⁻**

Best solution: 
(best $\chi^2$ and higher yield)
- B.E. = 45 MeV/c²
- Width = 30 MeV/c²

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

For the best solution B.E. = 45 MeV/$c^2$, Width = 30 MeV/$c^2$

$$\frac{Yield}{K^-_{stop}} = (0.044 \pm 0.009^{stat} + 0.004^{syst} - 0.005^{syst}) \cdot 10^{-2}$$
Evaluation of the significance of the pp$K^-$ signal

For the best solution $B.E. = 45 \text{ MeV/c}^2$, $Width = 30 \text{ MeV/c}^2$

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

F-test evaluates extra parameter to the fit (corresponding to the bound state):
- Significance of “signal hypothesis” w.r.t “Null-Hypothesis” (no bound state)
Conclusions

The $\Sigma^0 p$ analysis has been completed for events in the DC wall $^{12}\text{C} + ^{27}\text{Al}$

- Obtention of the 2NA-QF yield:

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<td></td>
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- Bound state $ppK^-$ yield for B.E. 45 MeV/c$^2$ and Width 30 MeV/c$^2$

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

- The significance of the ppK$^-$ signal is of $1\sigma$ according to F-test

- Published in Physics Letters B 758 (2016) 134–139
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Thank you for your attention!