The AMADEUS experiment and the analysis of K⁻-He KLOE data

Oton Vázquez Doce
on behalf of the AMADEUS Collaboration

Excited QCD 09
Zakopane, February 12, 2009
The AMADEUS experiment

- The AMADEUS experiment at DAΦNE
- Experimental case: Deeply bound kaonic nuclear states
- The AMADEUS setup

KLOE data analysis

- KLOE experiment data, hadronic interactions of $K^-$
- Lambda identification
- Lambda correlations: $\Lambda+p, \Lambda+d, \Lambda(1405)$...and more to come
Study of deeply bound kaonic nuclear states at DAΦNE2

- The main aim of AMADEUS is to confirm or deny the existence of Kaonic Clusters, studying it in the formation and decay processes.

- Either situations: EXISTENCE or NON-EXISTENCE of the deeply bound kaonic nuclear clusters will have strong impact in kaon-nucleon/nuclei physics.
A hadron physics important and unresolved topic: **How the hadronic masses and interactions change in nuclear medium**

**Deeply bound kaonic nuclear states**

firstly suggested by S. Wycech (1986)


“**Nuclear bound states in light nuclei**”

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**Strong attractive I=0 KN interaction** favors discrete nuclear states **bound ~100** and **Γ ~ 30 MeV**.

- Prediction based on the interpretation of the s-wave, isospin I=0 **Λ(1405)** resonance as a **K^-p bound state**
- Creation of a KN potential as to simultaneously reproduce data from KN **scattering lengths** and binding energy and width of **kaonic hydrogen**
Theoretical debate

- Alternative interpretations of the present data: double nucleon absorption followed by FSI of the produced particles with daughter nucleus
- Theoretical development of KN interaction in free space in the framework of SU(3) Chiral unitary model, and modification due to many-body effects in nuclear medium
- Nature of the Λ(1405) resonance
- Bound kaon approach in the Skyrme model also predicts Kaonic Clusters
- Interpretations with not-so-strongly attractive KN potentials
- Nucleon-Nucleon repulsion
- Deeply bound states only in heavy nucleus

theoreticians demand new complete experimental results!
Experimental results from **FINUDA**

K-stopped in light nuclei

Invariant mass spectroscopy
Experimental results from **FINUDA**

K- stopped in light nuclei

Invariant mass spectroscopy

Results from **KEK**:

K- stopped in 4He

Invariant mass spectroscopy
Experimental data

Experimental results from **FINUDA**
K- stopped in light nuclei
Invariant mass spectroscopy

Results from **KEK**:
K- stopped in 4He
Invariant mass spectroscopy

**DISTO**
\( p + p \rightarrow K^+ + X \)

**OBELIX**
\( \bar{p}^4\text{He} \) annihilation

The AMADEUS experiment & analysis of K-He KLOE data

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AMADEUS phase-1: start in 2010/2011 (after KLOE2 step-0), study di- and tri–baryon kaonic nuclei and low-energy kaon-nucleon/nuclei interactions

AMADEUS phase-2: after 2012, higher integrated luminosity, refined study; extend to other nuclei (kaonic nuclei spectroscopy along the periodic table)
**The AMADEUS experiment**

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Requirements satisfied by... **DAΦNE2**

**KLOE**
The AMADEUS setup

Full acceptance and high precision measurements will be made by implementing the KLOE detector with an inner AMADEUS setup (50 cm. gap in KLOE DC around the beam pipe)

Setup for AMADEUS within KLOE
- Cryogenic target
- Inner tracker
- Kaon trigger
Full acceptance and high precision measurements will be made by implementing an inner AMADEUS setup (50 cm gap in KLOE DC around the beam pipe) for AMADEUS in KLOE. The AMADEUS experiment will stop K-He KLOE data and analysis of K-He KLOE data.

The AMADEUS setup

\[
K^-_{\text{stopped}} + ^4\text{He} \rightarrow p + (K^-\text{pnn})
\]

\[
K^-_{\text{stopped}} + ^4\text{He} \rightarrow n + (K^-\text{ppn})
\]
KLOE without AMADEUS

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KLOE with AMADEUS

KLOE EMC

KLOE Drift Chamber

$K^-\text{stopped} + \ ^4\text{He} \rightarrow p + (K^-\text{ppn})$

$K^-\text{stopped} + \ ^4\text{He} \rightarrow n + (K^-\text{ppn})$
Reactions channels (simplified)

Measure 1 particle of a 2-body decay. Transform to cms of the decaying object. Gives 2nd particle properties. Missing mass spectroscopy

Measure all outgoing particles to obtain the total cms energy = invariant mass of the object
Exotic states produced with \((K, N)\) reactions will be observed by the energy distribution of the \textit{ejected protons and neutrons} via the \textit{missing mass spectra} of the \((K, p)\) and \((K, n)\) reactions.

\[ K^-_{\text{stopped}} + ^4\text{He} \rightarrow p + (K^-pnn) \]

\[ K^-_{\text{stopped}} + ^4\text{He} \rightarrow n + (K^-ppn) \]

\[ \rightarrow \text{The setup should be capable to measure:} \]
- Position of \(K^-\) stop: primary vertex and \(K^+\) tracking (trigger)
- Outgoing \textit{neutrons} and \textit{protons} 400 - 600 MeV/c

\[ \rightarrow \text{KLOE has an experimentally proved capability for neutron detection (KLOnE)} \]
Decay processes

→ all decay products have to be identified, including hyperons decay products
→ 4-momenta of charged an neutral particles must be determined
- protons 200 - 500 MeV
- pions 50 -200 MeV
- neutrons 200 -500 MeV
- deuterons...

Invariant mass spectroscopy
The AMADEUS setup

- **Inner tracker** (eventually, a first tracking stage before the DC)
- **Target** (A gaseous He target for a first phase of study)
- **Trigger** (1 or 2 layers of ScFi surrounding the interaction point)
The AMADEUS setup

• **Inner tracker** (eventually, a first tracking stage before the DC)

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**AMADEUS**

Low-mass cryogenic gas target cell:
- \( T = 10 \text{ K} \)
- \( P = 1.0 \text{ bar} \)
- \( \text{Rin} = 5 \text{ cm} \)
- \( \text{Rout} = 15 \text{ cm} \)
- \( L = 20 \text{ cm} \)
The AMADEUS setup

**AMADEUS**

Low-mass cryogenic gas target cell:
- T = 10 K
- P = 1.0 bar
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- Rout = 15 cm
- L = 20 cm

**SIDDHARTA**

working T 22 K working P 1.5 bar
Alu-grid
Side wall: Kapton 50 µm
Entrance window: Kapton 50 µm

Current target installed at DAΦNE

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The AMADEUS setup

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- working T 22 K
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SI DDHARTA

- working T 22 K
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Inner tracker (eventually, a first tracking stage before the DC)

Target (A gaseous He target for a first phase of study)

Trigger (1 or 2 layers of ScFi surrounding the interaction point)

Current target installed at DAΦNE

SIDHARTA Monte Carlo

- selected target radius
- stop position in r-region

boost side

degraded

target entrance

target

cryostat entrance

red: stop event
blue: in-flight decay
green: in-flight reaction

entrance window: Kapton 50 µm

Kapton 50 µm
The AMADEUS setup

- Low-mass cryogenic gas target cell:
  - T = 10 K
  - P = 1.0 bar
  - Rin = 5 cm
  - Rout = 15 cm
  - L = 20 cm

- Amedeus Monte Carlo
- Siddharta Monte Carlo

- Upper tracker: eventually, a

- Entrance window: Kapton 50 µm

- SIDHARTA
  - Working T = 22 K
  - Working P = 1.5 bar
  - Alu-grid

The AMADEUS experiment & analysis of K-He KLOE data

- Inner tracker (eventually, a first tracking stage before the DC)
- Target: a gaseous He target for a first phase of study
- Trigger: 1 or 2 layers of ScFi surrounding the interaction point

Current target installed at DAΦNE

Boost for 55 mrad crossing: 29 MeV/c
The AMADEUS experiment & analysis of K-He KLOE data

The AMADEUS setup

- **Inner tracker** (eventually, a first tracking stage before the DC)

- **Target** (A gaseous He target for a first phase of study)

- **Trigger** (1 or 2 layers of ScFi surrounding the interaction point)

- Cylindrical layer of scintillating fibers surrounding the beam pipe to trigger $K^+ K^-$ in opposite directions

- Readout to be done by SiPM

![Diagram of the AMADEUS setup with scintillating fibers and SiPM readout](image)
For a good behavior stability in the applied voltage with great precision is needed for every single detector.

Electronics: New CAMAC modules providing:

• Variable $V_{\text{bias}}$ for 5 channels with a **stability for nominal voltages below 1 mV**
• 2 output / channel:
  - Amplified (x50-x100) signal
  - Discriminated signal (variable threshold)

Designed by G. Corradi, D. Tagnani, C. Paglia

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**Trigger system: SiPM tests**

SiPM (HAMAMATSU U50) (400 pixels)
Operating voltage ~70V

Dedicated fast pre-amplifiers design
Gain x20 – x100
Small size
The AMADEUS experiment & analysis of K-He KLOE data

Trigger system: ScFi + SiPM setup

New mechanical support for
5 ScFi read from both sides
10 SiPM + readout card

Precision support for efficiencies studies

Instrumented fibers:
- Pol.Hi.Tech 46 (Blue )
- Saint Gobain BCF- 10 single cladding:
  - Emission peak 432 nm
  - Decay time 2,7 ns
  - 1/e 2.2 m
  - 80000 ph./MeV

90Sr β source tests:

Trigger SiPM
Signal SiPM

November, 2008
Trigger system tests: installation at DAΦNE

SIDDHARTA setup

DAΦNE beam pipe
Trigger system tests: installation at DAΦNE

SIDDHARTA setup

DAΦNE beam pipe
Installation of AMADEUS trigger test setup in DAΦNE
22-24 January 2009
Trigger system tests: installation at DAΦNE

Installation of AMADEUS trigger test setup in DAΦNE 22-24 January 2009

Kaon peak around ch 1600 (adc) ~ X 10 from mips as expected by simulation
Conclusions

“In conclusion, an initial programme based on the study of the $^3\text{He}$ and the $^4\text{He}$ targets, to investigate dibaryonic and tribaryonic states, would require an integrated luminosity from 2 to 6 fb$^{-1}$, according to depth of the investigation”

A complete determination of all formation and decay channel measuring, binding energies, widths, angular momentum, isospin, sizes...

- Detection of: - charged and neutral particles
  - high efficiency and resolution
  - in $4\pi$ geometry (full acceptance)

The goal is to definitely clarify the existence of Kaonic Clusters
Analysis of $K^-$He KLOE data
Hadronic interactions of $K^-$ in KLOE

- The Drift Chambers of KLOE contain mainly $^4\text{He}$.
- From analysis of KLOE data and Monte Carlo: 0.1% of $K^-$ from daΦne should stop in the DC volume.
- This would lead to hundreds of possible kaonic clusters produced in the 2 fb$^{-1}$ of KLOE data.
Statistics:
- Total amount of data analyzed up to an integrated luminosity of $\sim 1.1 \text{ fb}^{-1}$ from KLOE data (K-charged group).
- Special ntuples of KLOE data were created, with kaons tagged by 2-body decay or by the dE/dx signature in the DC gas.

Strategy:
Search for hadronic interactions with $\Lambda(1115)$ as products:
- $\Lambda \to p + \pi^-$ (64% BR) vertex made by KLOE reconstruction
- Construct a vertex with $\Lambda + \text{an extra particle}$
Lambda invariant mass

$\Lambda \rightarrow p + \pi^-$

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

-Dedicated event selection to avoid Eloss in the DC wall
  - Best $\chi^2$ tracks and vertices

KLOE:

$M_{\text{inv}} = 1115,723 \pm 0.003 \text{ stat (MeV/c}^2\text{)}$

PDG:

$M_\Lambda = 1115,683 \pm 0.006 \text{ stat} \pm 0.006 \text{ syst (MeV/c}^2\text{)}$

-Sistematics dependent of momentum calibration
-Evaluated by 2-body decay of $K^\pm$:

$K^\pm \rightarrow \mu^\pm \nu$

$K^\pm \rightarrow \pi^\pm \pi^0$
Particle identification

• Search for the proton with first DC measurement around the lambda vertex (30 cm. cylinder)
• Vertex lambda + (proton or deuteron) assumption

\[ K^-_{\text{stopped}} + {}^4\text{He} \rightarrow n + n + (K^-\text{pp}) \]

\[ K^-_{\text{stopped}} + {}^4\text{He} \rightarrow n + (K^-\text{ppn}) \]

Particle identification

The AMADEUS experiment & analysis of K^-He KLOE data

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Correlations with Lambda

- Improved $\Lambda d$ vertex reconstruction
- Improved mass recognition (PID) of deuterons and protons
- Improved selection of events in DC-gas

- Proton/deuteron candidates are required to have an associated cluster in the EMC and its mass is measured by time of flight.

- Require the presence of the tracked/extrapolated $K^-$
- Check event display
The AMADEUS experiment & analysis of $K^-\text{He}$ KLOE data

**Lambda-d**

$K^-_{\text{stopped}} + ^4\text{He} \rightarrow n + (K^-\text{ppn})$

Events in the DC volume

$M_{\text{inv}} \Lambda d \ (\text{MeV/c}^2)$

$\Lambda + d$

Cos $\theta (\Lambda d)$
\( \Lambda d \) analysis

\[ K^-_{\text{stopped}} + {}^4\text{He} \rightarrow n + (K^-ppn) \]

Events in the DC volume

Momentum of lambda and deuteron:

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

\[ M_d + M_p + M_{\pi^-} \]

\[ M_d + M_p + M_K \]

\[ P_{\Lambda} \ (\text{MeV}/c) \]

\[ P_d \ (\text{MeV}/c) \]

Cos \( \theta \) (\( \Lambda d \))

The AMADEUS experiment & analysis of \( K^-\text{-He} \) KLOE data

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The AMEDEUS experiment & analysis of $K^- + ^4\text{He} \to n + (K^-\text{ppn})$

**Lambda-d**

$K^-_{\text{stopped}} + ^4\text{He} \to n + (K^-\text{ppn})$

$\Lambda + d$

Events in the DC volume

**lambda momentum vs. Minv**

**deuteron momentum vs. Minv**

$M_{\text{inv}} \Lambda d (~\text{MeV}/c^2)$

$P_\Lambda (~\text{MeV}/c)$

$P_d (~\text{MeV}/c)$

$M_{\text{inv}} \Lambda d (~\text{MeV}/c^2)$

$\cos \theta (\Lambda d)$

$M_{\text{inv}} \Lambda d (~\text{MeV}/c^2)$

$\cos \theta (\Lambda d)$
Lambda-d

$$K_{\text{stopped}} + ^4\text{He} \rightarrow n + (K^{-}\text{ppn})$$

FINUDA
K- stopped in light nuclei

KEK
K- stopped in 4He

The AMADEUS experiment & analysis of $K^{-}\text{He}$ KLOE data

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KLOE has an experimentally proved capability for neutron detection (KLOnE)

The equation is:

\[ K^-_{\text{stopped}} + ^4\text{He} \rightarrow n + (K^-\text{ppn}) \]

Outgoing neutrons 400-600 MeV/c

The AMADEUS experiment & analysis of K^-He KLOE data

Neutron search

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KLOE has an experimentally proved capability for neutron detection (KLOnE)
Λ(1405)/Λ(1420) search
- Strongly related with the deeply bound kaonic states prediction
- Lack of experimental data
Λ(1405)/Λ(1420) search
- Strongly related with the deeply bound kaonic states prediction
- Lack of experimental data
\( \Sigma^0 \pi^0 \)

\( \Lambda(1405)/\Lambda(1420) \) search

- Strongly related with the deeply bound kaonic states prediction
- Lack of experimental data

**Kinematic fit:**

- \( \chi^2 \) computing:
  - momentum of proton and pion
  - Covariance matrix elements for every track
  - time and positions plus resolutions for photons

- Allows to reject background selecting the right combination of photons

- Constraints: \( \Delta t \) for the arrival time of photons

- No mass assumption -> unbiased mass spectras
$\Sigma^0\pi^0$

$\Lambda(1405)/\Lambda(1420)$ search
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The AMADEUS experiment & analysis of K–He KLOE data

$$\Sigma^0\pi^0$$

M_{inv} \gamma \gamma (\text{MeV}/c^2)

M_{inv} \Lambda \gamma (\text{MeV}/c^2)
The AMADEUS experiment & analysis of K⁻He KLOE data

Σ⁰π⁰

DC wall

DC volume

$M_{\text{inv}} \, \Lambda \gamma \,(\text{MeV/c}^2)$

$M_{\text{inv}} \, \gamma \gamma \,(\text{MeV/c}^2)$

$M_{\text{inv}} \, \gamma \gamma \,(\text{MeV/c}^2)$
The AMADEUS experiment & analysis of $K^-$He KLOE data

$\Sigma^0\pi^0$

$M_{\text{inv}} \Lambda\gamma$ (MeV/$c^2$)

$M_{\text{inv}}$ $\Sigma^0\pi^0$ (MeV/$c^2$)

DC wall

DC volume

Entries 1284

Entries 267

Entries 531

Entries 2633
\[ \Sigma^0 \pi^0 \]

\[ \pi^- p \rightarrow K^0 \Sigma^0 \pi^0 \] (solid line) PDG

\[ K^- p \rightarrow \pi^+ \pi^- \Sigma^+ \pi^- \] (dotted line) PDG

\[ pp \rightarrow p K^+ \gamma^0 \] (points with errors) 2007

Comparison with available experimental data
Conclusions

• **1.1 fb⁻¹** of the KLOE data have been analyzed looking for physics generated by the 0.1 % of K⁻ stopped in the DC volume (no target).

• Excellent $\Lambda(1115)$ measurement has been performed showing the KLOE capabilities to study KN interactions at low E.

• Capacity to analyze $\Lambda_d$ in a broad kinematic range with high acceptance representing key ingredients for AMADEUS success.

Future goals

• Refine selection criteria for $\Lambda p$ and $\Lambda t$
• Analyze neutron-events in the $\Lambda_d$ case
• Improve the algorithm for Kinematical fit in the search for $\Lambda(1405)$
• Increase the statistics to the whole 2004-2005 KLOE data set ($x2$)
Lambda momentum

Simulation: expected signals for inclusive \( \Lambda \) production in \(^4\)He and \(^{12}\)C

FINUDA \(P_\Lambda\) (MeV/c)
(all tracks, short+long, \(\mu\) coincidence)

Thanks to S. Piano, A. Filippi

- Well defined double structure in both cases
- Similar momentum range
- Differences at lower momentum due to acceptancy
- Perfectly compatible!!!
Installation of AMADEUS trigger test setup in DAΦNE

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January 2009

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Kaon peak around ch 1600 (adc) ~ X 10 from mips as expected by simulation
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