Kaonic atoms at the DAFNE Collider: strangeness from accelerators to the stars

Catalina Curceanu on behalf of the SIDDHARTA-2 Collaboration
Kaonic Atoms to Investigate
Global Symmetry Breaking
Symmetry 12 (2020) 4, 547

On self-gravitating strange dark matter halos around galaxies
Phys.Rev.D 102 (2020) 8, 083015

Dark Matter studies

The modern era of light kaonic atom experiments:
Rev.Mod.Phys. 91 (2019) 2, 025006

Fundamental physics
New Physics

Kaonic atoms
Kaon-nuclei interactions (scattering and nuclear interactions)

Merger of compact stars in the two-families scenario

Part. and Nuclear physics
QCD @ low-energy limit
Chiral symmetry, Lattice

Astrophysics
EOS Neutron Stars

The equation of state of dense matter:
Stiff, soft, or both?
Width $\Gamma$ and shift $\varepsilon$ obtained by measuring the X-rays emitted.

Kaonic atom Formation

A new renaissance for kaonic atoms at DAΦNE: future measurements and perspectives.
**SIIDHARTA-2**

**Silicon Drift Detector for Hadronic Atom Research by Timing Applications**

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<td>LNF-INFN, Frascati, Italy</td>
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To perform the *first measurement ever of kaonic deuterium X-ray transition* to the ground state (1s-level) such as to determine its shift and width induced by the presence of the strong interaction.

Analysis of the combined measurements of kaonic deuterium and kaonic hydrogen

\[
\varepsilon_{1s} - \frac{i}{2} \Gamma_{1s} = -2\alpha^2 \mu_c^2 a_{K^-p} (1 - 2\alpha \mu_c (\ln \alpha - 1) a_{K^-p})
\]

(\(\mu_c\) reduced mass of the \(K^-p\) system, \(\alpha\) fine-structure constant)

next-to-leading order, including isospin breaking

Experimental determination of the isospin-dependent K-N scattering length
Kaonic atoms – scattering amplitudes

Kaonics atoms are fundamental tools for understanding QCD in non-perturbative regime:

- Explicit and spontaneous chiral symmetry breaking (mass of nucleons)
- Dense baryonic matter ->
- Neutron (strange?) stars EOS

Role of Strangeness in the Universe from particle and nuclear physics to astrophysics
A new renaissance for kaonic atoms at DAΦNE: future measurements and perspectives

- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy $K^-$
  ($\sim 127$ MeV/c; $\Delta p/p = 0.1\%$)
Laboratori Nazionali di Frascati (LNF-INFN)

- $\Phi \rightarrow K^- K^+ \ (49.1\%)$
- Monochromatic low-energy $K^- \ (\sim 127 \text{ MeV/c} \ ; \ \Delta p/p = 0.1\%)$
The DAFNE principle

Flux of produced kaons: about 1000/second
Suitable for low-energy kaon physics: kaonic atoms

**Φ → K^- K^+ (49.1%)**

**Monochromatic low-energy K^- (~127MeV/c)**

- Less hadronic background due to the beam
  (compare to hadron beam line: e.g. KEK / JPARC)
SIDDHARTA overview

Target

Inside vacuum

Detected by SDDs

Detect by two scintillators

$\Delta p/p = 0.1\%$

$510 \text{ MeV/c}$

$127 \text{ MeV/c}$
SIDDHARTA-2 setup

- Cooling line
- Luminosity Monitor
- Kaon Trigger
- Cryogenic gaseous target
- SDD detectors
- Veto-2 system
- Veto-1 system

Veto-1
Veto-2
384 SDDs
Target
Kaon Trigger

SIDDHARTA-2 Luminosity Monitor
DAFNE Luminosity Monitor
SIDDHARTINO installed on DAFNE (17 April 2019)
SIDDHARTINO: phase 1 of SIDDHARTA-2
1/6 of SIDDHARTA-2

Evaluation of the machine background during the DAΦNE beams commissioning phase in preparation for the K-d run through the measurement of K-⁴He 3d->2p transition

- Detector tuning for SIDDHARTA-2:
  - SDDs
  - Kaon Trigger

- Concluded in July 2021
Silicon Drift Detectors

8 SDD units (0.64 cm²) for a total active area of 5.12 cm²
Thickness of 450 μm which ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV
Kaon Trigger

The ToF is different for Kaons, $m(K) \sim 500$ MeV/c$^2$ and light particles originating from beam-beam and beam-environment interaction (MIPs). Can efficiently discriminate by ToF Kaons and MIPs!
Kaon Trigger

Triggered rejection factor $\sim 10^{-5}$
Kaonic $^4$He 3d → 2$p$ measurement

SIDDHARTINO spectrum before applying the kaon trigger and the drift time rejection

More details in Aleksander Khreptak’s poster: *Calibration of Silicon Drift Detectors for the SIDDHARTA-2 Experiment*
A new renaissance for kaonic atoms at DAΦNE: future measurements and perspectives

$E_{K^4\text{He} L_\alpha} = 6463.7 \pm 2.5 \text{ (stat)} \pm 2 \text{ (syst)} \text{ eV}$

$\epsilon_{2p} = 0.2 \pm 2.5 \text{ (stat)} \pm 2 \text{ (syst)} \text{ eV}$

$\Gamma_{2p} = 8 \pm 10 \text{ eV}$

$X^2/\text{ndf} = 1.05$

Integrated luminosity = 26 pb$^{-1}$

SIDDHARTA-2 setup
Installed on DAFNE autumn 2021
Run: KHe and Kd
7 April – 11 July 2022
SDD installation

SDD installed around the target
A new renaissance for kaonic atoms at DAΦNE: future measurements and perspectives

BONUS: first data with SIDHARTA-2 full setup with $^4$He target

Total statistics (SIDHARTINO + SIDHARTA-2) $\rightarrow \delta E (K^4He_{L\alpha}) = 1.0 \text{ eV}$

Very preliminary
**SIDDHARTA-2 K-d measurement**

*Kaonic deuterium run in (all)*

**2022**

**Monte Carlo for an integrated luminosity of 800 pb⁻¹**

to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as K-p)!

**Significant impact in the theory of strong interaction with strangeness**
SIDDHARTA-2 K-d measurement

A new renaissance for kaonic atoms at DAΦNE: future measurements and perspectives
SIDDHARTA-2 K-d measurement

SIDDHARTA-2 KD 1.1%
Date: 03/06/2022 to 24/06/2022 (run from ID 166 to ID 305)
Degrader: deg_rot1_475um
N° SDDs: 98 (bus1 + bus4)
L (lumi) = 30.248 pb^{-1}

Very preliminary
First spectrum with deuterium target
**Phase 2**

**SIDDHARTA-2 strategy and requests**

Setup with all the SDDs (48 SDD arrays) **2022/3** and the *kaonic deuterium measurement* for a run of **800 pb⁻¹**

Action plan for Kd measurement:
- **First run of test** with SIDDHARTA-2 setup as planned (about **50 pb⁻¹ integrated**) - **2022**
- **Second run** with optimized shielding, readout electronics and other necessary optimizations; (for other **750 pb⁻¹ integrated**) - **2023**

Test runs for other kaonic atoms measurements (HPGE...)**
Strangeness precision frontier at DAΦNE: a unique opportunity for measurements of kaonic atoms along the periodic table: will represent a reference in physics with strangeness

Present status: old and very old measurements with low precision (some even wrong: kaonic helium puzzle)

We propose to do precision measurements along the periodic table at DAΦNE for:

- Selected light kaonic atoms
- Selected intermediate mass kaonic atoms
- Selected heavy kaonic atoms charting the periodic table
For future:
Physics at the strangeness frontier at DAΦNE studies:
High Precision Kaonic Atoms Measurements on DAΦNE:

The strangeness Mendeleev table

We presented a program for performing unique measurements of kaonic atoms along the periodic table to contributing to understand physics going from the strong interaction (symmetry breaking) to neutron stars, and from Dark Matter to Physics Beyond Standard Model.

A strong international community is putting forward this realistic and feasible programme in particular in terms of the required integrated , that can be delivered within the upcoming 3-5 years, with support from National and European projects.
EXtensive Kaonic Atoms research: from Lithium and Beryllium to Uranium
WEIGHTED AVERAGE
493.677±0.013 (Error scaled by 2.4)

leads to ±0.17 eV uncertainty of EM value of K-⁴He 3d→2p x-ray

Large difference
60 keV

Pb, W
C

Most recent two experiments

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493.696 ± 0.007 [MeV]
493.636 ± 0.011 [MeV]

(Confidence Level 0.001)

Uncertainty in electron screening. Gamma-ray contamination (Pb, W).
→ new measurement with low-Z gas targets
Parallel run with SIDDHARTA-2: (already installed)

\[ \delta E \sim 3 \text{ eV needed for} \]
\[ \delta m_K = 5 \text{ keV} \]

\[ \text{K}^7\text{Pb}(9\rightarrow8) : 290 \text{ keV} \]

\[ \sigma m_K = \frac{m_K^2}{\mu_{KN}^2} \left( \frac{1}{Z^2} + \frac{6}{26} \right) \frac{10^6 E_{X\rightarrow Y}}{Z^2} \]

Resolutions (FWHM) obtained with \(^{60}\text{Co},^{133}\text{Ba}\) sources:

- 0.870 keV @ 81 keV
- 1.106 keV @ 302.9 keV
- 1.143 keV @ 356 keV
- 1.167 keV @ 1330 keV

HPGe detector available, Croatian Science Foundation project 8570
Present status
First HPGe spectrum (we plan a technical paper)
CZT: proposal for new measurements at DAFNE

A new renaissance for kaonic atoms at DAΦNE: future measurements and perspectives
1 mm$^2$ 5mm thick CZT detector produced by IMEM-Parma

Light-tight box with Electronics (UniPa)

Entrance window

Goal: background and resolution assessment in machine environment (first time)

Aligned with SIDDHARTA-2 luminometer

Al plate (thickness not optimized) + $^{241}$Am source for calibration
CZT: test prototype mounted in DAFNE (22/06/2022)

511 keV peak
(e^+e^- annihilation)

Np peaks
Am
Pb peaks

FWHM / E = 6 %
@ 60 keV
Conclusions

➢ Kaonic Atoms measure the kaon-nucleon/nuclei interaction at threshold (no other way to perform direct measurements!)
  • Tool to directly probe low-energy QCD
  • With implications from nuclear and particle physics to astrophysics and cosmology

➢ Phase1: SIDDHARTINO concluded
  • SDDs and Kaon Trigger tuned
  • Evaluation of the machine background
  • Performed the most precise $K^{-}{}^{4}He$ 3d → 2p measurement in gas

➢ SIDDHARTA-2 presently on DAFNE
  • Installation of the full SIDDHARTA-2 setup: autumn 2021
  • First technical kaonic deuterium run performed in 2022; run to be continued in 2023 (800 pb)
Feasibility studies in parallel with Siddharta-2

Various setups in preparation:
- HPGe
- Crystal spectrometers (VOXES)
- CdZnTe detectors
- SDD 1mm for kaonic atoms measurement

Proposal for Extension of the Scientific Program at DAFNE:
- Kaon mass - precision measurement at a level < 7 keV
- Kaonic helium transitions to the 1s level
- Other light kaonic atoms (K−Bi, Li, B, K−C,...)
- Heavier kaonic atoms (K−Si, K−Pb,...)
- Radiative kaon capture – Λ(1405) study
- Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen)
Cold Dense matter

Strangelets & Dark Matter

Strangeness Fundamental Physics

Neutron star EOS

Particles structure

QCD Chiral symm.

Mass generation, visible Universe
New insights into the strong interaction with strange exotic atoms

The strong interaction plays a fundamental role in our universe. The difficulty of performing precision measurements has limited our understanding of this interaction. Dr Catalina Curceanu at the National Institute for Nuclear Physics (INFN) in Frascati-Rome is leading ambitious new efforts to study and measure the strong interaction in her lab. Her team's work is centred around an intriguing form of matter in which the electrons of regular atoms are replaced by exotic strange particles named 'kaons,' and could help to explain mysteries ranging from the composition of neutron stars, to the origin of mass itself.
Thank You