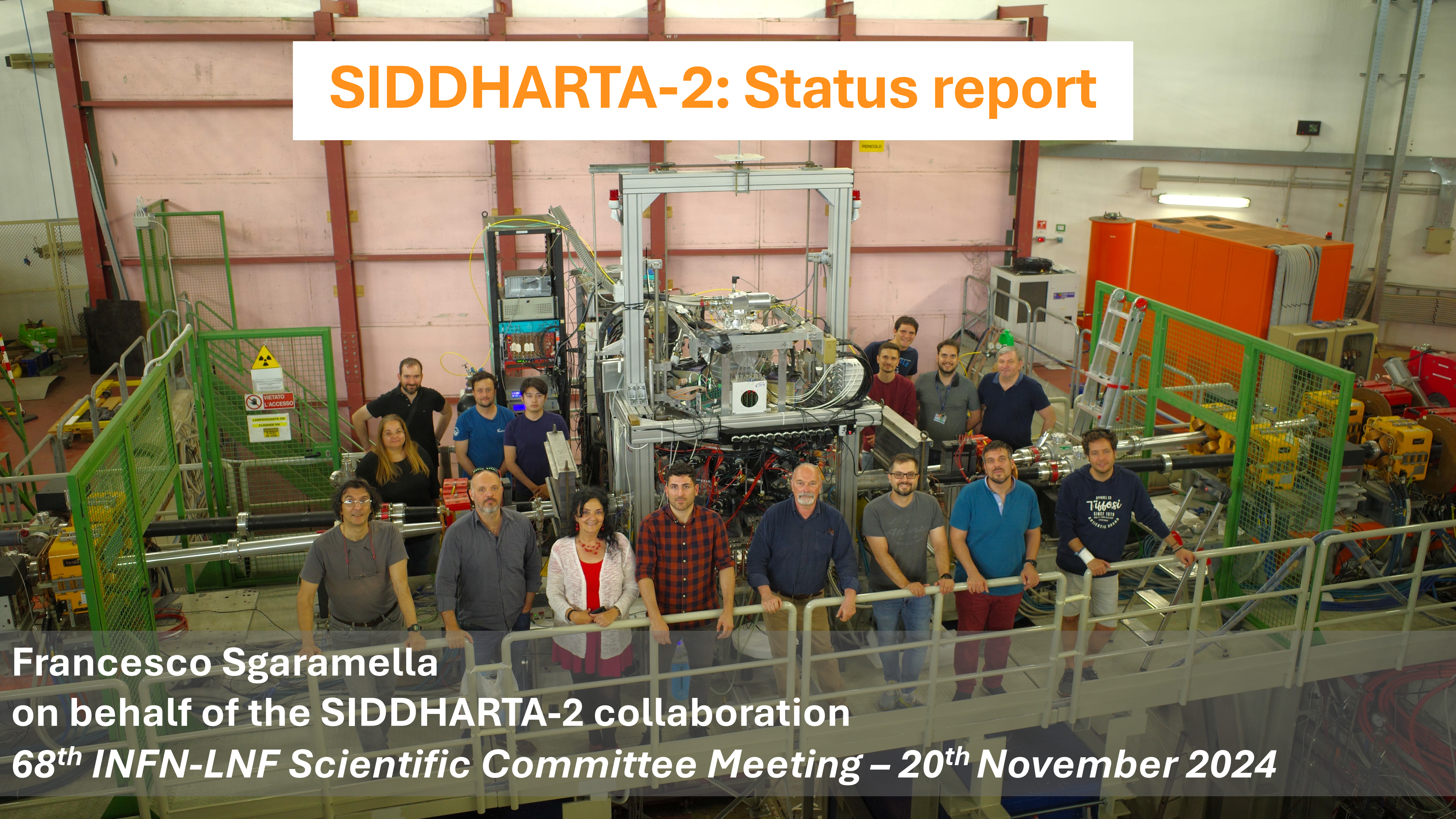
SIDDHARTA-2: Status report



Francesco Sgaramella
on behalf of the SIDDHARTA-2 collaboration

68th INFN-LNF Scientific Committee Meeting – 20th November 2024

We commemorate our dear colleague and friend **Dr Johann Zmeskal** who passed away in July 2024 you’ll be very much missed!

Contents

- Summary of the SIDDHARTA-2 data taking and of final run
- Kaonic Deuterium Run: analysis status and plans
- Post Kd calibration run (Boron – Fluorine), also as feasibility test for light kaonic atoms measurements
- Kaonic neon and CdZnTe updates
- Reminder and update on future plans: EXKALIBUR – first module
- Scientific output and news on collaboration

Data Taking Summary

SIDDHARTA2: kaonic deuterium measurement

- *Kaonic neon*: initial calibration and optimization of the setup, int. lumi $\sim 125\ \mathrm{pb}^{-1}$ (April 2023)
- **Run-1: int. luminosity 196 pb^{-1} (May – July 2023)**
- *Kaonic helium-4*: final calibration of the setup , int. lumi $\sim 40\ \mathrm{pb}^{-1}$ (July 2023)

- *Kaonic neon*: initial calibration of the setup, int. lumi $\sim 36\ \mathrm{pb}^{-1}$ (Sept 2023)
- **Run-2: int. luminosity 344 pb^{-1} (October – December 2023)**
- *Kaonic hydrogen*: final calibration of the setup , int. lumi $\sim 26\ \mathrm{pb}^{-1}$ (Dec 2023)

- *Kaonic hydrogen*: initial calibration of the setup, int. lumi $\sim 70\ \mathrm{pb}^{-1}$ (Jan 2023)
- **Run-3: int. luminosity 435 pb^{-1} (February – April 2024)**
- *Kaonic hydrogen*: final calibration of the setup , int. lumi $\sim 150\ \mathrm{pb}^{-1}$ (April 2023)

- **Low density run: int. luminosity 200 pb^{-1} (May – July 2024)** → From last Scicom
- **Post Kd calibration run (July 2024) – 20 pb^{-1} with solid target**

Total integrated luminosity good for physics 815 pb^{-1} (delivered 975 pb^{-1}) + 200 pb^{-1} low density run

Summary of activities since last SciCom

2024, 27th May

67th Scientific Committee

2024, May - July

Kaonic deuterium: low density run

(Kd run 4)

2024, July (3 days)

Post Kd calibration run

with solid targets (Boron - Fluorine)

2024, July - August

X-ray tube calibration (DAΦNE off) :

Study of the SDDs energy response at high energy (50 keV)

2024, Sept – 20 Nov.

Kaonic deuterium analysis

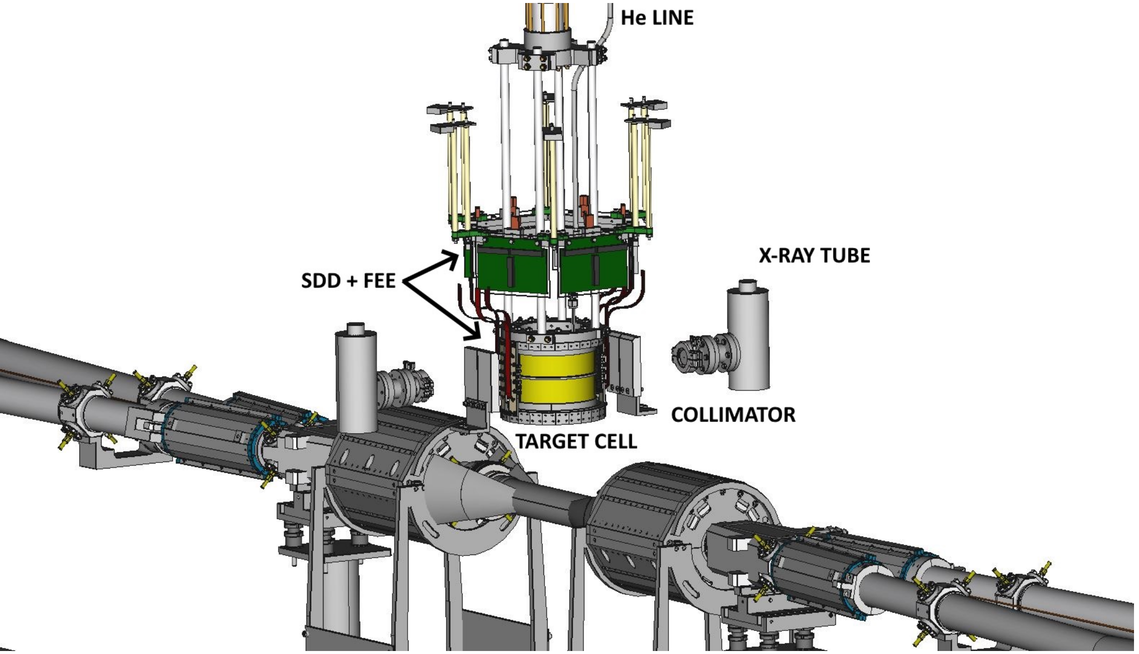
Calibration data analyses

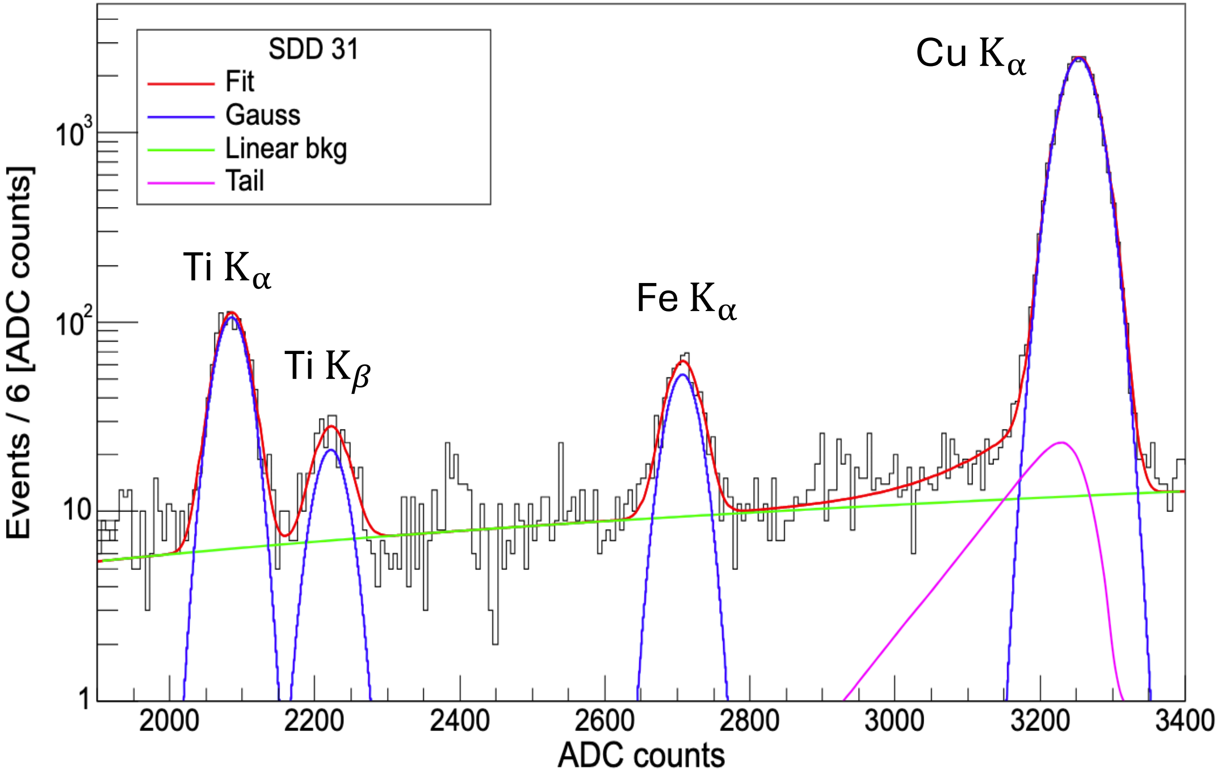
CZT data analyses

BTF test 1 mm SDD

SDD Calibration Runs Analysis

- ~ **20 000 calibration spectra** acquired periodically during the kaonic deuterium runs
- **Calibration target:** Ti Ka (4.5 keV) – Fe Ka (6.4 keV) – Cu Ka (8.0 keV) -> **matching the K-d ROI**
- **Check of the SDDs energy response during the whole data taking** (linearity, energy resolution and stability)
- Kaonic deuterium requirement: **energy calibration accuracy better than 10 eV**

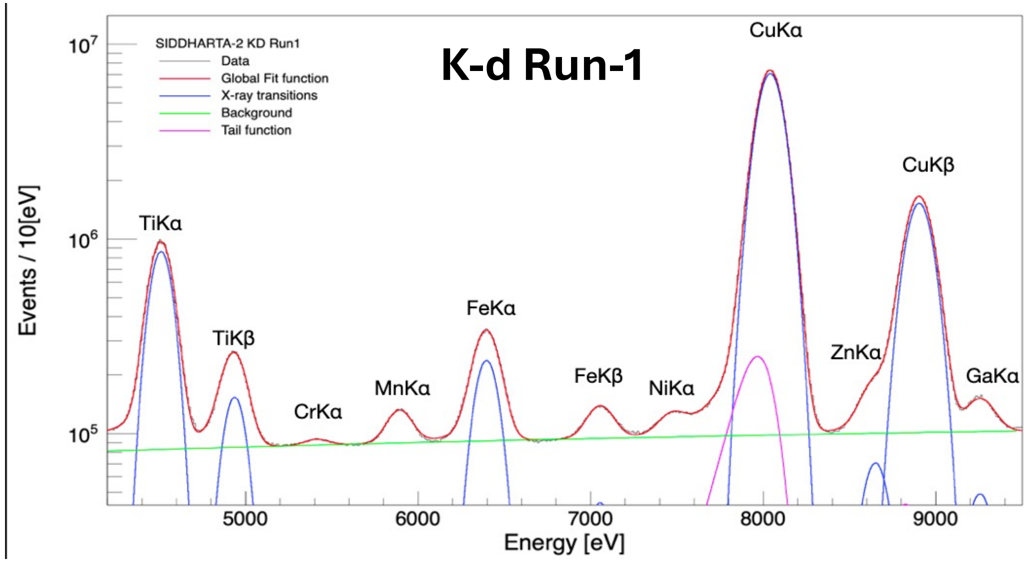


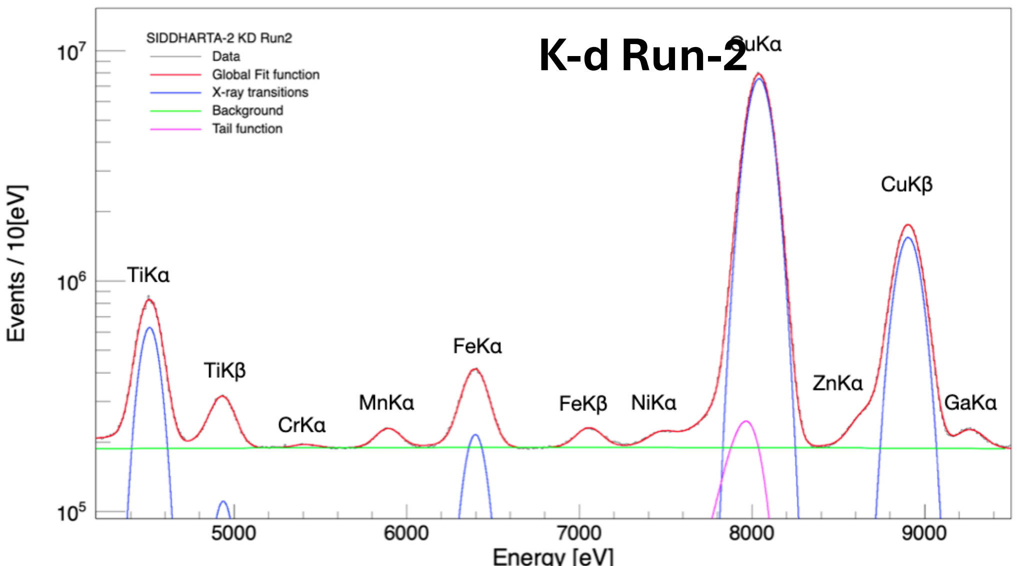


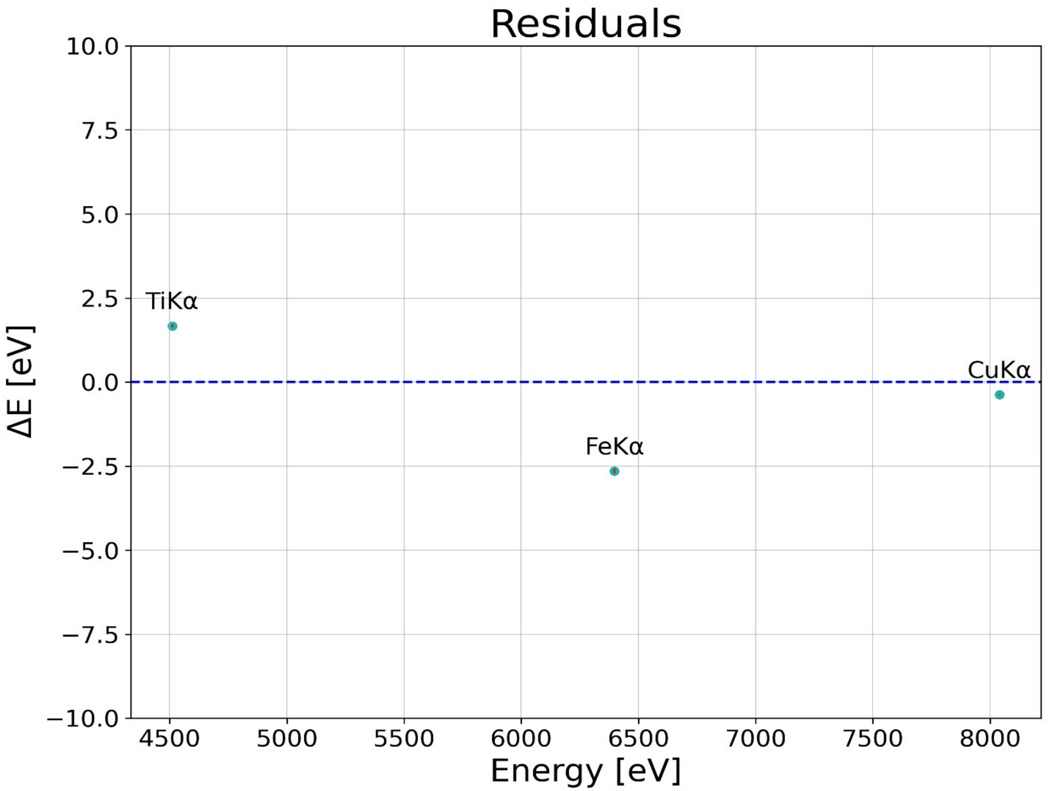
Example of a SDD calibration spectrum

SDD Calibration Runs Analysis

Sum of the calibration data to study the energy response of the whole SDD detectors system
-> evaluation of the systematic uncertainty and calibration accuracy



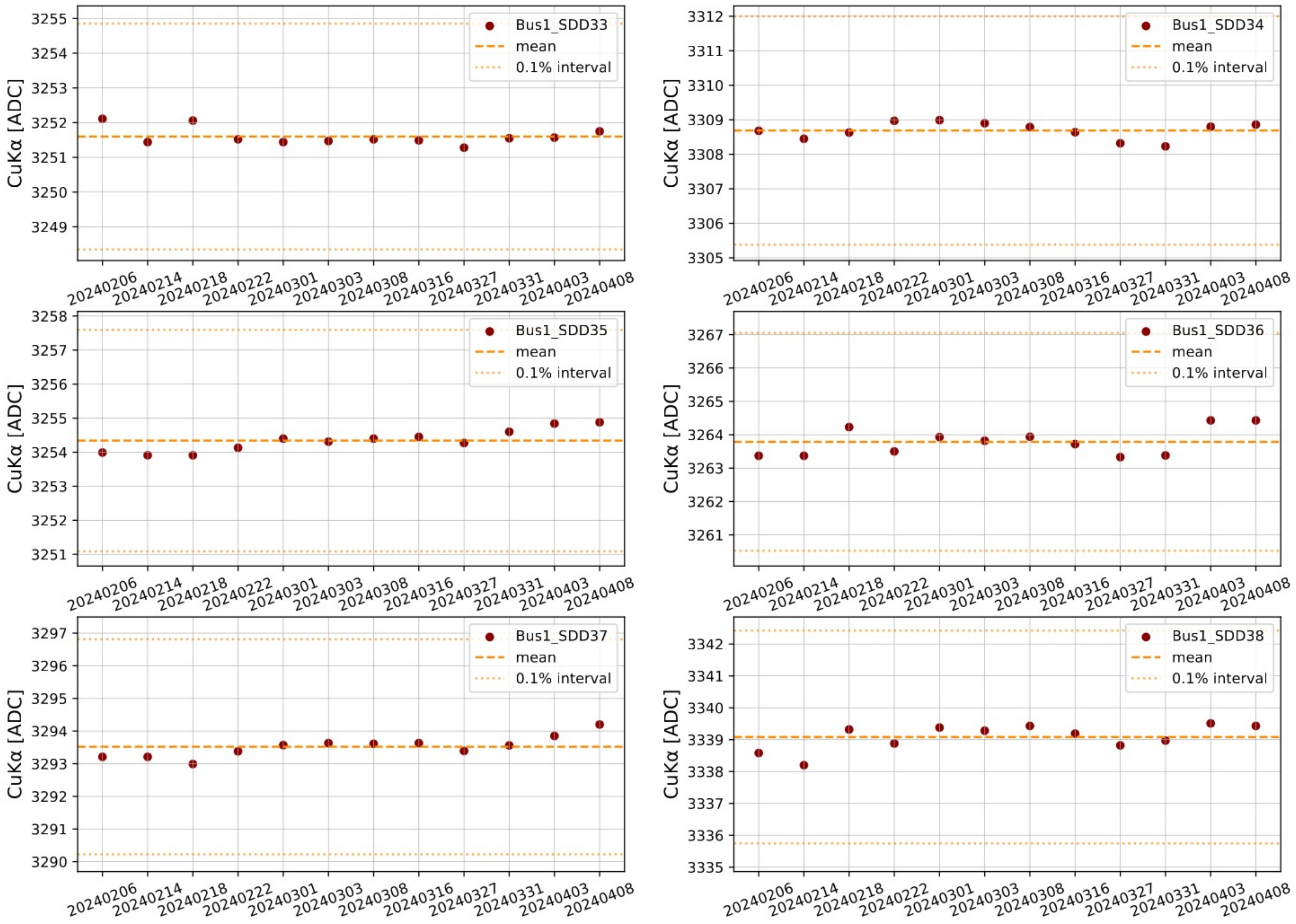




The accuracy of the energy calibration is **better than 3 eV** exceeding the requirements for the measurement of kaonic deuterium

Calibration Runs : Stability

- Run1 and Run2 stability analysis **completed**
- Run3 and low density run **analysis ongoing**: data analyzed for the first 2 months
- **The SDDs detectors shown an excellent long-term stability: fluctuations within 1 eV**



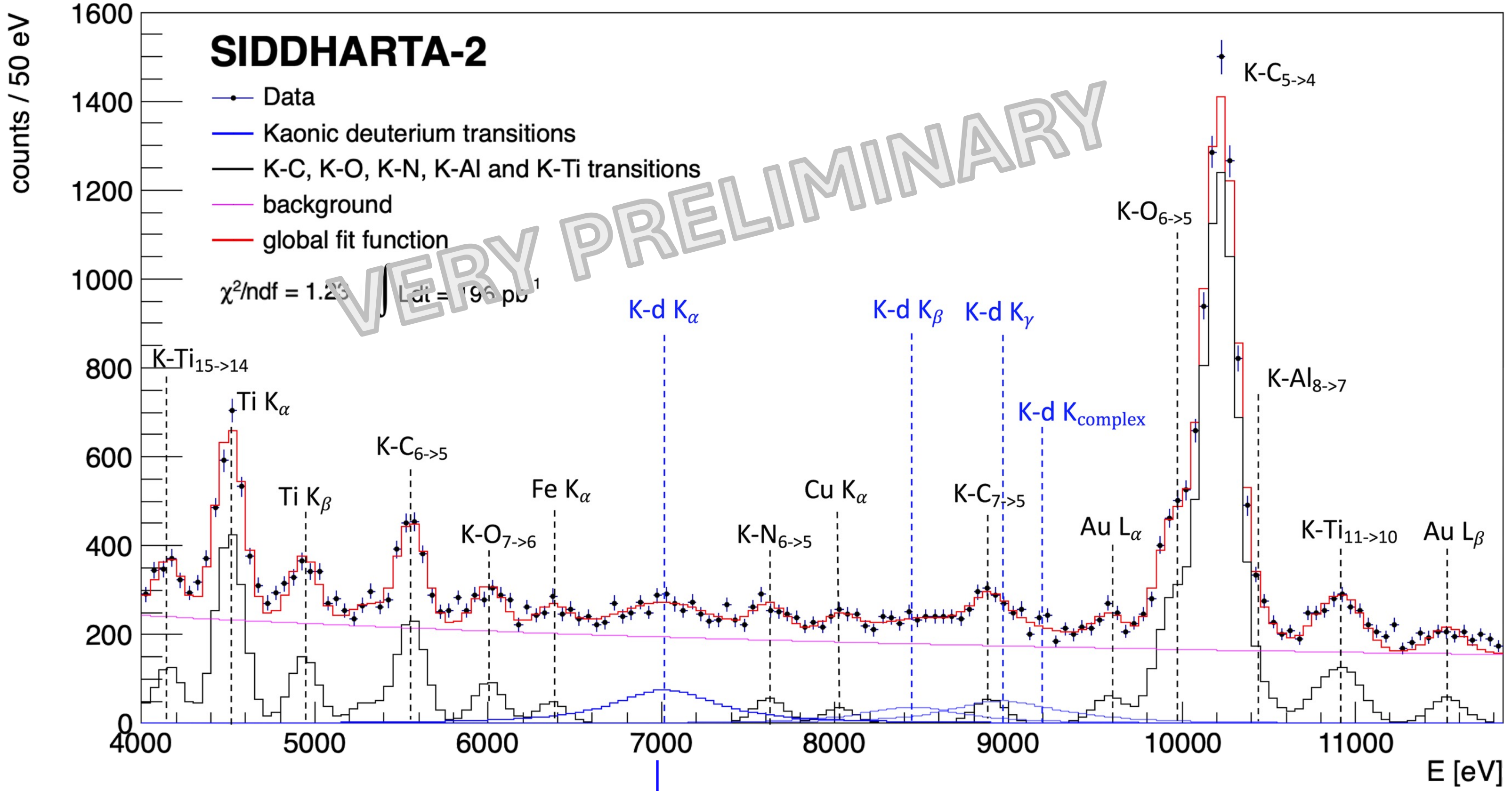
SDD Calibration Runs Analysis: summary

- ~ 20 000 calibration spectra acquired during the 4 kaonic deuterium runs

- Run-1 and Run2 calibration data analysis completed
  - ✓ Energy calibration accuracy ~ 3 eV @ 4 -10 keV range
  - ✓ Energy resolution 170 eV @ 6.4 keV
  - ✓ Long-term stability ~ 1 eV

- Run3 and low density run calibration data analysis ongoing

Kaonic Deuterium Run1: preliminary result (reminder)

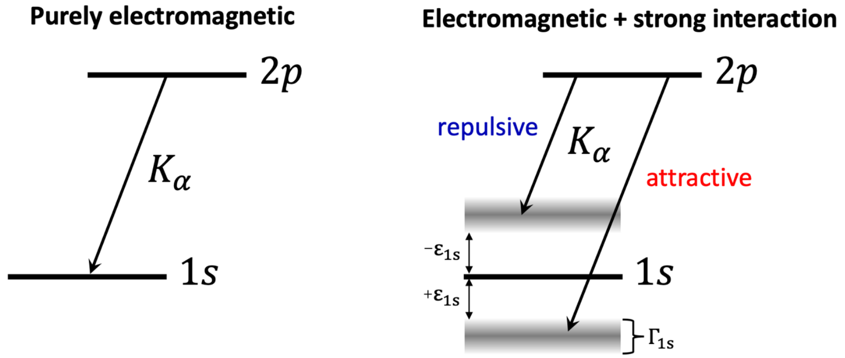


$$\varepsilon_{1s} = E^{meas}_{2p\to 1s} - E^{e.m.}_{2p\to 1s} = -816 \pm 53\ (\text{stat}) \pm 2\ (\text{syst})\ \text{eV}$$

$$\Gamma_{1s} = 756 \pm 271\ (\text{stat})\ \text{eV}$$

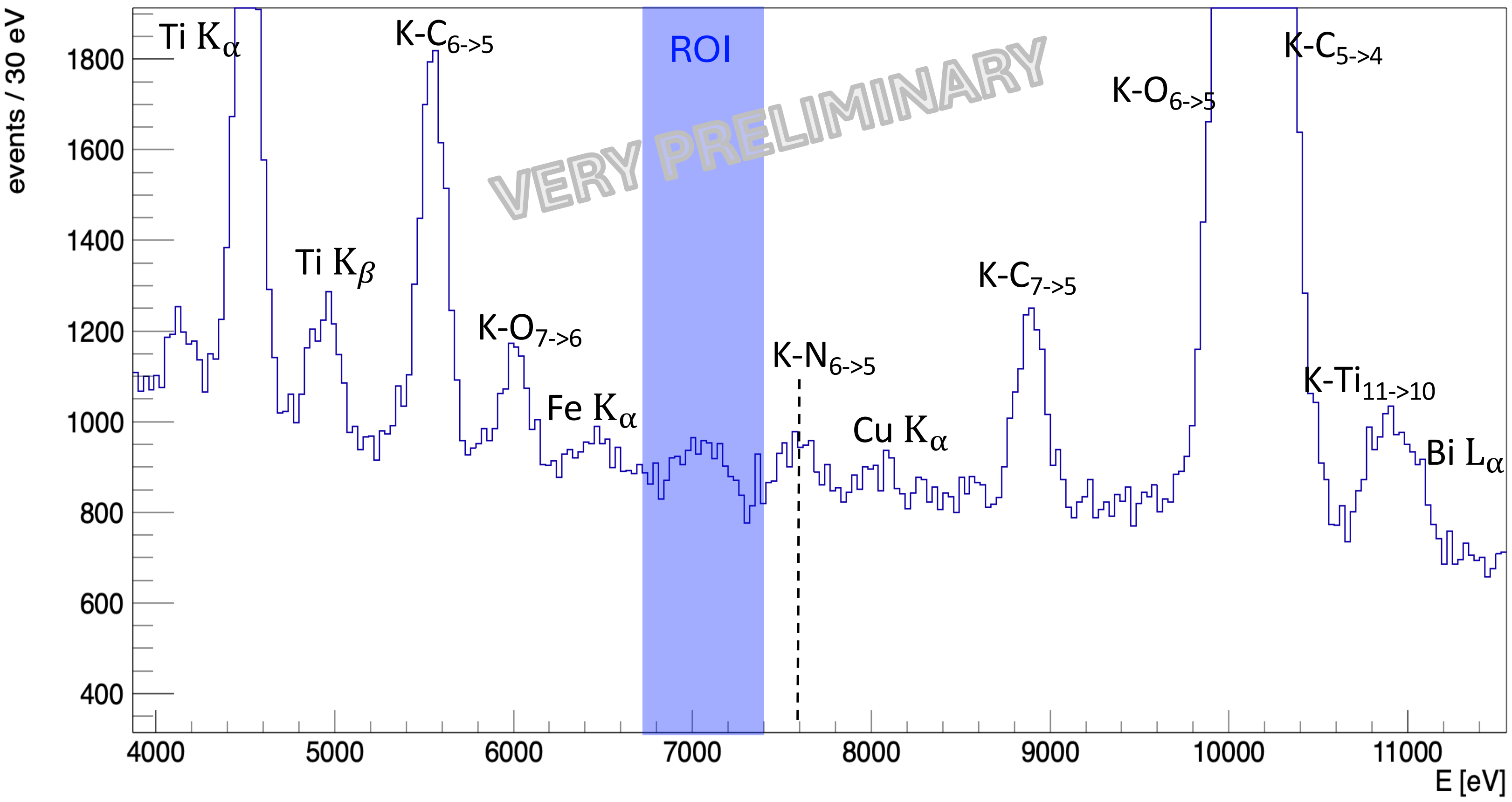
"The **most important experiment to be carried out in low energy K-meson physics today** is the **definitive determination of the energy level shifts in the K−p and K−d atoms**, because of their direct connection with the physics of $\overline{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H. Dalitz (1982)



Kaonic Deuterium analysis status

Kaonic deuterium energy spectrum (preliminary) from run1 – run2 and run3 – run 4 (low density run)



Next Step of the analysis:

- Refined calibration of Run3 and low density run data (ongoing): X-ray tube and post Kd calibration data
- Complete the run3 and low density run data selection Veto-1 to determine the origin of the signal(similar to run1 analysis)
- Fit of the energy spectrum to extract the energy shift and with

Kaonic Deuterium analysis: next steps

Short-term goals:

- Finalize the data analysis (calibration and events selection of the entire data set) ~ 6 month
  - **Evaluation of the 1s level energy shift and width and implications for the low energy QCD with strangeness**
- **Submission of an article about Kd shift and width**

Medium-long term goals:

- Evaluation of the **kaonic deuterium X-ray yield** (high and low density runs) -> article
- Evaluation of the **kaonic deuterium scattering length** (in collaboration with theoreticians) -> article
- **Combined analysis of kaonic hydrogen and deuterium** to determine the **isospin dependent antikaon-nucleon scattering lengths** (in collaboration with theoreticians) and implication for theory -> article(s)

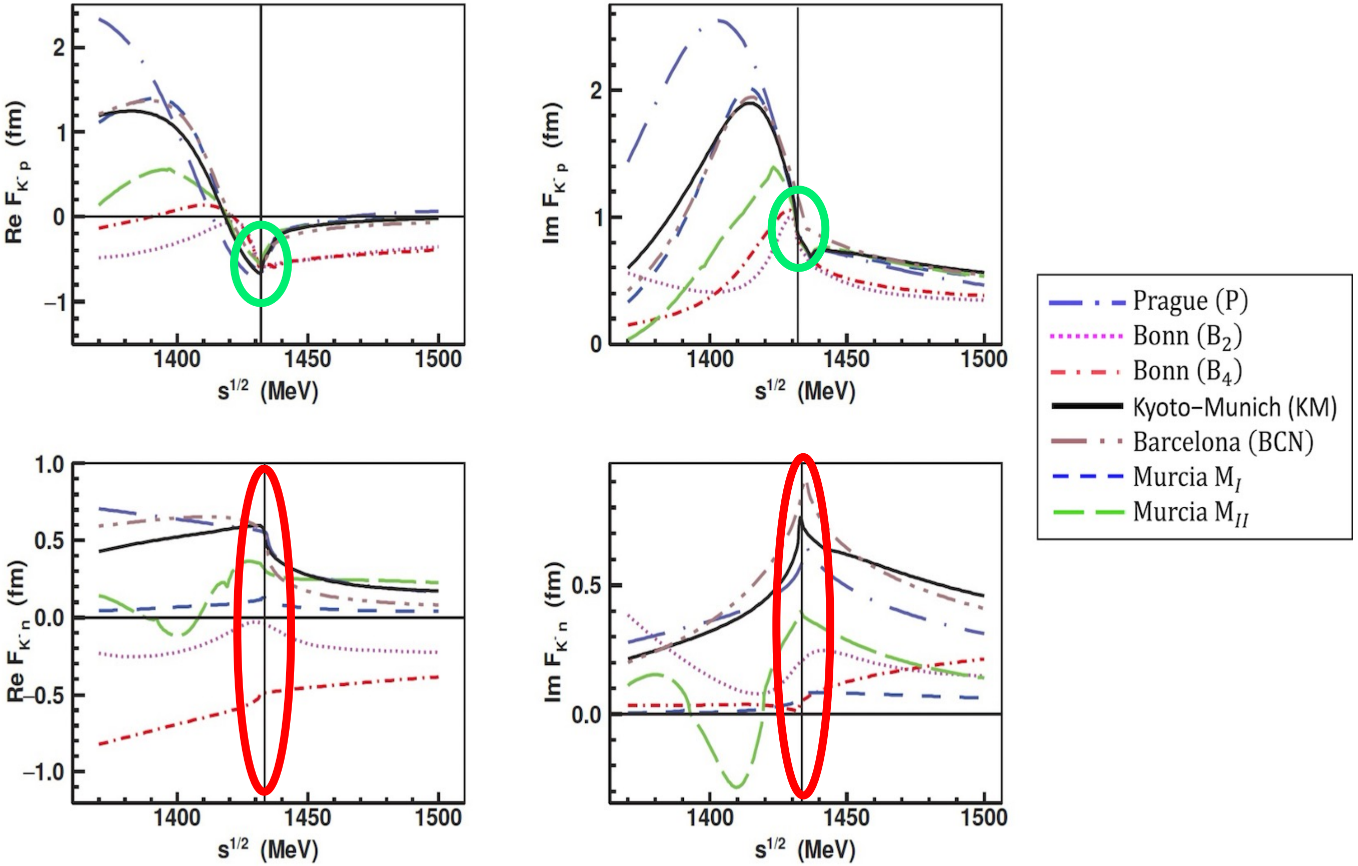
Kaonic Deuterium analysis: next steps

The combined analysis of kaonic deuterium and hydrogen will have implications in nuclear, particle and astrophysics, providing experimental inputs to solve the discrepancy between the theoretical prediction for K-n scattering amplitudes

K-p and K-n scattering amplitudes

K-p: agreement

K-n: disagreement

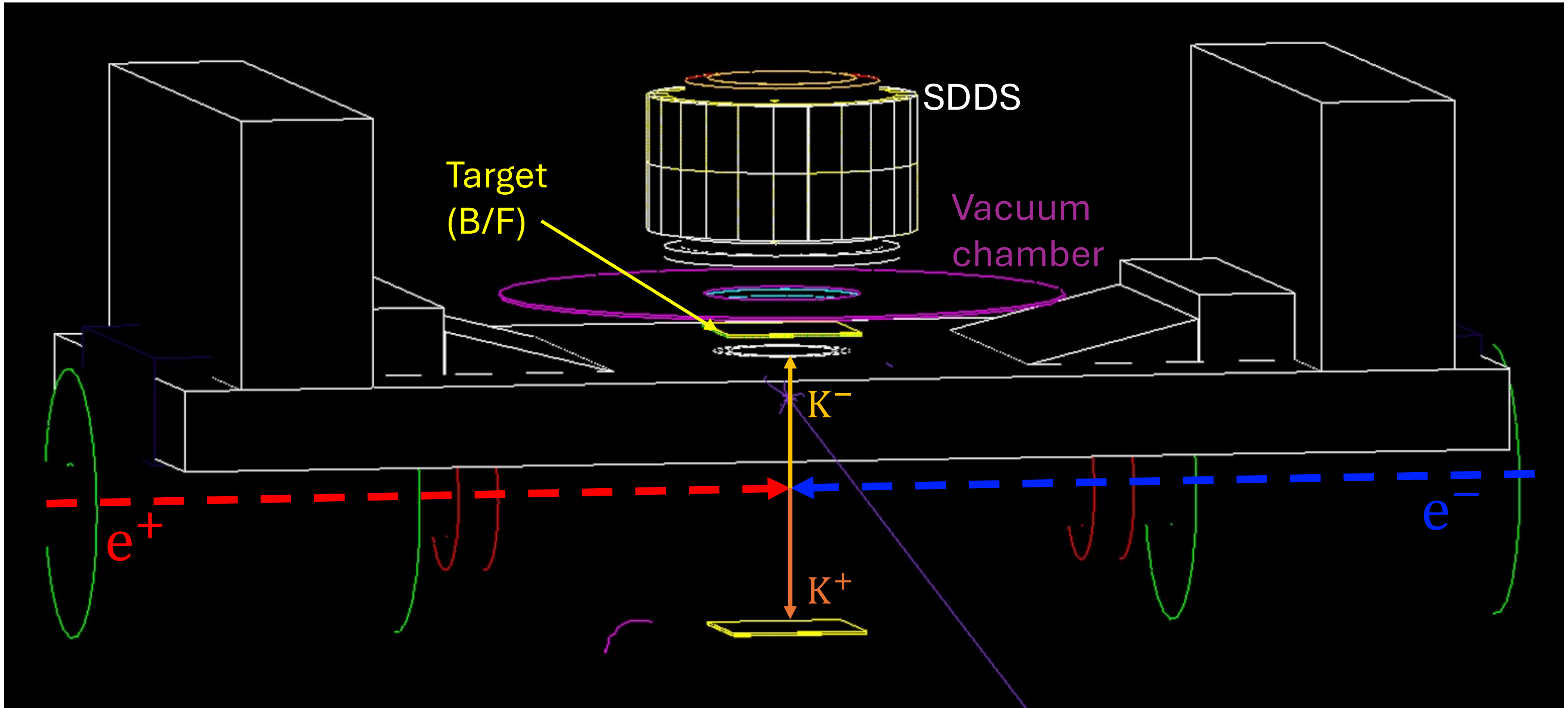


Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

Post K-d calibration run

The **final calibration was performed with two solid targets Boron and Fluorine (Teflon):**

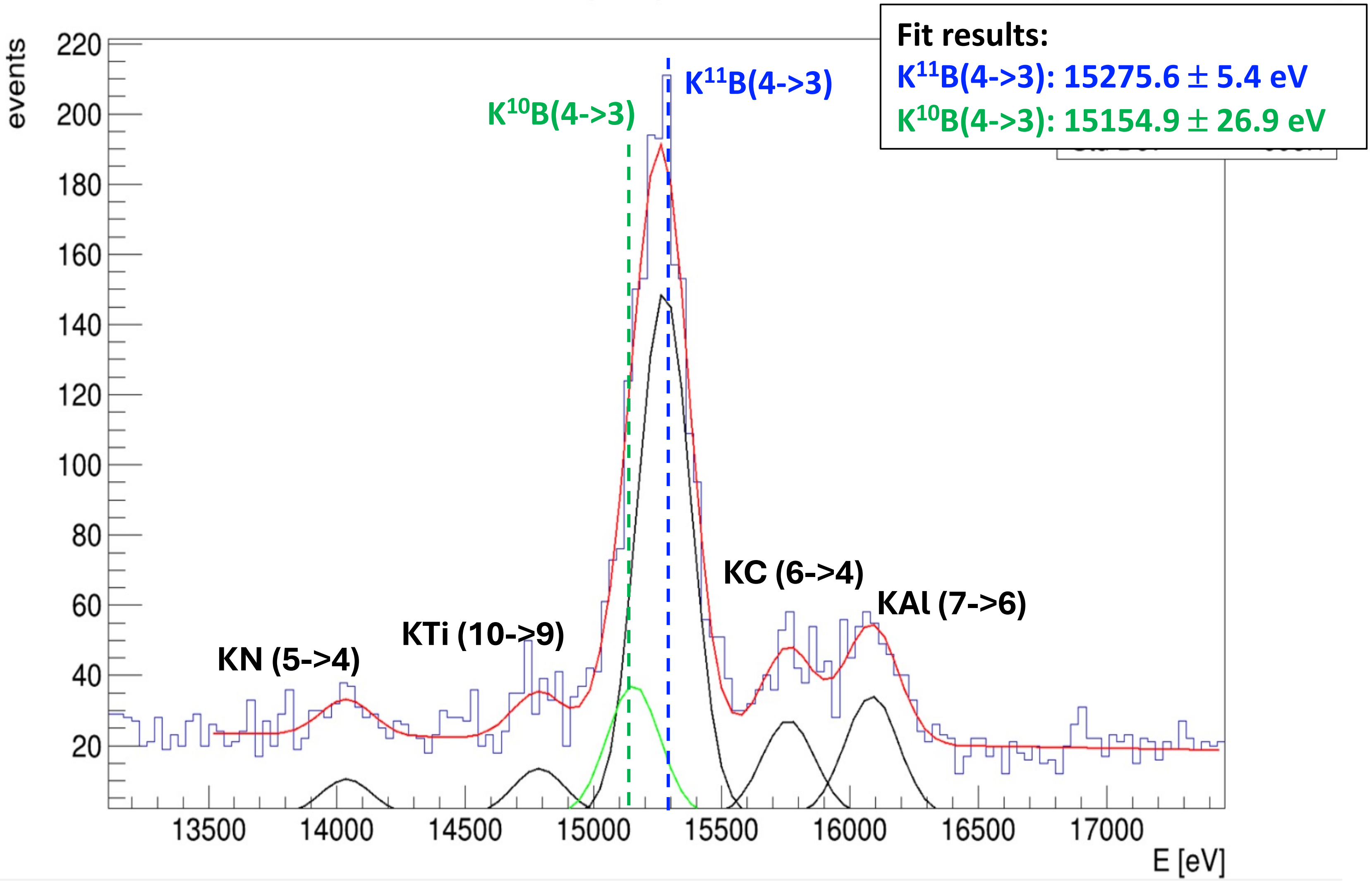
- To **exploit the last days of data taking maximizing the number of stopped kaons**
- Thanks to the **high yield of KB and KF**, it is possible to observe a signal with limited **integrated luminosity**
- **Combined with the calibration performed with the X-ray tubes** this data will be used to **check the performance of detectors and veto systems** at the end of the data taking and **to investigate the performance of the apparatus in the view of the EXKALIBUR first module**



Kaonic Boron

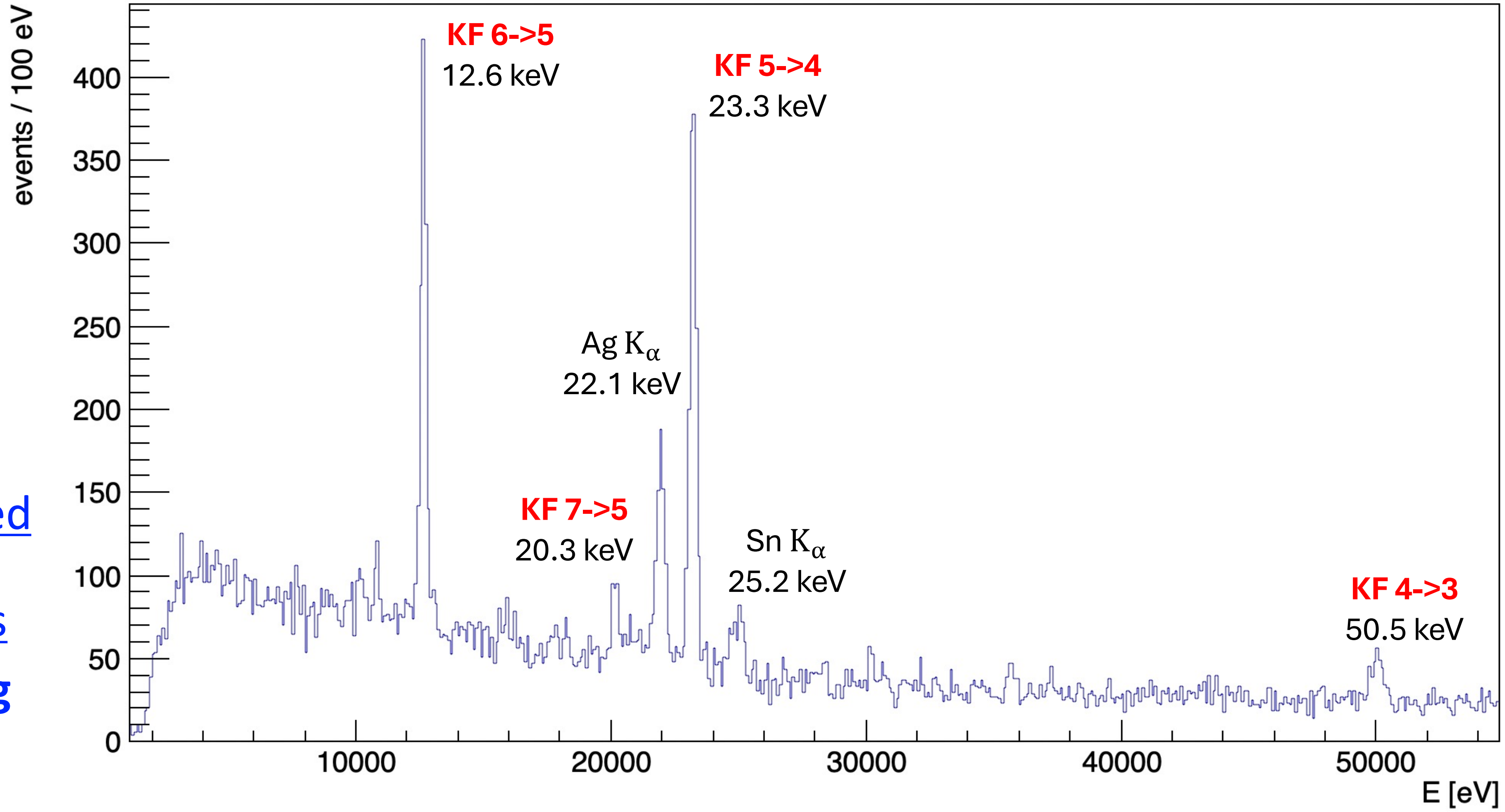
- 2 mm thick boron sheet placed in front of the window of the vacuum chamber
- Integrated luminosity 20 pb^{-1}
- Feasibility test for solid target experiment with SDDs

➢ Analysis ongoing -> article



Kaonic Fluorine

- 2 mm thick Teflon sheet
- Integrated luminosity 20 pb^{-1}
- Observed a kaonic Fluorine transition at 50 keV
- First time that SDDs have been used to perform kaonic atoms spectroscopy at such high energies
- The KF 4→3 is influenced by **strong interaction effect**



➢ Analysis ongoing -> 2 articles

Kaonic Neon: updates

We are developing/upgrading a theoretical model

(MCDFGME code written by Prof. Indelicato and Prof. Desclaux [Desclaux 9 (1975) 31-45]), originally used for muonic and antiprotonic atoms, **to calculate transition energies and yields in kaonic atoms**, taking into account corrections such as relativistic corrections, first and second-order QED effects, recoil effects, and electron screening effects.

Kaonic Ne energy transition as function of the kaon mass

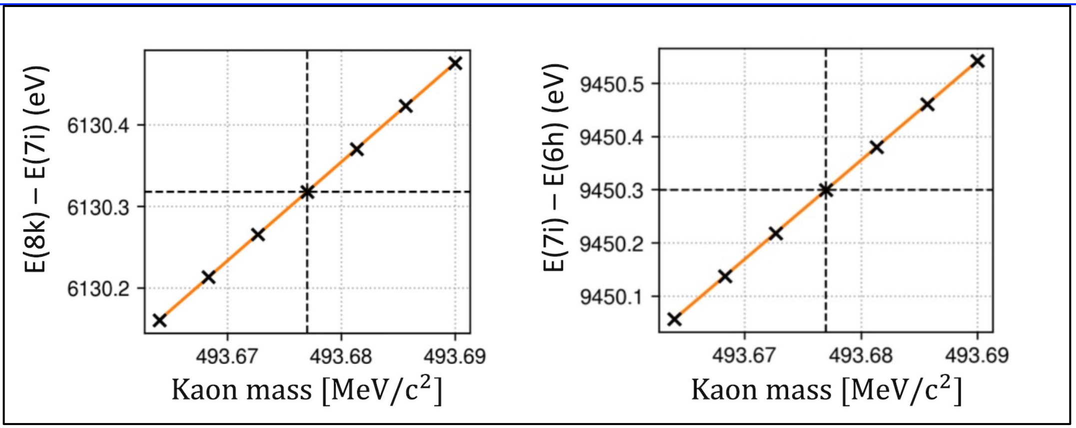
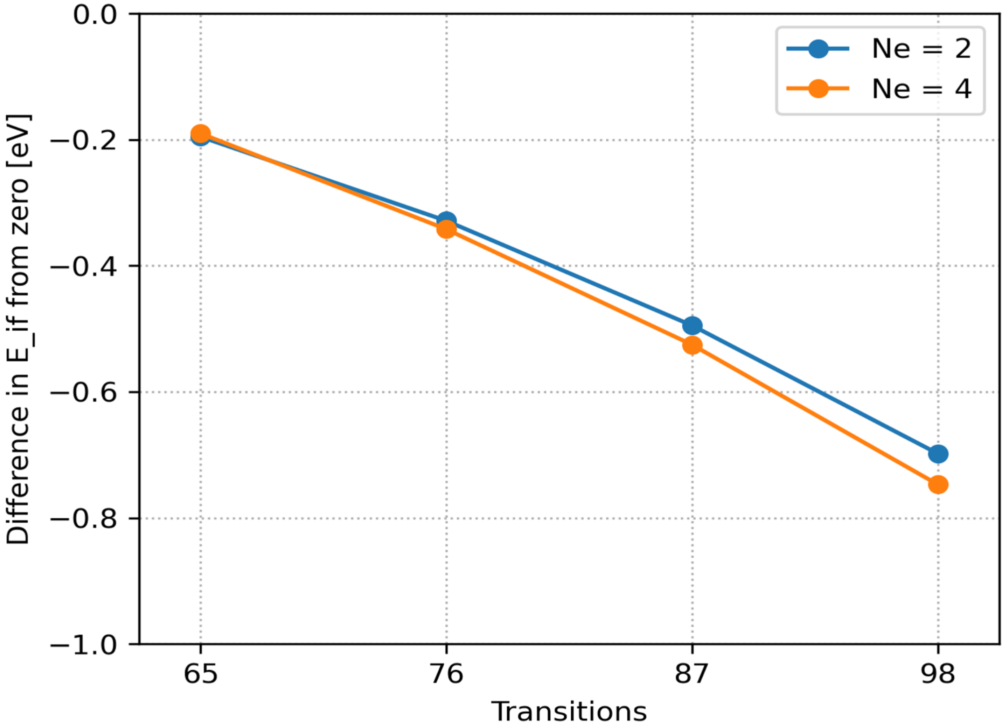


Table 1: Kaonic neon energy transitions and absolute yields at the density of 3.60 ± 0.18 g/l.

Transition	Energy [eV]	Yield
K-Ne ($10 \to 8$)	7191.21 ± 4.91 (stat) ± 2.00 (syst) eV	0.010 ± 0.001 (stat) ± 0.001 (syst)
K-Ne ($10 \to 7$)	11428.30 ± 8.37 (stat) ± 3.00 (syst) eV	0.004 ± 0.002 (stat) ± 0.001 (syst)
K-Ne ($9 \to 8$)	4206.35 ± 3.75 (stat) ± 2.20 (syst) eV	0.137 ± 0.012 (stat) ± 0.010 (syst)
K-Ne ($8 \to 7$)	6130.86 ± 0.71 (stat) ± 1.50 (syst) eV	0.228 ± 0.004 (stat) ± 0.011 (syst)
K-Ne ($7 \to 6$)	9450.08 ± 0.41 (stat) ± 1.50 (syst) eV	0.277 ± 0.002 (stat) ± 0.014 (syst)
K-Ne ($6 \to 5$)	15673.30 ± 0.52 (stat) ± 9.00 (syst) eV	0.308 ± 0.003 (stat) ± 0.015 (syst)

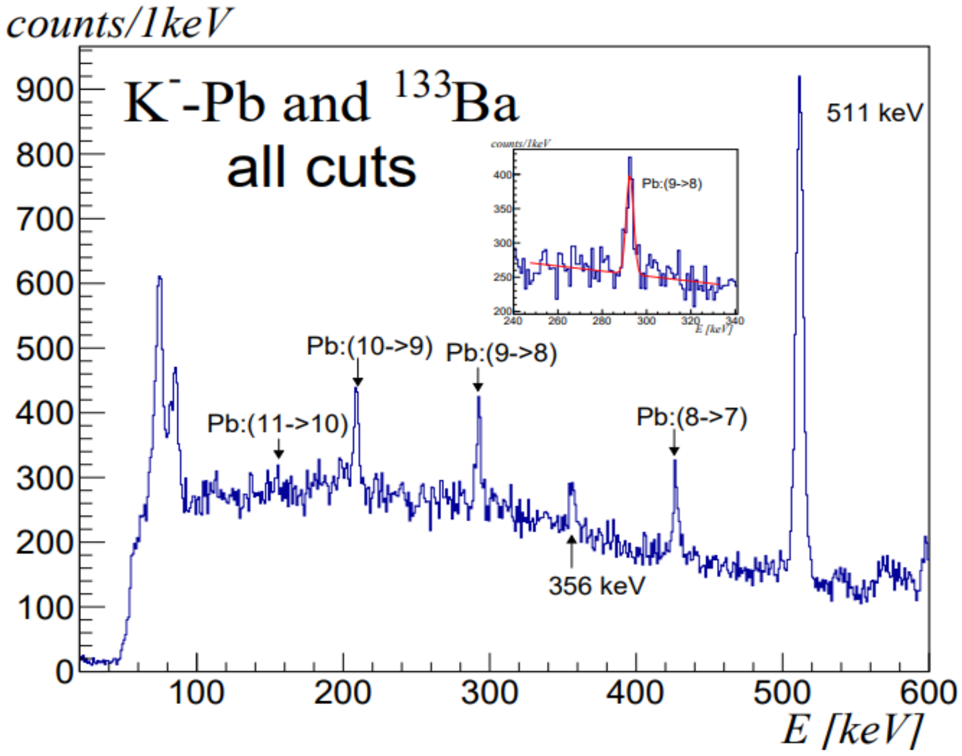
Electron screening effect in KNe for several energy transition



(provided by Simone Manti)

Kaonic Lead Measurement at DAΦNE with HPGe

First article about kaonic lead measurement at DAΦNE published



K^--Pb transition	Peak position (keV)	Resolution (FWHM) (keV)	Number of events
$10 \to 9$	208.92 ± 0.17	3.68 ± 0.42	584 ± 30
$9 \to 8$	292.47 ± 0.17	3.97 ± 0.49	770 ± 65
$8 \to 7$	427.07 ± 0.24	4.37 ± 0.54	457 ± 45

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Full Length Article

A feasibility study of the measurement of kaonic lead X-rays at DAΦNE for the precise determination of the charged kaon mass

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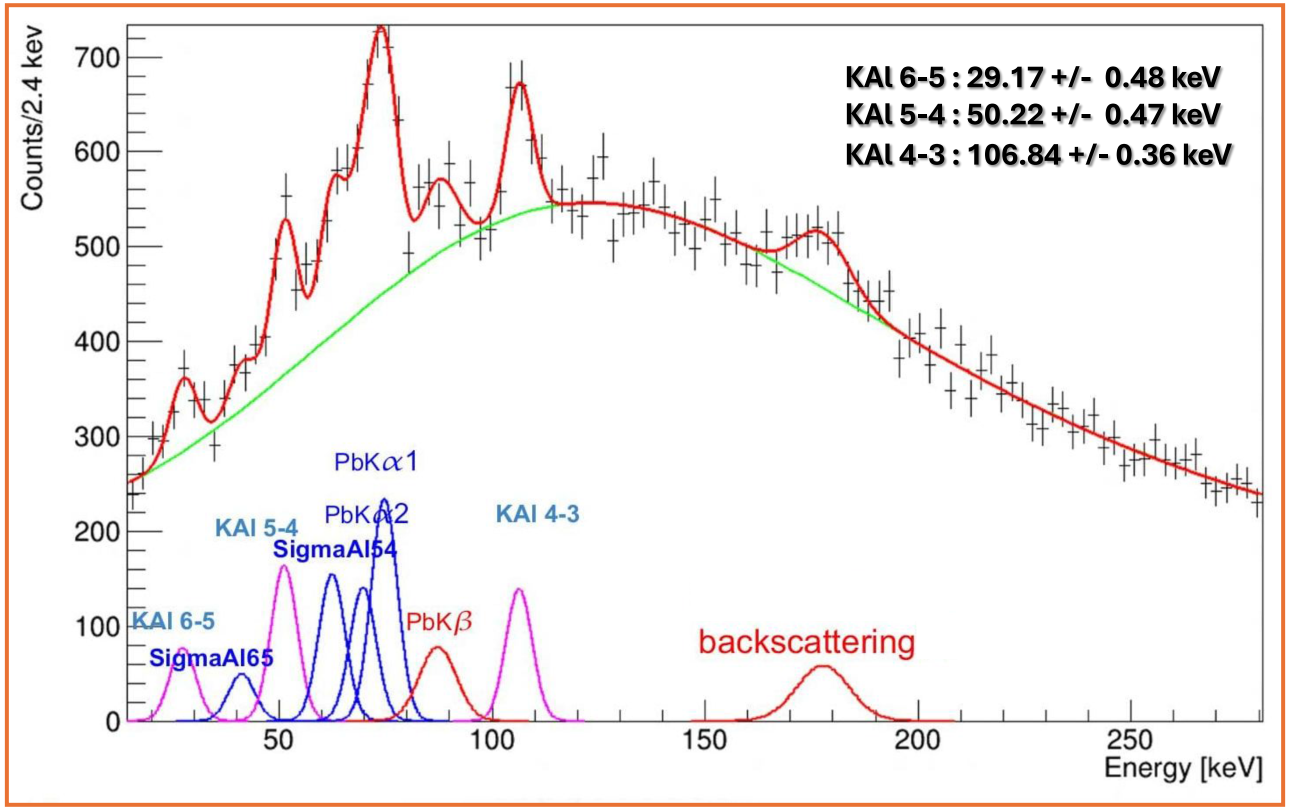
Kaonic atoms
HPGe detector
Fast pulse digitizer

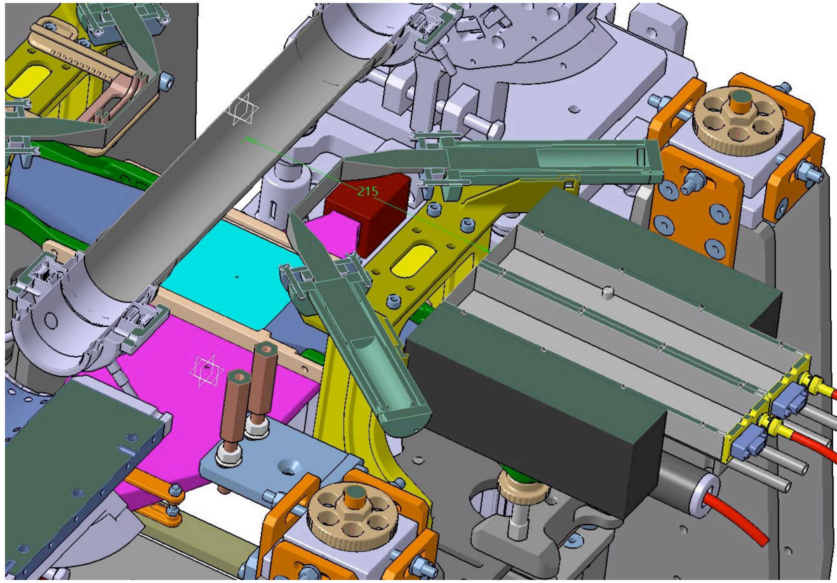
ABSTRACT

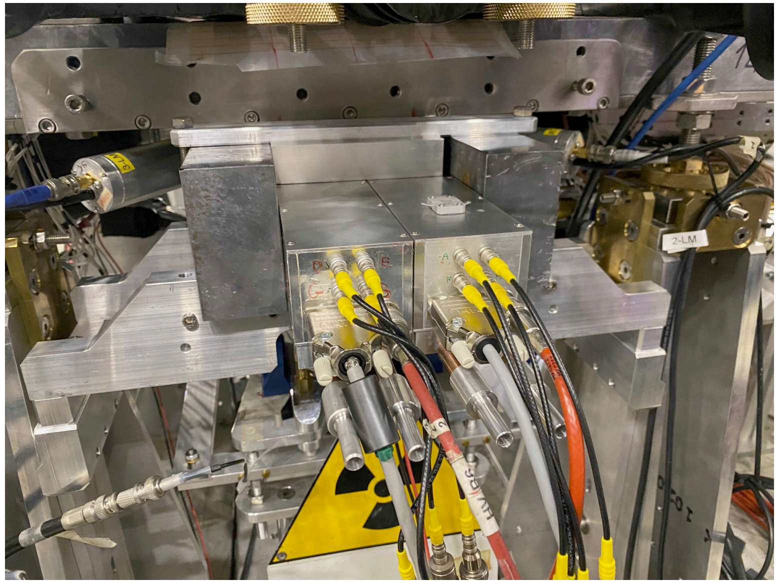
An HPGe detector equipped with a transistor reset preamplifier and readout with a CAEN DT5781 fast pulse digitizer was employed in the measurement of X-rays from kaonic lead at the DAΦNE e^+e^- collider at the Laboratori Nazionali di Frascati of INFN. A thin scintillator in front of a lead target was used to select kaons impinging on it and to form the trigger for the HPGe detector. We present the results of the kaonic lead feasibility measurement, where we show that the resolution of the HPGe detector in regular beam conditions remains the same as that without the beam and that a satisfactory background reduction can be achieved. This measurement serves as a test bed for future dedicated kaonic X-rays measurements for the more precise determination of the charged kaon mass.

CdZnTe system: update

First kaonic atoms' spectrum measured with CZT detectors



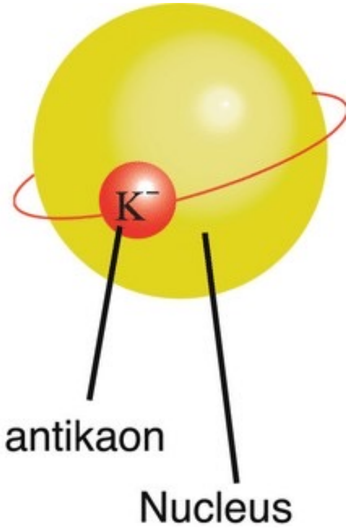




➢ **CdZnTe detectors are easy to be used in parallel with already existing experiments requiring very small space and not invasive electronics**

EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

EXKALIBUR



67th Scientific Committee Recommendation:

*The Scientific Committee considers that the first module of the **EXKALIBUR experiment is a very interesting scientific proposal of great value and merit**, although its final realization depends, of course, on the operational situation of DAΦNE. **Our recommendation is that it may be worth studying whether there is a possibility to carry out the first part of the module** (8 weeks of dedication on gaseous Ne target) after the PADME Run IV are completed and in compatibility with other construction activities.*

[Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements,](#)
C. Curceanu et al., Front.in Phys. 11 (2023) 1240250

Future plans - EXKALIBUR

EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

- **Feasibility** with **minimal modifications/addings** of the already existent SIDDHARTA-2
  - New calibration system (0.2 eV accuracy)
  - New 1mm thick SDDs
  - New and improved CZT setup
  - Ready from September 2025
- **Impact**: i.e. the **maximal scientific outcome**

FIRST MODULE

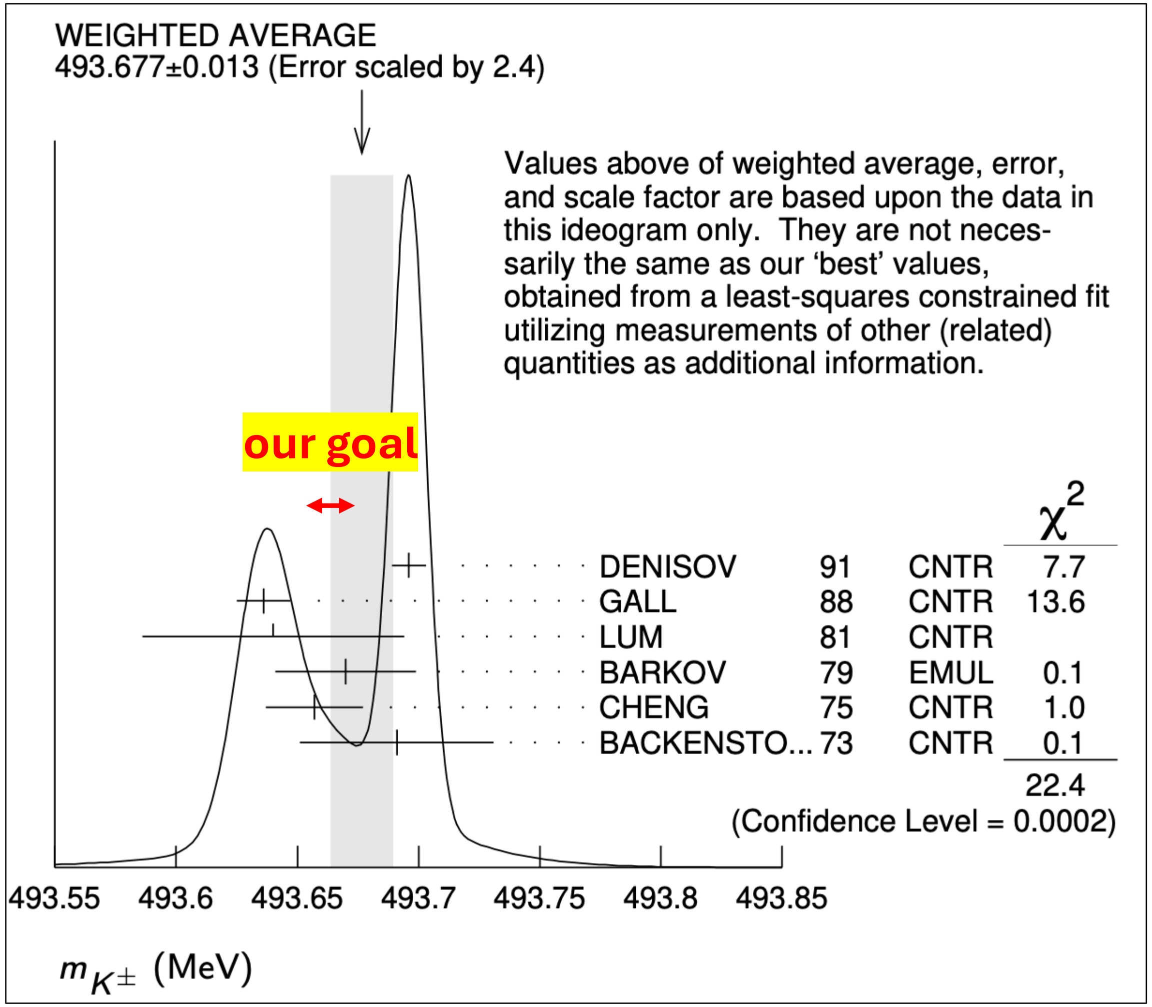
1.1 - Kaon mass by Kaonic neon measurement
- Use the SIDDHARTA2 setup
- Minimal modification
– new calibration system
- 300 pb^{-1} of integrated luminosity

1.2 - Light kaonic atoms (LHKA)
- Use the SIDDHARTA2 setup
– solid target Li, Be, B
- Minimal modification of the target
– integration of 1mm SDD
- 200 pb^{-1} of integrated luminosity

Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs for kaonic atoms (*O, Al, S*) with different types of detectors:
CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

1.1 - Kaon mass by Kaonic neon measurement
- Use the SIDDHARTA2 setup
- 300 pb^{-1} of integrated luminosity

The charged kaon mass puzzle



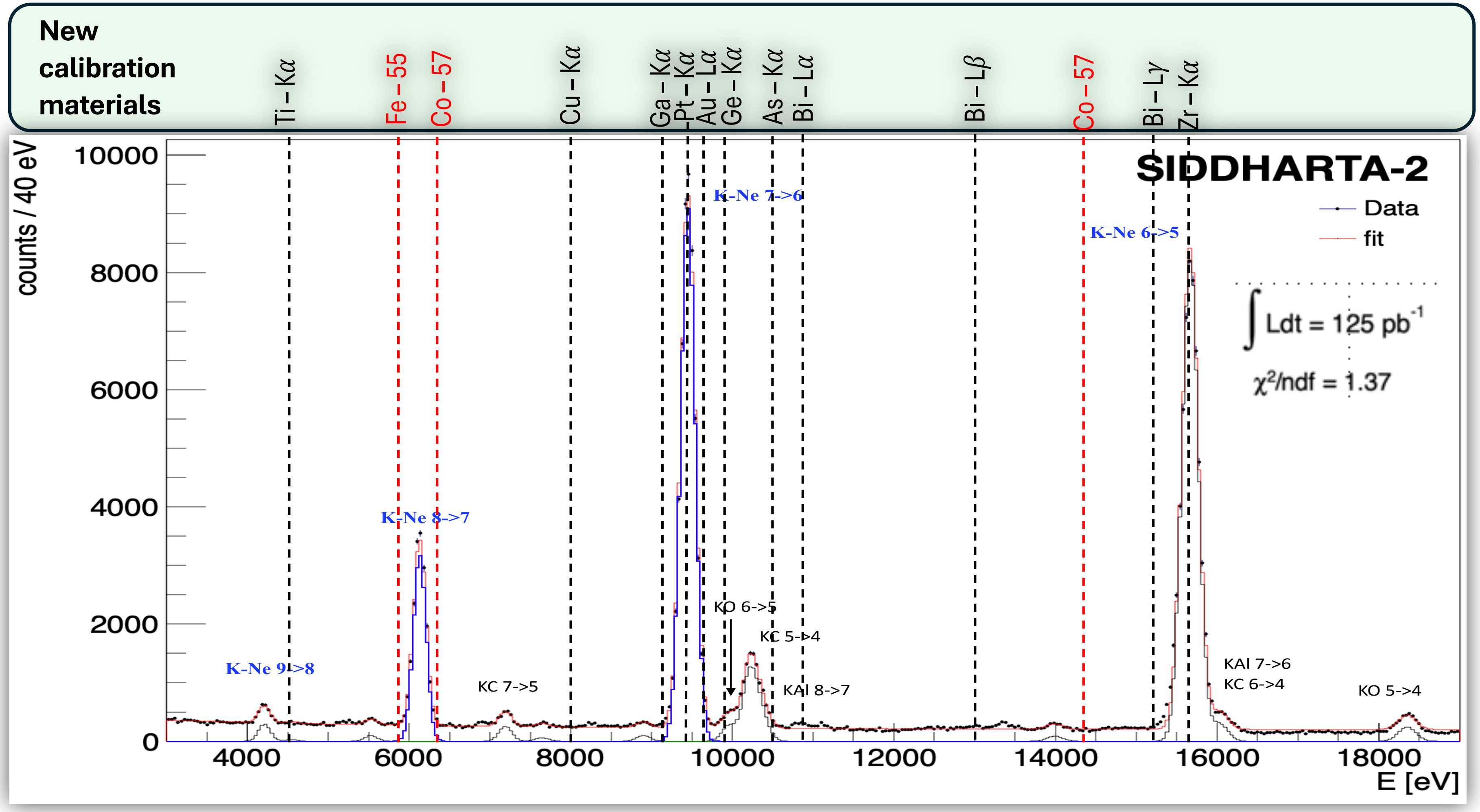
- The first measurement we plan doing is the **kaonic neon** high-n levels transition with precisions below 1 eV, **to extract the charged kaon mass with a precision of about 5 keV**.

- By using a **gaseous target**, we can resolve the ambiguity in the charged kaon mass de-termination, providing **a new precise value through the measurement of kaonic neon high-n transitions**. Moreover, the measurement also provides **a precision test of QED in atomic systems with strangeness** (BSQED).

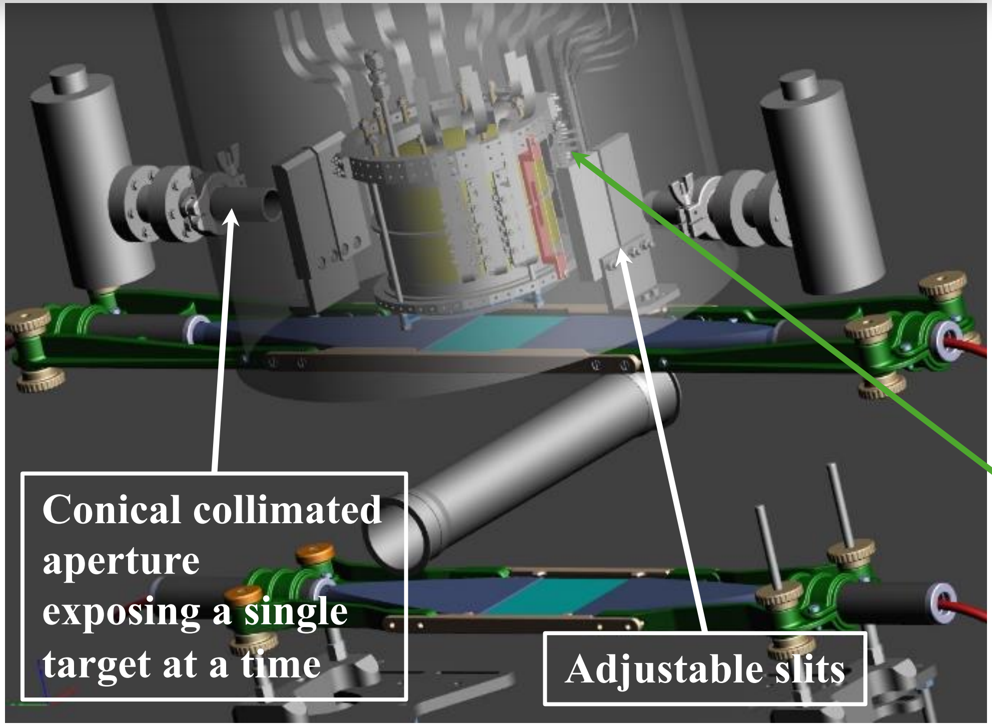
1.1 - Kaon mass by Kaonic neon measurement
- Use the SIDDHARTA2 setup
- 300 pb^{-1} of integrated luminosity

Transition	Energy [eV]
K-Ne $(9 \to 8)$	4206.35 ± 3.75 (stat) ± 2.00 (syst) eV
K-Ne $(8 \to 7)$	**6130.86 ± 0.71 (stat) ± 1.50 (syst) eV**
K-Ne $(10 \to 8)$	7191.21 ± 4.91 (stat) ± 2.00 (syst) eV
K-Ne $(7 \to 6)$	**9450.08 ± 0.41 (stat) ± 1.50 (syst) eV**
K-Ne $(10 \to 7)$	11428.30 ± 8.37 (stat) ± 3.00 (syst) eV
K-Ne $(6 \to 5)$	**15673.30 ± 0.52 (stat) ± 9.00 (syst) eV**

Kaonic neon (2023)



1.1 - Kaon mass by Kaonic neon measurement
- Use the SIDDHARTA2 setup
- Minimal modification (integration of 1mm SDDs)
– new calibration system financed and under construction

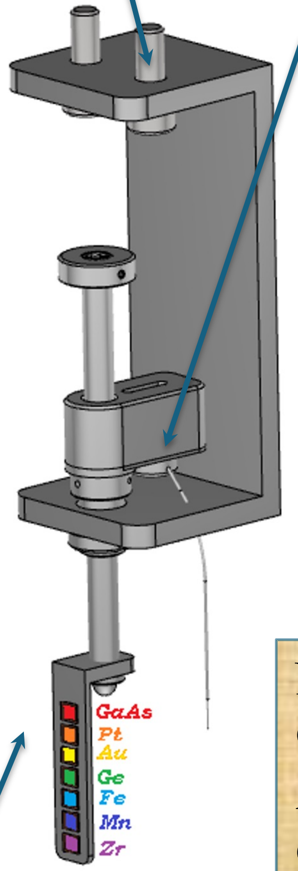


External Laser system
for alignment Fluke PLS 6G RBP SYS

Modifying the calibration target system from 3 fixed to 7 movable fluorescent foils

Holding structure

The 8303-V Vacuum Compatible Picomotor™ Actuator

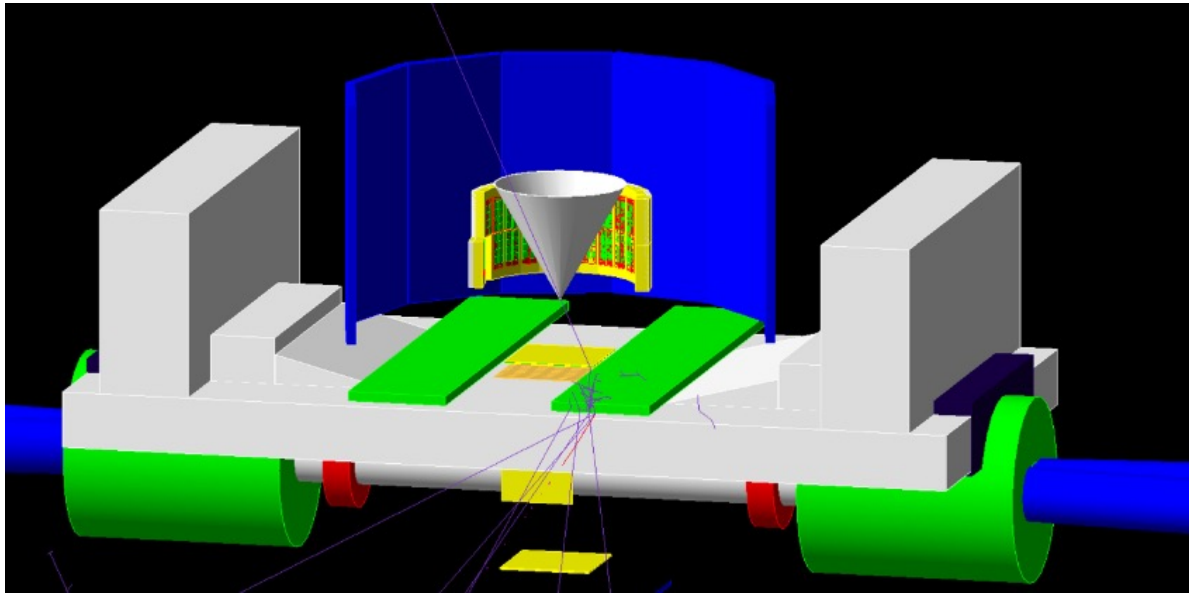


New calibration materials
Ga (Ka 9243 eV)
As (Ka 10532 eV)
Ge (Ka 9876 eV)
Au (La 9685 eV)
Pt (La 9416 eV)

Movable targets arm inserted behind the collimator.
Selected materials: GaAs, Pt, Au, Ge, Fe, Mn, Zr

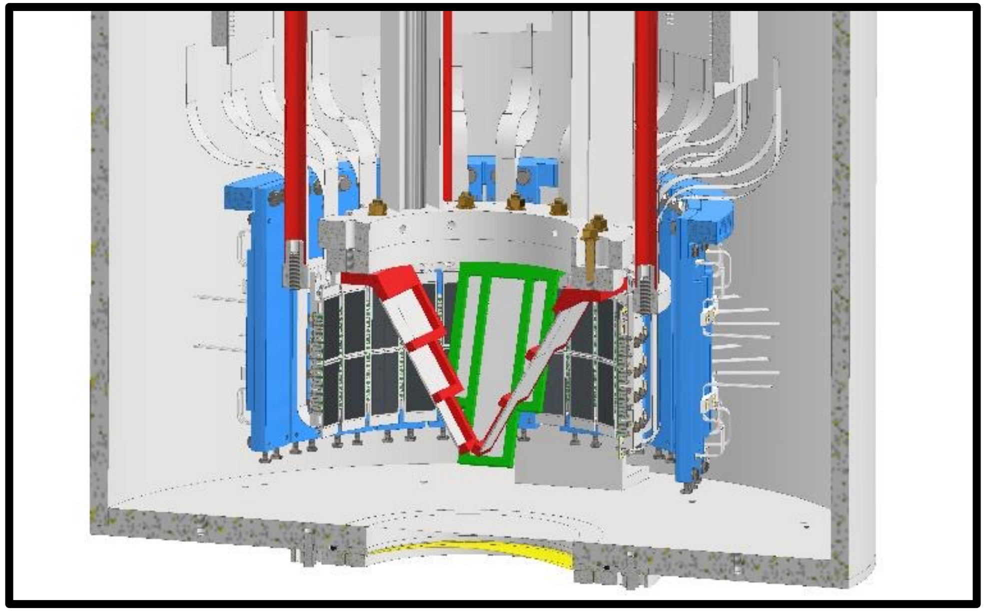
1.2 - Light kaonic atoms (LHKA)
- Use the SIDDHARTA2 setup
– solid target Li, Be, B
- Add 1 mm thick SDDs
- 200 pb^{-1} of integrated luminosity

Lithium-6		Lithium-7		Beryllium-9	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
3 → 2	**15.085**	**3 → 2**	**15.261**	**3 → 2**	**27.560**
4 → 2	**20.365**	**4 → 2**	**20.603**	**4 → 3**	**9.646**
5 → 2	**22.809**	**5 → 2**	**23.075**	**5 → 3**	**14.111**
4 → 3	5.280	4 → 3	5.341	5 → 4	4.465
5 → 3	7.724	5 → 3	7.814	6 → 4	6.890
5 → 4	2.444	5 → 4	2.472	6 → 5	2.425
6 → 4	3.771	6 → 4	3.815		



Solid targets system

- Construction of new support system
- conical shape to maximize the solid angle
- MC simulations ongoing
- material procurement done



Boron-10		Boron-11	
Transition	Energy (keV)	Transition	Energy (keV)
3 → 2	**43.568**	**3 → 2**	**43.768**
4 → 3	**15.156**	**4 → 3**	**15.225**
5 → 3	**22.171**	**5 → 3**	**22.273**
5 → 4	7.015	5 → 4	7.047
6 → 4	10.826	6 → 4	10.875
6 → 5	3.811	6 → 5	3.828

1.2 - Light kaonic atoms (LHKA)
- Use the SIDDHARTA2 setup
– integration of 1mm SDD

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati
POLITECNICO MILANO 1863
FONDAZIONE BRUNO KESSLER

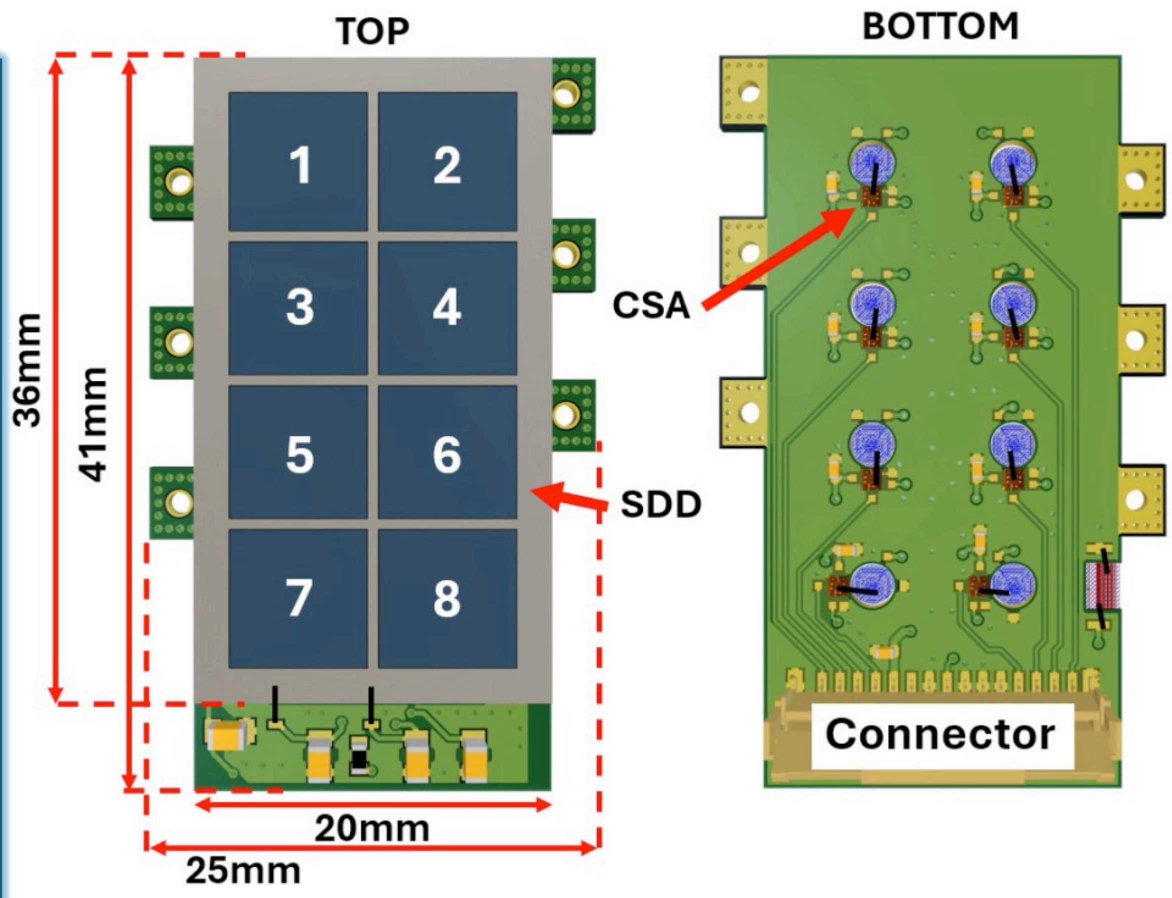
1 mm thick Silicon Drift Detectors

New SDD modules produced at **FBK**:

- 2 X 4 matrix, pixel dimensions: 7.9 mm X 7.9 mm
- Special features: new **focusing electrode** on the **window** to **reduce charge sharing**
- **Very good Leakage** Current Density @ 24°C:
- **1-mm-thick SDDs: ~ 0.5-2 nA/cm^2**

New detection module design developed for experiment upgrade.

- **PCB dimensions enlarged** to host a wider SDD chip
  PCB material changed from ceramic to more standard material in order to move from a 2-layer structure to a **6-layer structure**, to improve signal integrity and to reduce noise and cross-talk problems



1.2 - Light kaonic atoms (LHKA)
- Use the SIDDHARTA2 setup
– integration of 1mm SDD

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FONDAZIONE BRUNO KESSLER

1 mm thick Silicon Drift Detectors: Energy response

Spectroscopic measurements with a first prototype:

- irradiation with an ^{55}Fe X-ray source;
- detector temperature: -30° C;
- spectra acquired with SFERA chip;
- Best energy resolution of 140.5 eV FWHM @ 5.9 keV (Mn K_α)

Jinst
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Development of high-efficiency X-ray detectors based on 1 mm thick monolithic SDD arrays

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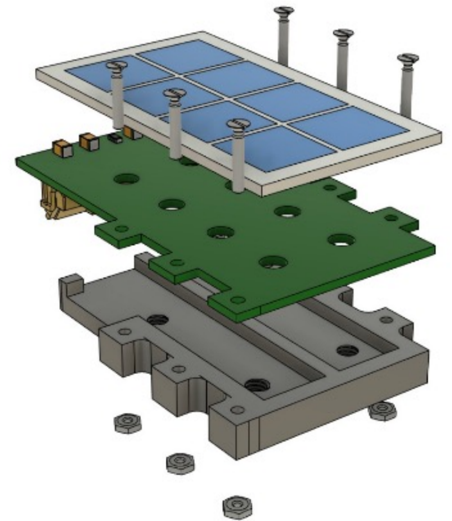
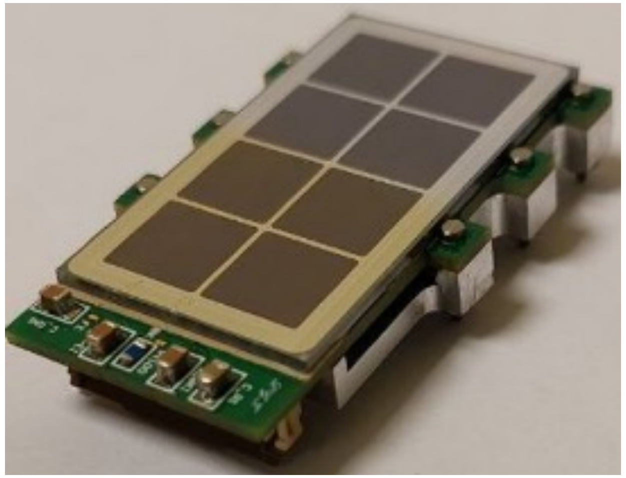
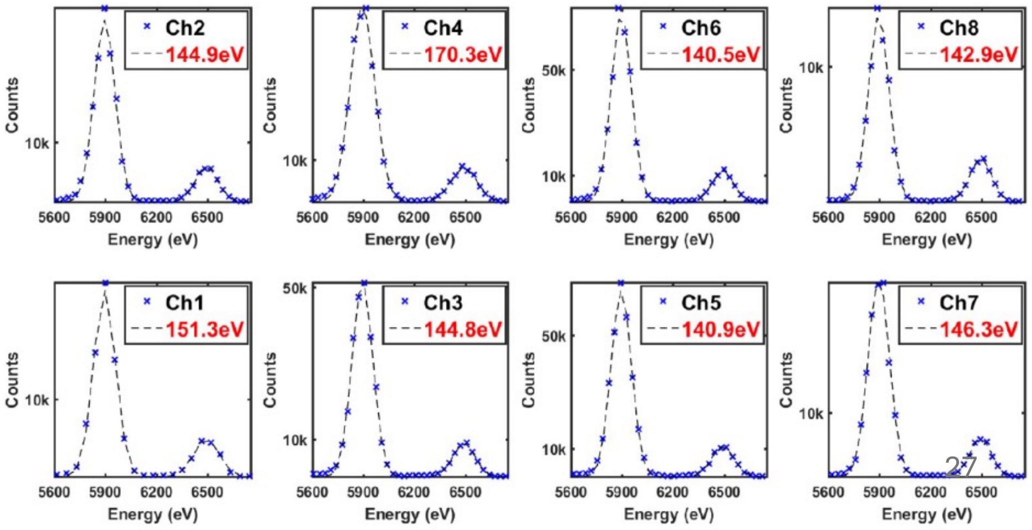




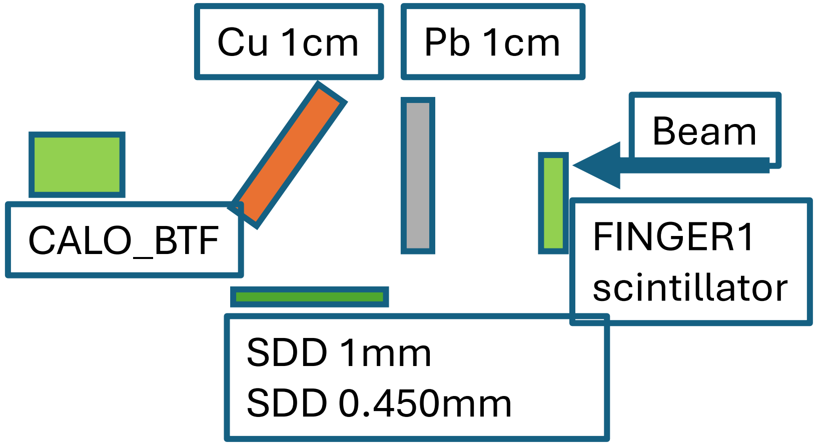


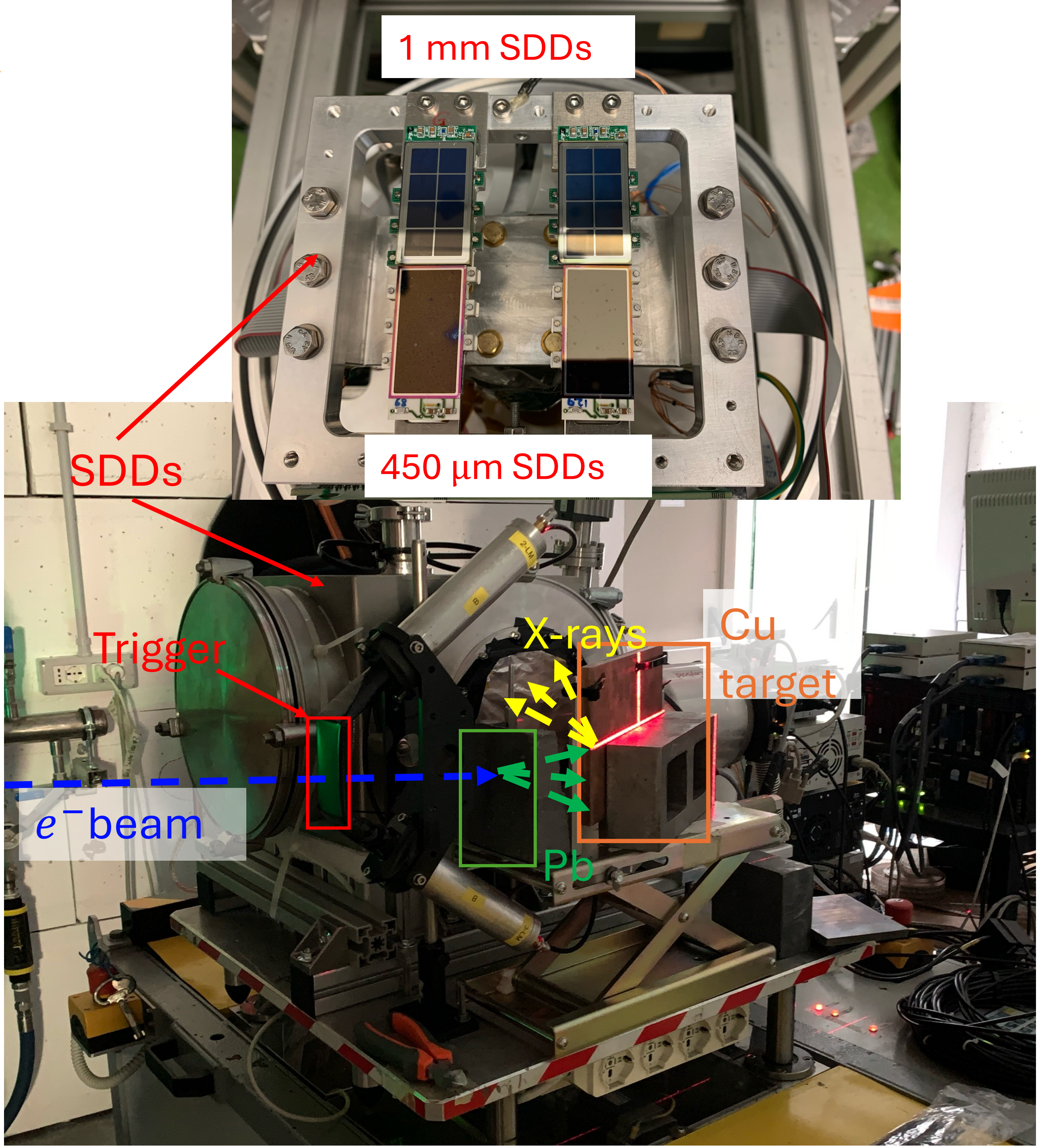
Characterization of 1 mm thick Silicon Drift Detectors at BTF

Spectroscopic measurement with first module by LNF group

- ❖ Dedicated beam time in June and October 2024 at BTF
- ❖ Irradiation with e^- beam and X-ray sources

- Characterization of the 1 mm SDDs **time response** as function of the temperature
- Characterization of the **energy response: new energy range 50 keV**
- Study of the **energy response in a high background environment** (ionizing particles and radiation)



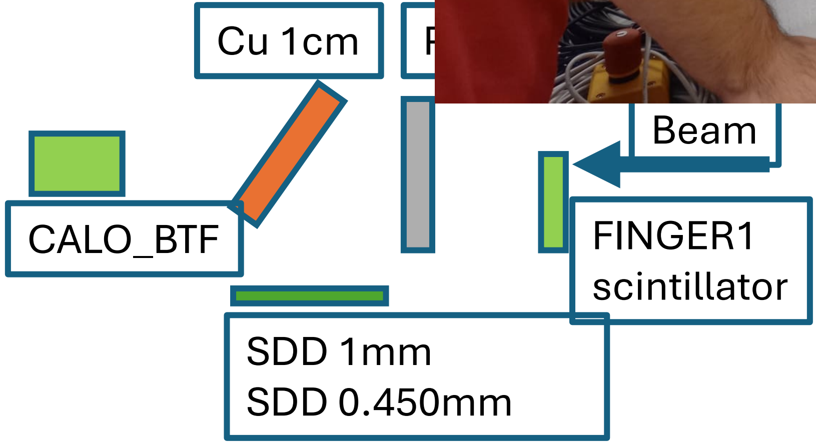


Characteriz
Silicon Drif

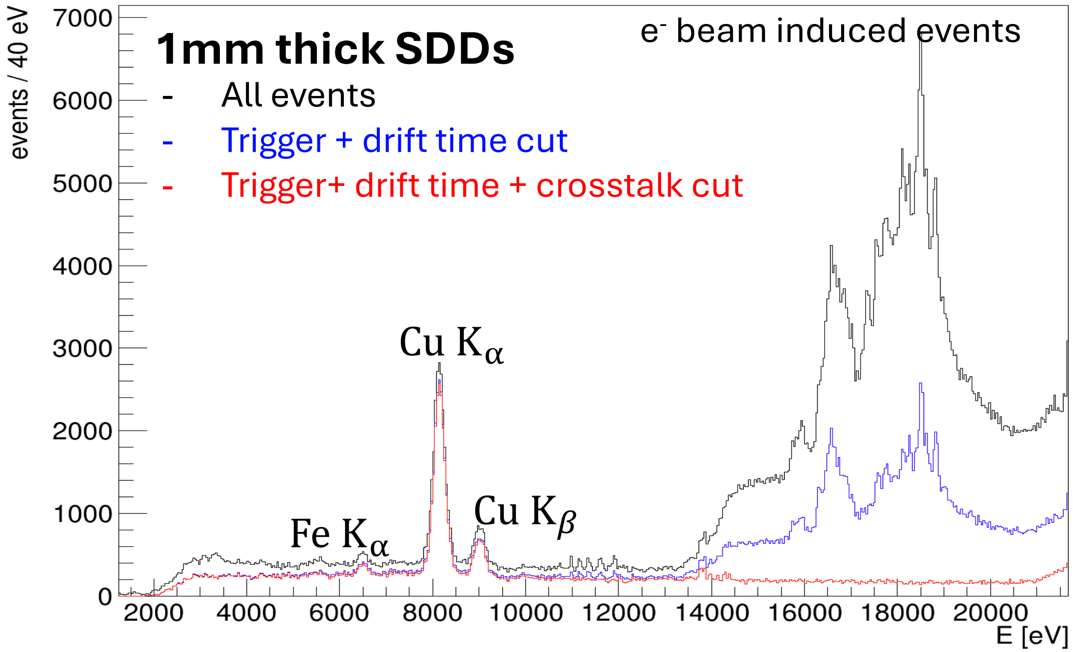
Spectroscopic measureme group

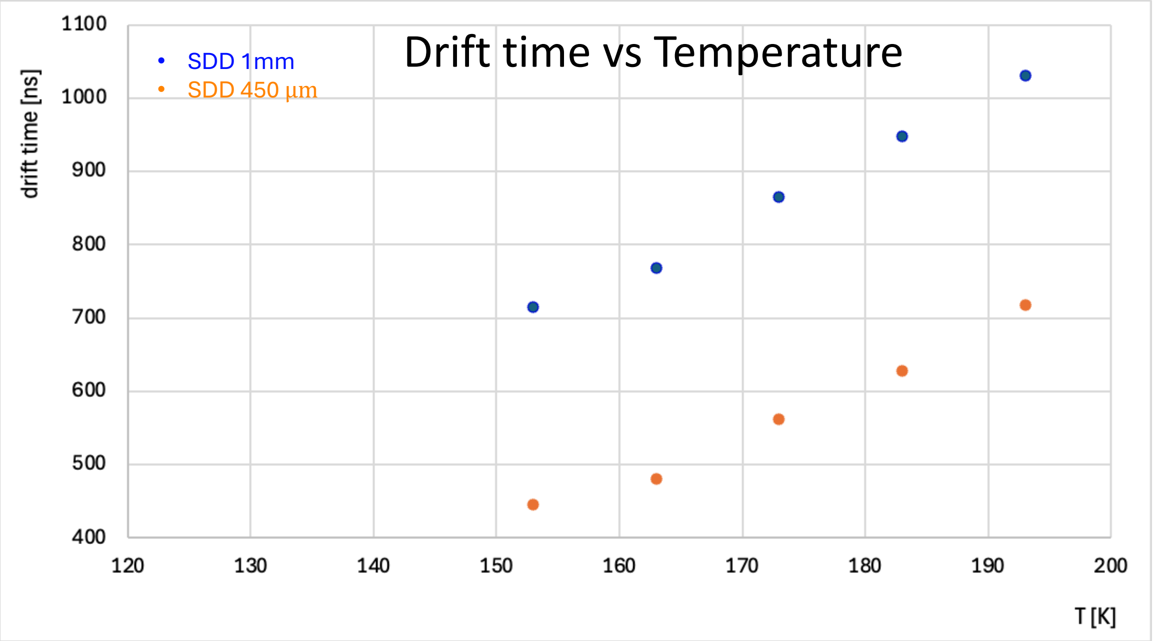
- ❖ Dedicated beam time in
- ❖ Irradiation with e⁻

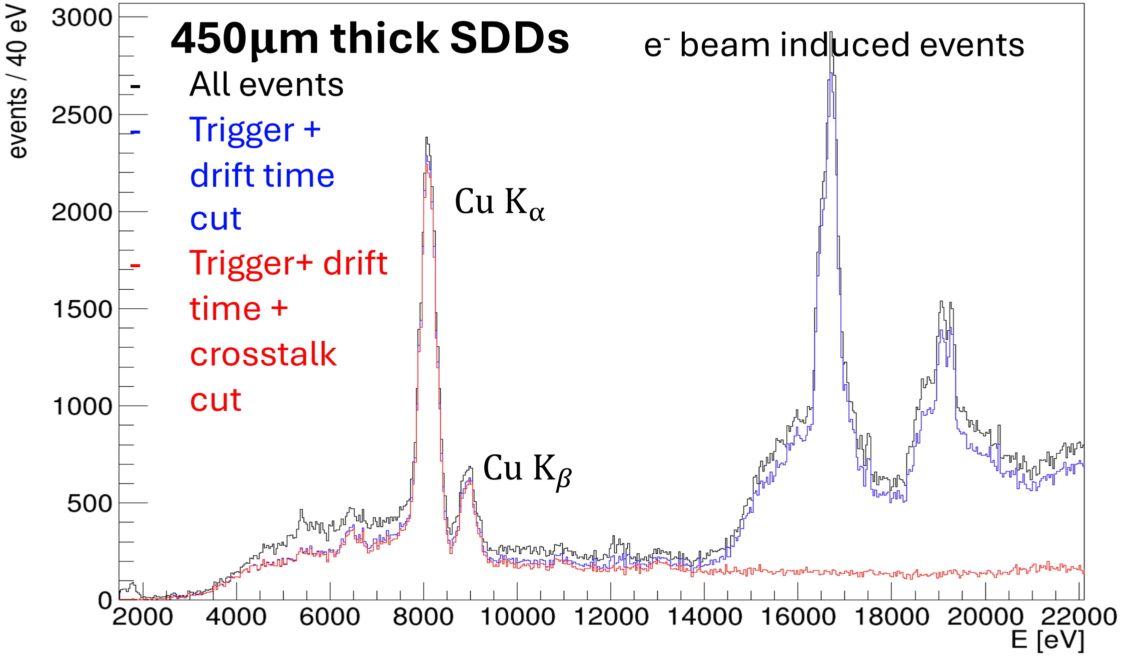
- Characterization of the function of the tempera
- Characterization of **new energy range 50 ke**
- Study of the **energy re environment** (ionizing p

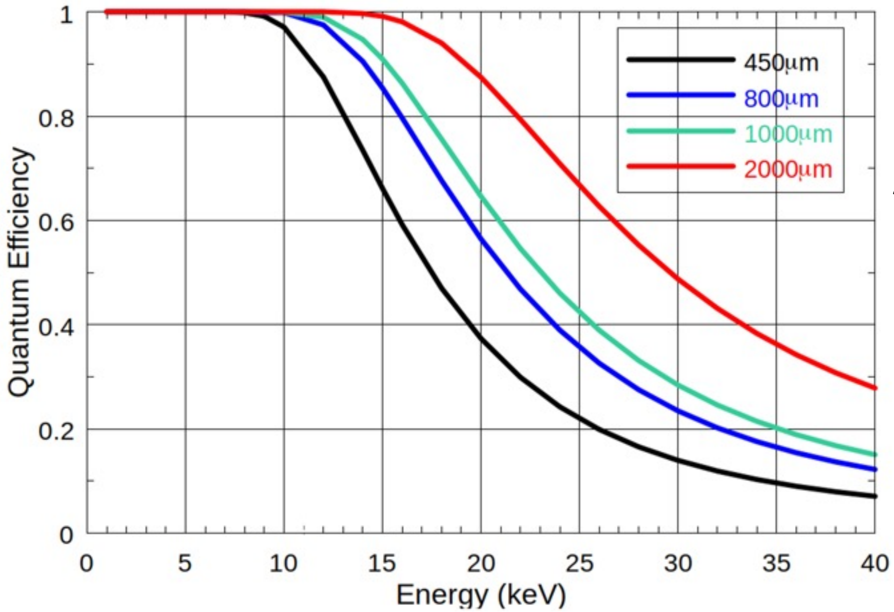


Characterization of 1 mm thick Silicon Drift Detectors







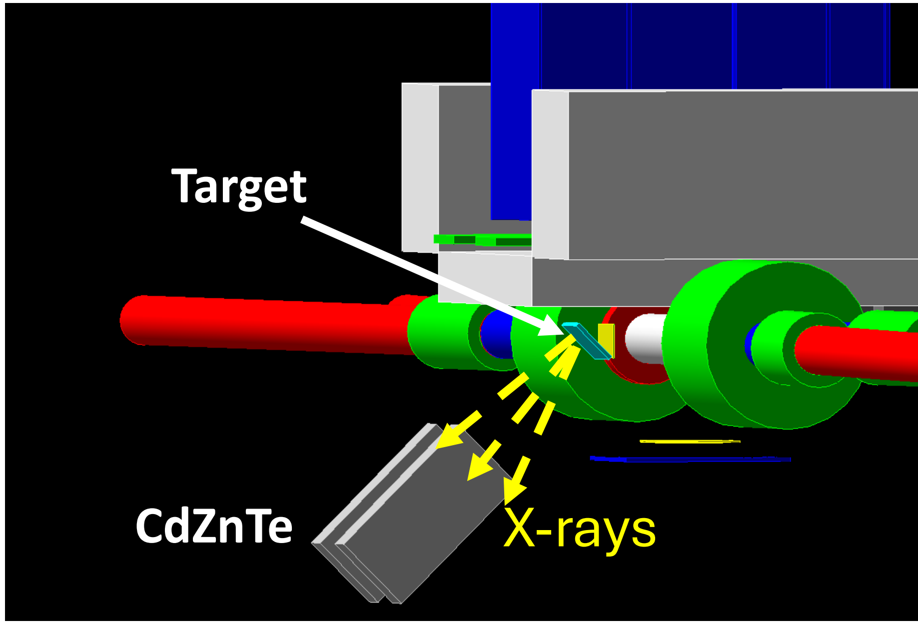


Analysis of the energy spectra ongoing to confirm the improved detection efficiency

Intermediate kaonic atoms (IMKA)

In parallel we plan dedicated runs for kaonic atoms (*O*, *Al*, *S*) with different types of detectors: CdZnTe detectors

- 200 -300 pb-1 of integrated luminosity/target



Scientific goals

- ❑ The energy and width of the **KAl(3->2) and KO(3->2)** transitions;
- ❑ The energies (E) and widths (W) of the **KO(4->3), KS(4->3) and KAl(4->3)** with precisions better than the present ones;
- ❑ **The first measurements ever of the absolute yields** of the Δn=1,2 transitions towards n=2,3 levels in KO, n=3,4,5 in KS and KAl

We are developing an optimized CdZnTe based setup

- **Larger active area:** 32 detectors instead of 8
- **Optimized geometry and shielding** to reduce the background

MC simulation: estimated precision for 300 pb^{-1}

$K^{32}S(4\rightarrow3)$ @ 160 keV : $\delta E = 41$ eV, $\delta\Gamma = 81$ eV (91 eV and 181 in the S/B = 1/10 case) for 16 cm^2

$K^{32}S(4\rightarrow3)$ @ 160 keV : $\delta E = 19$ eV, $\delta\Gamma = 37$ eV (42 eV and 83 in the S/B = 1/10 case) for 2% FWHM

EXKALIBUR: first module - Timescale

- New calibration system and 1mm thick SDDs financed by INFN Gr3
  - Construction of the new calibration system
  - Construction of 3 buses of 1mm thick SDDs (192 detectors)
  - Construction of the multi element solid target

  } Potentially ready from Sept. 2025

- Data taking runs:

	Month				
	1	2	3	4	5
Kaonic Neon measurement					
Commissioning and calibration of the experimental apparatus with beam					
Data taking: kaonic neon (300 pb^{-1} integrated luminosity)					
Light mass solid target measurements					
Installation of the solid target					
Commissioning with beam					
Kaonic atoms from solid target measurement (200 pb^{-1} Integrated luminosity)					
Intermediate mass solid target measurements (CZT detectors)					
Commisisoning with beam					
Data taking: Kaonic Carbon/Oxygen and Sulfur (300 pb^{-1})					
Data taking: Kaonic Aluminum and C/O or S (200 pb^{-1})					

Publications since last SciCom – May 2024

1. F. Sirghi, M. Iliescu, et al., "**SIDDHARTA-2 apparatus for kaonic atoms research on the DAΦNE collider**", 2024, JINST, 19, P11006

2. Bosnar D., et al., "**A feasibility study of the measurement of kaonic lead X-rays at DAΦNE for the precise determination of the charged kaon mass**", 2024, Nucl. Instrum. Methods Phys. Res. A, 1069, 169966.

3. Toscano L.G., et al., "**Development of high-efficiency X-ray detectors based on 1 mm thick monolithic SDD arrays**", 2024, JINST, 19(07), P07039.

4. Sgaramella F., et al., "**The SIDDHARTA-2 experiment for high precision kaonic atoms X-ray spectroscopy at DAΦNE**", 2024, Nuovo Cim. C, 47(5), 285.

5. F. Artibani, F. Clozza et al., "**Intermediate Mass Kaonic Atoms at DAΦNE**", Acta Phys. Pol. B, 17, 6-A2 (2024)

6. Abbene L., F. Artibani, et al., "**First linearity and stability characterization for CZT detection system in a e^+e^- collider environment**", submitted to Sensors.

7. F. Napolitano et al., "**Kaonic atoms with the SIDDHARTA-2 experiment at DAΦNE**", submitted to Acta Phys. Pol. A

8. F. Artibani et al., "**Kaonic atoms studies with the SIDDHARTA-2 experiment**", submitted to PoS

9. F. Clozza et al., "**A New Measurement of kaonic helium L-lines with SIDDHARTA-2 at DAΦNE**" Frascati Physics Series Vol. 76
10. F. Artibani et al., "**New opportunities in kaonic atoms spectroscopy with novel CZT Detector**" Frascati Physics Series Vol. 76

Present and future perspectives in Hadron Physics

STRONG 2020

17–21 Jun 2024
Laboratori Nazionali di Frascati INFN
Europe/Rome timezone

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This workshop will be dedicated to the memory of Professor Carlo Guaraldo, from INFN-LNF, Deputy Scientific Coordinator of the STRONG-2020 project, who passed away on 19th May 2024 in Roma.

The Workshop will be held in person from 17 to 19 June 2024, in Frascati (Italy) in the context of the project STRONG-2020

(http://www.strong-2020.eu/).

The objective is to gather a broad Hadron Physics Community, including both young and experienced researchers.

The first day will be dedicated to selected contributions. STRONG-2020 offers an opportunity to cover local and travel expenses for young researchers.

During the second and third days, invited speakers will present their work and perspectives in various areas of Hadron Physics and related fields.

The Workshop will be followed by the STRONG-2020 Annual Meeting organized in Frascati on 20-21 June 2024 and open to a large audience. The Agenda will be soon available and the Registration is

FONDAZIONE BRUNO KESSLER | ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS | 30 1993-2023

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KAMPAI - KAONIC, ANTIPROTONIC, MUONIC, PIONIC AND "ONIA" EXOTIC ATOMS: INTERCHANGING KNOWLEDGE AND RECENT RESULTS

30 September 2024 — 04 October 2024

Organizers

Alessandro Scordo (Laboratori Nazionali di Frascati INFN)
alessandro.scordo@lnf.infn.it

Paul Indelicato (Laboratoire Kastler Brossel)
paul.indelicato@lkb.upmc.fr

Jaroslava Obertova (Czech Technical University in Prague)
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Catalina Curceanu (Laboratori Nazionali di Frascati INFN)
catalina.curceanu@lnf.infn.it

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Magdalena Skurzok (Jagiellonian University of Krakow)
mskurzok@gmail.com

Tadashi Hashimoto (Japan Atomic Energy Agency (JAEA))
tadashi.hashimoto@a.riken.jp

Good news about SIDDHARTA folks:

- **Francesco Clozza – Ph.D. at University of Rome Tor Vergata**
- **Riccardo Gasbarrini – bachelor degree student**
- **Francesco Sgaramella: best talk STRONG-2020**

Conclusions

- The SIDDHARTA-2 Kd data taking (Runs 1, 2, 3 and 4) has been **successfully completed**, integrating **975/815 pb^{-1} + 200/185 pb^{-1} of data;** Run 1 and 2: SDD detectors calibrated ; Runs 3 and 4 calibration ongoing;

- **Full data analyses of Kd ongoing** (to be completed within about 6 months); to be followed by extraction of antikaon-nucleon scattering lengths and theoretical interpretations (12 months);

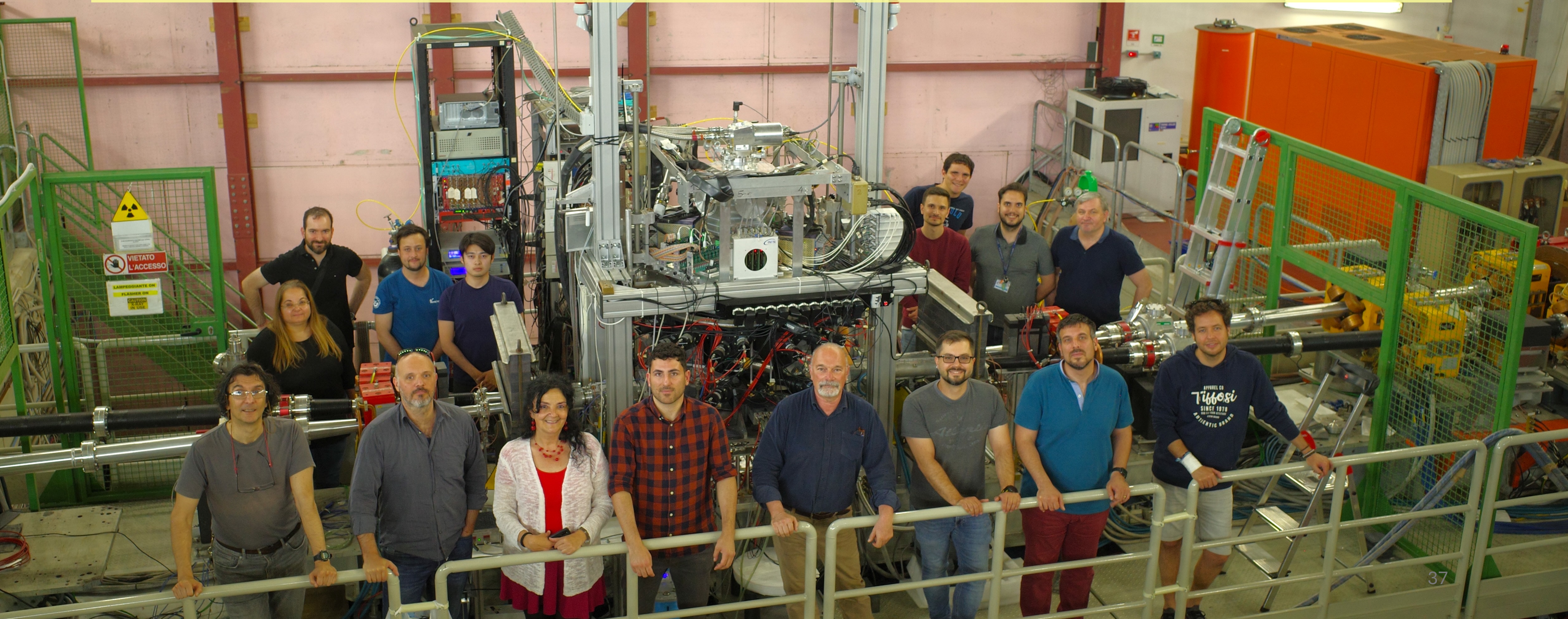
- Kaonic atoms: boron and fluorine (calib runs) -> under analyses (scientific and technological impact) -> at least 3 articles;

- Data analyses for CZT setup run (KAl) –ongoing; KPb data acquired with HPGe: paper published;

- >10 articles were published/submitted since the last Sci Com, 4 are in preparation and > 10 talks in International Workshops and Conferences;

- **For the first EXKALIBUR measurements module:** realization of refined calibration system ongoing; successful tests of 1 mm SDDs at BTF; ready to start as soon as possible

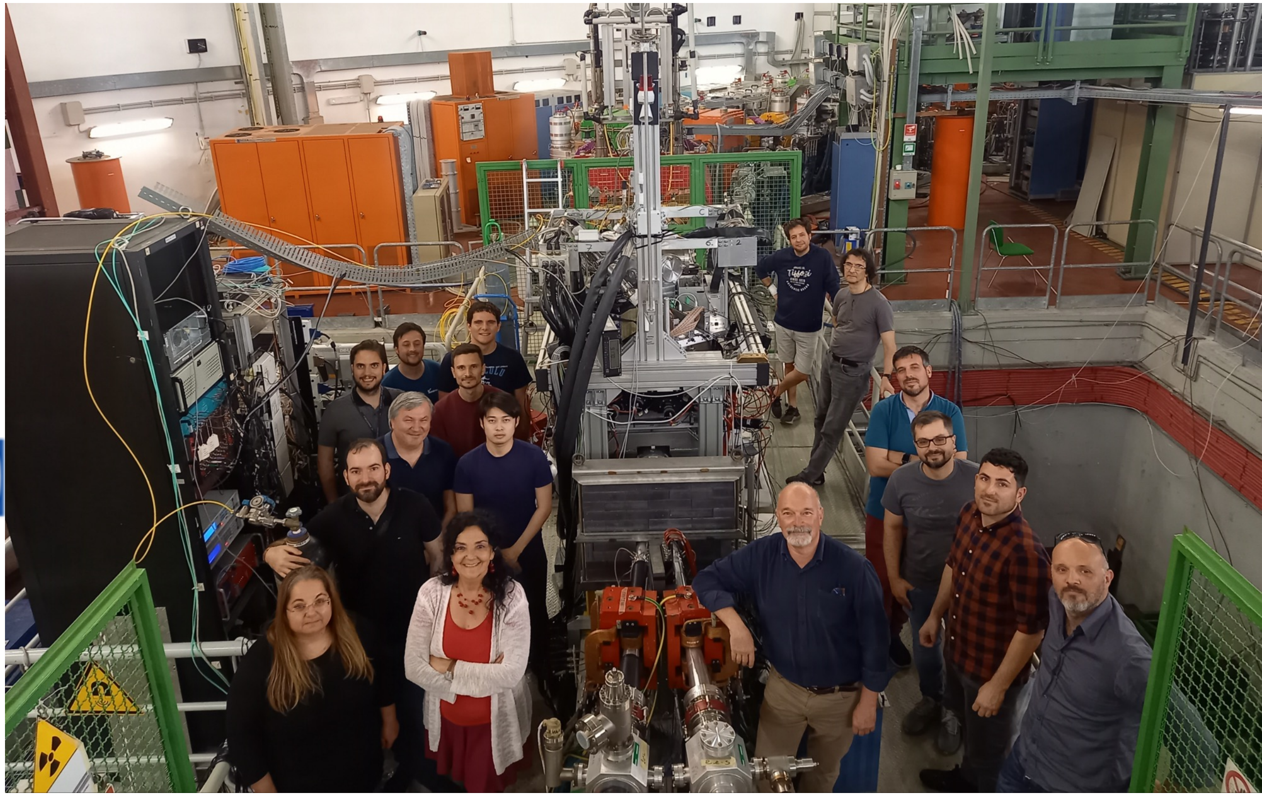
Special thanks to the accelerator, research and technical divisions, to the DAΦNE staff, in particular to Catia Milardi, the LNF Director, to the Gruppo 3-INFN and to all those who made this possible!



SPARE

SIDDHARTA-2 Collaboration

Silicon **D**rift **D**etectors for **H**adronic **A**tom **R**esearch by **T**iming **A**pplication



- LNF-INFN, Frascati, Italy
- SMI-ÖAW, Vienna, Austria
- Politecnico di Milano, Italy
- IFIN –HH, Bucharest, Romania
- TUM, Munich, Germany
- RIKEN, Japan
- Univ. Tokyo, Japan
- Victoria Univ., Canada
- Univ. Zagreb, Croatia
- Univ. Jagiellonian Krakow, Poland
- ELPH, Tohoku University
- Univ. of Palermo, Italy
- IMEM-CNR, Parma, Italy

INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

STRONG-2020

HrZZ Croatian Science Foundation

FWF Der Wissenschaftsfonds.

Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

HadronPhysics I3
Study of Strongly Interacting Matter

HadronPhysics2
Study of Strongly Interacting Matter

Intermediate mass kaonic atoms with CZT Detectors

Motivations:

Kaonic Oxygen is a key element to provide information on the nuclear-matter distribution. The lowest measured transition in kaonic oxygen is the 4→3 one; however, when compared to other typical values of strong interaction induced shift and widths on the lower levels in various elements, the weaker measured ones suggest the possibility that the KO(3→2) transitions could be measured as well. This transition is expected around 113 keV.

In the KAl case the measured values of the shift and width on the lowest level suggest that, probably, transitions to an even lower level may be observed; the **KAl(3→2) transitions could be then observed and measured at 300 keV**

There exist three and two measurements of KS(4->3) and KAl(4->3), respectively, not compatible among themselves and with large errors on the widths.

For KS, the values of the shift and the width are compatible with those of a typical lowest level, so a new measurement of the **KS(4→3) transition, laying around 160 keV, would be crucial and strongly demanded by the theoretical community.**

Most of the **Δn=1,2 transitions in KC, KAl, and KS have never been measured and will provide new experimental inputs both to the Kaon-Nucleon(s) interaction theoretical models and to the EM atomic cascade ones**.

Light Mass (low-Z) Kaonic Atoms

- The second module of measurement are **light mass (Li, Be, B)** kaonic atoms, **to study in detail the strong interaction between kaon and few nucleons (many body).**

- Now precise measurements for these kaonic atoms of the shifts, widths and yields will result in a **significative improvement on the knowledge of the interactions of kaons in matter**, with a great impact on the **low energy QCD and astrophysics** (equation of state for neutron stars) .

Lithium-6		Lithium-7		Beryllium-9		Boron-10		Boron-11	
Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)	Transition	Energy (keV)
$3 \to 2$	**15.085**	**$3 \to 2$**	**15.261**	**$3 \to 2$**	**27.560**	**$4 \to 3$**	**15.156**	**$4 \to 3$**	**15.225**
$4 \to 2$	**20.365**	**$4 \to 2$**	**20.603**	**$4 \to 3$**	**9.646**	**$5 \to 3$**	**22.171**	**$5 \to 3$**	**22.273**
$5 \to 2$	**22.809**	**$5 \to 2$**	**23.075**	**$5 \to 3$**	**14.111**	$5 \to 4$	7.015	$5 \to 4$	7.047
$4 \to 3$	5.280	$4 \to 3$	5.341	$5 \to 4$	4.465	$6 \to 4$	10.826	$6 \to 4$	10.875
$5 \to 3$	7.724	$5 \to 3$	7.814	$6 \to 4$	6.890	$6 \to 5$	3.811	$6 \to 5$	3.828
$5 \to 4$	2.444	$5 \to 4$	2.472	$6 \to 5$	2.425				
$6 \to 4$	3.771	$6 \to 4$	3.815						

The charged kaon mass discrepancy

Severe consequences for nuclear and particle physics
and all the processes in which charged kaons are involved

- The uncertainty on the charged kaon mass leads to an error of 50 keV (σ) on the D^0 mass
- Large uncertainty on the charmonium spectrum, in particular on precise values of charm-anticharm meson thresholds
- A particular case is that of $D^0\overline{D}^{*0}$ which lies within the measured width of the best-known candidate for a hadron-hadron molecule, the X(3872), an improved K-mass measurement would lead to a better interpretation of the X(3872), and of its radius.

C. Amsler, "Impact of the charged kaon mass on the charmonium spectrum", workshop, Frascati, 19 April 2021

- Impact on the K-N scattering lengths and sub eV measurement of K-nuclei interaction (kaonic atoms)

A new kaonic helium measurement in gas by SIDDHARTINO at the DAFNE collider
D. Sirghi, F. Sirghi, F. Sgaramella, et al., J.Phys.G 49 (2022) 5, 055106

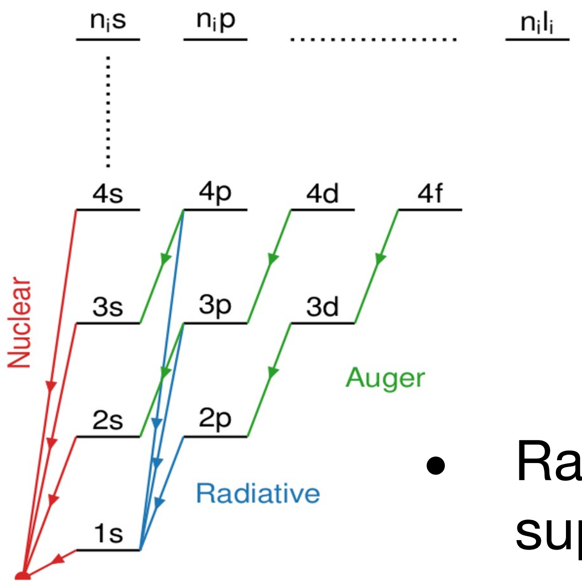
Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters, J-PARC E62 Collaboration, Phys.Rev.Lett. 128 (2022) 11, 112503

- Implications for studies in Bound State QED (BSQED)

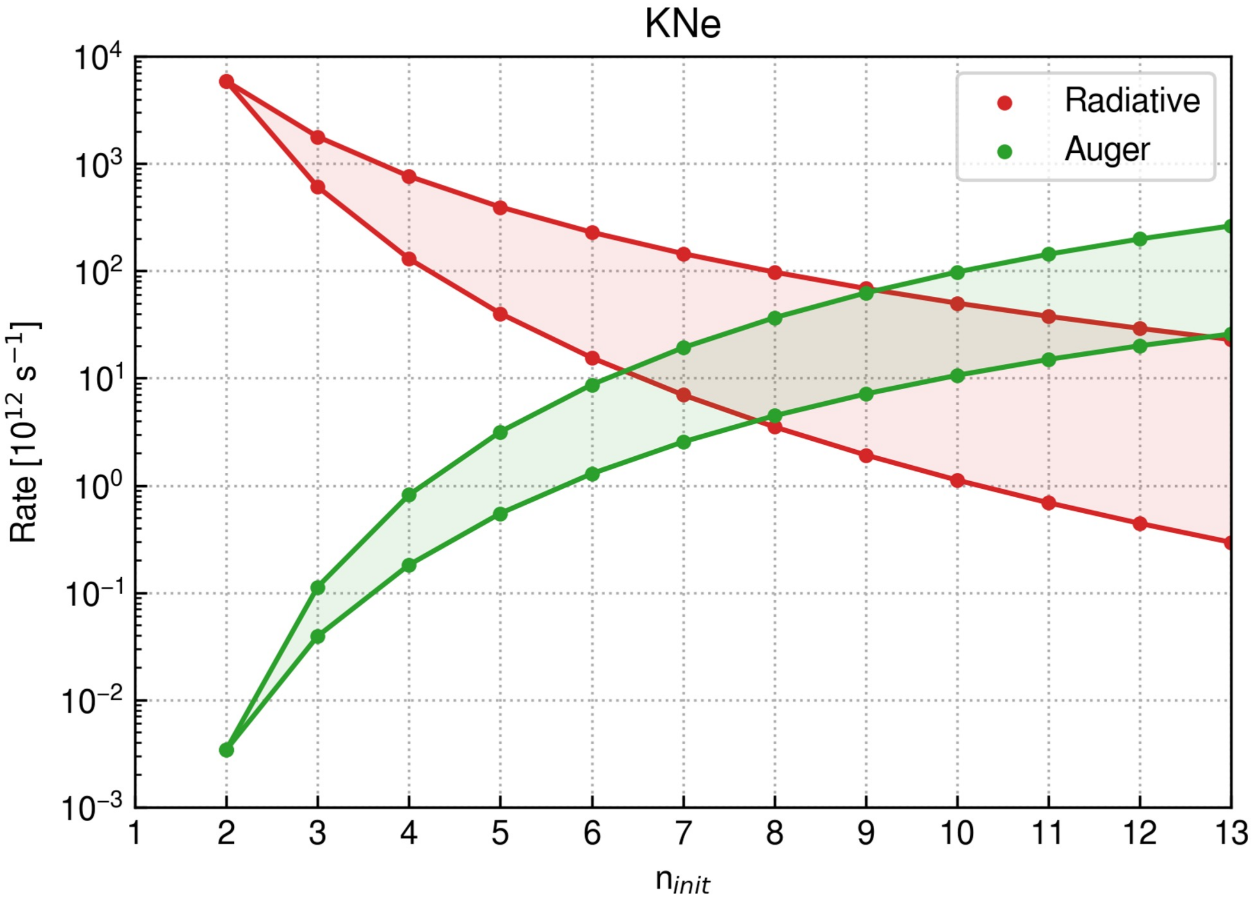
Testing Quantum Electrodynamics with Exotic Atoms
N. Paul, G. Bian, T. Azuma, S. Okada, and P. Indelicato, Phys. Rev. Lett. 126 (2021), 173001

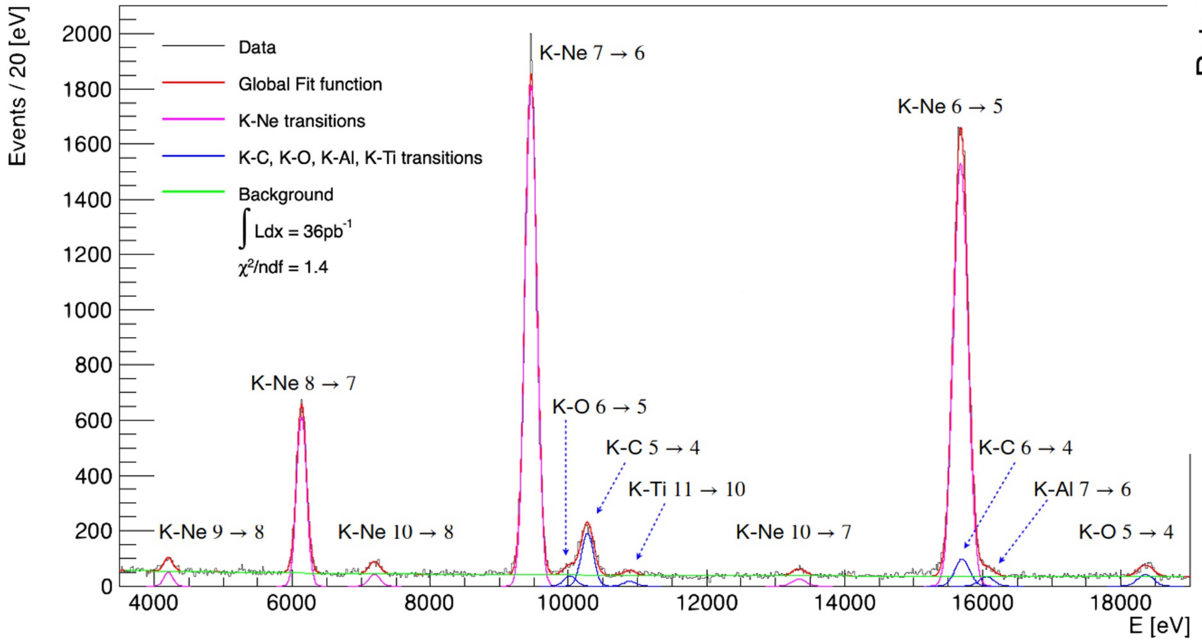
Kaonic Neon: Cascade calculation - Radiative and Auger

(Simone Manti)



- Radiative Rate suppressed for n>9





- Lower np-1s-transition
- Upper circular-transition

Cascade for Kaonic Neon: Connection with the Experiment

(Simone Manti)

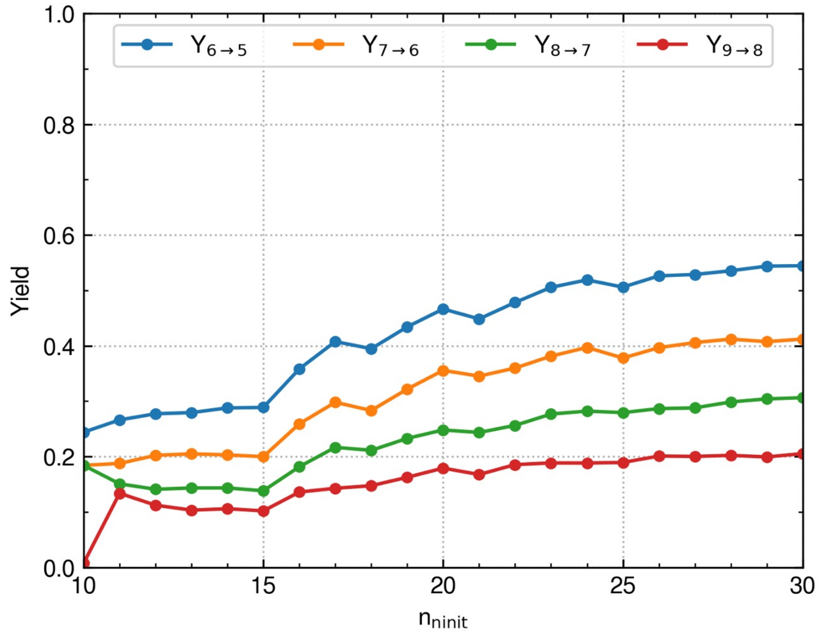
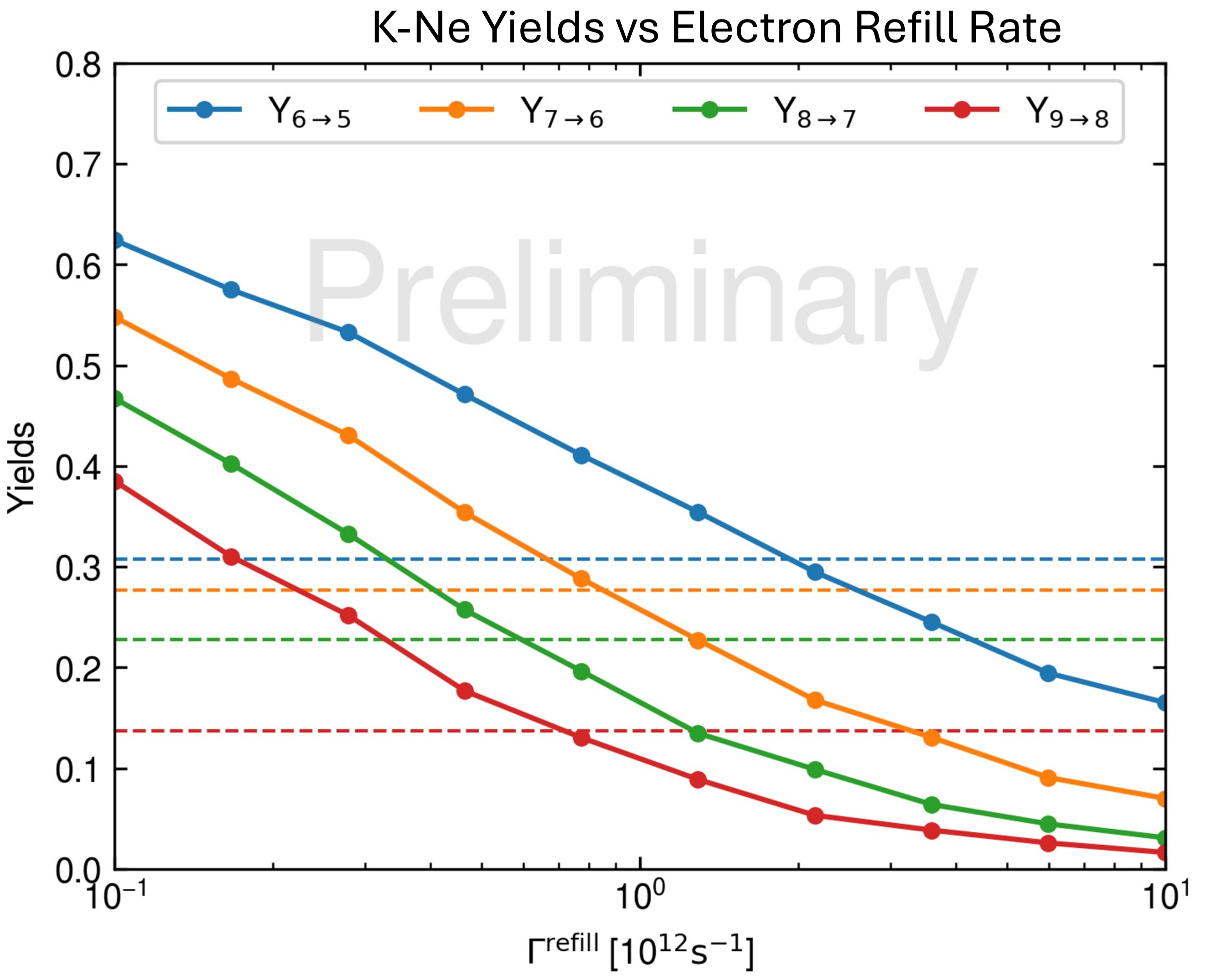


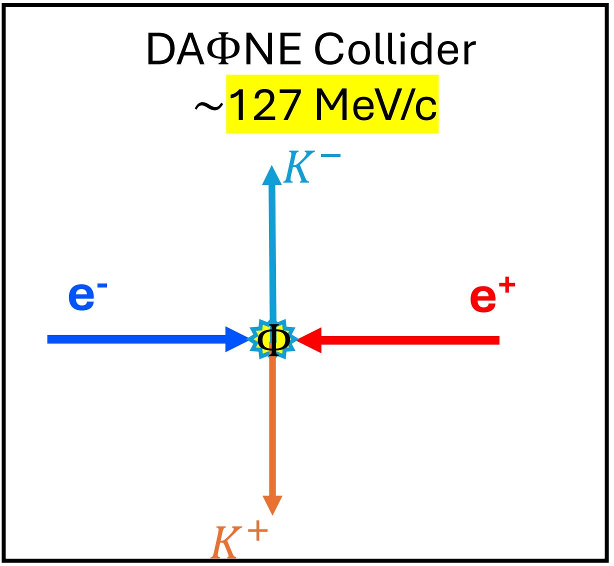
Table 1: Kaonic neon energy transitions and absolute yields at the density of 3.60 ± 0.18 g/l.

Transition	Energy [eV]	Yield
K-Ne (10 → 8)	7191.21 ± 4.91 (stat) ±2.00 (syst) eV	0.010 ± 0.001 (stat) ± 0.001 (syst)
K-Ne (10 → 7)	11428.30 ± 8.37 (stat) ±3.00 (syst) eV	0.004 ± 0.002 (stat) ± 0.001 (syst)
K-Ne (9 → 8)	4206.35 ± 3.75 (stat) ±2.20 (syst) eV	0.137 ± 0.012 (stat) ± 0.010 (syst)
K-Ne (8 → 7)	6130.86 ± 0.71 (stat) ±1.50 (syst) eV	0.228 ± 0.004 (stat) ± 0.011 (syst)
K-Ne (7 → 6)	9450.08 ± 0.41 (stat) ±1.50 (syst) eV	0.277 ± 0.002 (stat) ± 0.014 (syst)
K-Ne (6 → 5)	15673.30 ± 0.52 (stat) ±9.00 (syst) eV	0.308 ± 0.003 (stat) ± 0.015 (syst)

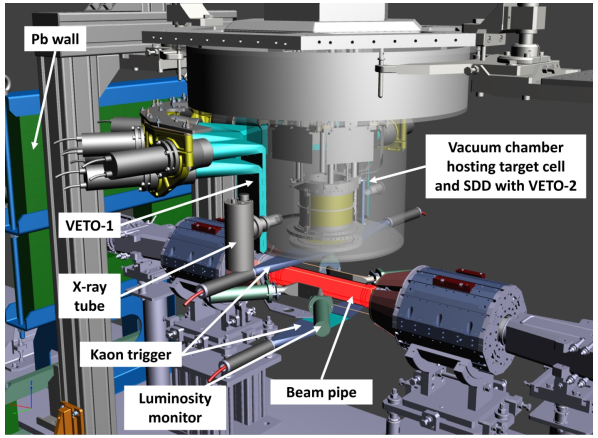


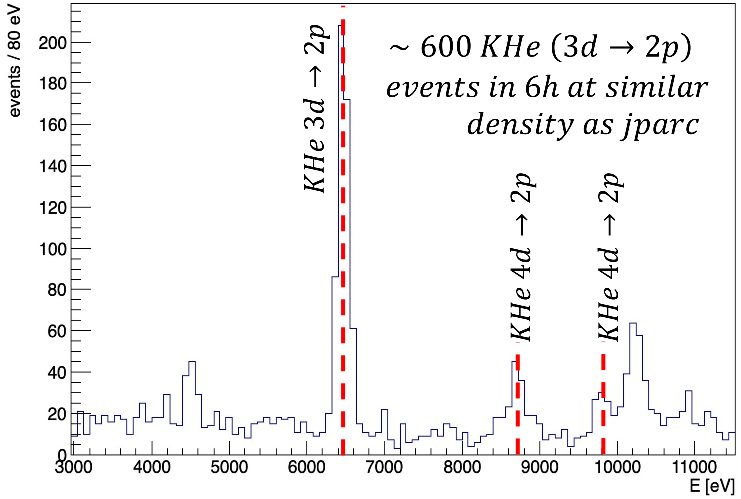
DAΦNE('s uniqueness) – JPARC for gaseous target

Kaon production	Setup	Kaonic helium measurement	Kaon mass measurement

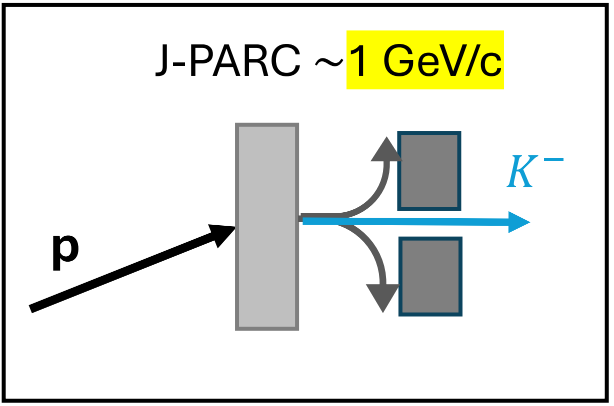


SIDDHARTA-2

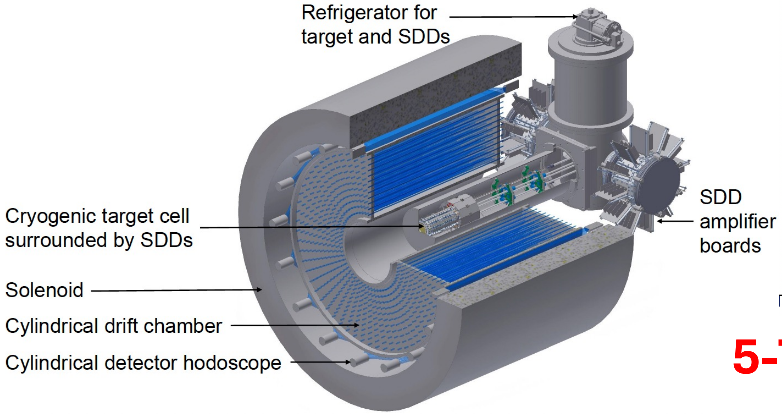


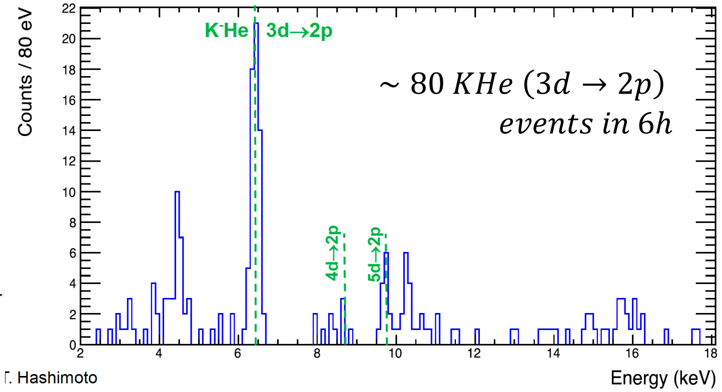


2 months of data taking to achieve a precision on the kaon mass below 7 keV



J- PARC E57 Setup





10-15 months of data taking to achieve a precision on the kaon mass below 7 keV

5-7.5 times more time to achieve the same statistical accuracy as SIDDHARTA-2