ROMA TRE UNIVERSITÀ DEGLI STUDI

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Novel CZT Detectors for Kaonic Atoms Spectroscopy

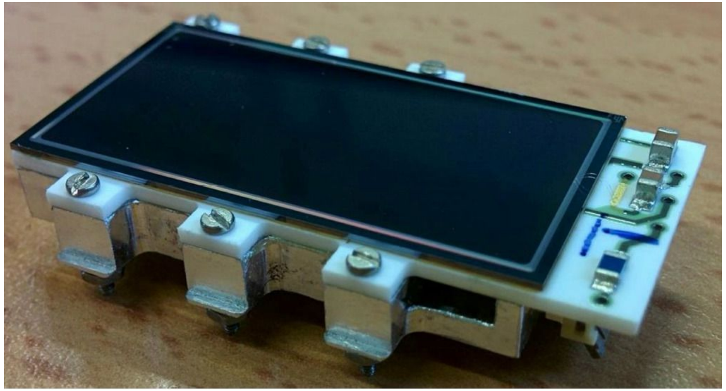
Francesco Artibani

Outline

1. CZT Detector
    a. Why CZT?
    b. CZT Properties
    c. New CZT Detector at DAFNE
2. Kaonic Atoms Research
    a. Formation and Cascade
    b. Motivations
    c. Intermediate Mass Kaonic Atoms
3. New Measurement with CZT Detector
    a. DAFNE Collider
    b. Requirements in a Collider
    c. First Results

Why Cadmium Zinc Telluride?

- **Silicon** represents the best semiconductors in terms of availability, efficiency and resolution, to build a compact X-ray detectors, but **his efficiency falls down fast after tens of keV energies**.



(See F. Clozza talk)

Pennicard, D. *et al.* Semiconductor materials for x-ray detectors. *MRS Bulletin* **42**, 445–450 (2017). https://doi.org/10.1557/mrs.2017.95

Why Cadmium Zinc Telluride?

- **Silicon** represents the best semiconductors in terms of availability, efficiency and resolution, to build a compact X-ray detectors, but **his efficiency falls down fast to tens of keV energies**.

- **Germanium** is a natural semiconductor, which is a great advantage for producing high-quality crystals for detectors. However, HPGe detectors **cannot be operated at room temperature**, and need invasive setups.

See D. Bosnar talk

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CZT Detectors: Properties

- **Compound semiconductor** (interesting because of the possibility to grow materials with many physical properties making them **suitable to almost any application**)

- **Good spectroscopy performances at room temperature, from tens to hundreds keV**. Ideal to build compact systems without the need of cooling.

- Intense studies to upgrade the quality of the crystals and electronics in last decades can lead to a **further improvement in terms of resolution, efficiency, especially at high rate**. In recent years successful applications in the field of medical imaging and astrophysics.

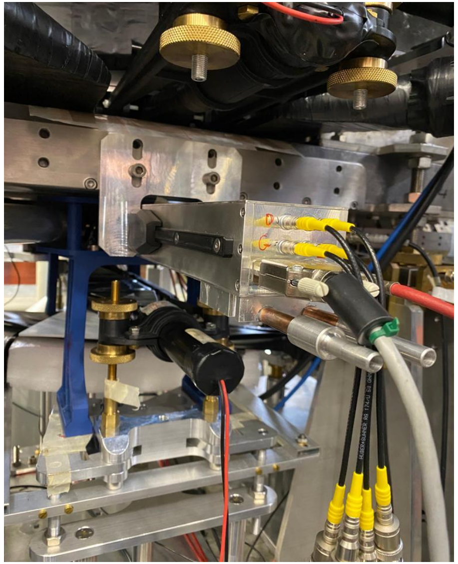
CZT Detector at DAFNE Collider

- Use of quasi-hemispherical CZT crystals grown by REDLEN (Canada) and **IMEM-CNR** (Parma)

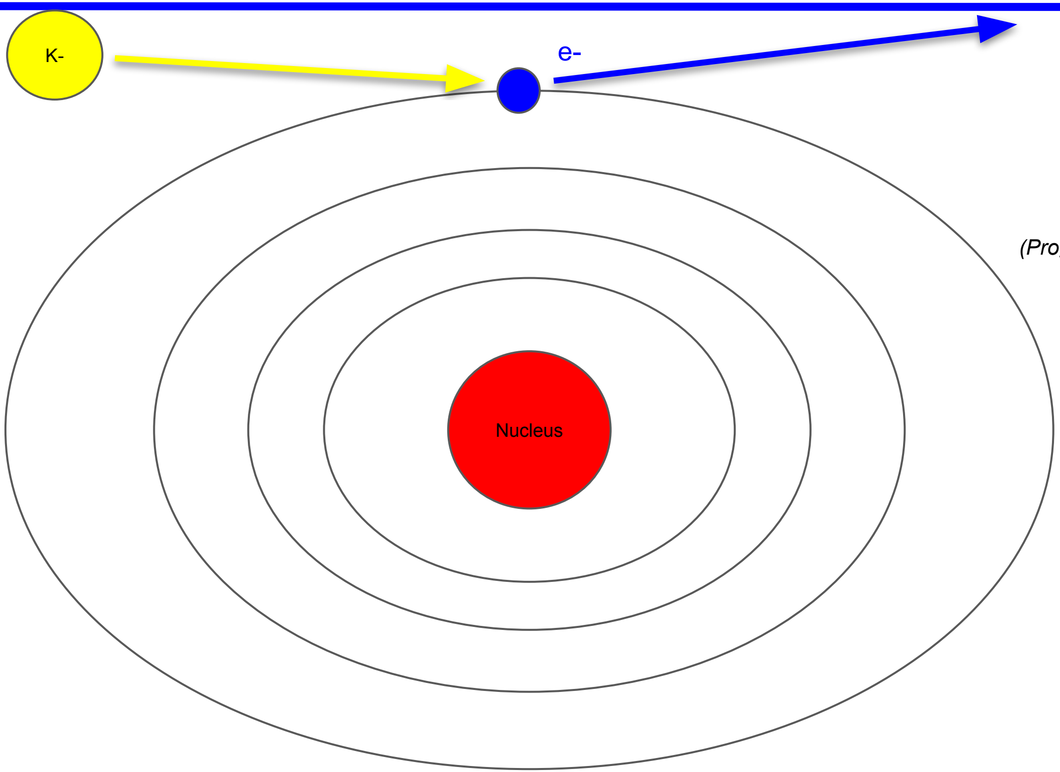
- Expertise of the **UniPa DiFC** group for the custom electronics.

- First tests and Data Analysis done in **Frascati National Laboratories** (LNF)

★ **GOAL: Measure Intermediate Mass Kaonic Atoms.**



Kaonic Atoms: Formation



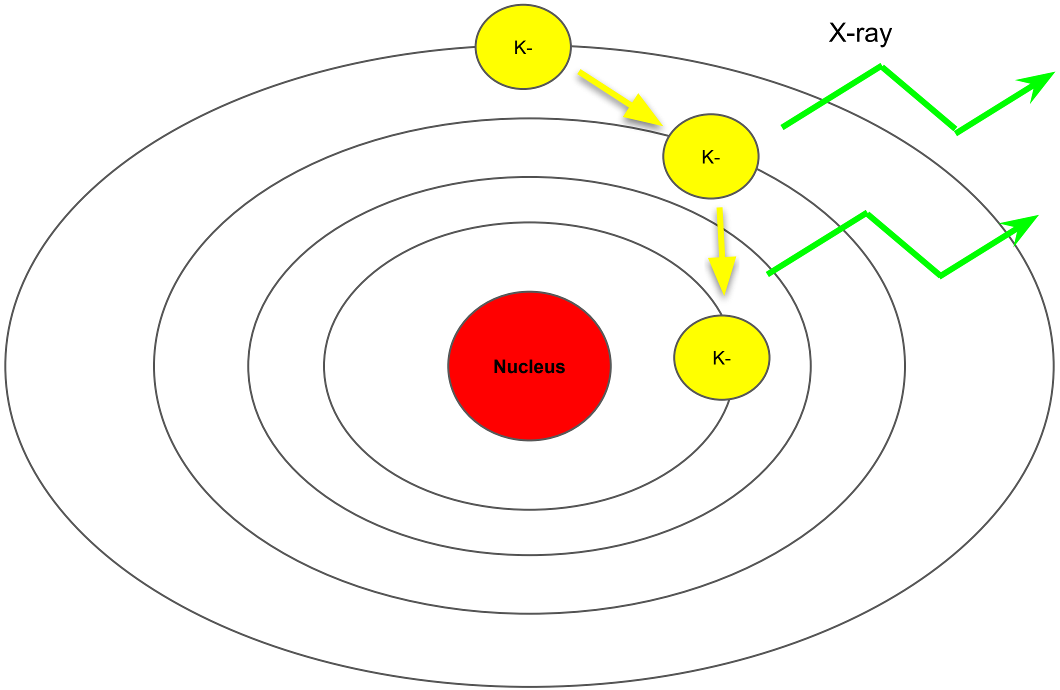
$r_b^e \sim r_b^k$

*(Prog. Part. Nucl. Phys. **61,** 512–550, 2008)*

$$n \approx \sqrt{\frac{\mu}{m_e}} n_e$$

H n=1 level ~ KH n=25 level

Kaonic Atoms: Cascade



The de-excitation cascade in its last part is radiative and in the X-ray region.

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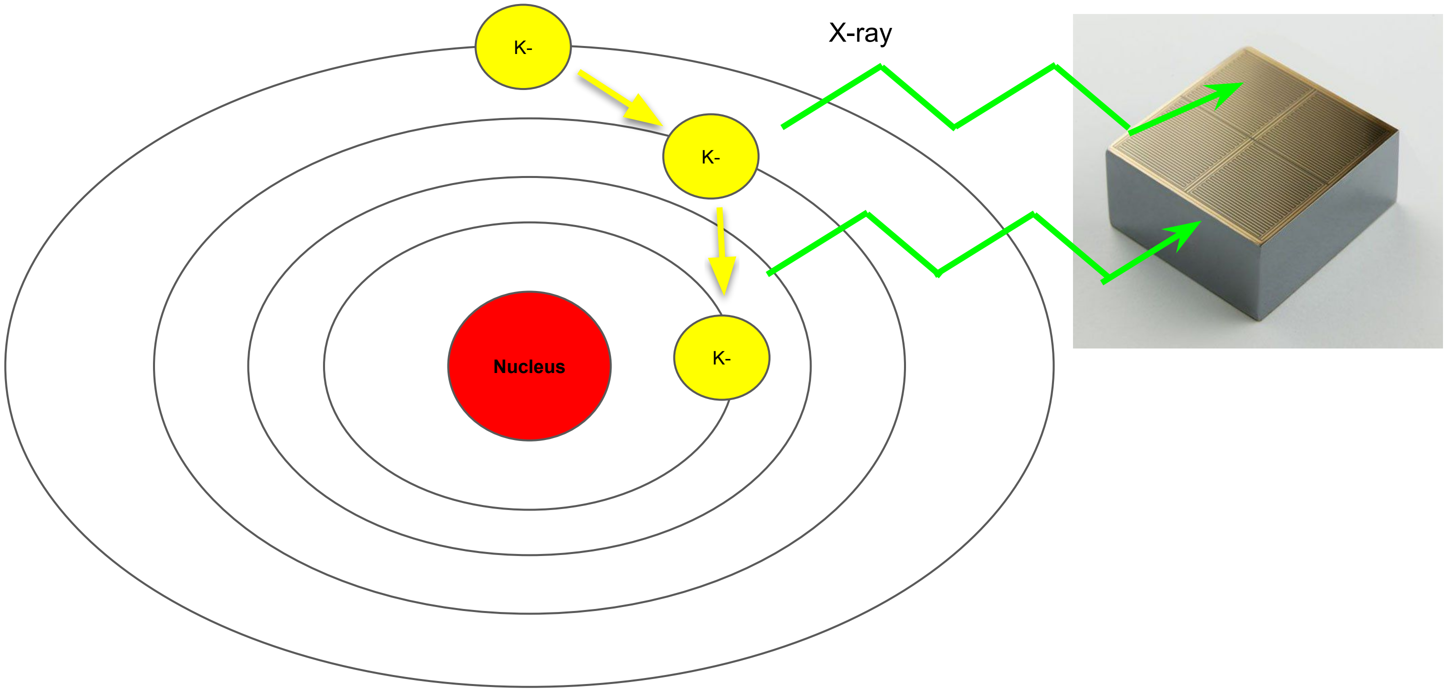

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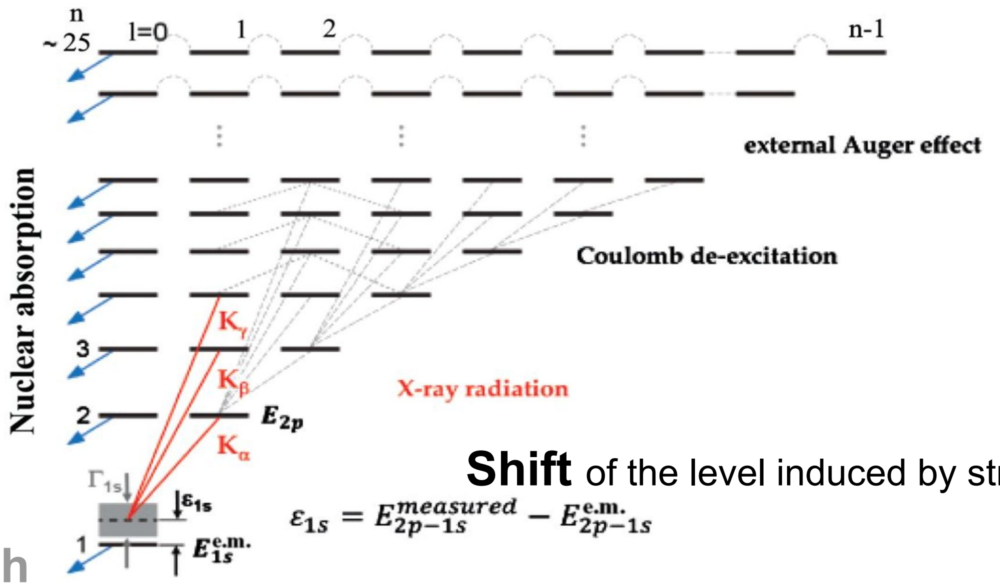
Kaonic Atoms: Importance for Strong Interactions

KH example

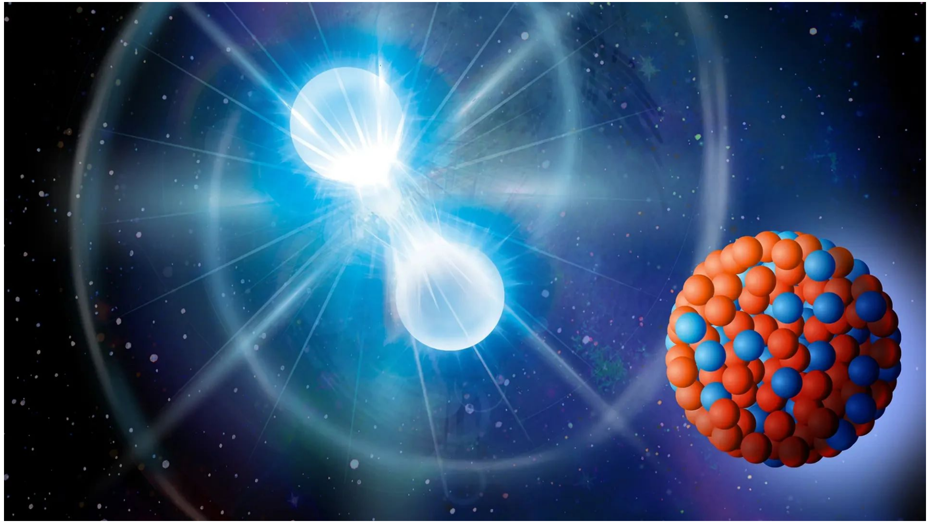


Shift of the level induced by strong interactions.

Width
of the level induced by the small lifetime.

Kaonic Atoms: Importance

- Strong Interaction studies
- Cascade model studies
- High precision QED measurements



Intermediate-mass Kaonic Atoms

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)
He	$3 \to 2$	-0.04 ± 0.03	–	–	–
		-0.035 ± 0.012	0.03 ± 0.03	–	–
Li	$3 \to 2$	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–
Be	$3 \to 2$	-0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02
^{10}B	$3 \to 2$	-0.208 ± 0.035	0.810 ± 0.100	–	–
^{11}B	$3 \to 2$	-0.167 ± 0.035	0.700 ± 0.080	–	–
C	$3 \to 2$	-0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20
O	$4 \to 3$	-0.025 ± 0.018	0.017 ± 0.014	–	–
Mg	$4 \to 3$	-0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03
Al	$4 \to 3$	-0.130 ± 0.050	0.490 ± 0.160	–	–
		-0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04
Si	$4 \to 3$	-0.240 ± 0.050	0.810 ± 0.120	–	–
		-0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06
P	$4 \to 3$	-0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30
S	$4 \to 3$	-0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36
		-0.43 ± 0.12	2.310 ± 0.170	–	–
		-0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5
Cl	$4 \to 3$	-0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7
		-0.94 ± 0.40	3.92 ± 0.99	–	–
		-1.08 ± 0.22	2.79 ± 0.25	–	–
Co	$5 \to 4$	-0.099 ± 0.106	0.64 ± 0.25	–	–
Ni	$5 \to 4$	-0.180 ± 0.070	0.59 ± 0.21	0.30 ± 0.08	5.9 ± 2.3
		-0.246 ± 0.052	1.23 ± 0.14	–	–
Cu	$5 \to 4$	-0.240 ± 0.220	1.650 ± 0.72	0.29 ± 0.11	7.0 ± 3.8
		-0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1
Ag	$6 \to 5$	-0.18 ± 0.12	1.54 ± 0.58	0.51 ± 0.16	7.3 ± 4.7
Cd	$6 \to 5$	-0.40 ± 0.10	2.01 ± 0.44	0.57 ± 0.11	6.2 ± 2.8
In	$6 \to 5$	-0.53 ± 0.15	2.38 ± 0.57	0.44 ± 0.08	11.4 ± 3.7
Sn	$6 \to 5$	-0.41 ± 0.18	3.18 ± 0.64	0.39 ± 0.07	15.1 ± 4.4
Ho	$7 \to 6$	-0.30 ± 0.13	2.14 ± 0.31	–	–
Yb	$7 \to 6$	-0.12 ± 0.10	2.39 ± 0.30	–	–
Ta	$7 \to 6$	-0.27 ± 0.50	3.76 ± 1.15	–	–
Pb	$8 \to 7$	–	0.37 ± 0.15	0.79 ± 0.08	4.1 ± 2.0
		-0.020 ± 0.012	–	–	–
U	$8 \to 7$	-0.26 ± 0.4	1.50 ± 0.75	0.35 ± 0.12	45 ± 24

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- Incompatible measurements
- Measurement with wide errors

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Al	$4 \to 3$	-0.130 ± 0.050	0.490 ± 0.160	–	–
		-0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04
Si	$4 \to 3$	-0.240 ± 0.050	0.810 ± 0.120	–	–
		-0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06
P	$4 \to 3$	-0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30
S	$4 \to 3$	-0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36
		-0.43 ± 0.12	2.310 ± 0.170	–	–
		-0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5
Cl	$4 \to 3$	-0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7
		-0.94 ± 0.40	3.92 ± 0.99	–	–
		-1.08 ± 0.22	2.79 ± 0.25	–	–
Co	$5 \to 4$	-0.099 ± 0.106	0.64 ± 0.25	–	–
Ni	$5 \to 4$	-0.180 ± 0.070	0.59 ± 0.21	0.30 ± 0.08	5.9 ± 2.3
		-0.246 ± 0.052	1.23 ± 0.14	–	–
Cu	$5 \to 4$	-0.240 ± 0.220	1.650 ± 0.72	0.29 ± 0.11	7.0 ± 3.8
		-0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1

- Incompatible measurements
- Measurement with wide errors
- Relative yields not always measured

Intermediate-mass Kaonic Atoms

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)
C	$3 \rightarrow 2$	-0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20
O	$4 \rightarrow 3$	-0.025 ± 0.018	0.017 ± 0.014	–	–
Mg	$4 \rightarrow 3$	-0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03
Al	$4 \rightarrow 3$	-0.130 ± 0.050	0.490 ± 0.160	–	–
		-0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04
Si	$4 \rightarrow 3$	-0.240 ± 0.050	0.810 ± 0.120	–	–
		-0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06
P	$4 \rightarrow 3$	-0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30
S	$4 \rightarrow 3$	-0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36
		-0.43 ± 0.12	2.310 ± 0.170	–	–
		-0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5
Cl	$4 \rightarrow 3$	-0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7
		-0.94 ± 0.40	3.92 ± 0.99	–	–
		-1.08 ± 0.22	2.79 ± 0.25	–	–
Co	$5 \rightarrow 4$	-0.099 ± 0.106	0.64 ± 0.25	–	–
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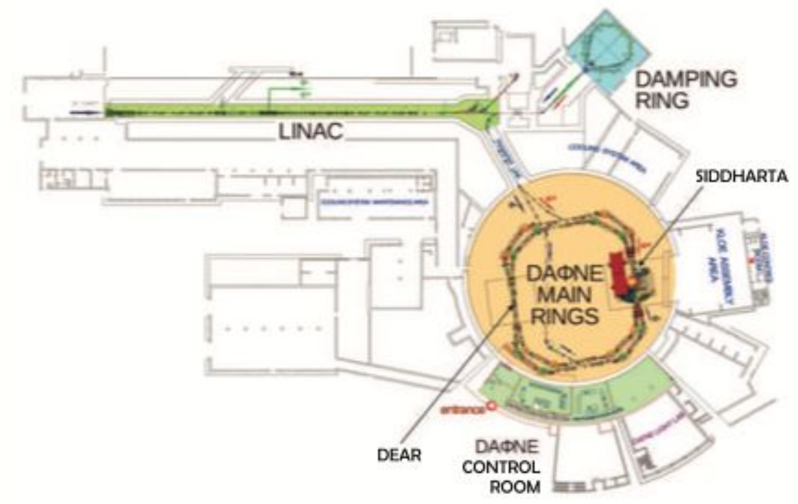
		-0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1

- Incompatible measurements
- Measurement with wide errors
- Relative yields not always measured
- Total yields almost unknown

The DAΦNE Collider



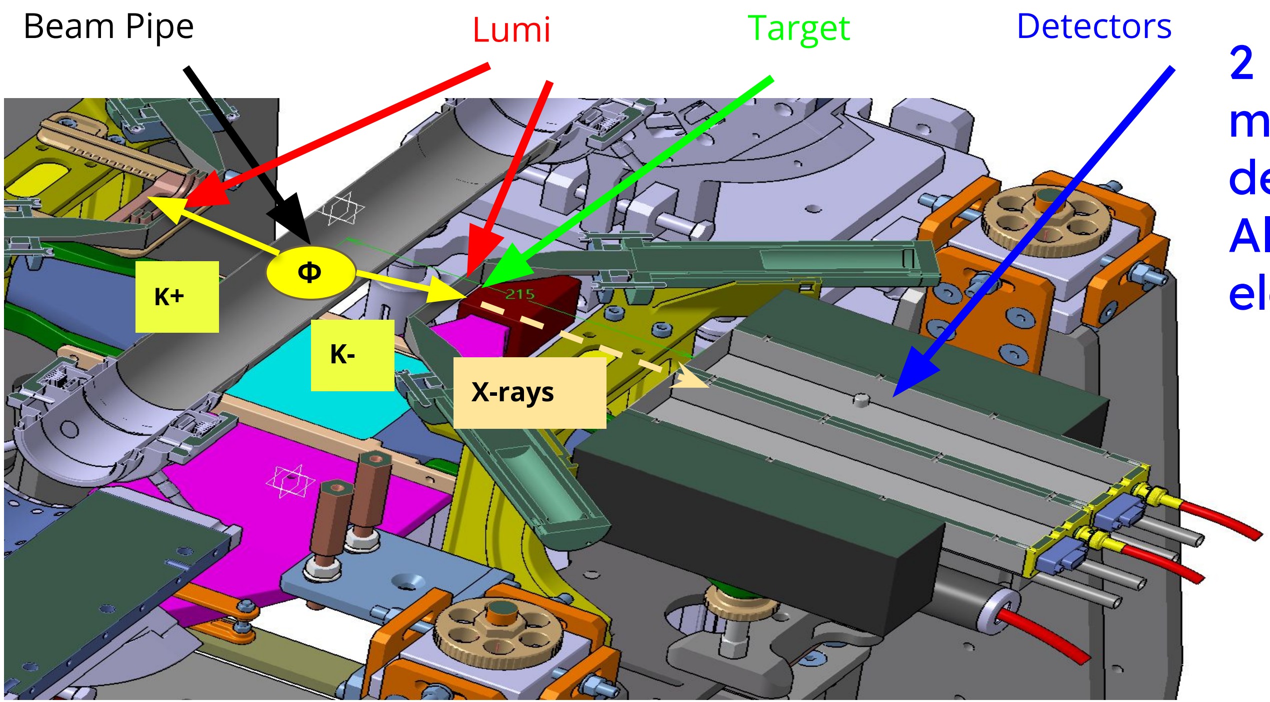
- double ring lepton collider working at the **c.m. energy of Φ resonance** (Φ-factory) (m_Φ= 1.02 GeV)

- Φ decays in a couple of charged kaons with a **BR($\Phi \rightarrow K^+K^-$) = 48%**

- The kaons are produced almost at rest (m_K = 493 MeV ⇒ **p_K =127 MeV**, β~0.26) with a small boost through the center of the rings.

- The Ks' momentum spread is almost null ($\Delta p/p < 0.1\%$)

The Setup in DAFNE Collider



2 modules with four 13 mm x 15 mm x 5 mm CZT detectors, enclosed in an Aluminum box with the electronics.

Requirements in a Collider

To perform measurements in DAFNE, an X-ray detector needs

- **A good energy resolution** → to resolve shifts and widths in months of data-taking.
- **A compact setup** to be as closer as possible to beam-pipe compatibly with other systems.
- **High resistance to radiation damage and stability** over the months of data-taking.
- A good timing for **background rejection capability.**

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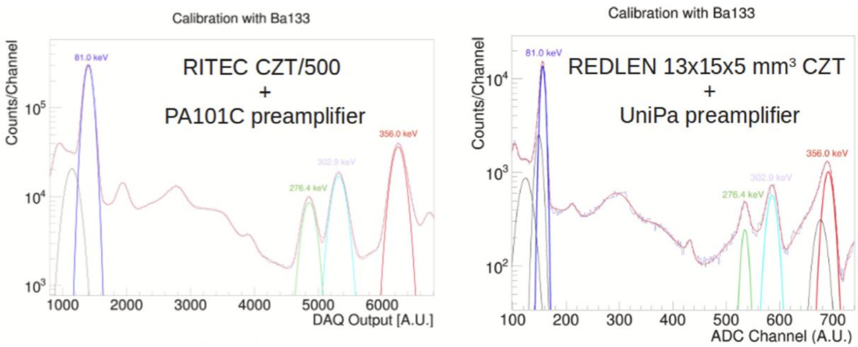

	RITEC CZT/500		REDLEN M1535	
^{133}Ba Peak (keV)	R (10^{-3})	FWHM/E	R (10^{-3})	FWHM/E
81.0	1.3	0.110	-2.4	0.064
276.4	-0.7	0.048	1.4	0.028
302.9	-0.4	0.046	-0.2	0.036
356.0	0.5	0.037	-0.1	0.030

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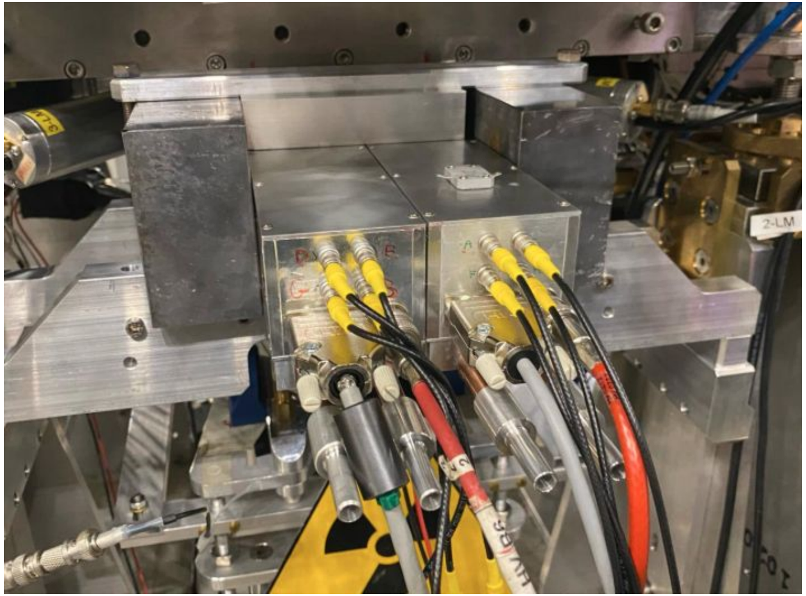
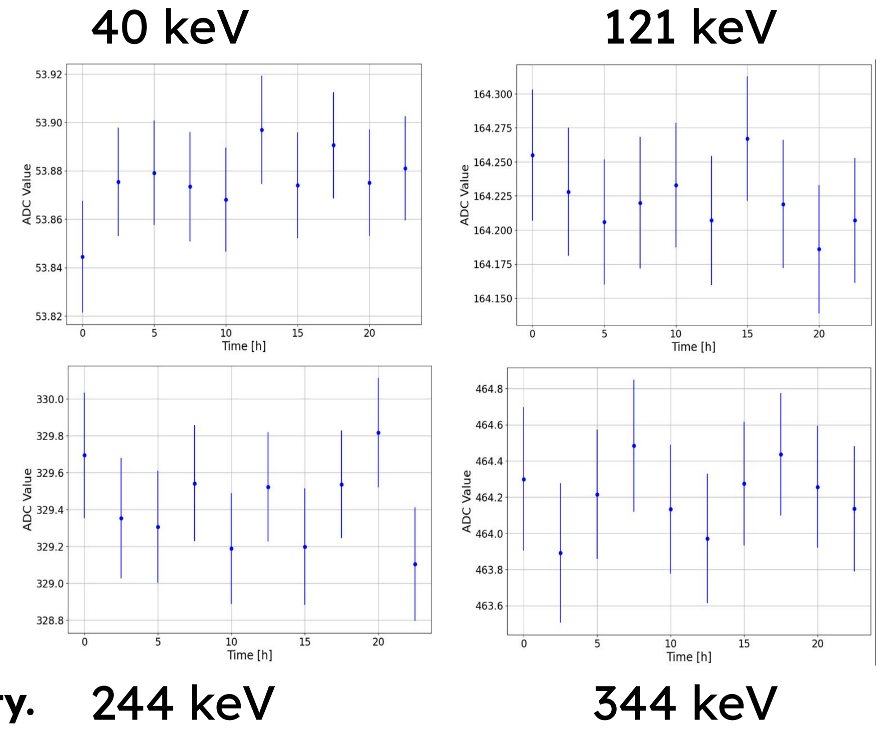


~ 20 cm from IP

Requirements in a Collider

To perform measurements in DAFNE, an X-ray detector needs

- ✔ **A good energy resolution** → to resolve shifts and widths in months of data-taking.
- ✔ **A compact setup** to be as closer as possible to beam-pipe compatibly with other systems.
- ✔ **High resistance to radiation damage and stability** during data-taking.
- A good timing for **background rejection capability.**



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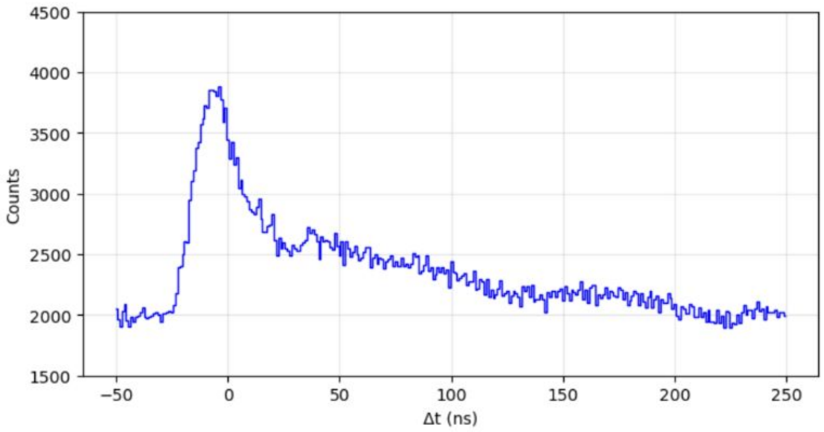
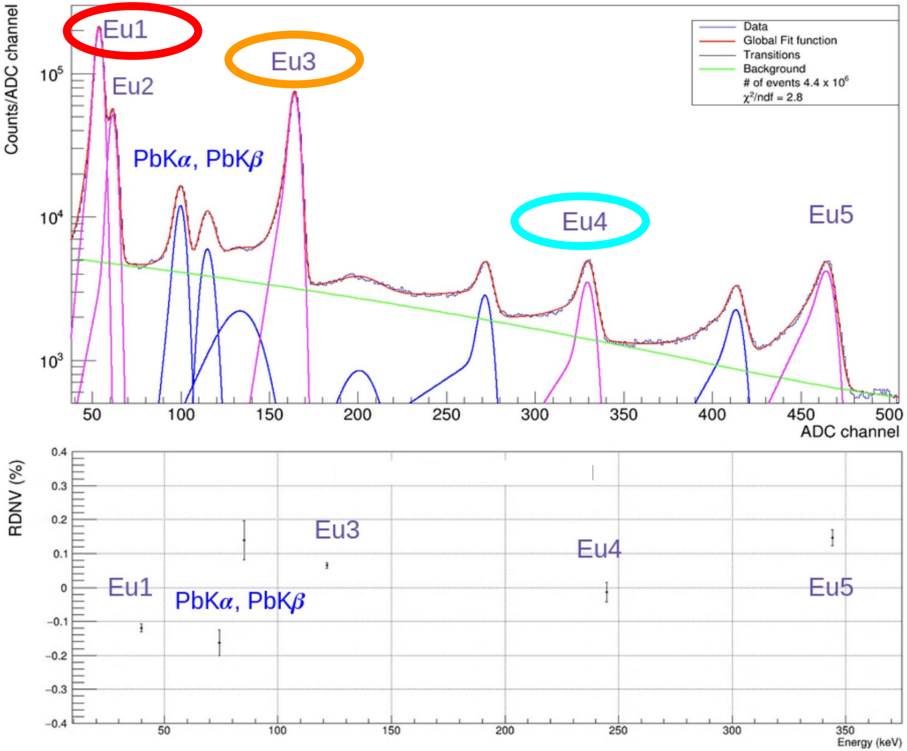


Time difference between trigger and signal ~10-100 ns

Analysis: Calibration



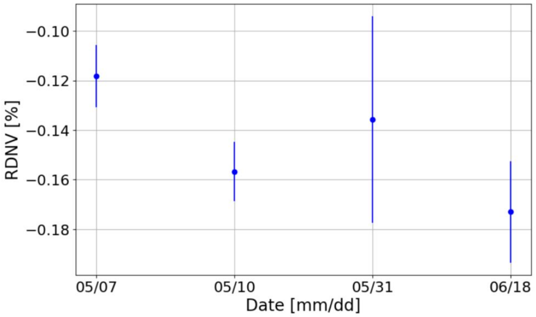
$$f_{peak}(x) = N \times \exp\left(-\frac{x-\mu}{2\sigma^2}\right) + \epsilon \times N \times \exp\left(\frac{x-\mu}{\beta\sigma}\right) \times \mathrm{erfc}\left(\frac{x-\mu}{\sqrt{2}\sigma} + \frac{1}{\sqrt{2}\beta}\right)$$

Gaussian + Tail

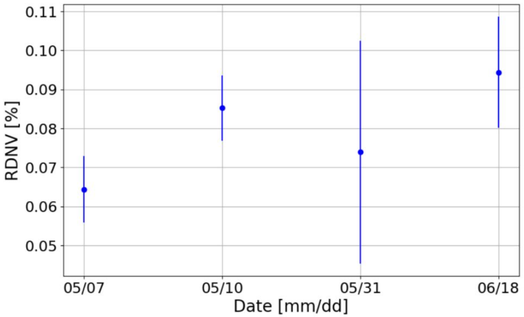
Energy (keV)	Intensity (%)	Type	Origin	ID [1]
40.1186 (-)	37.7 (5)	X $K_{\alpha1}$	Sm	Eu1
121.7817 (3)	28.41 (13)	γ	^{152}Sm	Eu3
344.2785 (12)	26.59 (12)	γ	^{152}Gd	Eu5
39.5229 (-)	20.8 (3)	X $K_{\alpha2}$	Sm	Eu1
45.4777 (-)	11.78 (19)	X $K_{\beta1}$	Sm	Eu2
244.6974 (8)	7.55 (4)	γ	^{152}Sm	Eu4
46.6977 (-)	3.04 (8)	X $K_{\beta2}$	Sm	Eu2

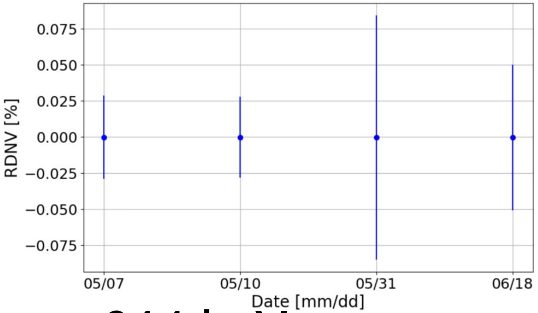
Analysis: Calibration and Stability

40 keV

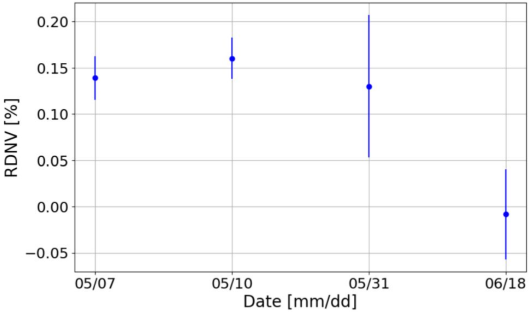


121 keV





244 keV

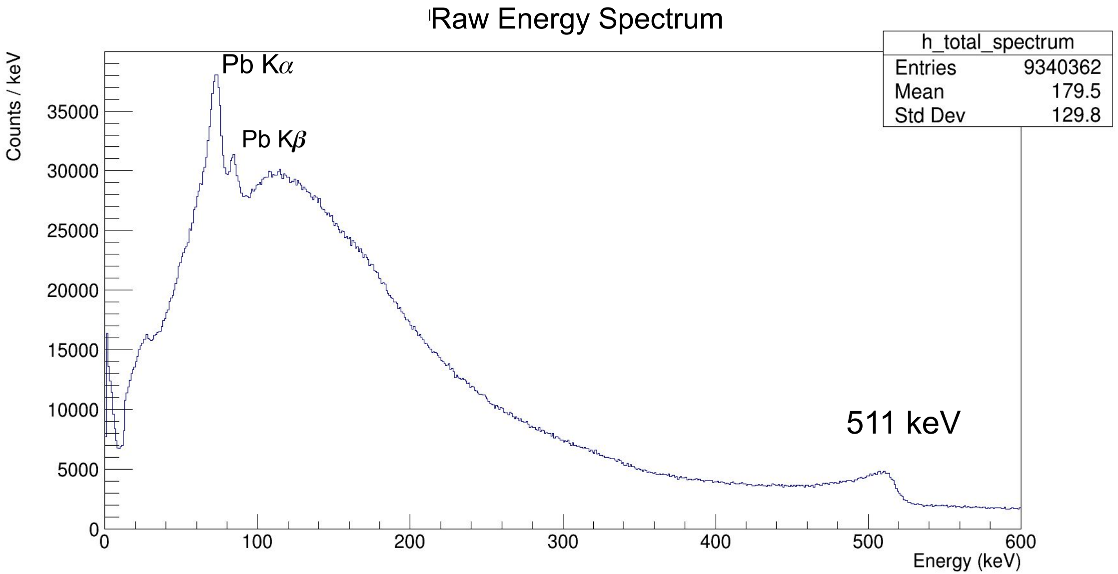


344 keV

All Relative Differences respect to Nominal Value (RDNV) are 1‰ or below, from 40 keV to 344 keV

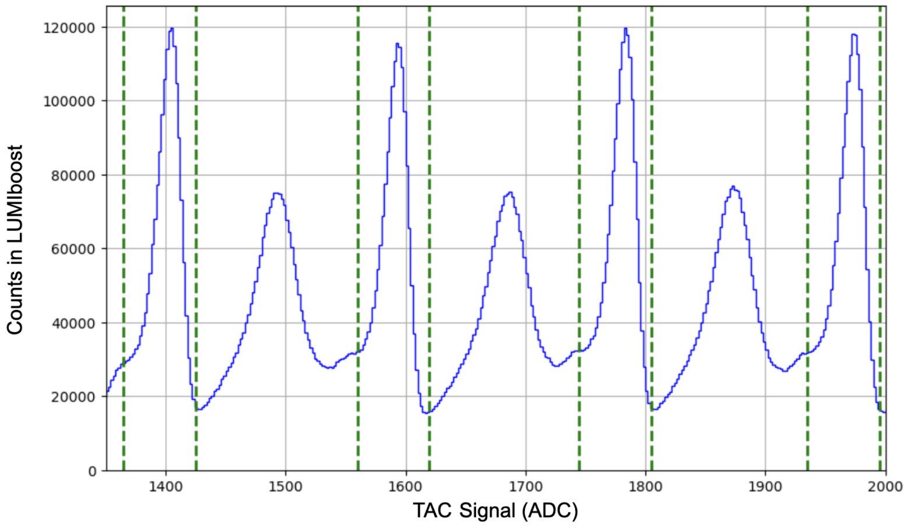
Analysis: Time of Flight + Delta t Cuts

~ 40 pb-1 delivered

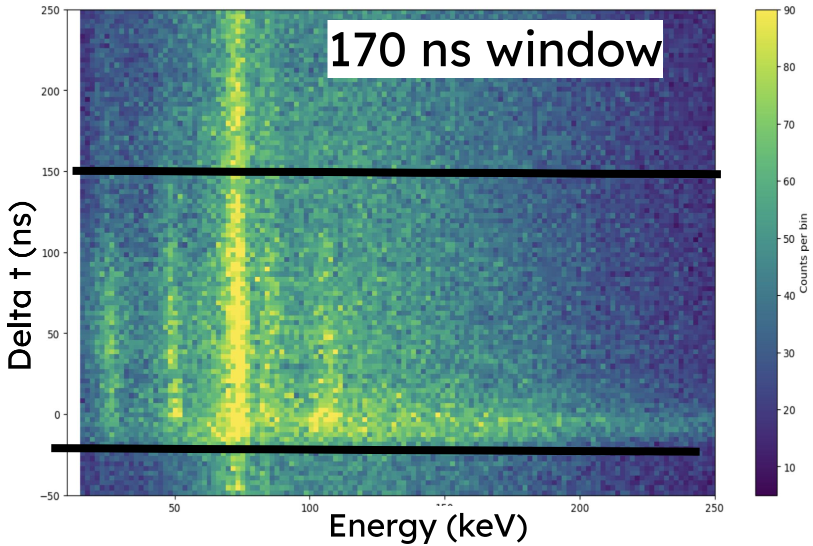


Analysis: Time of Flight + Delta t Cuts

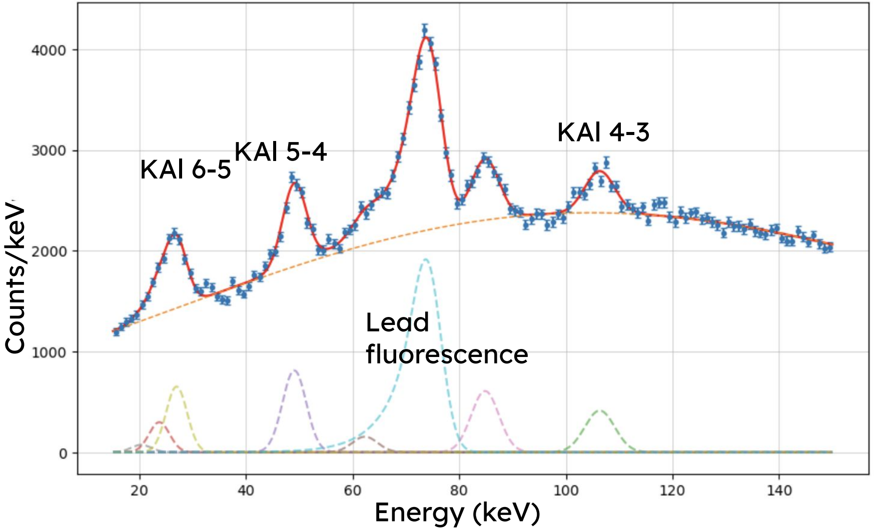
Kaon reconstruction through time-of-flight cut with LUMI scints



Signal selection through a cut on the time difference between trigger and event on CZT



Firsts Results: Aluminum

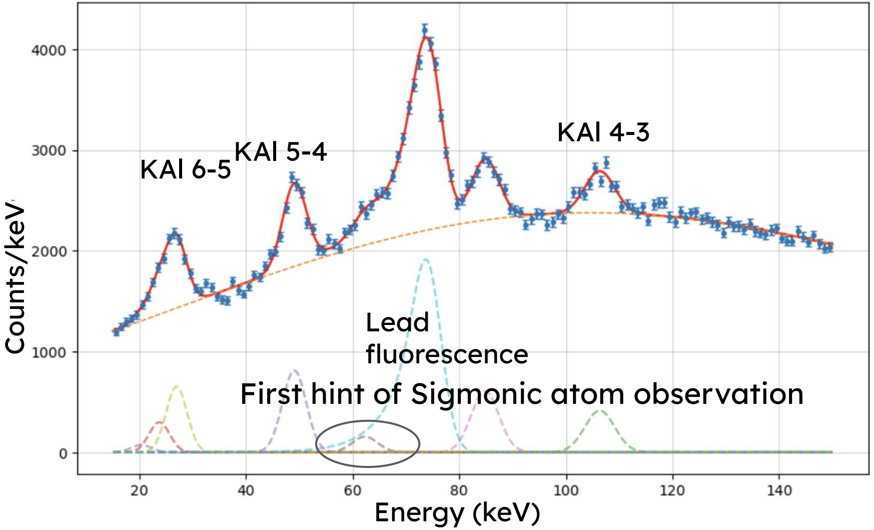


Transition	Energy (keV)	Th. Energy (keV)
KAl 4-3	106.48 ± 0.16	106.57
KAl 5-4	49.108 ± 0.068	49.23
KAl 6-5	26.67 ± 0.10	26.707

26 days run with Al Target
(>100 pb-1 delivered)

width KAl 4-3: < 0.3 keV
width KAl 5-4: < 0.05 keV

Firsts Results: Aluminum



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KAl 4-3	**106.48 ± 0.16**	**106.57**
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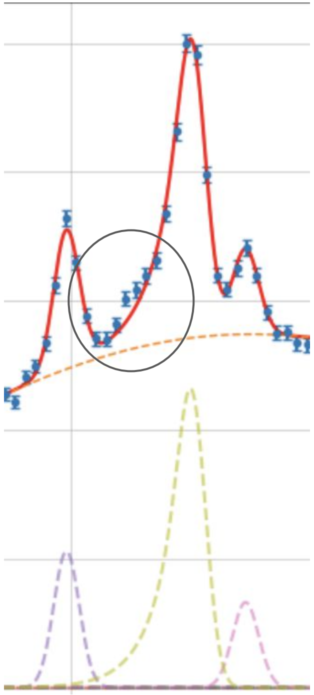
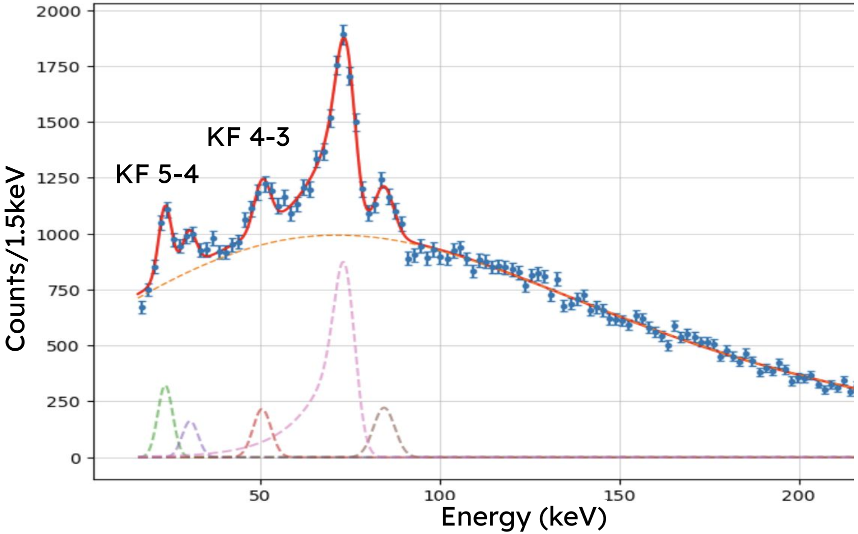
ΣAl 6-5	**62.73 ± 0.50**	**63.2**

26 days run with Al Target
(>100 pb-1 delivered)



Fit without Sigmonic line shows a clear excess

Firsts Results



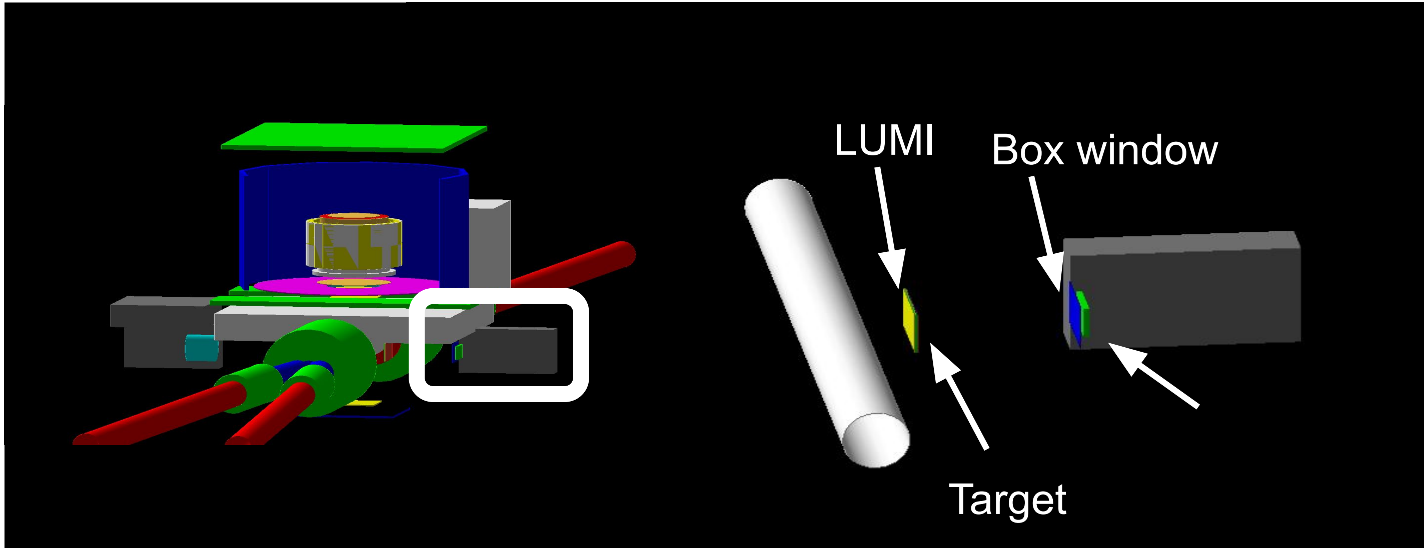
Transition	Energy (keV)	Th. Energy (keV)
KF 4-3	50.58 ± 0.29	50.59
KF 5-4	23.60 ± 0.15	23.4

18 days run with Teflon (C2F4) Target
(~70 pb-1 delivered)

First Results

work in progress:

- Relative and Total Yields evaluation

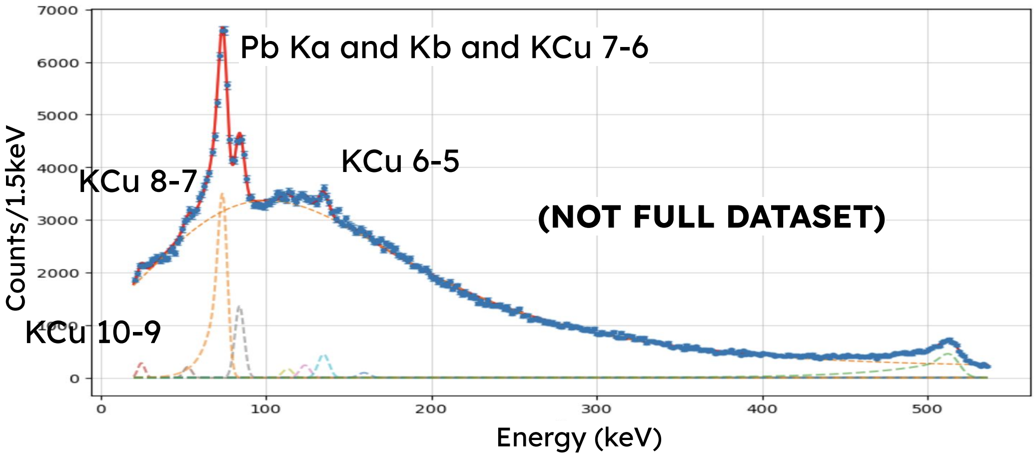


First Results

work in progress:

- Relative and Total Yields evaluation

- Analyzing data with different targets (Cu, Pb)



Transition	Energy (keV)	Th. Energy (keV)
KCu 6-5	134.79 ± 0.24	134,81
KCu 8-7	52.69 ± 0.36	52.63

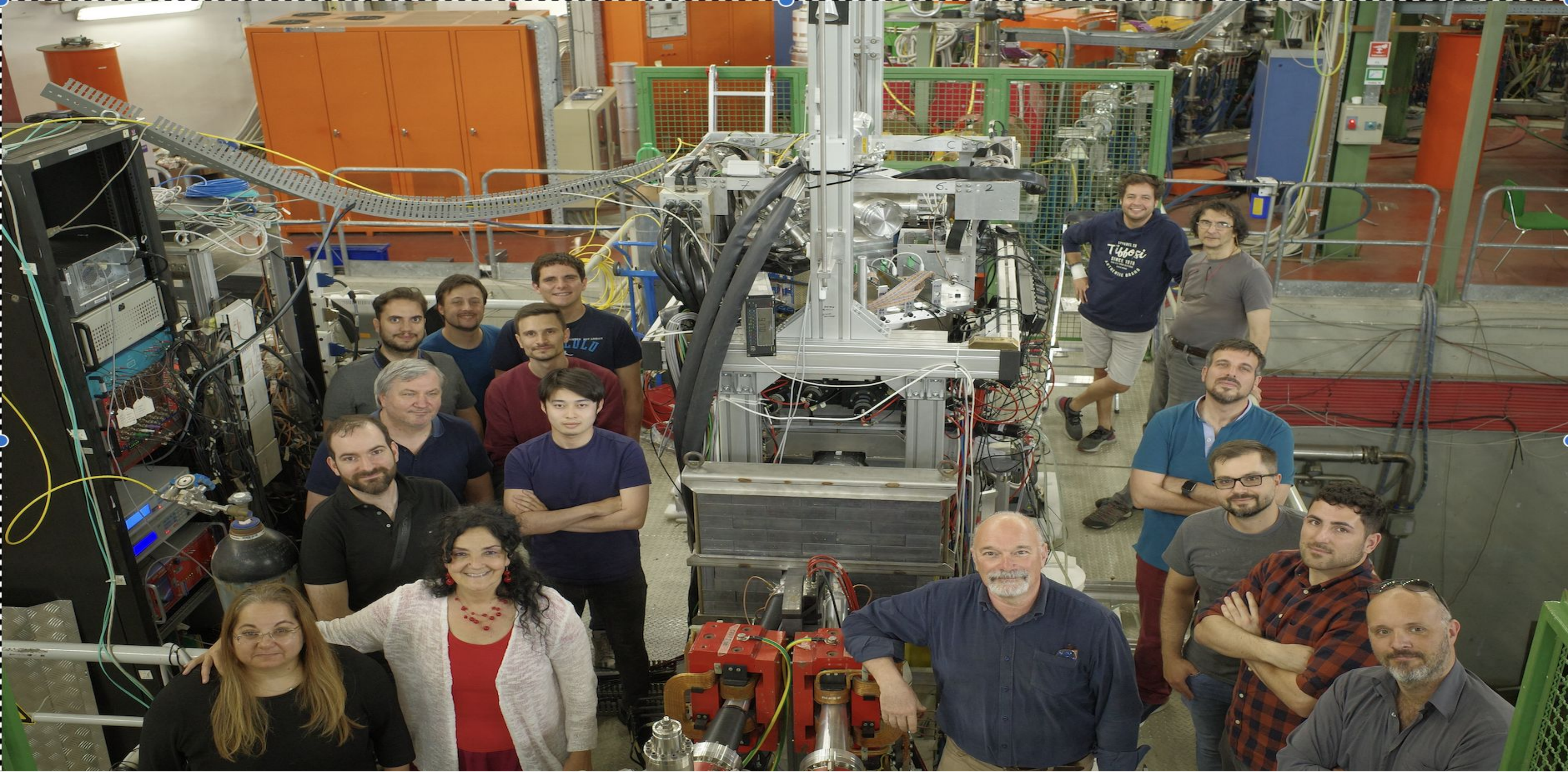
First Results

work in progress:

- Relative and Total Yields evaluation
- Analyzing data with different targets (Cu, Pb)
- Evaluating the impact of the results on fundamental physics.

Conclusions

- CDZnTe is a promising semiconductor to build compact X-ray detection systems at room temperature in the range from tens to hundreds keV.
- The SIDDHARTA-2 collaboration managed to first apply this new technology in a high background environment as the DAFNE collider, for fundamental physics research linked to kaonic atoms.
- The last data taking at DAFNE collider is promising and already led to first observations of intermediate mass kaonic atoms transitions with the new detection system.
- These results represent a solid basis for the future EXCALIBUR project at DAFNE, and for future applications in other accelerators (JPARC).

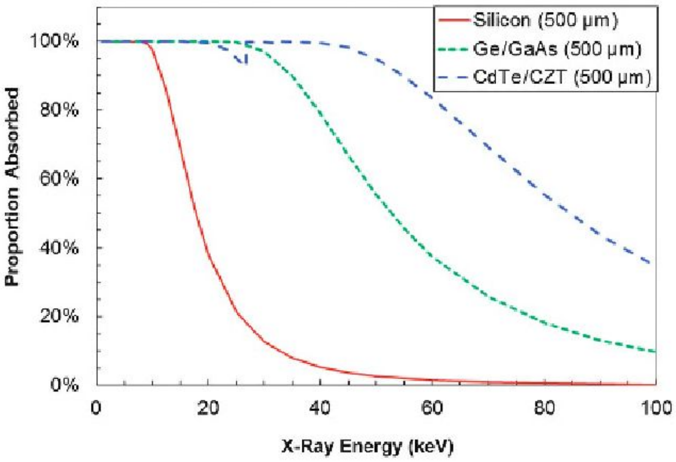


THANK YOU FOR YOUR ATTENTION

Why Cadmium Zinc Telluride?

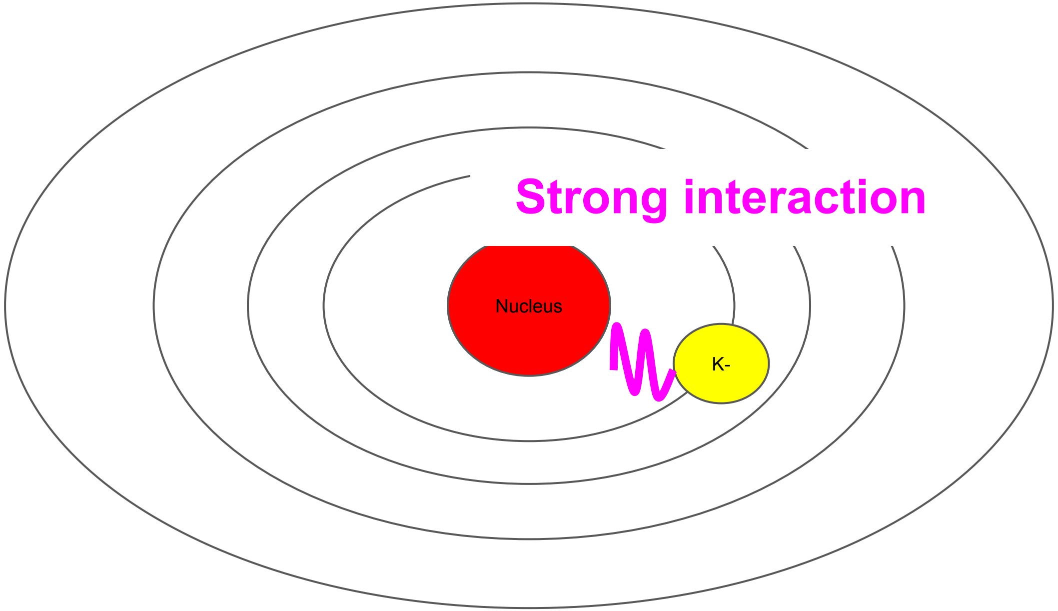
- **Silicon** represents the best semiconductors in terms of availability, efficiency and resolution, to build a compact X-ray detectors, but **his efficiency falls down fast to tens of keV energies**.

- **Germanium** is a natural semiconductor, which is a great advantage for producing high-quality crystals for detectors. However, HPGe detectors **cannot be operated at room temperature**, and need invasive setups.



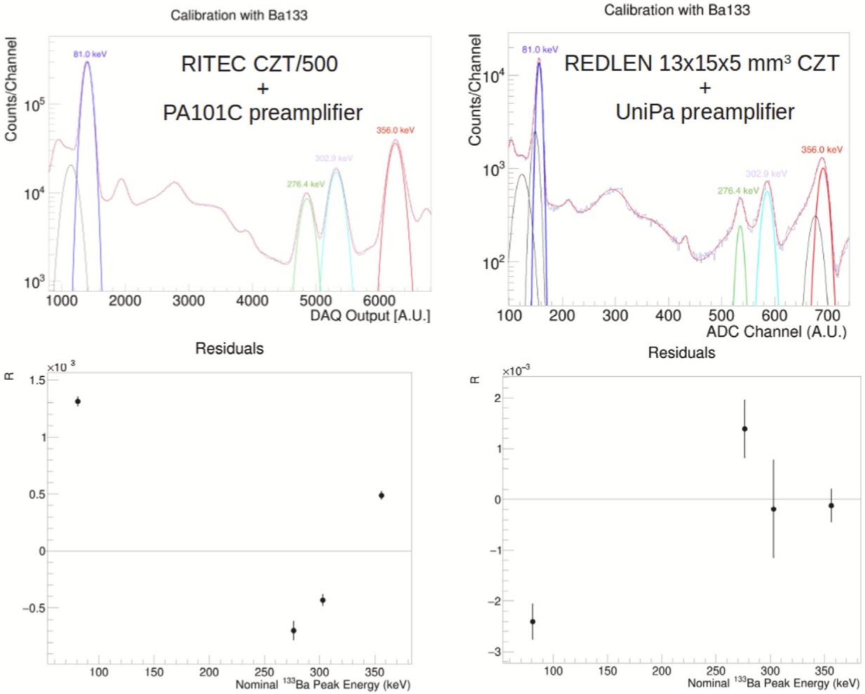
Pennicard, D. *et al.* Semiconductor materials for x-ray detectors. *MRS Bulletin* **42**, 445–450 (2017). https://doi.org/10.1557/mrs.2017.95

Kaonic Atoms: K-N Interaction



In the last level of the atom kaon interact with nucleus also by strong interaction, and then **interact at threshold with nucleons and** is absorbed.

The time to reach the last level is 1e-9s - 1e-12s, while τ_K=1e-8s


Calibration with Ba133
RITEC CZT/500
+
PA101C preamplifier
Counts/Channel
DAQ Output [A.U.]
81.0 keV
276.4 keV
302.9 keV
356.0 keV
Residuals
Nominal 133Ba Peak Energy (keV)
Calibration with Ba133
REDLEN 13x15x5 mm3 CZT
+
UniPa preamplifier
ADC Channel (A.U.)
Residuals

First Results

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work in progress:

Analyzing data with different targets

evaluating the impact of the results on fundamental physics