New CdZnTe Detectors for Exotic Atoms Research

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Outline

01	X-ray Detectors at LNF	• Descriptions • Characteristics • Applications
02	New CdZnTe Detectors	• Why CdZnTe? • Detector Properties • Development of the new detector
03	Kaonic Atoms	• Theory of Kaonic Atoms • Relevance in Physics Researches • Intermediate Mass Kaonic Atoms
04	Tests and Measurements	• Experimental Setup • Test on Resolution • Recent Kaonic Atoms Observations
05	Conclusions	

X-ray Detectors at LNF

X-Ray Detectors for Physics Researches at LNF

The development of different X-ray (and gamma ray) detection systems is essential to explore a wide gap of energy regions and observables.

For applications in many fields of physics research, it is useful to develop detectors with:

- Different features (efficiency/resolution/radiation damage in different energy range)
- Different usage in X-ray measurements. (high rate vs low rate)
- Different operation conditions (cooling vs no cooling)

X-Ray Detectors for Physics Researches at LNF

Crystal Spectrometer

Silicon Drift Detectors

Cadmium Zinc Telluride Detectors

High Purity Germanium Detectors

X-Ray Detectors Properties

Crystal Spectrometer →

- High Resolution
- Low Efficiency
- 0-20 keV Range

Silicon Drift Detectors →

- 130 eV FWHM at 6 keV Resolution
- High Efficiency
- 0-40 keV Range

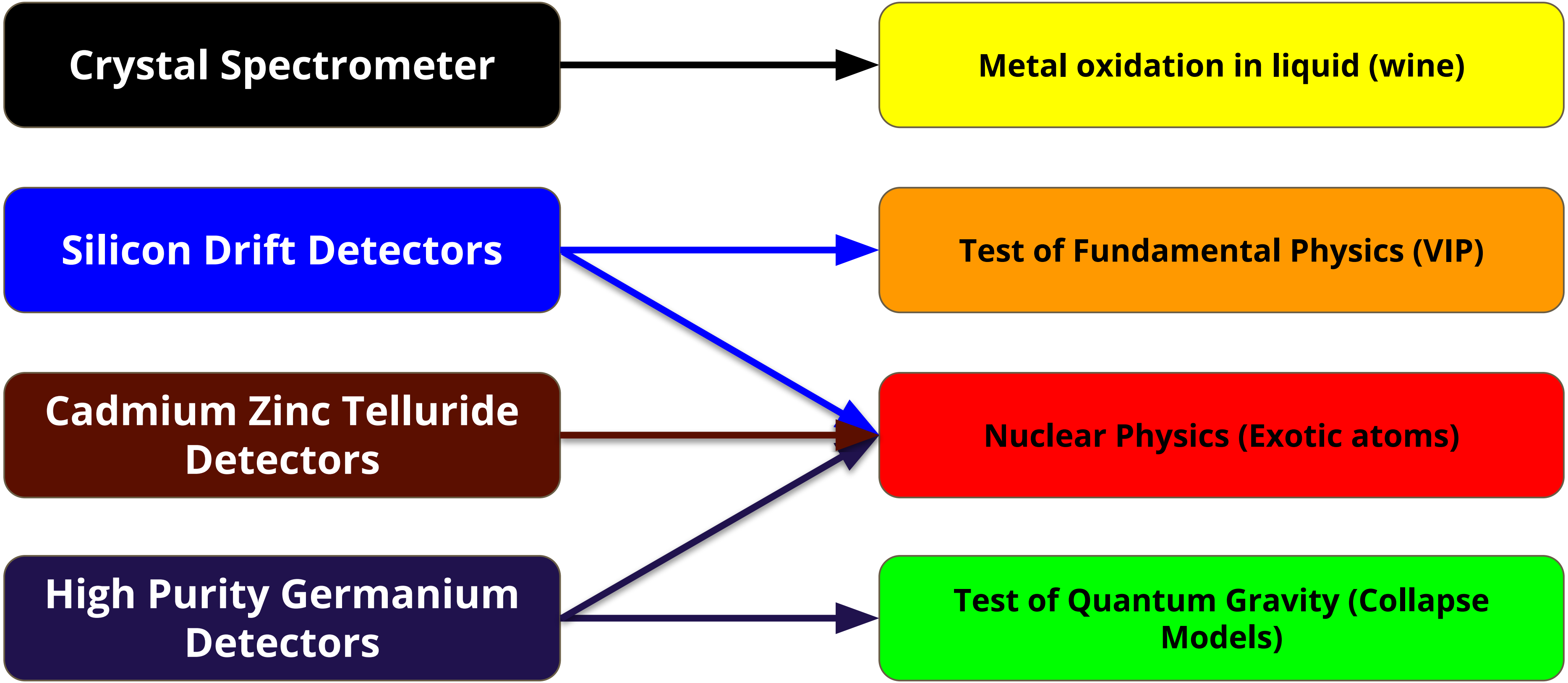
Cadmium Zinc Telluride Detectors →

- Resolution ~ 5% at 100 keV
- High Efficiency at **room temperature**
- 20-400 keV Range

High Purity Germanium Detectors →

- High Efficiency
- ∽1% at 383 keV Resolution
- 10 keV to MeV Range

X-Ray Detectors Applications

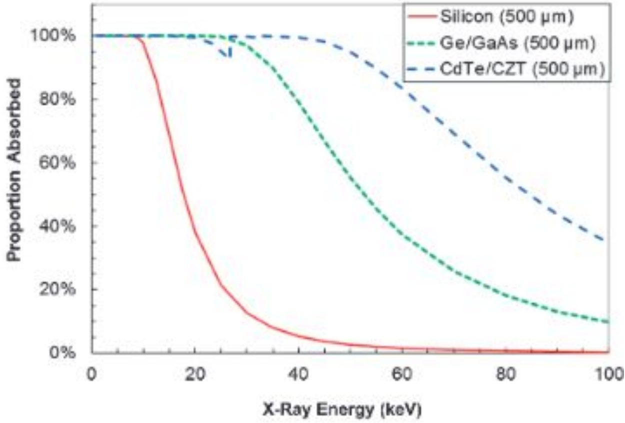


Cadmium Zinc Telluride Detectors

Why Cadmium Zinc Telluride

- **Silicon** represents nowadays 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**. To go to higher energies one needs high-Z semiconductors

- **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**.



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

CdZnTe 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**. Ideal to build compact systems without the need of cooling.

- Impurities during the growth alter the performances.

- Intense studies to upgrade the quality of the crystals in last decades, that **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.

Del Sordo, S. et al., *Sensors* **9**. Number: 5, Iniewski, K. *Journal of Instrumentation* **9**, C11001, Tang, J., Kislat, F. & Krawczynski, H. *Astroparticle Physics* **128**, 102563,
Schlesinger, T. E. et al. *Materials Science and Engineering: R: Reports* **32**, 103–189, Abbene, L. et al. *Journal of Synchrotron Radiation* **27**.

The Development of New CdZnTe Detectors at LNF

- Use of different CZT crystals produced by REDLEN (Canada) and IMEM-CNR (Parma)

- Expertise of the UniPa DiFC Emilio Segré group (now part of the SIDDHARTA-2 Collaboration) for the electronics.

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

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

Kaonic Atoms

Physics Case: Kaonic Atoms

- Exotic atoms are atoms in which a negatively charged particle replaces the outermost electron in an atom and bounds to a nucleus.

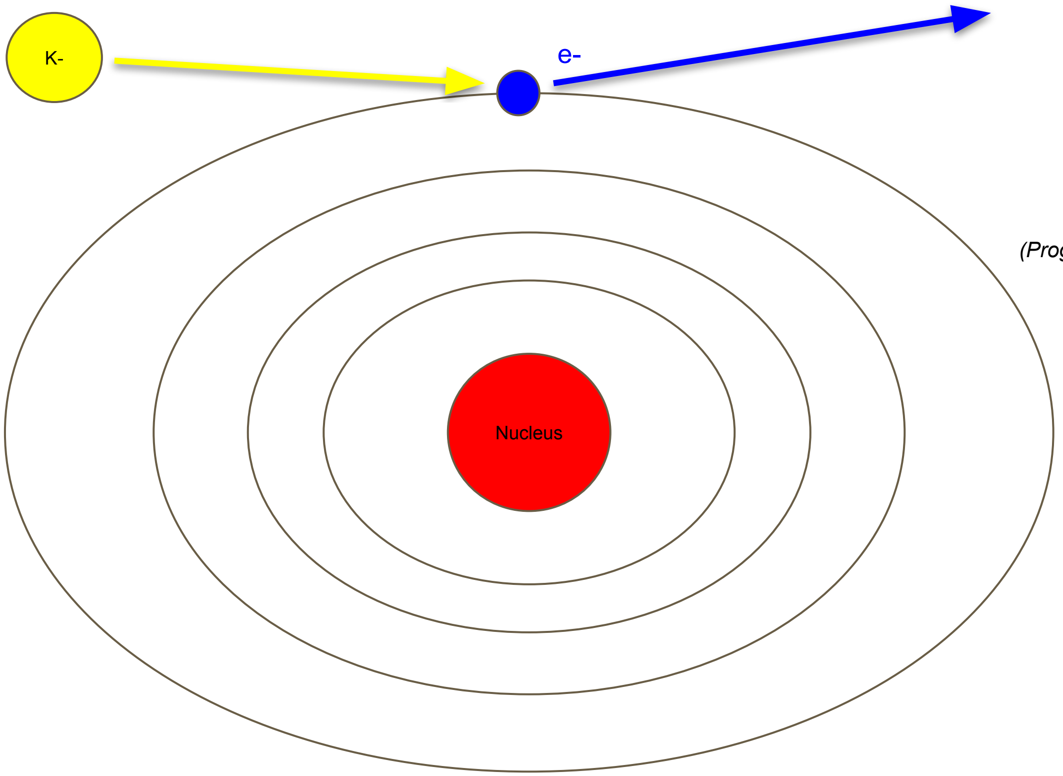
- Exotic atoms with muons, pions, kaons, antiprotons and hyperons were observed.

- Predicted by Tomonaga and Araki (*phys. Rev.* ***58*** *90-91, 1940)*, Conversi Pancini and Piccioni (*phys. Rev.* ***68*** *232-232, 1945, phys. Rev.* ***71*** *209-210, 1947)*, Fermi and Teller(*phys. Rev.* ***72*** *399-408, 1947).*

- Finally produced and studied exploiting accelerators. Important for low-energy QCD Studies.

(Rev. Mod. Phys, **91**, *June 2019)*

Kaonic Atoms: Formation



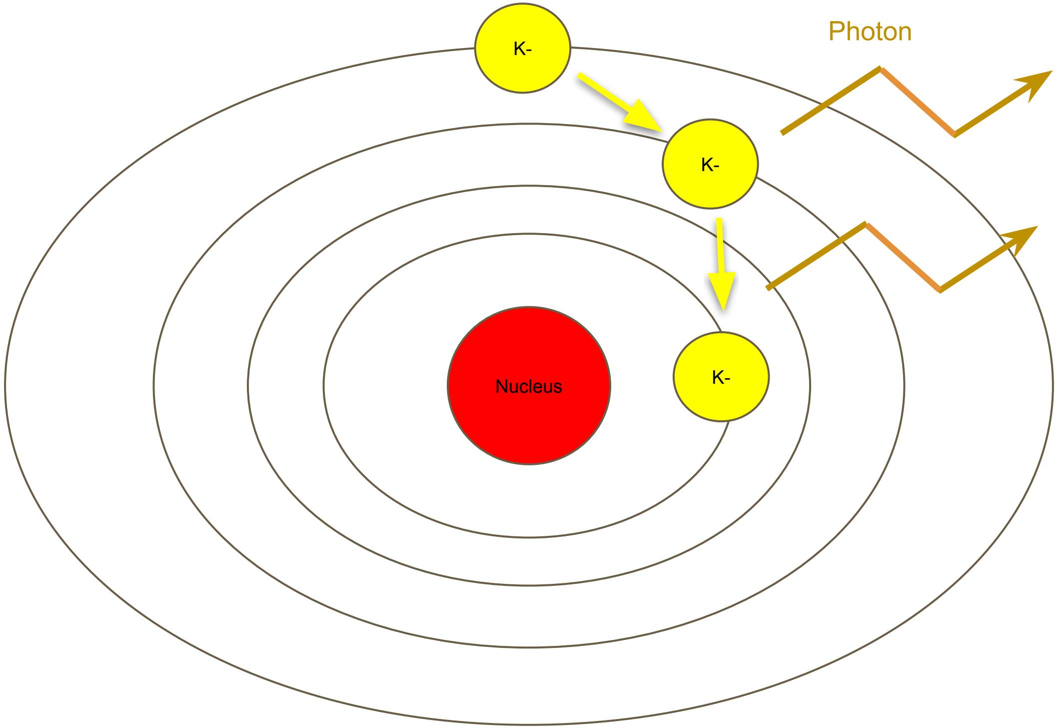
$r_b^e \sim r_b^k$

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

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

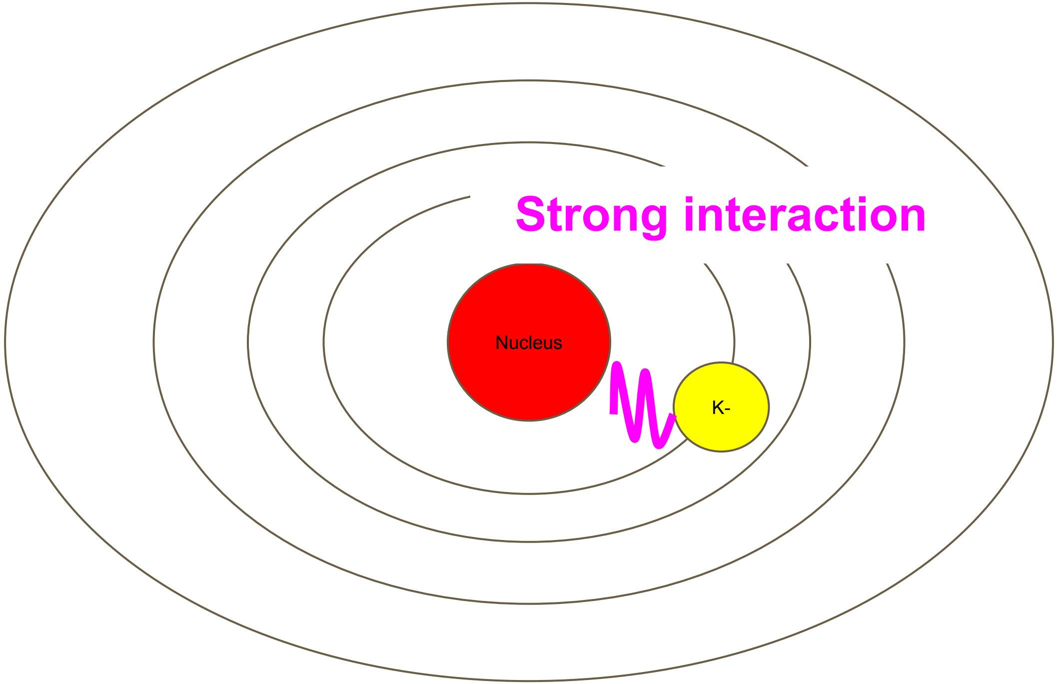
H n=1 level ~ KH n=25 level

Kaonic Atoms: Cascade



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

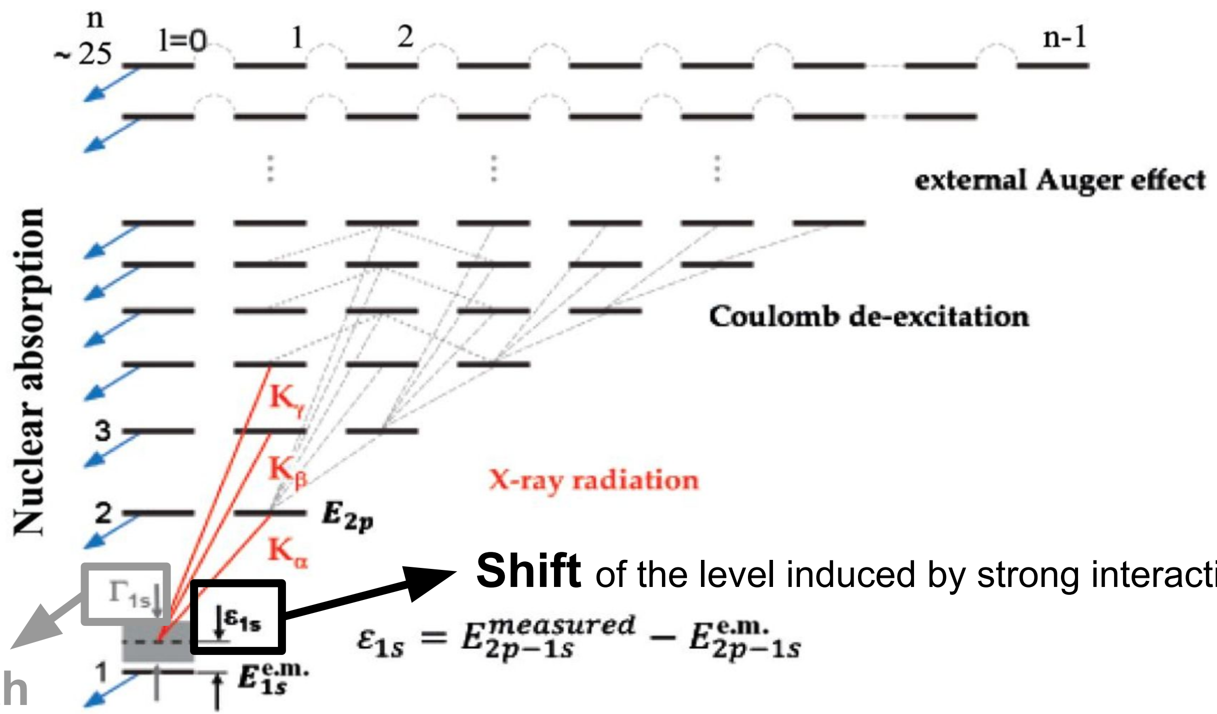
Kaonic Atoms: K-N Interaction



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

Importance of kaonic Atoms in QCD



Shift of the level induced by strong interactions.

$$\varepsilon_{1s} = E_{2p-1s}^{measured} - E_{2p-1s}^{e.m.}$$

Width

of the level induced by the small lifetime.

Importance of kaonic Atoms in QCD

Compute **σ** using a potential for strong interactions coming from different models based on χPT theory.

The cross-section at threshold is proportional to

Measurement of **shift** and **widths** of kaonic atoms

Deser-Trueman Formula

THEORY

Scattering Length

EXPERIMENT

(Rev. Mod. Phys, ***91****, June 2019)*

Importance of kaonic Atoms in QCD

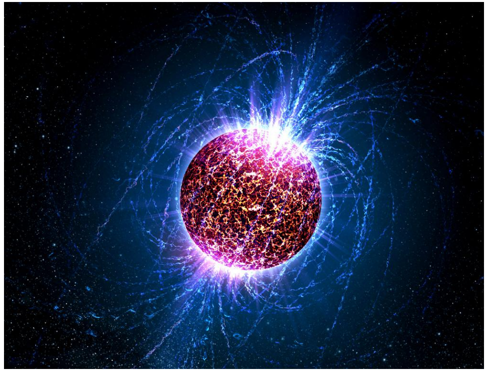
- From **K-H** and **K-D** one can get info on **K-p** and **K-n** scattering lengths.

- Combining K-H and K-D measurement one can disentangle the two **K-N isospin dependent scattering lengths**.

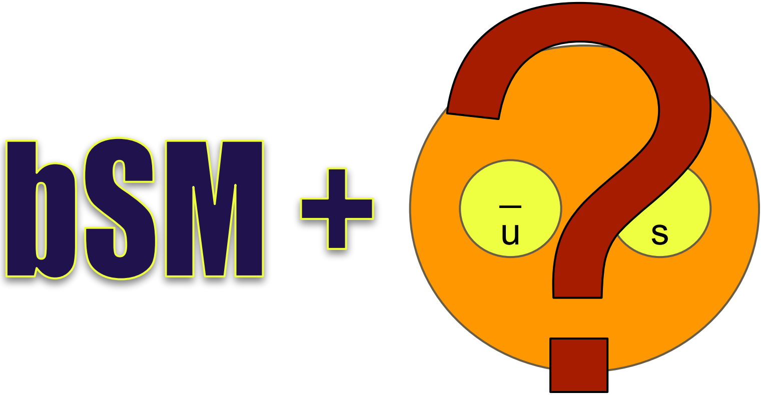
Importance of kaonic Atoms in QCD (and more)

It is also important to study the kaonic atoms transitions with different:

- **Z,** because it is important to have a clear picture on the K-N and K-multiN interactions in function of the nuclear density.



- **n**, because it is a test of QED and it is important for possible measurement of kaon mass and atomic cascades.



Intermediate Mass Kaonic Atoms

- Measurement performed recently casted doubts about the whole kaonic Atoms dataset, from experiment done more than 40 years ago.

- Some kaonic atoms are problematic in models, and present incompatible measurements.

- With new detection techniques, more precise results are achievable.

Target	Transition	Energy (keV)	Shift* (keV)	Width* (keV)	Yield* (%)
C	$3 \to 2$	62.9	-0.590 ± 0.080	$1.730 \pm .150$	7.0 ± 1.3
Al	$3 \to 2$	302.3	//	//	//
Al	$4 \to 3$	105.8	-0.130 ± 0.050	0.490 ± 0.160	//
			-0.076 ± 0.014	0.4 ± 0.022	55 ± 3
S	$4 \to 3$	160.8	-0.550 ± 0.060	2.330 ± 0.200	22 ± 2
			-0.43 ± 0.12	2.310 ± 0.170	//
			-0.462 ± 0.12	1.96 ± 0.17	23 ± 3

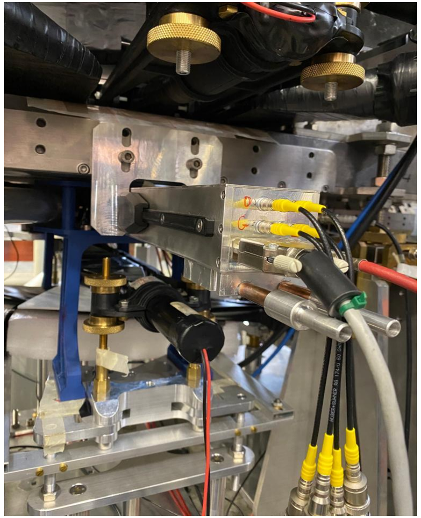
New Tests and Measurements with CZT Detector

Firsts Tests in DAFNE

Test with 1cm^2 commercial CdZnTe (RITEC).

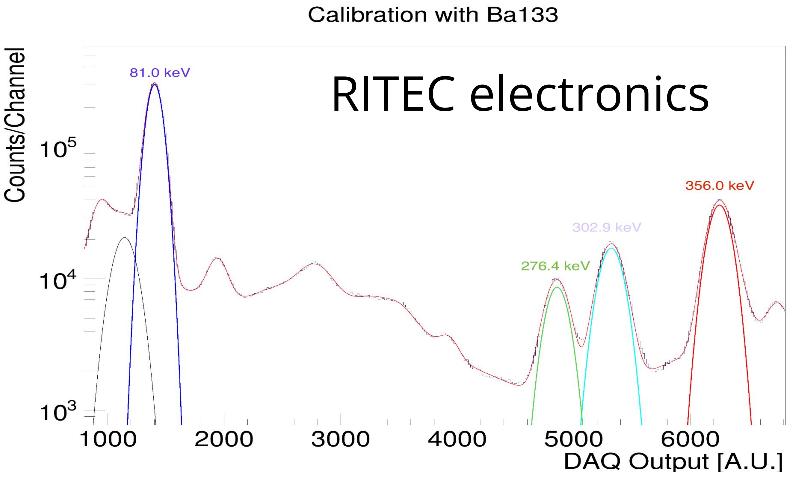
+

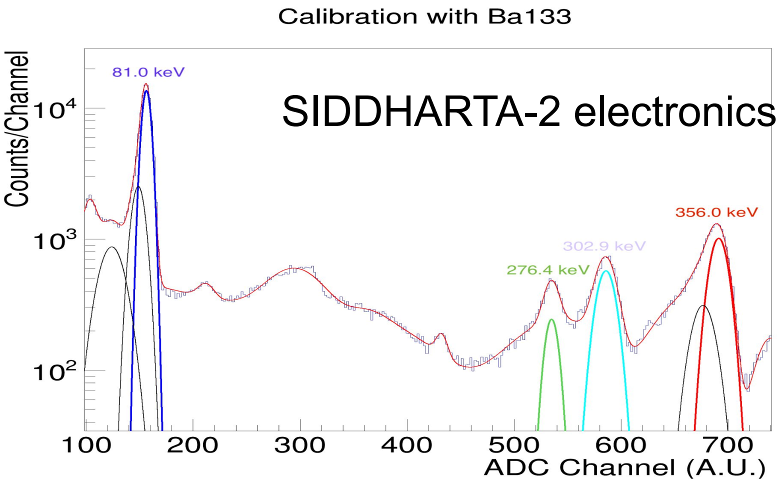
Test with 8cm^2 REDLEN CdZnTe in DAFNE and customized electronics.



Test on timing and resolution to notice improvements with the new electronics.

Test on Resolution



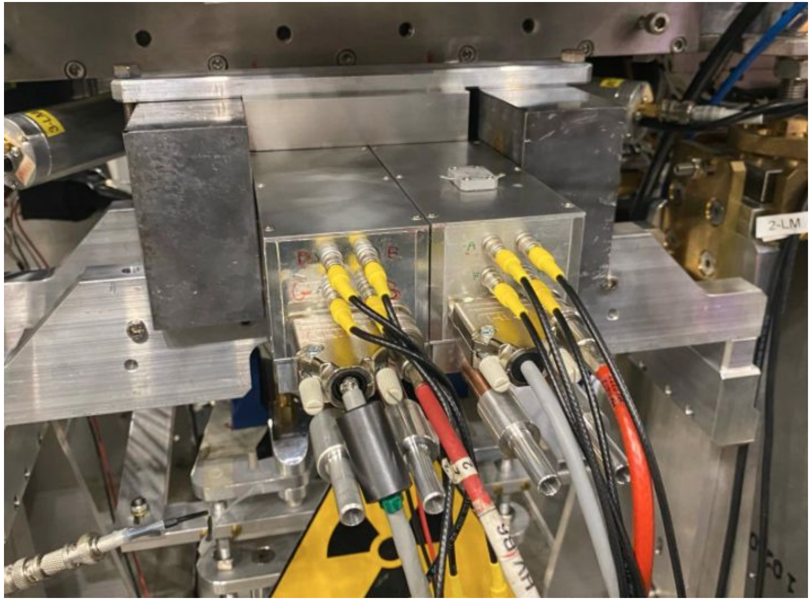


A. Scordo *et al. Nuclear Inst. and Methods in Physics Research, A* **1060** *(2024) 169060*

	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

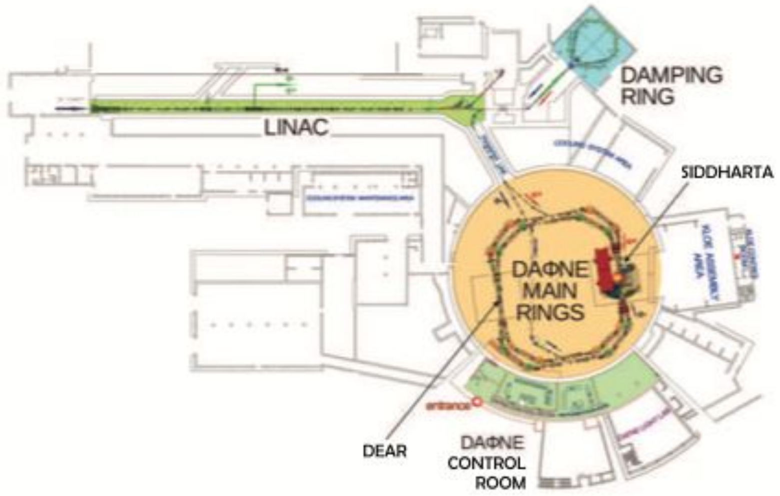
Significant improvements in terms of resolution, maintaining a good linearity.

Kaonic Atoms Measurements in DAFNE



- Two array of four 13x15x5 mm^3 crystals from REDLEN, installed in DAFNE.
- Goal: Study the feasibility of an experiment to measure kaonic atoms transitions from K-Al, K-Cu, K-S with CZT detectors.
- Now taking data.

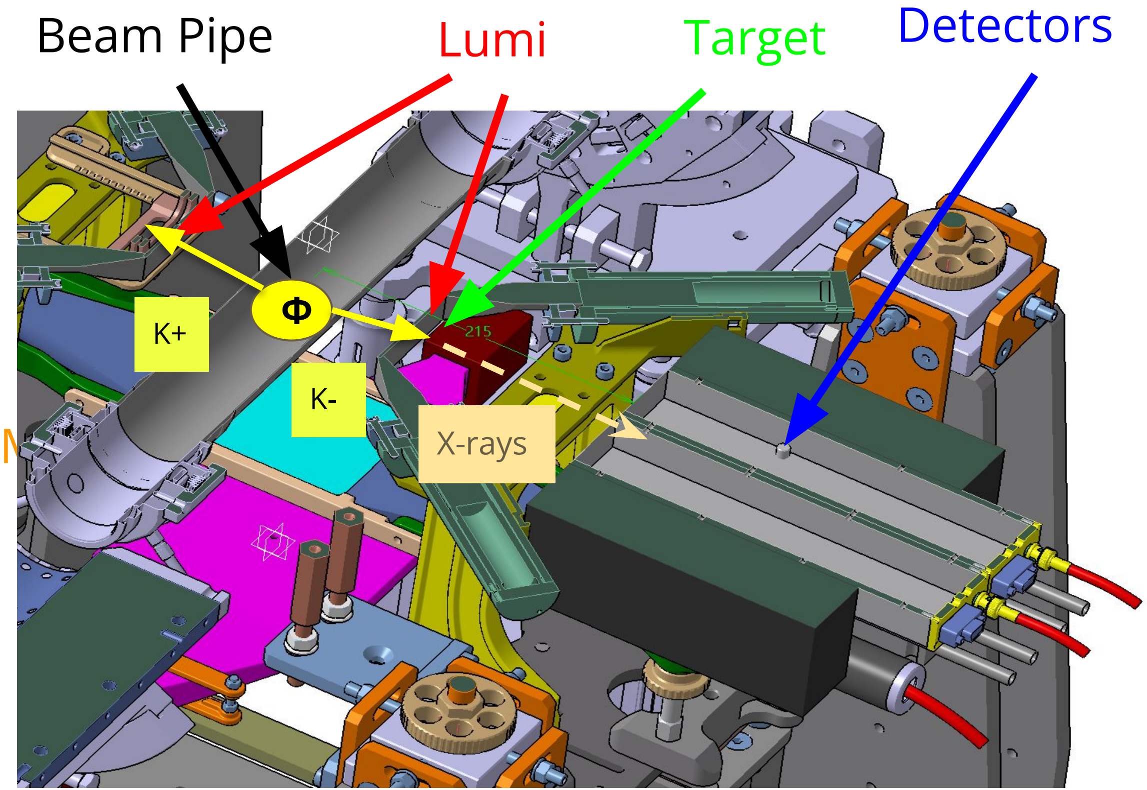
The DAΦNE Collider



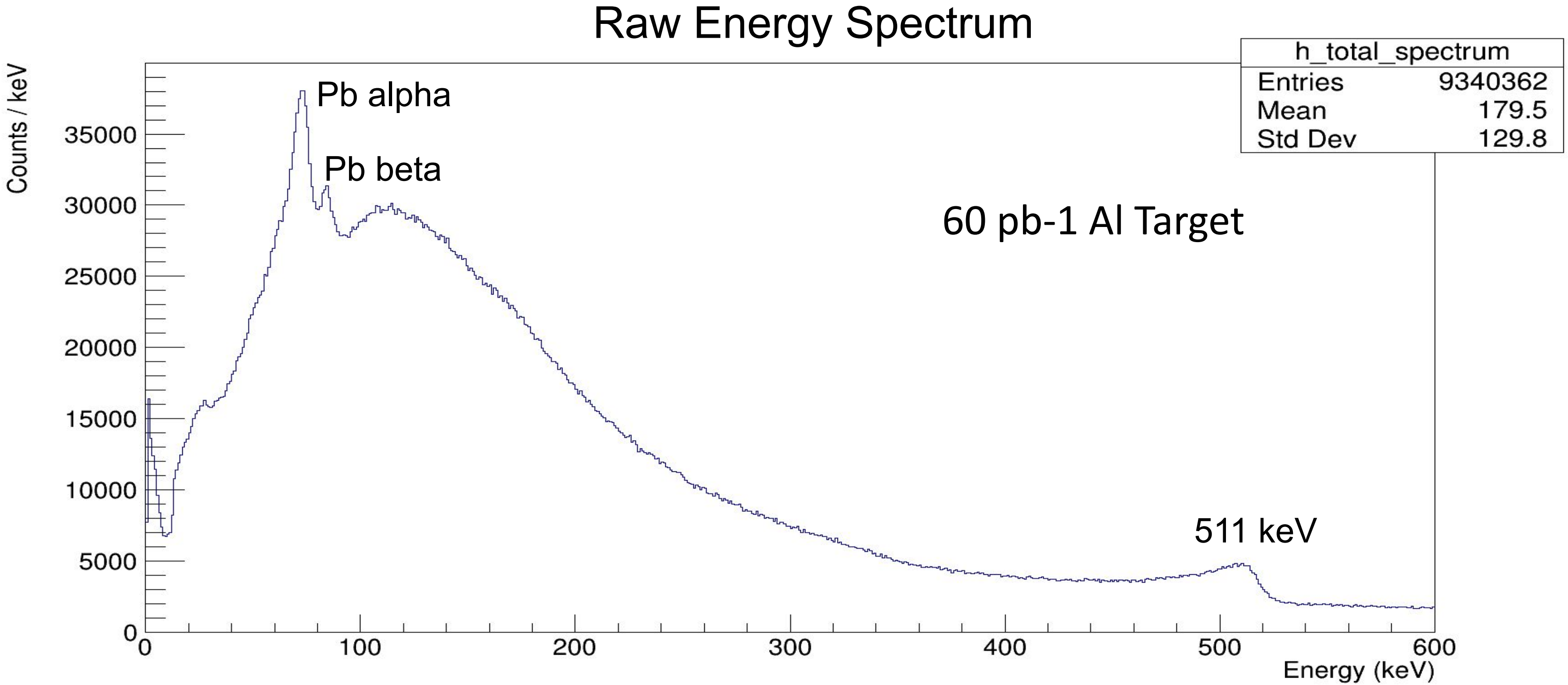
- double ring lepton collider working at the **c.m. energy of Φ resonance** (Φ-factory) (m_{Φ}= 1.02 GeV)
- Φ decays in a couple of charged kaons with a **BR(Φ → K^+K^-) = 48%**
- The kaons are produced almost at rest (m_K = 493 MeV ⇒ **p_K =127 MeV**, β~0.26) with a small boost through the center of the rings.
- The Ks' momentum spread is almost null (Δp/p < 0.1%)

The Experimental Setup

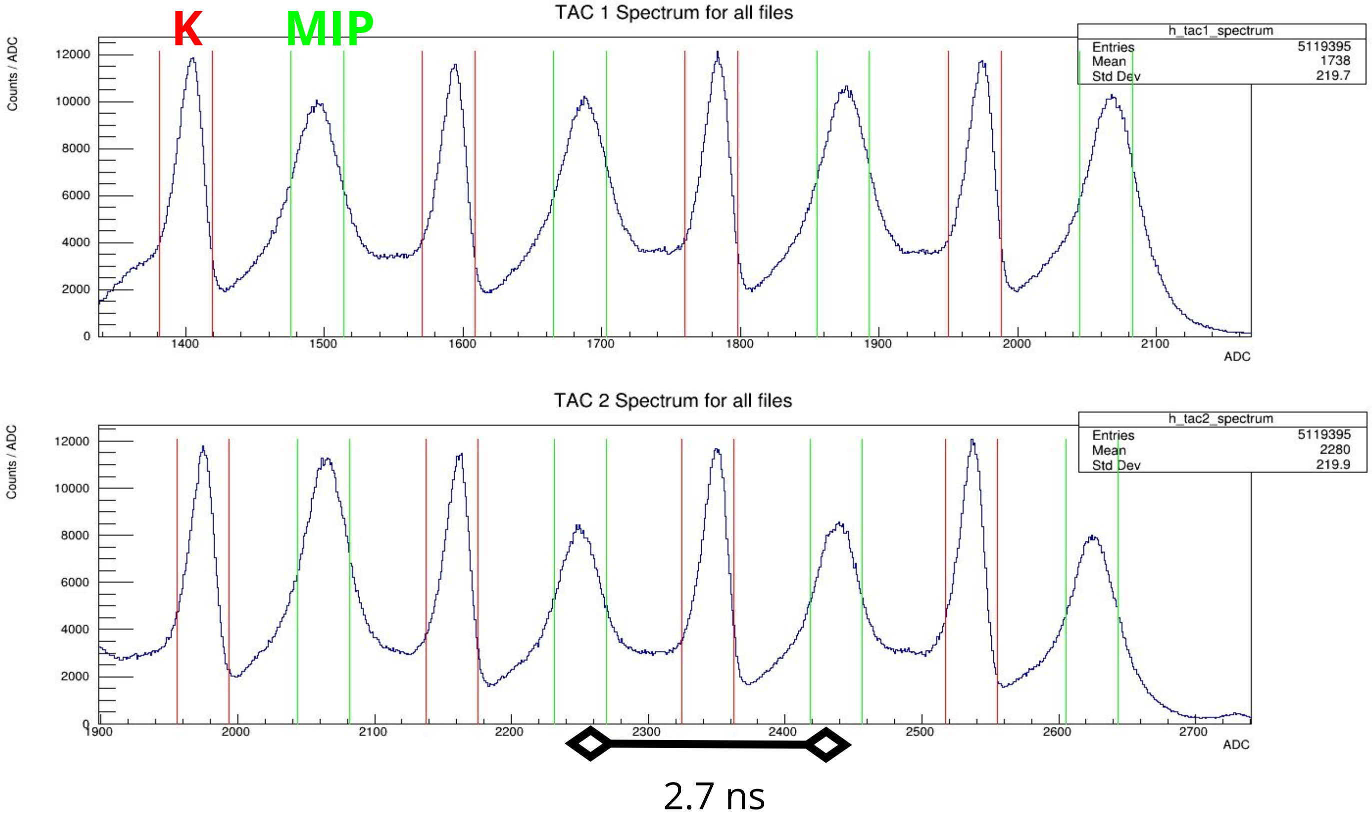
- Plastic Scintillators (Luminometers + TOF reconstruction)
- Target (optimized through M
Carlo simulations)
- New CZT Detector



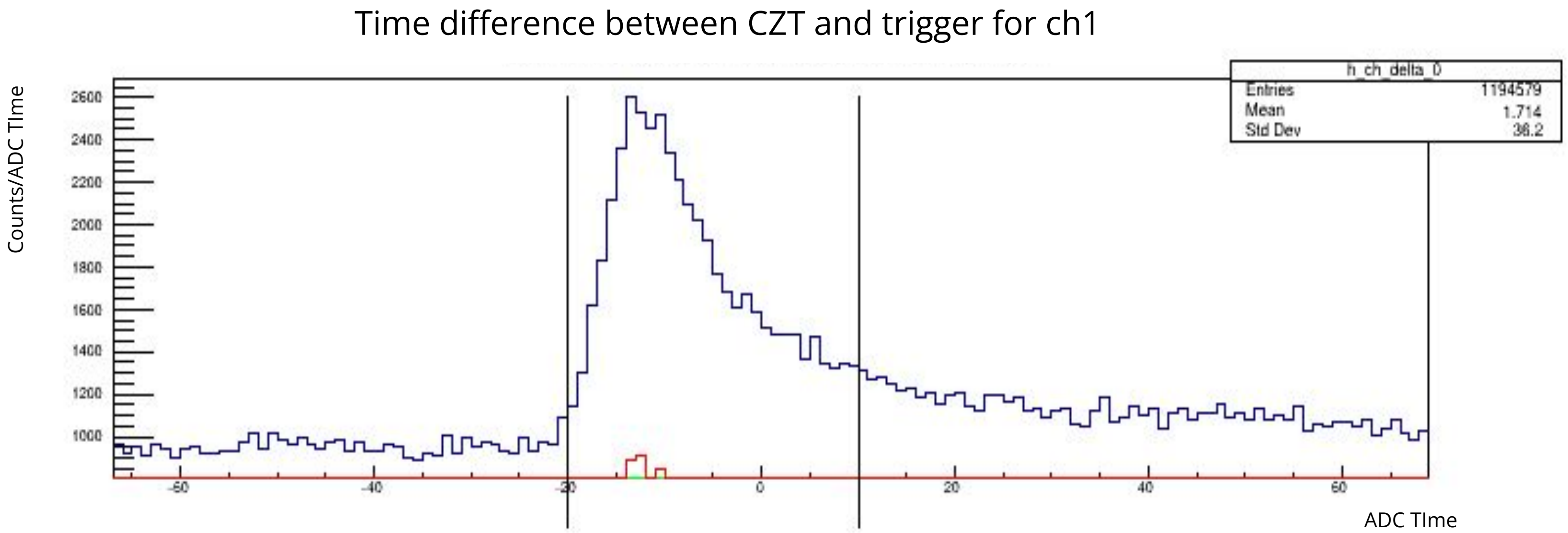
Measurements in DAFNE



Cut on Time Of Flight

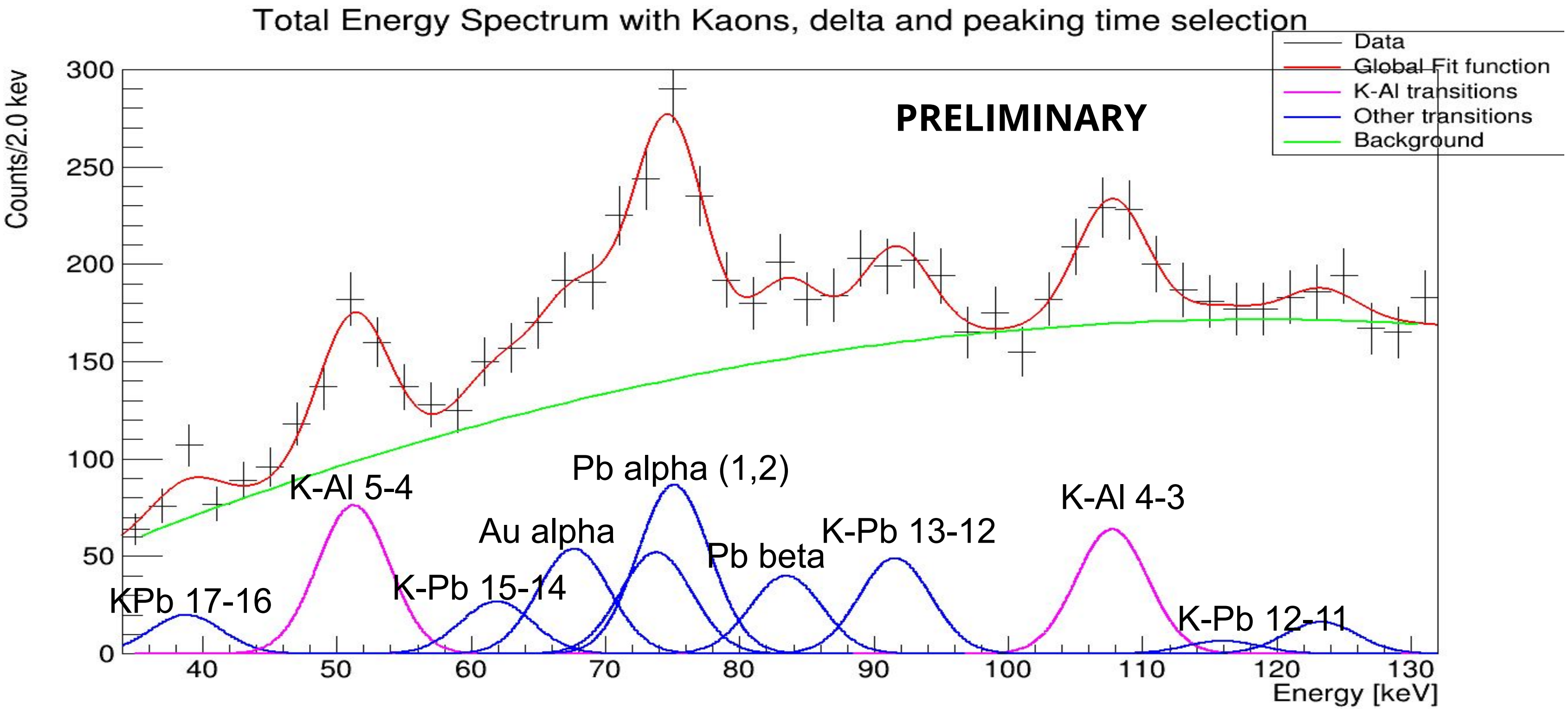


Cut on Time Difference



$< 1\mu s$

First Measurement in DAFNE



Resolution ~5% at 100 keV also in high rate measurements

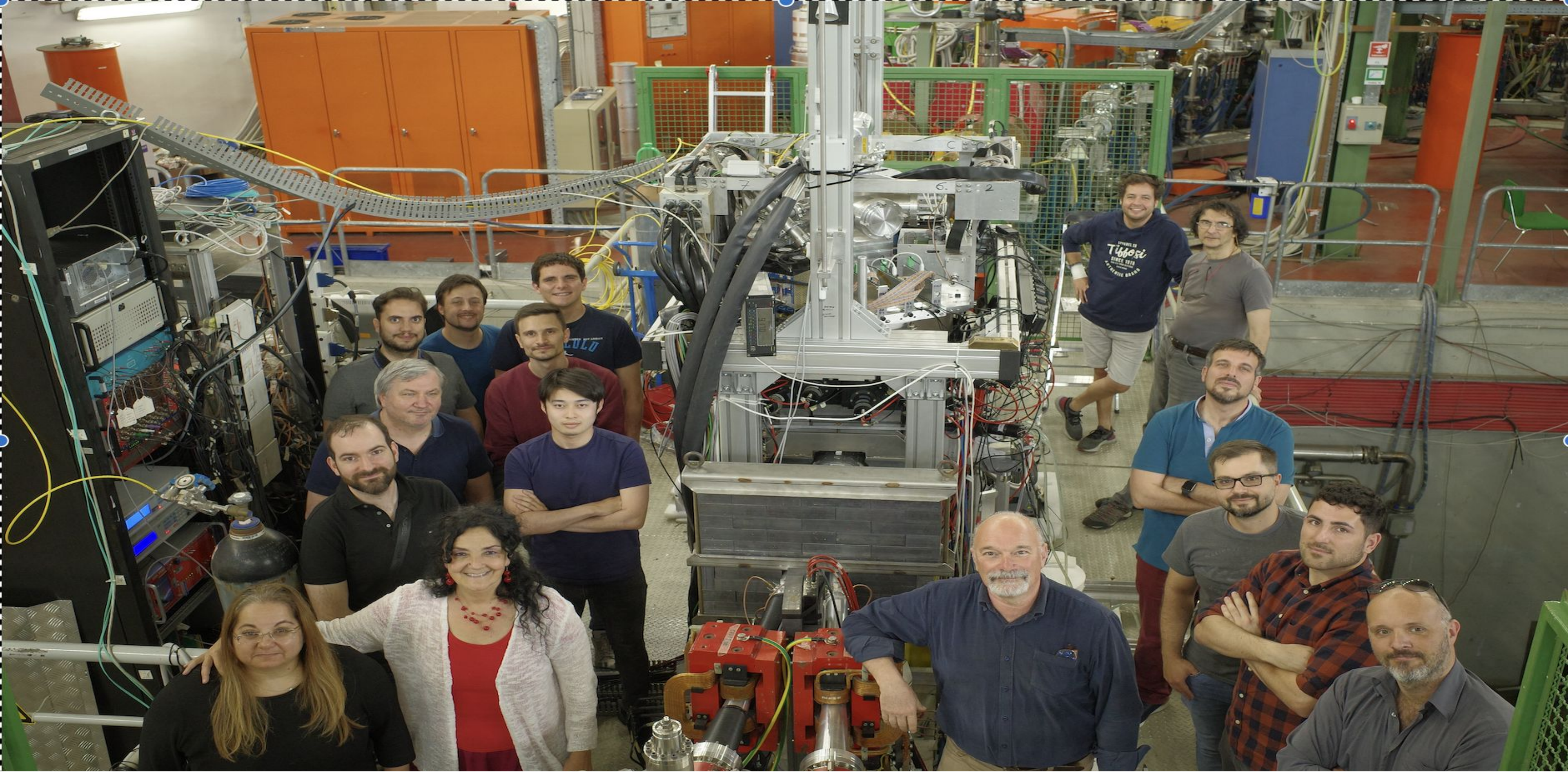
Conclusions

- CDZnTe is a promising semiconductor to build X-ray detection systems at room temperature in the range 20-400 keV.

- In recent times, the improvements on growth and electronics increased interest on these detector in the field particle and fundamental physics.

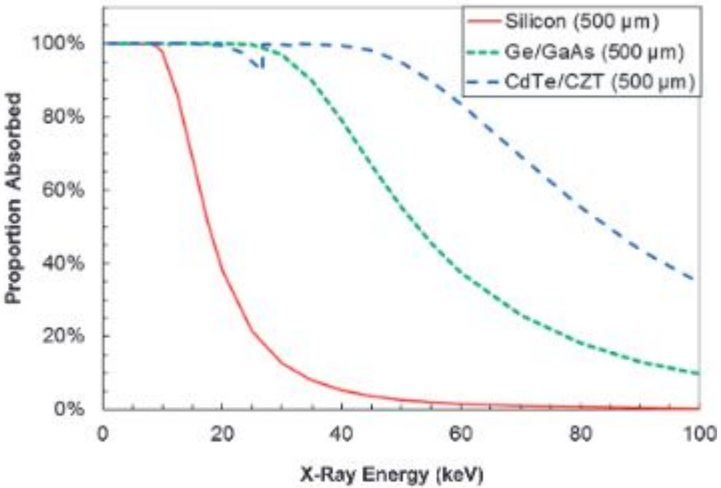
- The SIDDHARTA-2 collaboration managed to build new CZT detector with a resolution < 5% at 100 keV, beyond the current state of the art

- The current data taking at DAFNE collider is promising and already led to first observations of intermediate mass kaonic atoms transitions



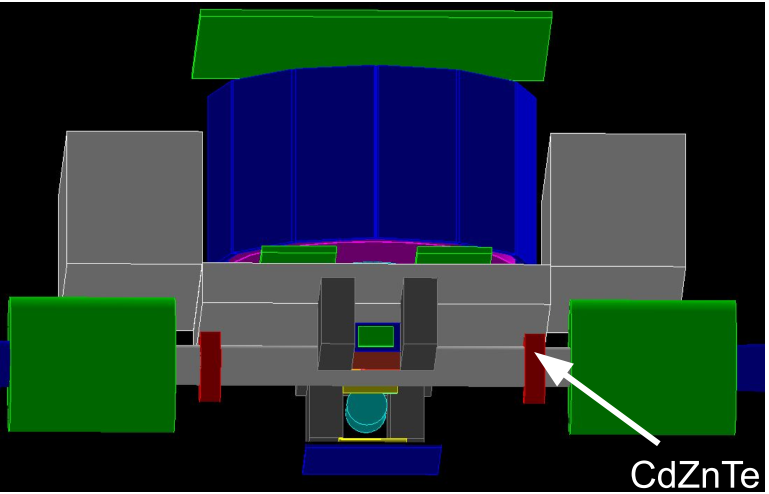
THANK YOU FOR YOUR ATTENTION

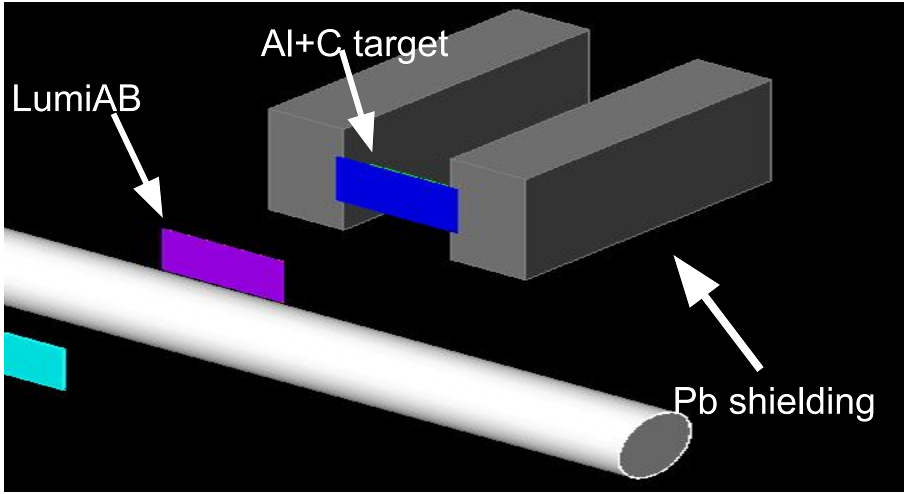
BACKUP



The notch in the curve at 30 keV occurs because, while x-ray absorption tends to fall with increasing photon energy, sudden increases in absorption occur at the point where the photon energy gets high enough to excite the inner-shell (k-shell) electrons of an atom

Long run with 16 cm^2 CdZnTe detector (from 11/2023): Simulations and expected results

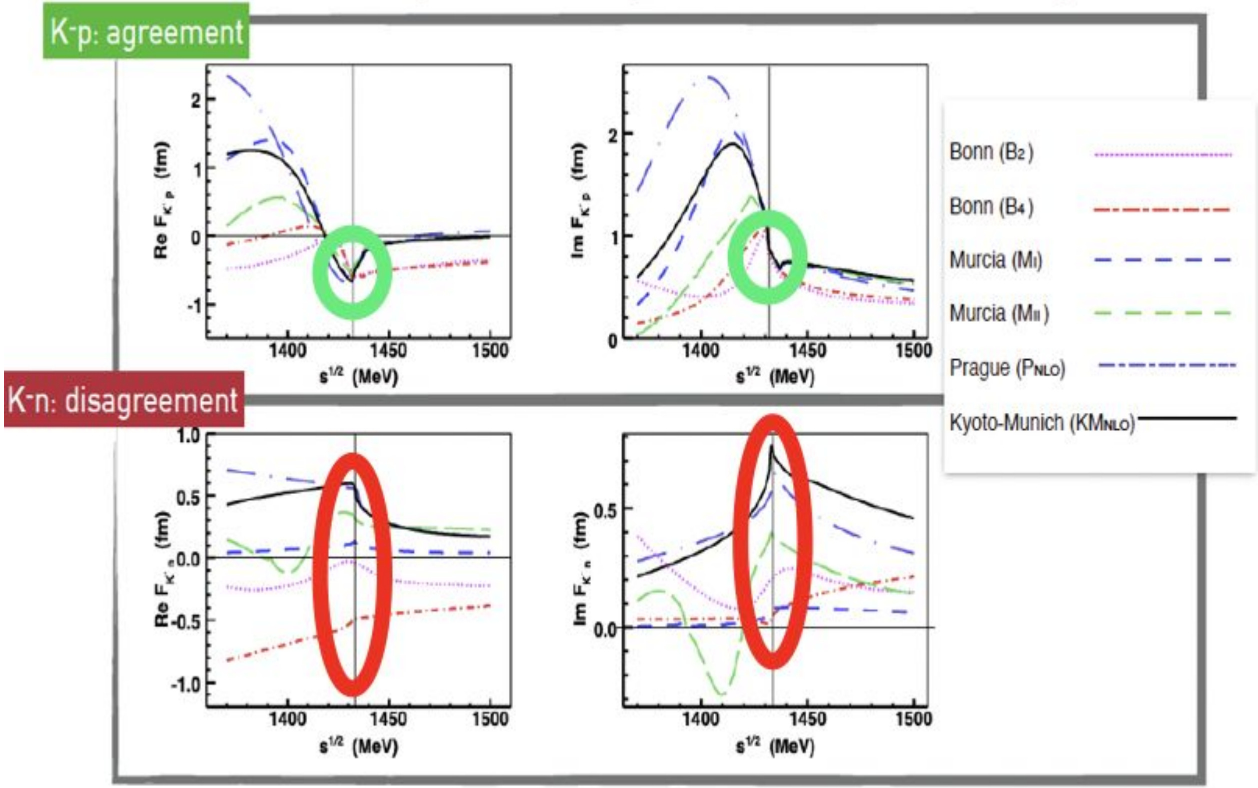




Main goals (for now):

- Optimize the set-up and targets' thickness.
- Estimate the results.

The SIDDHARTA-2 Experiment: Physics Goal

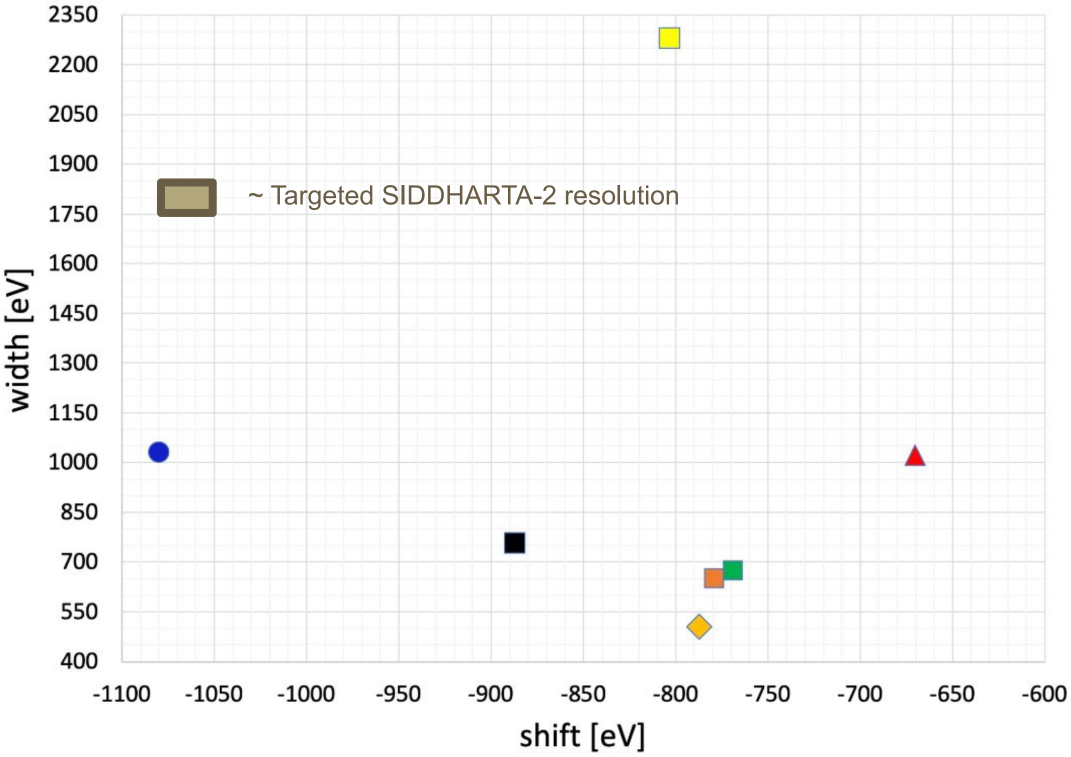


Measured by SIDDHARTA

To be measured…

A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

The SIDDHARTA-2 Experiment: Physics Goal

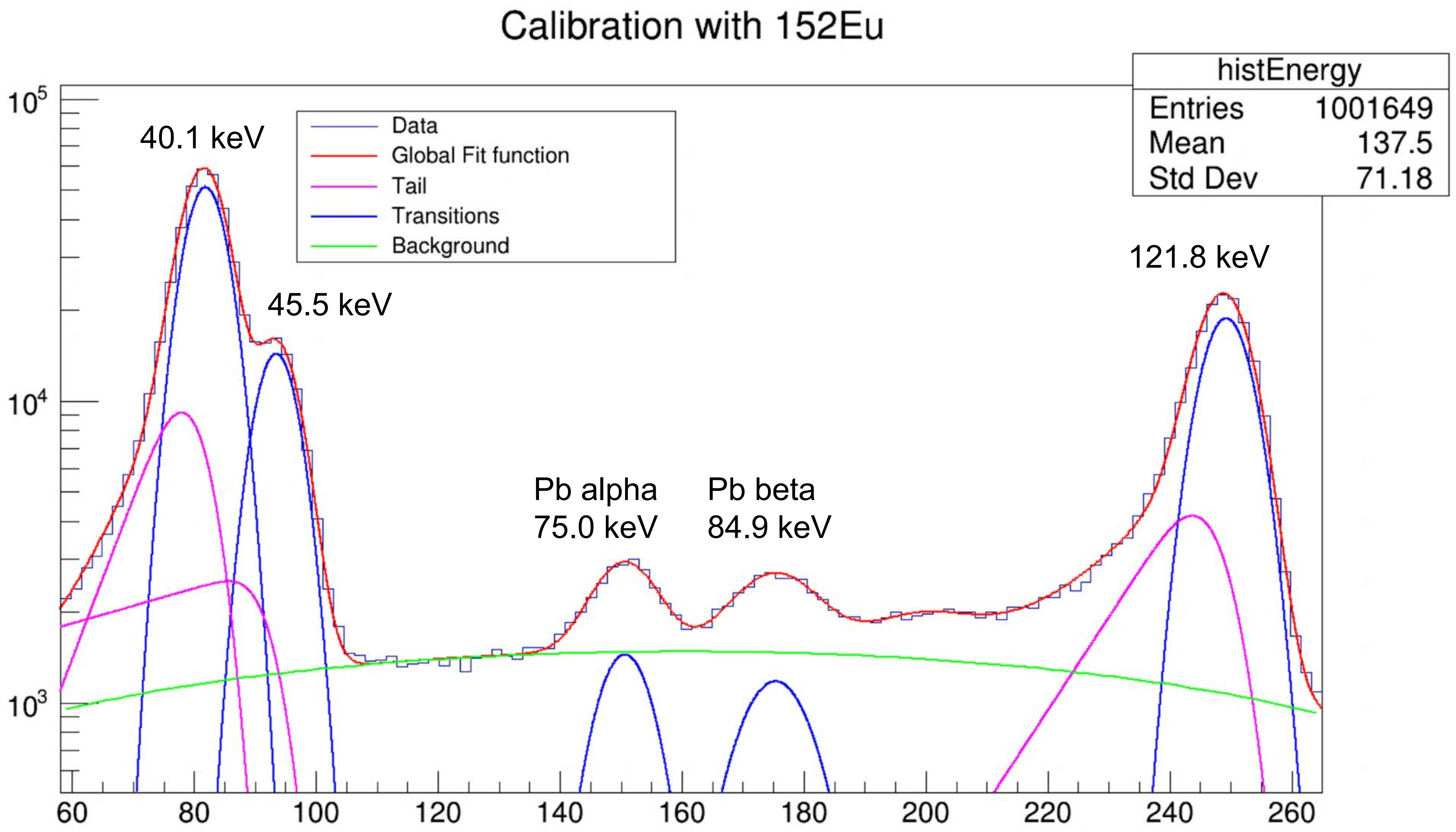


Old Era Experiments

Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	3 → 2	−0.04 ± 0.03	–	–	–	[15]
		−0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	3 → 2	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	3 → 2	−0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	3 → 2	−0.208 ± 0.035	0.810 ± 0.100	–	–	[18]
^{11}B	3 → 2	−0.167 ± 0.035	0.700 ± 0.080	–	–	[18]
C	3 → 2	−0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20	[18]
O	4 → 3	−0.025 ± 0.018	0.017 ± 0.014	–	–	[19]
Mg	4 → 3	−0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03	[19]
Al	4 → 3	−0.130 ± 0.050	0.490 ± 0.160	–	–	[20]
		−0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04	[19]
Si	4 → 3	−0.240 ± 0.050	0.810 ± 0.120	–	–	[20]
		−0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06	[19]
P	4 → 3	−0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30	[18]
S	4 → 3	−0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36	[18]
		−0.43 ± 0.12	2.310 ± 0.170	–	–	[21]
		−0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5	[19]
Cl	4 → 3	−0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7	[18]
		−0.94 ± 0.40	3.92 ± 0.99	–	–	[22]
		−1.08 ± 0.22	2.79 ± 0.25	–	–	[21]
Co	5 → 4	−0.099 ± 0.106	0.64 ± 0.25	–	–	[19]
Ni	5 → 4	−0.180 ± 0.070	0.59 ± 0.21	0.30 ± 0.08	5.9 ± 2.3	[20]
		−0.246 ± 0.052	1.23 ± 0.14	–	–	[19]
Cu	5 → 4	−0.240 ± 0.220	1.650 ± 0.72	0.29 ± 0.11	7.0 ± 3.8	[20]
		−0.377 ± 0.048	1.35 ± 0.17	0.36 ± 0.05	5.1 ± 1.1	[19]
Ag	6 → 5	−0.18 ± 0.12	1.54 ± 0.58	0.51 ± 0.16	7.3 ± 4.7	[19]
Cd	6 → 5	−0.40 ± 0.10	2.01 ± 0.44	0.57 ± 0.11	6.2 ± 2.8	[19]
In	6 → 5	−0.53 ± 0.15	2.38 ± 0.57	0.44 ± 0.08	11.4 ± 3.7	[19]
Sn	6 → 5	−0.41 ± 0.18	3.18 ± 0.64	0.39 ± 0.07	15.1 ± 4.4	[19]
Ho	7 → 6	−0.30 ± 0.13	2.14 ± 0.31	–	–	[23]
Yb	7 → 6	−0.12 ± 0.10	2.39 ± 0.30	–	–	[23]
Ta	7 → 6	−0.27 ± 0.50	3.76 ± 1.15	–	–	[23]
Pb	8 → 7	–	0.37 ± 0.15	0.79 ± 0.08	4.1 ± 2.0	[24]
		−0.020 ± 0.012	–	–	–	[25]
U	8 → 7	−0.26 ± 0.4	1.50 ± 0.75	0.35 ± 0.12	45 ± 24	[24]

Table in (*Nucl. Phys. A,* **579,** *518-538, October 1994)* reporting the measured shifts and widths from 10 experiments for 25 kaonic atoms.
Nowadays, models are also based on these measurements


Calibration with 152Eu
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Std Dev 71.18
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Tail
Transitions
Background
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45.5 keV
Pb alpha
75.0 keV
Pb beta
84.9 keV
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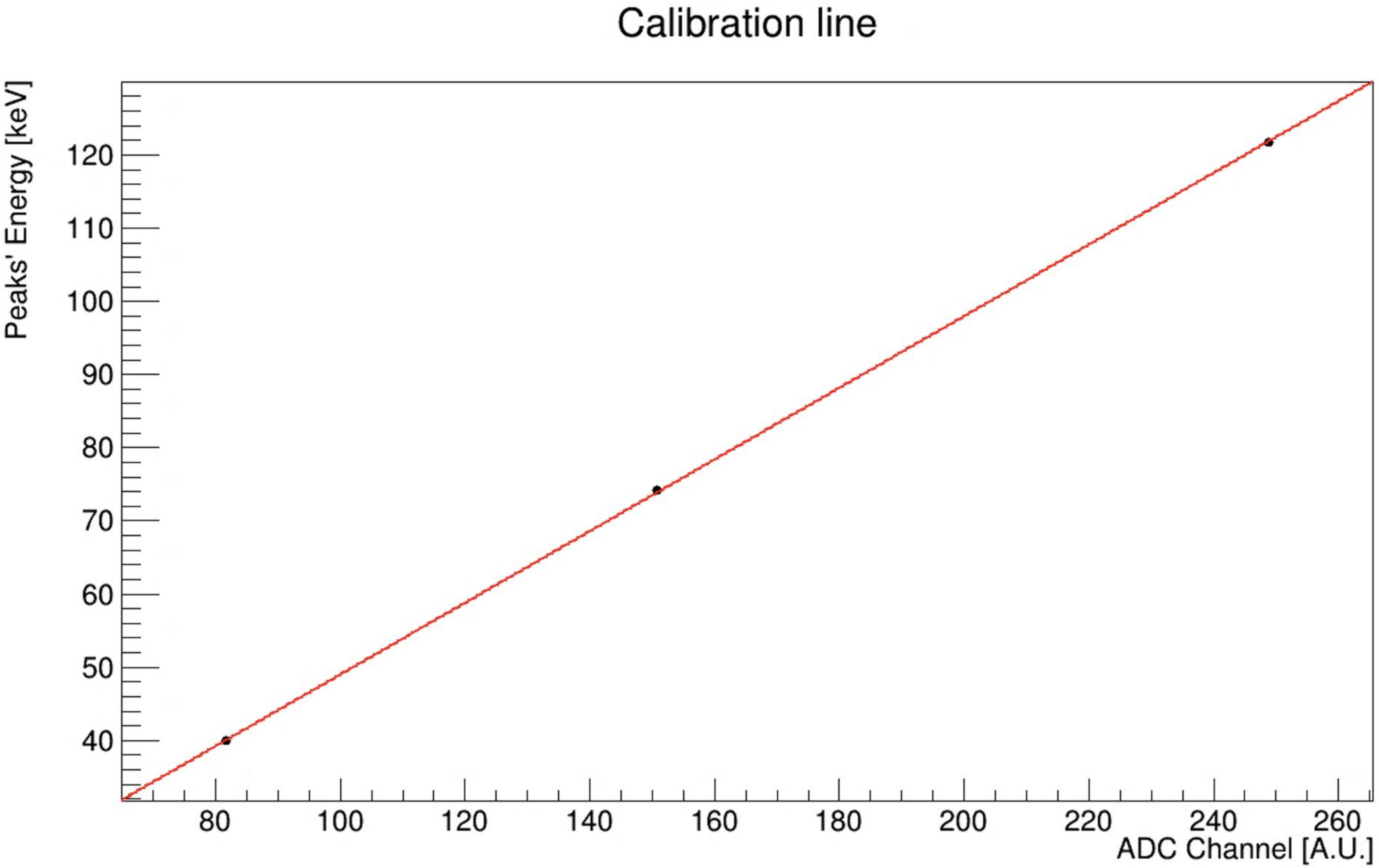
260


Calibration line
Peaks' Energy [keV]
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110
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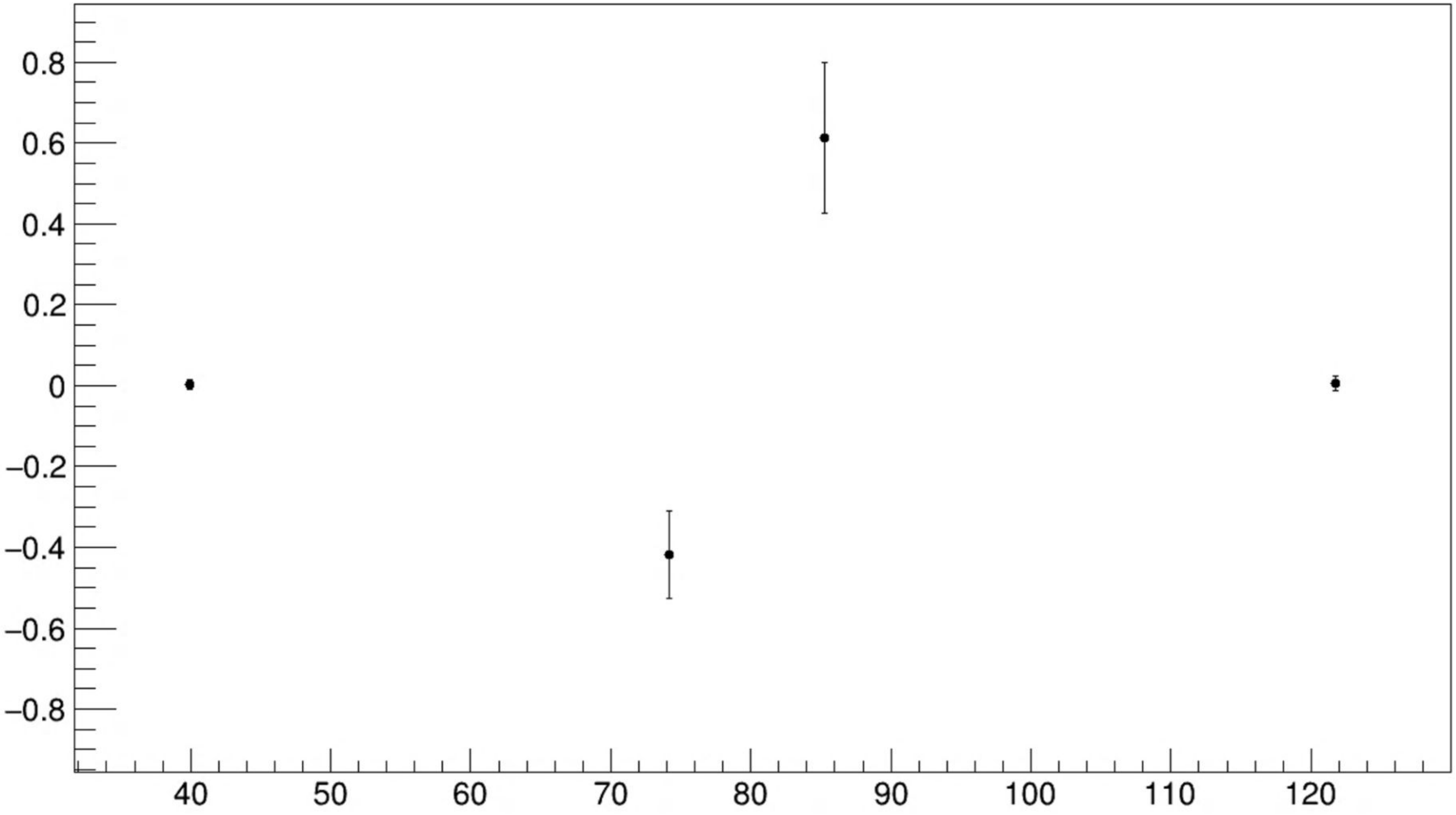
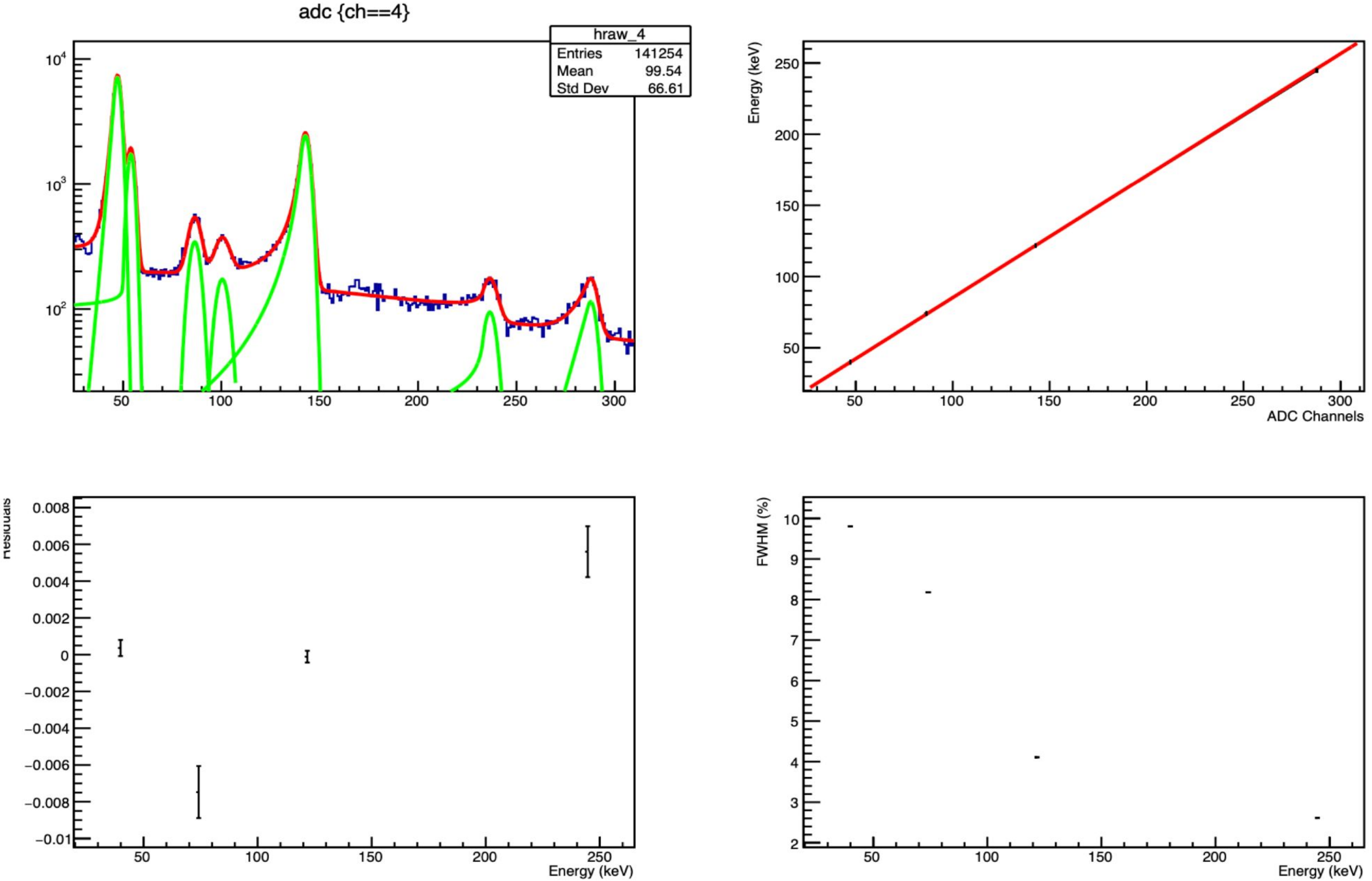
ADC Channel [A.U.]

RESIDUALS (Calibration Eu152)

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Entries 141254
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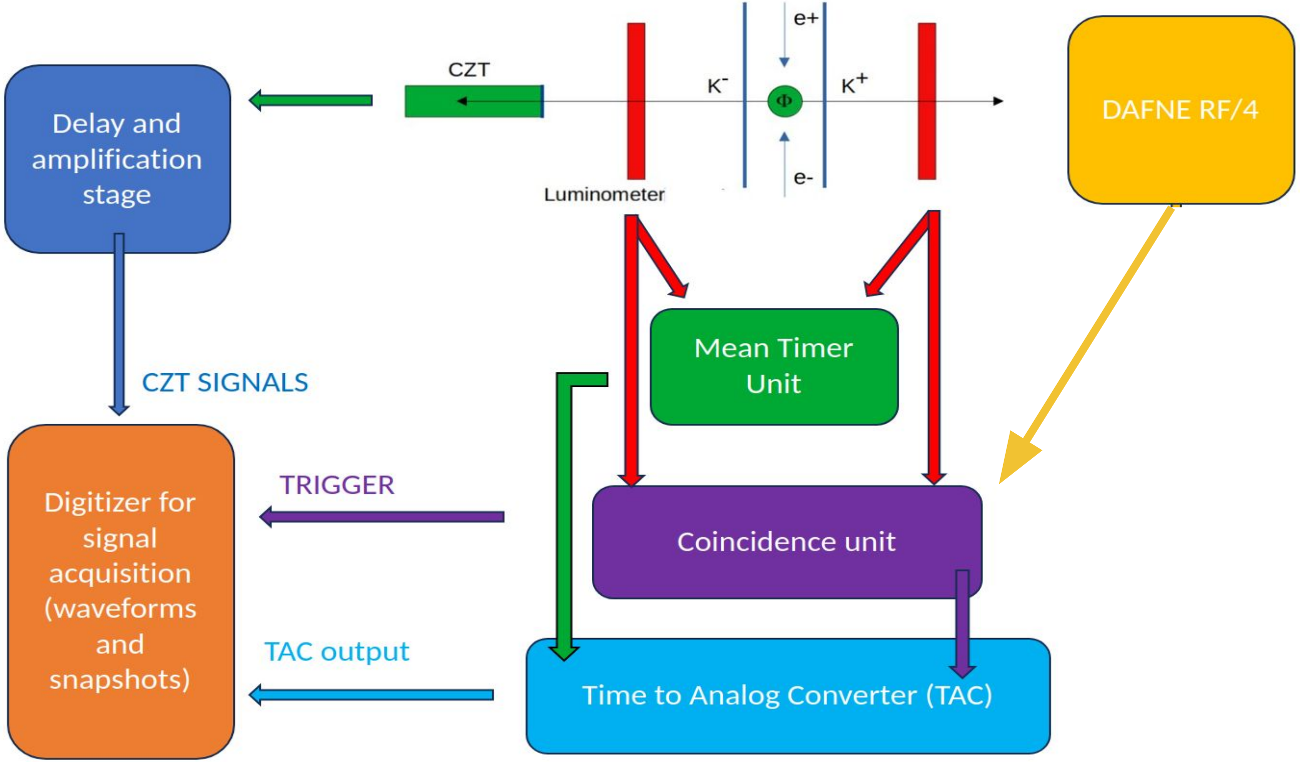
Std Dev 66.61
Energy (keV)
ADC Channels
Residuals
FWHM (%)
Energy (keV)
Energy (keV)

DAQ general logic

CFD limitation



Importance of kaonic Atoms in QCD

Why are these measurements so important?

$$\varepsilon_{1s}^{H} + \frac{i}{2}\Gamma_{1s}^{H} = 2\alpha^3\mu^2 a_{\bar{K}p}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}p} + \ldots\right] \qquad \varepsilon_{1s}^{D} + \frac{i}{2}\Gamma_{1s}^{D} = 2\alpha^3\mu^2 a_{\bar{K}d}\left[1 - 2\alpha\mu(ln\alpha - 1)a_{\bar{K}d} + \ldots\right]$$

Antikaon-nucleon scattering lenghts

$$a_{K^-p} = \frac{1}{2}\left[a_1 + a_0\right] \qquad a_{\bar{K}n} = a_1$$

$$a_{\bar{K}d} = \frac{4\left[m_N + m_K\right]}{2m_N + m_K} Q + C$$

Isospin-dependent scattering lenghts:
either **input or output of phenomenological models on low-energy QCD**

$$Q = \frac{1}{2}\left[a_{\bar{K}p} + a_{\bar{K}n}\right] = \frac{1}{4}\left[a_0 + 3a_1\right]$$

⇒ To fully disentangle the Isospin-dependent scattering lengths one needs the kaonic deuterium measurement

(Rev. Mod. Phys, **91**, *June 2019)*