The SIDDHARTA-2 experiment: Kaonic Atoms measurements at DAΦNE

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Outline

EXOTIC ATOMS

What is an Exotic Atom?

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

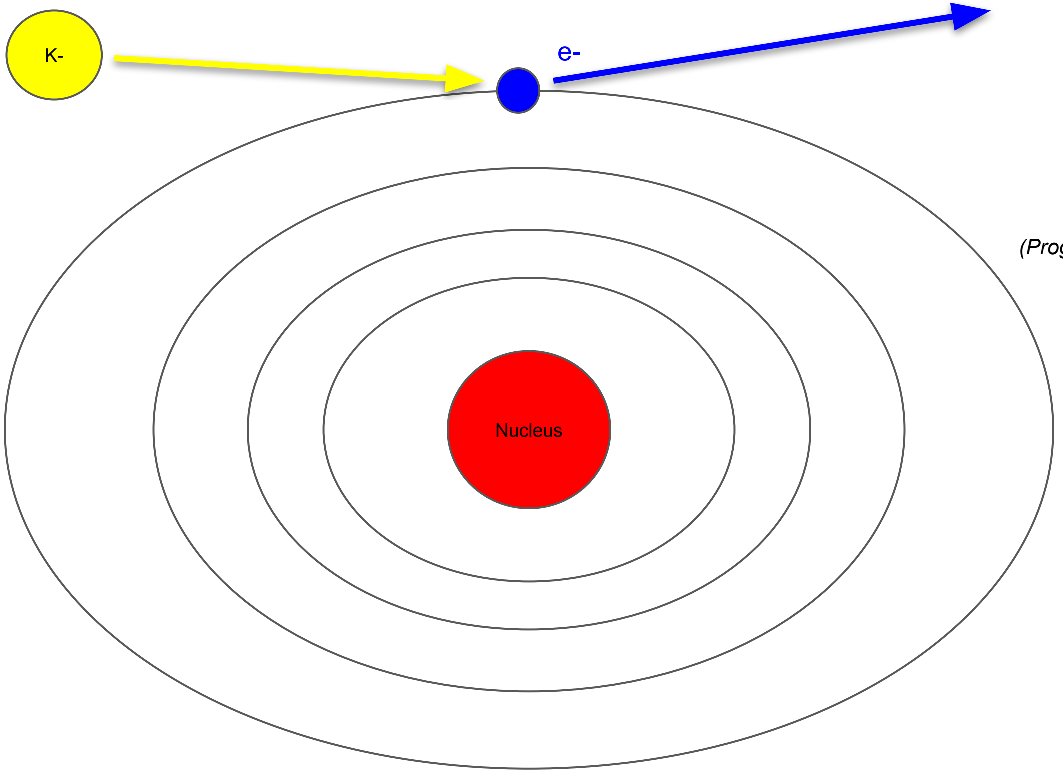
- Exotic atoms with muons, pions, kaons, antiprotons and hyperons were observed.

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

- Discovered by Fry in 1951 with a bubble chamber on a balloon (*phys. Rev.* ***83*** *594-597, 1951)*.

- Finally produced and studied exploiting hadronic accelerators.

Kaonic Atoms: Formation



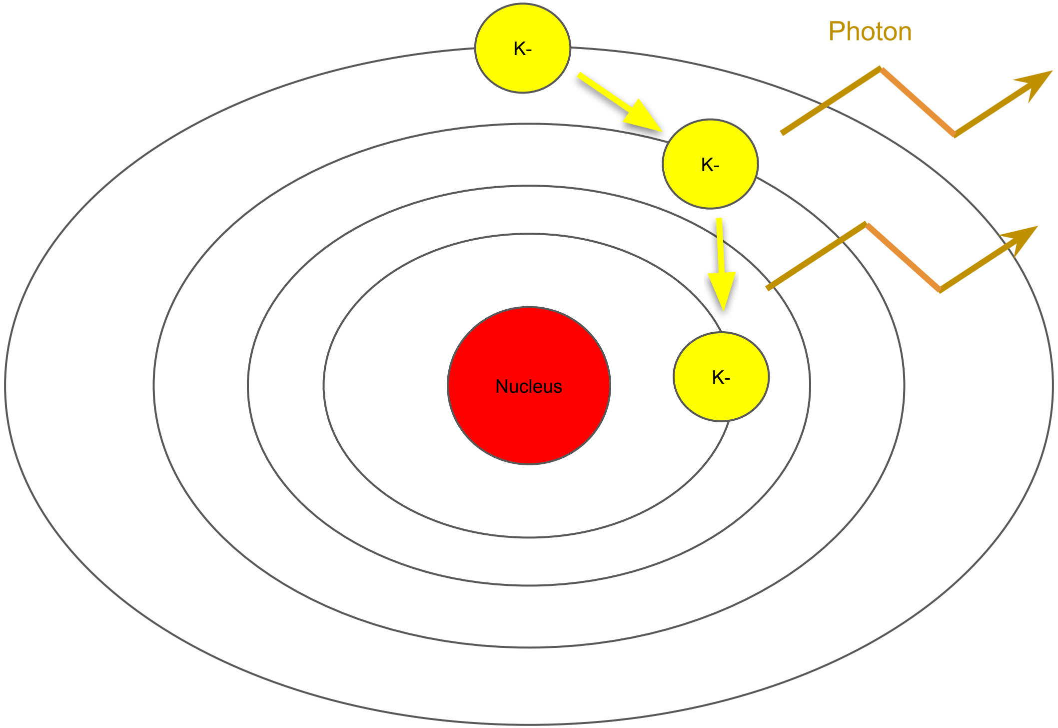
$r_b^e \sim r_b^k$

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

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

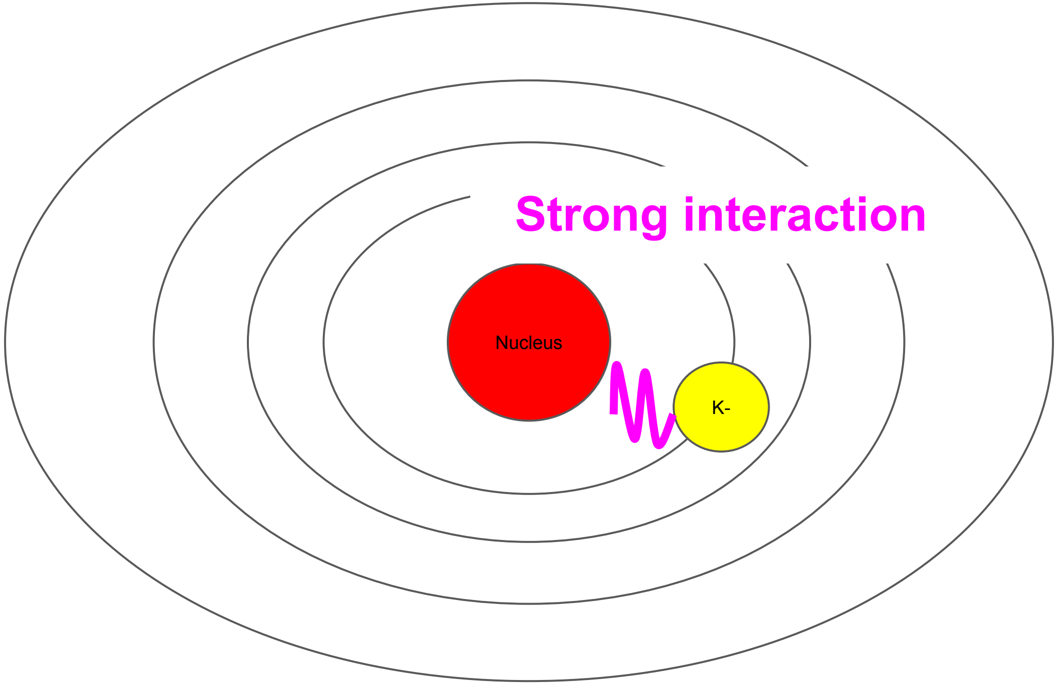
H n=1 level ~ KH n=25 level

Kaonic Atoms: Cascade



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

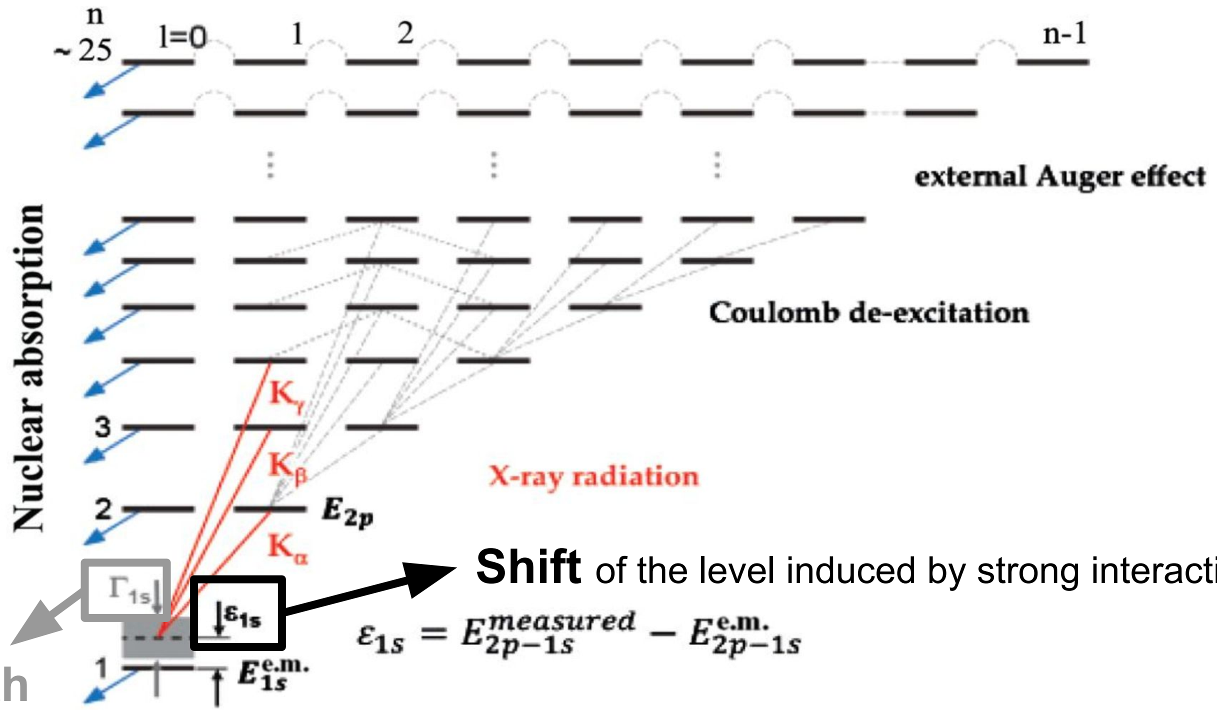
Kaonic Atoms: K-N Interaction



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-9 - 1e-12, while τ_K=1e-8

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

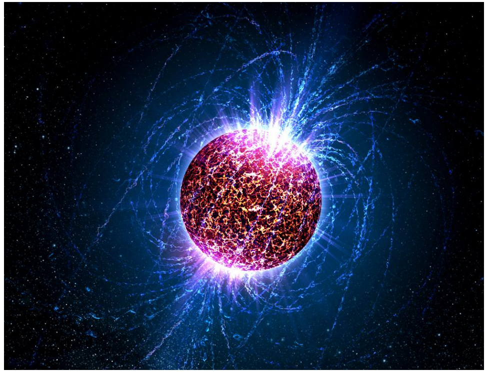
- From **K-H** and **K-D** one can get info on **K-p** and **K-n** scattering lengths.

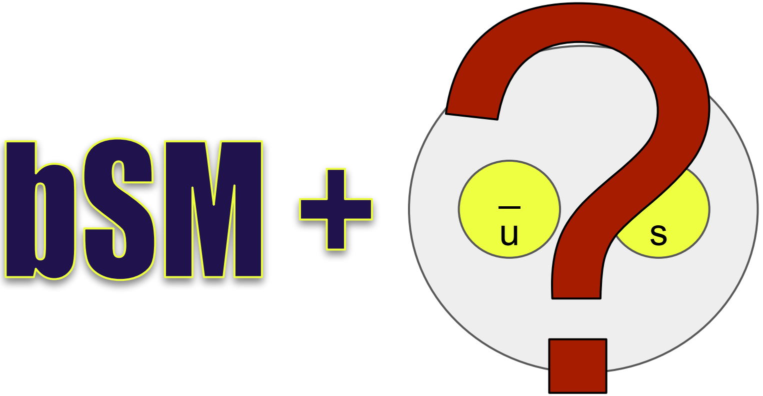
- Combining K-H and K-D measurement one can disentangle the two **K-N isospin dependent scattering lengths**.

Importance of kaonic Atoms in QCD (and more)

It is also important to study the kaonic atoms transitions with different **Z** and **n**:

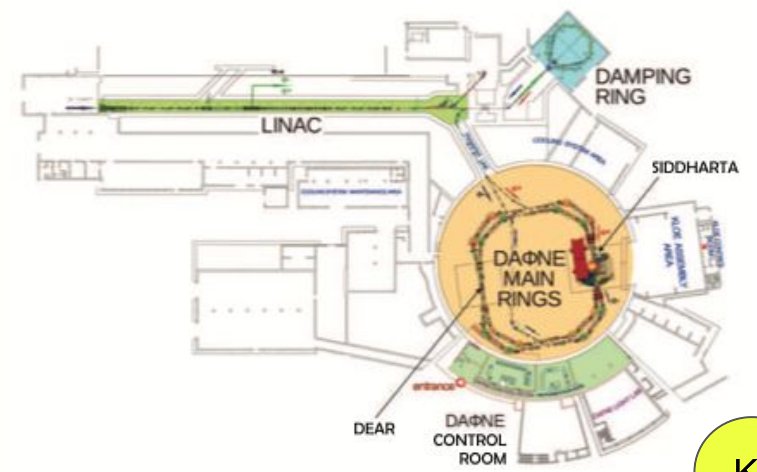
- **Z,** because it is important to have a clear picture on the K-N and K-multiN interactions in function of the nuclear density.
- **n**, because it is a test of QED and it is important for possible measurement of kaon mass and atomic cascades.

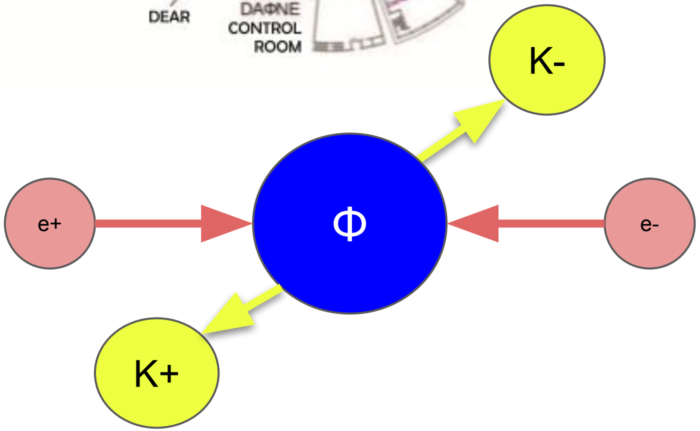




THE SIDDHARTA-2 EXPERIMENT

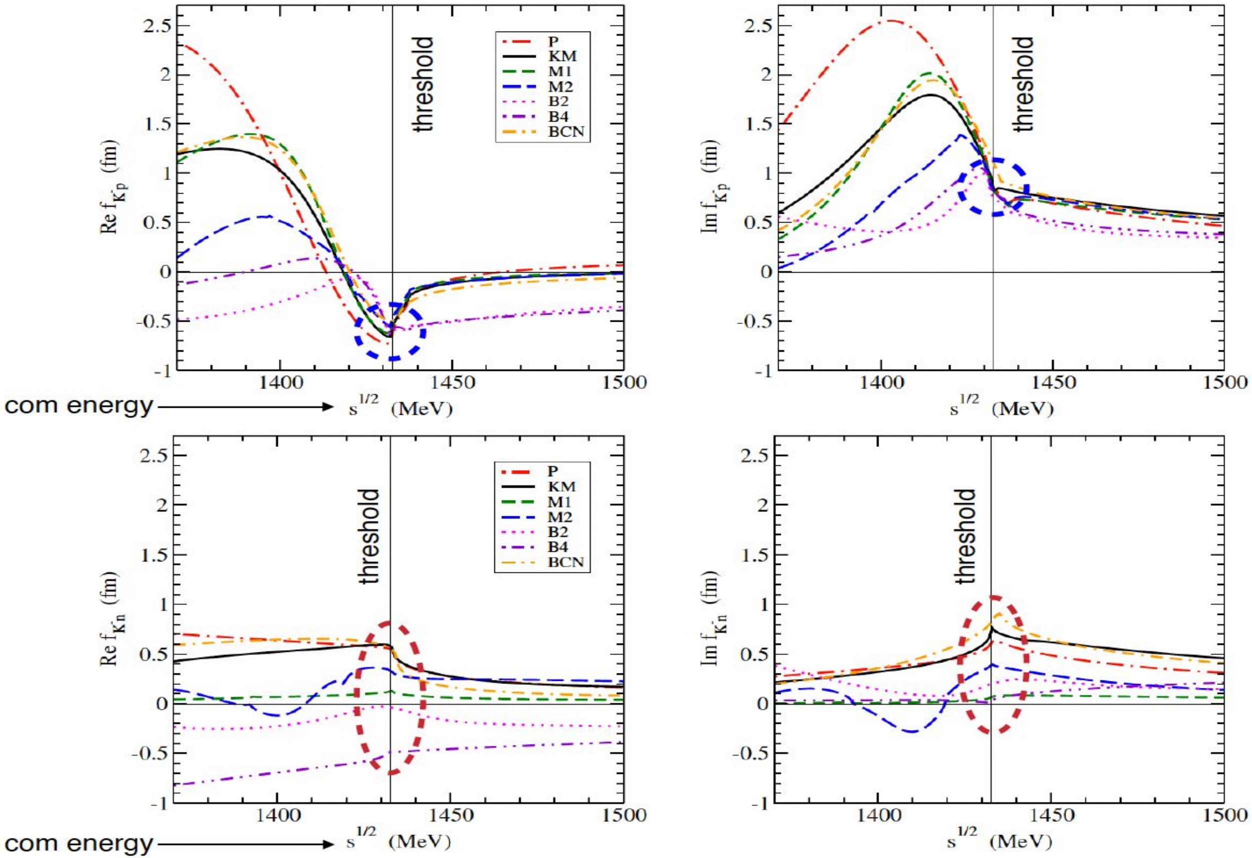
The DAΦNE Collider





- 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%)

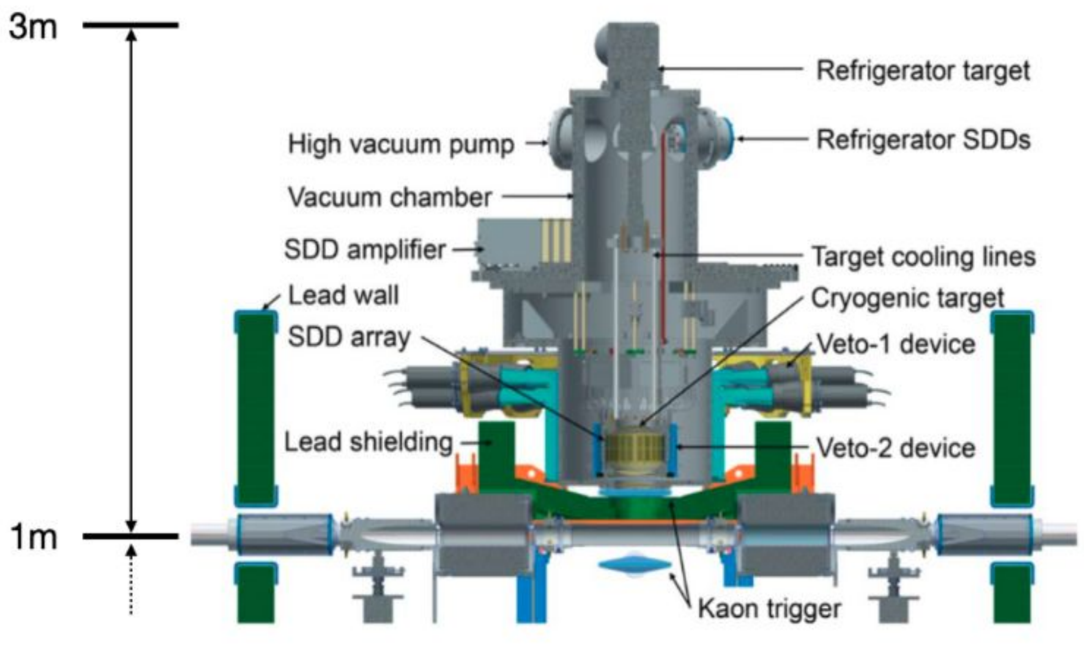
The SIDDHARTA-2 Experiment: Physics Goal



Measured by SIDDHARTA

To be measured…

Experimental Setup



arXiv:2311.16144 [physics.ins-det]

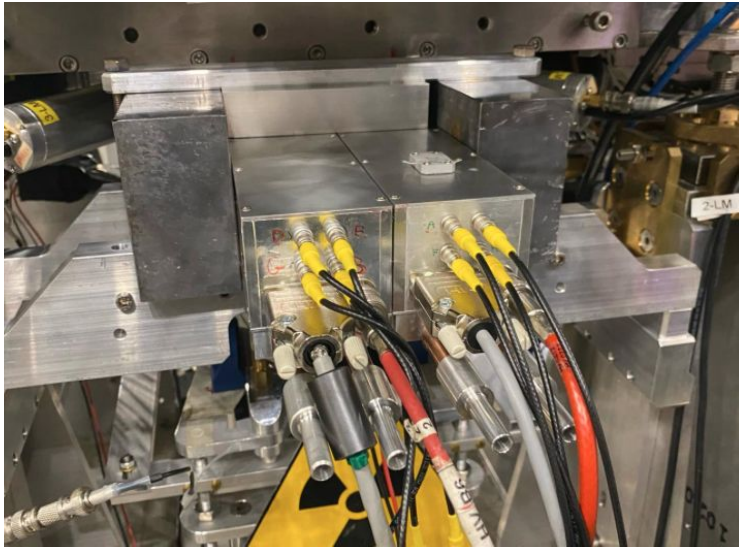
- **384 Silicon Drift Detectors (SDDs)**, specially developed for kaonic atoms x-ray spectroscopy, providing a high energy efficiency (>98%) for x-ray energies between 5 keV and 12 keV
- Cryogenic gaseous target in a Kapton Cell enclosed in a Vacuum chamber
- Kaon Trigger: two fast plastic scintillators to cut on tof
- Complex veto systems: the key upgrade wrt SIDDHARTA together with the new, dedicated, SDDs.

PARALLEL GOALS AND FUTURE PERSPECTIVE

Parallel Goal: The CZT Detector

Reminder: it is important to study kaonic atoms with different Z to have a clear picture on the K-N and K-multiN interactions in function of the nuclear density.

→ To study intermediate mass kaonic atoms a new detector is being tested in DAΦNE: The CZT detector

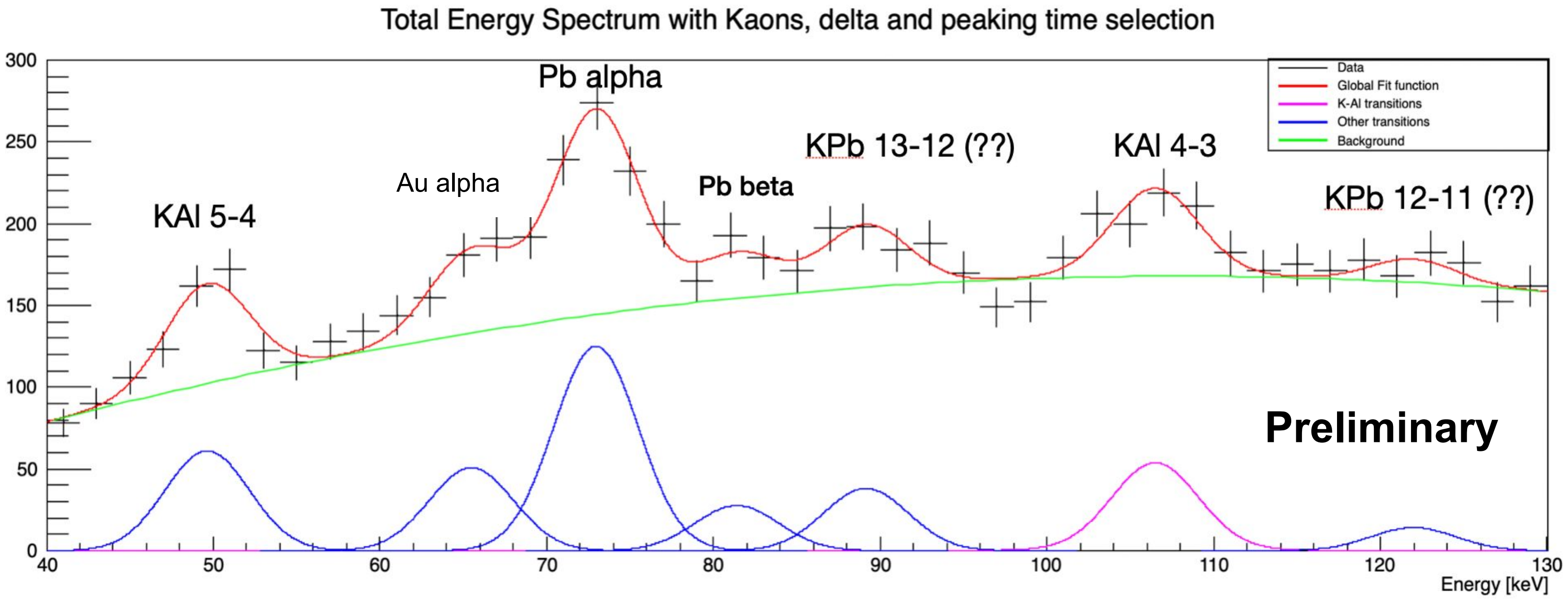


- \+ Good timing, resolution and efficiency in the 30 keV - 400 keV range at room temperature.
- \+ Ideal to build compact and reliable detection systems (no cooling needed)
- \- Tested for the first time in a collider by the collaboration.

Nucl. Instrum. Methods Phys. Res. A **1060**, 169060 (2024).

Parallel Goal: The CZT Detector

Fixed shift and width to the values calculated with BCN K^-N + phen. multiN model



Future Perspective: EXKALIBUR

EXtensive Kaonic Atoms research:
from LIthium and Beryllium to Uranium

Two accelerators and many detectors to measure kaonic atoms, with applications from particle physics and QCD to Astrophysics and Dark Matter.

Conclusions

- **Measurements of kaonic atoms are important in the framework of low-energy QCD**, the upcoming measurement of the KD shift and width by the SIDDHARTA-2 collaboration is going to be revolutionary: it will permit to **fully disentangle the isospin-dependent scattering lengths**, giving theoretician an important input/output on which assess the models.

- In general, other kaonic atoms measurement are important to **understand the behaviour of the K-N and K-multiN interactions**, with the possible existence of neutron stars with strange matter in their interior (Hyperon puzzle)

- Kaonic atoms measurements are also important to solve one of the issues highlighted by the PDG: **the kaon mass puzzle.**

\+ Parallely to the main goal, the SIDDHARTA-2 collaboration is also **developing new state-of-art X-ray deterctors** (CZT, SDDs)

THANK YOU FOR YOUR ATTENTION

Bibliography (for those who are interested)

- Theory:
  - Fermi, Teller, The Capture of Negative Mesotrons in Matter. *Physical Review* **72** **(Exotic Atoms)**
  - Zmeskal, *Progress in Particle and Nuclear Physics* **61**
  - Cieply, Mai, Meißner, Smejkal, *Nuclear Physics A* **954**

- Kaonic Atoms at DAΦNE
  - Curceanu C and others 2019 *Reviews of Modern Physics* **91**
  - Artibani, Clozza, Toho, et al., Acta Physica Polonica B **55**, 5-A2 (2024)

BACKUP

Importance of kaonic Atoms in QCD

Why are these measurements so important?

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

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**

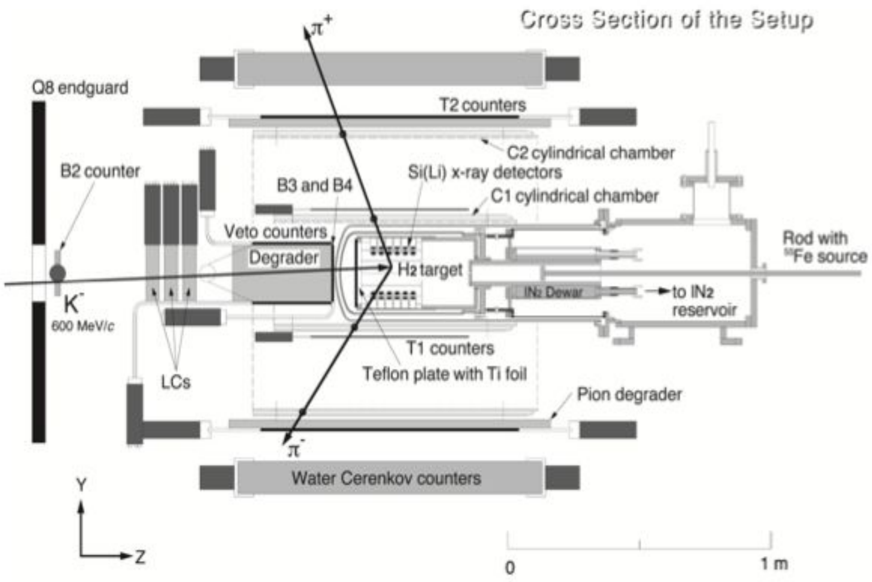
$$Q = \frac{1}{2}\left[a_{\bar{K}p} + a_{\bar{K}n}\right] = \frac{1}{4}\left[a_0 + 3a_1\right]$$

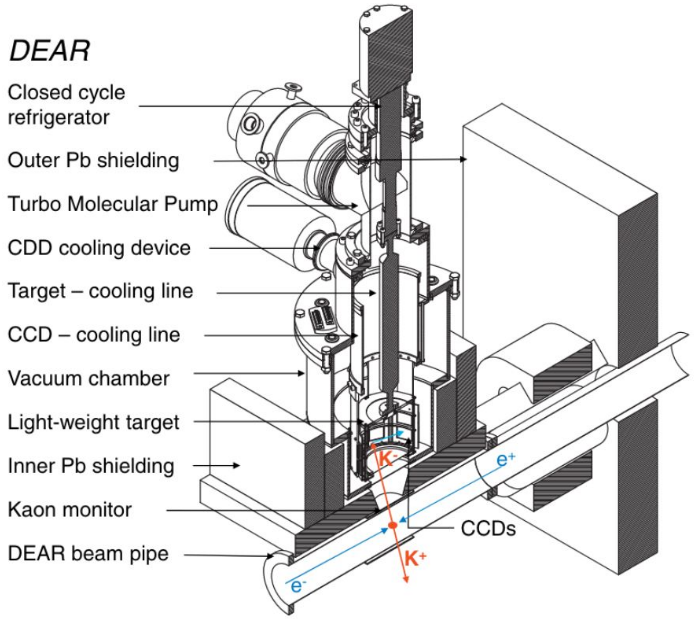
⇒ To fully disentangle the Isospin-dependent scattering lengths one needs the kaonic deuterium measurement

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

Modern Era Experiments

KpX at KEK vs **DEAR** at DAΦNE





- \+ A lot of Statistics
- \- High Background

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

- ● Acceptable statistics
- \+ Low Background

Old Era Experiments

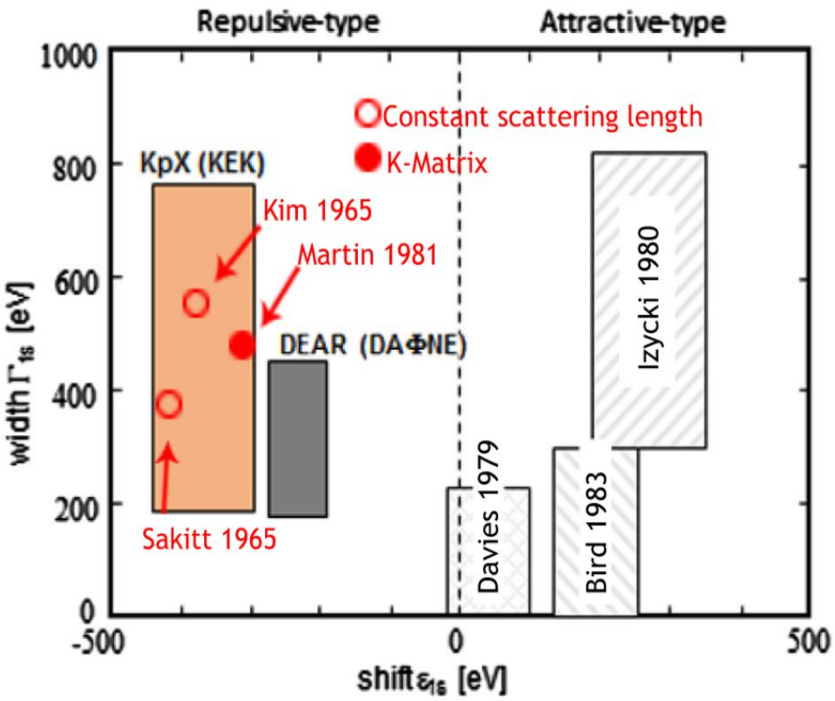
Table 1
Compilation of K^- atomic data

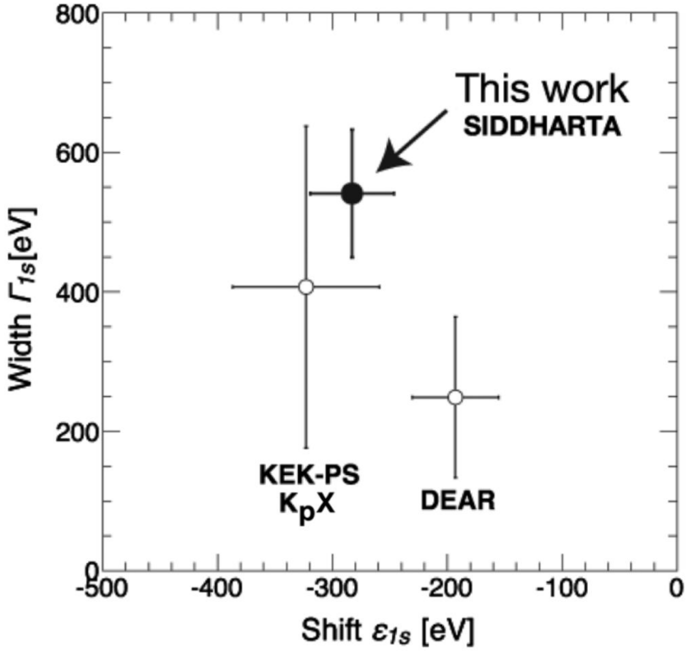
Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	$3 \to 2$	-0.04 ± 0.03	–	–	–	[15]
		-0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	$3 \to 2$	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	$3 \to 2$	-0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	$3 \to 2$	-0.208 ± 0.035	0.810 ± 0.100	–	–	[18]
^{11}B	$3 \to 2$	-0.167 ± 0.035	0.700 ± 0.080	–	–	[18]
C	$3 \to 2$	-0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20	[18]
O	$4 \to 3$	-0.025 ± 0.018	0.017 ± 0.014	–	–	[19]
Mg	$4 \to 3$	-0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03	[19]
Al	$4 \to 3$	-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	$4 \to 3$	-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	$4 \to 3$	-0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30	[18]
S	$4 \to 3$	-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	$4 \to 3$	-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	$5 \to 4$	-0.099 ± 0.106	0.64 ± 0.25	–	–	[19]
Ni	$5 \to 4$	-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	$5 \to 4$	-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	$6 \to 5$	-0.18 ± 0.12	1.54 ± 0.58	0.51 ± 0.16	7.3 ± 4.7	[19]
Cd	$6 \to 5$	-0.40 ± 0.10	2.01 ± 0.44	0.57 ± 0.11	6.2 ± 2.8	[19]
In	$6 \to 5$	-0.53 ± 0.15	2.38 ± 0.57	0.44 ± 0.08	11.4 ± 3.7	[19]
Sn	$6 \to 5$	-0.41 ± 0.18	3.18 ± 0.64	0.39 ± 0.07	15.1 ± 4.4	[19]
Ho	$7 \to 6$	-0.30 ± 0.13	2.14 ± 0.31	–	–	[23]
Yb	$7 \to 6$	-0.12 ± 0.10	2.39 ± 0.30	–	–	[23]
Ta	$7 \to 6$	-0.27 ± 0.50	3.76 ± 1.15	–	–	[23]
Pb	$8 \to 7$	–	0.37 ± 0.15	0.79 ± 0.08	4.1 ± 2.0	[24]
		-0.020 ± 0.012	–	–	–	[25]
U	$8 \to 7$	-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

KAONIC ATOMS EXPERIMENTS

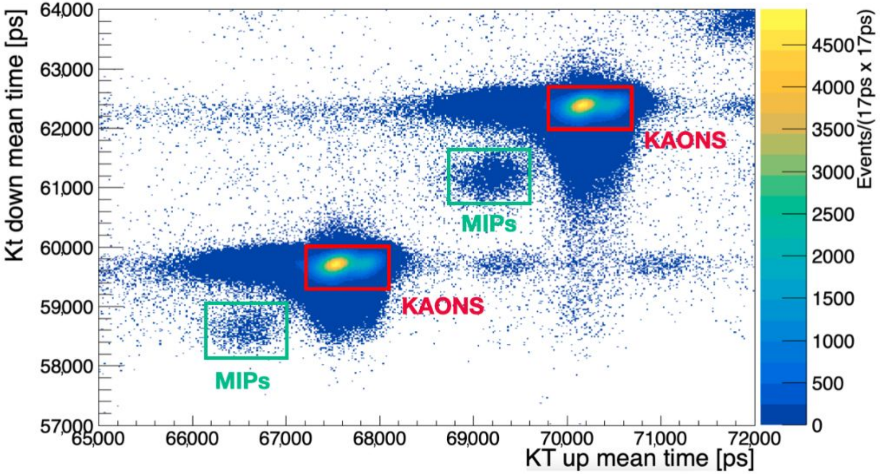
The Kaonic Hydrogen Puzzle



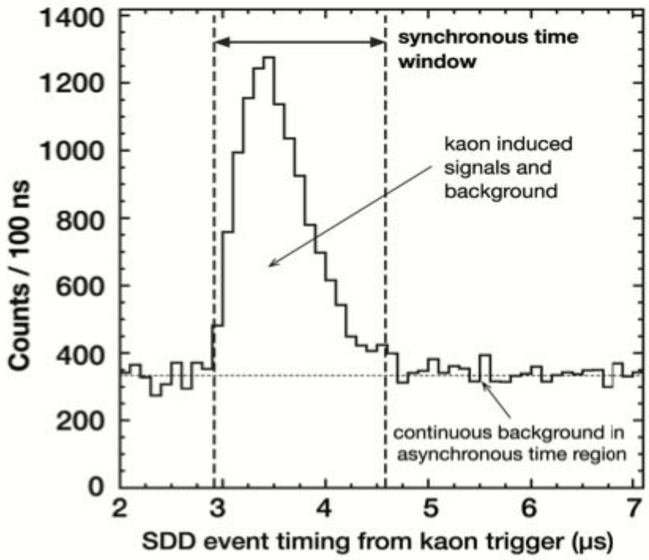


From *Rev. Mod. Phys*, **91**, *June 2019*

Experimental Setup: The Importance of Timing

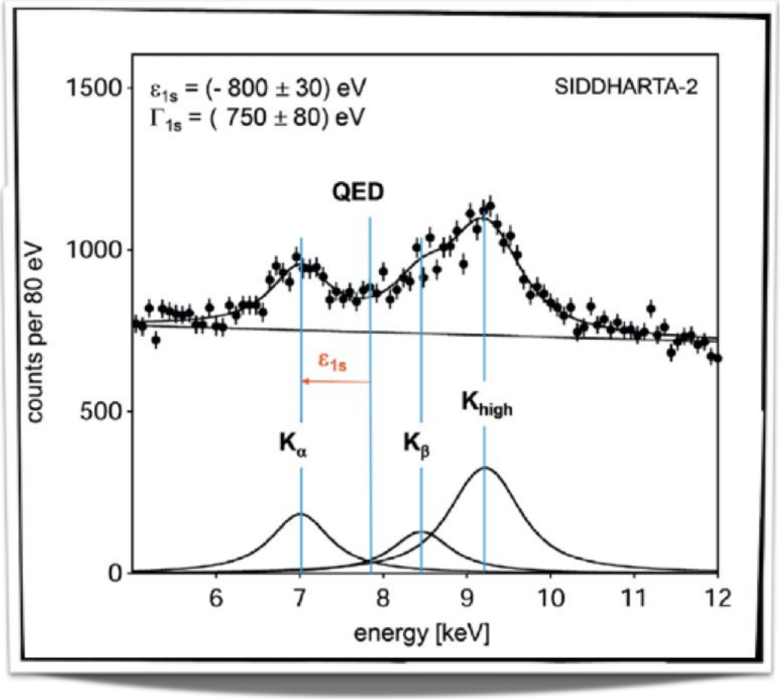


Time difference between DAΦNE RF and signal on kaon trigger, a window of slower particles (kaons) is clearly distinguishable from background



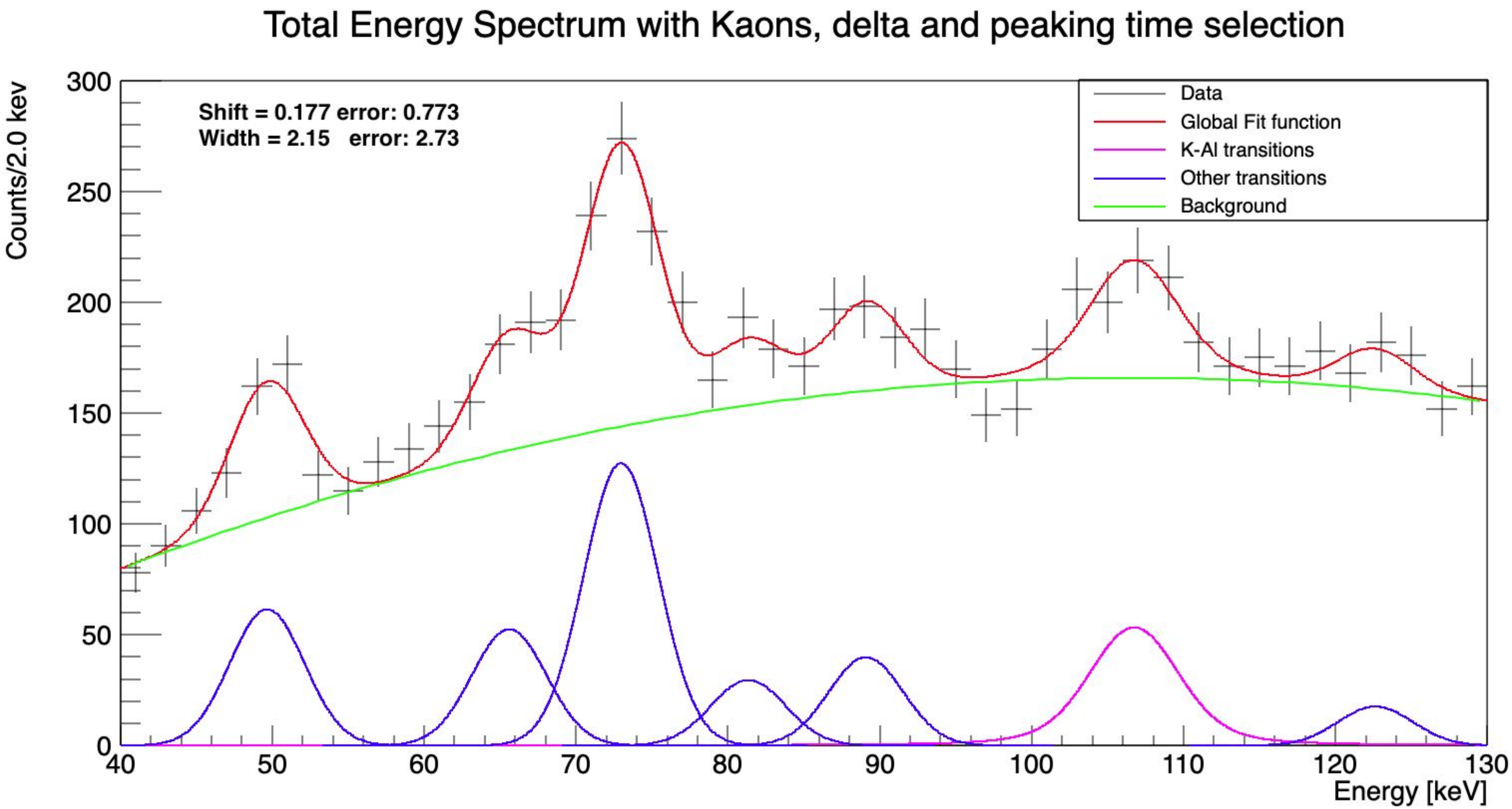
Time difference between a signal on the kaon trigger and a signal on SDDs, a clear signal due to the kaon induced events is distinguishable from uniform bkg.

Experimental Setup: The MC Simulation

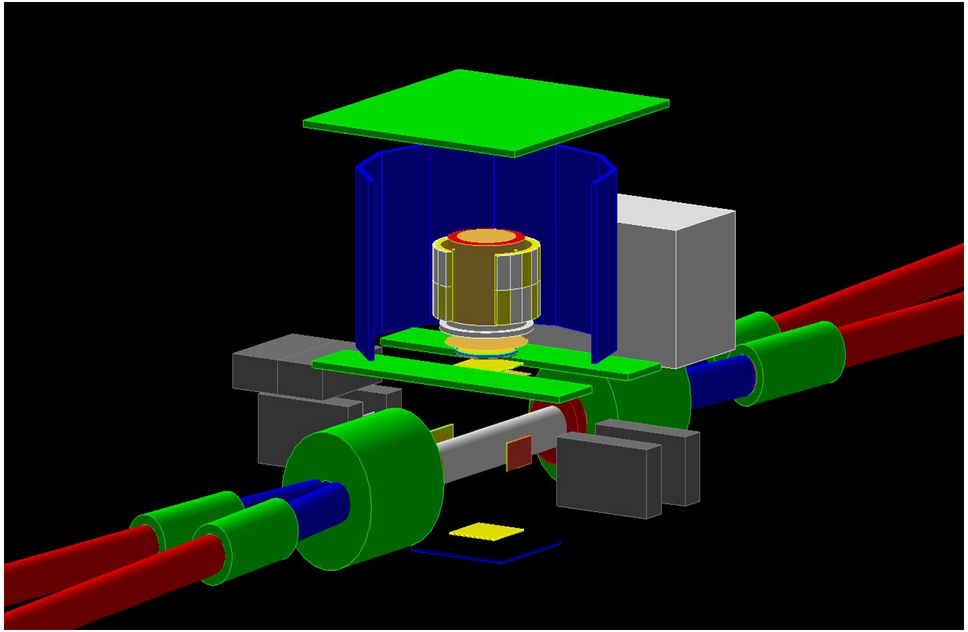


- 800 pb^{-1} simulated luminosity
- precision of about 30 eV and 80 eV respectively on shift and width obtained

Parallel Goal: The CZT Detector



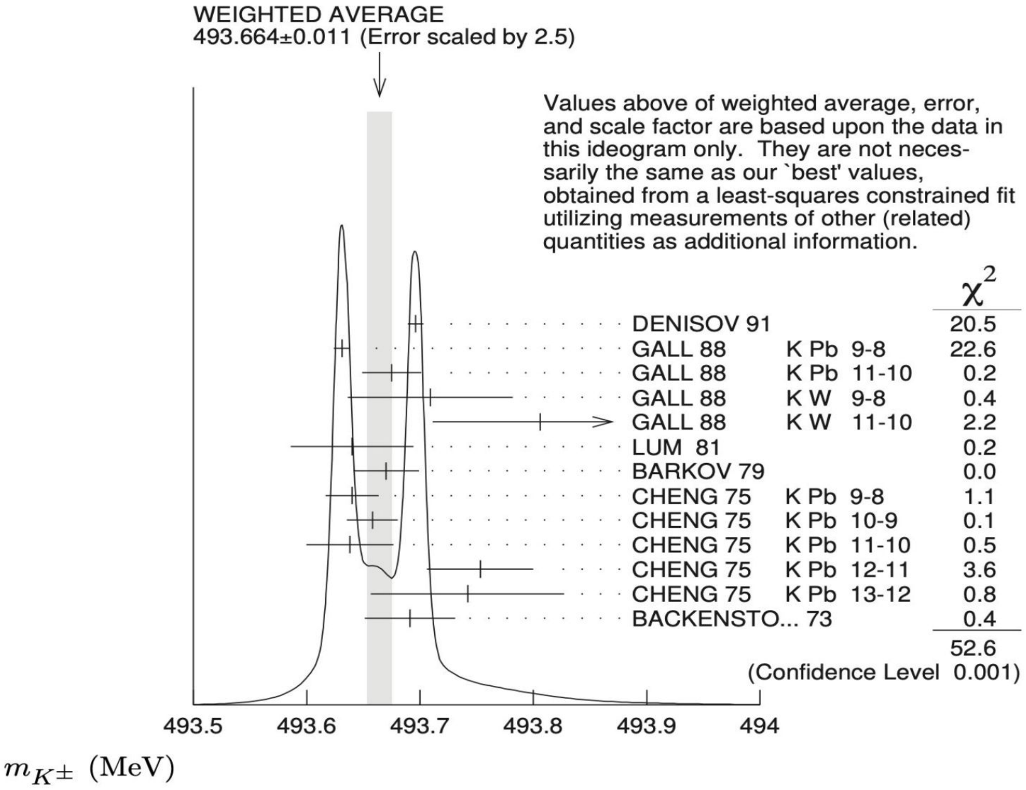
Experimental Setup: The MC Simulation



The MC simulation is essential to:

- **Study the material thickness** (~100 um can reduce a lot the statistics)
- **Study the expected results** (other kaonic atoms can be a background themselves)
- Study the **yield of the transition**, almost unknown.
- **Study possible cuts on timing and position** exploiting veto systems.

Parallel Goal: The Kaon Mass Puzzle



- The two most precise measurement of the kaon mass exploits kaonic atoms, but the measurements are not compatible, propagating the large uncertainty in other particle physics observables (D0 mass)

Aims of the collaboration:

1. Reproduce the “pathological” measurement of GALL88 using HPGe detectors and K-Pb transitions

2. Do an independent measurement exploiting K-Ne transitions → AI techniques to control systematics.

The SIDDHARTA-2 Experiment: Physics Goal

+ From SIDDHARTA exploratory measurement, combining data and Monte Carlo simulation, it turned out that the expected yield must be **Y(K_α KD) ~ 0.1%**

An accurate control on background is needed!

The SIDDHARTA-2 Experiment: Physics Goal