Present and future kaonic atoms measurements with new generation radiation detectors

A. Scordo, University of Krakow – 04/12/2023

STRANGE exotic atoms

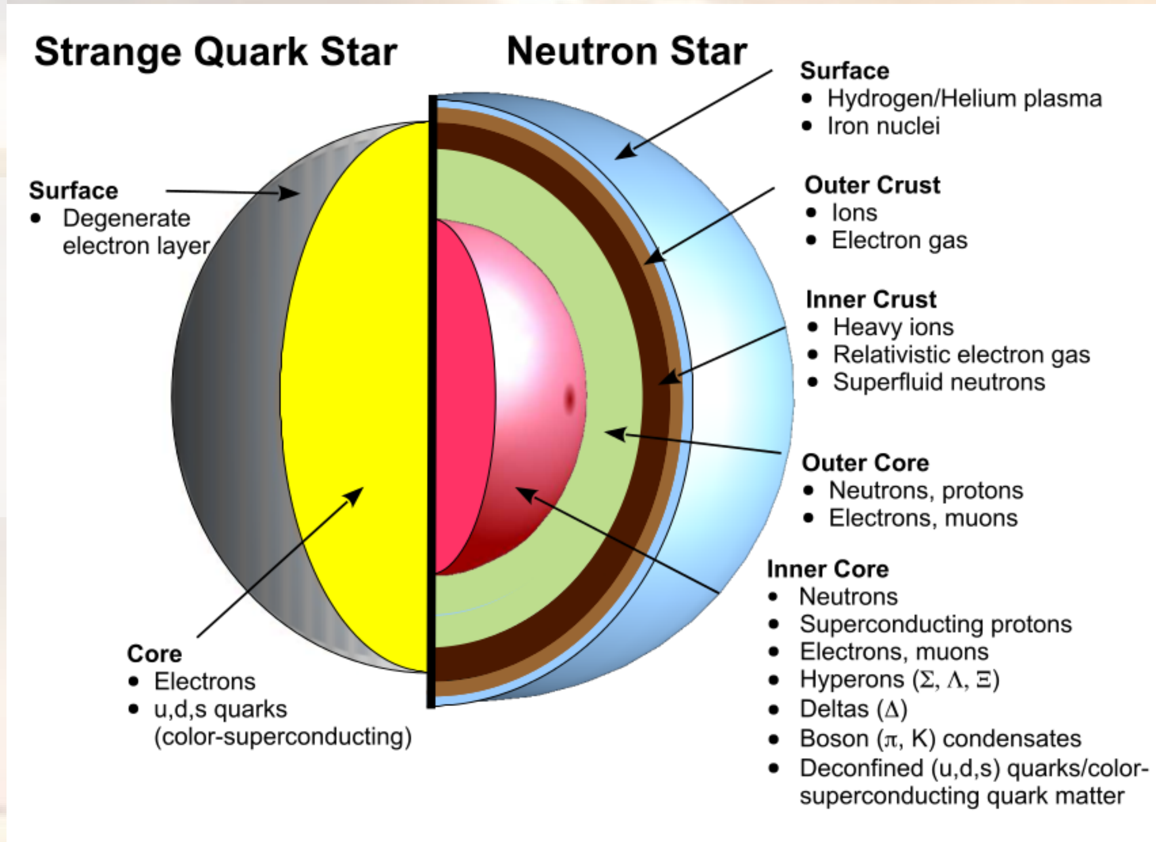
Strange quark mass is still, together with the u,d quark masses, lower than the Λ_{QCD} parameter (≈ 217 MeV)

$$\alpha_s(k^2) \stackrel{\text{def}}{=} \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln(k^2/\Lambda^2)}$$

How strong is the strange quark interaction with 'standard' matter?
Is there any place for strange matter?

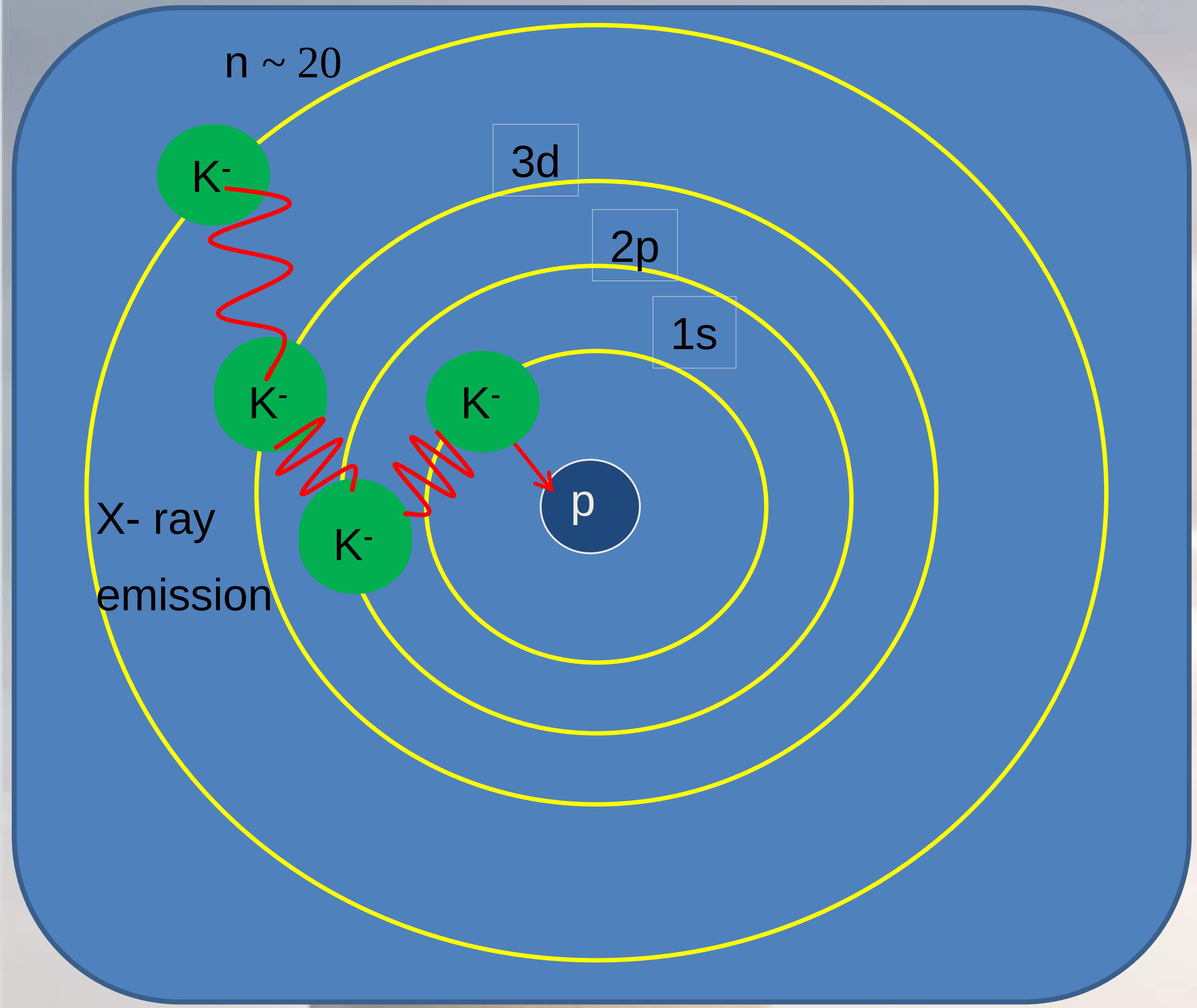
At low energies, the (running) coupling constant of QCD becomes higher and color confinement is observed. A perturbative approach is not anymore possible!

Kaons are the lowest mass strange particles and their interaction with protons and neutrons at very low energy is fundamental to be investigated



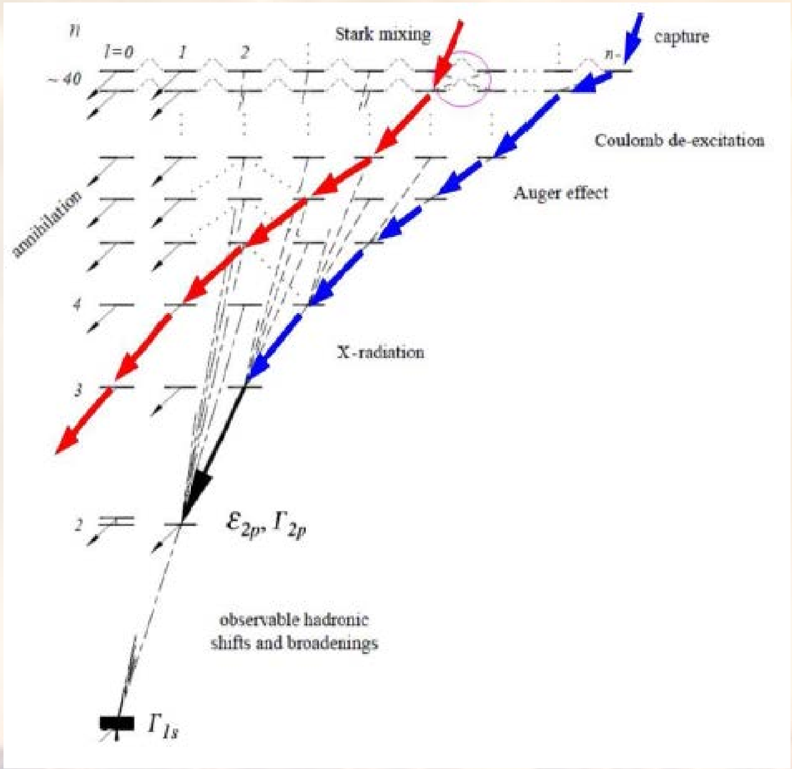
How strong is the interaction of kaons (strangeness) with nuclear matter?

Silicon Drift Detectors for kaonic atoms



$$E_{1s} \simeq m_{red} c^2 \frac{\alpha^2 Z^2}{2}$$

$$n \simeq \sqrt{\frac{m_{red}}{m_e}} n_e$$



Shifts and widths with respect to pure electromagnetic calculations provide information on the strong interaction

Kaonic atoms

First Preface

" 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
Proc. Int. Conf. on "Hypernuclear and Kaon Physics",
Heidelberg 1982.

also cited by

C.J. Batty
Proc. Int. Conf. on "Intense Hadron Facilities and Antiproton Physics", Torino 1990.

Energy shift ε and line width Γ of 1s state are related to real and imaginary part of the S-wave scattering length (Deser-Trueman formula) :

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-p} = 412\,\tfrac{eV}{fm}\,a_{K^-p}$$

$$\varepsilon + \frac{i\Gamma}{2} = 2\alpha^3\mu^2 a_{K^-d} = 601\,\tfrac{eV}{fm}\,a_{K^-d}$$

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_{K^-p}\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}\right)$$

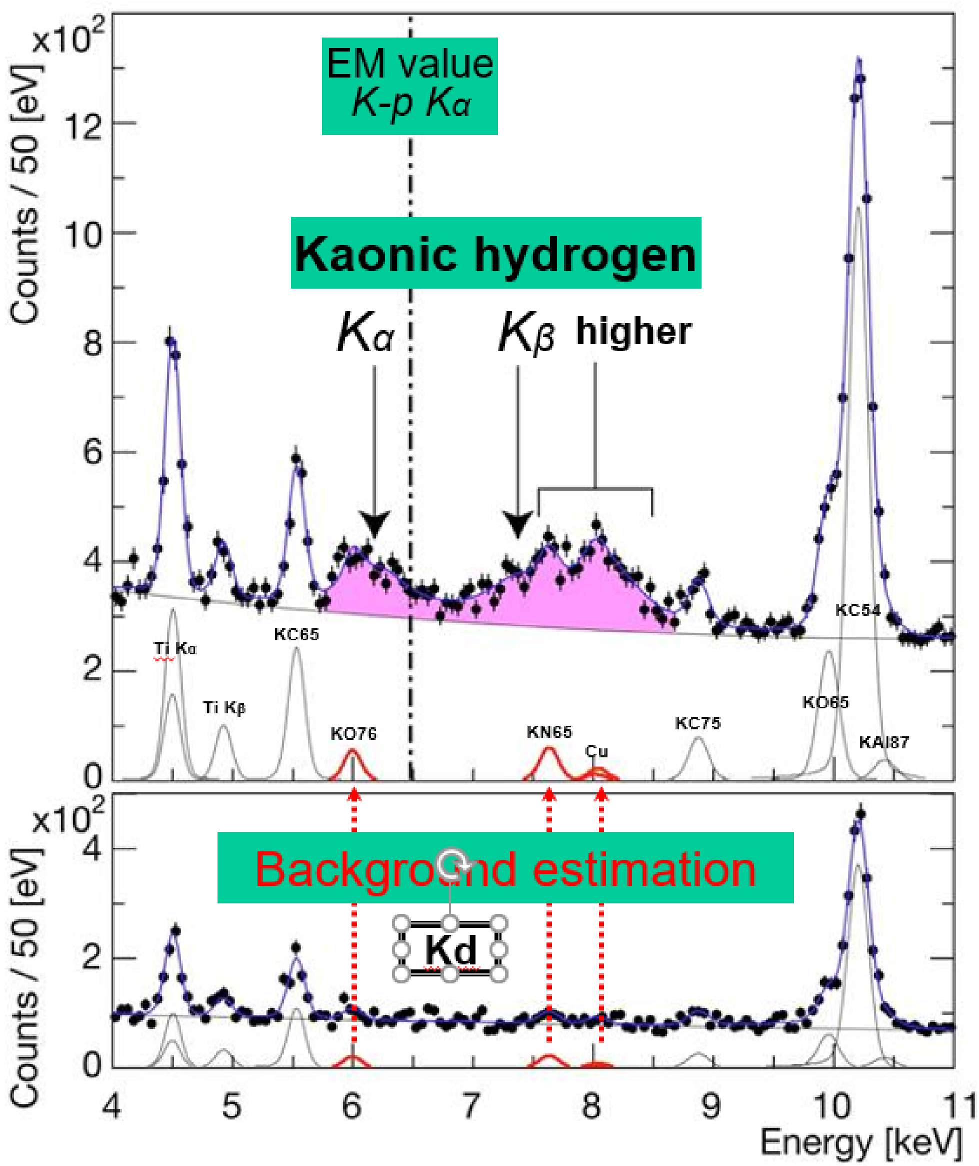
U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order, including isospin breaking

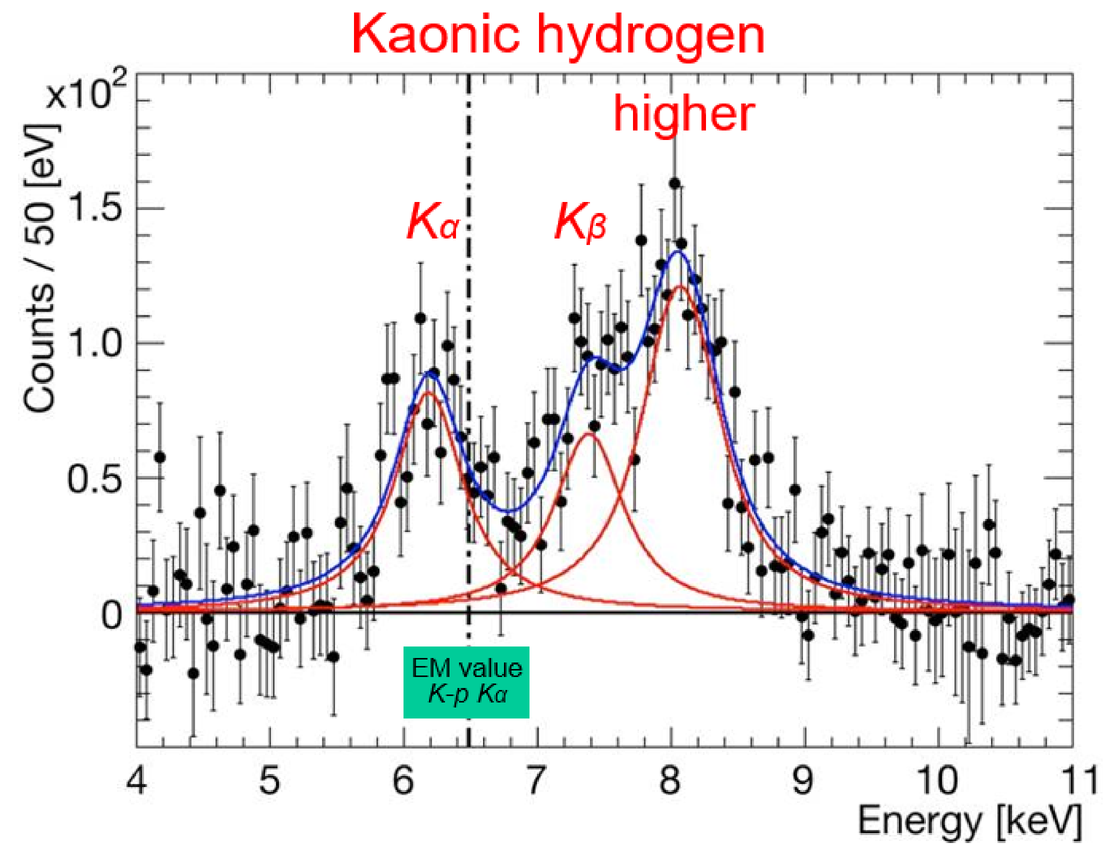
Scattering lengths can be expressed in terms of antiK-N isospin dependent scattering lengths:

$$a_{K^-p} = \frac{a_0(I=0) + a_1(I=1)}{2}$$

$$a_{K^-d} = \frac{1}{2}\frac{m_N + m_K}{m_N + \frac{m_K}{2}}(3a_1 + a_0) + C$$

SIDDHARTA – KH & KD





Residuals of K-p x-ray spectrum after subtraction of fitted background

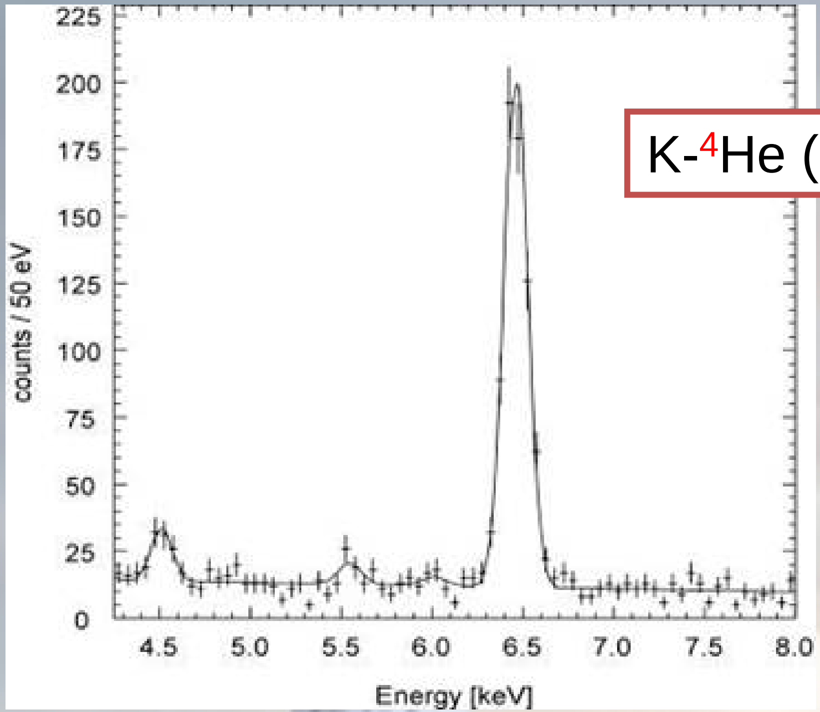
$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})$ eV

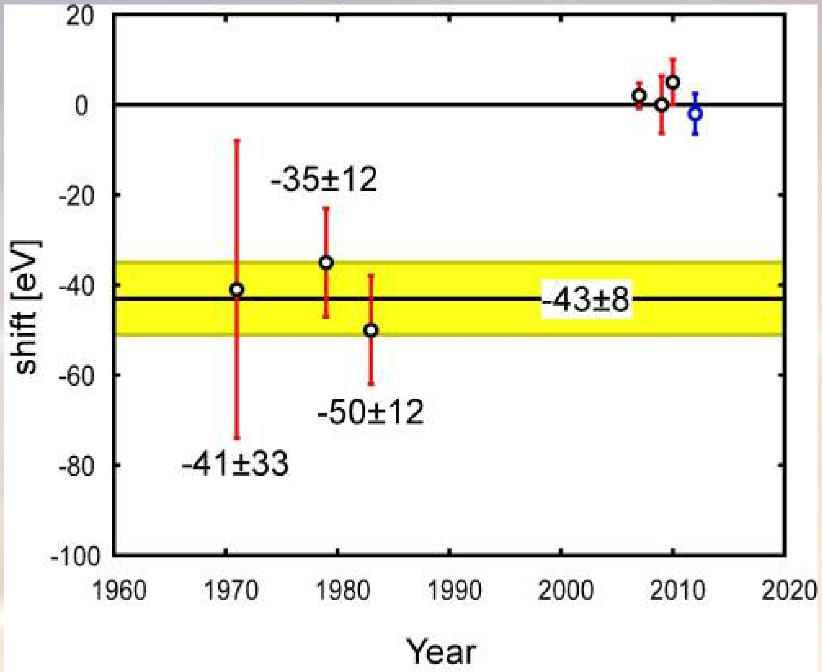
$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})$ eV

Only exploratory measurement for Kd, no measured ε,Γ values obtained

M. Bazzi et al.. 2011. (SIDDHARTA Coll.), Phys. Lett. B704, 113

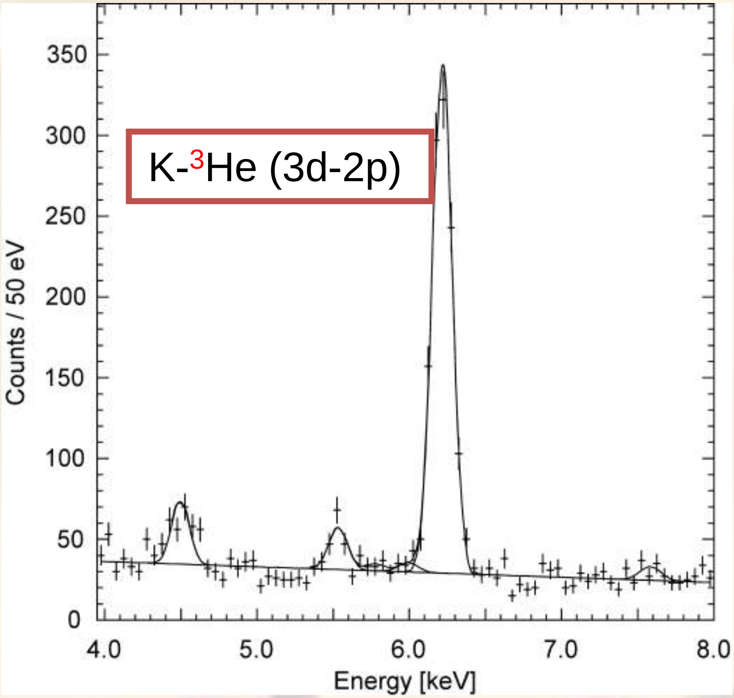
SIDDHARTA – $K^{3,4}He$





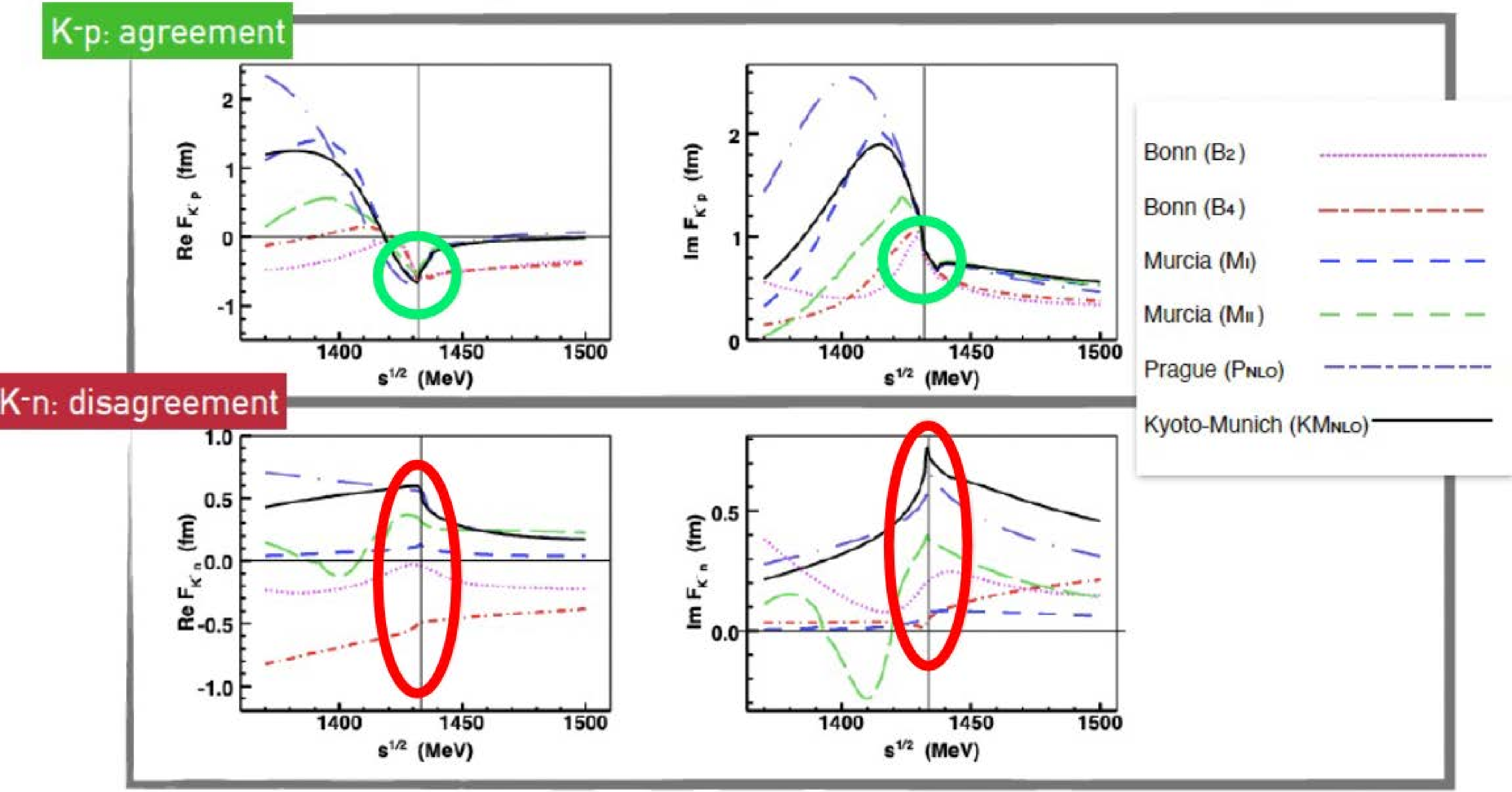
ε_{2p} = 5 ± 3 (stat) ± 4(syst) eV

	Shift [eV]	Reference
KEK E570	+2±2±2	PLB653(07)387
SIDDHARTA (He4 with 55Fe)	+0±6±2	PLB681(2009)310
SIDDHARTA (He4)	+5±3±4	arXiv:1010.4631, PLB697(2011)199
SIDDHARTA (He3)	-2±2±4	



ε_{2p} = -2 ± 2 (stat) ± 4(syst) eV

The importance of measuring isotopes

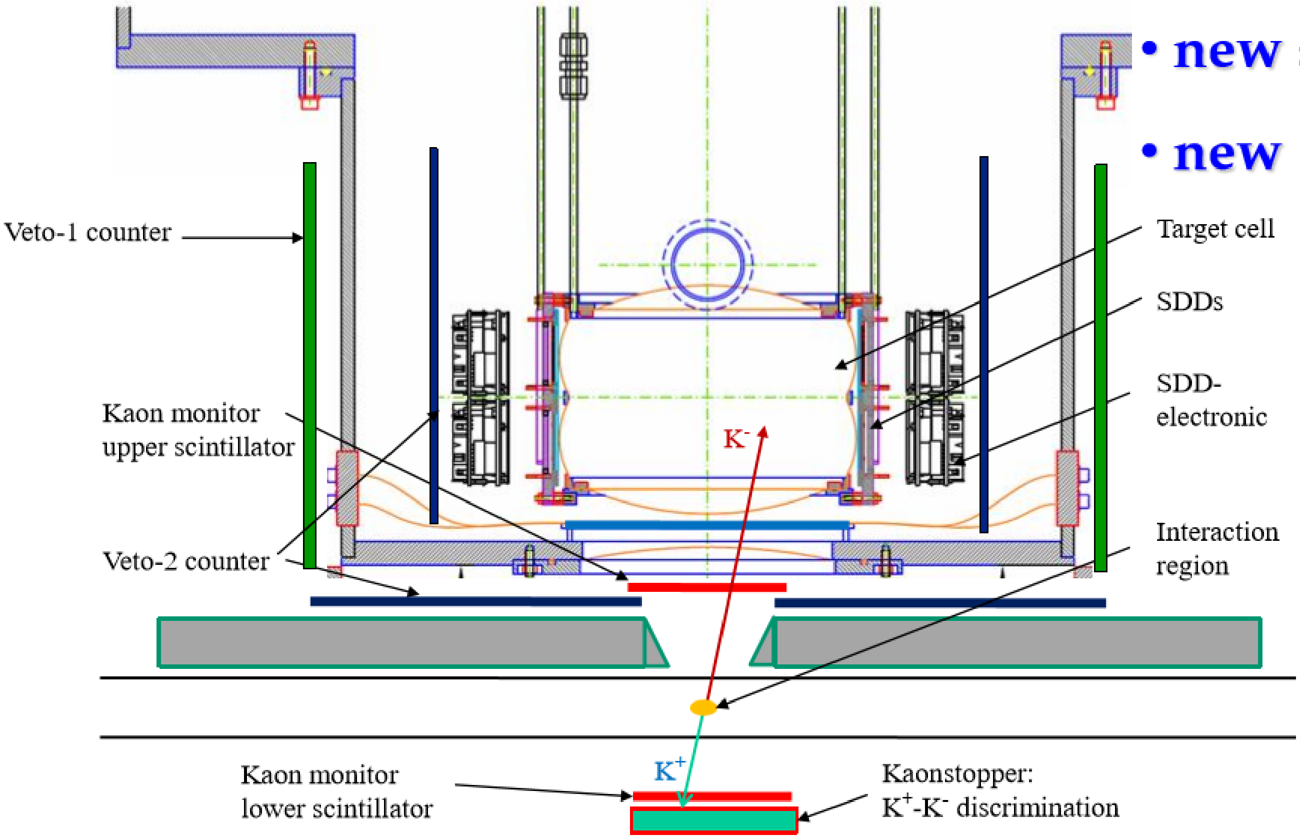


A. Cieplý, M. Mai, Ulf-G. Meißner, J. Smejkal, https://arxiv.org/abs/1603.02531v2

From SIDDHARTA to SIDDHARTA-2

	signal	hadronic BG	machine BG	S/B	K_α events
SIDDHARTA	1.00	1.00	1.00	1:40	
IP - target	1.38	1.33		1:11	6075
3% LHD	1.64	1.08			
geometry	1.25	0.56	0.25		
Trigger 1	0.71	0.48		1:7.6	4320
Trigger 2	0.79	0.59	0.33	1:5.7	3415
Trigger 3	0.98	0.73		1:4.2	3350
K+ discrimination	0.70	0.78		1:3.3	2345
drift time 400ns			0.49	1:3.0	2345
SIDDHARTA-2	**1.09**	**0.12**	**0.04**	**1:3**	**2345**

- **new target cell**
- **new vacuum chamber**
- **new cooling system**
- **new kaon monitor/trigger**
- **two veto systems**
- **K^+ induced backg. discriminator**
- **new shielding structure**
- **new SDD detectors**



With the new S/B, Kd measurement will be possible

$(Y_{KH} / Y_{Kd} \approx 10)$

Expected KD spectrum

MC simulation for 800 pb^{-1}

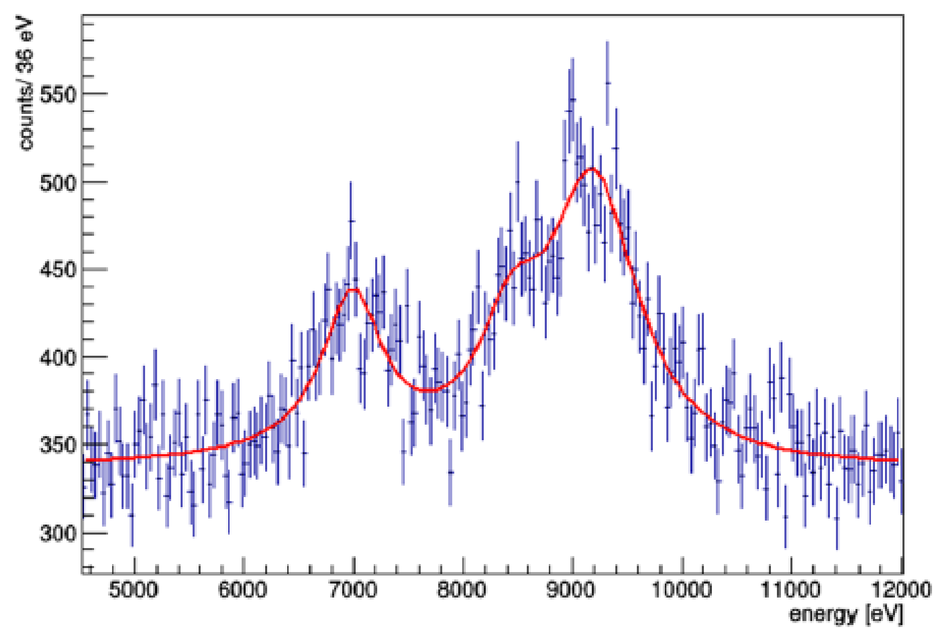
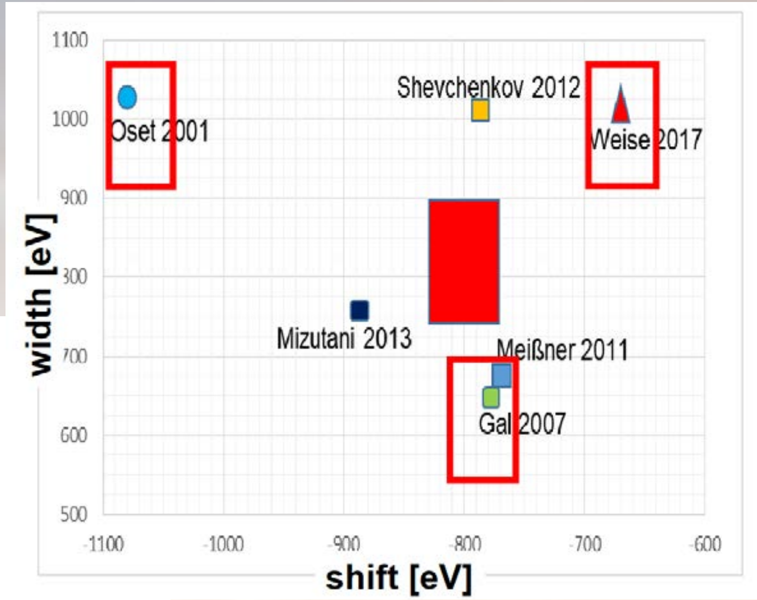


Figure 21: The simulated spectrum of K^-d for SIDDHARTA-2 for 800 pb^{-1} (the K_α line is at 7 keV, while from 8 to 10 keV there is the K-complex)



Assumptions
signal: shift - 800 eV
width 750 eV
density: 5% (LHD)
detector area: 246 cm^2

Kα yield: 0.1 %
yield ratio as in K^-p

Achievable precisions:
$\Delta\varepsilon(1s) = 30$ eV and $\Delta\Gamma(1s) = 70$ eV

First SIDDHARTA-2 results

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JID:NUPHA AID:122567 /FLA [m1+; v1.358] P.1 (1-10)
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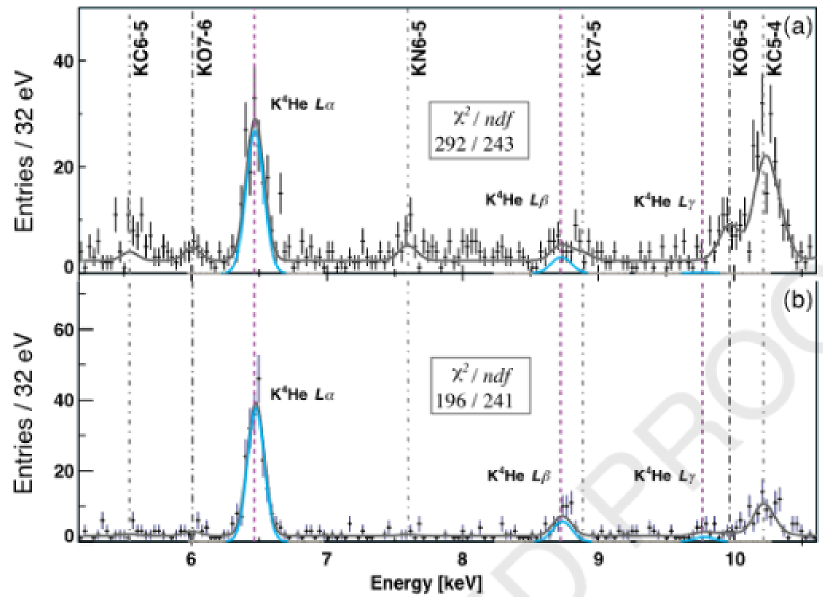
New measurements of kaonic helium-4 L-series X-rays yields in gas with the SIDDHARTINO setup

D.L. Sirghi [a,b,c,*], H. Shi [d], C. Guaraldo [a], F. Sgaramella [a,**], C. Amsler [d], M. Bazzi [a], D. Bosnar [e], A.M. Bragadireanu [c], M. Carminati [f,g], M. Cargnelli [d], A. Clozza [a], G. Deda [f,g], L. De Paolis [a], R. Del Grande [a,h], L. Fabbietti [h], C. Fiorini [f,g], M. Iliescu [a], M. Iwasaki [i], J. Marton [d], M. Miliucci [a], P. Moskal [j], F. Napolitano [a], S. Niedzwiecki [j], H. Ohnishi [k], K. Piscicchia [b,a], Y. Sada [k], A. Scordo [a], M. Silarski [j], F. Sirghi [a,c], M. Skurzok [j], A. Spallone [a], K. Toho [k], M. Tüchler [d,l], O. Vazquez Doce [a], J. Zmeskal [d], C. Yoshida [k], C. Curceanu [a]



. 2. X-ray kaonic helium-4 spectra measured by SIDDHARTINO for: (a) 0.82 g/l target gas density; (b) 1.90 g/l targ gas density. The kaonic helium-4 peaks L_α, L_β and L_γ are shown. Several kaonic atom X-ray lines produced in th Kapton foils are also shown: Kaonic Carbon 6 → 5, Kaonic Oxygen 7 → 6, Kaonic Nitrogen 6 → 5, Kaonic Carbo 7 → 5, Kaonic Oxigen 6 → 5, Kaonic Carbon 5 → 4 transitions. The solid line shows the fit function of the spectrun The blue line shows the L series L_α, L_β and L_γ kaonic helium-4 components. (For interpretation of the colors in th figure(s), the reader is referred to the web version of this article.)

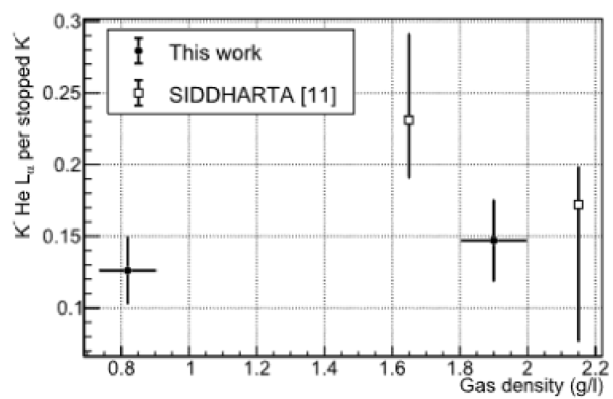
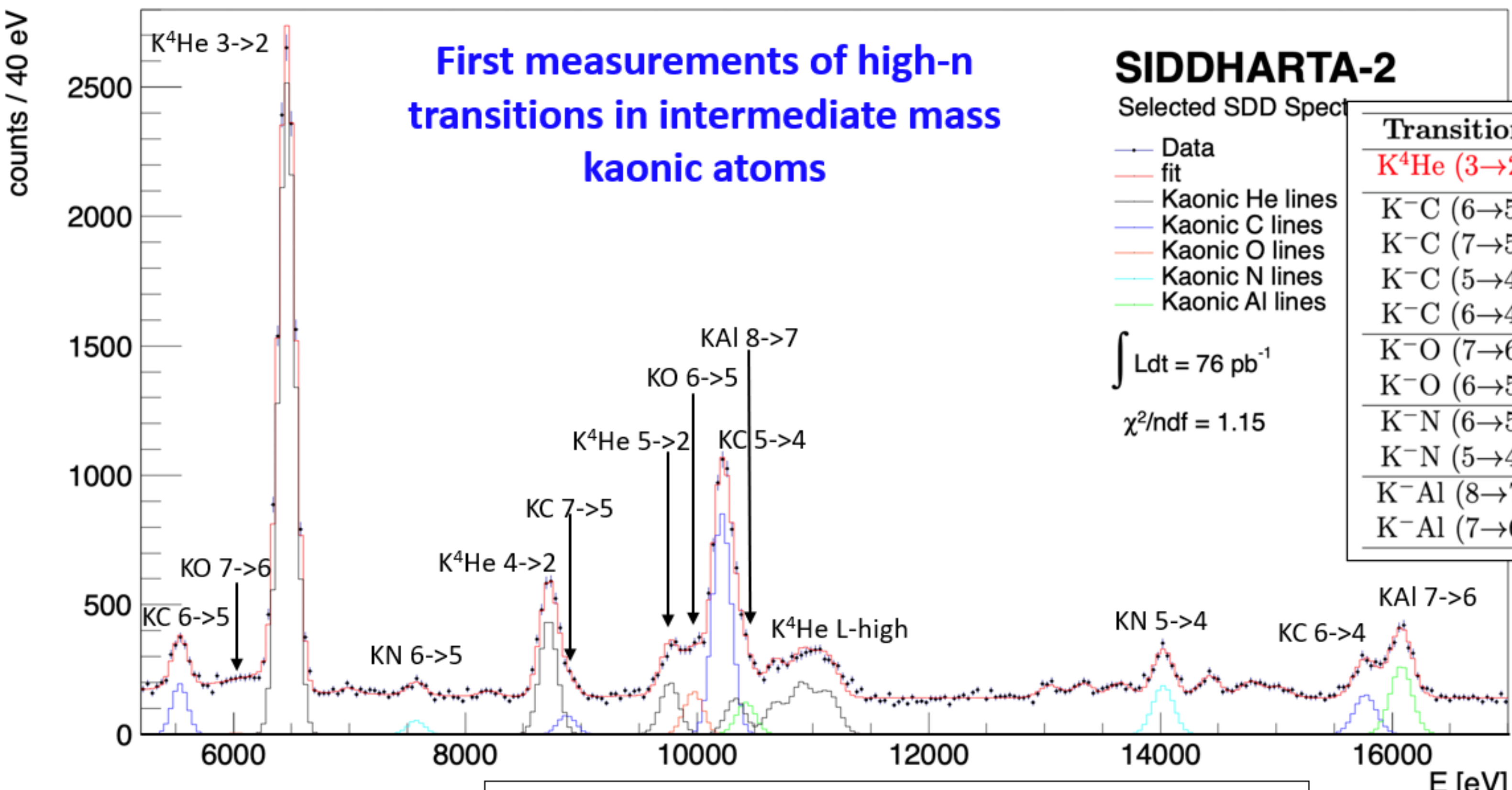


Fig. 3. The L_α X-ray yield of K^- ^{4}He as function of the target density from all gaseous target measurements: this work (filled dots) and SIDDHARTA [16] (hollow squares).

First SIDDHARTA-2 results

The Kaonic ^{4}He measurement (2022)

- Kaonic He measurement with the full SIDDHARTA-2 setup
- Improved accuracy on the Lα energy shift and width
- Measurement of kaonic carbon – nitrogen – oxygen and aluminium



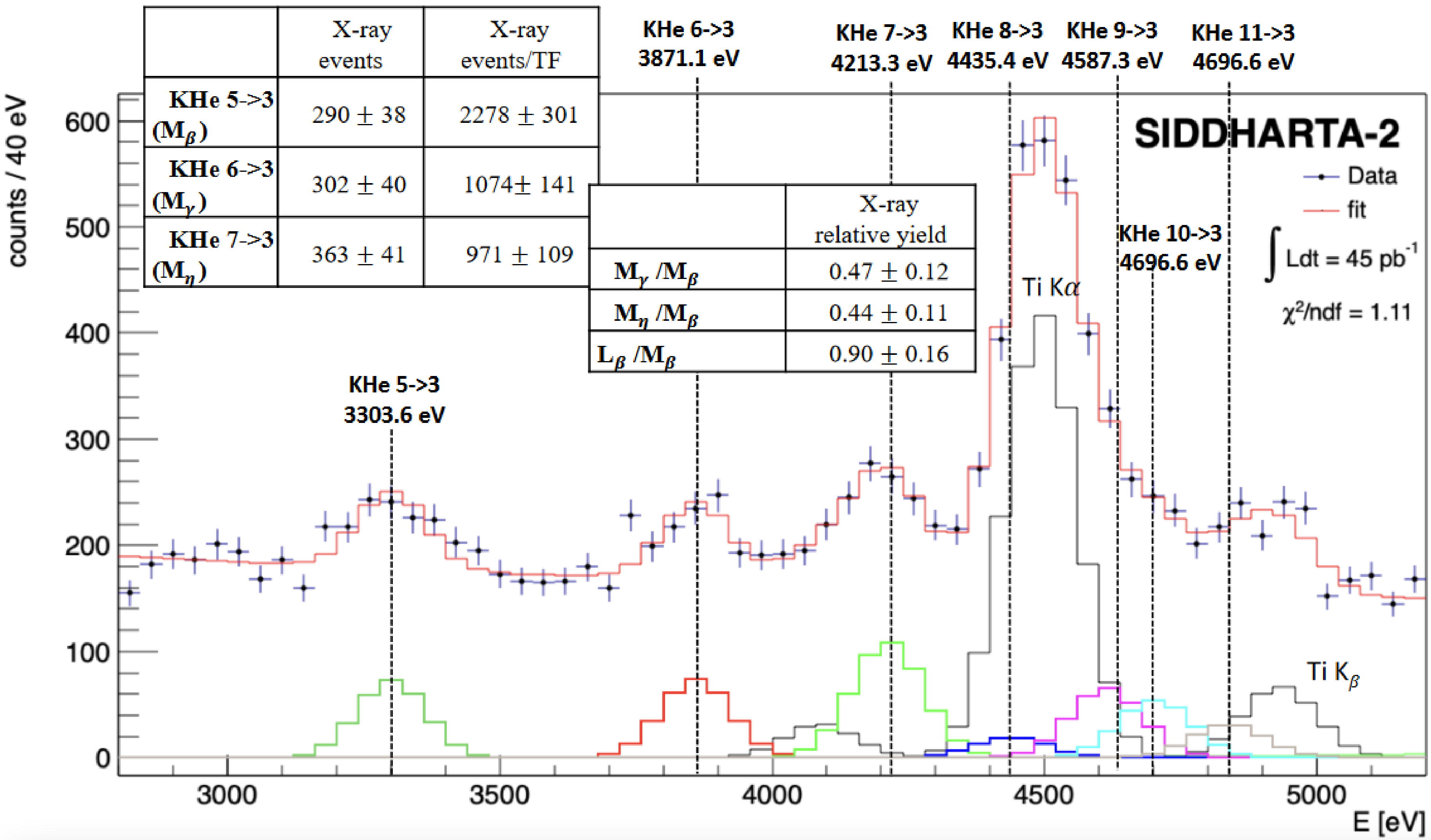
Transition	Energy (eV)
K^4He (3→2)	6461.4 ± 0.8 (stat) ± 2.0 (syst)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890 ± 13 (stat) ± 2.0 (syst)
K^-C (5→4)	10216.6 ± 1.8 (stat) ± 3.0 (syst)
K^-C (6→4)	15760.3 ± 4.7 (stat) ± 12.0 (syst)
K^-O (7→6)	6016 ± 60 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-N (6→5)	7577 ± 17 (stat) ± 2.0 (syst)
K^-N (5→4)	14010.6 ± 8.2 (stat) ± 9.0 (syst)
K^-Al (8→7)	10441.0 ± 8.5 (stat) ± 3.0 (syst)
K^-Al (7→6)	16083.4 ± 3.8 (stat) ± 12.0 (syst)

Sgaramella F., Tüchler M., et al., 2023, Eur. Phys. J. A, 59 (3) 56

First SIDDHARTA-2 results

SIDDHARTA-2 Kaonic ^{4}He SURPRISE

First measurememt M-line transitions – article



	X-ray events	X-ray events/TF
KHe 5->3 (M_β)	290 ± 38	2278 ± 301
KHe 6->3 (M_γ)	302 ± 40	1074± 141
KHe 7->3 (M_η)	363 ± 41	971 ± 109

	X-ray relative yield
M_γ / M_β	0.47 ± 0.12
M_η / M_β	0.44 ± 0.11
L_β / M_β	0.90 ± 0.16

First SIDDHARTA-2 results

The Kaonic ^{4}He yield

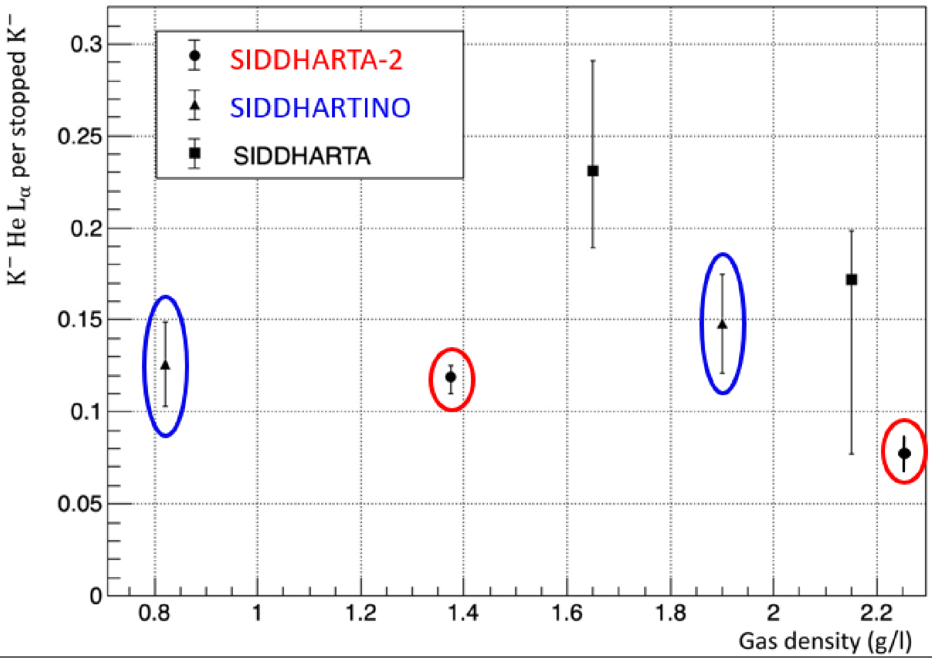
New experimental data for cascade models calculations
The X-ray yield is the key observable to understand the de-excitation mechanism in kaonic atoms and develop more accurate models.

First measurement of K-^{4}He M-series transition

Density	1.375 g/l
L_α *yield*	$0.119 \pm 0.002\,(\text{stat})^{+0.006\,(\text{sys})}_{-0.009\,(\text{sys})}$
M_β *yield*	$0.026 \pm 0.003\,(\text{stat})^{+0.010\,(\text{sys})}_{-0.001\,(\text{sys})}$
L_β / L_α	$0.172 \pm 0.008\,(\text{stat})$
L_γ / L_α	$0.012 \pm 0.001\,(\text{stat})$
L_β / M_β	$0.91 \pm 0.14\,(\text{stat})$
M_γ / M_β	$0.48 \pm 0.11\,(\text{stat})$
M_δ / M_β	$0.43 \pm 0.12\,(\text{stat})$

Sgaramella F., et al, submitted to J. Phys. G Nucl. Part. Phys

Study of yield density dependence for the K-^{4}He $L\alpha$ transition



Sirghi D.L., Shi H., Guaraldo C., Sgaramella F., et al., 2023, Nucl. Phys. A,1029 122567

First SIDDHARTA-2 results

STRONG-2020

SIDDHARTA-2 main outcomes 2022-2023

27 Publications (2022-2023)
Organization of 4 workshops

- **The most precise KHe L-transition measurement in gas :** J. Phys. G 49 (2022) 5, 055106
- **Kaonic helium-4 yields L-lines in gas :** Nucl. Phys. A 1029 (2023) 122567
- **First measurement ever of intermediate mass kaonic atoms:** Eur. Phys. J. A 59(2023)3, 56
- **First Measurement of KHe M-lines :** paper ready to be submitted to J. Phys. G
- **First Measurement ever of kaonic Neon (record of precision < 1 eV) :** analysis on going with implication on the kaon mass
- **First measurement of kaonic deuterium (200 pb^{-1}) :** analysis on going

$$\epsilon_{2p} = E_{exp} - E_{e.m} = 0.2 \pm 2.5(stat) \pm 2.0(syst)\ eV$$

$$\Gamma_{2p} = 8 \pm 10\ eV\ (stat).$$

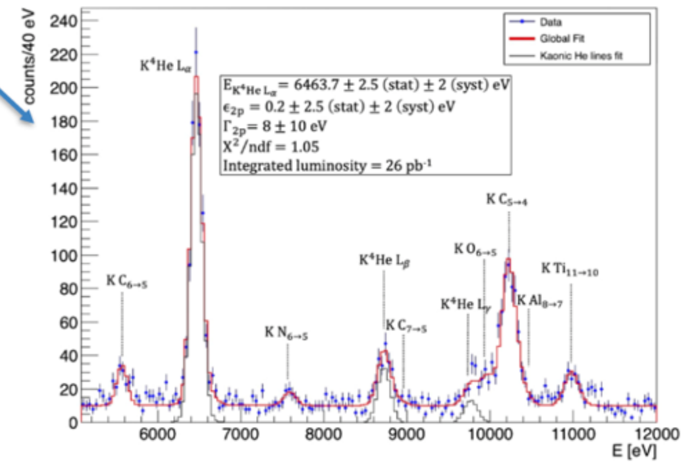


Figure 7. Fit (red line) of the K^{4}He energy spectrum. The Lα peak is seen together with the Lβ and Lγ ones (black lines). The peaks labeled as KN, KC, KAl, KTi (dotted lines) are the kaonic atoms lines produced by the kaons stopped in the Kapton ($C_{22}H_{10}O_5N_2$)

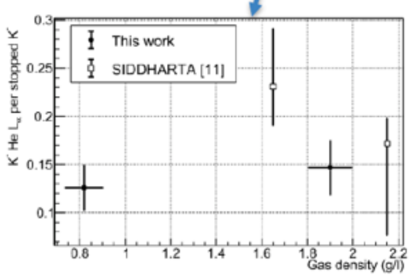


Fig. 3. The L_α X-ray yield of K^- ^{4}He as function of the target density from all gaseous target measurements: this wc (filled dots) and SIDDHARTA [16] (hollow squares).

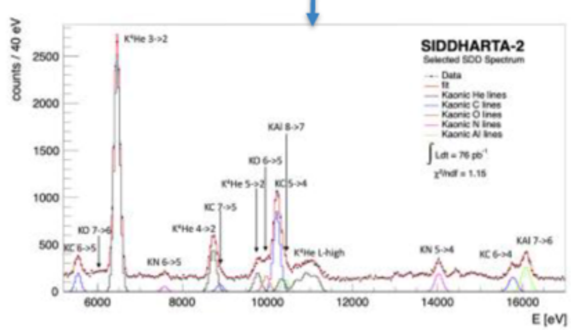
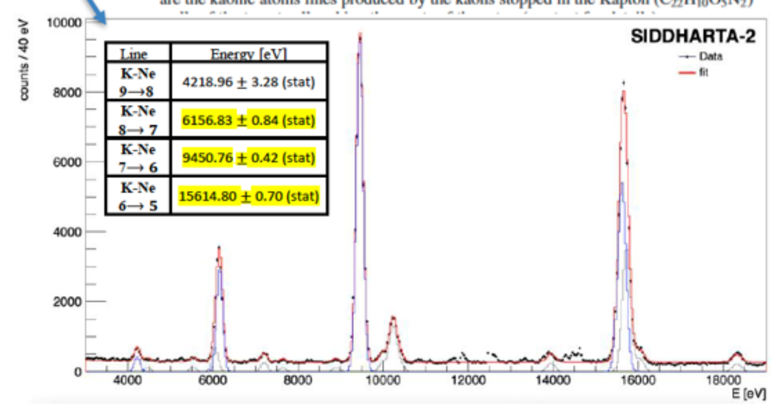


Fig. 6 SDD energy spectrum and fit of SIDDHARTA-2 and SIDDHARTINO summed data after background suppression (see text). The kaonic helium signals are seen as well as the kaonic carbon (KC), oxygen (KO), nitrogen (KN) and aluminium (KAl) peaks



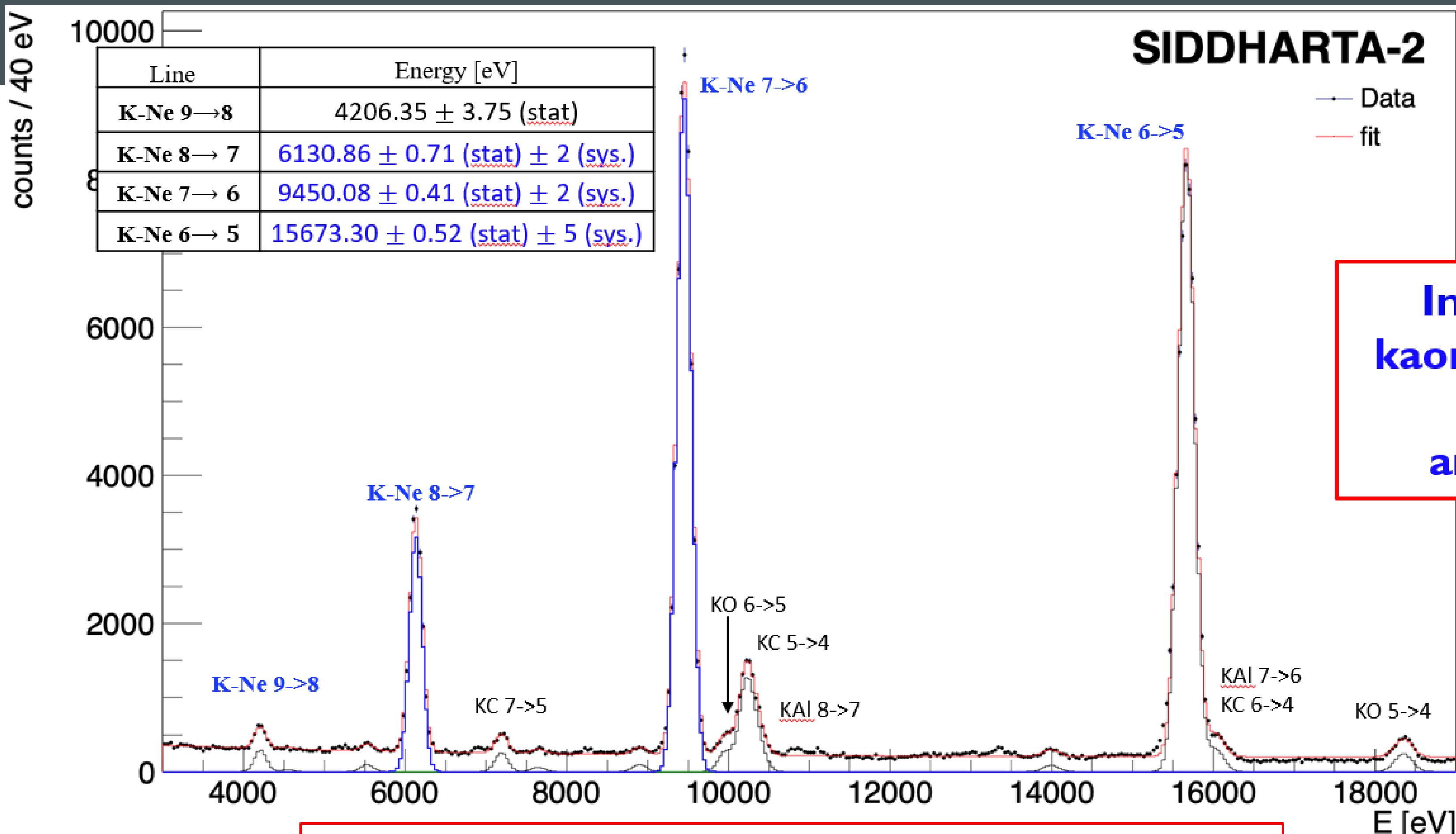
Line	Energy [eV]
K-Ne 9→8	4218.96 ± 3.28 (stat)
K-Ne 8→7	6156.83 ± 0.84 (stat)
K-Ne 7→6	9450.76 ± 0.42 (stat)
K-Ne 6→5	15614.80 ± 0.70 (stat)

First SIDDHARTA-2 results

The Kaonic Neon measurement (2023)

First measurement of kaonic neon X-ray transitions (record of precision < 1 eV)

Line	Energy [eV]
K-Ne 9⟶8	4206.35 ± 3.75 (stat)
K-Ne 8⟶ 7	6130.86 ± 0.71 (stat) ± 2 (sys.)
K-Ne 7⟶ 6	9450.08 ± 0.41 (stat) ± 2 (sys.)
K-Ne 6⟶ 5	15673.30 ± 0.52 (stat) ± 5 (sys.)



Implications on kaon - multinucleon interaction and kaon mass

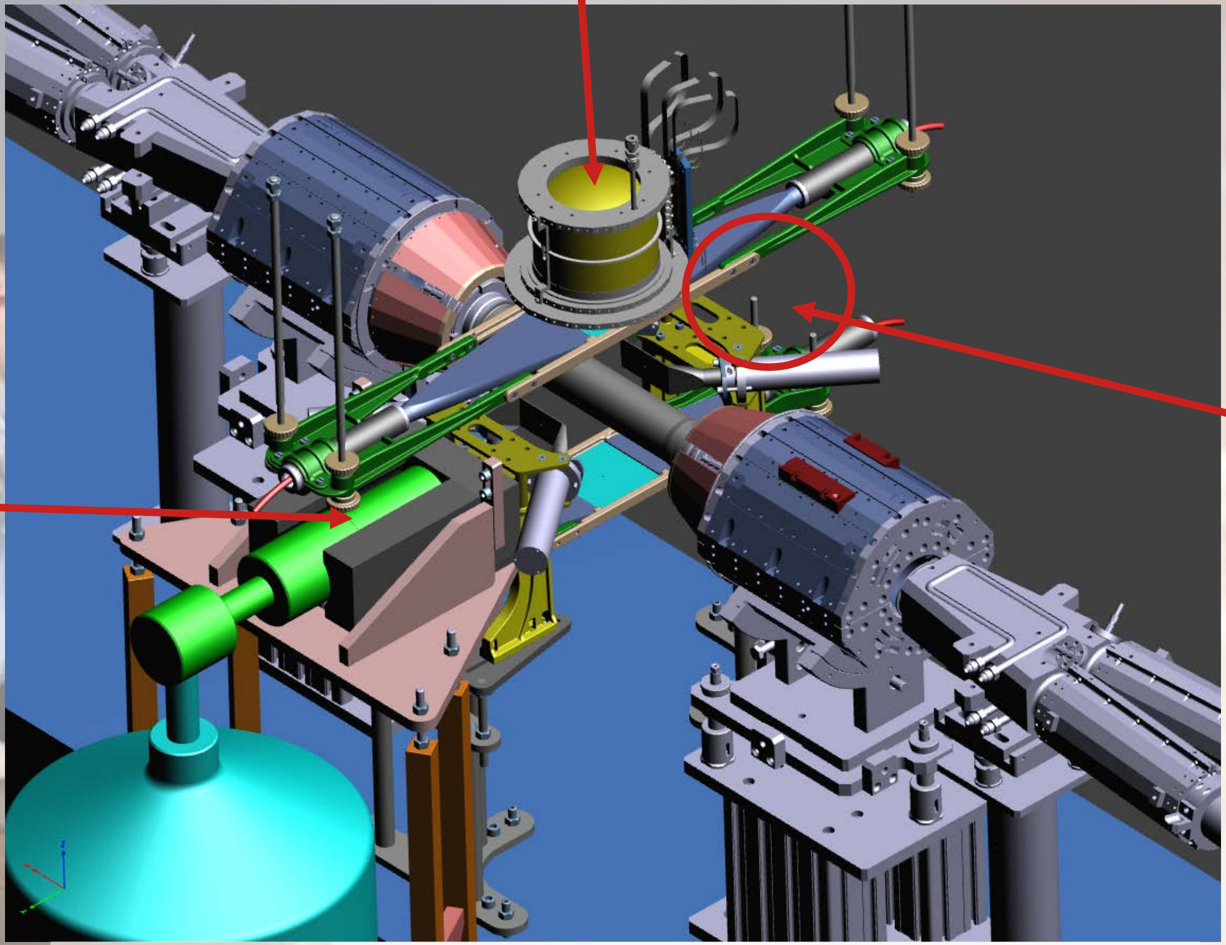
Kaonic Neon Yield analysis on going ⟶ paper in preparation

Exploiting DAΦNE

SDDs (4-30 keV) - Light Kaonic Atoms

HPGe
(0,1-1 MeV)

Heavy Kaonic Atoms



CdZnTe
(30-300 keV)

Intermediate Kaonic Atoms

DAΦNE delivers almost 4π K^-

We want to exploit this uniqe beam as much as possible to perform important physics measurements

Why (again and still) kaonic atoms?

402 *C.J. Batty et al. / Physics Reports 287 (1997) 385–445*

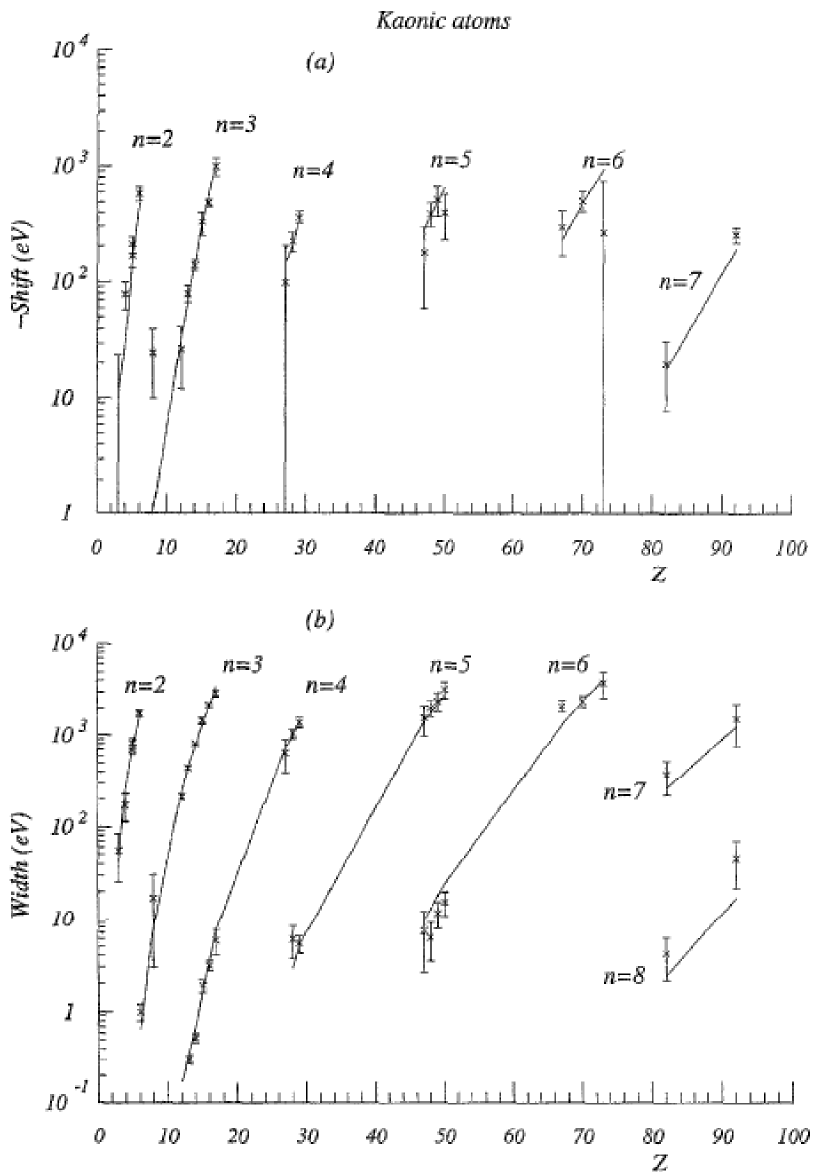


Fig. 7. Shift and width values for kaonic atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 4.2.

Except for the most recent measurements at DAΦNE and JPARC on KHe and KH, the whole knowledge on kaonic atoms dates back to 1970s and 1980s

These data are the experimental basis for all the developed theoretical models

These theoretical models are used to derive, for example:

- KN interaction at threshold
- KNN interaction at threshold
- Nuclear density distributions
- Possible existence of kaon condensates
- Kaon mass
- Kaonic atoms cascade models

Why (again and still) kaonic atoms?

E. Friedman et al. / Nuclear Physics A579 (1994) 518–538 — 521

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]

The available data on “lower levels” have big uncertainties

Many of them are actually UNmeasured

Many of them are hardly compatible among each other

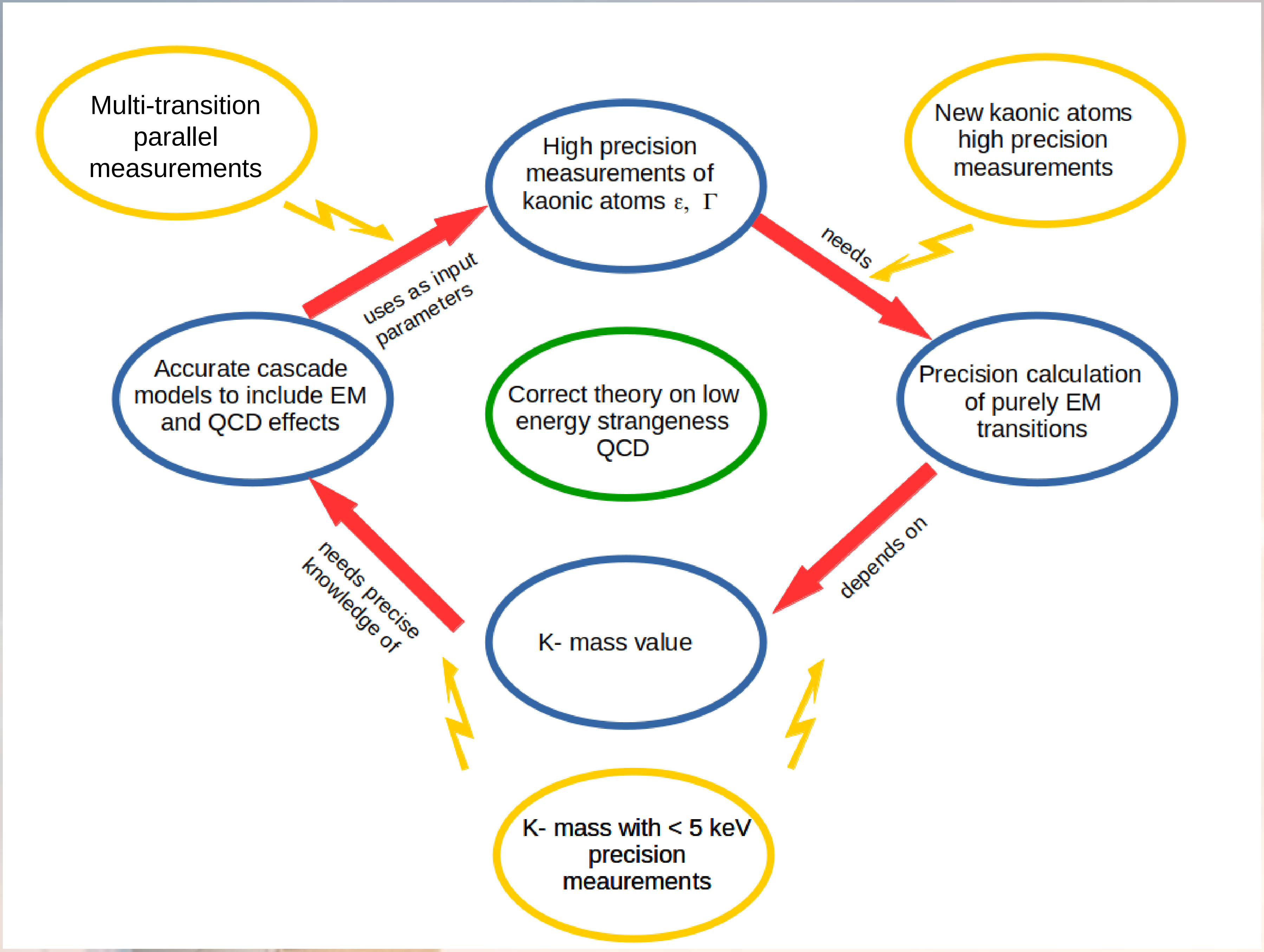
Relative yields with upper levels are not always measured

Absolute yields are basically unknown (except for few transitions)

The REmeasured ones have been proved WRONG

This situation would already be a proper justification for new measurements

What more can we learn from new measurements?



Transitions: energies and widths…which detector?

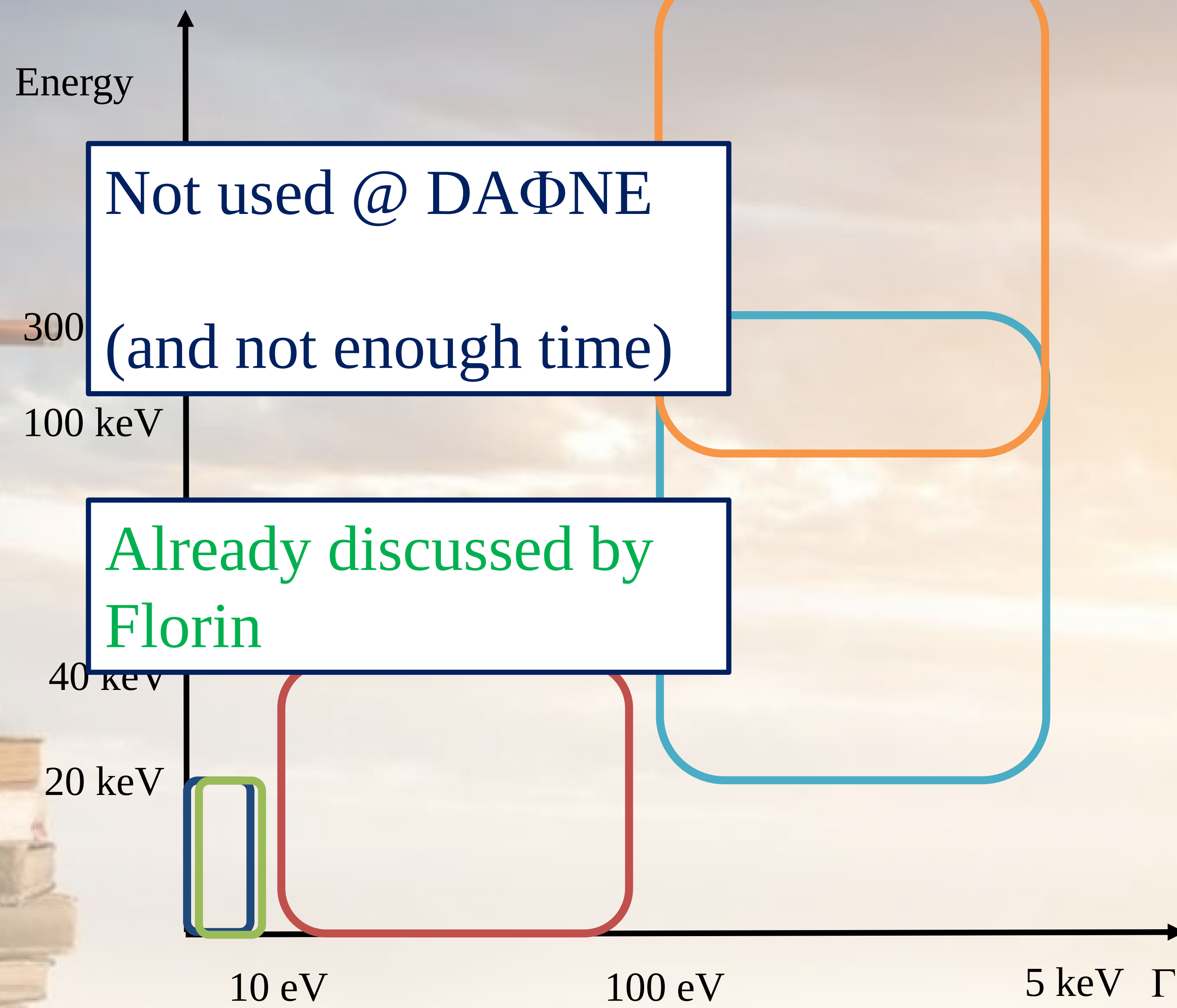
…tromet…
- …range

…calorimeters
- acce…
- …cult calibration

- …fficiency

Cd(Zn)Te
- 20-300 keV range
- FWHM / E ~ %
- High efficiency
- Room Temperature

HPGe
- 100-1000 keV range
- FWHM / E ~ %
- High efficiency
- Cooling needed

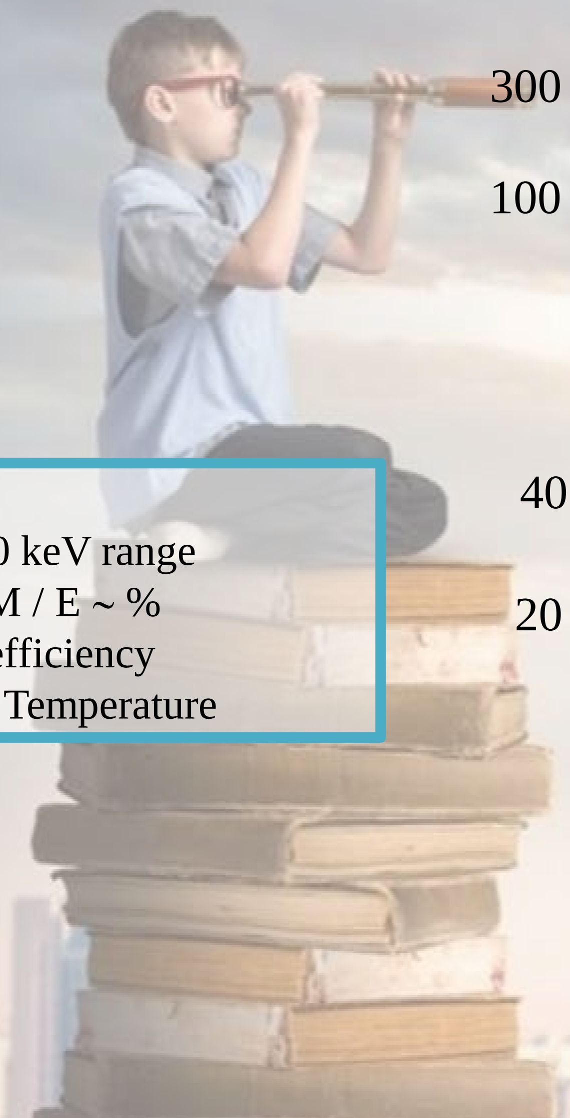


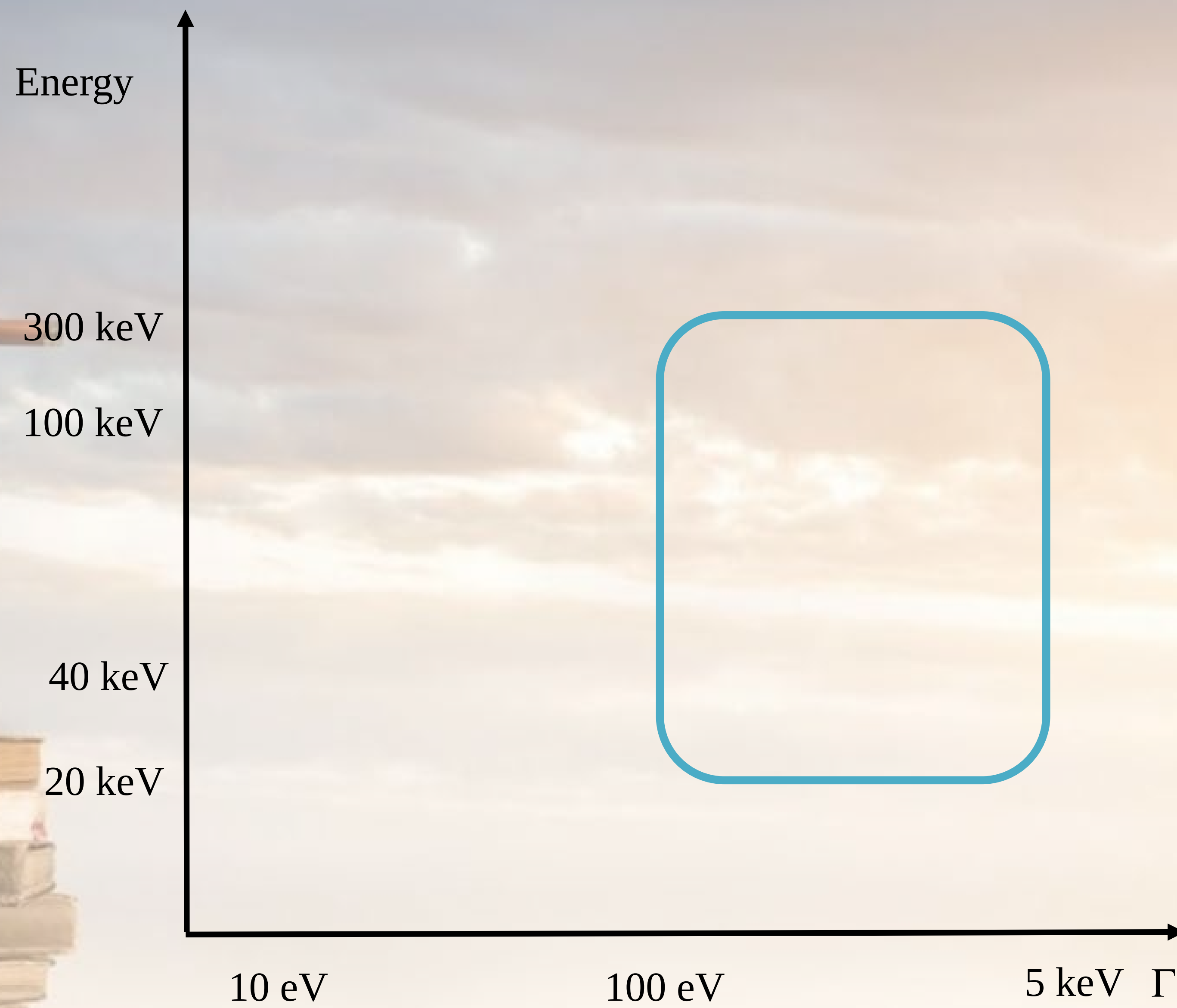
Not used @ DAΦNE

(and not enough time)

Already discussed by Florin

Transitions: energies and widths…which detector?





Cd(Zn)Te
- 20-300 keV range
- FWHM / E ~ %
- High efficiency
- Room Temperature

Advanced ultra-fast solid STate detectors for high precision RAdiation spectroscopy : ASTRA

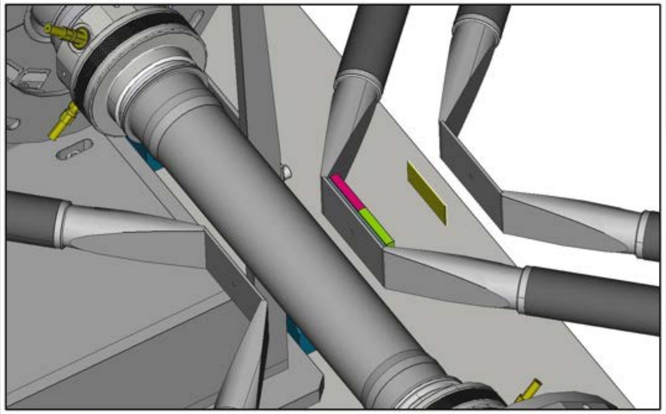
Organization legal name	Short name	Activity leader
Austrian Academy of Sciences, Stefan Meyer Institute, Austria	OEAW	**J. Zmeskal**
Istituto Materiali per Elettronica e Magnetismo, CNR, Parma, Italy	CNR	A. Zappettini
Jagiellonian University, Krakow, Poland	UJ	P. Moskal
Laboratori Nazionali di Frascati (LNF) – INFN, Italy	INFN	A. Scordo
Politecnico Milano, Dipartimento di Elettronica, Italy	POLIMI	C. Fiorini
University of Zagreb, Croatia	UNIZG	D. Bosnar

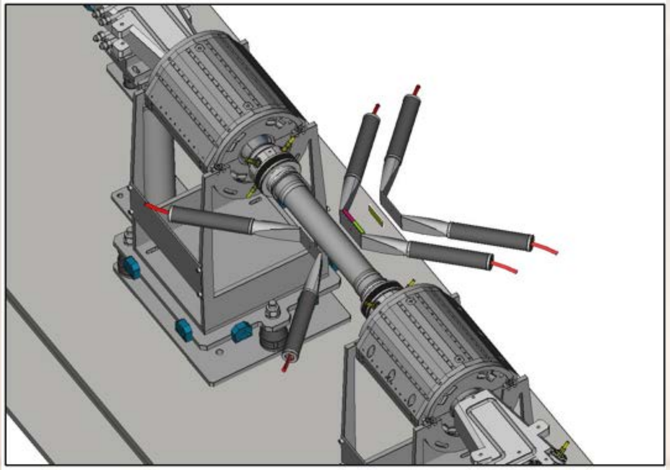
The main objective of the ***ASTRA*** project is to develop beyond state-of-art ultra-fast CdZnTe/CdTe radiation detector systems for high-precision measurements of gamma- and X-ray events in a broad energy range, **few keV to MeV**.

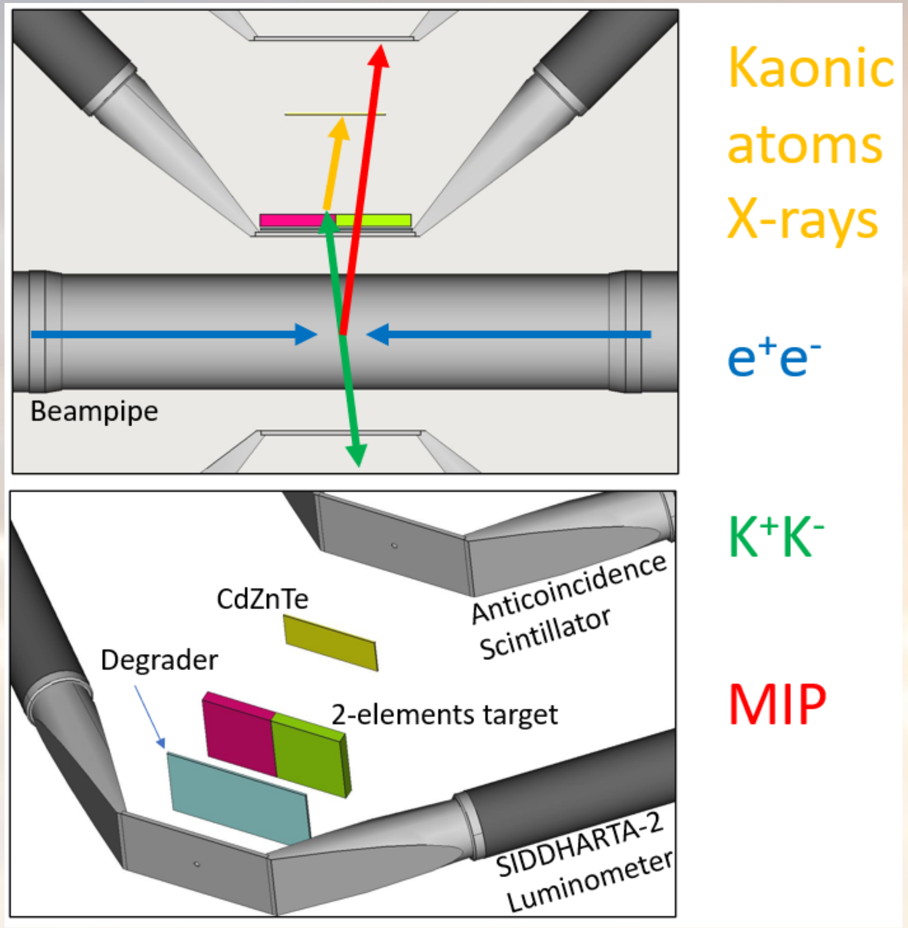
CZT: proposal for new measurements at DAΦNE

Detector Key Points:

- High efficiency in the 20-100 keV region
- Reasonable efficiencies up to 300 keV
- Good resolution (FHWM/E ~ %)
- Fast response and time resolution (< 50 ns)
- No need for cooling
- Compact readout and installation package







Feasibility:

CdTe (and also CdZnTe) detectors developed in the JRA8-ASTRA (STRONG-2020) project

Further prototypes will be available by mid 2023

CZT: proposal for new measurements at DAΦNE

E. Friedman et al. / Nuclear Physics A579 (1994) 518–538

Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)
He	3 → 2	−0.04 ± 0.03	–	–	–
		−0.035 ± 0.012	0.03 ± 0.03	–	–
Li	3 → 2	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–
Be	3 → 2	−0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02
^{10}B	3 → 2	−0.208 ± 0.035	0.810 ± 0.100	–	–
^{11}B	3 → 2	−0.167 ± 0.035	0.700 ± 0.080	–	–
C	3 → 2	−0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20
O	4 → 3	−0.025 ± 0.018	0.017 ± 0.014	–	–
Mg	4 → 3	−0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03
Al	4 → 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 → 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 → 3	−0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30
S	4 → 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

Element	Transition	E (keV)
K^{12}C	3-->2	63
K^{12}C	4-->2	85
K^{12}C	5-->2	95
K^{12}C	6-->2	101
K^{12}C	7-->2	104
K^{12}C	4-->3	22
K^{12}C	5-->3	32
K^{12}C	6-->3	38
K^{12}C	7-->3	41

Element	Transition	E (keV)
K^{32}S	4-->3	161
K^{32}S	5-->4	74
K^{32}S	6-->4	115
K^{32}S	7-->4	139
K^{32}S	8-->4	155
K^{32}S	9-->4	166
K^{32}S	10-->4	174

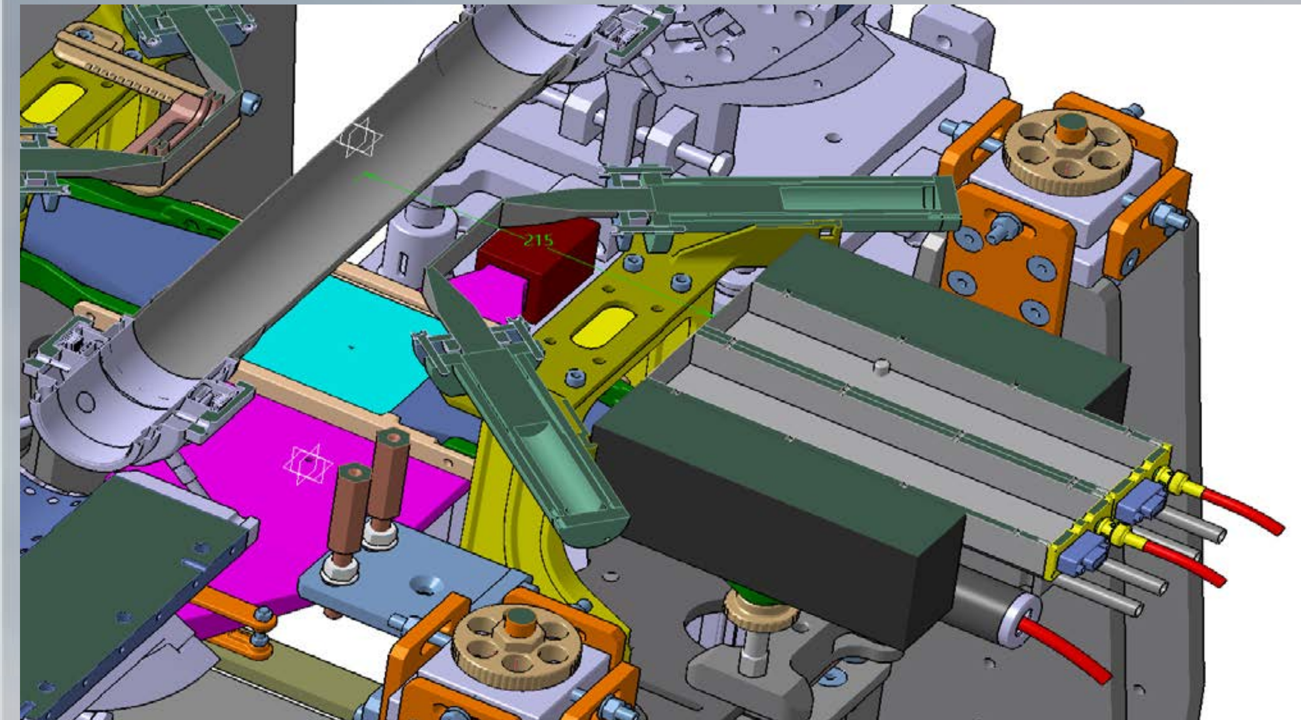
Element	Transition	E (keV)
K^{27}Al	3-->2	302
K^{27}Al	4-->3	106
K^{27}Al	5-->3	155
K^{27}Al	6-->3	181
K^{27}Al	7-->3	197
K^{27}Al	8-->3	208
K^{27}Al	5-->4	49
K^{27}Al	6-->4	76
K^{27}Al	7-->4	91
K^{27}Al	8-->4	102
K^{27}Al	9-->4	109
K^{27}Al	10-->4	114

KC(3→2), KAl(3→2), KS(4→3):

Precisions < 20 eV (ε) and <40 eV (Γ) are reachable in few months

Measurements of several parallel transitions → new inputs for cascade casculations

CdZnTe 2023: MC and expectations



15,6 cm^2 CZT detector has been inserted in the GEANT4 MC simulation code of SIDDHARTA-2, the experiment presently installed at DAFNE, to estimate the expected results in real beam conditions

Detectors were placed at a distance of 216 mm from the IR surrounded by Pb bricks for shielding.

Designed by C. Capoccia (LNF)

C/Al targets placed nearby of one of the two scintillators of the SIDDHARTA-2 Luminometer (LM)

Targets' thicknesses were optimized to stop in each one a similar fraction of K-.

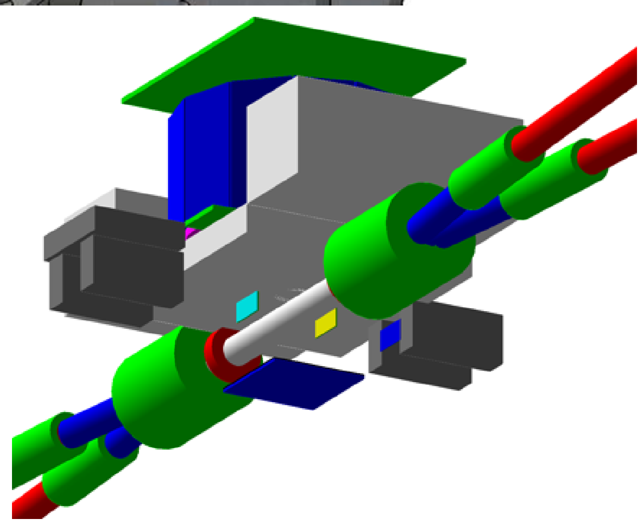
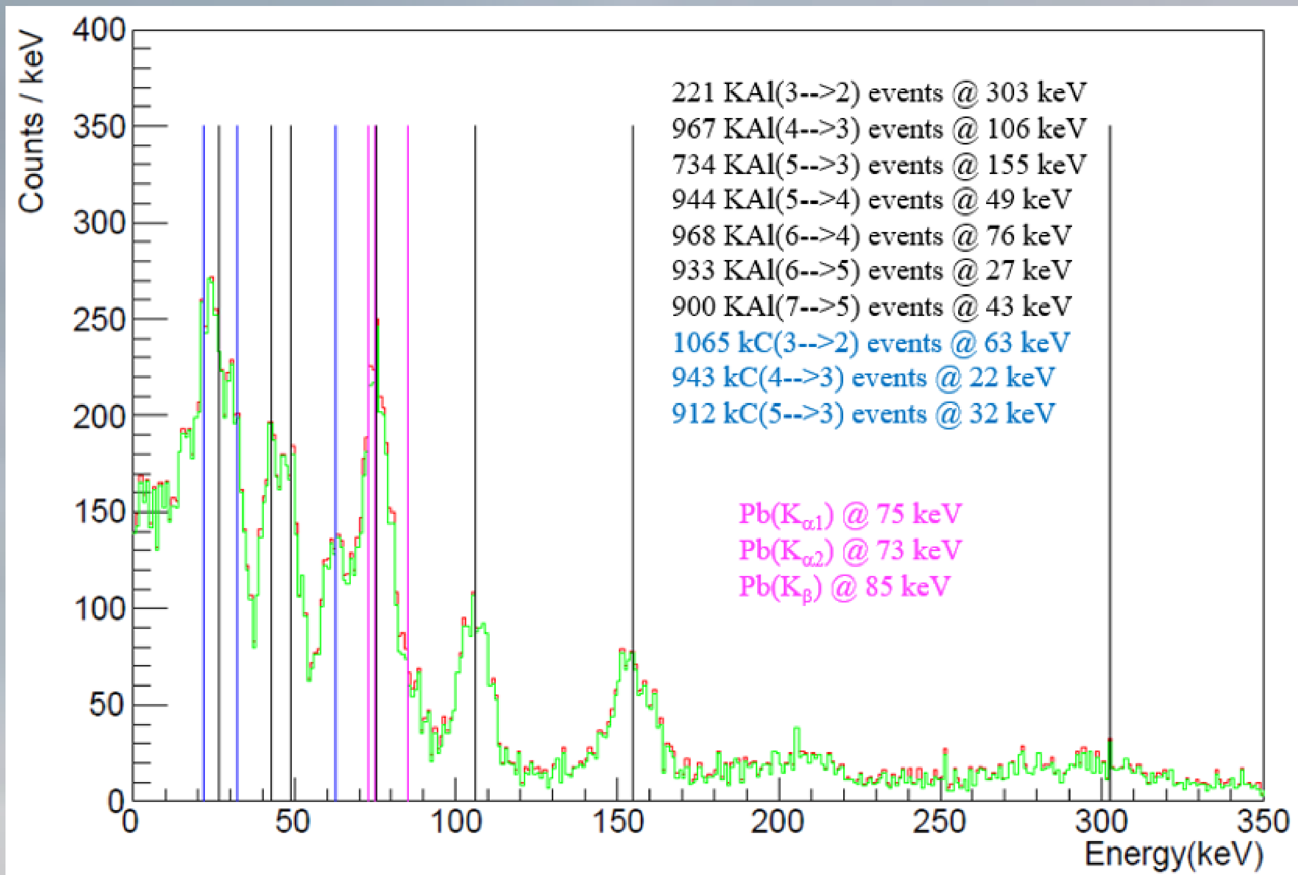


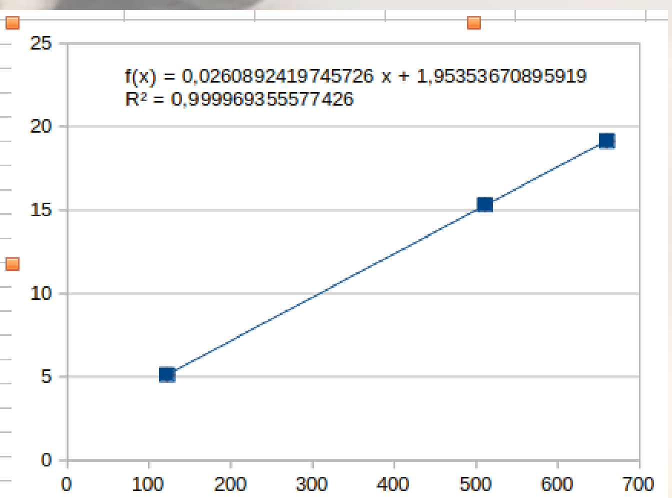
Fig. M2: Details of the GEANT4 simulations of 15,6 cm2 CdZnTe inserted in the main SIDDHARTA-2 simulation

CdZnTe 2023: MC and expectations



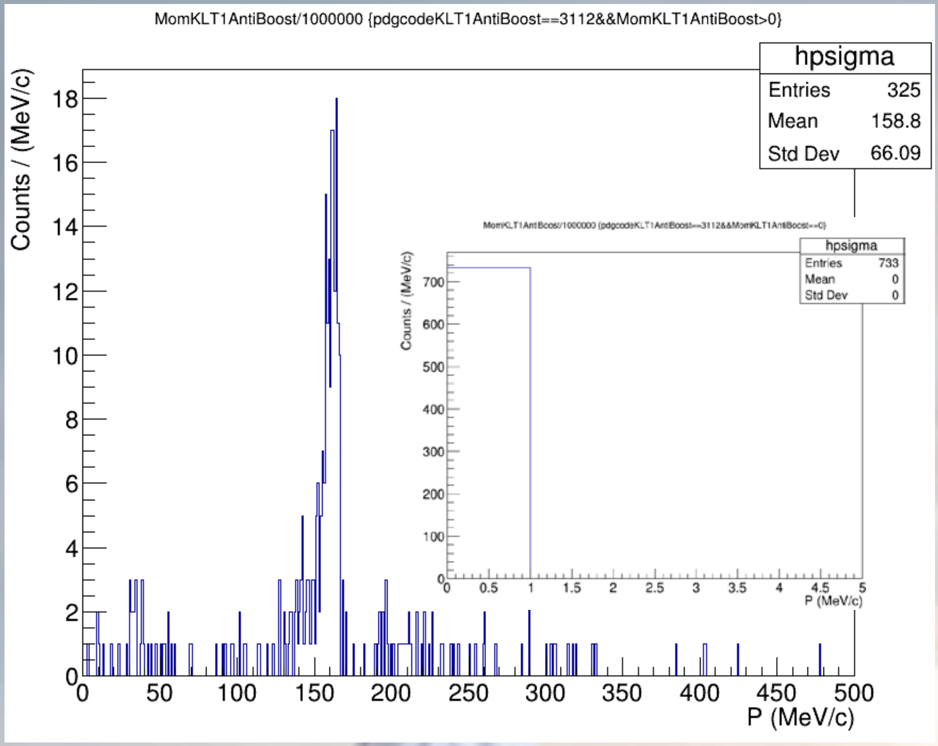
Transition	Energy (keV)	events / 10 pb^{-1} with 15,6 cm^2	Yield / K^- stop
KC(3-->2)	63	1065	0,07
KAl(4-->3)	106	967	0,55
KS(4-->3)	161	940	0,22
KC(4-->3)	22	943	0,07
KC(5-->3)	32	912	0,035
KAl(5-->4)	49	944	0,55
KAl(6-->4)	76	968	0,27
KAl(6-->5)	27	933	0,55
KAl(7-->5)	43	900	0,27
KS(5-->4)	74	1590	0,22
KS(5-->3)	235	560	0,11
KS(6-->5)	40	1350	0,22
KS(6-->4)	115	1310	0,11
KS(7-->5)	65	1700	0,11
KPb(9-->8)	289	170	0,79
KPb(10-->9)	207	190	0,4
KPb(11-->10)	153	370	0,79
KPb(12-->10)	269	130	0,4
KPb(11-->9)	359	80	0,79
KPb(12-->11)	116	360	0,79
KPb(13-->11)	207	270	0,4

Energy (keV)	FWHM (%)	FWHM (keV)
122	4,2	5,124
511	3	15,33
660	2,9	19,14



Very interesting measurements could be done in a few months of data taking with a dedicated and optimized setup

Interlude (BONUS from MC to be further investigated)

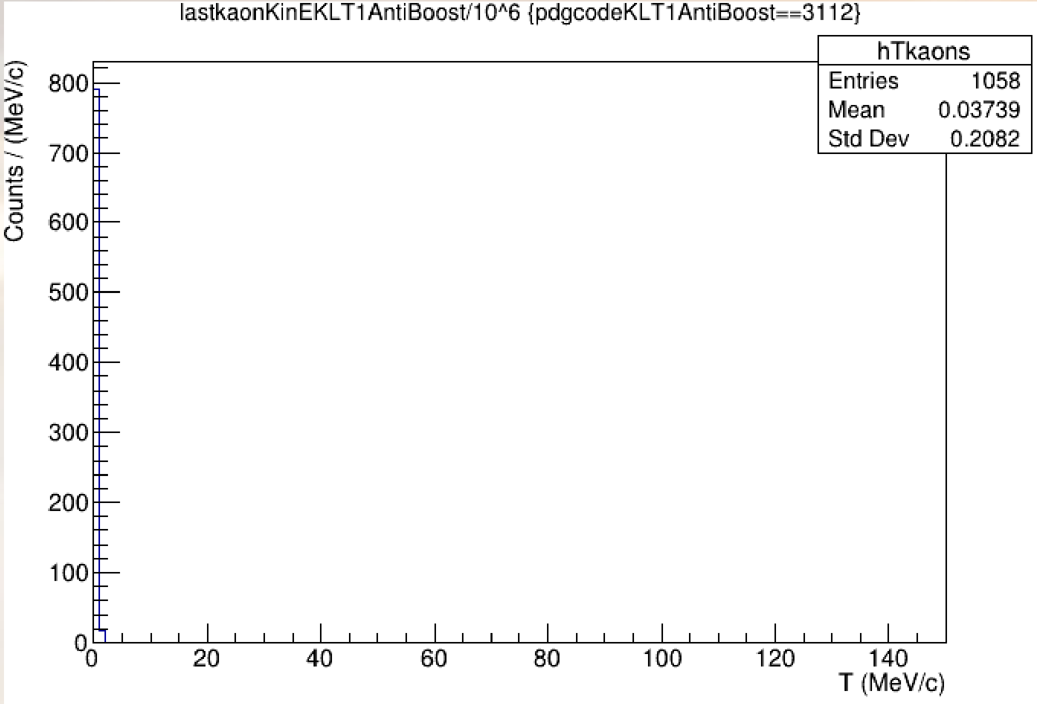


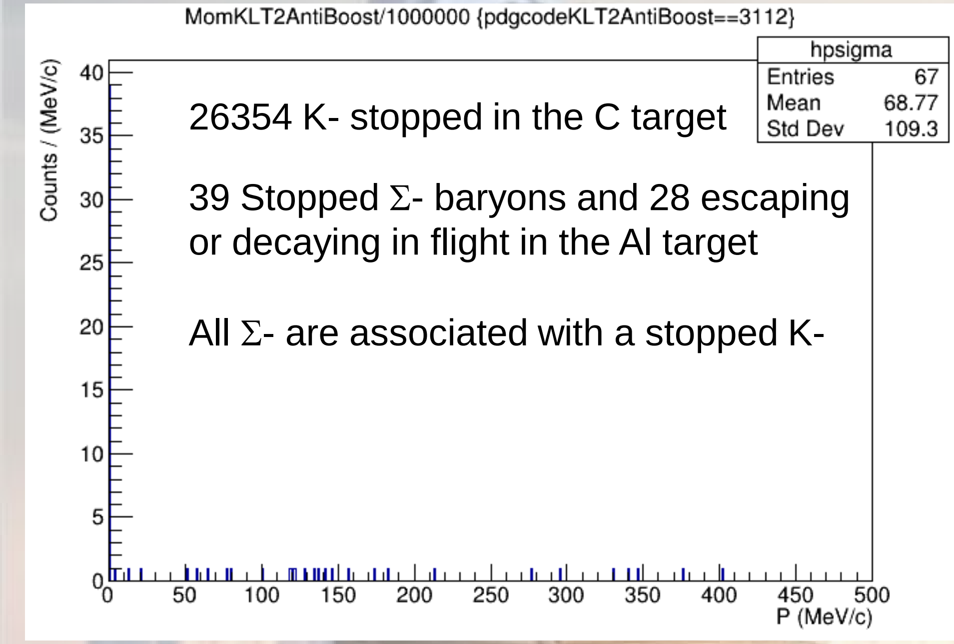
75 μm Al + 1mm C target, 1 pb^{-1} equivalent statistics

36633 K- stopped in the Al target

733 Stopped Σ- baryons and 325 escaping or decaying in flight in the Al target

All Σ- are associated with a stopped K-





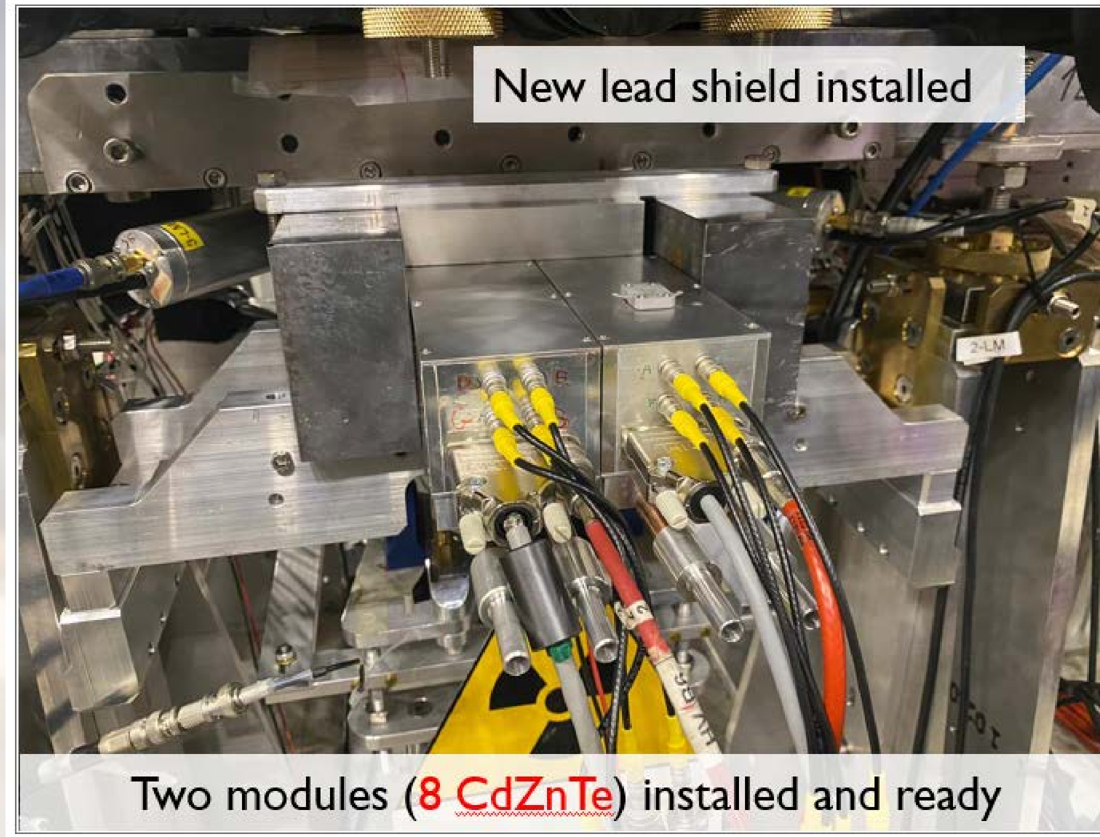
26354 K- stopped in the C target

39 Stopped Σ- baryons and 28 escaping or decaying in flight in the Al target

All Σ- are associated with a stopped K-

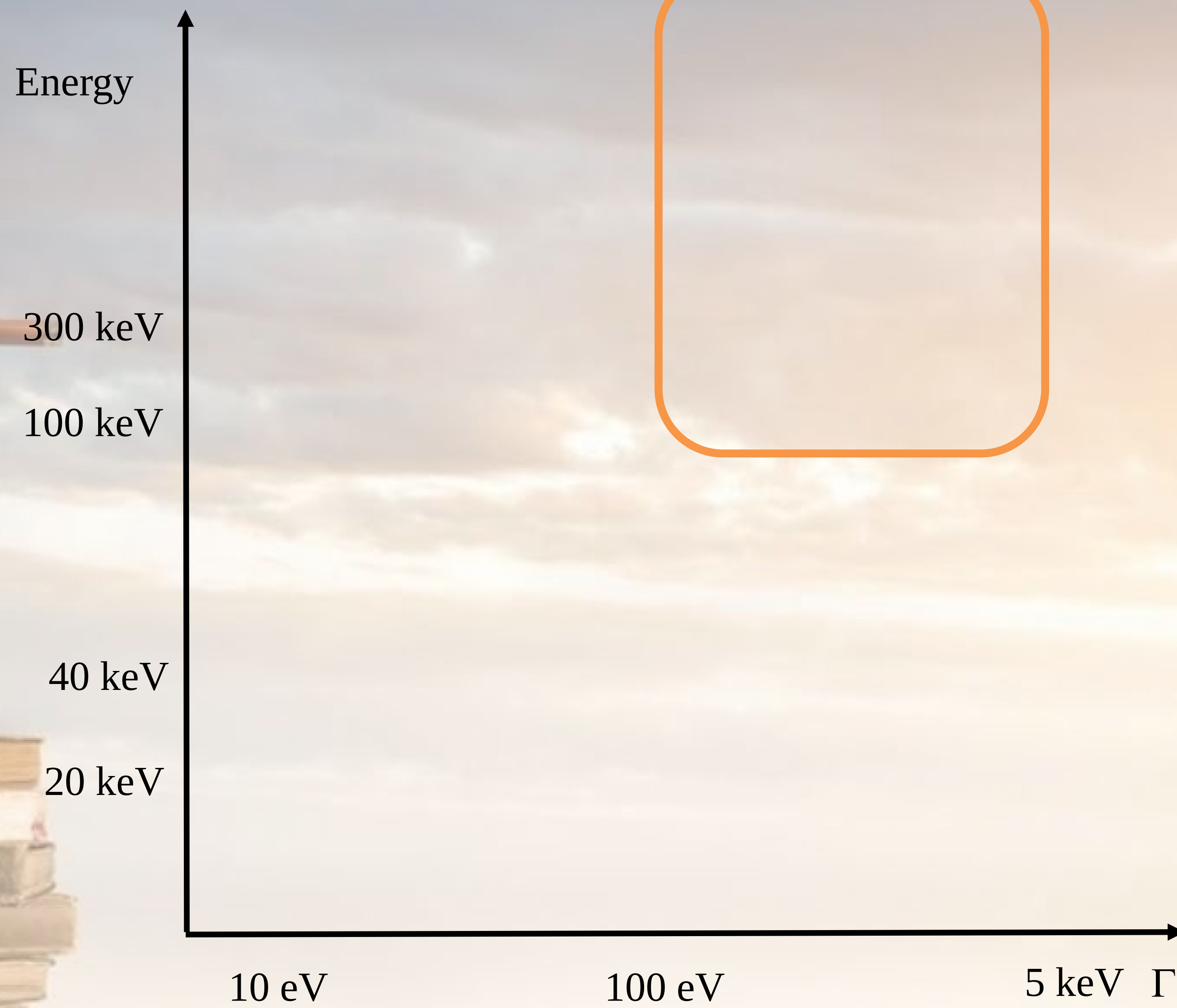
If confirmed, within SIDDHARTA-2 we would also have the possibility to stydi Sigmonic Atoms

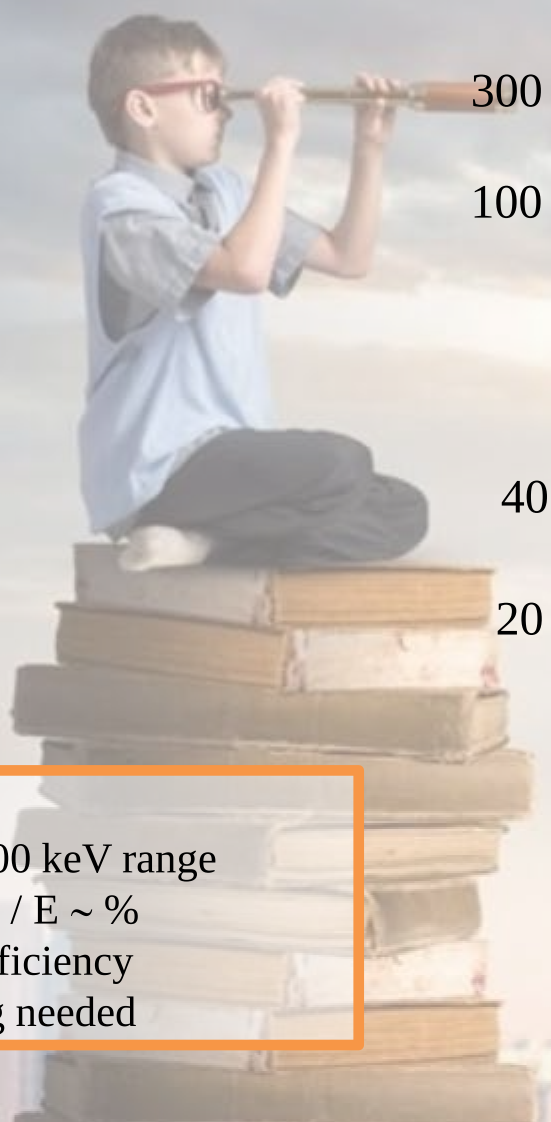
CdZnTe 2023: first outcomes from the new 8 channels setup



Presently in data taking @ DAFNE

Transitions: energies and widths…which detector?

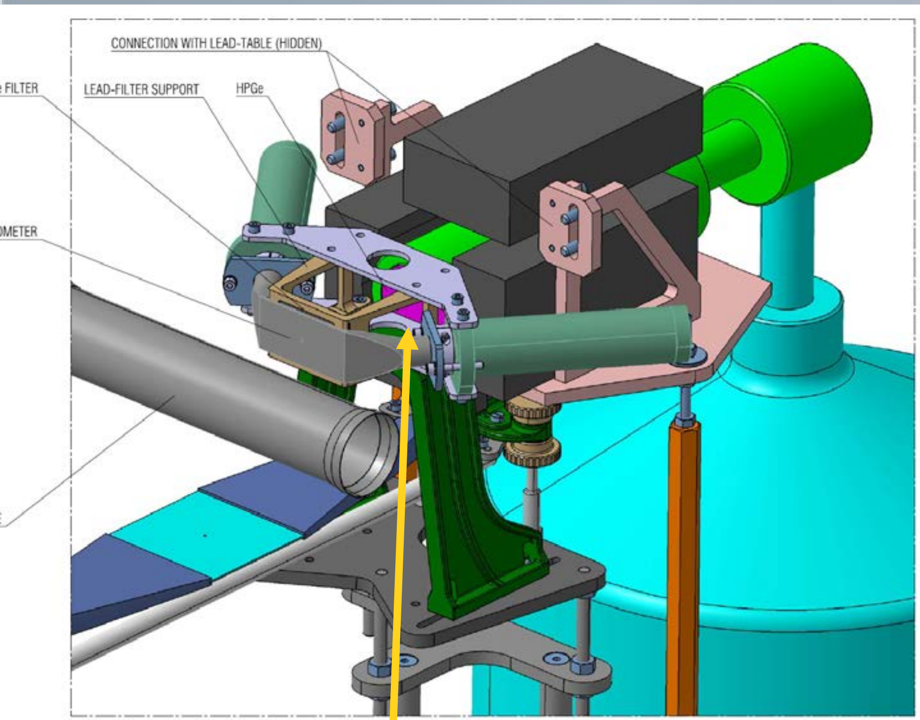


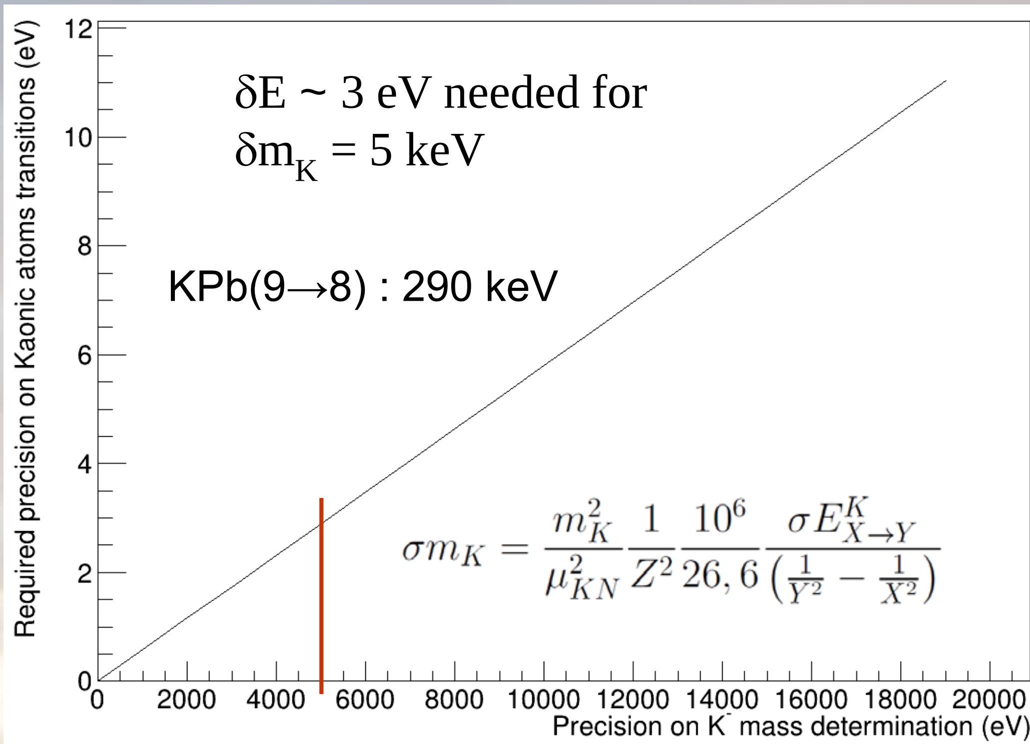


HPGe

- 100-1000 keV range
- FWHM / E ~ %
- High efficiency
- Cooling needed

New Kaon Mass measurement with HPGe





Pb target just behind
the SIDDHARTA-2 luminometer,
which is used as trigger

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

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

HPGe detector provided by the group of the University of Zagreb (Croatian Science Foundation project 8570)

New Kaon Mass measurement with HPGe

Kaonic Lead Measurement at DAΦNE with HPGe

HPGe provided by Zagreb University (Croatian Science Foundation project 8570) to perform the kaonic lead measurement in parallel with the SIDDHARTA-2 kaonic deuterium measurement

- BSI HPGe detector with transistor reset preamplifier (TRP).
- DAQ based on CAEN DT5781 digitizer
- Coincidence between:
  - -> ch0 Luminometer
  - -> ch1 HPGe signal
  - -> ch2 TAC signal
- Data acquired:
  - -> June-July 2023: 109.38 pb^{-1}
  - -> September-now 2023: 117.67 pb^{-1}

New Kaon Mass measurement with HPGe

The Kaonic Lead Measurement (Zagreb Uni; Krakow, Jagiellonian Uni – Lumi)

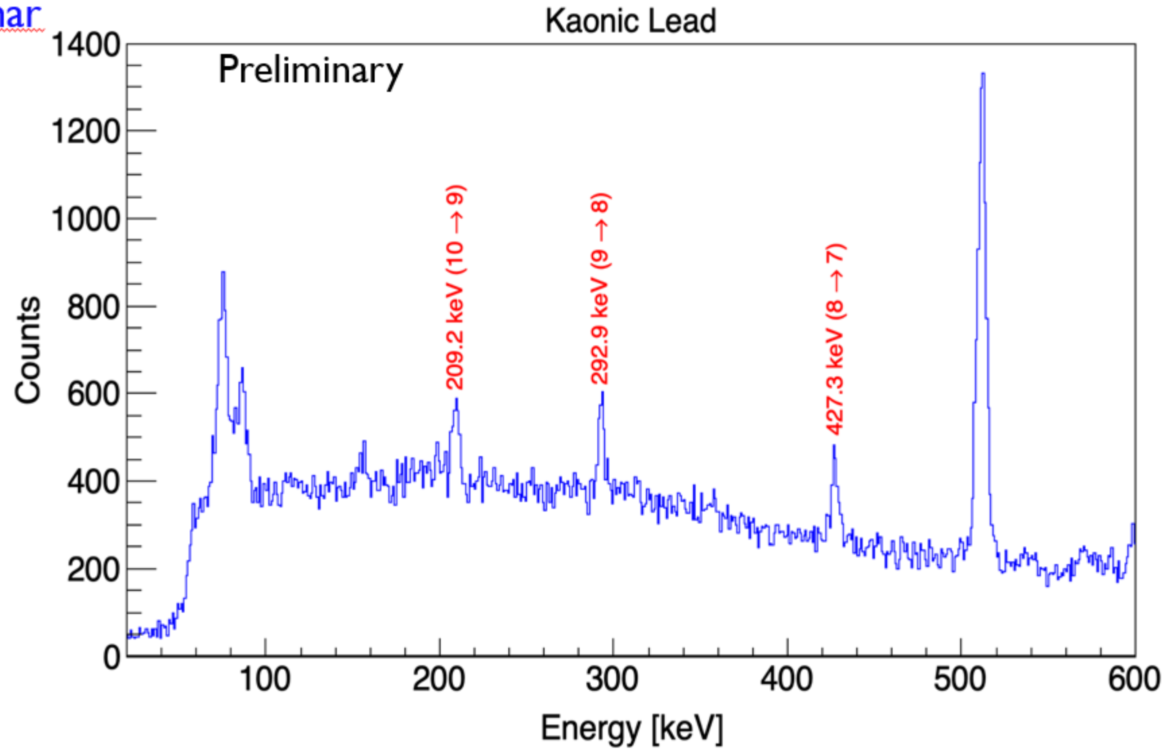
Integrated luminosity: 109.38 pb^{-1} (June – July 2023)

Preliminary analysis of June-July 2023 data (D.. Bosnar and I. Friščić) :

Gaus+linear function was fitted for each peak:

- (10 -> 9) : 906 events in peak,
  position 209.191 ± 0.171 keV
- (9 -> 8) : 947 events in peak,
  position 292.939 ± 0.134 keV
- (8 -> 7) : 943 events in peak,
  position 427.200 ± 0.152 keV

Optimization and detailed analysis is in progress-> towards a publication

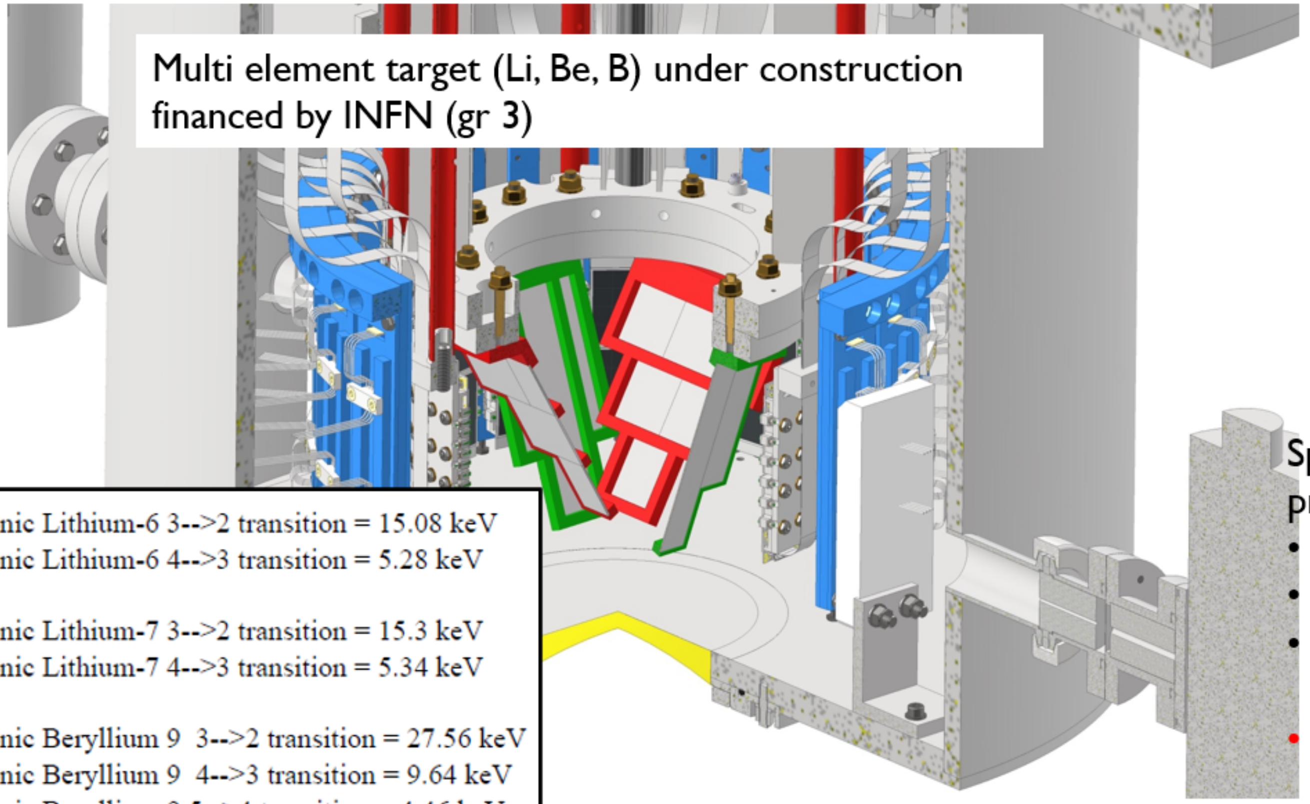


Near and far future measurments

Light kaonic atoms measurement with SIDDHARTA-2

The energy spectra of light kaonic atom transitions for Li, Be and B can achieve a precision below 2-3 eV, for an integrated luminosity of about 100-150 pb^{-1};

Use of present SDDs + 1mm SDDs and target materials financed – construction ongoing



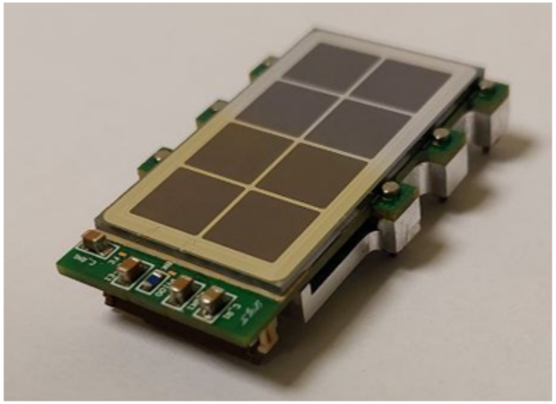
Multi element target (Li, Be, B) under construction financed by INFN (gr 3)

kaonic Lithium-6 3-->2 transition = 15.08 keV
kaonic Lithium-6 4-->3 transition = 5.28 keV

kaonic Lithium-7 3-->2 transition = 15.3 keV
kaonic Lithium-7 4-->3 transition = 5.34 keV

kaonic Beryllium 9 3-->2 transition = 27.56 keV
kaonic Beryllium 9 4-->3 transition = 9.64 keV
kaonic Beryllium 9 5-->4 transition = 4.46 keV

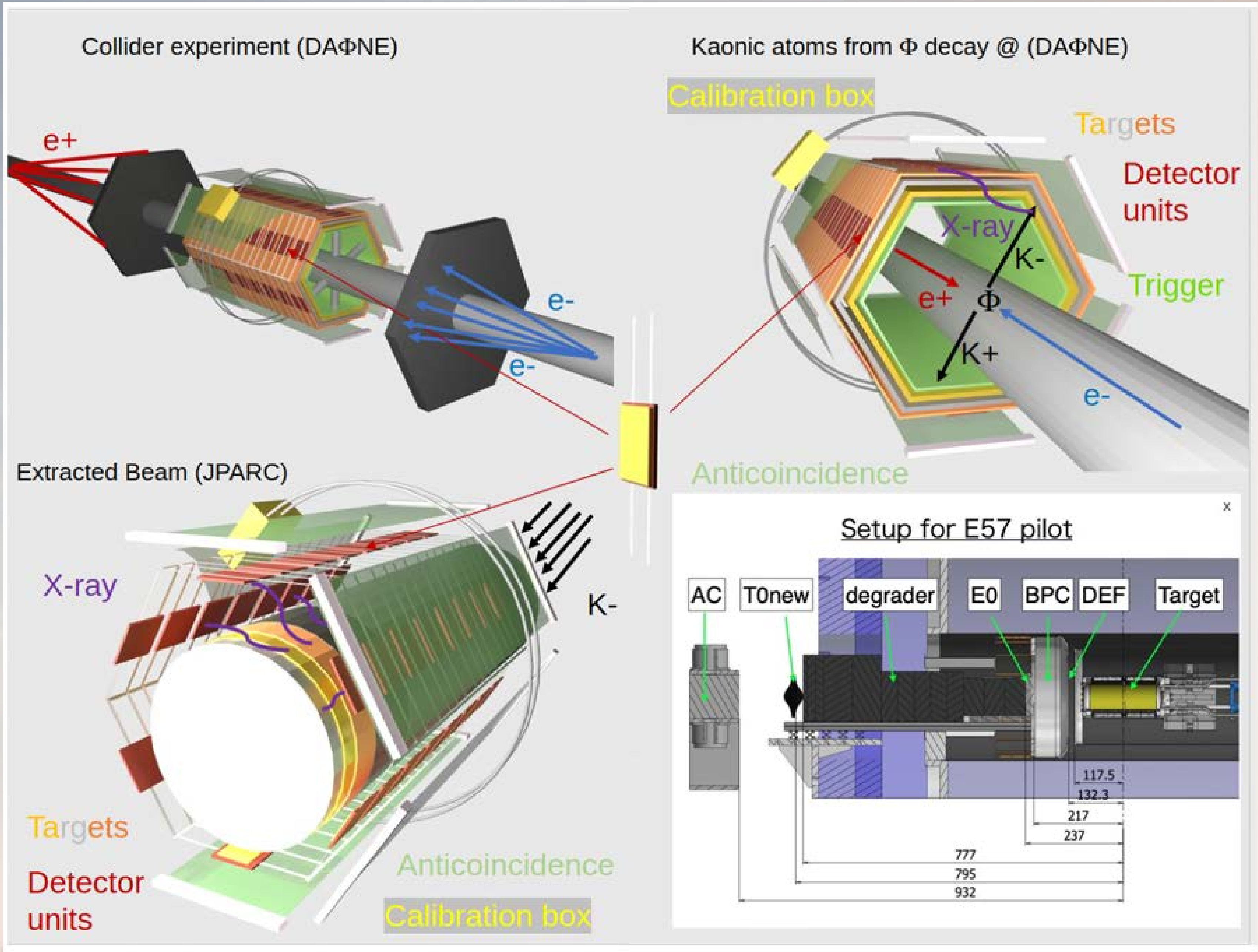
SDD 1mm detector



Spectroscopic measurements with a first prototype with partially working channels:

- irradiation with an ^{55}**Fe** X-ray source;
- detector temperature: -30° C;
- spectra acquired with **SFERA APP**, shaping time 6 μs;
- best **energy resolution** @5.9keV (Mn-Kα peak): **138.2 eV**, (channel 2).

EXOTIC (EXOtic atoms' spectroscopy with ultra-fast TIming CdZnTe detectors)

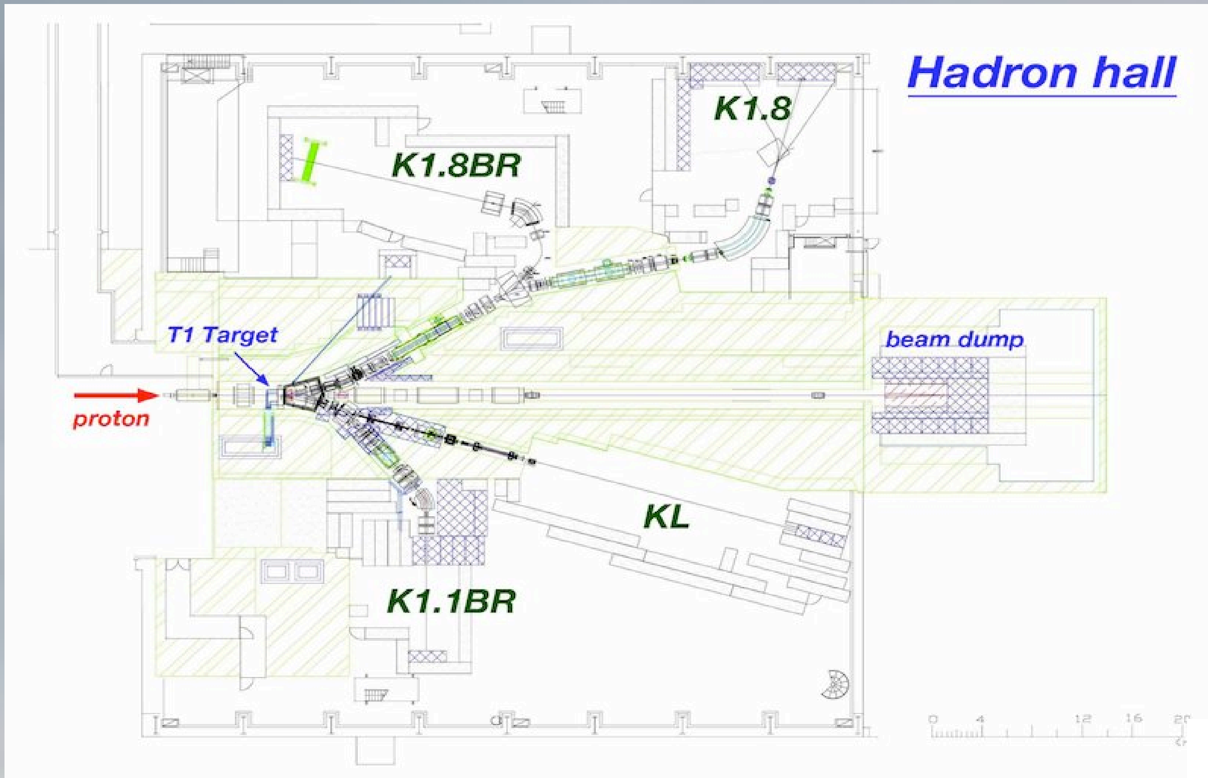


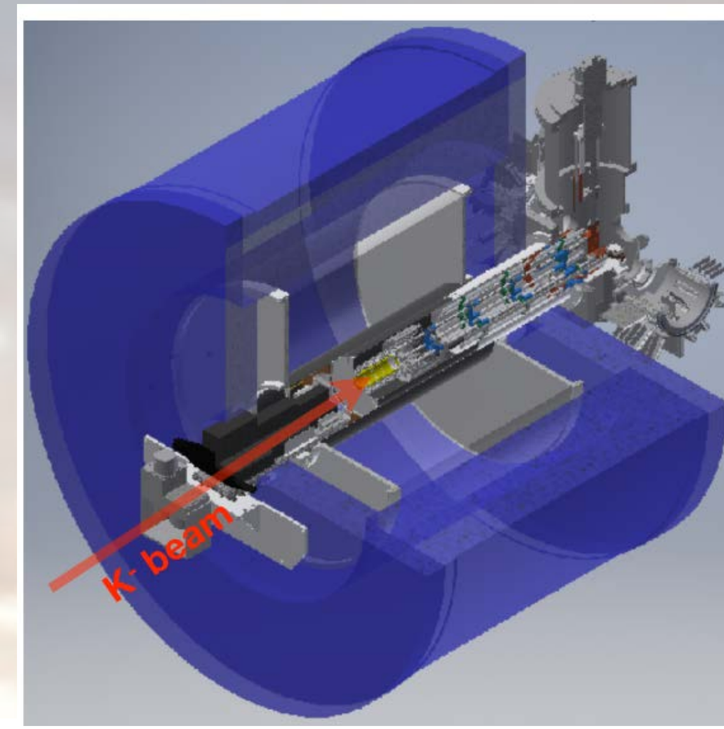
EXOTIC @ DAFNE

Transition	Energy (keV)	events / 10 pb^{-1} with 15,6 cm^2	Yield / K^- stop	Expect events in 60 days with 300 cm^2	Natural Linewidth Γ (keV)	CdZnTe resolution σ (keV)	Convoluted resolution σ (keV)	estimated error on the energy (keV) for S/B=1/5	estimated error on the width Γ (keV) for S/B=1/5	estimated error on the energy (keV) for S/B=1/50	estimated error on the width Γ (keV) for S/B=1/50
KC(3-->2)	63	1065	0,07	28386	1,8	1,26	1,475	0,020	0,039	0,062	0,124
KAl(4-->3)	106	967	0,55	202512	0,45	2,12	2,129	0,011	0,021	0,033	0,067
KS(4-->3)	161	940	0,22	78743	2,2	3,22	3,353	0,027	0,053	0,084	0,169
KC(4-->3)	22	943	0,07	25135	0	0,44	0,440	0,006	0,012	0,020	0,039
KC(5-->3)	32	912	0,035	12154	0	0,64	0,640	0,013	0,026	0,041	0,082
KAl(5-->4)	49	944	0,55	197695	0	0,98	0,980	0,005	0,010	0,016	0,031
KAl(6-->4)	76	968	0,27	99518	0	1,52	1,520	0,011	0,022	0,034	0,068
KAl(6-->5)	27	933	0,55	195392	0	0,54	0,540	0,003	0,005	0,009	0,017
KAl(7-->5)	43	900	0,27	92527	0	0,86	0,860	0,006	0,013	0,020	0,040
KS(5-->4)	74	1590	0,22	133193	0	1,48	1,480	0,009	0,018	0,029	0,057
KS(5-->3)	235	560	0,11	23455	0	4,7	4,700	0,069	0,137	0,217	0,434
KS(6-->5)	40	1350	0,22	113088	0	0,8	0,800	0,005	0,011	0,017	0,034
KS(6-->4)	115	1310	0,11	54869	0	2,3	2,300	0,022	0,044	0,069	0,139
KS(7-->5)	65	1700	0,11	71204	0	1,3	1,300	0,011	0,022	0,034	0,069
KPb(9-->8)	289	170	0,79	51137	0	5,78	5,780	0,057	0,114	0,181	0,361
KPb(10-->9)	207	190	0,4	28938	0	4,14	4,140	0,054	0,109	0,172	0,344
KPb(11-->10)	153	370	0,79	111299	0	3,06	3,060	0,021	0,041	0,065	0,130
KPb(12-->10)	269	130	0,4	19800	0	5,38	5,380	0,085	0,171	0,270	0,541
KPb(11-->9)	359	80	0,79	24065	0	7,18	7,180	0,103	0,207	0,327	0,655
KPb(12-->11)	116	360	0,79	108291	0	2,32	2,320	0,016	0,032	0,050	0,100
KPb(13-->11)	207	270	0,4	41123	0	4,14	4,140	0,046	0,091	0,144	0,289

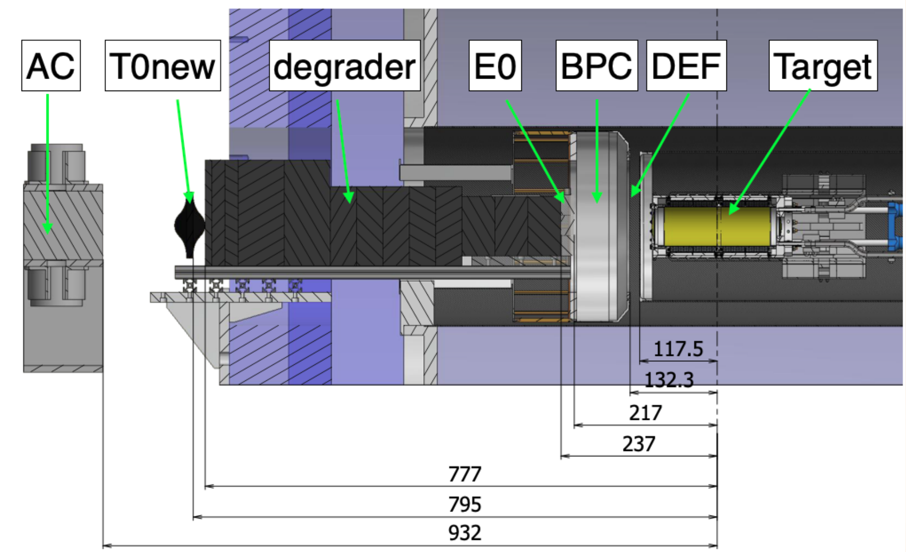
The expected number of events in 60 days assumes a very conservative integrated luminosity of 5 pb^{-1} /day.
The yields for the lower transitions from the database, while for the upper ones no experimental data are available.
For the ΔN=1 (green) upper-level transitions the yields are taken, conservatively, equal to the lowest ones
In case of ΔN=2 (red), a further factor 2 less is assumed.
The upper levels Γ are order of magnitude smaller than those of the lower levels
The errors are estimated from the peak resolution and the number of events assuming a highly conservative scenario of a signal-to-background ratio of 1/5, as well as for a 'worst case' scenario of a signal-to-background ratio of 1/50.

EXOTIC @ JPARC





Setup for E57 pilot



At J-PARC, the 10^{7-8} K^-/s stopping in the target/degrader will ensure a statistic of orders of magnitude higher than that collectable at DAΦNE.

Additional targets (O, Si, Co, Cu, etc.) may be used at J-PARC to improve the precisions, renewing and enlarge the present kaonic atoms' database.

Thanks for your attention

We are looking forwards for new PhD students and collaborators