Kaonic atoms at the DAΦNE collider:

Future perspectives beyond the SIDDHARTA-2 experiment

LUCA DE PAOLIS

on behalf of the SIDDHARTA-2 collaboration

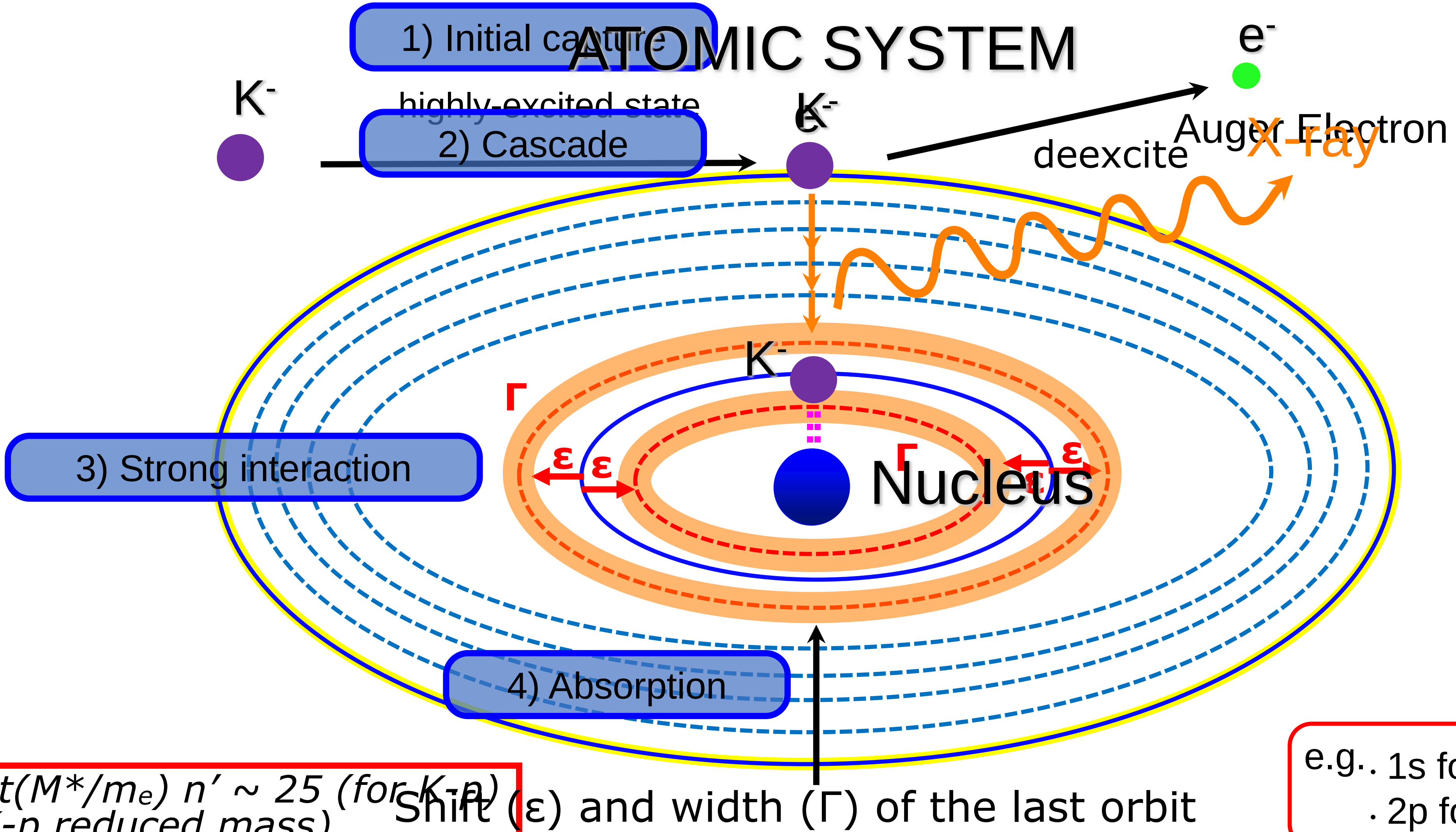
STRONG-2020

INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

17th International Workshop on Meson Physics, 22-27 June 2023, Krakow

Kaonic atoms formation

Kaonic atoms are formed by stopping a negatively charged kaon in a target medium

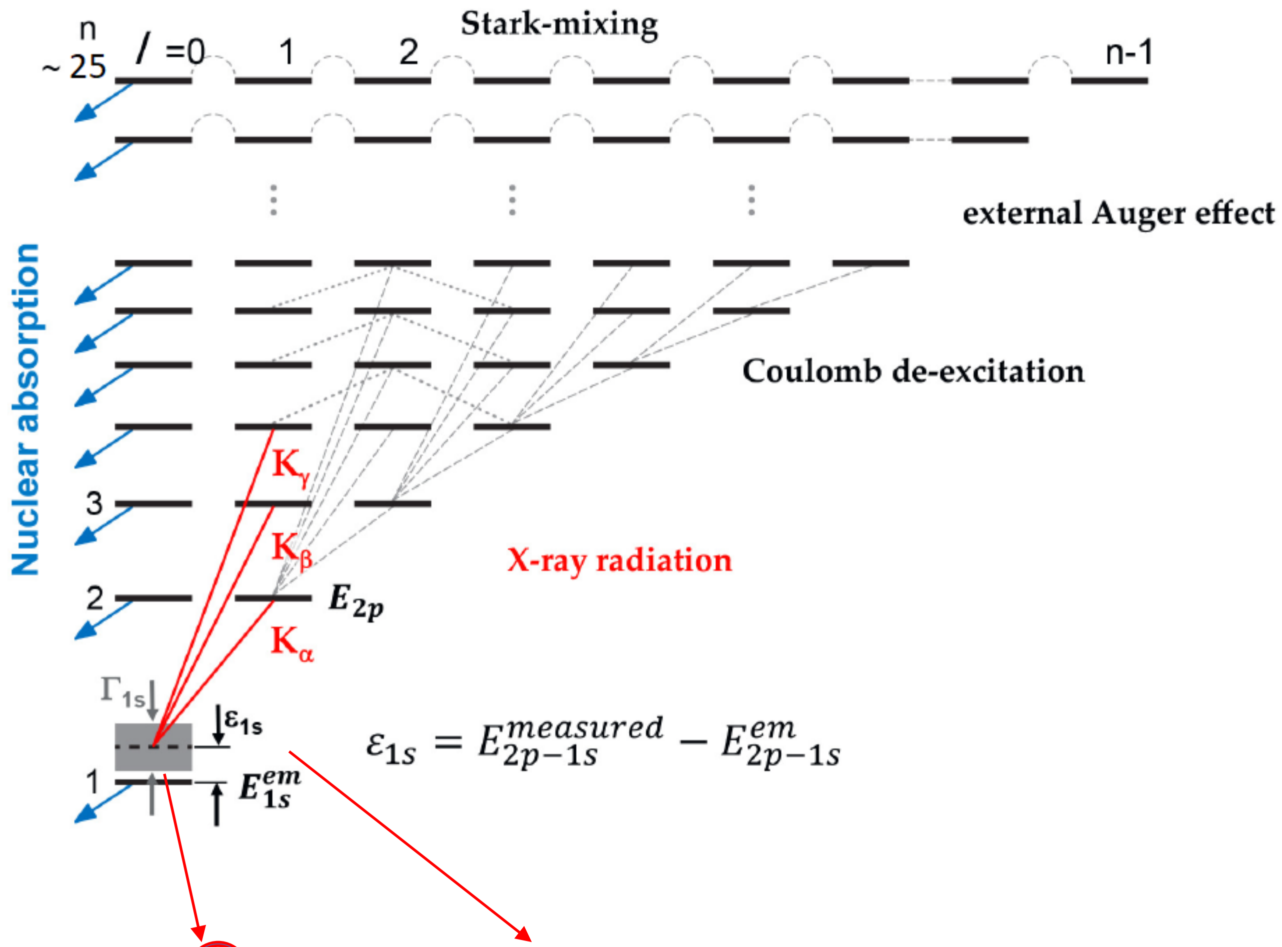


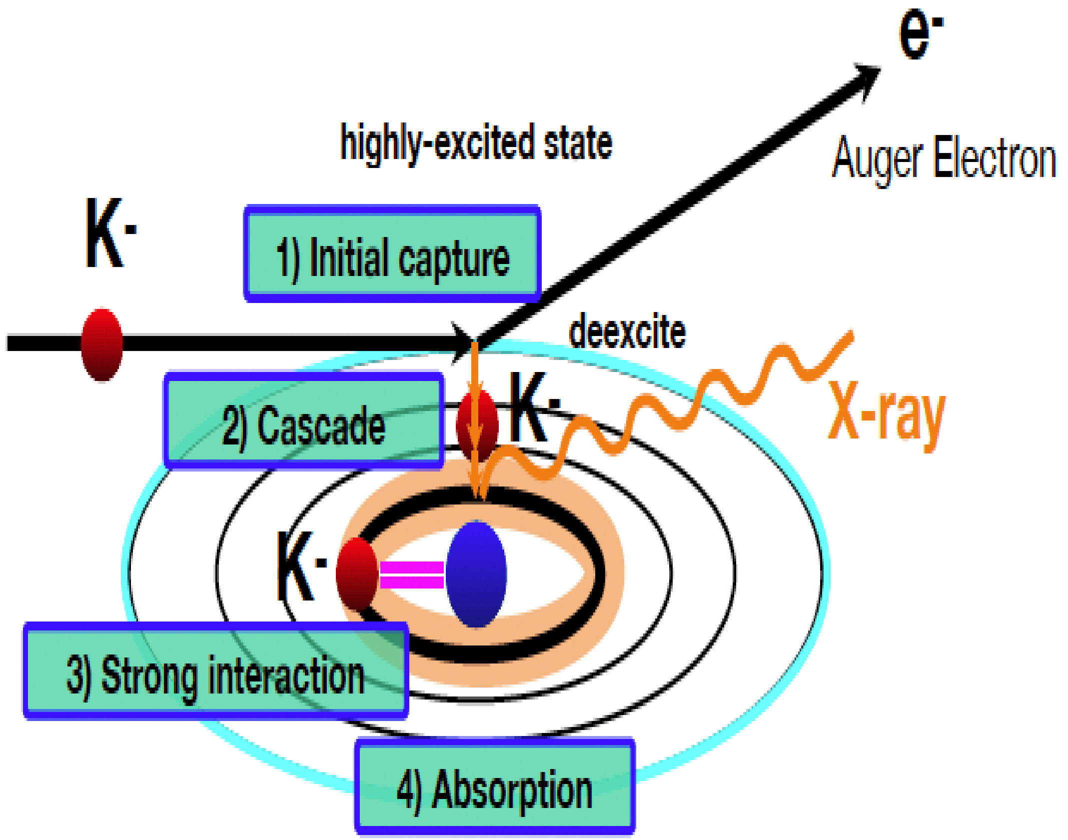
$n \sim sqrt(M^*/m_e)$ $n' \sim 25$ (for K-p)
(M^* : K-p reduced mass)

e.g.. · 1s for K-p, K-d
· 2p for K-He

Kaonic atoms formation

In kaonic atoms, part of the shift (ε) and width (Γ) of the innermost atomic levels is due to the strong kaon-nucleus interaction, thus allowing the study of the strong interaction at low energy (keV) in the *strange* sector.





Width Γ and shift ε obtained by measuring the X-rays emitted

THE SIDDHARTA-2 EXPERIMENT

The MAIN GOAL of the SIDDHARTA-2 experiment is the measurement of shift and width of the 1S orbital in Kaonic Deuterium, which provides fundamental and unique information on kaon-proton and kaon-neutron strong interaction at low energies.

THE SIDDHARTA-2 EXPERIMENT WILL BE ACCURATELY PRESENT BY FLORIN SIRGHI ON MONDAY 26

Knowledge on doubly-strange hypernuclei and experimental prospect	*Kazuma Nakazawa*
Medium lecture hall (A and B), Auditorium Maximum	10:30 - 11:00
Coffee break	
Exhibition room, Auditorium Maximum	11:00 - 11:30
Kaonic atoms measurements performed by SIDDHARTA-2 collaboration: results and expectations.	*Florin Catalin Sirghi*
Medium lecture hall (A and B), Auditorium Maximum	11:30 - 12:00
Sound velocity, equation of state, and strangeness in neutron star matter	*Wolfram Weise*
Medium lecture hall (A and B), Auditorium Maximum	12:00 - 12:30

Beyond SIDDHARTA-2: EXKALIBUR

The SIDDHARTA-2 collaboration proposes fundamental physics measurements via kaonic atoms, at the strangeness frontier, to be performed at the DAΦNE collider for a 3-years period (beyond-SIDDHARTA-2).

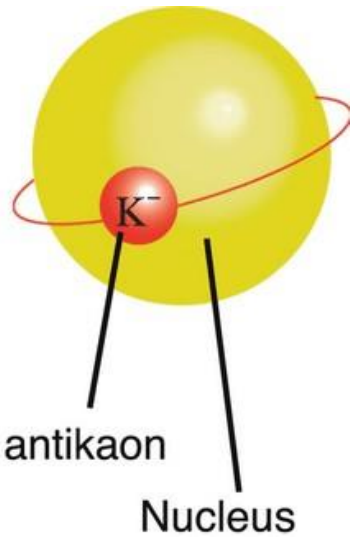
We propose to do precision measurements along the periodic table at DAFNE for:

- Kaonic Hydrogen: 200 pb^{-1} – with SIDDHARTA-2 setup – to get a precision < 10 eV (KH)
- Selected light kaonic atoms (LHKA)
- Selected intermediate and heavy kaonic atoms charting the periodic table (IMHKA)
- Ultra-High precision measurements of Kaonic Atoms (UHKA)

Fundamental physics at the strangeness frontier at DAΦNE. Outline of a proposal for future measurements,
C. Curceanu et al., e-Print: 2104.06076

EXtensive
Kaonic
Atoms research:
from
LIthium and
Beryllium to
URanium

EXKALIBUR



Beyond SIDDHARTA-2: EXKALIBUR

Except for the most recent measurements at DAFNE and JPARC on KHe and KH, the database 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 <u>used to derive</u>, for example:

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

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

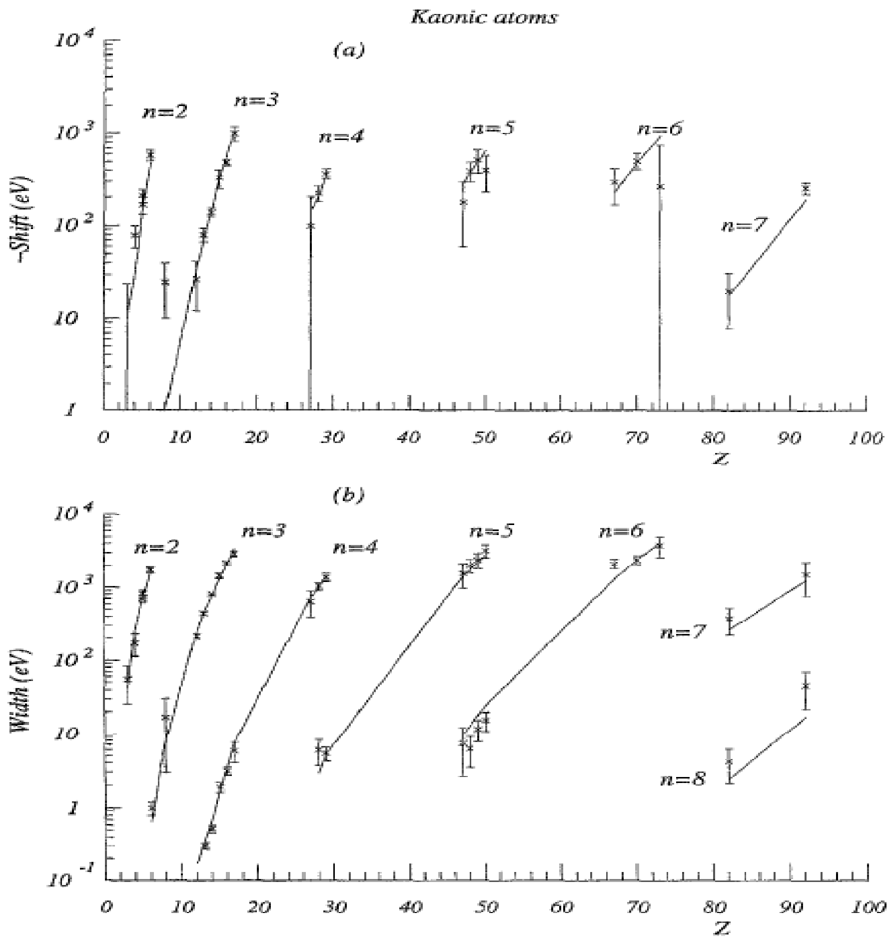


Fig. 7. Shift and width values for kaonic atoms. The continuous lines join points calculated with the best-fit optical potential discussed in Section 4.2.

Beyond SIDDHARTA-2: EXKALIBUR

Kaonic atoms present database

1. The available data on "lower levels" have big uncertainties
2. Many of them are actually UNmeasured
3. Many of them are hardly compatible among each other
4. Relative yields with upper levels are not always measured
5. Absolute yields are basically unknown (except for few transitions)
6. The REmeasured ones have been proved WRONG

This situation would already be a proper justification for new measurements

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]

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

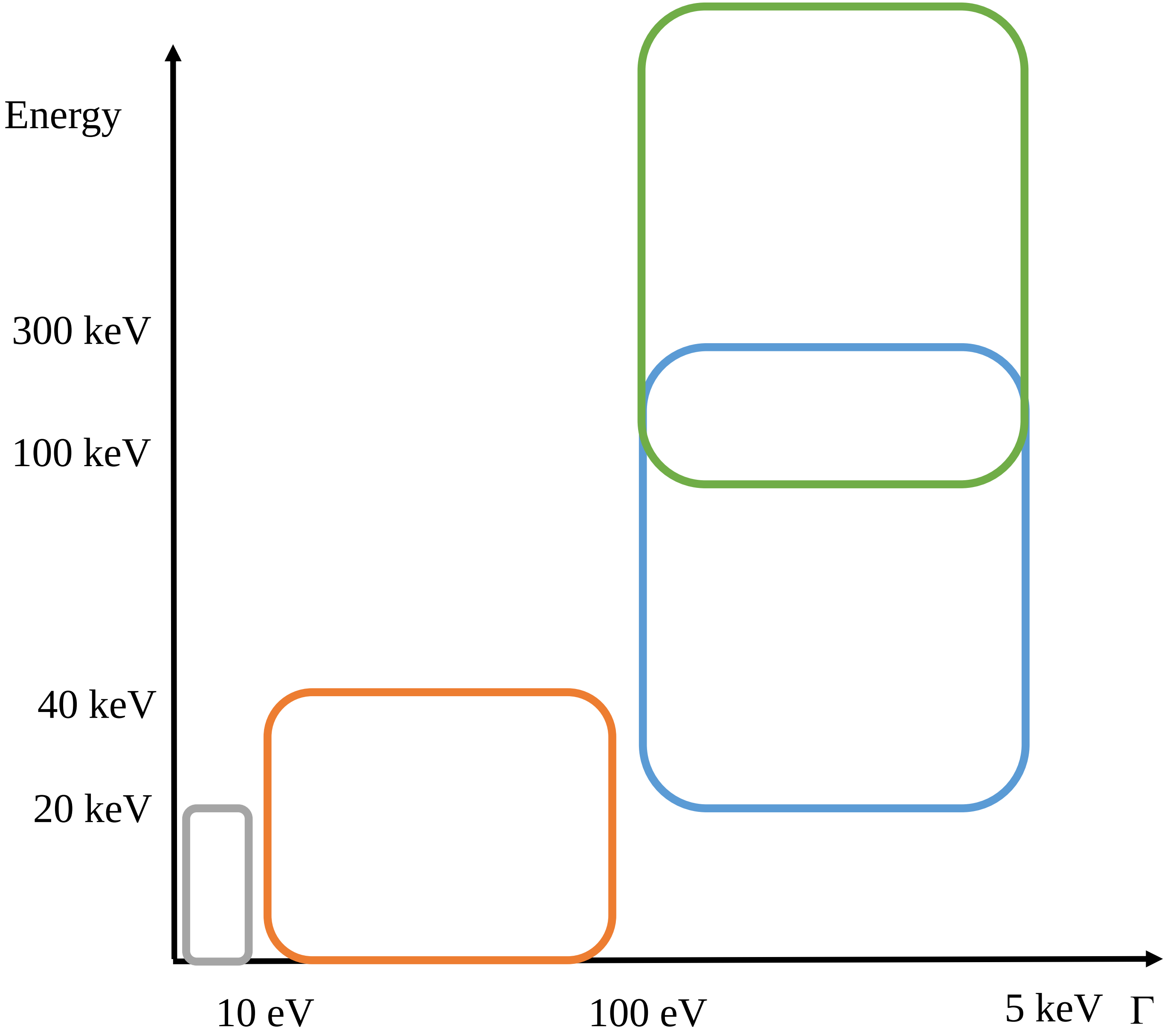
EXKALIBUR: which detector?

Crystal spectrometers (VOXES):
- High resolution
- Low efficiency
- 0-20 keV range

Silicon Drft Detectors (SDDs)
- 100 eV max resolution
- 4-40 keV range
- High efficiency

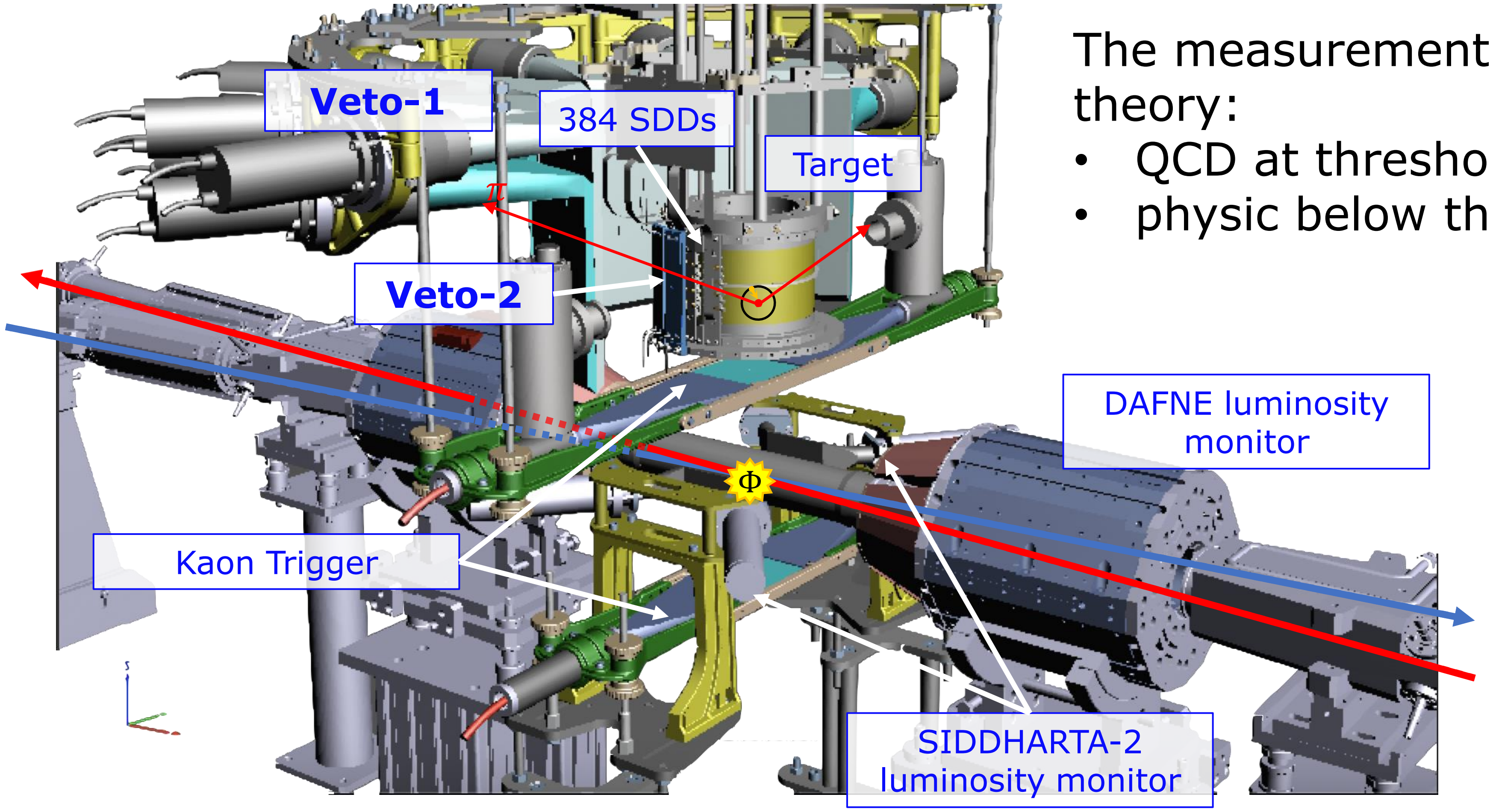
Cadmium-Zinc-Telluride (CdZnTe)
- 20-300 keV range
- FWHM / E ~ %
- High efficiency
- Room Temperature

High Purity Germanium (HPGe)
- 100-1000 keV range
- FWHM / E ~ %
- High efficiency
- Cooling needed



LIGHT KAONIC ATOMS MEASUREMENTS

1) *Kaonic Hydrogen 1s level shift and width*: **200 pb^{-1}** – with SIDDHARTA-2 setup – to get a precision < 10 eV (present precision about 40 eV shift and 90 eV width) – PERFORMED with a gas target and SDDs 0.64 cm^2, 450 μm thick.



The measurement is very important for theory:

- QCD at threshold with strangeness
- physic below threshold.

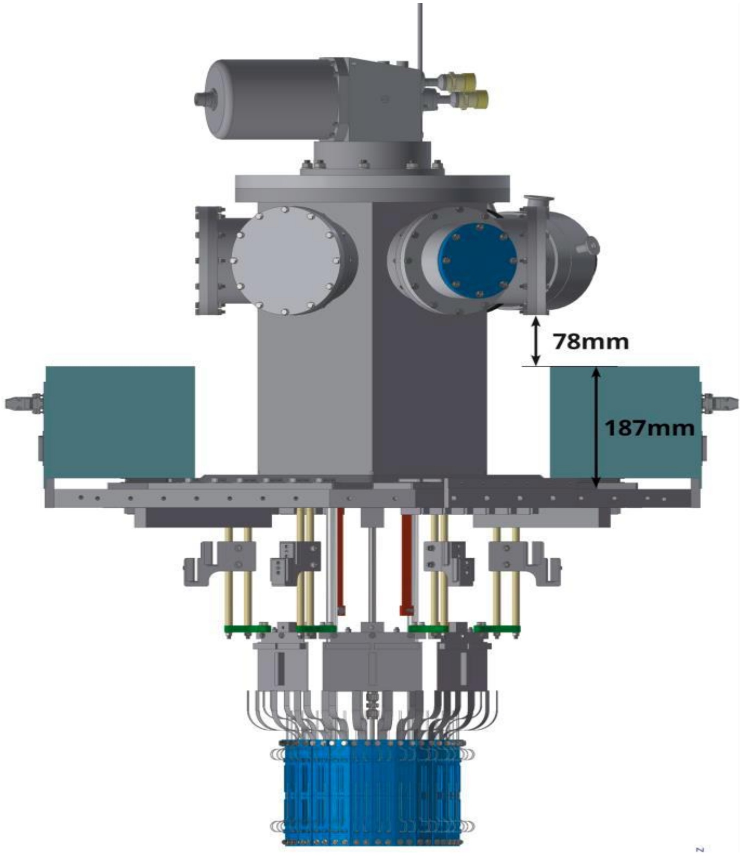
(Weise, Nucl Phya A 2021)

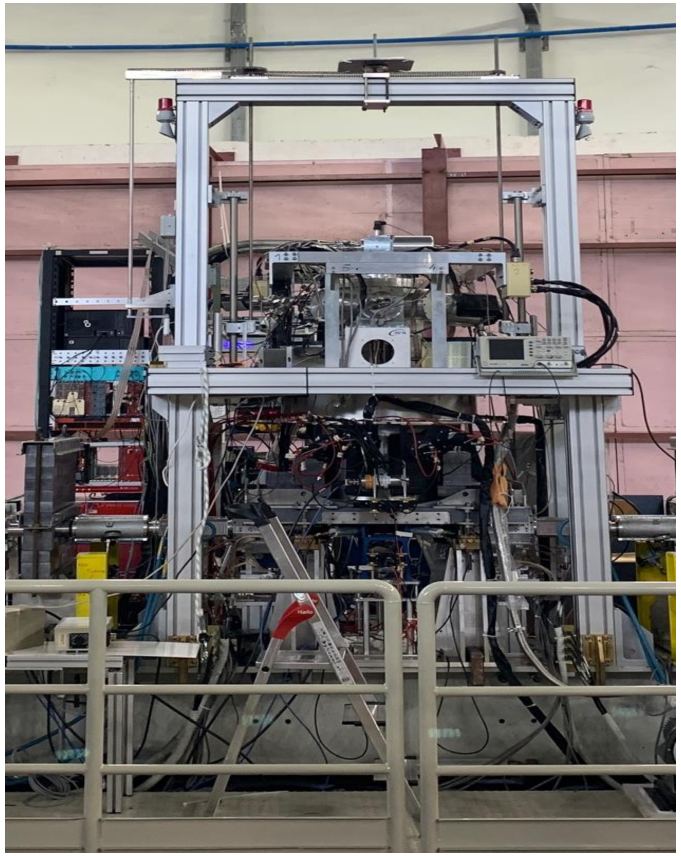
It will be performed as soon as possible after the kaonic deuterium measurement

LIGHT KAONIC ATOMS MEASUREMENTS

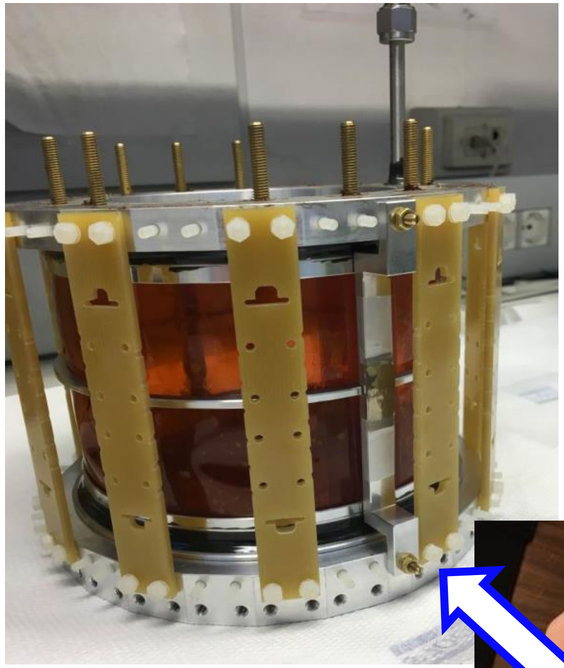
2) *Kaonic Helium 3 and 4 ($2p \rightarrow 1s$* transition): with SIDDHARTA-2 like setup – to get a precision < 2-3 eV (never measured because rare) - PERFORMED with gas targets SDDs 0.64 cm^2, **1 mm thick**

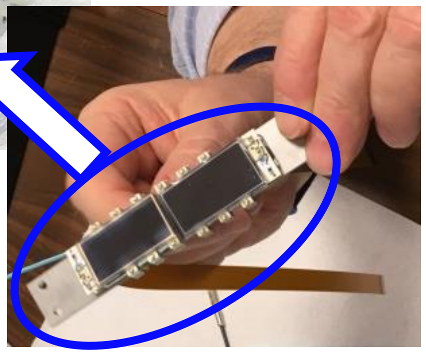
SIDDHARTA-2 – like setup with 1 mm thick SDDs





TARGET with SDDs placed around

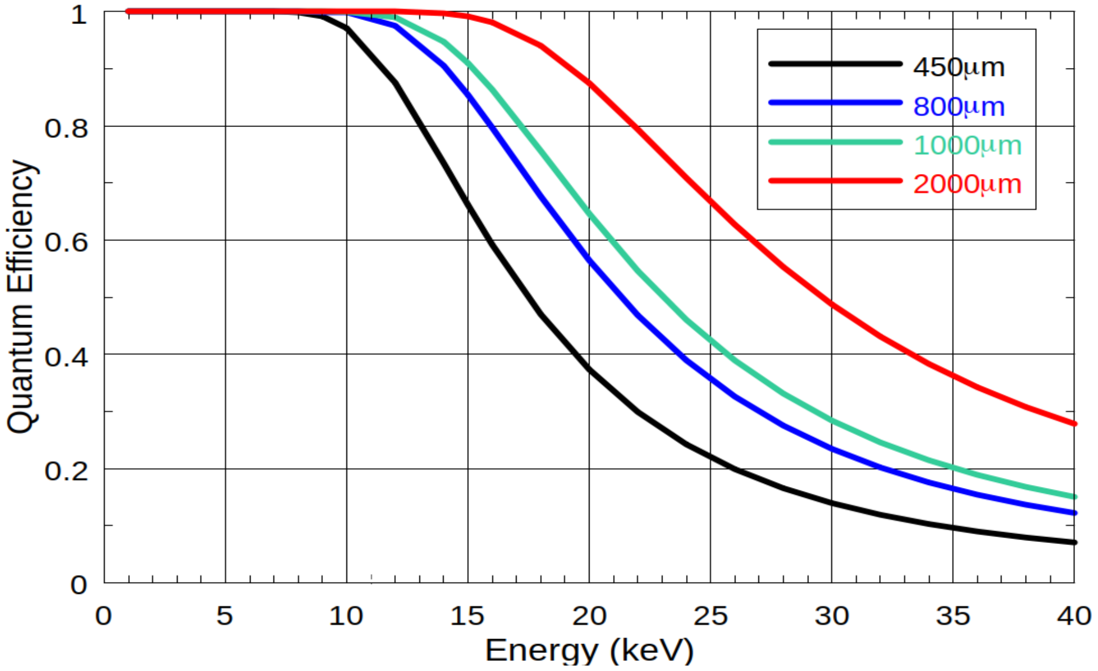


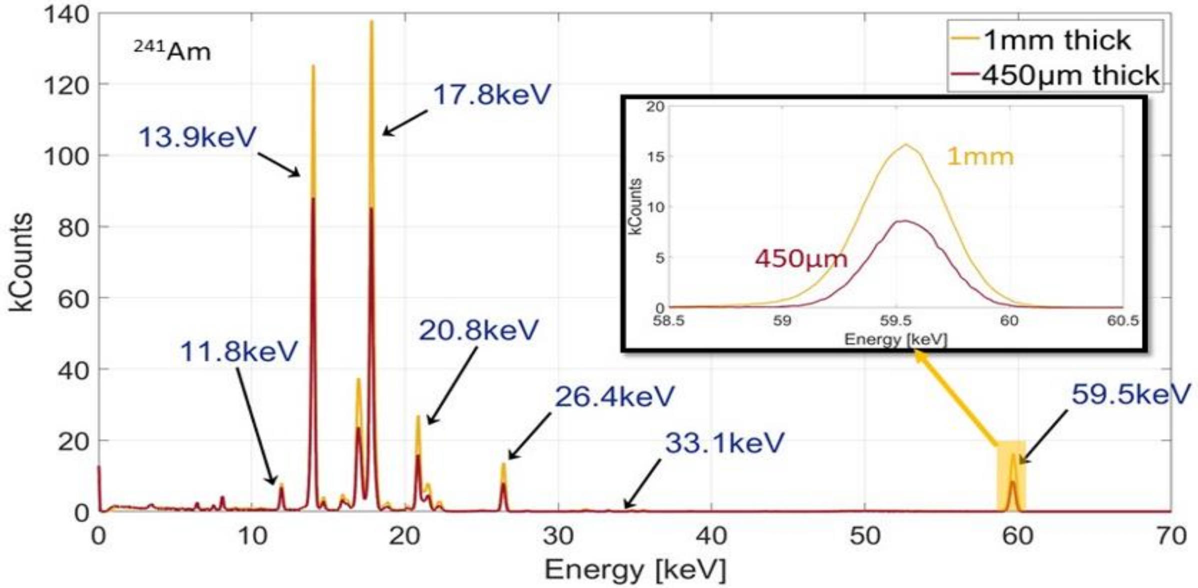


SDDs 1mm FOR KAONIC ATOMS

Kaonic Helium transitions on 1s level would be accessible (very difficult):

$K^3He(2\rightarrow1)$: 33 keV
$K^4He(2\rightarrow1)$: 35 keV





Electronics is similar to SIDDHARTA-2 SDDs

800mm and 1mm SDDs prototypes already produced by FBK for ARDESIA (INFN) and are being assembled with ceramics by Politecnico di Milano

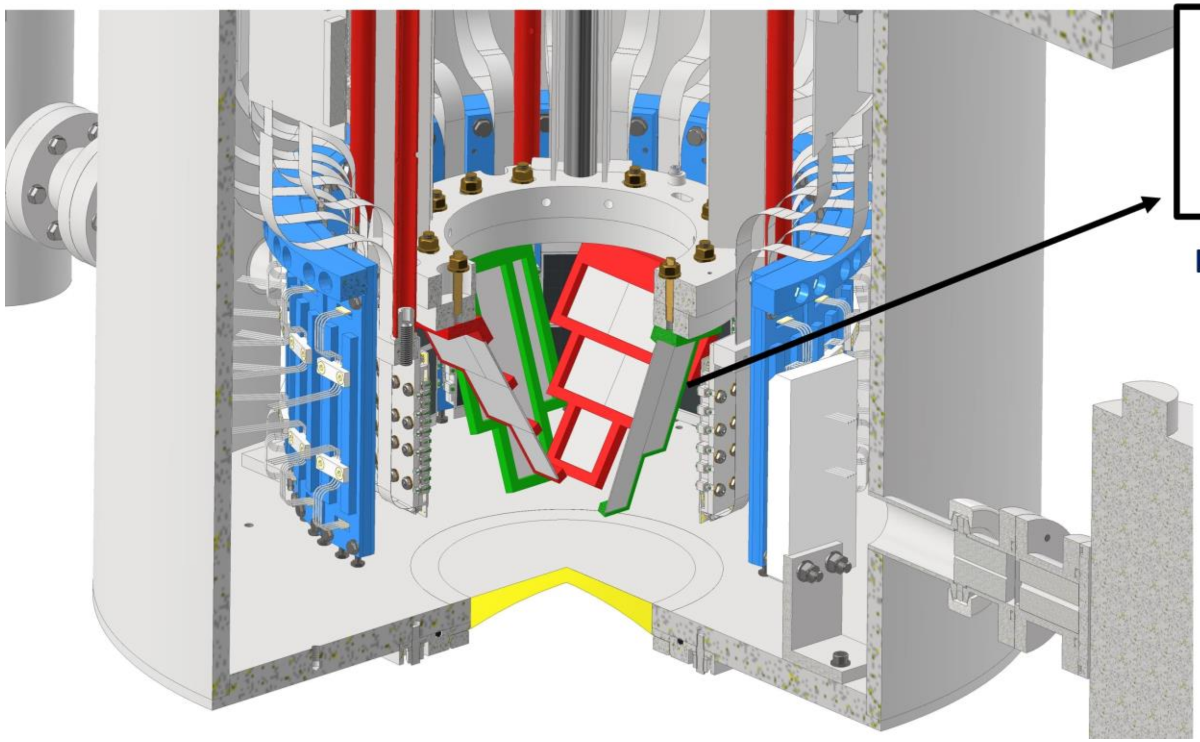
DETECTORS WILL BE READY IN 2023!

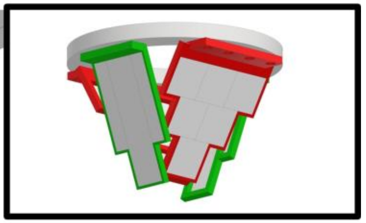
LIGHT KAONIC ATOMS MEASUREMENTS

3) *Kaonic Li, Be and B:* **150 pb^{-1}** transitions measurement in the energy region 10-40 keV , with a precision < 2-3 eV, using SDDs 1mm and **solid targets**

SIDDHARTA-2 – like setup prototipe with Li, Be, B solid targets

SIDDHARTA-2 setup





Li, Be, B solid targets

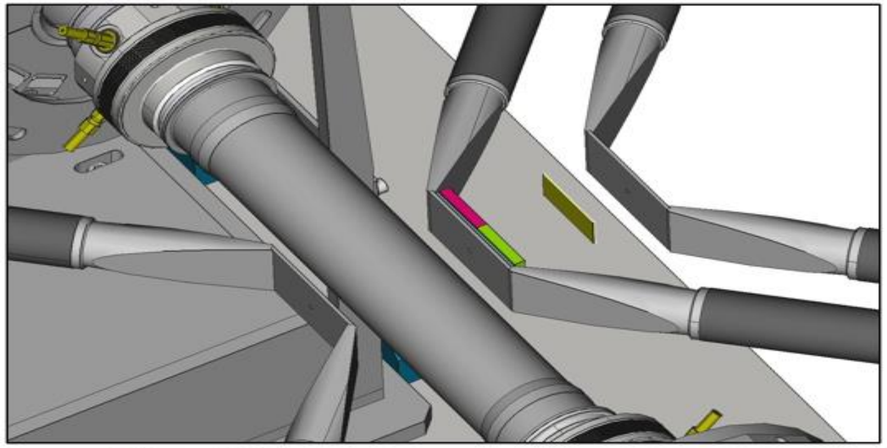
Transitions to be measured are (range 10-40 keV):

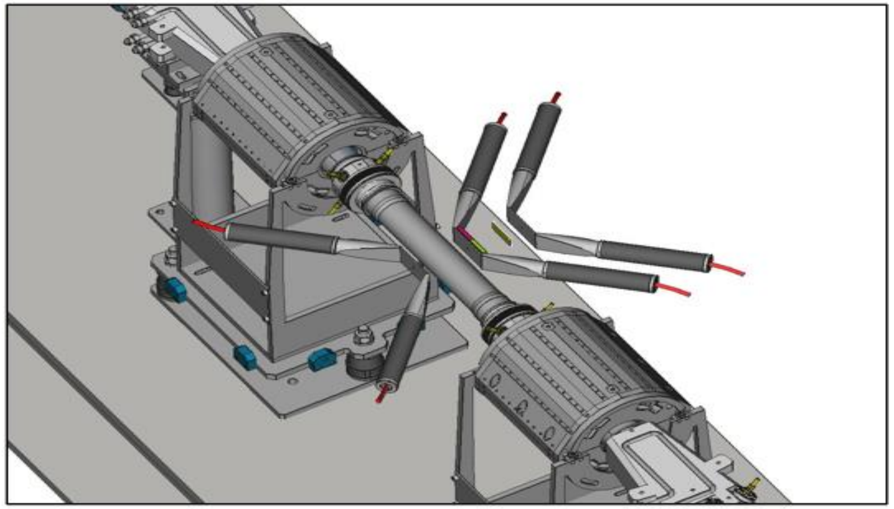
$K^{6,7}Li$ (4→3, 3→2)
$K^{9}Be$ (5→4, 4→3, 3→2)
$K^{9}B$ (5→4, 4→3, 3→2)

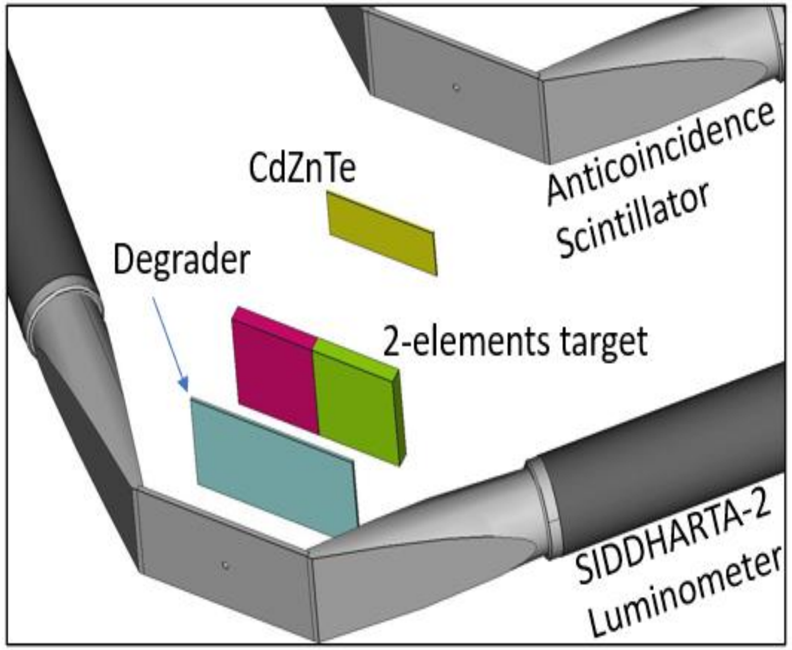
This measurements are estimated to **be performed in 2-3 months**, including the installations of 1mm SDDs and of the targets and tests and debugging phase.

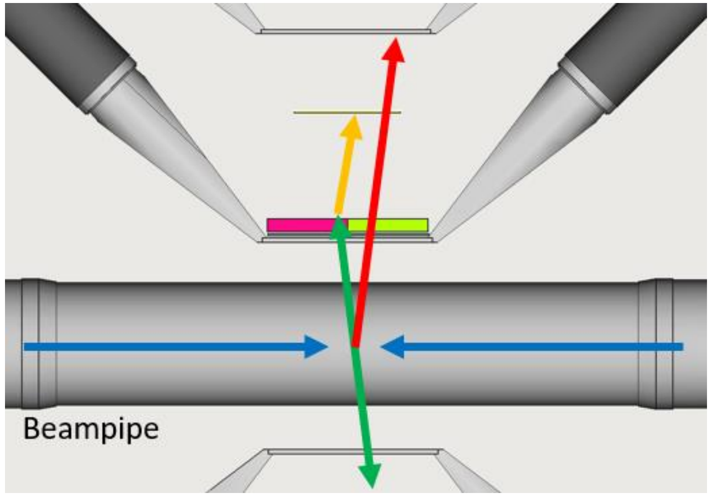
IMH KAONIC ATOMS MEASUREMENTS

1) *Kaonic Ti, S, Al, C, Ag, V, Zr:* transitions measurement in the energy region 70-300 keV using Cadmium-Zinc-Telluride (CdZnTe) detectors (precision at the level of 3-10 eV). These old measurements, used for theoretical models describing kaon nucleus interaction, are questionable and produce discrepancies.









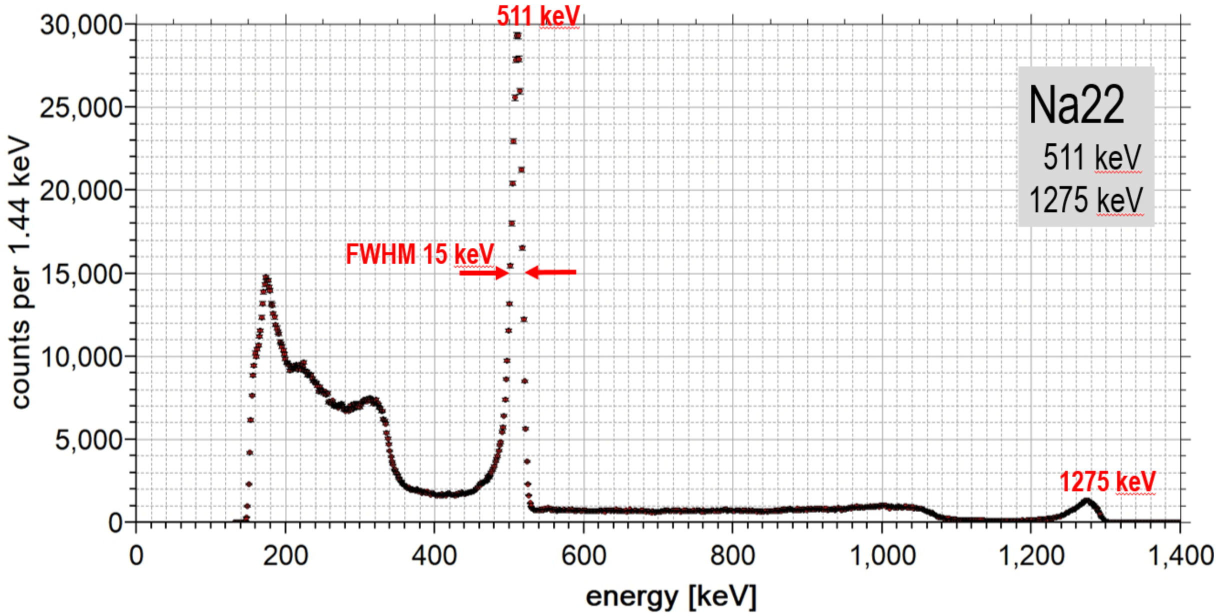
- e^+e^-
- K^+K^-
- Kaonic atoms x-rays
- MIP

CdZnTe detectors for kaonic atoms

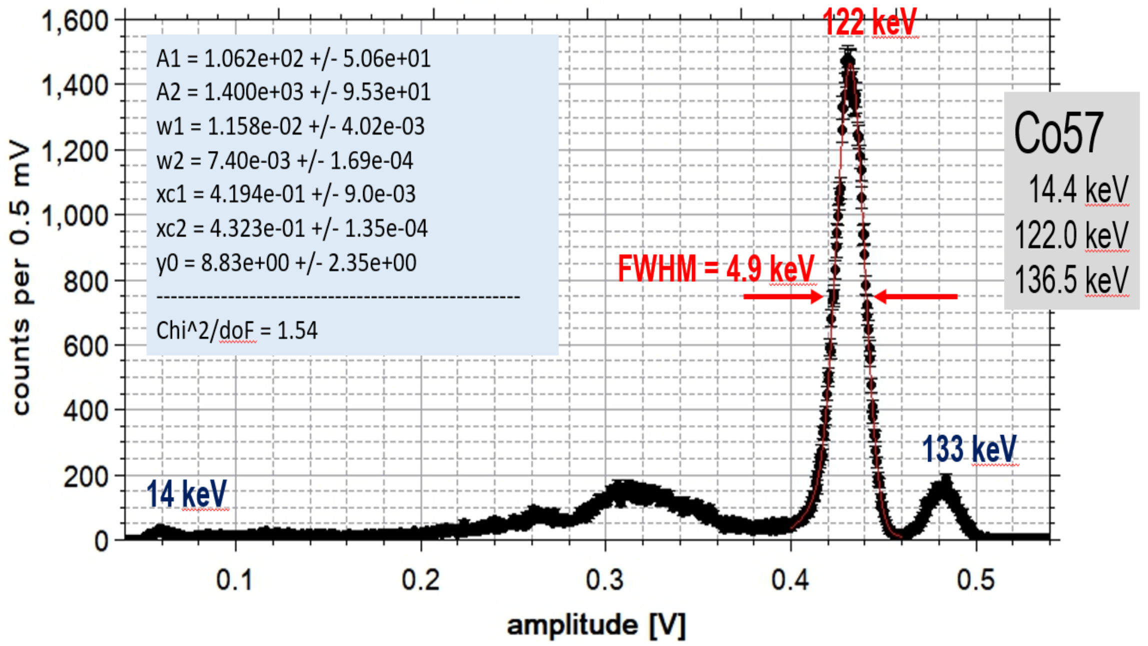
CdZnTe detectors Key Points:

- 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)

CZT-500 – Na22 bias: 600 V



Sample A – Co57 bias: 1000 V

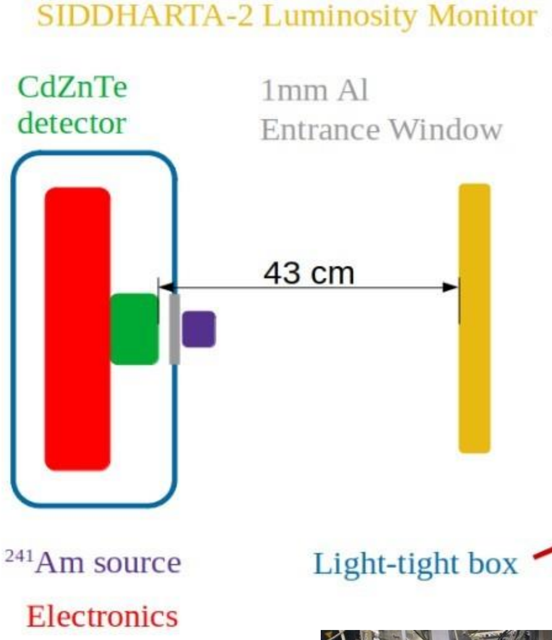


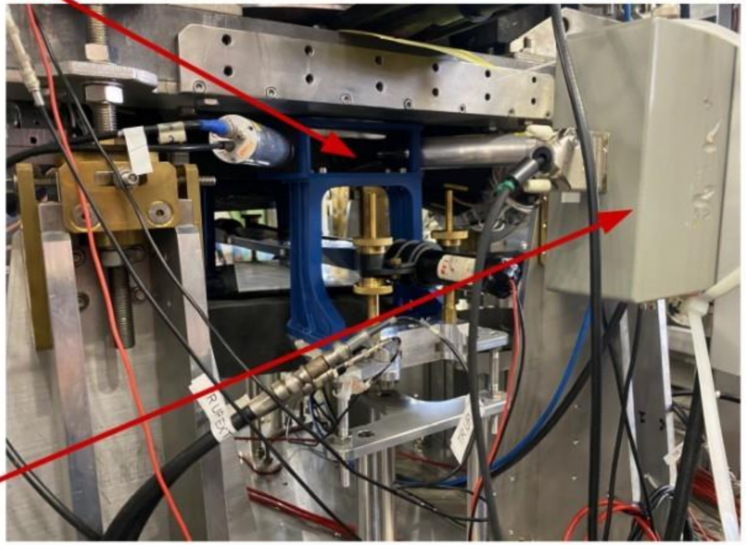
Precisions < 10 eV (ε) and <20 eV (Γ) are reachable in few months

First **prototypes of Cd(Zn)Te delivered by JRA8-ASTRA (STRONG-2020)**

CdZnTe test at DAΦNE collider

Goal: background and resolution assessment in machine environment (first time)





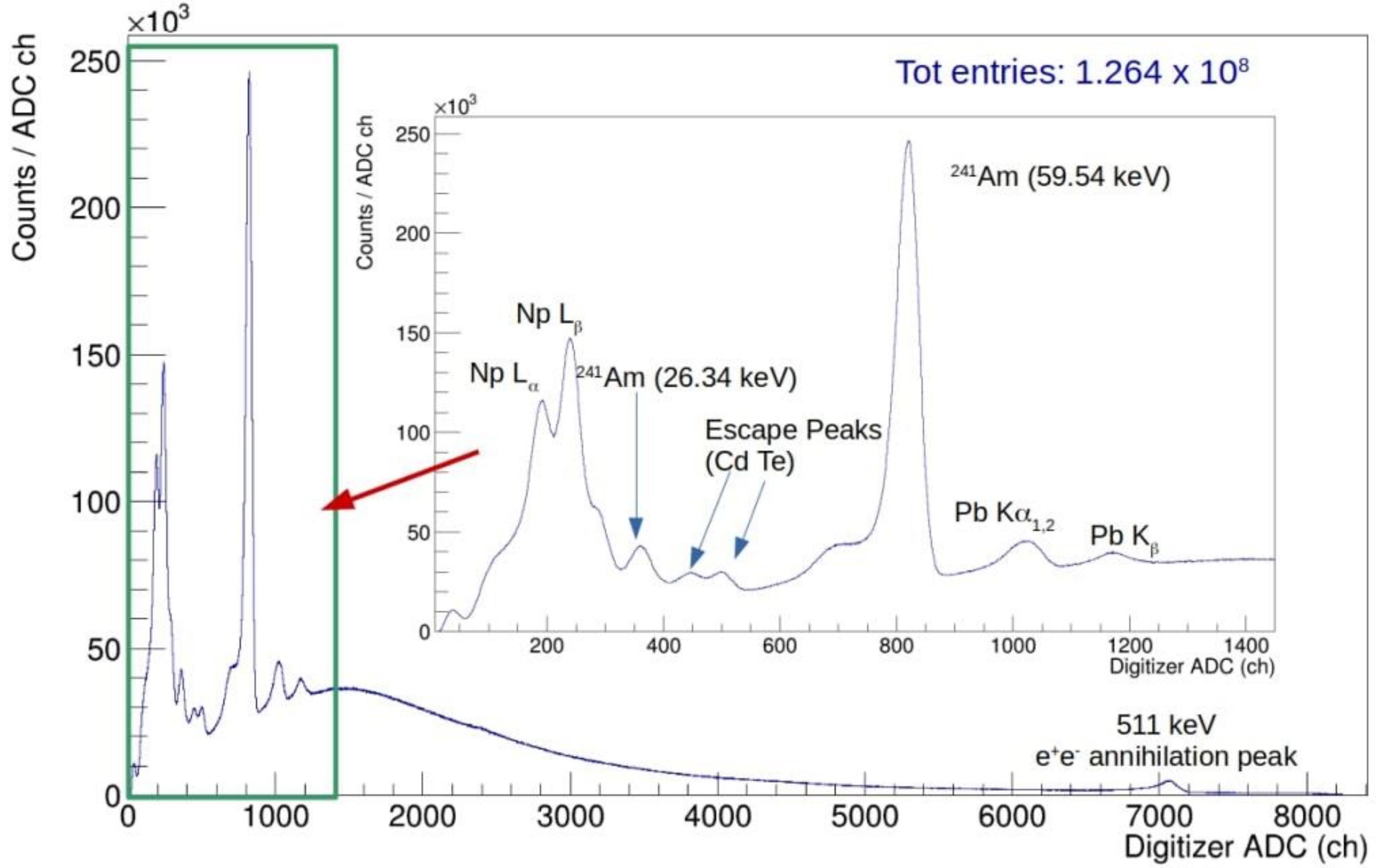
First technical paper submitted

New opportunities for kaonic atoms measurements from CdZnTe detectors

L. Abbene[1], M. Bettelli[2], A. Buttacavoli[1], F. Principato[1], A. Zappettini[2], C. Amsler[3], M. Bazzi[4], D. Bosnar[5], M. Bragadireanu[6], M. Cargnelli[3], M. Carminati[7], A. Clozza[4], G. Deda[7], L. De Paolis[4], R. Del Grande[8,4], L. Fabbietti[8], C. Fiorini[7], I. Friščić[5], C. Guaraldo[4], M. Iliescu[4], M. Iwasaki[9], A. Khreptak[4], S. Manti[4], J. Marton[3], M. Miliucci[4], P. Moskal[10,11], F. Napolitano[4], S. Niedźwiecki[10,11], H. Ohnishi[12], K. Piscicchia[13,4], Y. Sada[12], F. Sgaramella[4], H. Shi[3], M. Silarski[10,11], D. L. Sirghi[4,13,6], F. Sirghi[4,6], M. Skurzok[10,11], A. Spallone[4], K. Toho[12], M. Tüchler[3,14], O. Vazquez Doce[4], C. Yoshida[12], J. Zmeskal[3], A. Scordo[4*] and C. Curceanu[4]

CdZnTe test at DAΦNE collider

Spectrum acquired with the CdZnTe detector test system at the DAΦNE collider in 2022



The CdZnTe detector had an active surface of 1 cm^2 and a thickness of 5 mm.

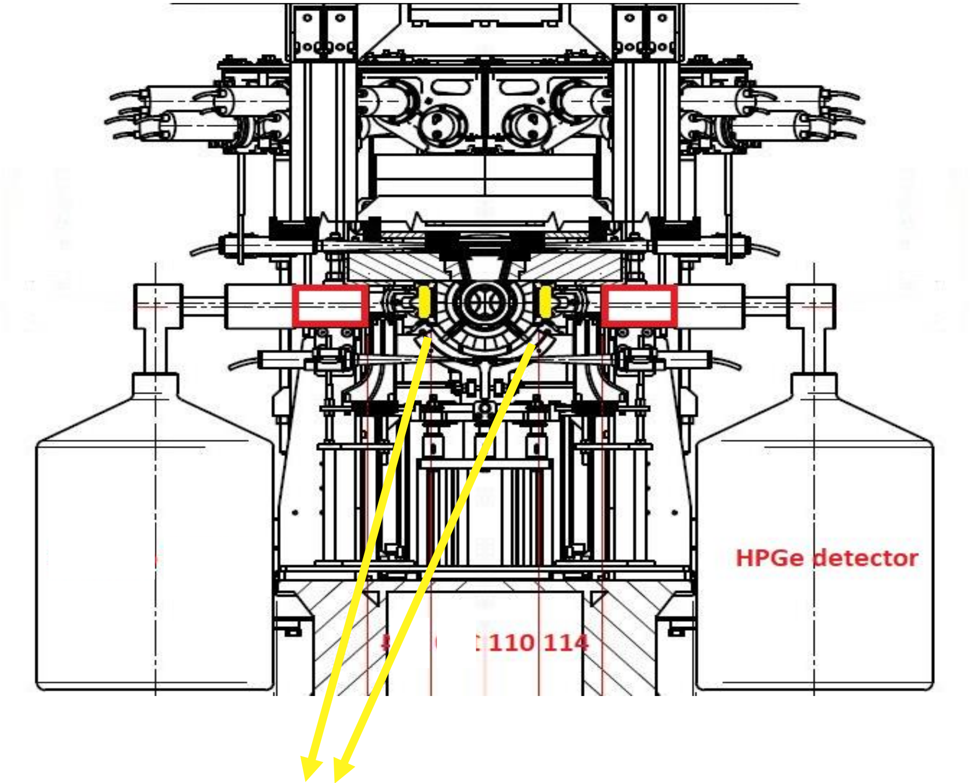
The ^{241}Am radioactive source produced a 500 Hz signal in the CdZnTe detector

The measured peak resolutions are 6% at 60 keV and 2.2% at 511 keV.

VERY PROMISING RESULTS!!

IMH KAONIC ATOMS MEASUREMENTS

2) *Kaonic Pb, W, Co, Au, Pt:* transitions measurement in the energy region above 70/100 keV using 2 High Purity Germanium (HPGe) detectors (precision at the level of 5-10 eV – depending on the energy transitions.



Solid targets

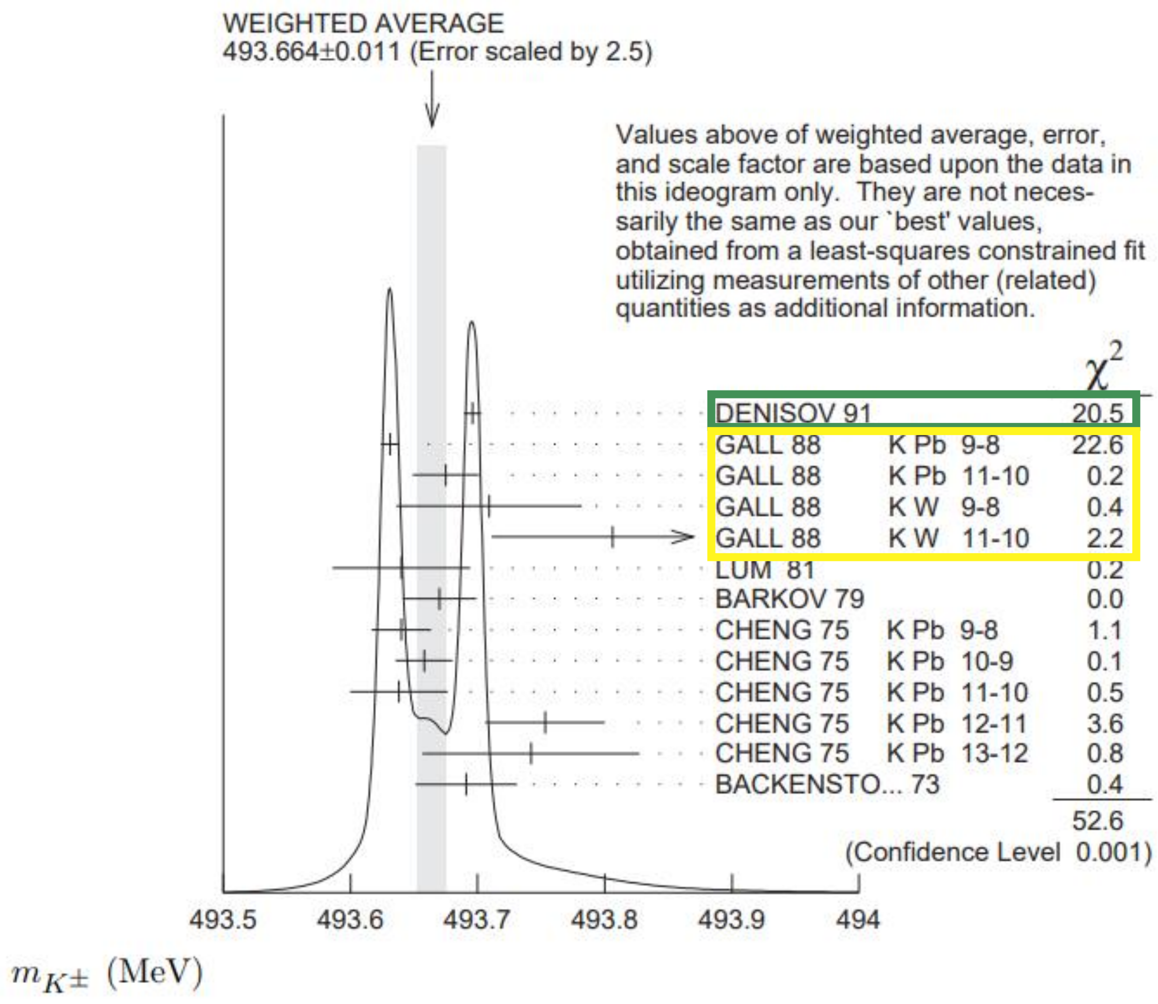
High-Z targets can be utilized to measure transitions to both low and high n-levels

- in the former case, results about multi-nucleon interactions can be obtained
- in the latter case, since high n-level transitions are purely QED, the charged kaon mass problem could be addressed.

Kaonic lead (KPb) is an ideal target for a measurement of the charged kaon mass

REVISITING CHARGE KAON MASS

Particle Data Group 2020



P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Disagreement before the two most recent measurements (~1990)

m_K=493.696±0.007 MeV

A.S. Denisov et al. JEPT Lett. 54 (1991)558

K^- ^{12}C, crystal diffraction spectrometer

(6.3 eV at 22.1 keV), 4f-3d

m_K=493.636±0.011 MeV

K.P. Gall et al. Phys. Rev. Lett. 60 (1988)186

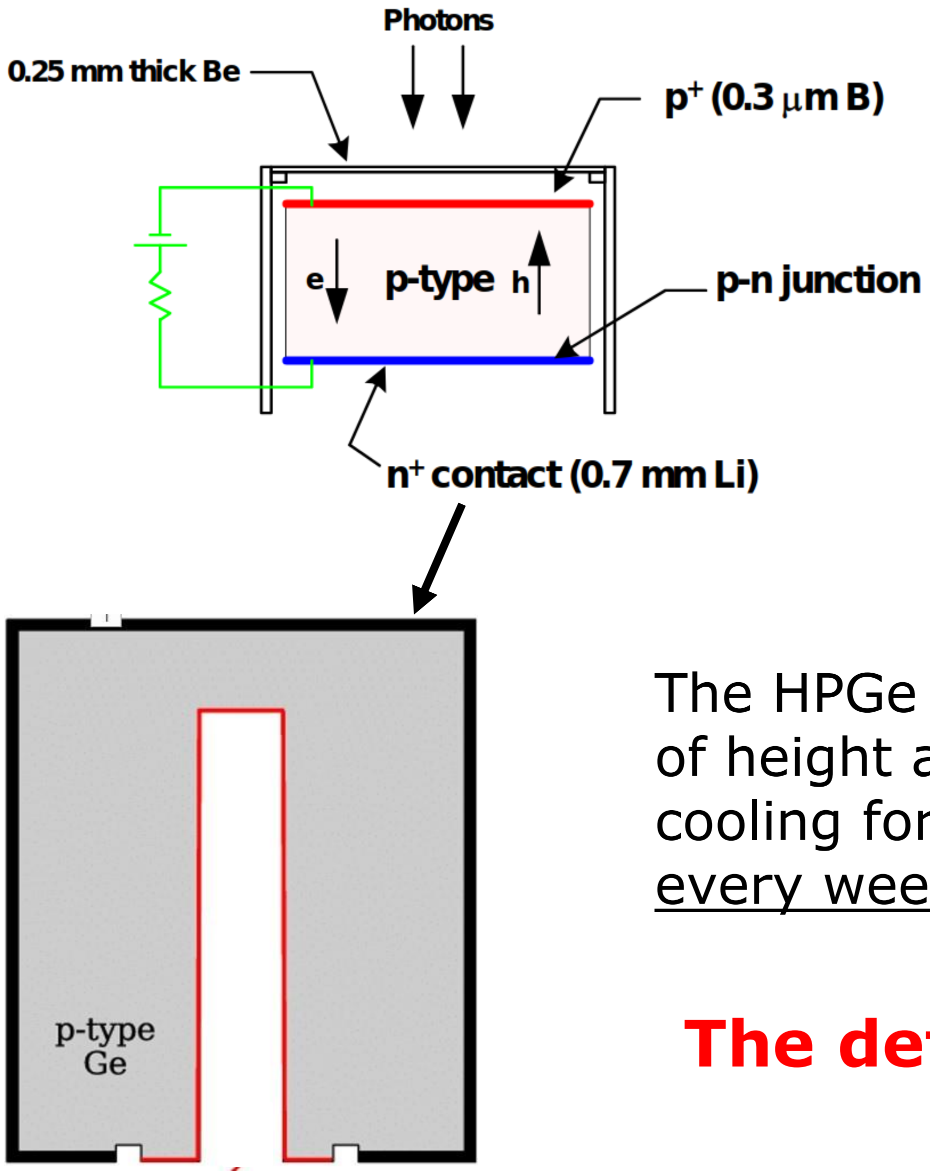
K^- Pb, K^- W; HPGe detector (1 keV), **K^-Pb (9 -> 8),**

K^-Pb (11 -> 10), K^-W (9 -> 8), K^-W (11 -> 10),

Average m_K=493.679 ± 0.006 MeV S=2.4

Discrepancy of 60 KeV

HPGe Detector for kaonic atoms



A High Purity p-type Germanium Detector (HPGe), designed by Baltic Scientific Instruments, could be used covering a wide energy range from hundred keV to a few MeV.

Such detector is able to work under high-rate conditions (to 150 kHz) and is ideal to perform the measurements in the DAΦNE facility.

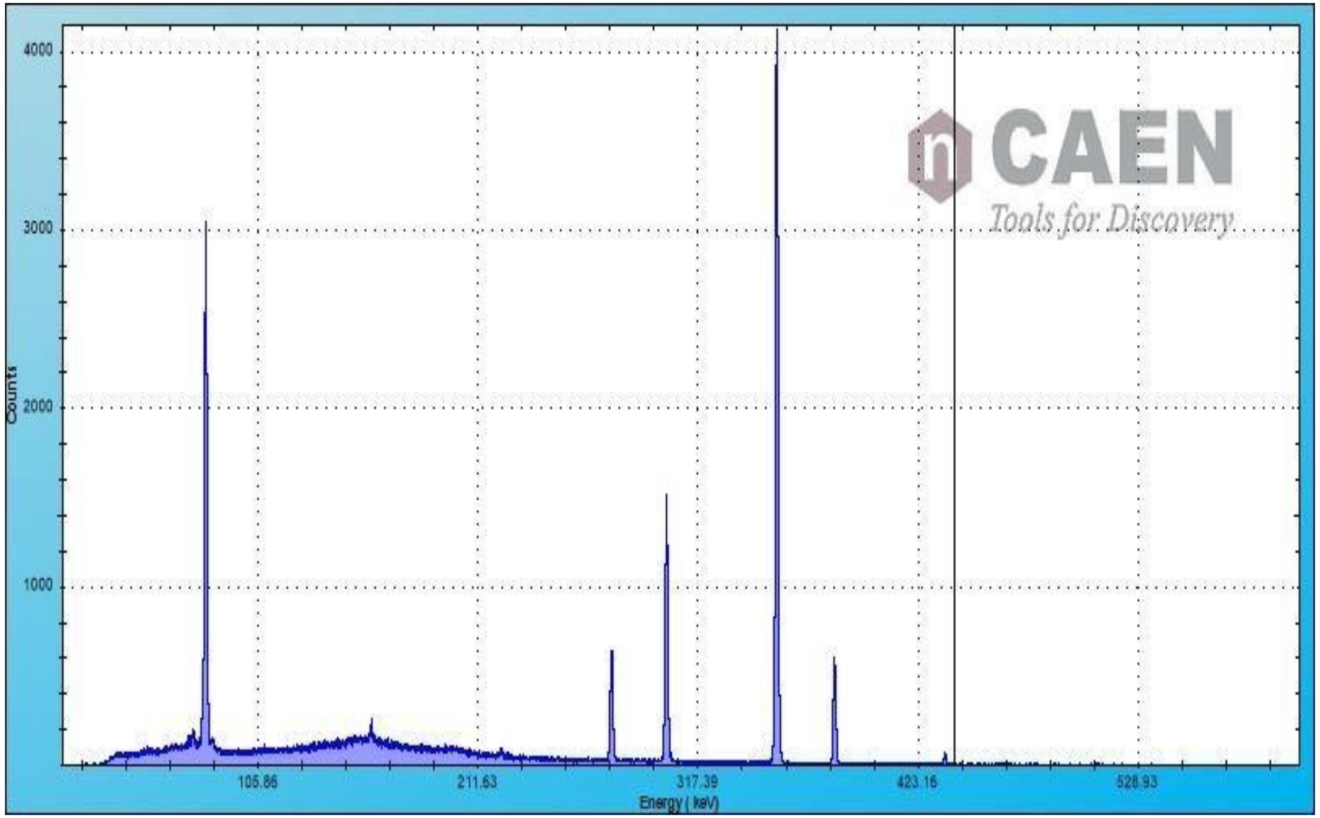
The HPGe detector has a cylindrical active volume with 59.3 mm of height and 59.8 mm of base diameter, and needs a cryogenic cooling for high-quality performances (refilling of liquid nitrogen every week).

The detector is subject to RADIATION DAMAGE

due to the DAΦNE collider

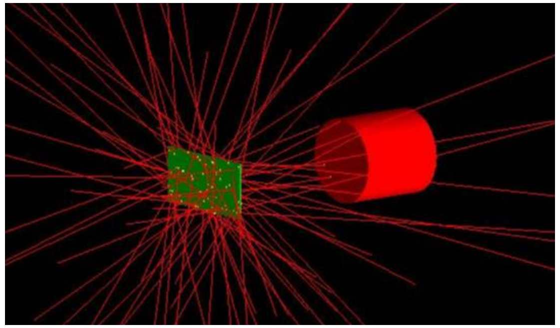
HPGe Detector for kaonic atoms

Spectrum of the HPGe detector

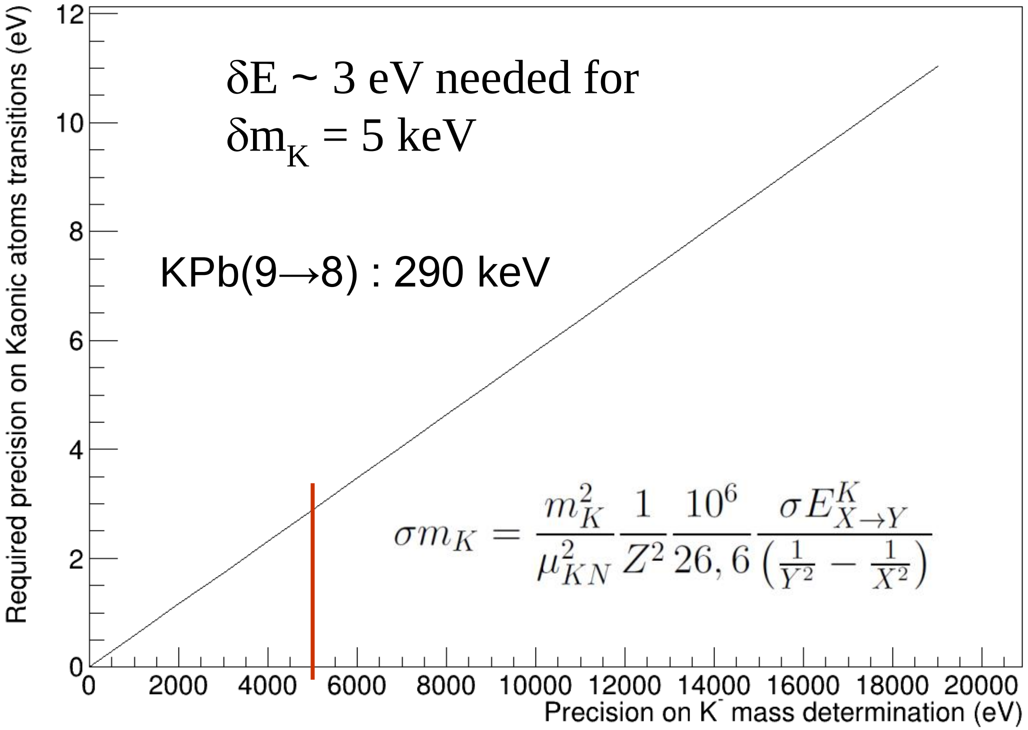


Resolutions (FWHM)
obtained with ^{60}Co, ^{133}Ba sources :

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

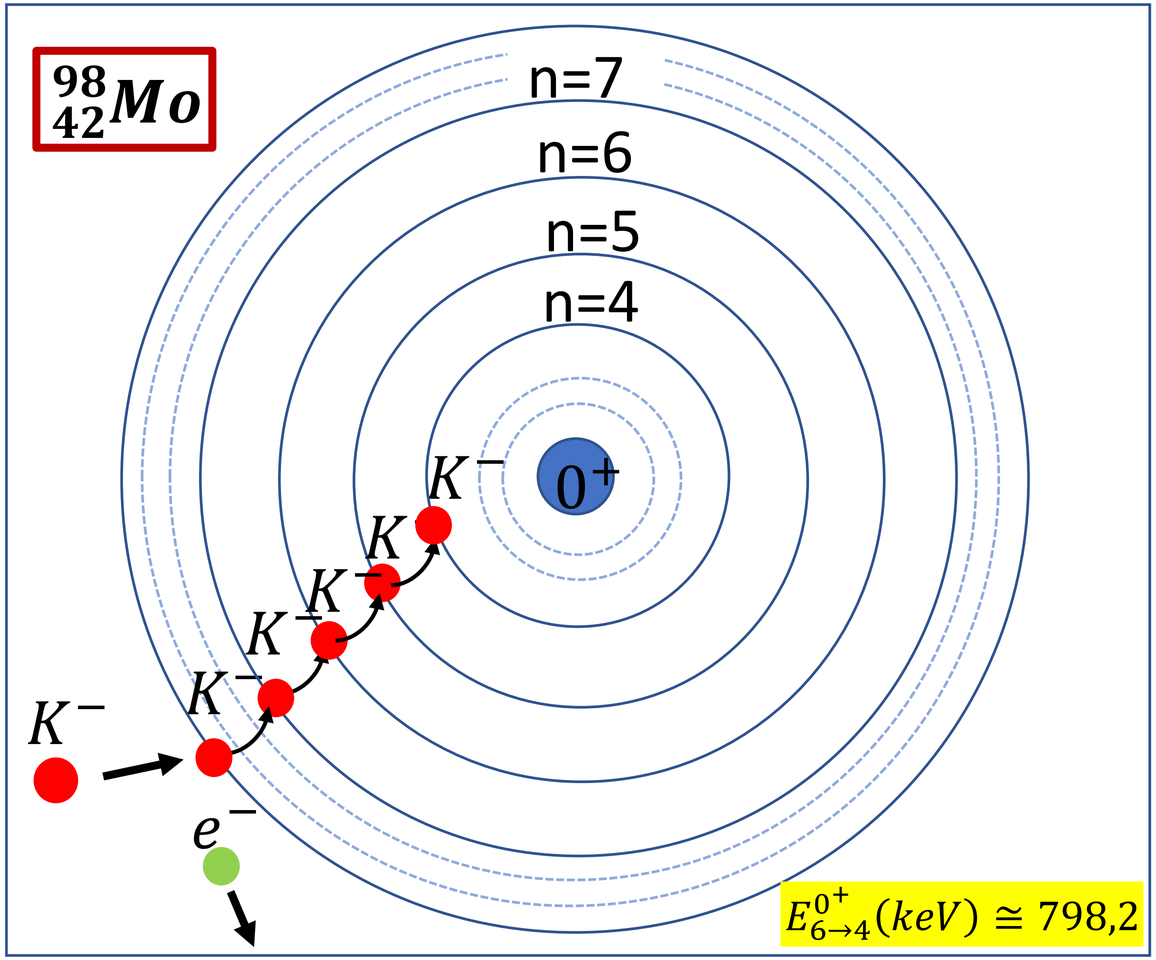


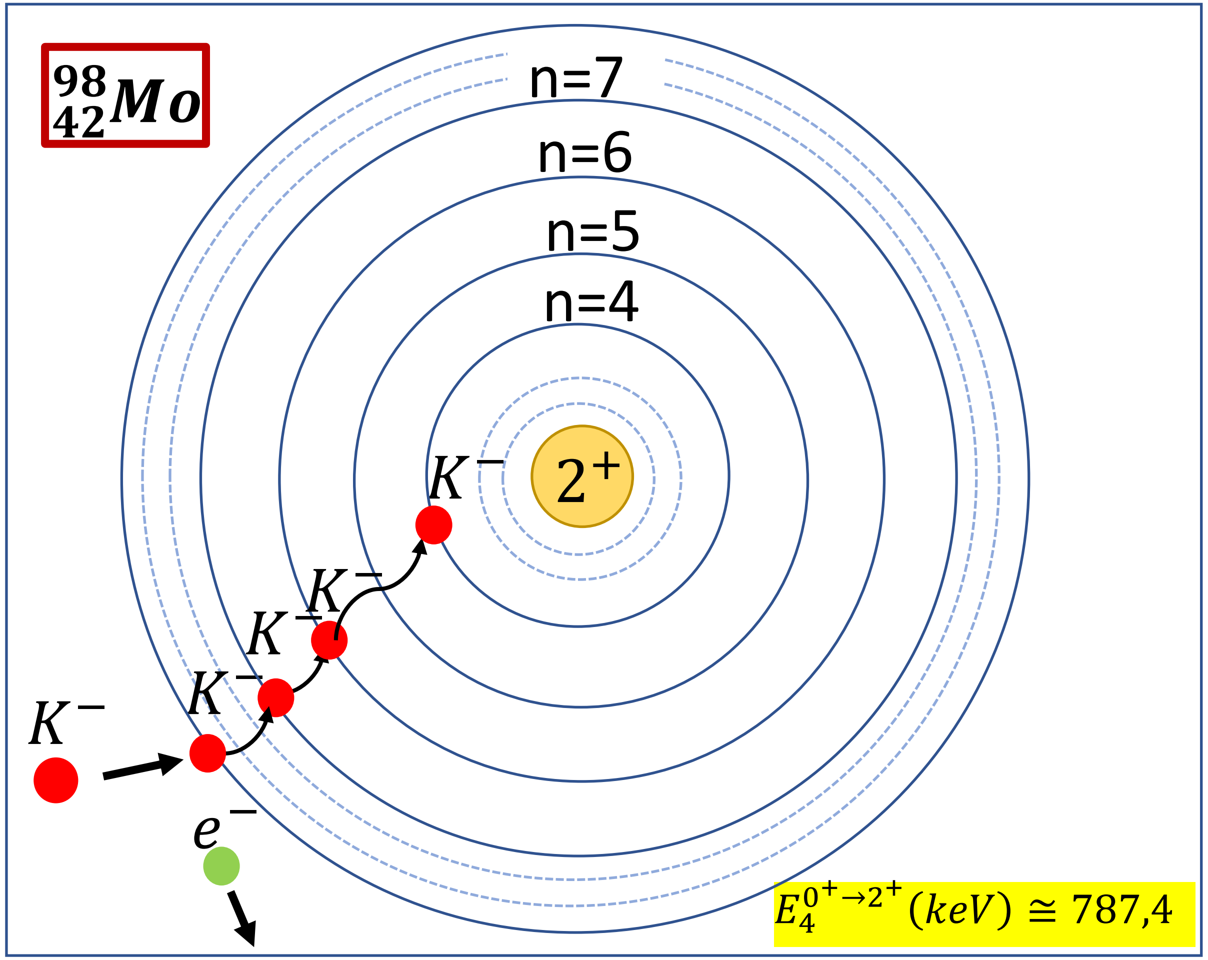
Monte Carlo simulation to estimate target dimensions, timing and signal/background ratio.



THE E2 NUCLEAR RESONANCE EFFECT

In “thicklish nuclei” kaonic atoms, when an atomic de-excitation energy is closely matched by a nuclear excitation energy, a resonance condition occurs, which produces an attenuation of some of the atomic x-ray lines from a resonant versus a normal isotope target – as Mo(98).





THE E2 NUCLEAR RESONANCE EFFECT

The E2 Nuclear Resonance effect is a mixing of the atomic states due to the electrical quadrupole excitations of nuclear rotational states.

Quanto-mechanically, *the effect mixes* $(n, l, 0^+)$ *levels with* $(n', l-2, 2^+)$ *levels* producing a wave function which contains a small admixture of excited nucleus-deexcited atom wavefunctions:

$$\psi = \sqrt{1 - |\alpha|^2}\, \phi(n, l, 0^+) + \alpha\, \phi(n', l-2, 2^+)$$

where the admixture coefficient $\alpha = \pm \frac{\langle n, l-2, 2^+ | H_q | n', l, 0^+ \rangle}{E_{(n,l,2^+)} - E_{(n,l,0^+)}}$ (very small), and H_Q expresses the *electric quadrupole interaction* between hadron and nucleus.

As example, for the nuclear E2 resonance effect in $K^- - Mo$ isotopes:

$$\psi = \sqrt{1 - |\alpha|^2}\, \phi(6h, 0^+) + \alpha\, \phi(4f, 2^+) \quad \text{with} \quad \alpha = \pm \frac{\langle 4f, 2^+ | H_q | 6h, 0^+ \rangle}{E_{(4f,2^+)} - E_{(6h,0^+)}}$$

THE E2 NUCLEAR RESONANCE EFFECT

HADRONIC ATOMS ARE VERY SENSITIVE TO QUITE AMOUNTS OF CONFIGURATION MIXING

The nuclear absorption rate increases very drasically (by a factor of several hundred) for each unit decrease of orbital angular momentum; thus for a decrease of $\Delta l = 2$, the factor may be around 10^5.

A very small admixture coefficient a (typically 1%) can mean a significant induced width!

INDUCED WIDTH: $\Gamma_{n,l}^{Ind} = |a^2|\Gamma_{n',l-2}^{0}$

A significant weakening/attenuation of corresponding hadronic x-ray line and any lower lines can be observed.

Moreover, comparing the ratio of intensities (attenuated line/reference) from the resonant isotope (thicklish) to a non resonant one, we have the **direct measure of the fraction of hadrons absorbed by the excited nucleus**.

THE E2 NUCLEAR RESONANCE EFFECT

Nuclear Resonances are expected also for kaonic atoms. Such predictions have been obtained by integrating the Klein-Gordon equation with a phenomenological kaon-nucleon potential.

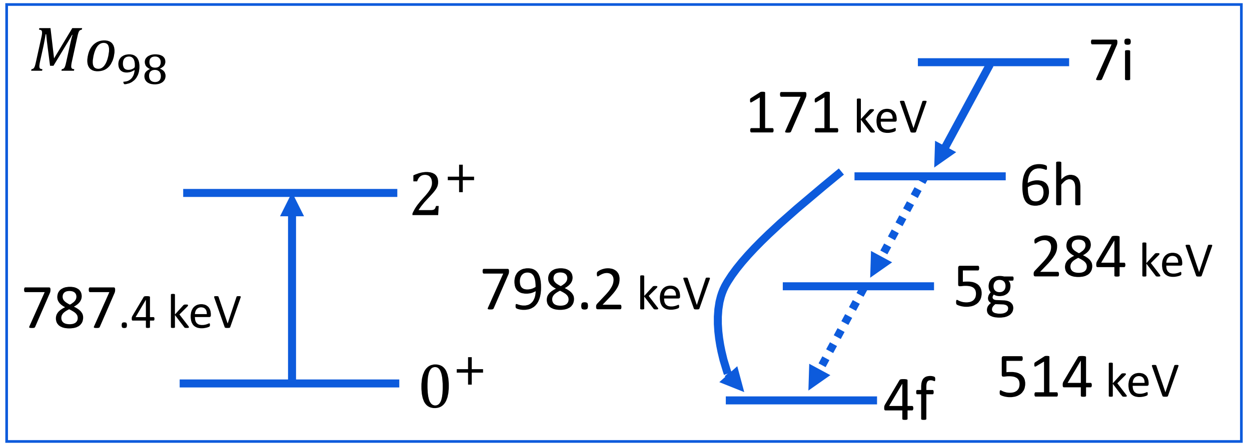
Nucleus	$E_{2^+} - E_{0^+}[keV]$	Levels mixed	$E_{n,l} - E_{n,l-2}[keV]$	$\Gamma_{n,l-2}[keV]$	Atten lines	Energy [keV]	Ref lines	Energy [keV]
$^{94}_{42}Mo$	871	(6,5)+(4,3)	798.8	24.8	$6 \rightarrow 5$	284.3	7 →6	171.1
$^{96}_{42}Mo$	778	(6,5)+(4,3)	798.5	25.2	$6 \rightarrow 5$	284.3	7 →6	171.1
$^{98}_{42}Mo$	787.4	(6,5)+(4,3)	798.2	25.5	$6 \rightarrow 5$	284.3	7 →6	171.1
$^{100}_{42}Mo$	535.5	(6,5)+(4,3)	797.9	25.8	$6 \rightarrow 5$	284.3	7 →6	171.2
$^{96}_{44}Ru$	832.3	(6,5)+(4,3)	874.9	29.8	$6 \rightarrow 5$	312.1	7 →6	187.9
$^{122}_{50}Sn$	1140.2	(6,5)+(4,3)	1105.8	70.4	$6 \rightarrow 5$	403.5	7 →6	243.1
$^{138}_{56}Ba$	1426.0	(6,5)+(4,3)	1346.3	126.1	$6 \rightarrow 5$	505.7	7 →6	305.4
$^{198}_{80}Hg$	411.8	(8,7)+(7,5)	406.1	7.8	$8 \rightarrow 7$	403.2	9 →8	276.1

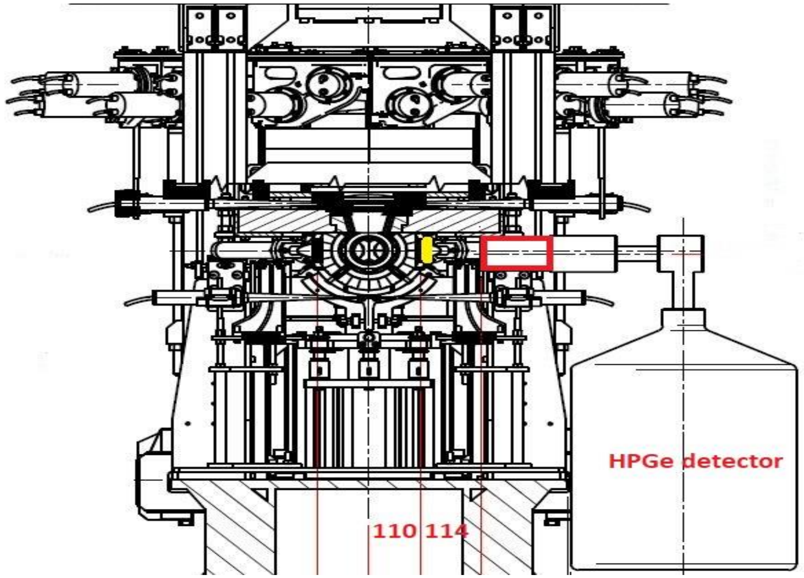
MOLYBDENUM OFFERS A UNIQUE OPPORTUNITY TO INVESTIGATE WITH NUCLEAR RESONANCES THE STRONG $K^- - N$ INTERACTION

THE E2 NUCLEAR RESONANCE EFFECT

The measurement of the kaonic molybdenum resonance effects could be performed exploiting the DAΦNE kaon production and the HPGe detectors.

Solid targets of ${}^{94,96,98,100}_{42}Mo$ can be exposed to the K^-, measuring the mixing coefficient through the attenuation of the $6 \rightarrow 5$ and $5 \rightarrow 4$ transitions respect to the non-resonant ${}^{92}_{42}Mo$ as reference.

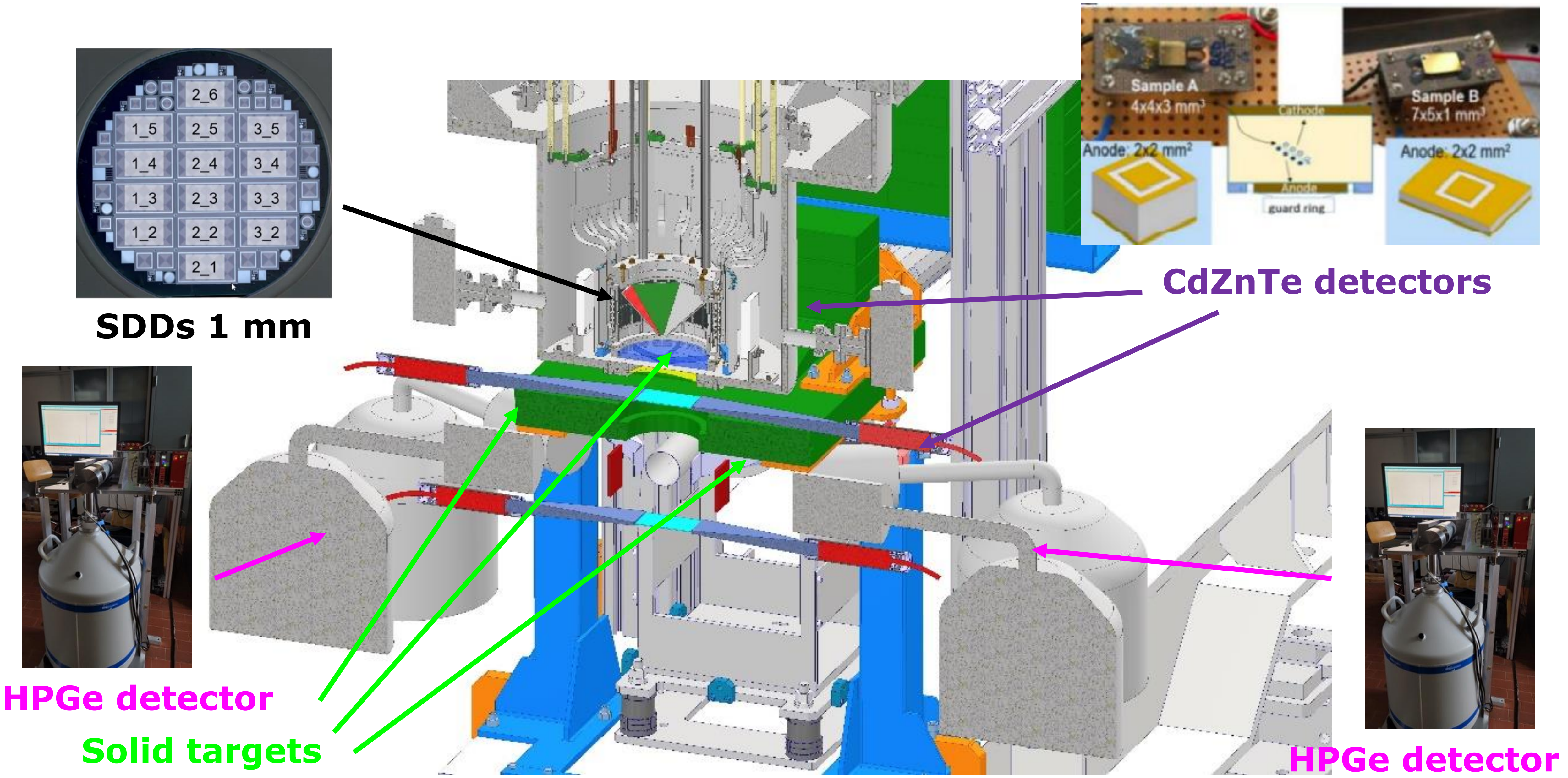




Calculations are being performed to determine the standard QED energy transitions to achieve the measurement of shift and width due to strong interaction in the 4f level with the excited nucleus (never measured)

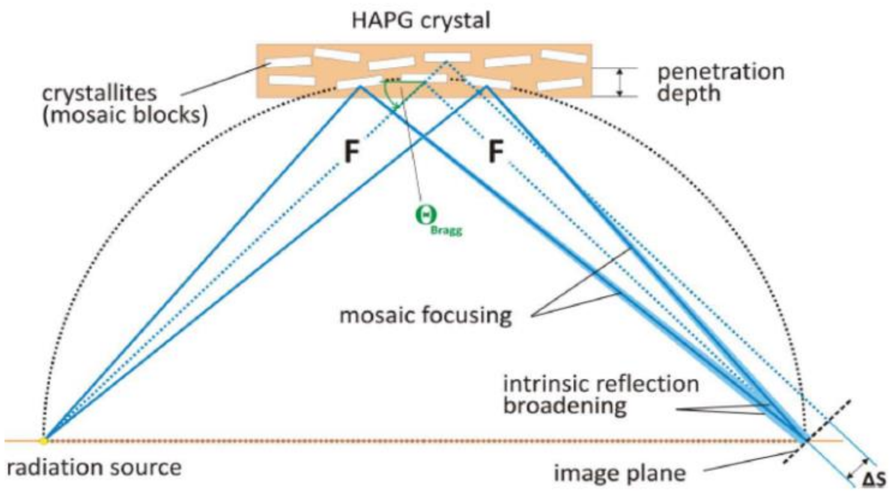
L. De Paolis, et al., "Investigating the E2 nuclear resonance effect in kaonic atoms", J. Phys.: Conf. Ser. 2446, 012038, 2023.

EXCALIBUR: SETUP IN PREPARATION



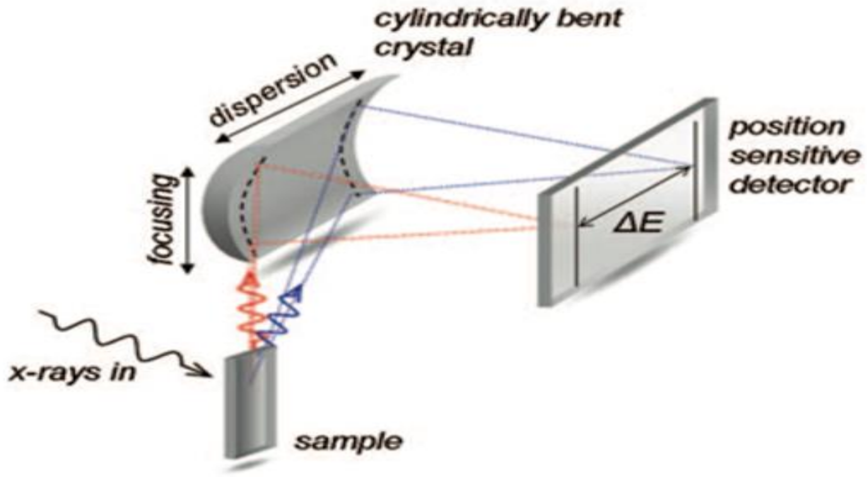
UHKA with Crystal Spectrometers: VOXES

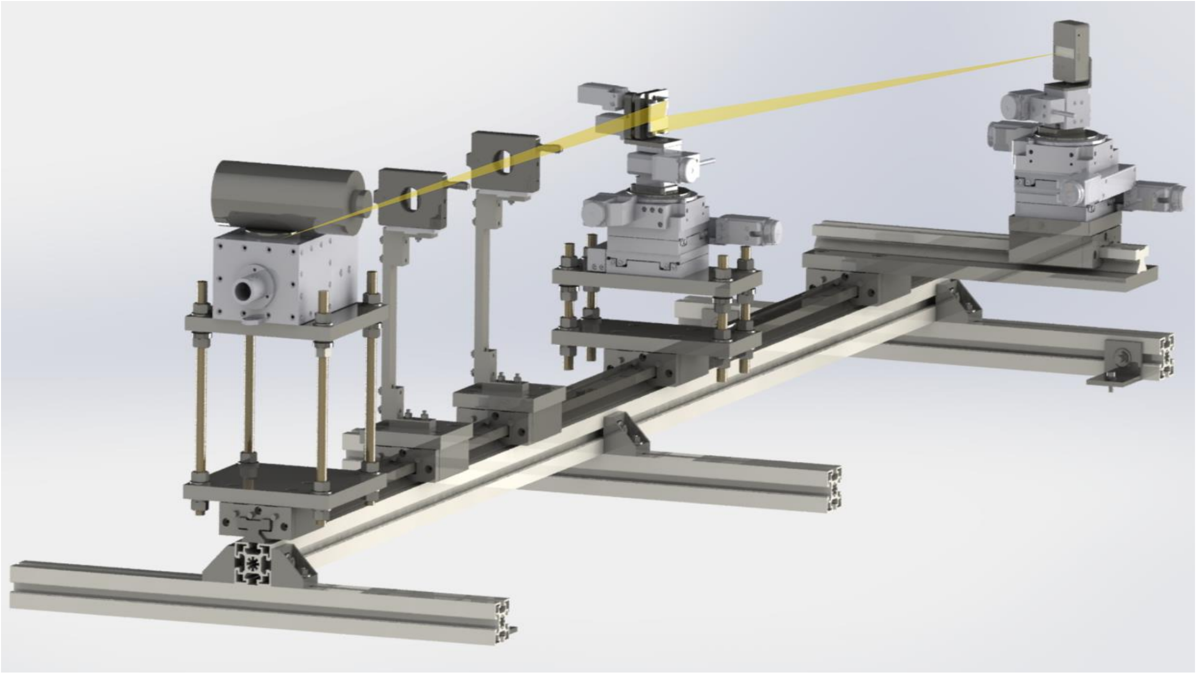
Spectrometer developed under CSN5 Young Researcher Grant (2016-2018)



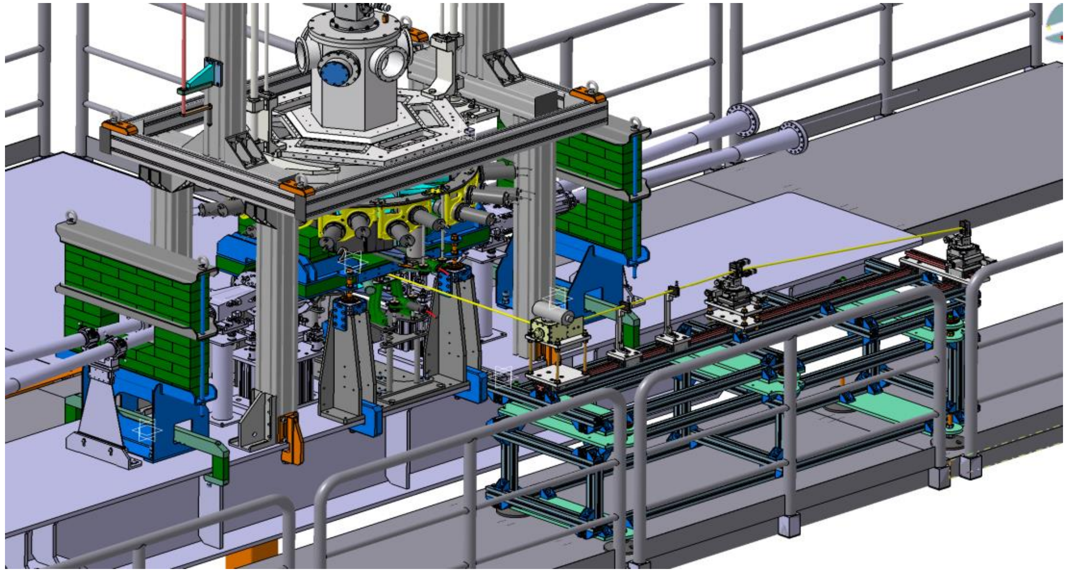
HAPG mosaic crystals in Von Hamos configuration:

- Higher intrinsic reflectivity wrt standard crystals
- VH configuration to exploit sagittal focusing
- Optical optimisation to work with milli/centimetric sources

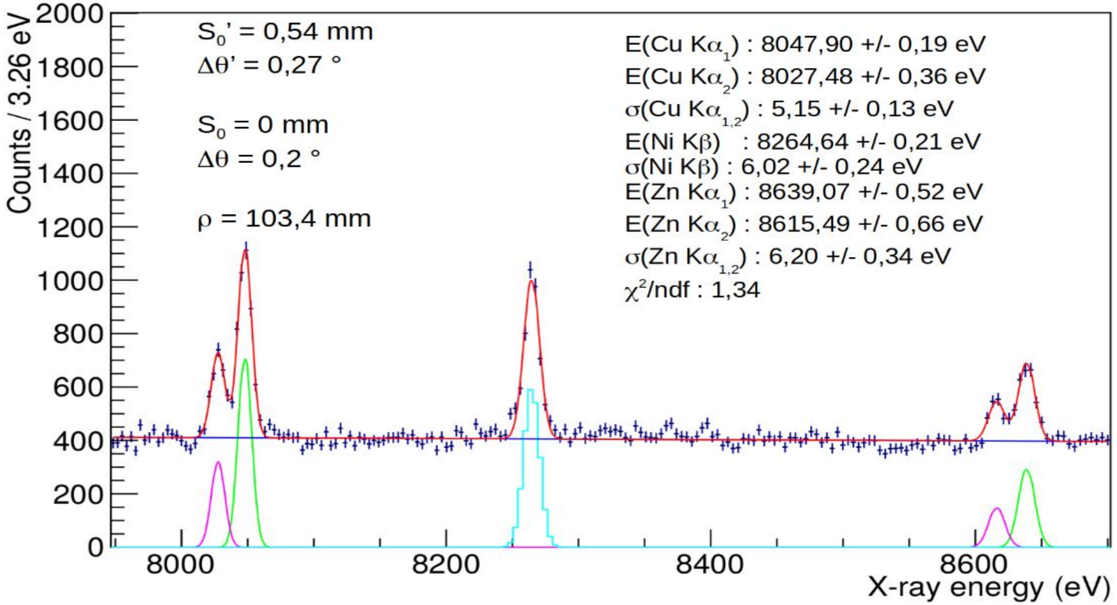


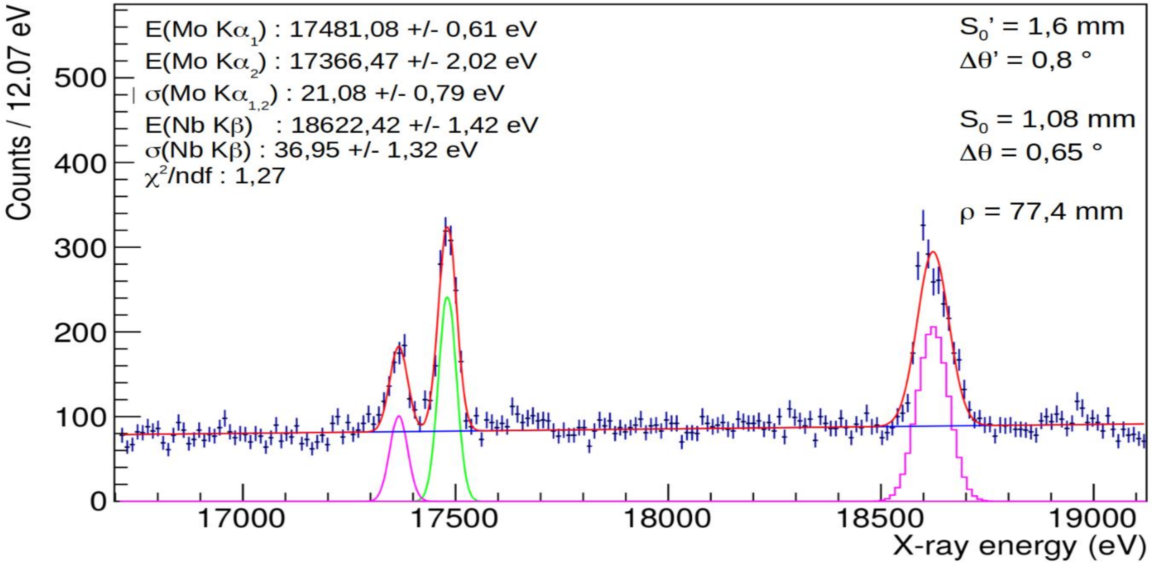


UHKA with Crystal Spectrometers: VOXES



High precision measurements with VOXES in LNF Lab



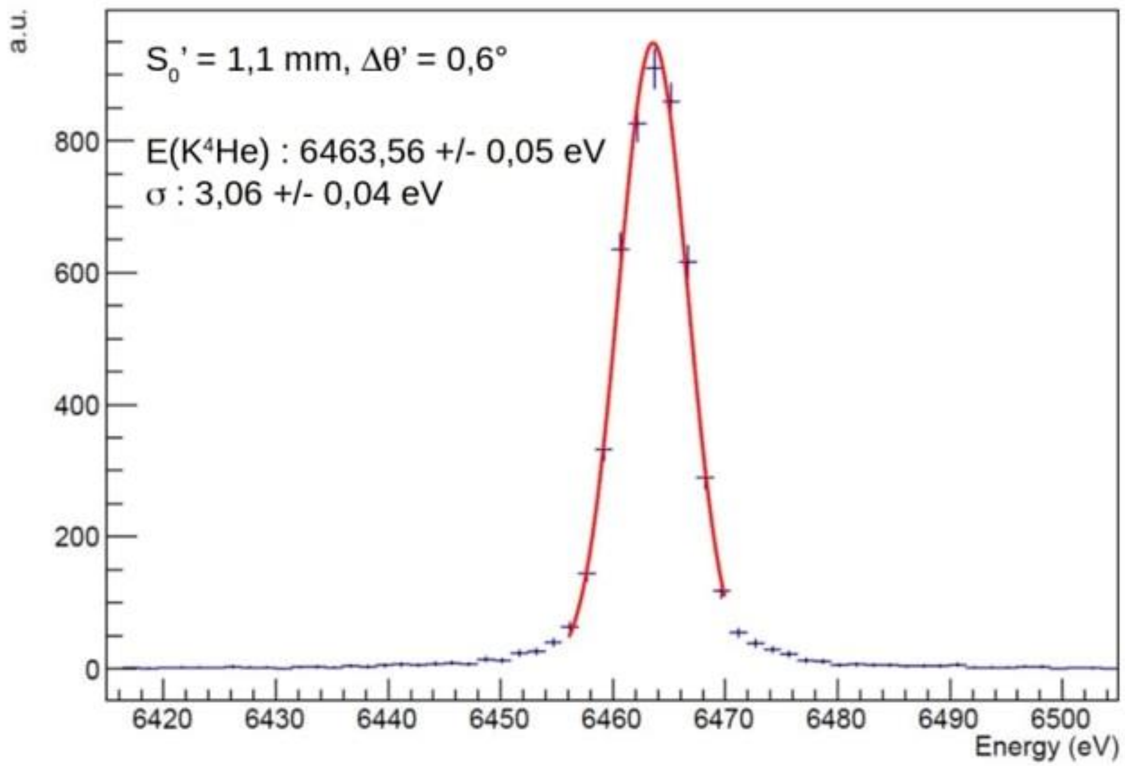


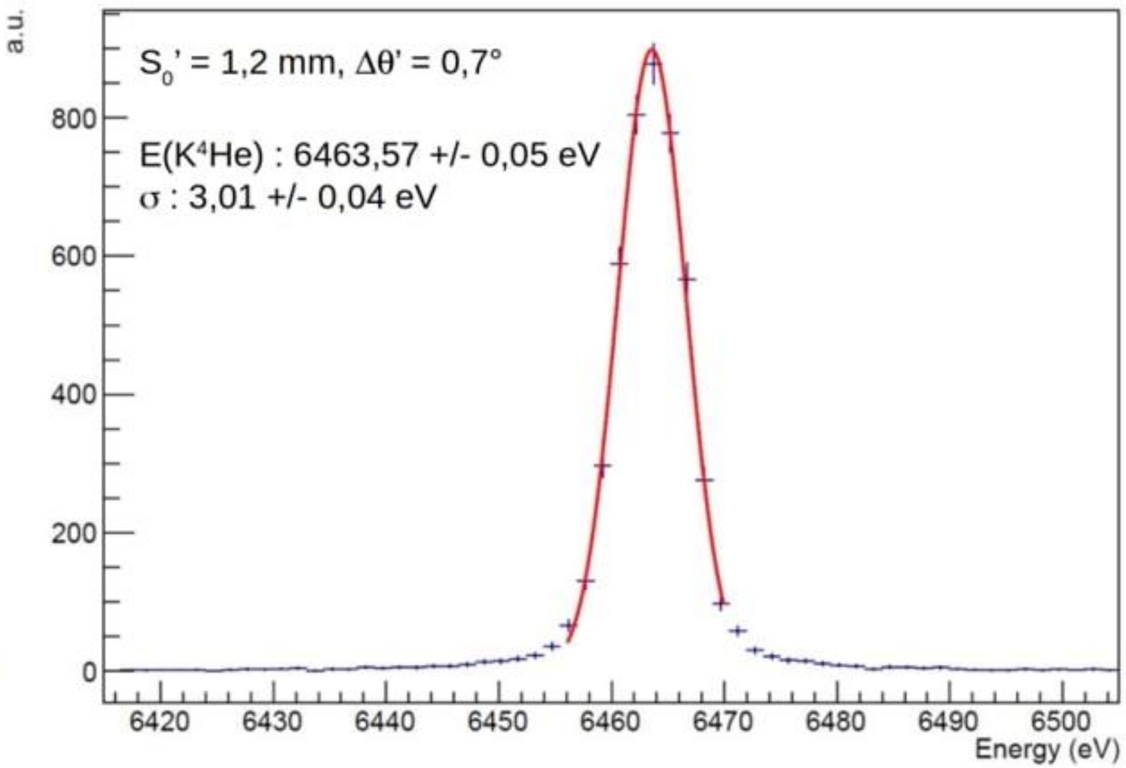
Possible feasibility test to be done in parallel with SIDDHARTA-2

Main goal: assess background and on beam behaviour of crystals and strip detector

UHKA with Crystal Spectrometers: VOXES

Simulated spectra of the $K^- - {}^4He$ 3d → 2p achievable measurement with Highly Annealed Pyrolitic Graphite mosaic crystale based x-ray detection system developed by VOXES project at LNF-INFN





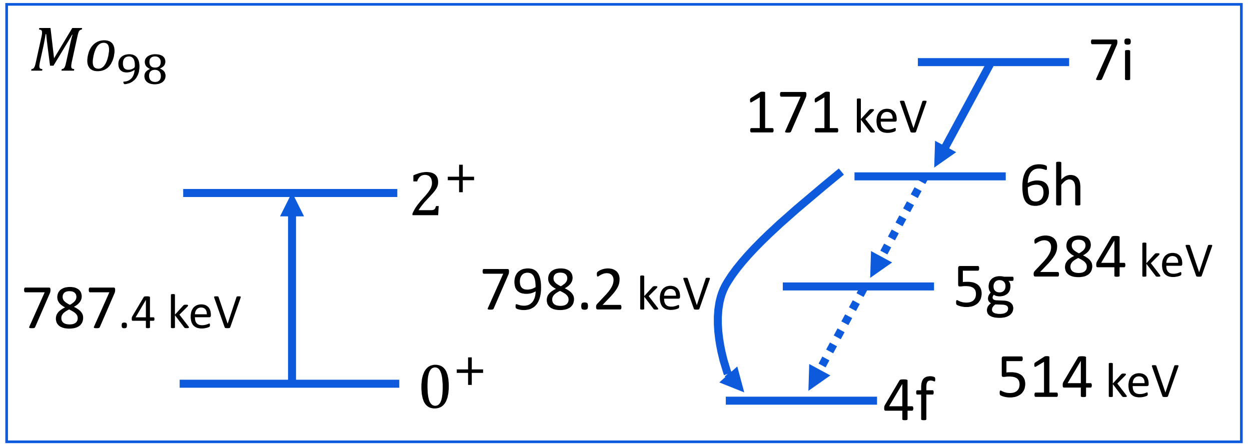
Scordo A et al. Efficiency measurements and simulations of a hapg based von hamos spectrometer for large sources. J. Anal. At. Spectrom. 36 (2021) 2485.

Thank you!

The Molybdenum 98 experiment

An experiment measuring E2 Nuclear Resonance Effects in Molybdenum 98 was performed in 1975 by G. L. Goldfrey, G- K. Lum and C. E. Wiegand at Lawrence Berkeley Laboratory (LBL) in California.

In kaonic molybdenum (98), the energy difference between 6h and 4f levels, 798.2 keV, is very nearly equal to the nuclear excitation energy of 787.4 keV.

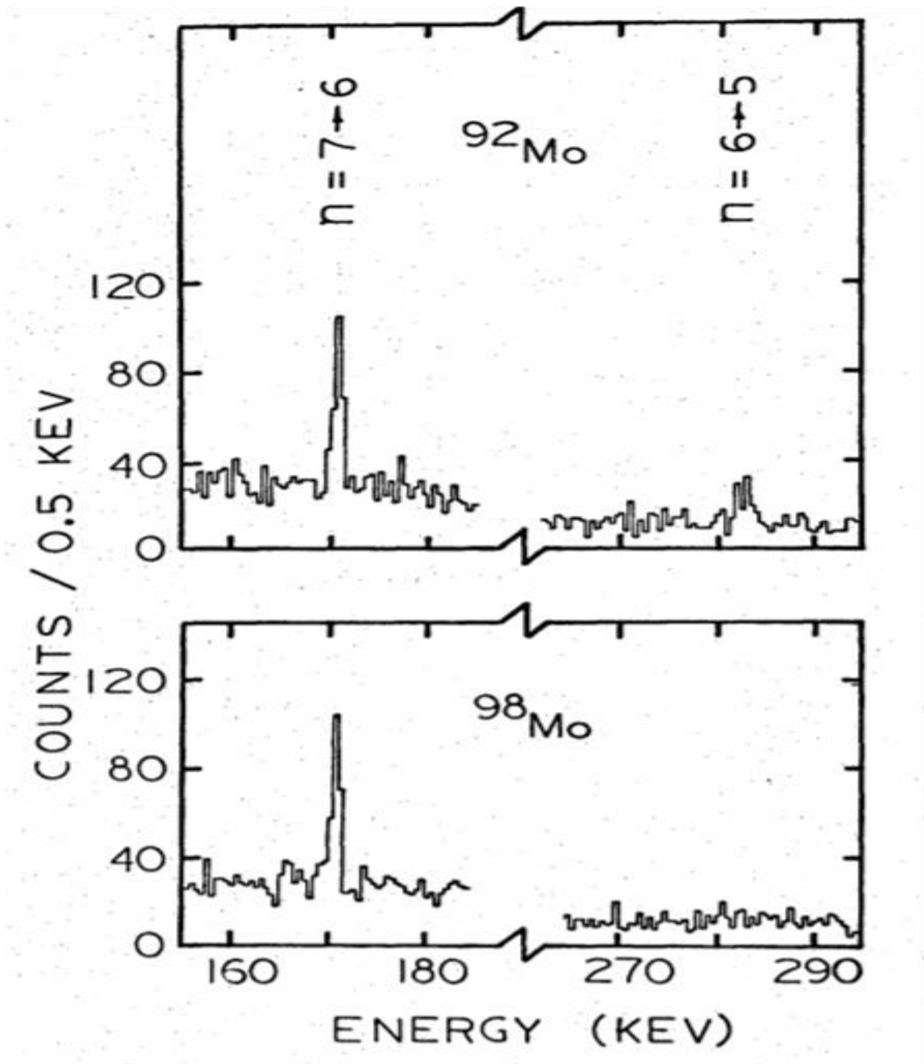


Experimental apparatus and measurement features:

- The experiment was performed with a negative kaon beam, turning the targets of Mo(98), and Mo(92) as reference.
- The spectra were collected using **germanium detectors** feeding a pulse height analyzer.

The Molybdenum 98 experiment

The E2 Nuclear Resonance effect was observed $K^- - {}^{98}_{42}Mo$, expressed as the attenuation of x-ray line .



Target	$E^{K-Mo}_{(6,5)\rightarrow(4,3)}(keV)$	$E^{Nucl}_{0^+\rightarrow 2^+}(keV)$	$\lvert a \rvert$	R_α
${}^{98}_{42}Mo$	798.2	787.4	0.033	0.16 ± 0.16
${}^{92}_{42}Mo$	799.1	1540.0	0.001	1.00 (ref)

Only 25 hours of data taking with K-beam was **not enough for a conclusive result!!**

↓

IMPROVABLE WITH MODERN DETECTORS AND MORE DATA TAKING TIME

Double-β decay in Mo-98 isotope

Double beta (ββ) decay is a nuclear process in which two neutrons turn in two protons (or vice versa) and two electrons are emitted.

STANDARD double-beta decay: $^{98}_{42}Mo \rightarrow\, ^{98}_{44}Ru + e^- + e^- + 2\overline{\nu}_e$ ➡ Lepton number conserved

Neutrinoless double-beta decay: $^{98}_{42}Mo \rightarrow\, ^{98}_{44}Ru + e^- + e^-$ ➡ **VIOLATION OF LEPTON NUMBER CONSERVATION LAW**

Neutrinoless double-beta decay is only possible if neutrino is a Majorana particle

The ββ-decay nuclear matrix elements can be calculated using two different theory frameworks: proton-neutron quasiparticle random phase approximation (pnQRPA) and microscopic interacting boson model (IBM-2)

These model depends on the relative distance between the two neutron decays, which is estimated to be:

$r_{12} \leq 2R_{nucl}$ with $R_{nucl} \approx 1.2A^{1/3}$

The *rms* neutron radius could provide further constrains to define relative distance among neutrons in $^{98}_{42}Mo$

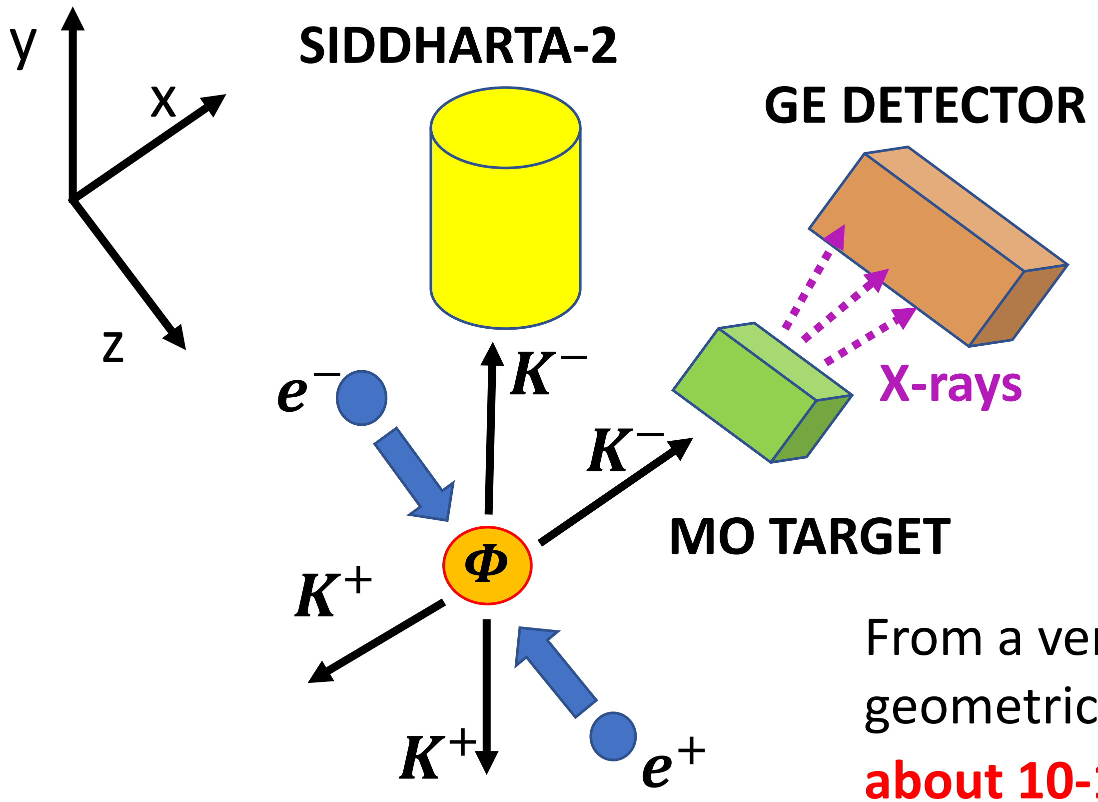
SCIENTICIC IMPORTANCE OF KAMEO

- To obtain informations on the properties of deeply bound kaonic atoms, not accessible by the kaonic cascade, in ticklish nuclei → shift and width of the $n = 4$ level!
- In $K^- - {}^{98}_{42}Mo$ the attenuation coefficient (α) due to the nuclear resonance effect can be measured with higher precision.
- The α coefficient can be measured in ${}^{94}_{42}Mo$, ${}^{96}_{42}Mo$ and ${}^{100}_{42}Mo$ for the first time, providing new reference value for theorical models.
- The comparison of measurements in ${}^{94}_{42}Mo$, ${}^{96}_{42}Mo$, ${}^{98}_{42}Mo$ and ${}^{100}_{42}Mo$ could reveal new properties of strong kaon-nucleon interaction (also ${}^{96}_{44}Ru$).
- The search for isotope effects in the level shift (ε) and width (Γ) would reveal sign of changes in the nuclear periphery when pair of neutrons are added to the lighest isotope (${}^{94}_{42}Mo$)
- To study nuclear distribution in ${}^{98}_{42}Mo$, providing important details to investigate neutrinoless double beta ($0\nu\beta\beta$) and two-neutrino double beta decay ($2\nu\beta\beta$)

EXPERIMENTAL PROPOSAL: KAMEO

Kaonic Atoms Measuring nuclear resonance Effects Observables

The measurement of Nuclear resonance E2 effects in Molybdenum kaonic isotopes could be performed during the SIDDHARTA-2 data taking period, exploiting the horizontal emitted kaons with dedicated targets and a Germanium detector.



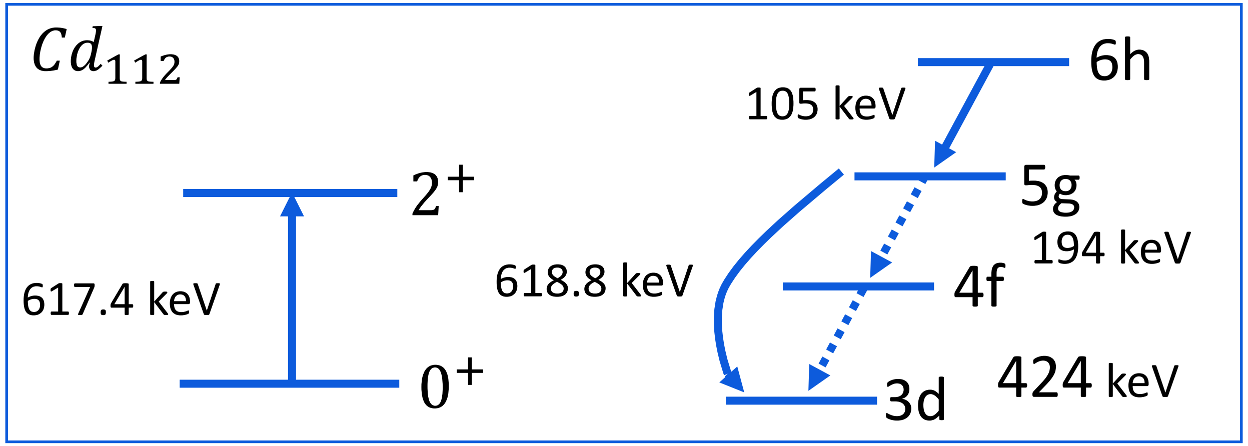
Mo isotope	Abundance	Half-Time
$^{94}_{42}Mo$	9%	*stable*
$^{96}_{42}Mo$	16%	*stable*
$^{98}_{42}Mo$	24%	*stable*
$^{100}_{42}Mo$	10%	$7.7 \times 10^{18}\ y$

From a very **preliminary estimation**, with a target maximizing the geometrical efficiency, **the measurements could be performed in about 10-15 days for each isotope, including (for reference) the $^{92}_{42}Mo$.**

The pionic cadmium 112 experiment

An experiment measuring E2 resonance effect cadmium 112 was performed in 1975 by J. N. Bradbury, H.Daniel, J. Reidy and M. Leon at the biomedical pion beam of Los Alamos Meson Physics Facility (LAMPF).

In pionic cadmium (112), the energy difference between 5g and 3d levels, 618.8 keV, is very nearly equal to the nuclear excitation energy of 617.4 keV.

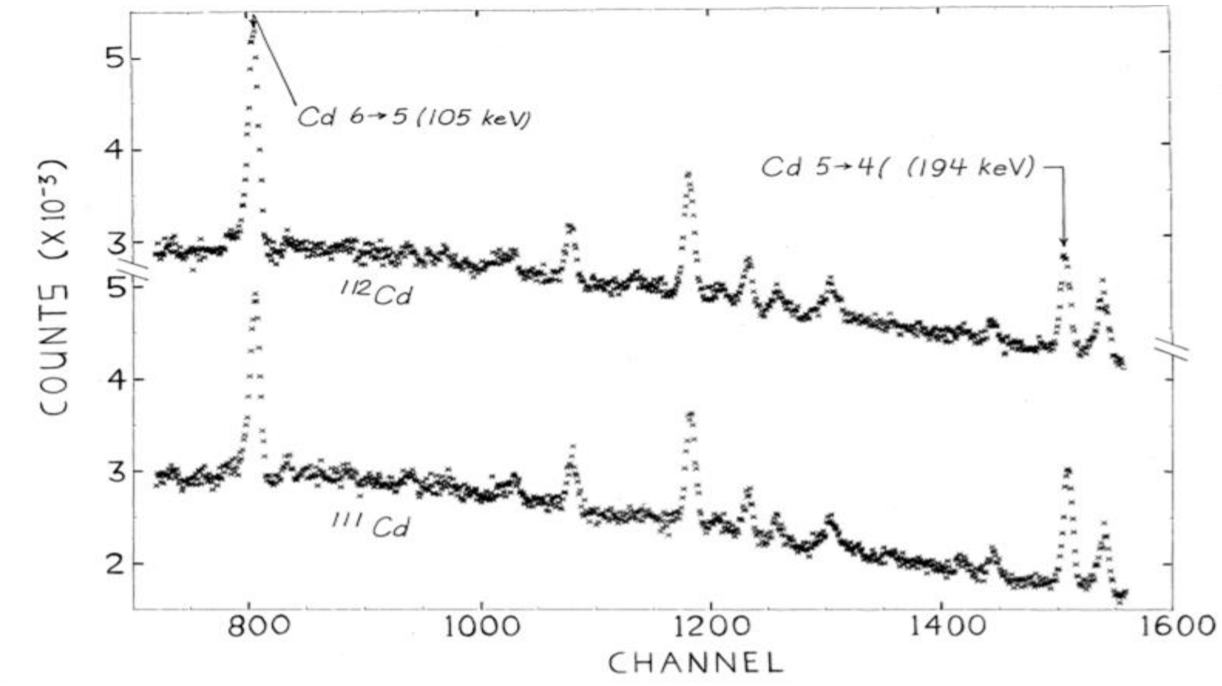


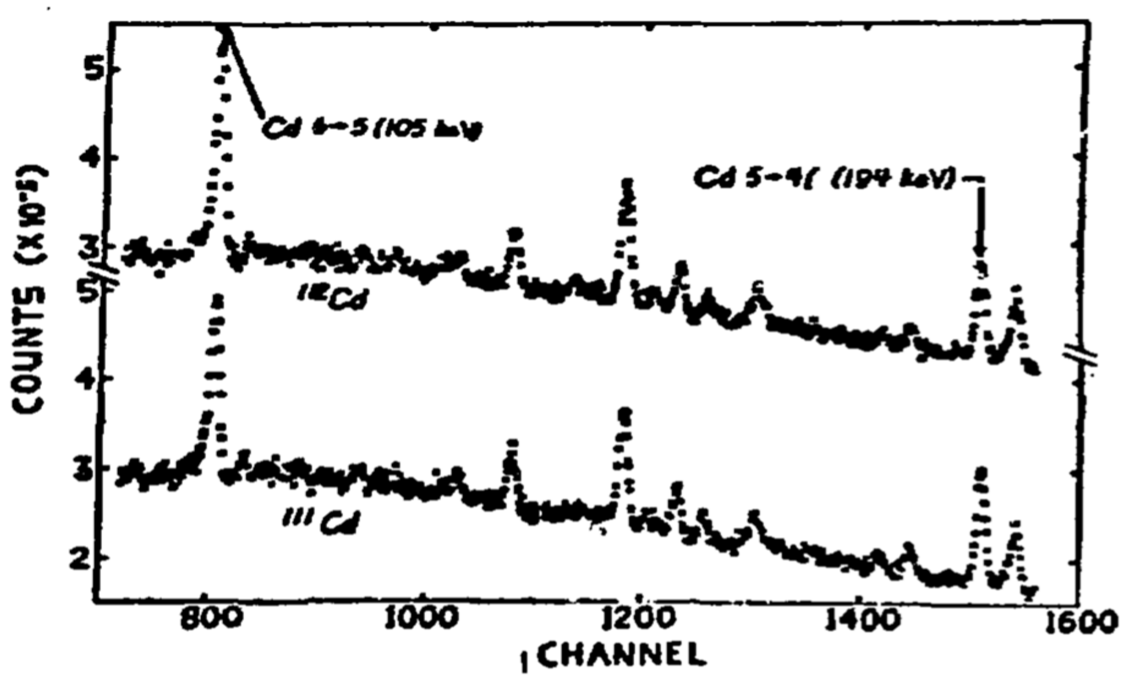
Experimental apparatus and measurement features:

- The experiment consisted of placing enriched isotope targets of Cd(111) e Cd(112) in turn into the negative pion beam for **2 hours**.
- The spectra were collected using a **germanium detector** feeding a pulse height analyzer.
- Natural Cadmio was exposed for a shorter time to provide consistency check.

Pionic cadmium 112 measurement

These results demonstrate the existence of the Nuclear Resonance Effect: the ratios are very significantly different from one.





Sample	6 → 5 (105 keV) (%)	5 → 4 (194 keV) (%)	Ratio $\frac{5 \to 4}{6 \to 5}$	4 → 3 (425 keV) (%)	Ratio $\frac{4 \to 3}{6 \to 5}$
^{112}CdO	26647 ± 3.6	9968 ± 5.5	0.374 ± 0.025	2446 ± 8.2	0.092 ± 0.008
^{111}CdO	21432 ± 3.7	12408 ± 5.1	0.579 ± 0.036	2526 ± 8.8	0.118 ± 0.011
Natural CdO	1953 ± 12	1293 ± 7.8	0.662 ± 0.096	···	···

Pionic cadmium 112 measurement

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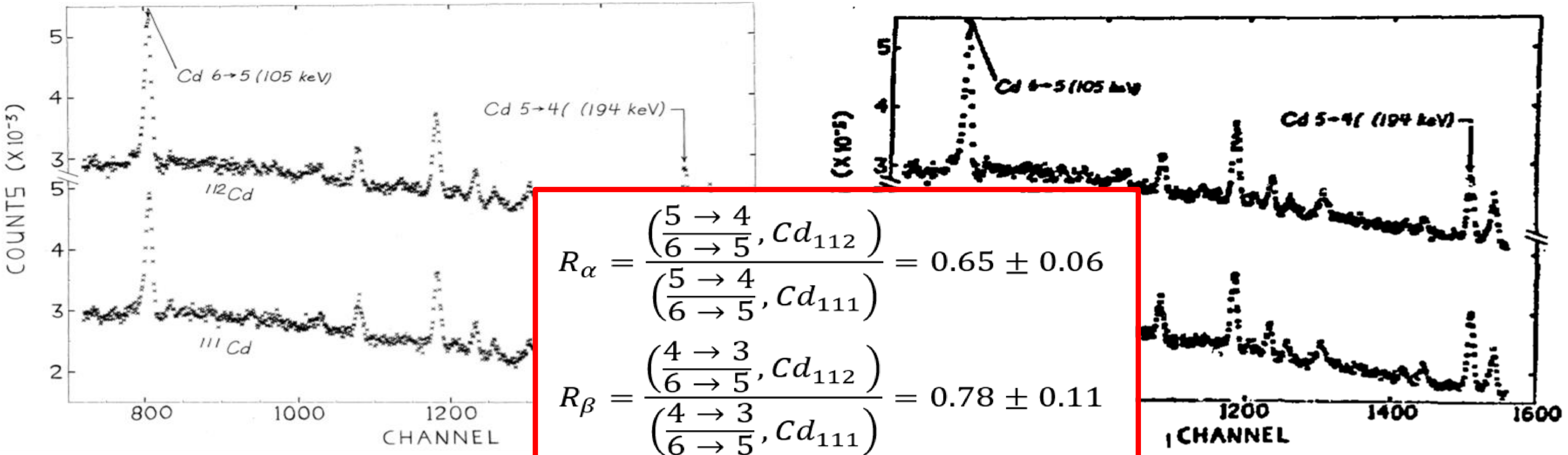

$$R_\alpha = \frac{\left(\frac{5\to 4}{6\to 5}, Cd_{112}\right)}{\left(\frac{5\to 4}{6\to 5}, Cd_{111}\right)} = 0.65 \pm 0.06$$

$$R_\beta = \frac{\left(\frac{4\to 3}{6\to 5}, Cd_{112}\right)}{\left(\frac{4\to 3}{6\to 5}, Cd_{111}\right)} = 0.78 \pm 0.11$$

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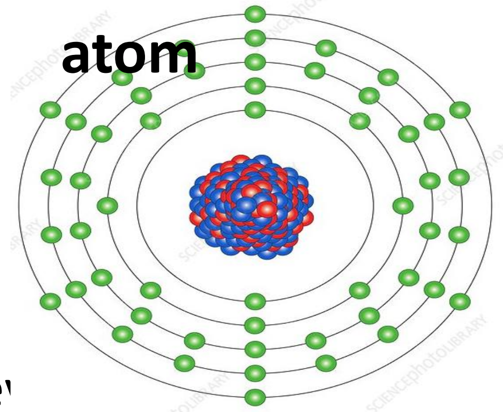
E2 effect in antiprotonic Te atoms

The nuclear E2 resonance effect was recently studied in even-A Te atoms for several reasons:

- The E2 effect allows to obtain informations on the properties of deeply bound antiprotonic atoms, not accessible by the antiprotonic cascade, in ticklish nuclei.

The attenuation of the $n = 8 \rightarrow n = 6$ x-ray transition affected by the E2 resonance measured in several even-A Te isotopes can lead to a precise determination of shift and width of the $n = 6$ level.

Tellurium atom



- The search for isotope effects in the level shift (ε) and width (Γ) would rev… n the nuclear periphery when pair of neutrons are added to the lighest isotope ($^{122}_{52}Te$).

SAME TOPICS COULD BE INVESTIGATED WITH KAONIC MOLYBDENUM ATOMS (4 even-A ISOTOPES)

The antiprotonic Te experiment

The $|n = 8, l = 7, 0^+\rangle$ states in Tellurium are mixed with the $|n = 6, l = 5, 2^+\rangle$ states. The small ratio of mixing strenght and level spacing (respectively $\cong 1\ keV$ and $\cong 15\ keV$) allows a perturbative treatment and the E2-induced, complex energy shift due to this mixing is approximately given by:

$$\varepsilon(E2; 8{,}7) - i\frac{\Gamma(E2; 8{,}7)}{2} \cong \frac{\langle 8{,}7; 0^+|H_q|6{,}5; 2^+\rangle^2}{E_{(8,7,0^+)} - E_{(6,5,2^+)}}$$

where:

- $E_{(8,7,0^+)}$ is the energy of the $|n = 8, l = 7, 0^+\rangle$ state
- $E_{(6,5,2^+)} = \mathrm{E}(2^+) + E_{em}(6{,}5) + \varepsilon(6{,}5) - i\Gamma(6{,}5)/2$ is the energy of the state $|n = 6, l = 5, 2^+\rangle$

TABLE VIII. Shifts and widths of the deeply bound n,l=6,5 level in ^{130}Te.

State (n,l)	Experimental ε (keV)		Experimental Γ (keV)		Calculated $\varepsilon - i\Gamma$ (keV)
(n,l)	$j=l+1/2$	$j=l-1/2$	$j=l+1/2$	$j=l-1/2$	
(6,5)	6.6±3.8	3.6±1.1	17.0±4.4	11.8±4.4	6.8−i18.2

B. Klos, S. Wycech *et al.*, PHYS. REV. C **69**, 044311 (2004)

The antiprotonic Te experiment

The measured level shifts (ε) and widths (Γ) of the energy levels n=8,6 in even-A antiprotonic tellurium isotopes allowed the investigation toward the **neutron density in nuclear periphery**.

Neutron and proton distribution in the Te nuclei were described with two-parameter Fermi model.

⬇

The *rms* neutron radius was adjusted through experimental data.

⬇

THE DIFFERENCE BETWEEN NEUTRON AND PROTON RMS RADII Δr_{np} WAS DETERMINE.