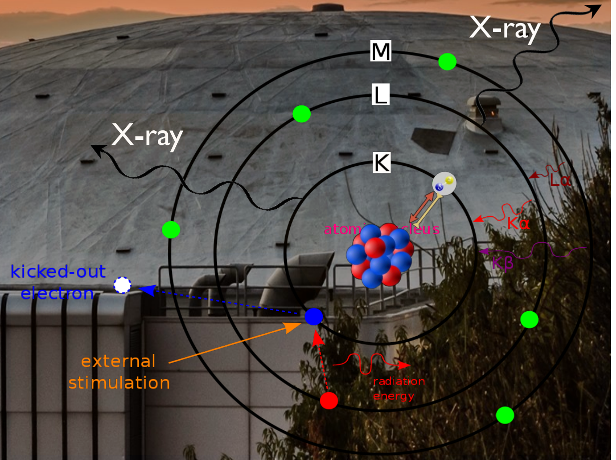
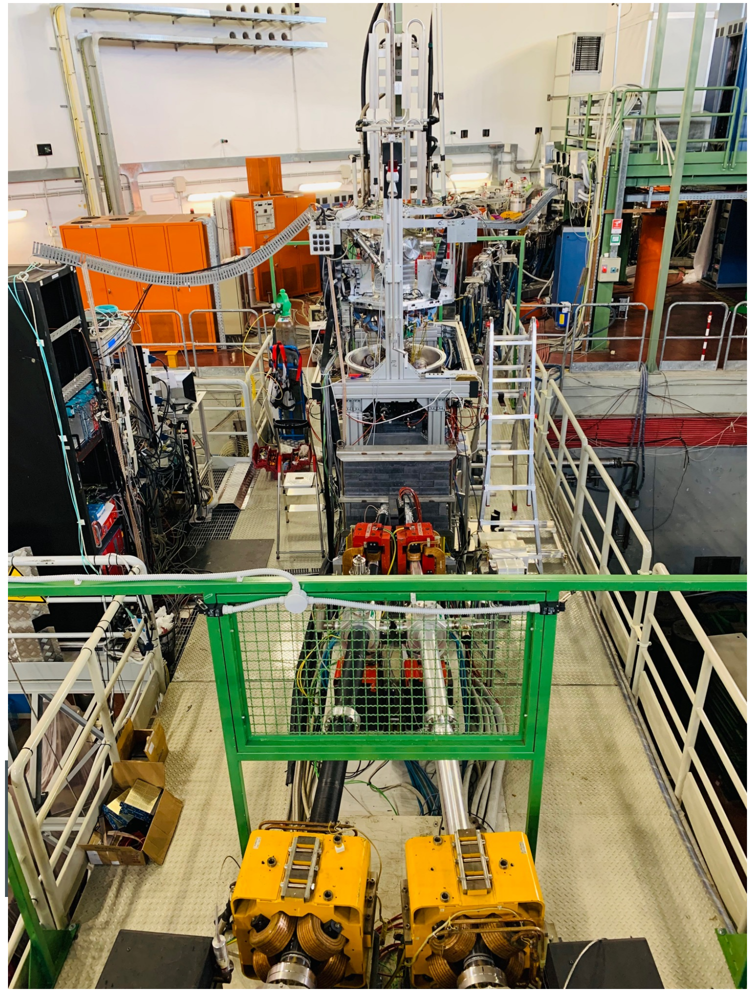
ECT* ROCKSTAR 9–13 Oct 2023

"KAONIC ATOM X-RAY SPECTROSCOPY: THE KAON MASS PUZZLE"

Francesco Sgaramella

on behalf of the SIDDHARTA-2 collaboration





INFN Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

STRONG-2020

ROCKSTAR

Charged kaon mass (K^+, K^-)

$$493.677 \pm 0.013 \text{ MeV}$$

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

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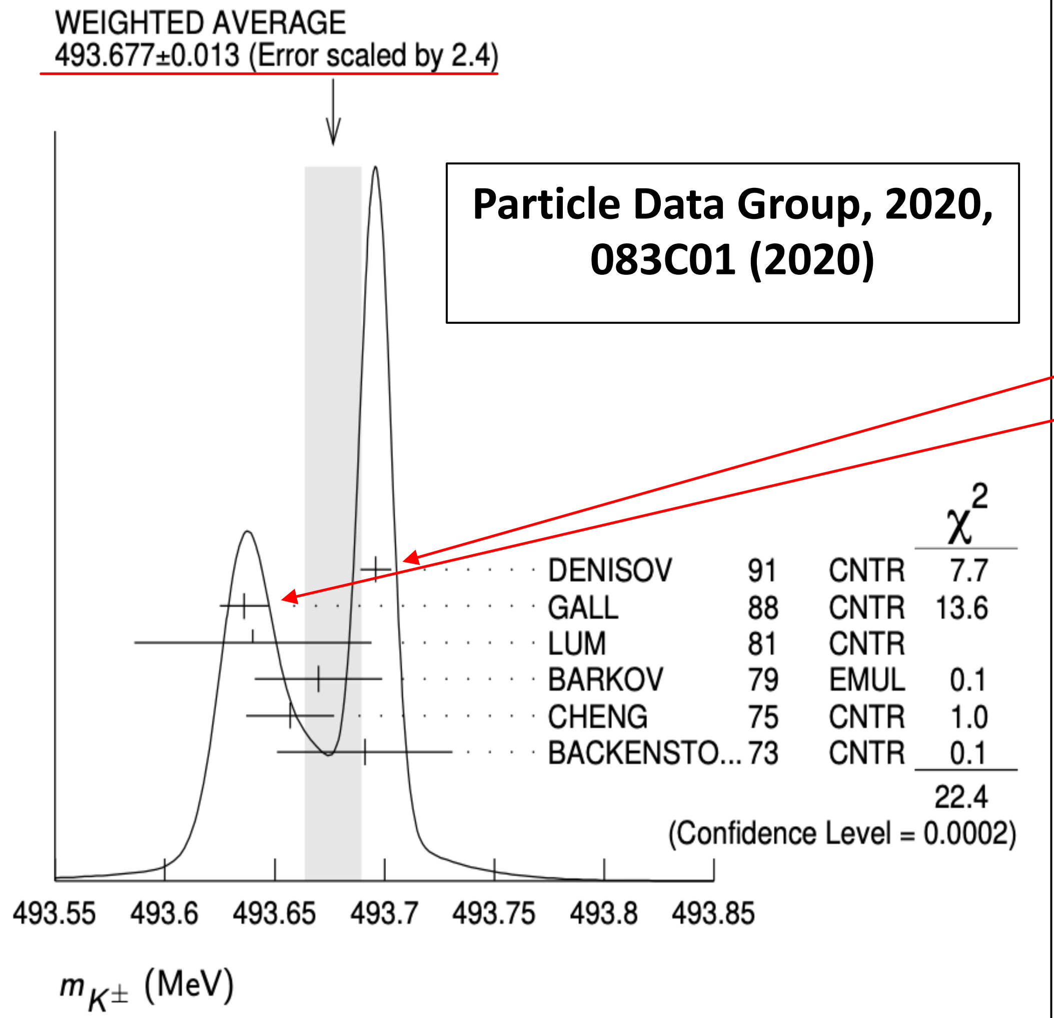
The charged kaon mass discrepancy

60 keV discrepancy between the two most accurate measurement



VALUE (MeV)	*DOCUMENT ID*	*TECN*	*CHG*	*COMMENT*
493.677±0.016 OUR FIT	Error includes scale factor of 2.8.			
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493.696±0.007	[1] DENISOV 91	CNTR	−	Kaonic atoms
493.636±0.011	[2] GALL 88	CNTR	−	Kaonic atoms
493.640±0.054	LUM 81	CNTR	−	Kaonic atoms
493.670±0.029	BARKOV 79	EMUL	±	$e^+e^- \rightarrow K^+K^-$
493.657±0.020	[2] CHENG 75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...73	CNTR	−	Kaonic atoms

Large uncertainty → 26 p.p.m,
compared to charged pion:
$m_\pi = 139.57061 \pm 0.00023$ MeV, 1.6 p.p.m

The charged kaon mass discrepancy

Severe consequences for nuclear and particle physics
and all the processes in which charged kaons are involved

- The uncertainty on the charged kaon mass leads to an error of 50 keV (σ) on the D^0 mass
- Large uncertainty on the charmonium spectrum, in particular on precise values of charm-anticharm meson thresholds
- A particular case is that of $D^0\overline{D}^{*0}$ which lies within the measured width of the best known candidate for a hadron-hadron molecule, the X(3872), an improved K-mass measurement would lead to a better interpretation of the X(3872), and of its radius.

C. Amsler, "Impact of the charged kaon mass on the charmonium spectrum", workshop, Frascati, 19 April 2021

- Impact on the K-N scattering lengths and sub eV measurement of K-nuclei interaction (kaonic atoms)

A new kaonic helium measurement in gas by SIDDHARTINO at the DAFNE collider
D. Sirghi, F. Sirghi, F. Sgaramella, et al., J.Phys.G 49 (2022) 5, 055106

Measurements of Strong-Interaction Effects in Kaonic-Helium Isotopes at Sub-eV Precision with X-Ray Microcalorimeters, J-PARC E62 Collaboration, Phys.Rev.Lett. 128 (2022) 11, 112503

Goal: solve the discrepancy and try to improve the kaon mass accuracy

GALL88

m_K = 493.636±0.011 MeV   K.P. Gall et al. Phys. Rev. Lett. 60 (1988)186

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

Experimental apparatus:

- Brookhaven National Laboratory Alternating Gradient Synchrotron
- Kaons of 680 MeV/c momentum
- Laminar target made of Pb and W
- 3 Ge detectors
- ^{57}Co, ^{133}Ba, ^{192}Ir and ^{132}Cs used as calibration source

TABLE II. Experimental mass measurements from each transition in megaelectronvolts. If the χ^2 per degree of freedom was greater than 1.0, the error listed with the weighted average is the statistical error scaled up by a factor of $(\chi^2/\nu)^{1/2}$.

Transition	M_{K^-}	Transition	M_{Σ^-}
K^-Pb(11 → 10)	493.675 ± 0.026	Σ^-Pb(14 → 13)	1197.731 ± 0.192
K^-Pb(9 → 8)	493.631 ± 0.007	Σ^-Pb(13 → 12)	1197.492 ± 0.098
K^-W(11 → 10)	493.806 ± 0.095	Σ^-Pb(12 → 11)	1197.412 ± 0.186
K^-W(9 → 8)	493.709 ± 0.073	Σ^-W(14 → 13)	1197.397 ± 0.396
		Σ^-W(13 → 12)	1197.388 ± 0.127
		Σ^-W(12 → 11)	1197.677 ± 0.109
Average	493.636 ± 0.011 χ^2/ν = 2.31	Average	1197.532 ± 0.057 χ^2/ν = 0.968

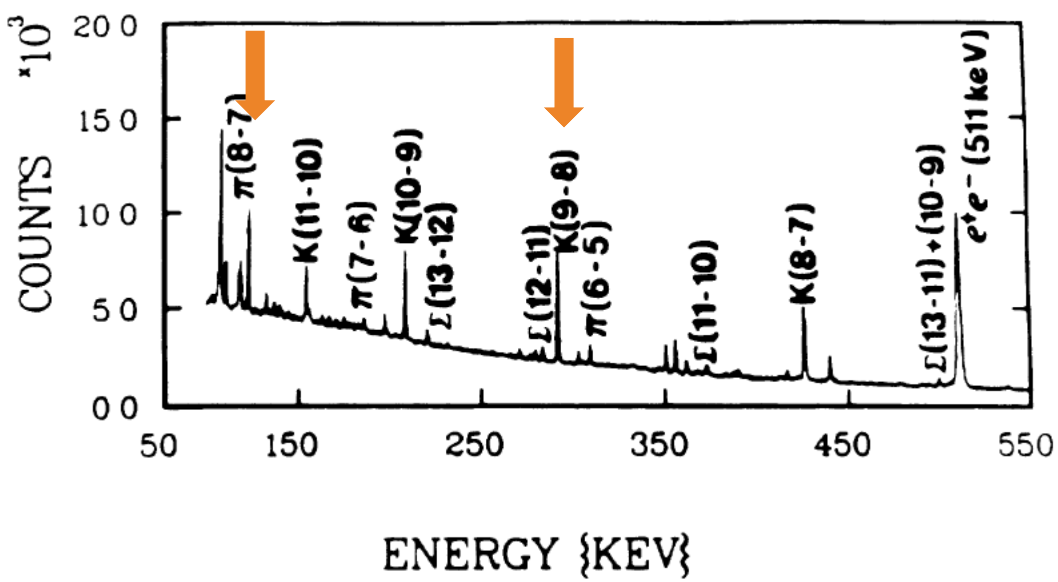


FIG. 1. Untagged Pb x-ray spectrum showing intense kaonic x-ray transitions.

DENISOV 91

m_K=493.696±0.007 MeV   A.S. Denisov et al. JEPT Lett. 54 (1991)558

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

Experimental apparatus:

- Proton synchroton of the Institute of High-Energy Physics
- Cauchois crystal diffraction spectrometer, high energy resolution (6.3 eV at 22 keV)
- Carbon target (4f→3d transition): negligible e- screening and strong interaction
- Light nucleus to reduce the probability for a superposition of γ-ray lines emitted when a K- is absorbed by a heavy nucleus
- Pionc carbon measurement was performed to validate the procedure

TABLE I. Calculated energies of the transitions with M_K = 493.6960 and M_π = 139.5688 MeV.

Component of transition energy	Value of component, Ev 4f–3d K^-–^{12}C	4d–2p π^-–^{12}C
Coulomb interaction	22033.941	24782.721
Vacuum polarization, $\alpha(Z\alpha)$	71.110	42.790
$\alpha^2(Z\alpha)$	0.496	0.314
$\alpha(Z\alpha)^3$	– 0.012	– 0.009
Strong interaction	0.009	2.850
Relativistic correction	0.085	0.047
Electron screening*	– 0.016	– 0.373
Polarization of nucleus	0.018	0.009
Finite dimensions of meson	– 0.004	– 0.002
Lamb shift	0.000	– 0.001
Nuclear recoil	– 0.022	– 0.028
Sum	22105.605	24828.318

*The correction was calculated for one 1s electron.

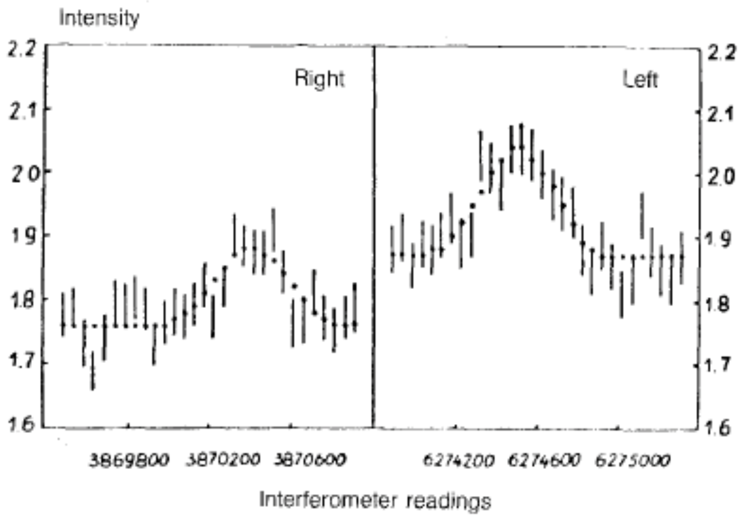


FIG. 1. Right and left reflections of the 4f–3d transition of the K^-–^{12}C atom. The interferometer readings are plotted along the abscissa; the detector count rate per 10^{12} protons is plotted along the ordinate. The vertical lines are the experimental values with the corresponding error; the heavy points are the results of a fit.

What is the correct value of kaon mass?

1. […] calculating transition energies in heavy atoms is a complicated task, since the higher-order quantum electrodynamics corrections must be taken into account, and the relatively large correction for electron screening must be calculated correctly
2. […] when a K- meson is absorbed by a heavy nucleus, a rich spectrum of γ-ray lines is emitted. When a semiconductor spectrometer with a resolution of about 1 keV is used, there is accordingly a significant probability for a superposition […]

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

The GALL 88 measurement uses a Ge semiconductor spectrometer which has a resolution of about 1 keV, so they run the risk of some contaminant nuclear γ rays. Studies of γ rays following stopped π^- and Σ^- absorption in nuclei (unpublished) do not show any evidence for contaminants according to GALL 88 spokesperson, B.L. Roberts. […]
The DENISOV 91 measurement is supported by their high-precision measurement of the 4d-2p transition energy in π^- 12C, which is good agreement with the calculated energy

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

While we suspect that the GALL 88 K− Pb (9 → 8) measurements could be the problem, we are unable to find clear grounds for rejecting it. Therefore, we retain their measurement in the average and accept the large scale factor until further information can be obtained from new measurements and/or from reanalysis of GALL 88 and CHENG 75 data.

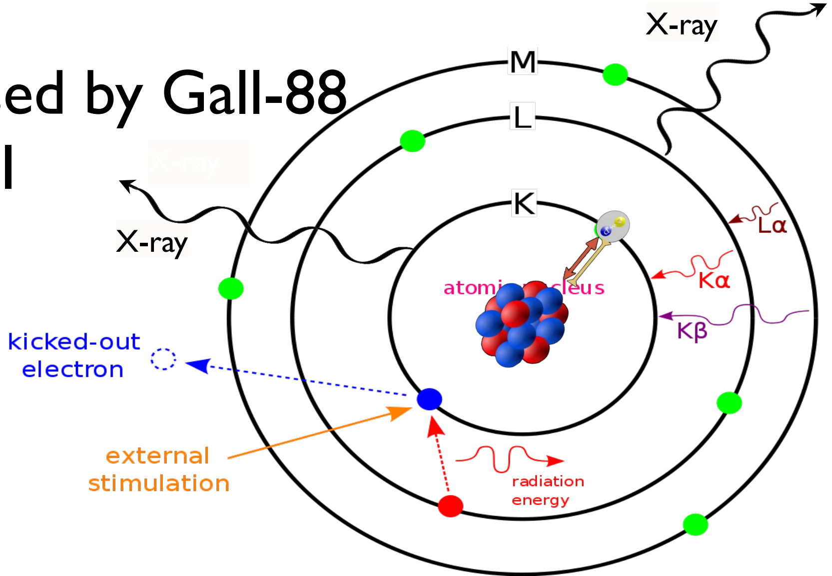
P.a. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

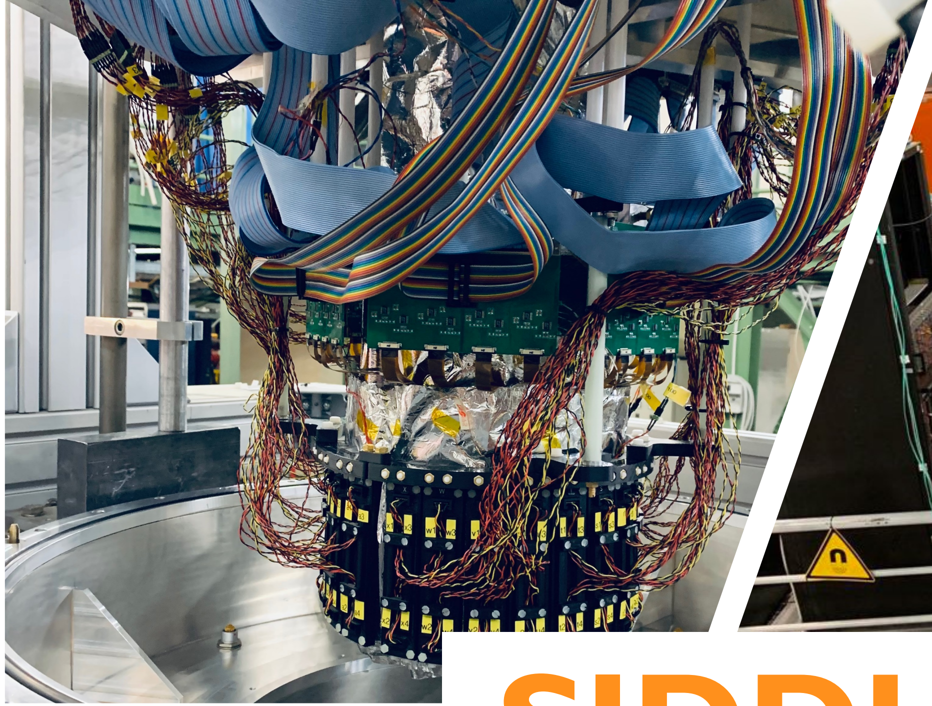
How can we solve the kaon mass puzzle?

Kaonic atom X-ray spectroscopy

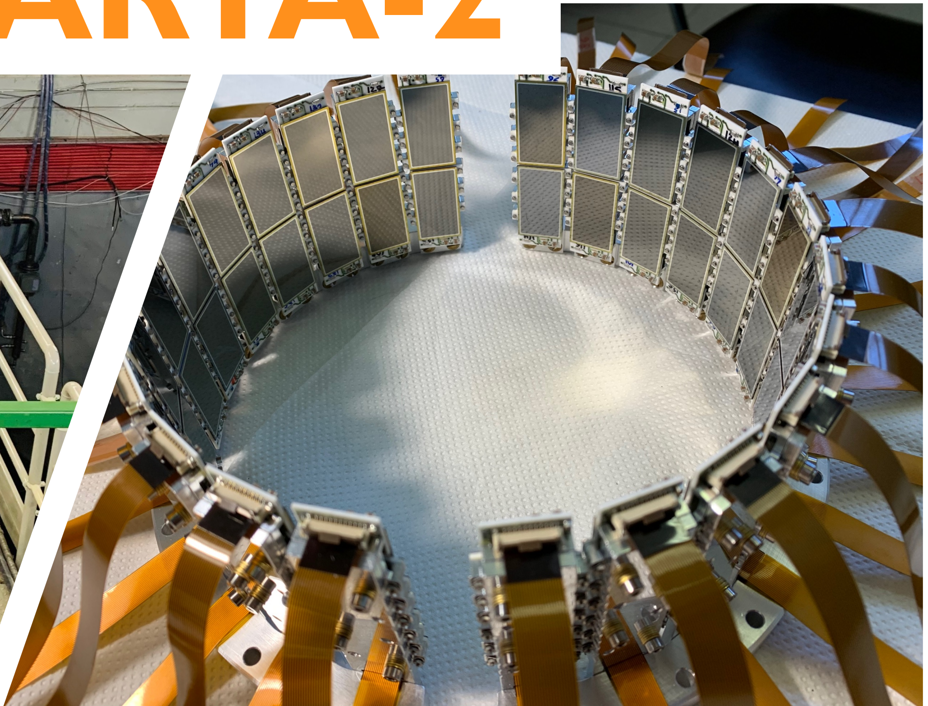
Repeat the kaonic lead and kaonic carbon measurement
with the same technique used by Gall-88 and Denisov-91

Using new state-of-the-art detectors and different type of target



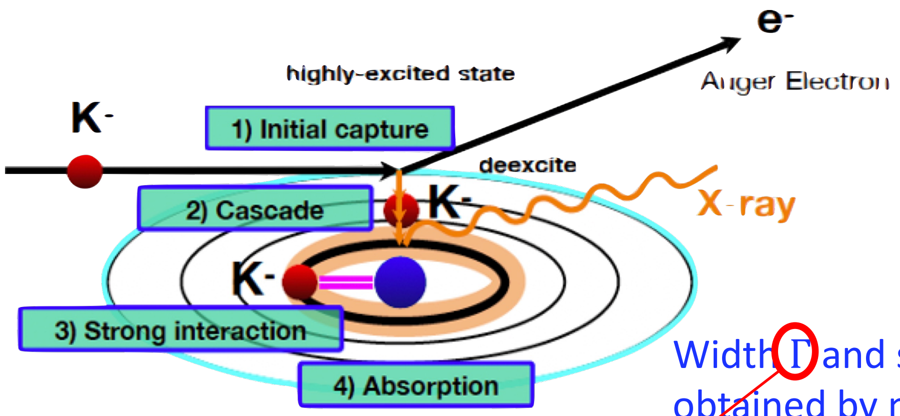


SIDDHARTA-2

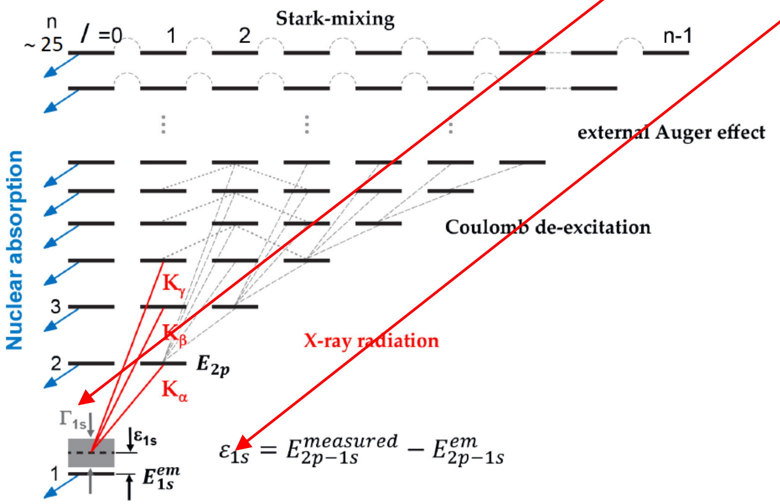


The SIDDHARTA-2 experiment

Scientific goal: *first measurement ever of kaonic deuterium X-ray* transition to the ground state (1s-level) such as to determine its shift and width induced by the presence of the strong interaction, providing unique data to investigate the QCD in the non-perturbative regime with strangeness.



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



$$\varepsilon_{1s} = E^{measured}_{2p-1s} - E^{em}_{2p-1s}$$

Combined analysis of the kaonic deuterium and kaonic hydrogen measurements

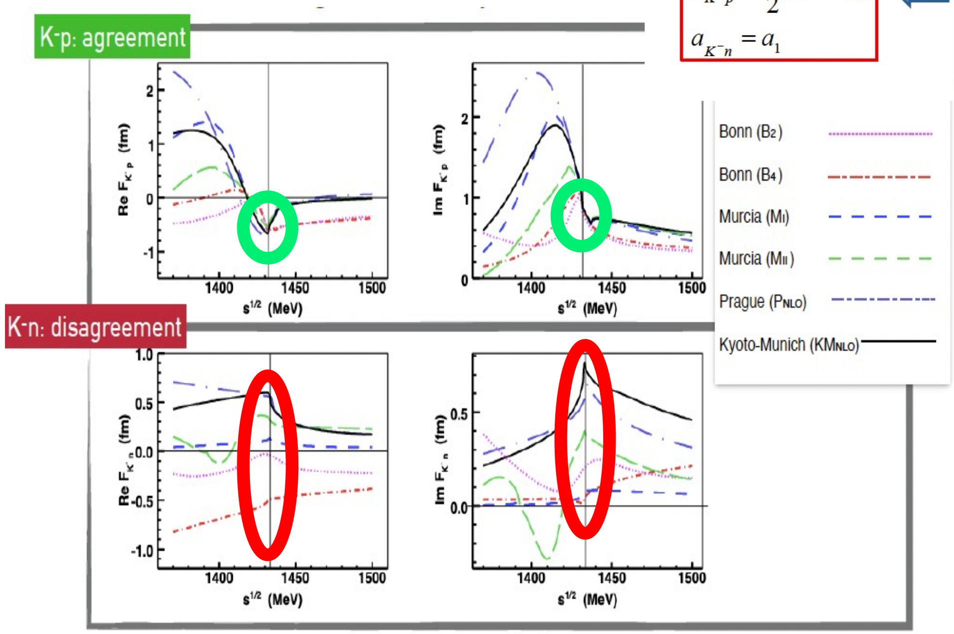
$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = -2\alpha^3\mu_c^2 a_{K^-p}\left(1 - 2\alpha\mu_c(\ln\alpha - 1)a_{K^-p}\right)$$

(μ_c reduced mass of the K^-p system, α fine-structure constant)

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

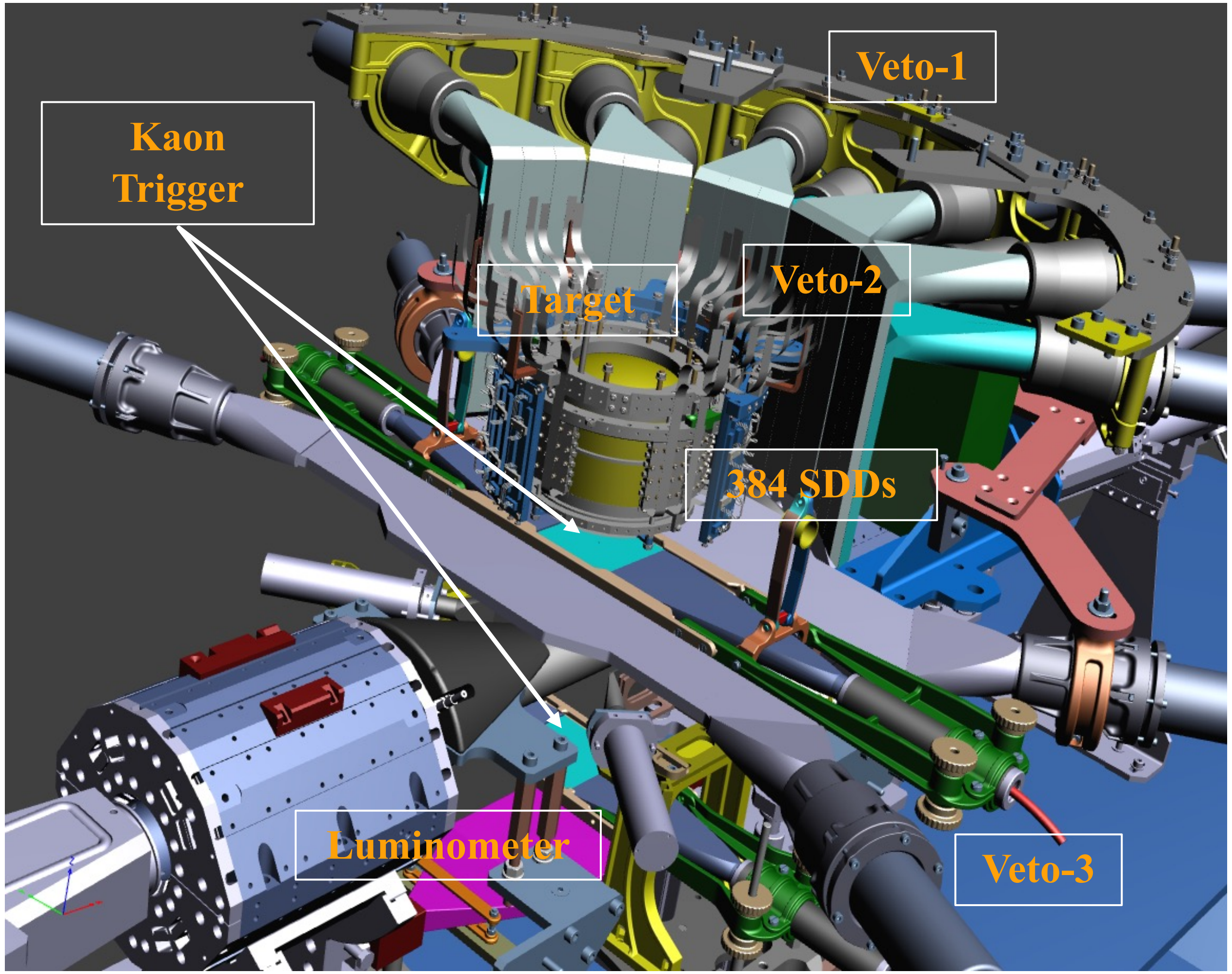
$$a_{K^-p} = \frac{1}{2}[a_0 + a_1] \qquad a_{K^-n} = a_1$$

$$a_{K^-d} = \frac{k}{2}[a_{K^-p} + a_{K^-n}] + C = \frac{k}{4}[a_0 + 3a_1] + C \qquad k = \frac{4[m_n + m_K]}{[2m_n + m_K]}$$



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

The SIDDHARTA-2 setup and DAΦNE collider



- $\Phi \rightarrow K^- K^+$ (48.9%)
- Monochromatic low-energy K^- (~127 MeV/c ; $\Delta p/p = 0.1\%$)
- Less hadronic background compared to hadron beam line

The kaonic deuterium measurement

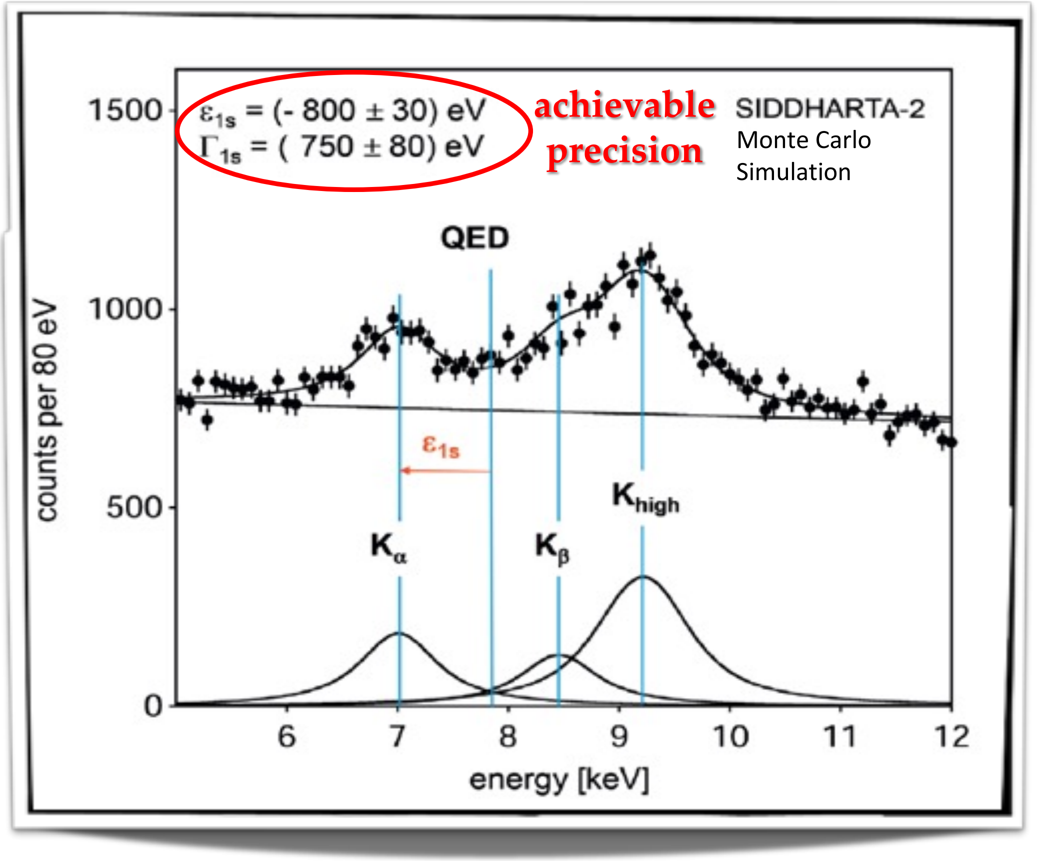
- First run with SIDDHARTA-2 optimized setup for 200 pb^{-1} integrated luminosity: May – July 2023 completed
- Second run Autumn – Winter 2023 goal: 300 pb^{-1} on going
- Third run 2024 – goal: 300 pb^{-1}
- Calibration runs: Kaonic He; Kaonic Ne;

Kaonic deuterium run ongoing

2023/24

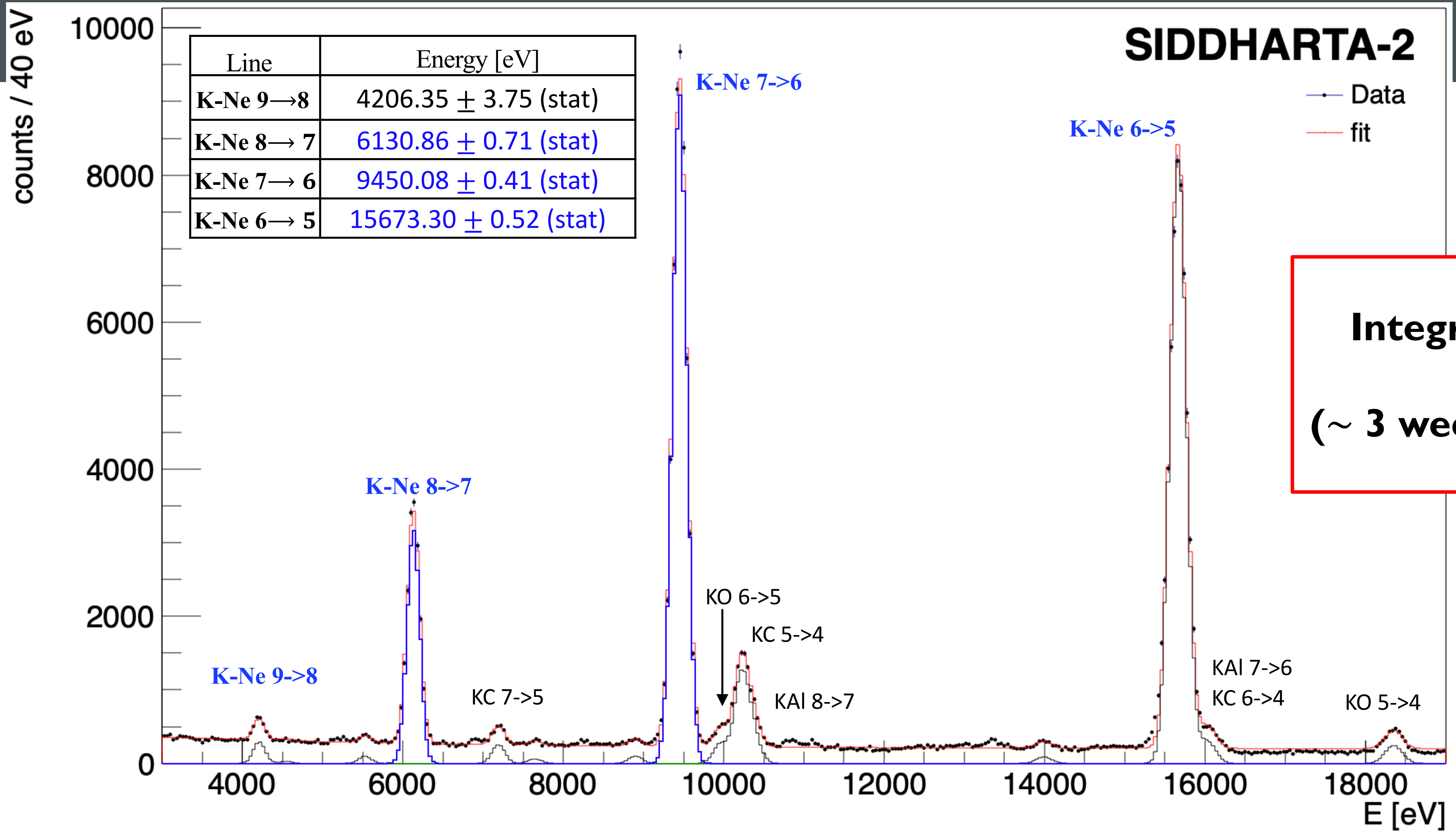
Monte Carlo for an integrated luminosity of 800 pb^{-1}

to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as K-p) !



The Kaonic Neon measurement

First measurement of kaonic neon X-ray transitions



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

Integrated luminosity
120 pb^{-1}
(~ 3 weeks of data taking)

The (charged) Kaon mass puzzle

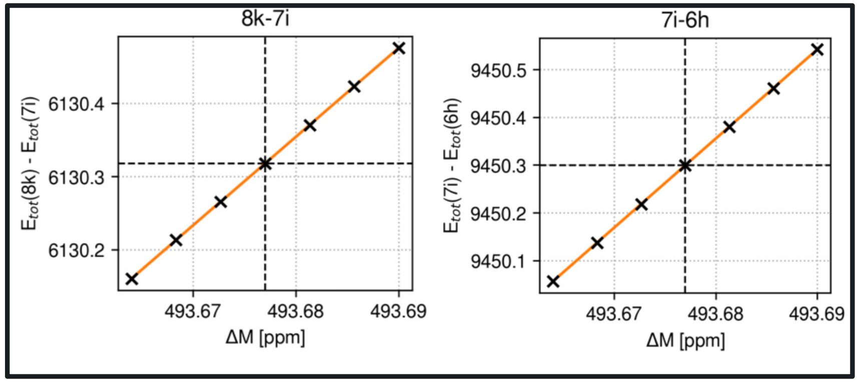
Kaon mass (K-Ne 8 ⟶ 7and K-Ne 7 ⟶ 6) = 493.671 ± 0.021 (stat) MeV
(stat. error ~ 15 keV including the K-Ne 6 ⟶ 5)

The kaonic Neon measurement to determine the K^- (K^+) mass

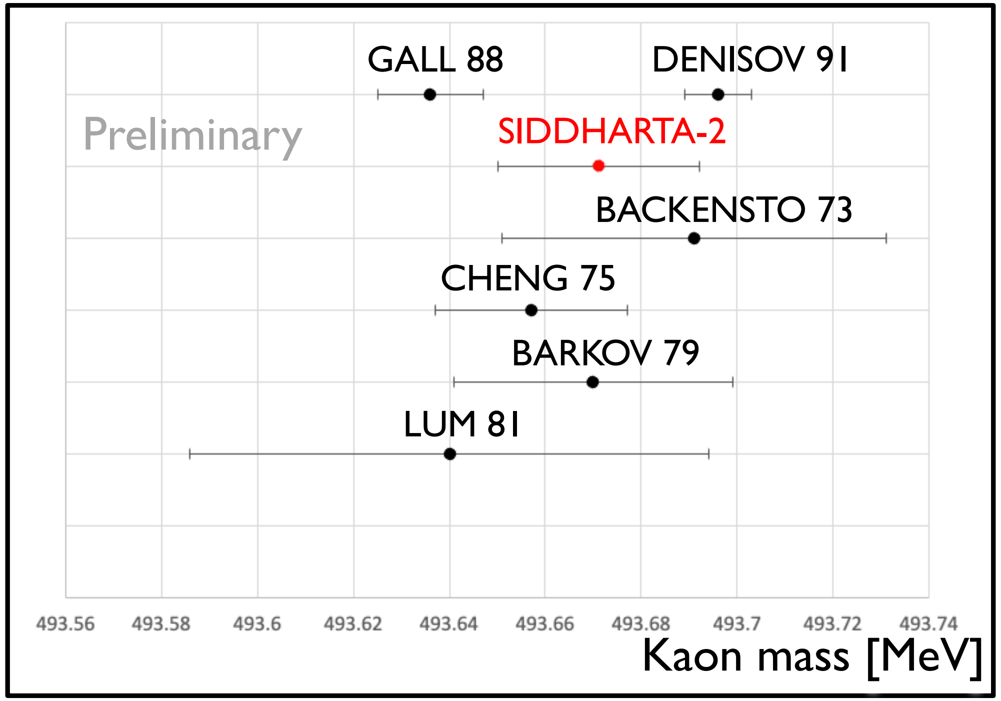
Less/different systematic uncertainty with respect to DENISOV 91 and GALL 88 measurements, thanks to the use of a low Z gas target

It could solve the kaon mass discrepancy issue

kaonic Ne energy transition as function of kaon mass



Santos, J. & Parente, F. & Indelicato, Paul & Desclaux, J.. (2005). X-ray energies of circular transitions and electron screening in kaonic atoms. Physical Review A. 71. 10.1103/PhysRevA.71.032501.



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493.657±0.020	[2] CHENG	75	CNTR	−	Kaonic atoms
493.691±0.040	BACKENSTO...	73	CNTR	−	Kaonic atoms

Particle Data Group, 2020, 083C01 (2020)

Exploiting DAΦNE

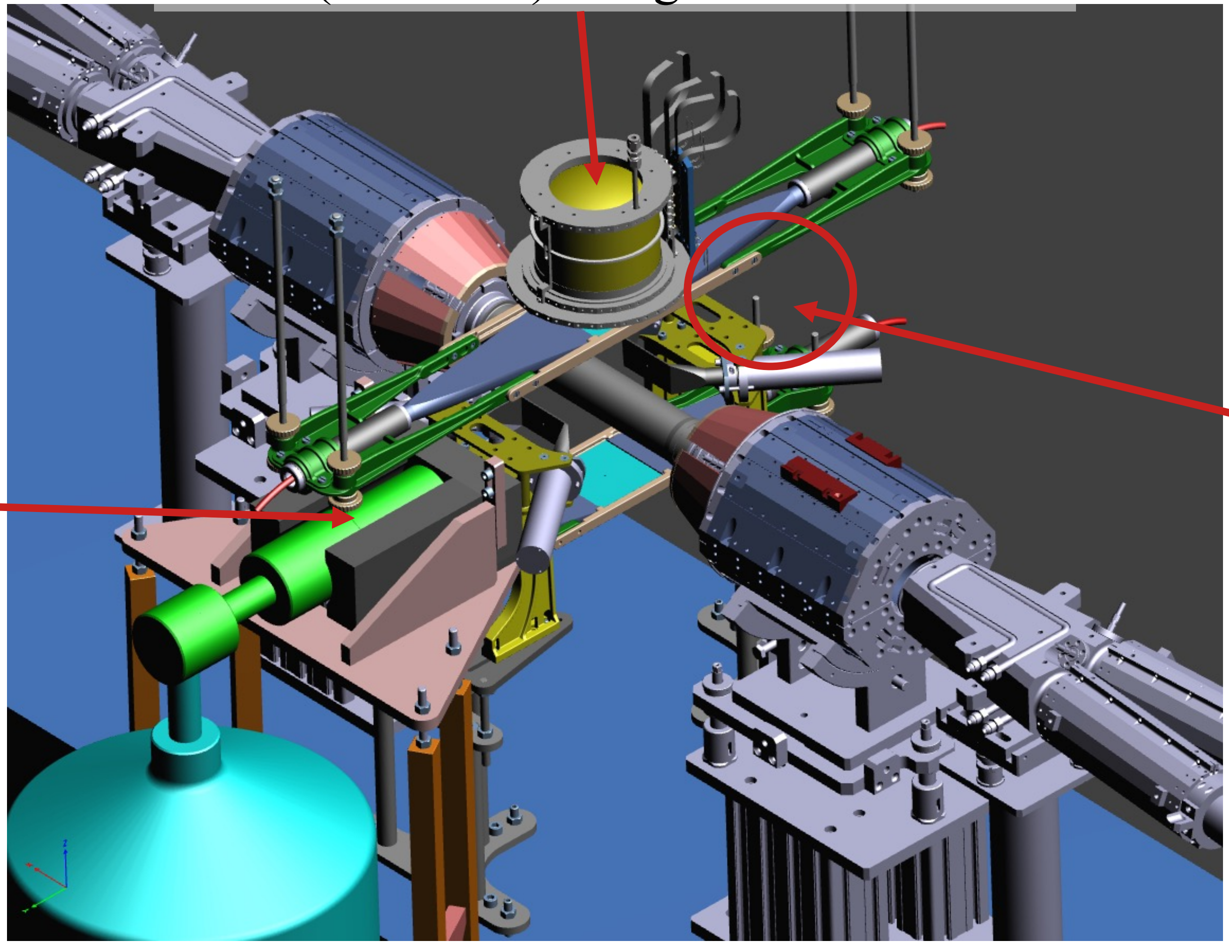
DAΦNE delivers almost 4π K^-

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

SDDs (4-15 keV) - Light Kaonic Atoms

HPGe
(0,1-1 MeV)

Heavy Kaonic Atoms

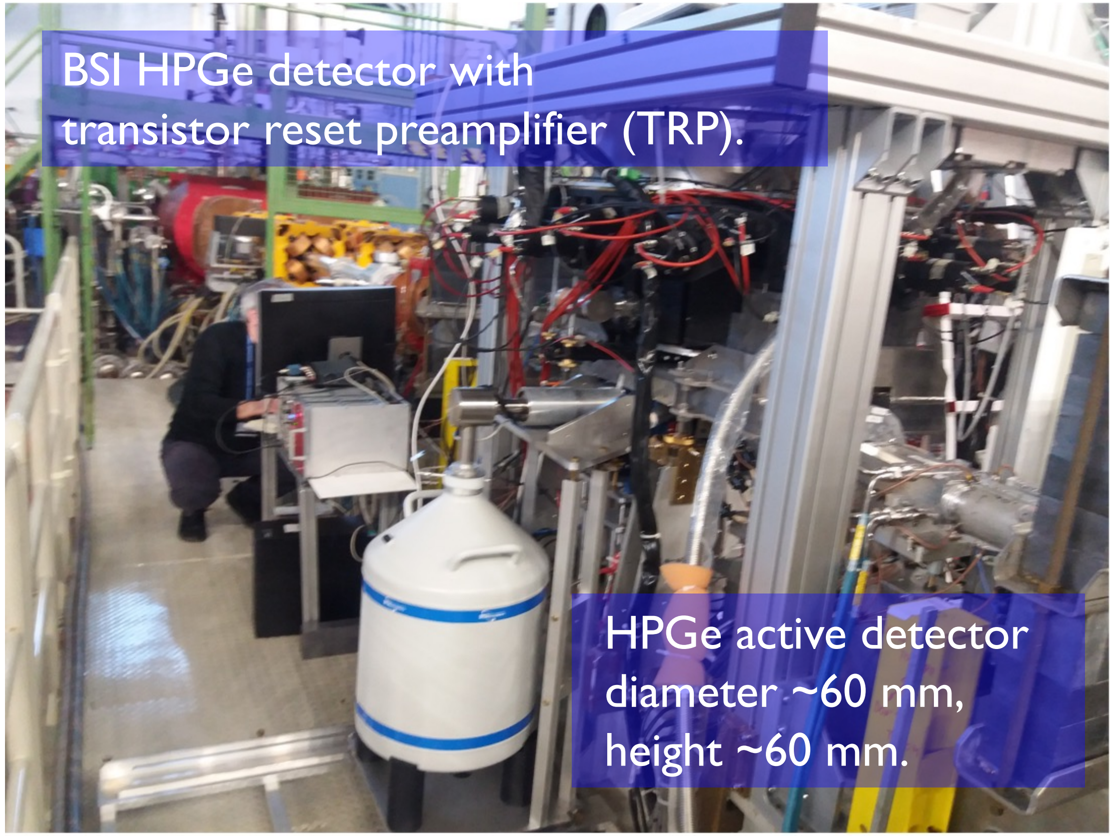


CdZnTe
(30-300 keV)

Intermediate Kaonic Atoms

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



3.1. Detection unit GCD-30185 characteristics

#	Parameter	Value
1.	Relative efficiency (with respect to 3'' x 3'' NaI detector and Co-60 source mounted 25 cm above the detector) at 1.33 MeV γ-photon	> 30 %
2.	Energy resolution* at • 122 keV • 477.6 keV • 1.33 MeV **Measured with spectrometric device MS Hybrid at input count rate 1000 pulses/sec, shaping time constant = 6 μsec*	875 eV 1400 eV 1850 ± 30 eV
3.	Peak shape: • FWTM/FWHM • FW.02M/FWHM	< 1.9 < 2.65
4.	Spectral Broadening of FWHM up to 100,000 counts/sec for 1.33 Mev	< 8 %
5.	Peak position shift	< +/- 0.018 %
6.	Peak to Compton ratio, not worse	58 : 1
7.	Energy range of detector operation	40 keV – 3 MeV
8.	Material of input window	Al
9.	Cooling time	< 8 hours
10.	Liquid nitrogen holding time in Dewar vessel	> 15 days
11.	Dewar volume	30 l
12.	Preamplifier (built – in detector capsule) with cooled FET and transistor reset preamplifier (TRP) • Preamplifier power supply is ±12 V with 9 pin connector compatible with NIM standards • TTL signal to shut down the HV: - detector warm -0V; - detector cold: +5V • HV INHIBIT – BNC	

The Kaonic Lead Measurement

First run performed in June - July 2023 (109 pb^{-1})

Preliminary

- (10 -> 9) : 906 events in peak (integration of fitting function gaus+linear)

  position 209.191 ± 0.171 keV; $\sigma/\sqrt{N}$ = 0.0057 keV

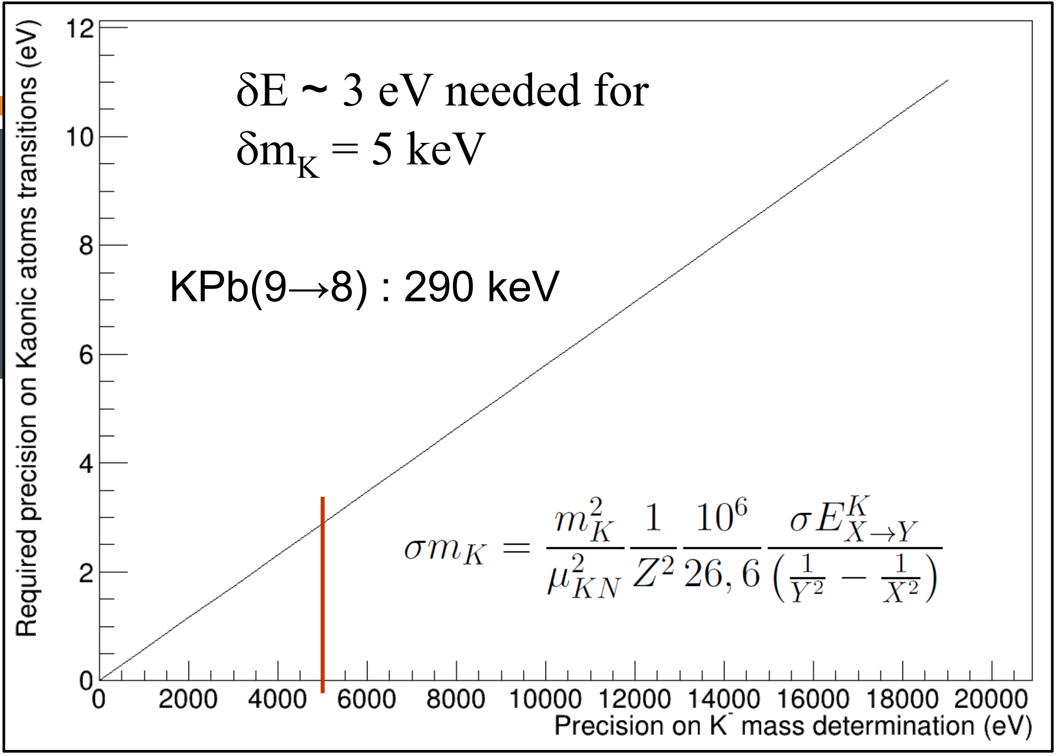
- (9 -> 8) : 947 events in peak (integration of fitting function gaus+linear)

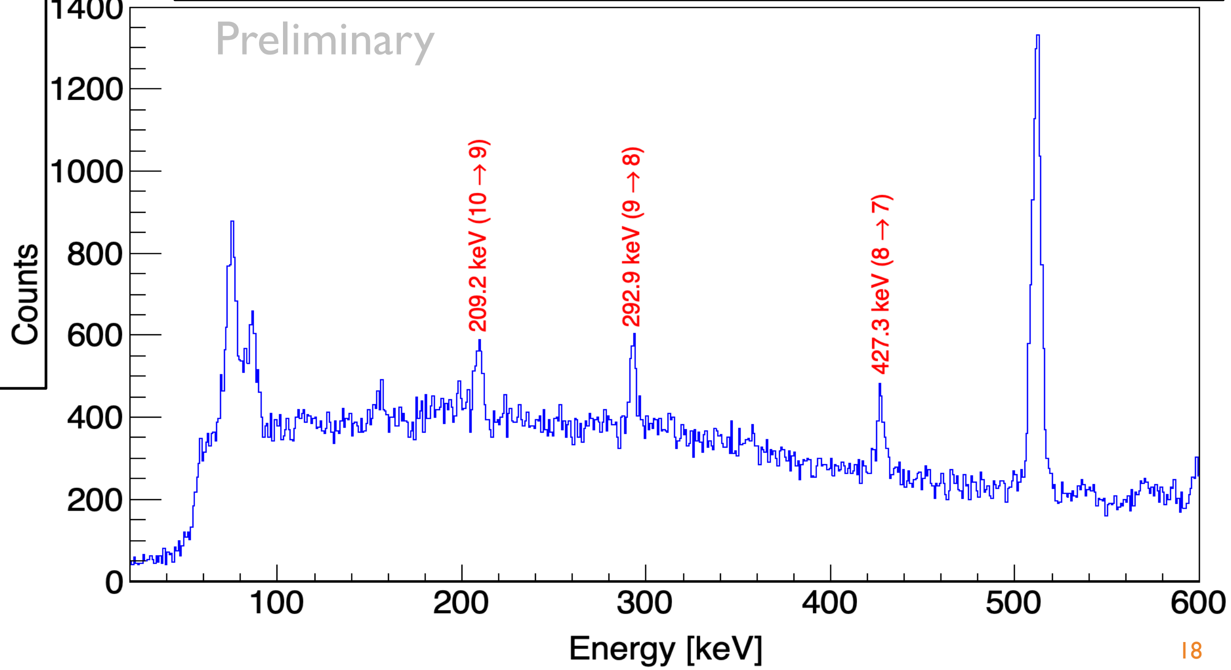
  position 292.939 ± 0.134 keV; $\sigma/\sqrt{N}$ = 0.0044 keV

- (8 -> 7) : 943 events in peak (integration of fitting function gaus+linear)

  position 427.2 ± 0.152 keV; $\sigma/\sqrt{N}$ = 0.0049 keV

Ivica Friščić (and SIDDHARTA-2 collaboration) -
Mini workshop on kaonic atoms: present status and future plans,
18th July 2023

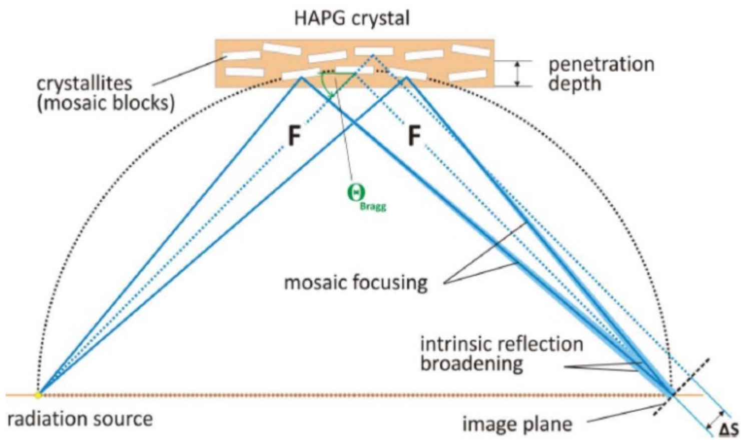




The Kaonic Carbon Measurement

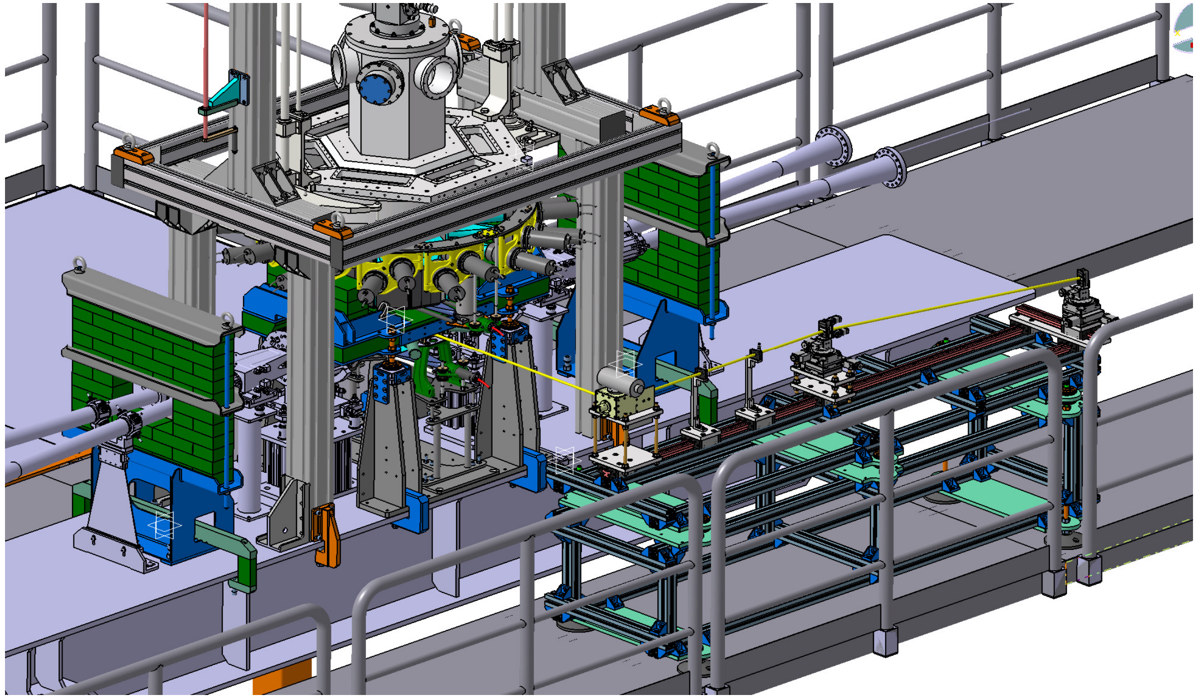
3 different option:

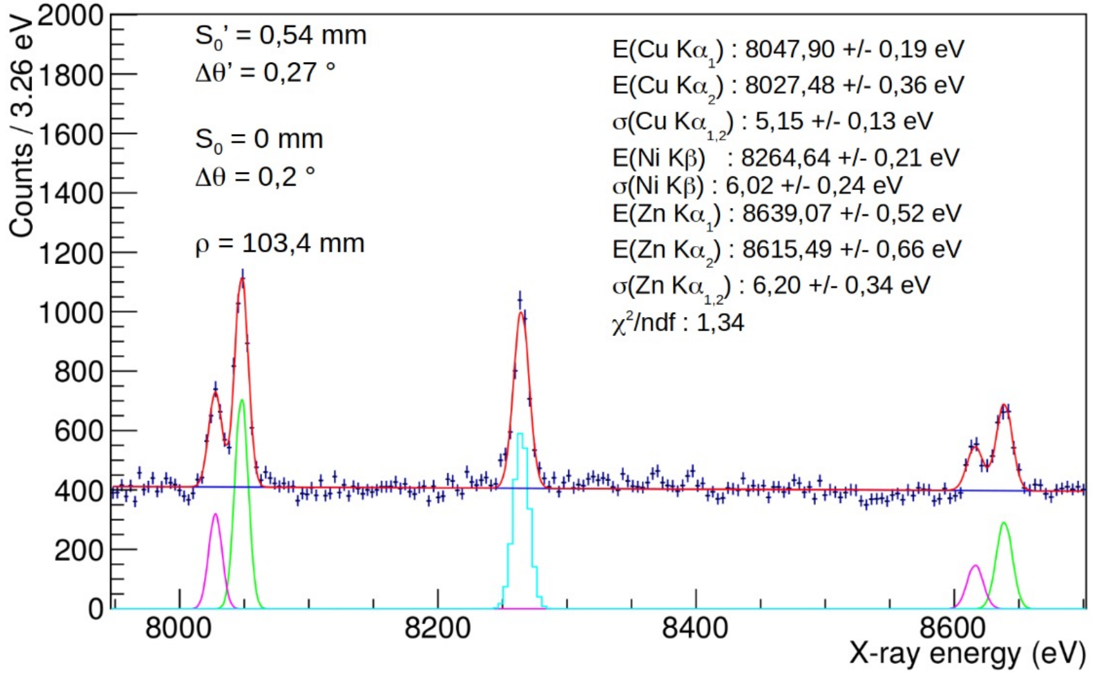
VOXES spectrometer



HAPG mosaic crystals in Von Hamos configuration:

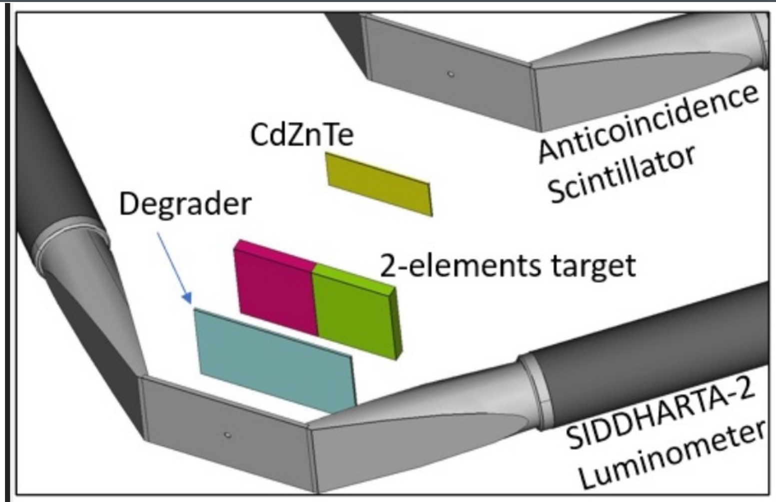
- Higher intrinsic reflectivity wrt standard crystals
- VH configuration to exploit sagittal focusing
- Optical optimisation to work with milli/centimetric sources

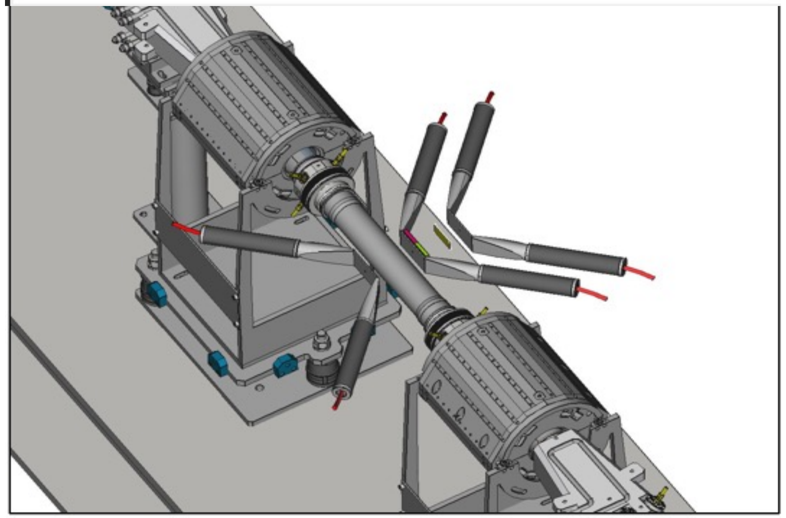




The Kaonic Carbon Measurement

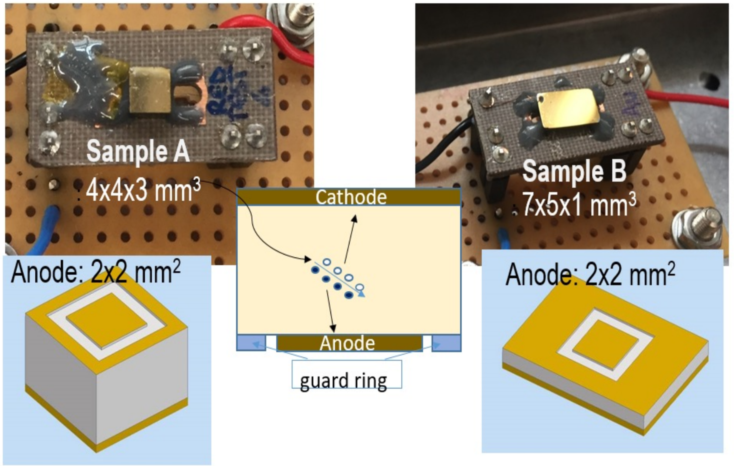
3 different option:
CdZnTe detectors,
developed in collaboration with University of Palermo





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



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

The Kaonic Carbon Measurement

3 different option:

SIDDHARTA-2 Silicon Drift Detectors

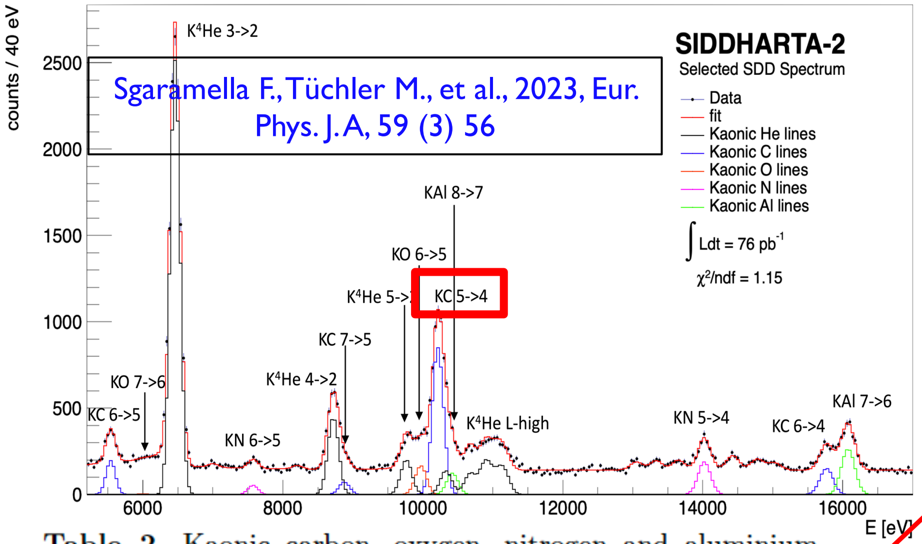
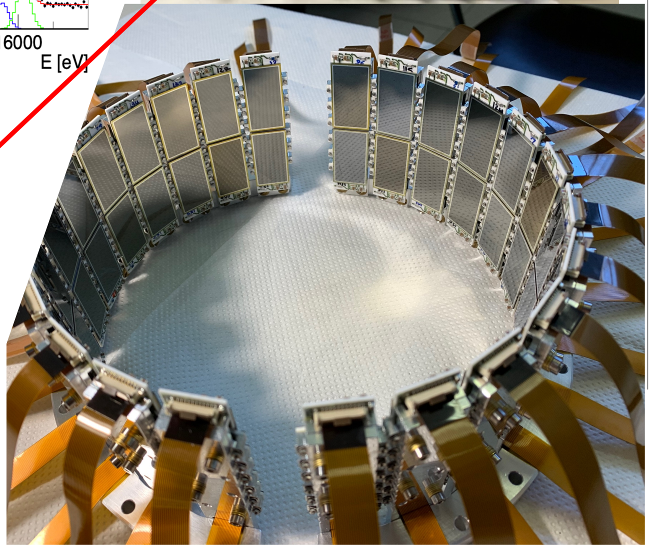
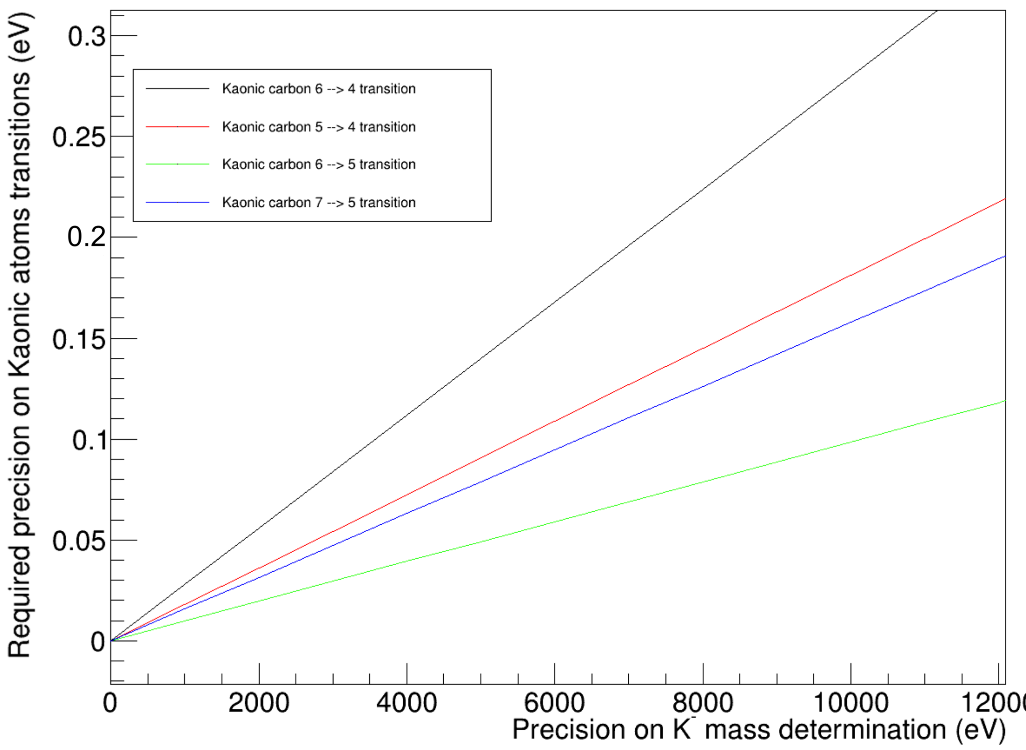


Table 2. Kaonic carbon, oxygen, nitrogen and aluminium transition energies from the fit of the data in Fig. 6.

Transition	Energy (eV)
K^-C (6→5)	5541.7 ± 3.1 (stat) ± 2.0 (syst)
K^-C (7→5)	8890.0 ± 13.0 (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)	6016.0 ± 60.0 (stat) ± 2.0 (syst)
K^-O (6→5)	9968.1 ± 6.9 (stat) ± 2.0 (syst)
K^-N (6→5)	7577.0 ± 17.0 (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)

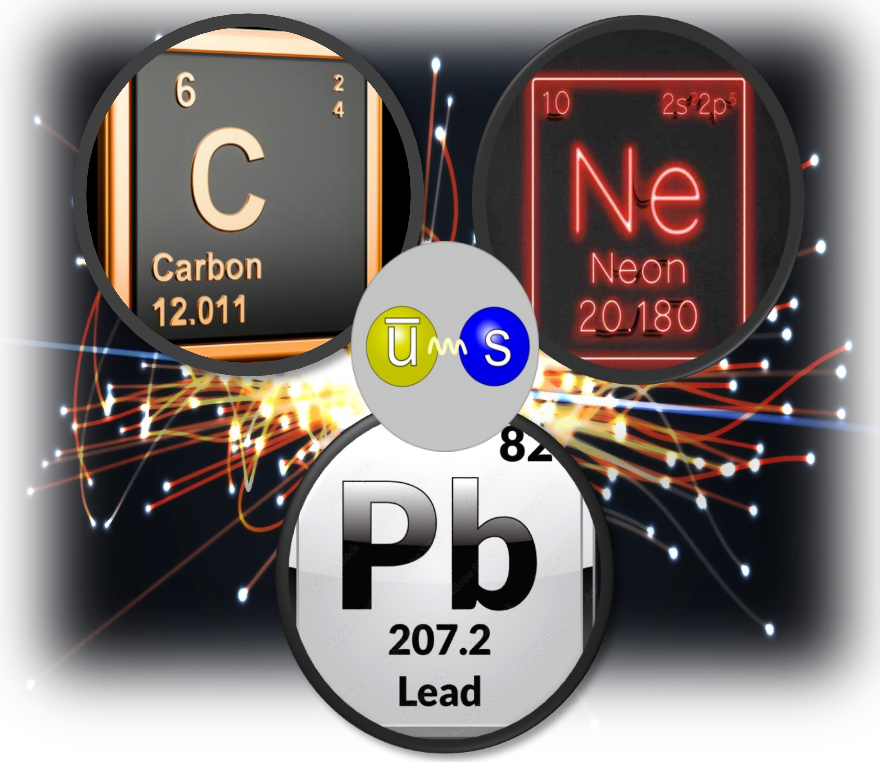




Conclusion

- The two most precise measurement of the charged kaon mass are not compatible

- The discrepancy of 60 keV leads to an error of 13 keV on the kaon mass with consequences on:
  1. The D^0 mass (error of 50 keV)
  2. The charmonium spectrum and the X(3872)
  3. High precision (<1 eV) measurement of kaonic atoms transition

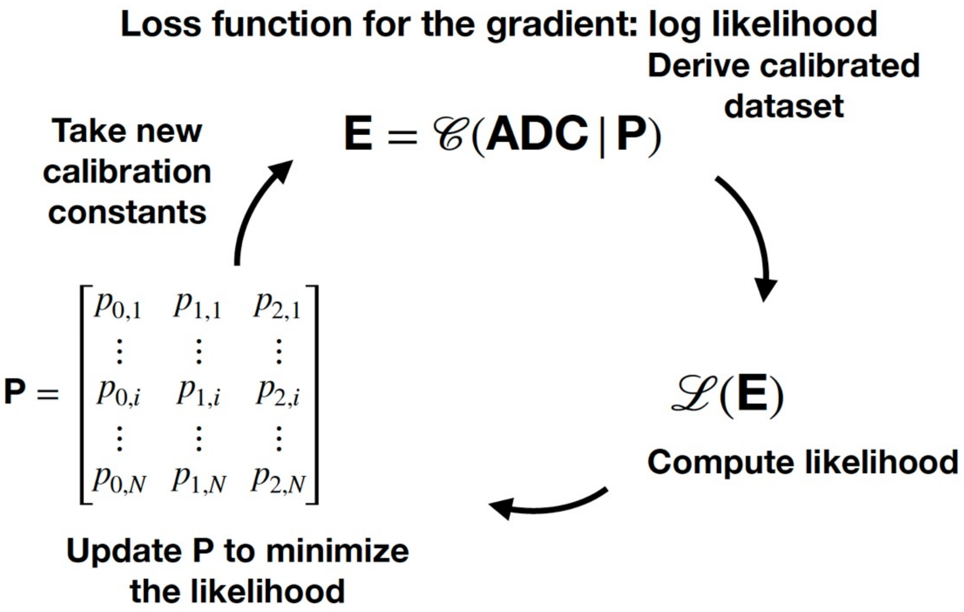


- Nowadays we have state-of-the-art X-ray detectors, and high quality kaon source (DAΦNE and J-PARC), to solve the kaon mass puzzle

- The SIDDHARTA-2 collaboration is performing 3 new kaon mass measurements in parallel with the kaonic deuterium measurement :
  - Kaonic Neon → $m_K = 493.671 \ \pm 0.021\ (stat)\ MeV$ (preliminary)
  - Kaonic Lead with HPGe → data taking on going
  - Kaonic Carbon with CdZnTe → detectors successfully tested in DAΦNE, the data taking will start soon

SPARE SLIDES

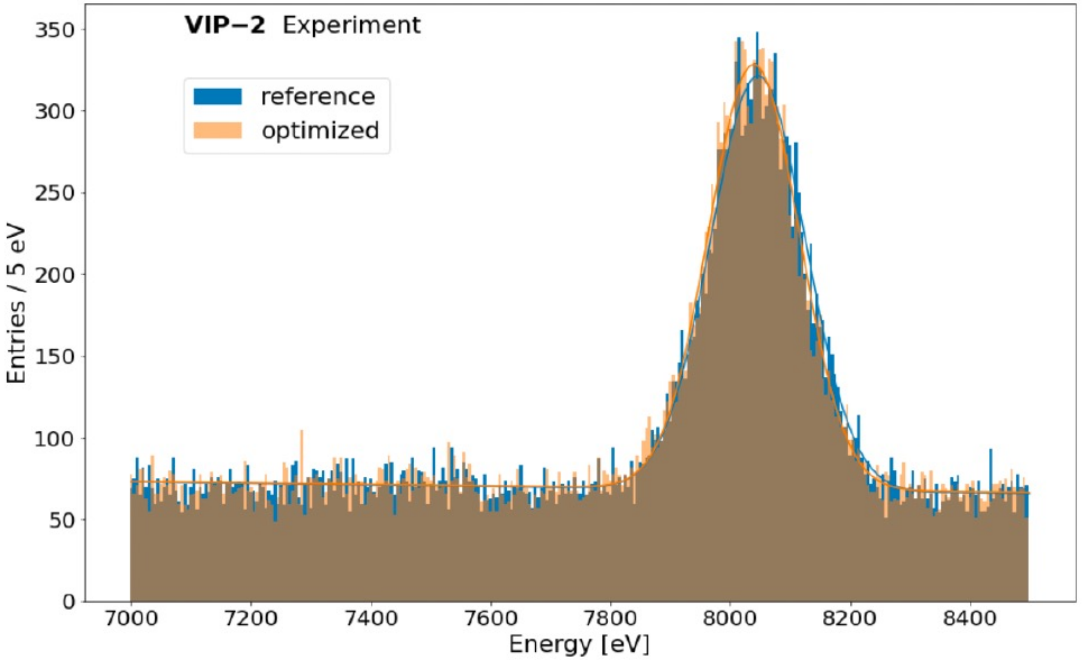
SDD energy calibration
with ML and Differential Programming



	Position [eV]	FWHM [eV]	χ^2/ndf
Reference	8050 ± 1	185 ± 2	1.64
Optimized	8048 ± 1	176 ± 2	1.25

F. Napolitano et al. paper accepted for publication on Meas. Sci. and Tech.

The method can correct for miscalibration improving the systematic error



SDDS INCLUSIVE ENERGY SPECTRUM