NEW EXOTICA: NEW FRONTIERS IN EXOTIC ATOMS: HIGH-PRECISION TESTS OF QCD AND QED AND PROBES OF BEYOND STANDARD MODEL PHYSICS



Kaonic Atom X-ray Spectroscopy with SIDDHARTA-2: from strong interactions to fundamental physics

Diana Laura Sirghi

INFN-LNF

on behalf of SIDDHARTA-2 collaboration

12-16 October 2026
ECT*, Trento, Italy

Hadronic Atoms as Precision Probes of the Strong Interaction

The strong interaction, described by QCD within the Standard Model, plays a fundamental role in understanding the structure and stability of matter.

Subatomic structure

Hadron masses and spectroscopy
Nucleon–nucleon forces

QCD symmetries

Chiral symmetry breaking
SU(3) symmetry breaking

Astrophysics

Dense baryonic matter
Neutron-star composition

The low energies QCD -> poorly understood direct experimental constraints are essential.

Hadronic atoms

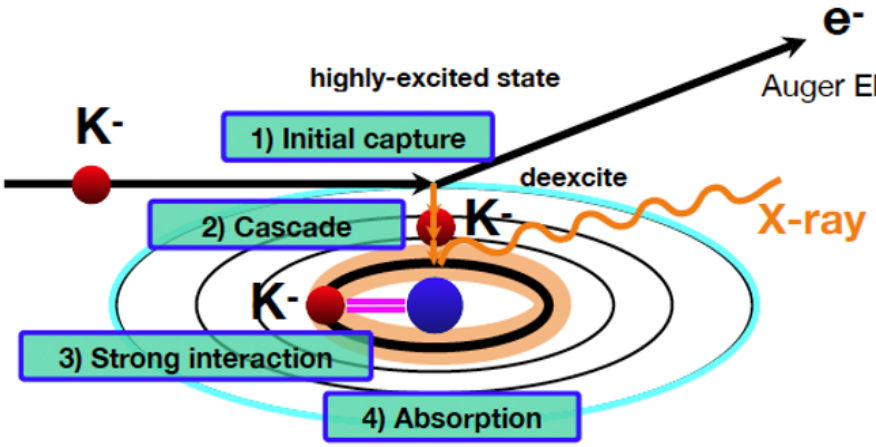
- Negatively charged hadron in an atomic orbit
- Atomic X-ray transitions are shifted and broadened by the strong interaction
- powerful tool for studing the low-energy strong interaction with high precision

Kaonic atoms

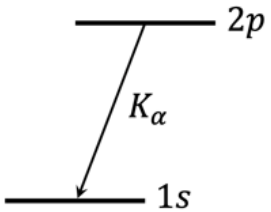
- Contain an antikaon with a **strange quark**
- Direct experimental probe of QCD in the strangeness sector
- Sensitive to kaon–nucleon and kaon–nucleus interactions

Kaonic Atoms X-ray Spectroscopy

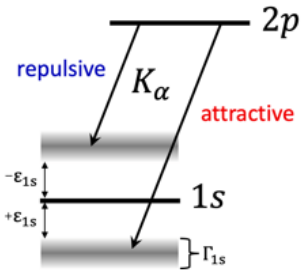
Kaonic atom formation



Purely electromagnetic

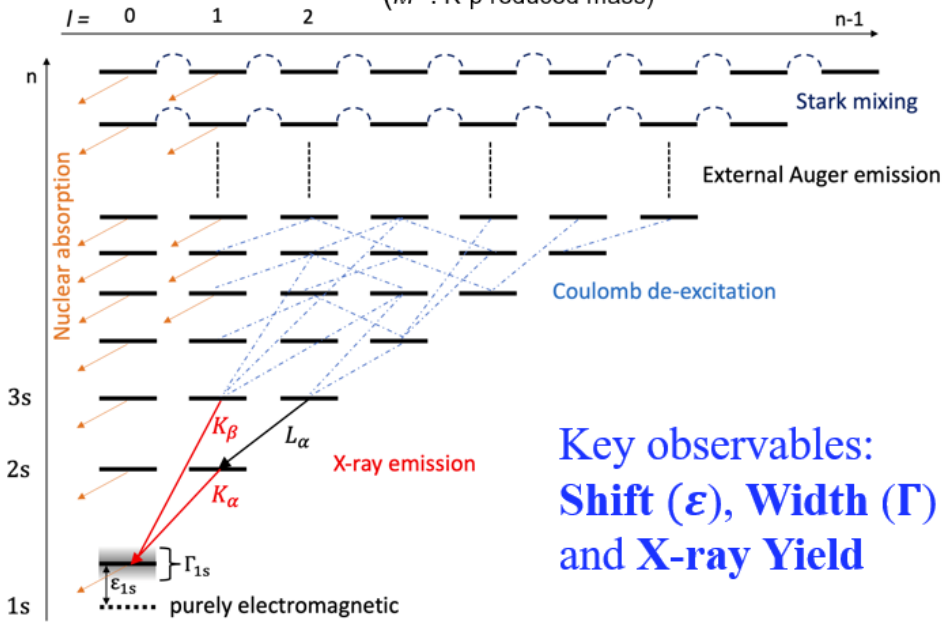


Electromagnetic + strong interaction



$$\varepsilon_{1s} = E^{2p-1s}_{\text{meas}} - E^{2p-1s}_{e.m.}$$

n ~ sqrt(*M*/m*e) *n'* ~ 25 (for K-p)
(*M**: K-p reduced mass)



Key observables:
Shift (ε), Width (Γ)
and **X-ray Yield**

Importance of kaonic atom studies

Atomic binding energies of **light systems are in the keV range**, namely the kaon interacts with the nucleus with a relative energy of few keV, instead of the **tens of MeV, as in the performed low-energy scattering experiments.**

atom	m (MeV/c^2)	μ (MeV/c^2)	B_1s (keV)	interaction
e^-p	0.511	0.511	13.6×10^{-3}	Electroweak
μ^-p	105.7	95.0	2.53	Electroweak
π^-p	139.6	121.5	3.24	Electroweak + strong
K^-p	**493.7**	**323.9**	**8.61**	**Electroweak + strong**
$\bar{p}p$	938.3	469.1	12.5	Electroweak + strong

Kaonic atoms: a unique opportunity to perform experiments equivalent to scattering at vanishing relative energies

Special role played by lightest kaonic atoms

Determination of the antikaon–nucleon/nucleus interaction at "threshold", without the need of extrapolation to zero relative energy.

Determined isospin dependent KN scattering lengths are key ingredients for all models and theories dealing with low-energy QCD in systems with strangeness

Light kaonic atoms

Low-energy observables from the lightest systems

Kaonic hydrogen isotopes → **basic low-energy parameters: antikaon–nucleon scattering lengths**

Kaonic deuterium → **antikaon–neutron system**

Other light kaonic atoms → **construct the antikaon–nucleus interaction from elementary reactions**

Light exotic atoms are formed almost “electron-free”

high-precision measurements, due to the absence of electron screening effect

Studies of Kaonic Atoms as Precision Probes: Experimental Challenges

1. Antikaon Sources

Significant Technical and scientific challenges for kaonic atoms experiments:

Intense kaon beams
enable efficient stopping and formation of kaonic atoms

→

Precise X-ray spectroscopy
resolves shifts and widths of atomic transitions

→

Background suppression
extracts weak signals in a high-rate environment

New kaon beams with excellent characteristics are the first necessary ingredient for precision kaonic-atom experiments.

Experimentally - kaonic atoms are explored at:

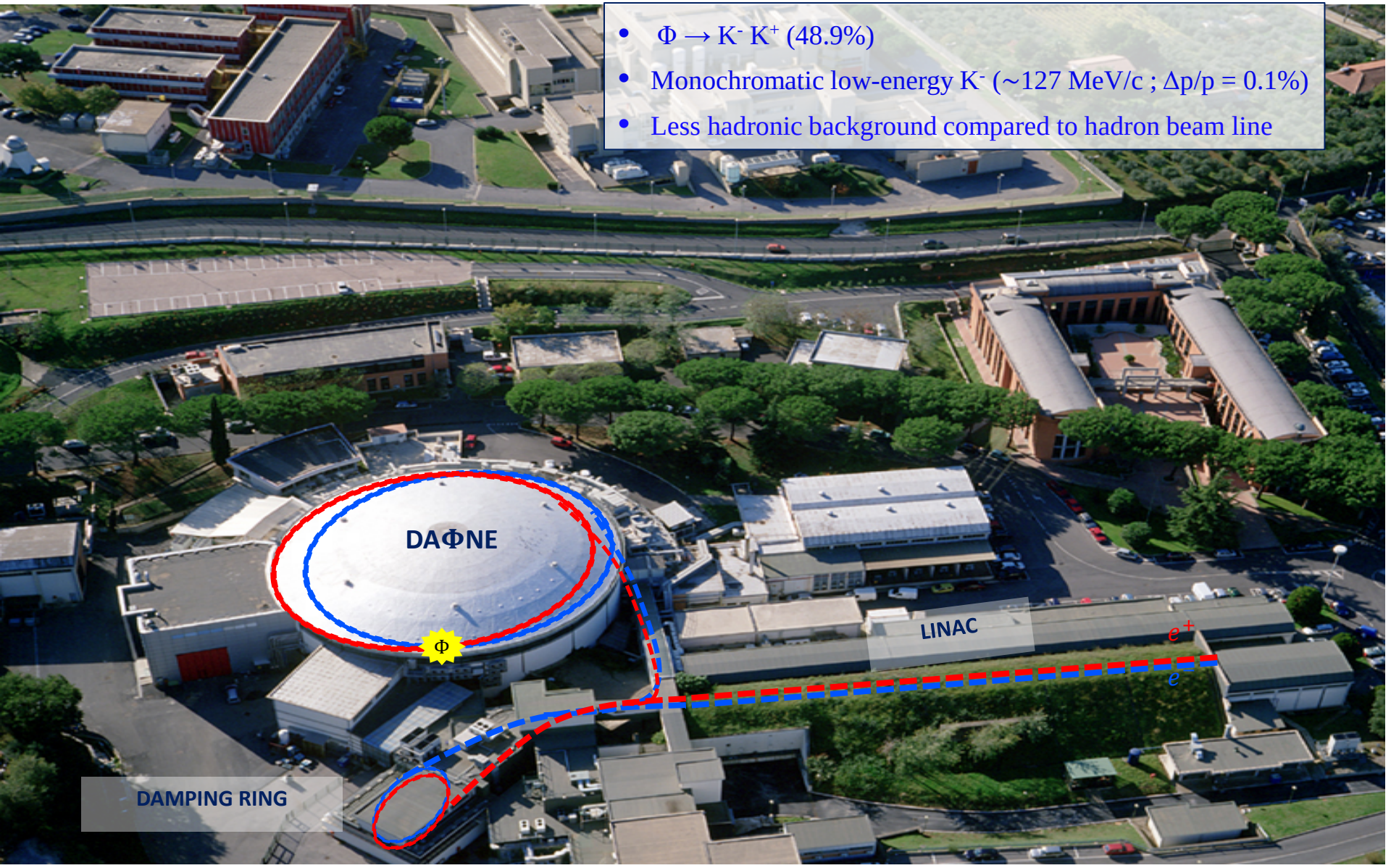
DAΦNE collider **LNF–INFN, Italy**

Low-momentum, monochromatic K^- beams from $\phi \rightarrow K^+K^-$ decays; ideal for stopping kaons in gaseous targets.

KEK, J-PARC Hadron Hall **Japan**

Extracted kaon beam lines provide complementary conditions for stopped-kaon and kaonic-atom measurements.

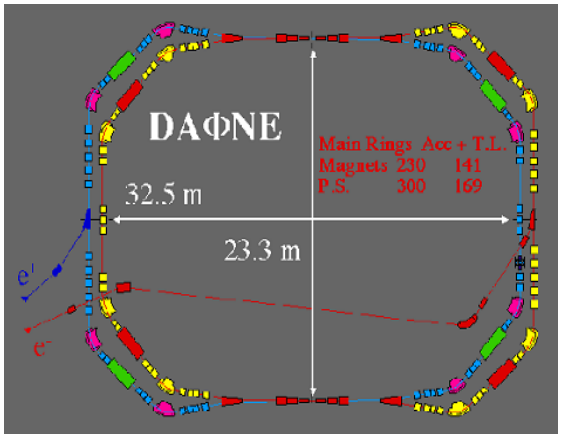
The DAΦNE collider of INFN-LNF, since 1998



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

DAΦNE : low-momentum kaon beam



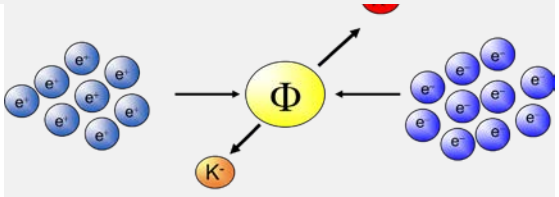


- $e^+ e^-$ at 510 MeV
- Φ ($\sigma(e^+e^- \rightarrow \Phi) \sim 5\ \mu b$) resonance decays at 49.2 % in **$K^+ K^-$ back-to-back pair**
- **Very low momentum (≈ 127 MeV) K^- beam**
- Flux of produced kaons: about 1000/second

operates at the centre-of-mass energy of the Φ meson

mass m = 1019.413 ± .008 MeV

width Γ = 4.43 ± 0.06 MeV



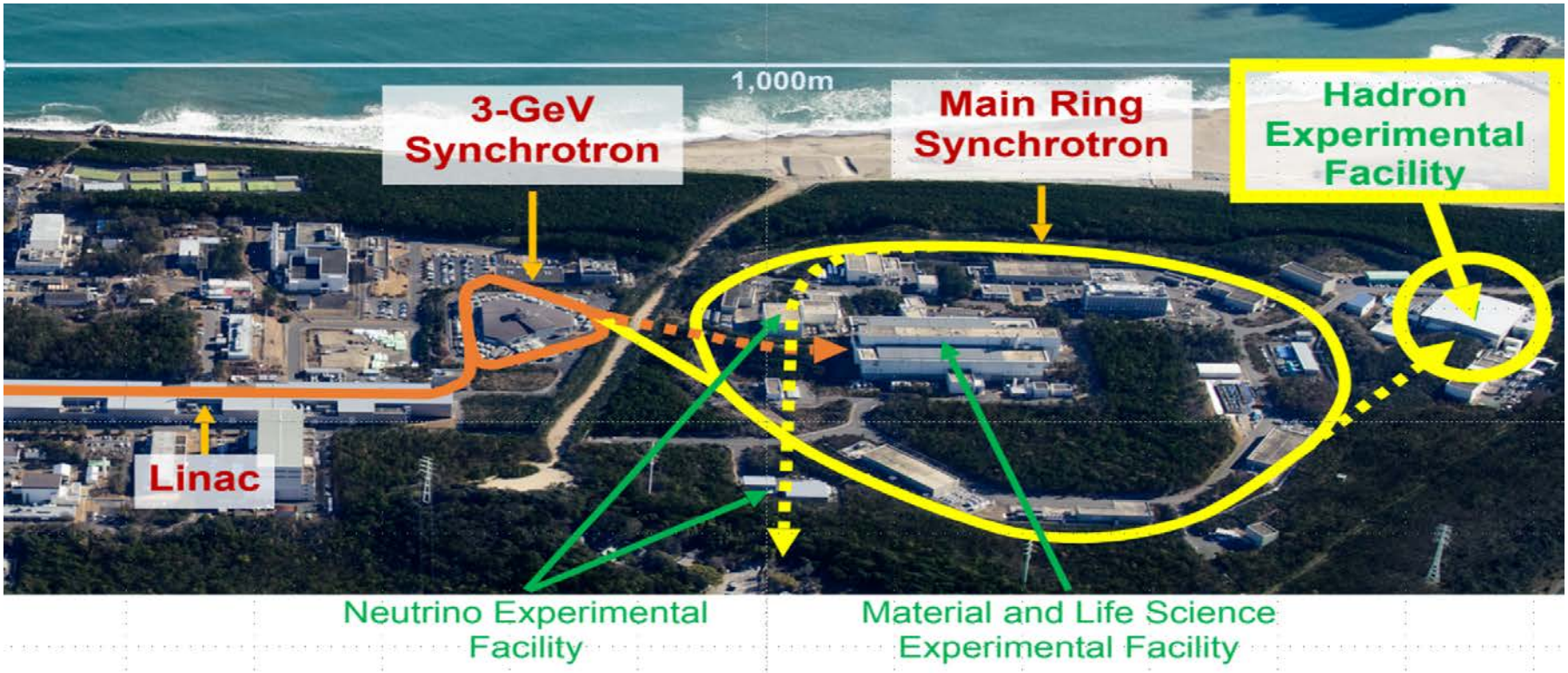
Best low momentum K^- factory in the world

Ideal beam to be stopped in the gaseous target and form, with high efficiency, kaonic atoms

Suitable for low-energy kaon physics:
→ Kaonic atoms (DEAR/ SIDDHARTA/ SIDDHARTA-2)

DAΦNE represents an (THE) EXCELLENT FACILITY in the sector of low-energy interaction studies of kaons with nuclear matter.

J-PARC: high momentum kaon beam



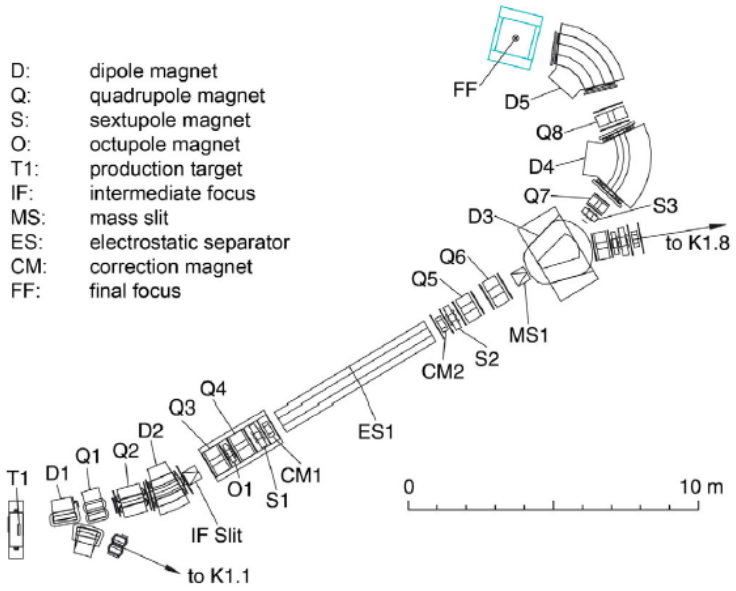
J-PARC consists of a series of world-class proton accelerators and experimental facilities using high-intensity proton beams.

unique in the variety of secondary beams: neutron, pion (muon), kaon and neutrino beams produced via collisions between the proton beams and target materials.

J-PARC: high momentum kaon beam

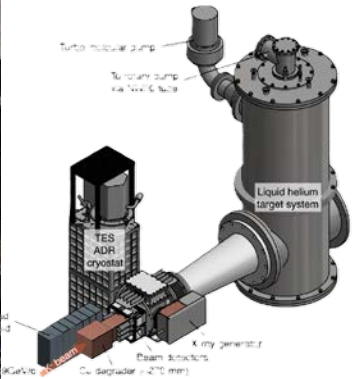
Main kaon beam lines K1.8 and K1.8BR were constructed at the Hadron Hall using primary protons from the J-PARC 50 GeV synchrotron (MR) (up to now, only 30 GeV primary proton beam are produced).

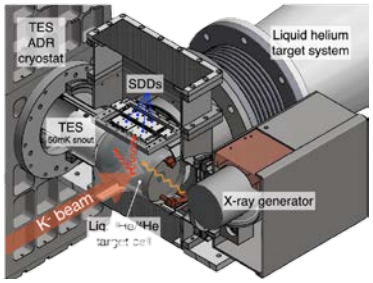
Primary beam	30 GeV/c proton
Repetition cycle	5.2 sec
Flat top	2.93 sec
Production target	Au
Production angle	6 degrees
Length (T1 - FF)	31.2 m
Momentum range	1.2 GeV/c (max.)
Acceptance	2.0 msr % ($\Delta\Omega \cdot \Delta p/p$)
Momentum bite	$\pm 3\%$

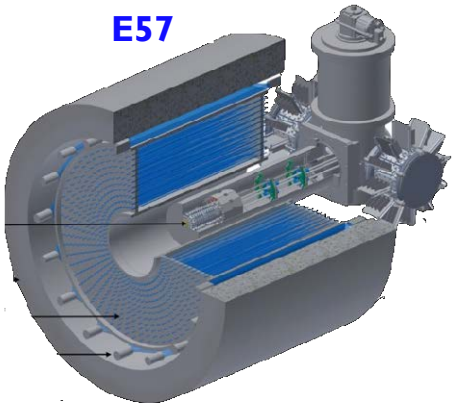


The kaon beam with momentum up to 1.2 GeV/c can be stopped in the target to form the kaonic atoms









Light kaonic atoms as probes of fundamental interactions in strange systems

Progress in Particle and Nuclear Physics 147 (2026) 104226

Catalina Curceanu, Francesco Sgaramella, Massimiliano Bazzi, Tadashi Hashimoto, Mihail Iliescu,
Alessandro Scordo, Diana Sirghi, Florin Sirghi



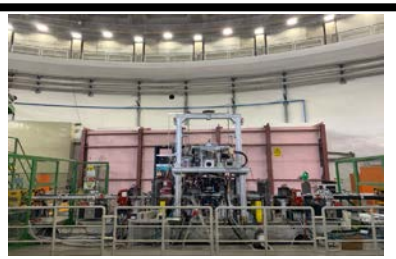
DEAR 2002

SIDDHARTA 2009

SIDDHARTA-2 2022







These experiments have progressively improved the precision of kaonic-atom X-ray spectroscopy

Kaonic Atoms as Precision Probes: Experimental Challenges

2. Target Systems

In parallel with the delivery of kaon beams -> development of:

Lightweight gaseous high-density cryogenic targets
replaced liquid hydrogen, avoiding the drastic reduction of X-ray yields due to the **Stark mixing effect.**

General requirements for target systems

- **high-purity gas target systems** to avoid kaon losses due to the Stark effect
- **cryogenic temperature** for stable and efficient atomic cascade conditions
- **reduced material budget** in front of the X-ray detectors for optimum X-ray detection
- **thin target walls** facing the X-ray detectors; geometry adapted to each kaon source

Design priorities

- **Purity** — minimize Stark losses
- **Temperature** — cryogenic gas target
- **Transparency** — thin entrance/ window walls
- **Geometry** — matched to kaon source

Target design directly affects X-ray yield, background, and achievable precision.

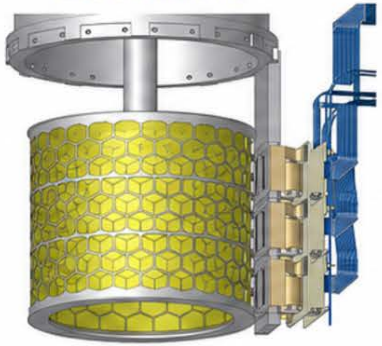
Representative Cryogenic Target Systems according with different kaon sources

SIDDHARTA, SIDDHARTA-2 and E57

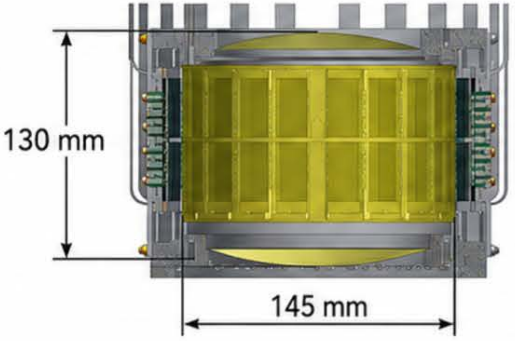
Parameter	SIDDHARTA	SIDDHARTA-2	E57
Active target volume (cm^3)	2400	**2100**	540
Target diameter (cm)	13.7	**14.5**	6.0
Working temperature (K)	20–25	**25–30**	25–30
Working pressure (MPa)	0.10	**0.25**	0.5
Gas density	1.8%[a]	**3%**[b]	4%[b]
Burst pressure (MPa)	0.40	**0.65**	0.80
Kapton entrance window (μm)	125	**125**	125
Kapton side wall (μm)	75	**140**	140

[a] Gas density as a fraction of the liquid hydrogen density (0.0708 g/cm^3).
[b] Gas density as a fraction of the liquid deuterium density (0.164 g/cm^3).

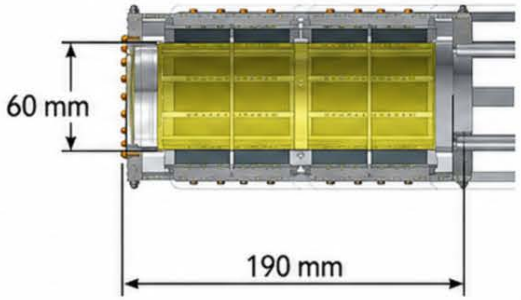
SIDDHARTA



SIDDHARTA-2



E57



Target design evolves with source conditions, density requirements, and X-ray detection constraints.

Kaonic Atoms as Precision Probes: Experimental Challenges

3. High-Performance X-ray Detectors

Progress in X-ray detector technology enabled higher precision, improved energy resolution and timing capability for modern kaonic-atom measurements: to measure weak signal of kaonic atoms over a large background.

Experiment	KpX 1998	DEAR 2005	E570 2007	SIDDHARTA 2009	SIDDHARTA-2, E57	E62
Detector	Si(Li)	CCD	SDD-KETEK	SDD-JFET	SDD-CUBE	TES
Effective area (mm^2)	200	724	1 × 100	3 × 100	8 × 64	~ 23
Thickness (mm)	5	0.03	0.26	0.45	0.45	0.003
Energy resolution @ 6 keV	410	150	190	160	170	5
Drift time (ns)	200	–	375	800	800	–

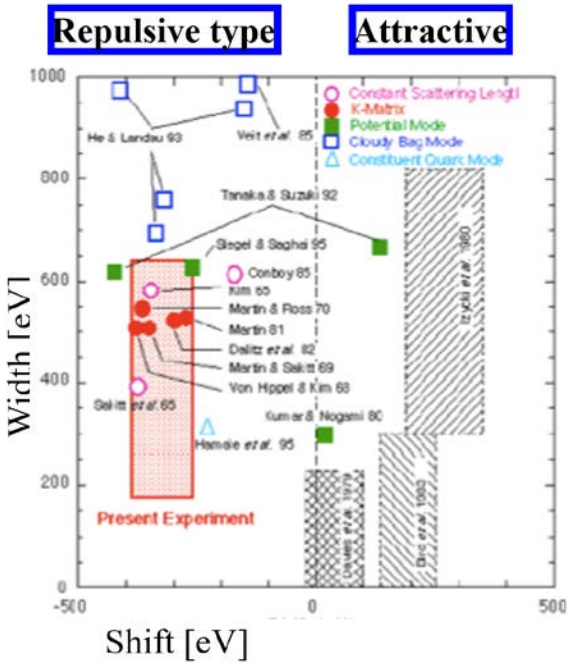
Modern SDD arrays: large active area and timing capability

TES: extreme energy resolution (~5 eV at 6 keV)

The new technologies and kaon beams: experiments which measured, with unprecedented precision, a series of kaonic atoms.

Kaonic Hydrogen Puzzle: SOLVED by KpX experiment (1998)

70-80's:
Kaonic Hydrogen Puzzle



Liquid Hydrogen target

Si(Li) as X-ray detector

Kaonic Hydrogen puzzle solved (KpX , 1998)

- **Gas Hydrogen target (100K, 4 atm)**
- **60 Si(Li) detectors**
- Each detector: 200 mm^2
- Hadron beam-line

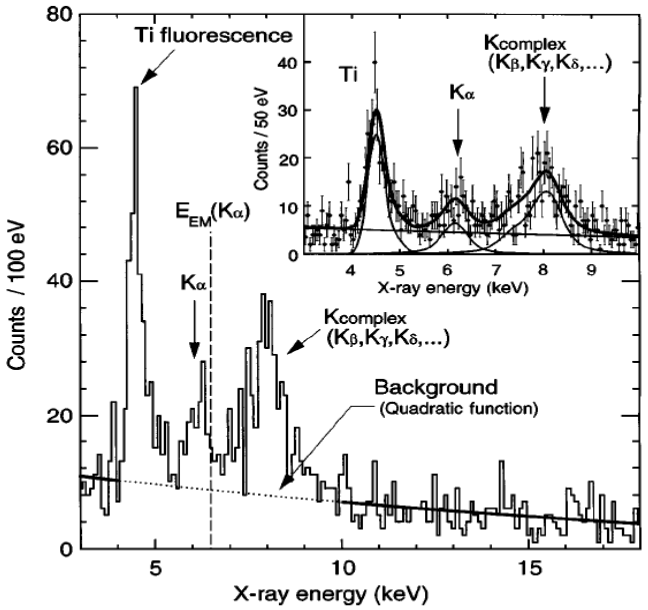


FIG. 3. Kaonic hydrogen x-ray spectrum. The inset shows the result of peak fitting and the components.

[T.M.Ito et al., Phys.Rev.C 58 (1997) 2366]

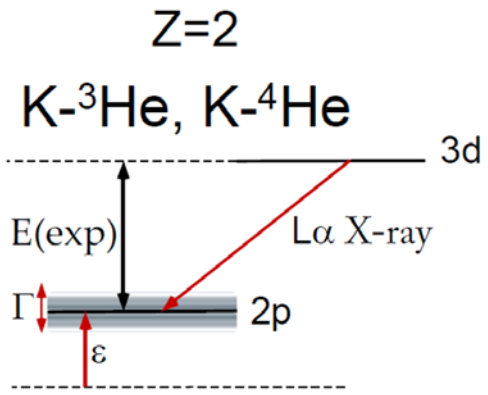
$$\Delta E_{1s} = E^{exp}_{2p\to 1s} - E^{E.M.}_{2p\to 1s}$$
$$= -323 \pm 63(stat.) \pm 11(syst.)\ eV$$
$$\Gamma_{1s} = 407 \pm 208\ (stat.) \pm 100\ (syst.)\ eV$$

Kaonic Hydrogen Puzzle: SOLVED

Kaonic Helium Puzzle: Origin of the Discrepancy

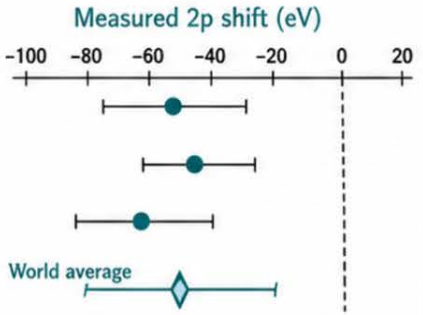
$$\varepsilon = E_{3d \to 2p}(\text{exp}) - E_{3d \to 2p}(\text{e.m.})$$

- The 3d → 2p transition is the most suitable probe of strong-interaction effects.
- Most kaons are absorbed before radiative transitions to the 1s state occur.



Experimental evidence (1971–1983)

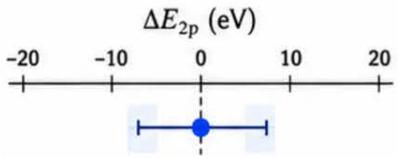
Reference	Year	ΔE_{2p} (eV)
Wiegand & Pahl	1971	−41 ± 33
Datty *et al.*	1979	−35 ± 12
Baird *et al.*	1983	−50 ± 12



$\Delta E_{2p} = -43 \pm 8$ eV

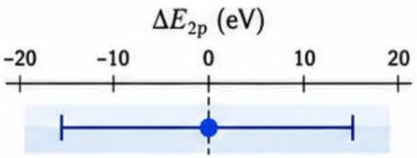
Theoretical expectations

Optical-potential calculations (based on kaonic atom data)



Predict a tiny shift (≈ 0 eV)

Akaishi–Yamazaki type calculations (deeply-bound K^-–nucleus states)



Predict at most ≈ ± 10 eV

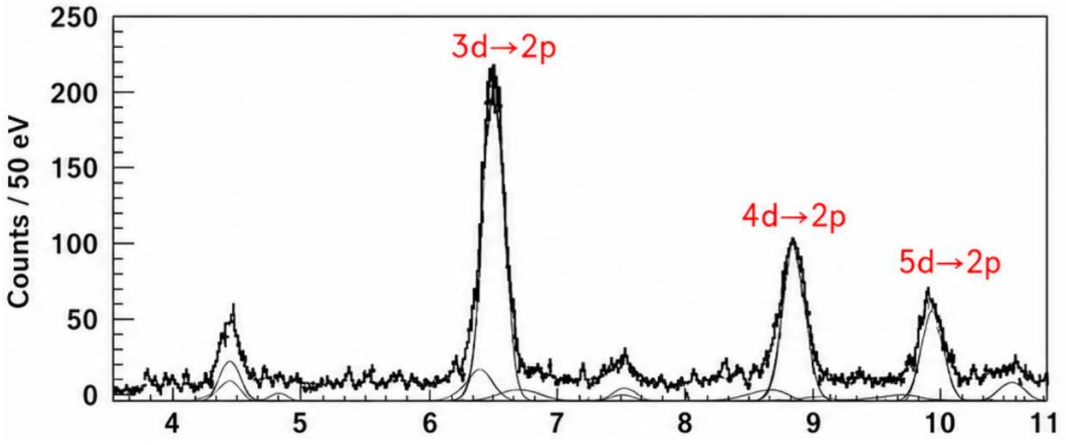
KHe Puzzle: experiments indicated a large shift (~−40 eV), whereas theory predicted a shift compatible with 0 eV

KHe and KH Puzzle:
to perform new measurements of light kaonic atoms using advanced technologies

Resolution of the $K^{-}{}^{4}He$ Puzzle: E570 (KEK, 2007)

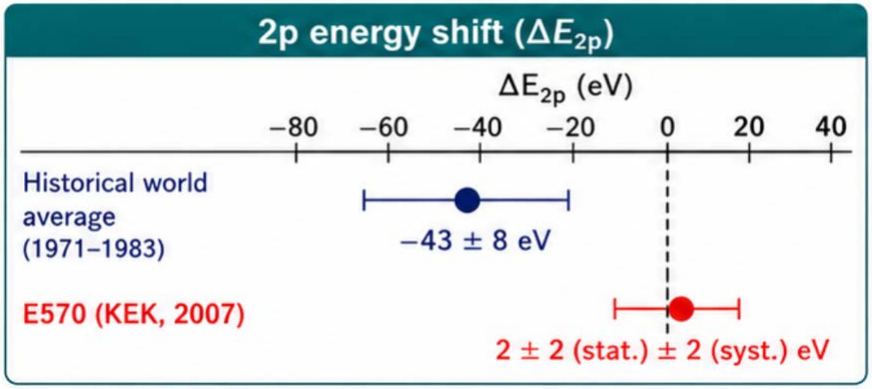
High-precision measurement

- **Liquid ^{4}He target**
- **SDD detectors**
- $K^{-}{}^{4}He$ 3d → 2p transition
- ~1500 events
- 3× higher statistics
- 2× better energy resolution
- 6× better signal-to-noise



PLB 653 (2007) 387

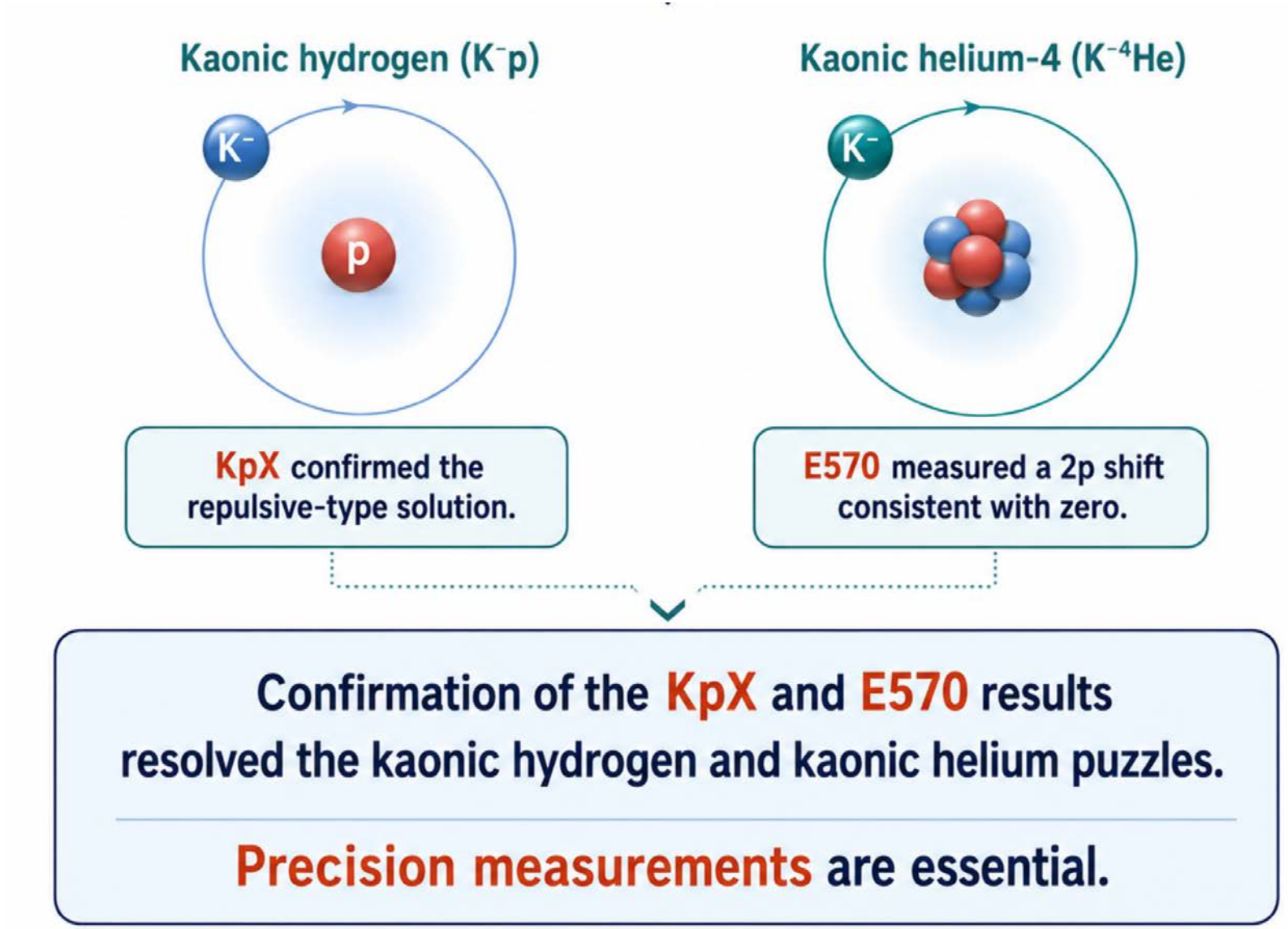
Transition	$3d \rightarrow 2p$	$4d \rightarrow 2p$	$5d \rightarrow 2p$
Measured energy (eV)	6466.7 ± 2.5	8723.3 ± 4.6	9760.1 ± 7.7
EM calc. energy (eV) [15]	6463.5	8721.7	9766.8



$$\Delta E_{2p} = 2 \pm 2(\text{stat.}) \pm 2(\text{syst.})\ \text{eV}$$

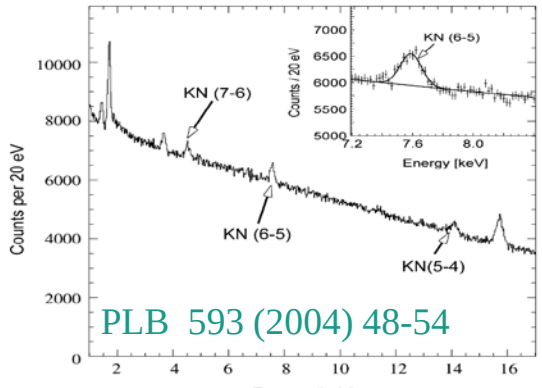
The $K^{-}{}^{4}He$ puzzle was solved:
the 2p shift is consistent with zero and with theoretical expectations.

Kaonic Hydrogen and Kaonic Helium Puzzels : SOLVED



DEAR outcomes and kaonic hydrogen results (2002-2005)

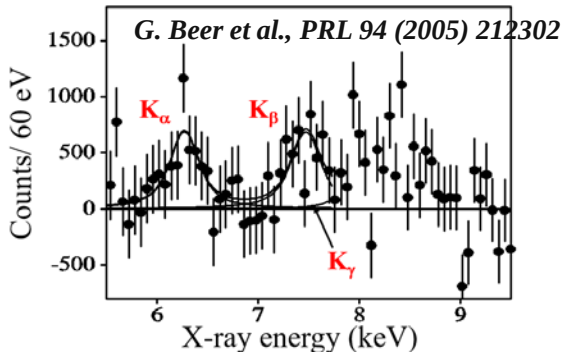
Kaonic nitrogen: first kaonic atom at DAΦNE



KN 7→6 (4.6 keV):	41.5 ± 8.7 ± 4.1%
KN 6→5 (7.6 keV):	55.0 ± 3.9 ± 5.5%
KN 5→4 (14.0 keV):	57.4 ± 15.2 ± 5.7%

Useful input for cascade calculations.

Kaonic hydrogen



$$\varepsilon = -193 \pm 37(stat.) \pm 6(syst.)eV$$
$$\Gamma = 249 \pm 111(stat.) \pm 39(syst.)eV$$

Best kaonic hydrogen measurement at that time.
confirms repulsive character of K- p interaction

Physics message

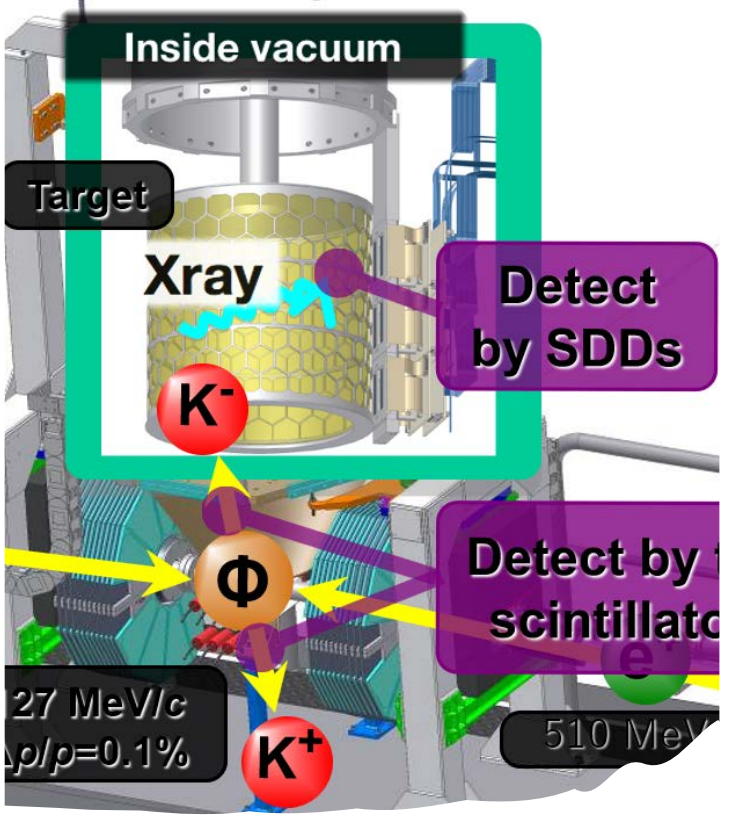
- Consistent with the KEK result within 1σ.
- Repulsive-type K^-p interaction confirmed.
- Full pattern of Kα, Kβ, and Kγ lines identified.

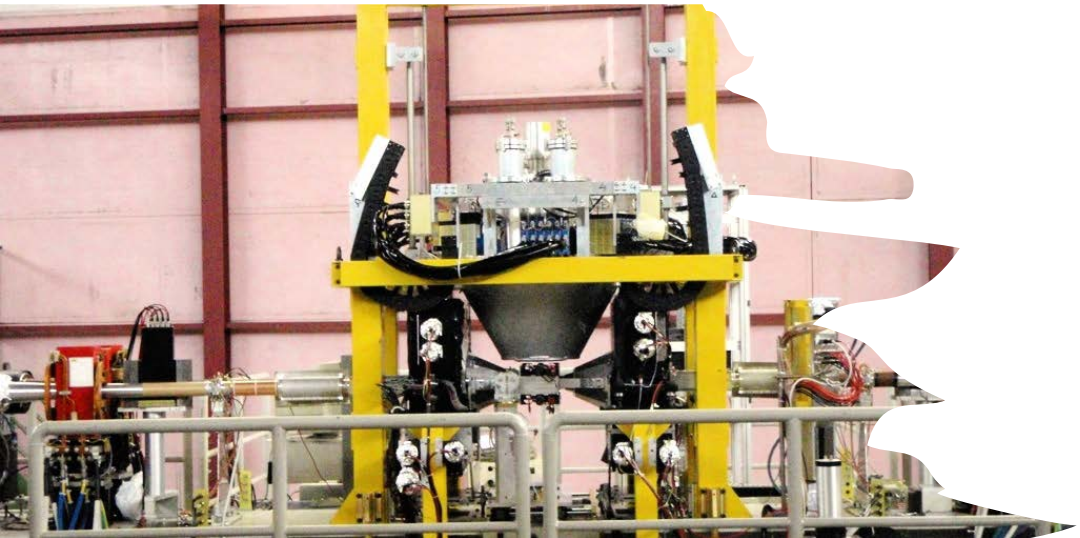
Limitation

the precision obtained for the shift and the width of 1s state in KH limited due to high background (S/B ≈ 1/70).

DEAR was a major milestone, but higher-precision measurements and a deuterium result were still needed.

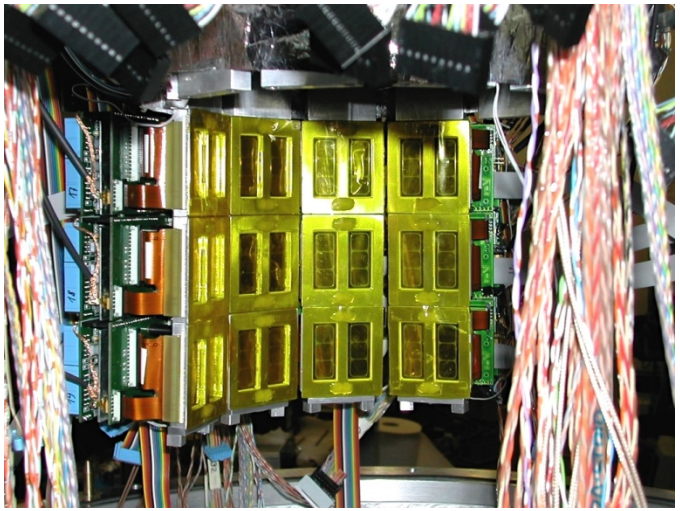


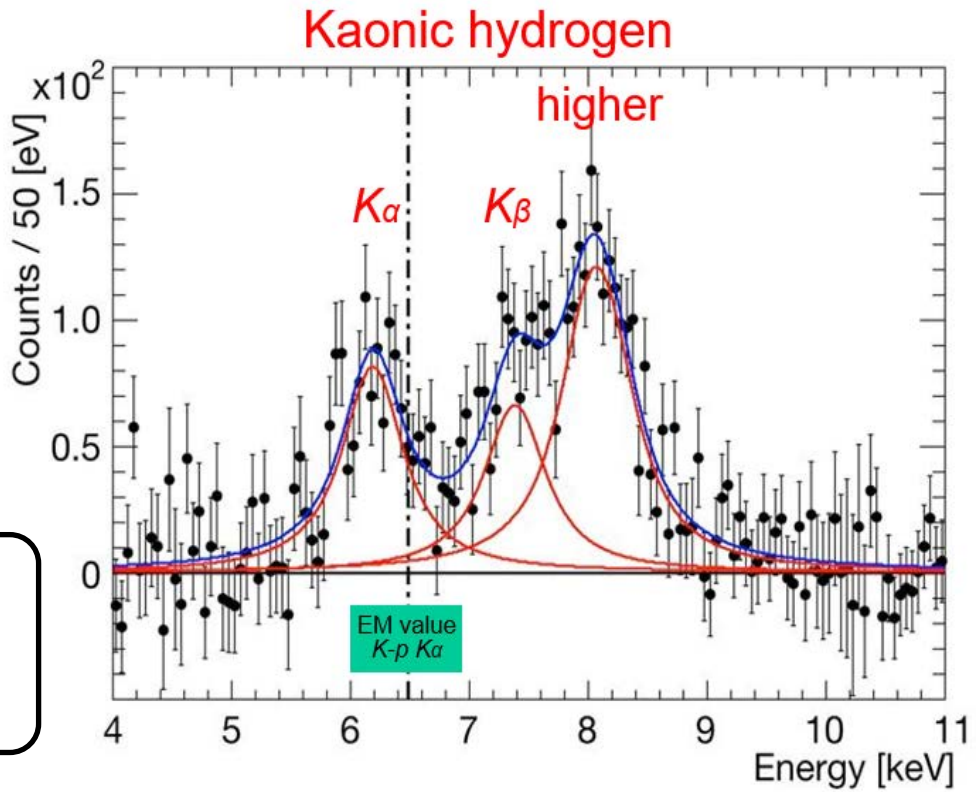




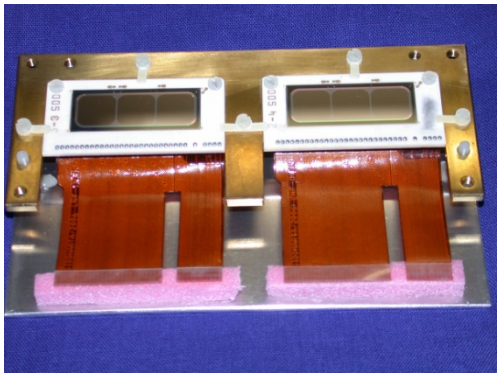
SIDDHARTA
(2007-2009)

KH results by SIDDHARTA (2009)





Gas target (22 K, 2.5 bar)
144 SDD used as X-ray detector
Good energy resolution (170eV @ 6 keV)
Timing capability (huge background)

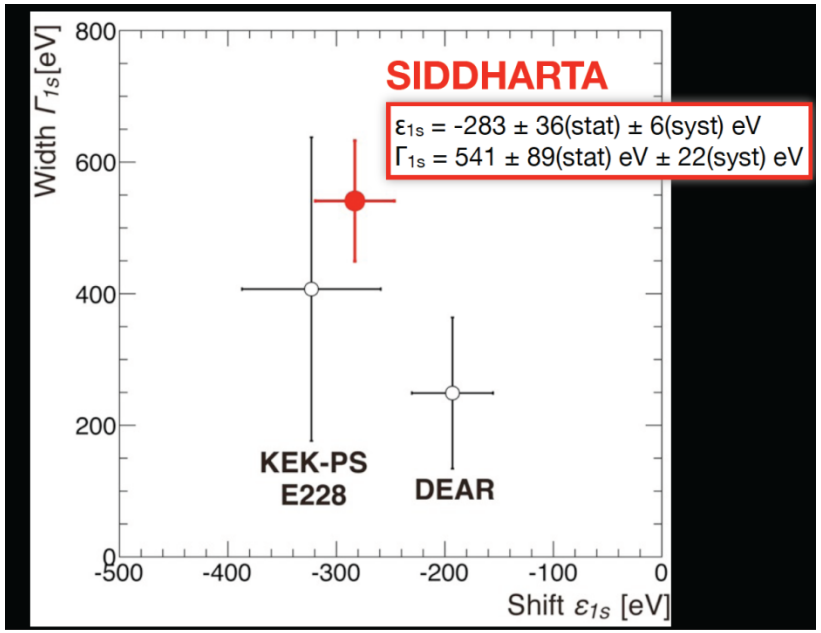


$$\varepsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV}$$
$$\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV}$$

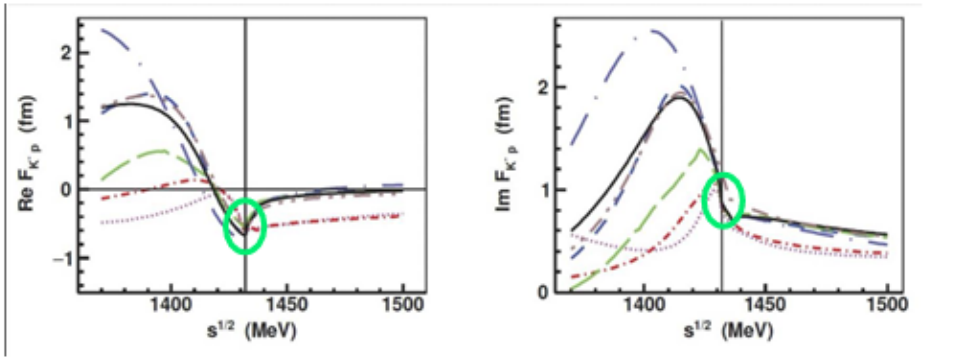
most reliable and precise measurement ever

Phys. Lett. B704 (2011), 113

KH results by SIDDHARTA (2009)



K-p scattering amplitudes generated by recent chirally motivated approaches. The vertical lines mark the threshold energy



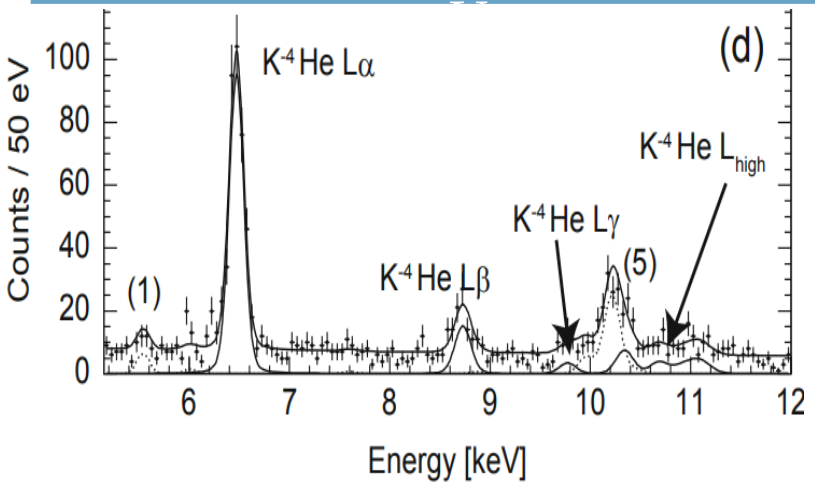
Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

The most precise measurement of kaonic hydrogen 1s shift and width performed by SIDDHARTA was fundamental to constrain the description of the K-p interaction at threshold

K^4He results by SIDDHARTA (2009)

Kaonic 4-Helium

K-4He (3d-2p)
E_{exp} = 6468.5±3 (stat.)±3.5(syst.)



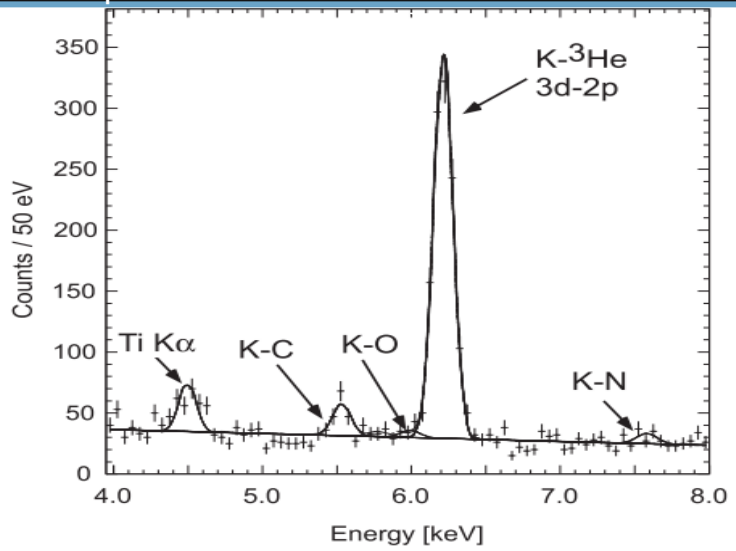
$$\Delta E_{2p} = +5 \pm 3(sta) \pm 4(sys)\ \text{eV}$$

Phys. Lett. B 681 (2009) 310

first time in a gaseous target for ^4He

Kaonic 3-Helium

K-3He (3d-2p)
E_{exp}=6223.0±2.4(stat)±3.5(syst.)



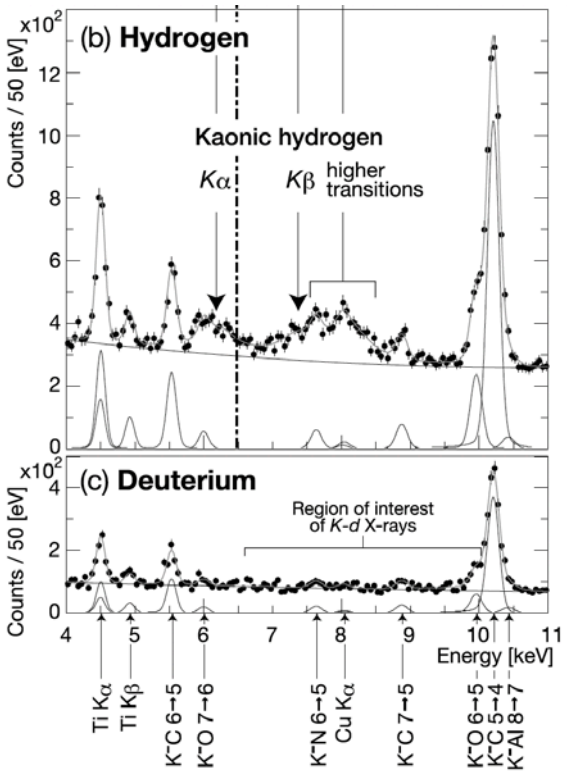
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

Phys. Lett. B 697 (2011) 199

first time for ^3He

The kaonic deuterium challenge

The measurement of Kaonic deuterium 2p → 1s is a true challenge: SIDDHARTA performed an exploratory run in 2009, collecting 100 pb^{-1} of data but without observing a visible signal.



Physics factors:

- Low X-ray yield (~ 10 times lower than KH)
- Transition width broader than KH 2p→ 1s

➢ Kd requires a higher integrate luminosity ~800 pb^{-1}

Background:

- The Kd measurement requires an improvement in signal/background ratio by a factor 10

➢ New experimental apparatus with improved SDDs, trigger and Veto systems

➢ Larger detection area

"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 $\bar{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

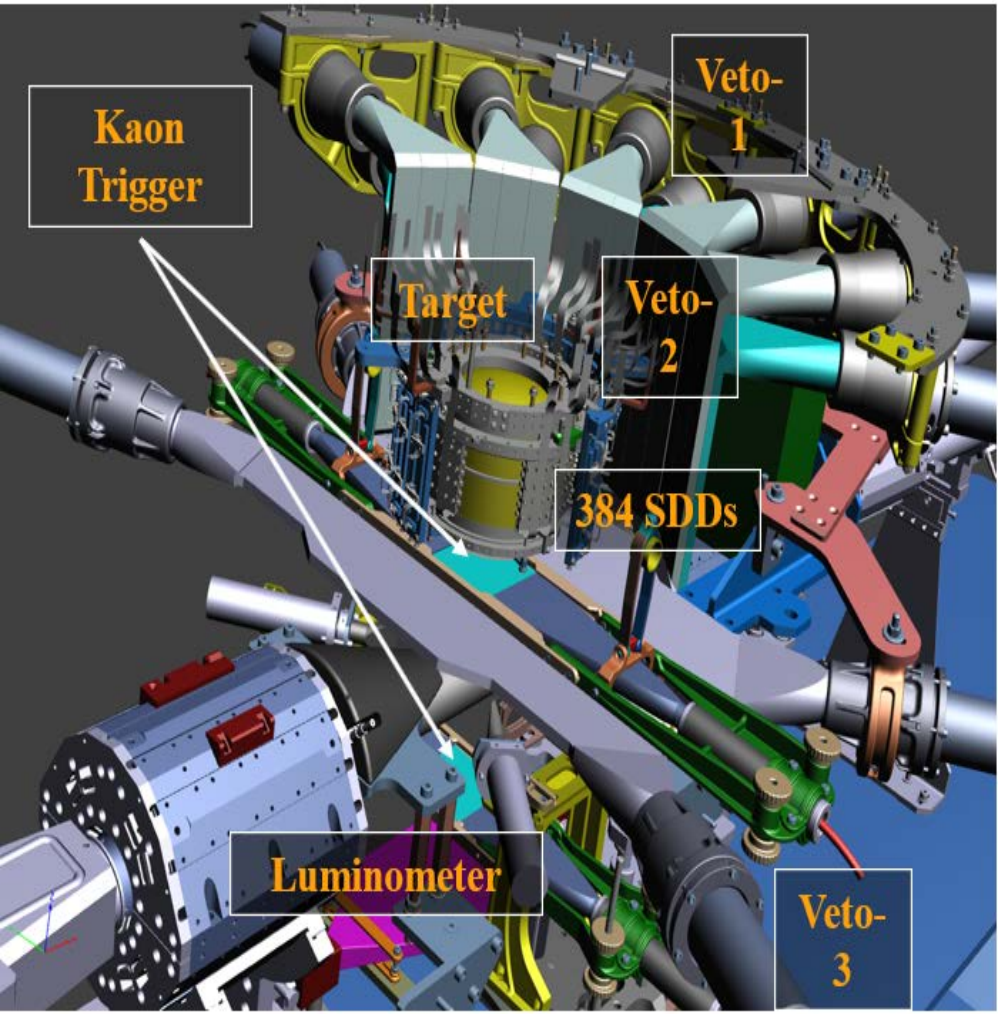
R.H. Dalitz (1982)



SIDDHARTA-2 (2010-2024)



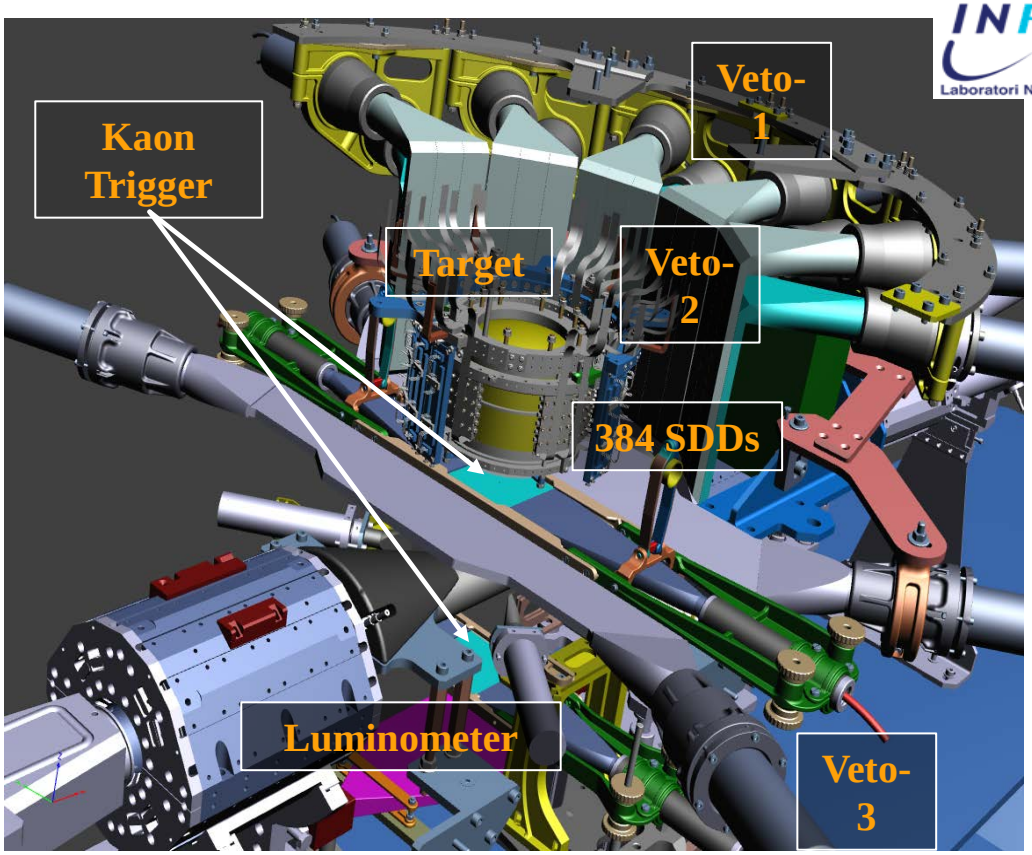
TheSIDDHARTA-2 setup



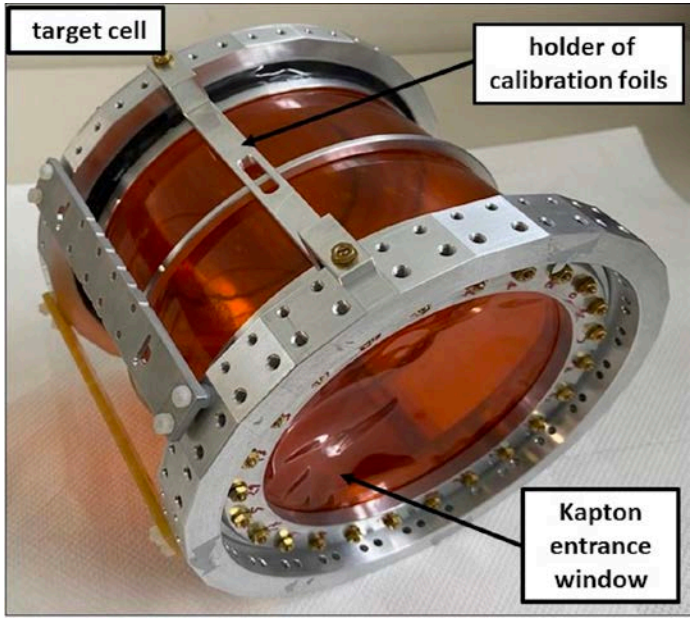
Key upgrades

- New generation of **Silicon Drift Detectors** and read-out electronics
- Active area **2 times larger**
- SDD drift time **450 ns** (instead of 800 ns in SIDDHARTA), improving electromagnetic background rejection by a **factor of 2**
- Thickness of **450 μm** ensures high collection efficiency for X-rays in the **5–12 keV** range
- **3 veto systems** for hadronic background suppression
- New vacuum chamber and lead-shield design for **better background reduction**

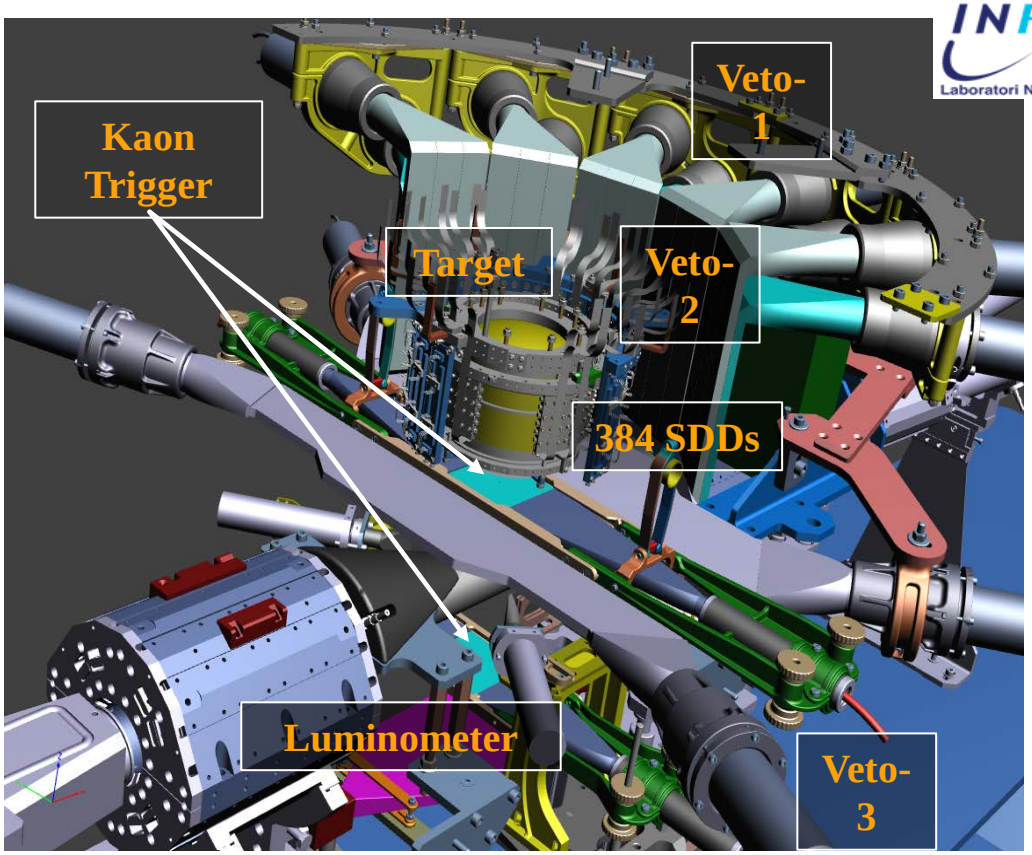
The SIDDHARTA-2 setup



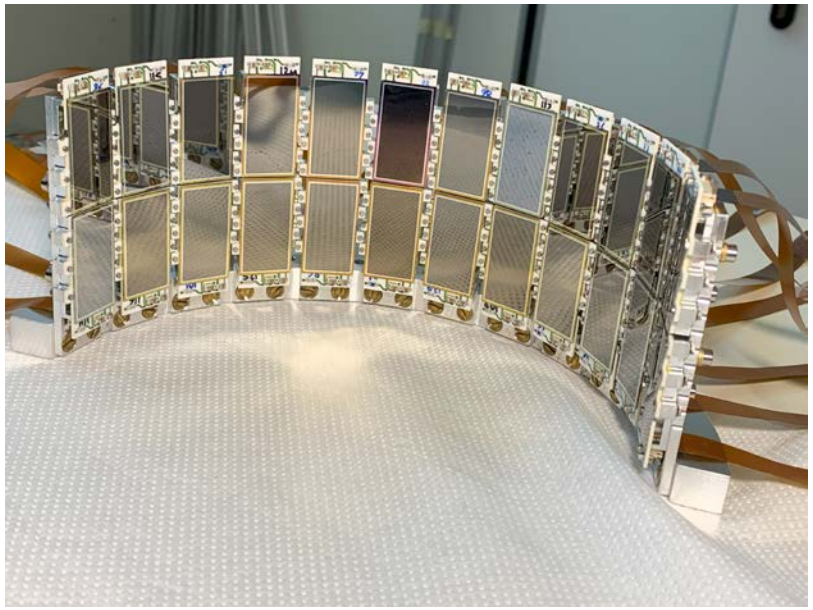
Cryogenic gaseous target cell



The SIDDHARTA-2 setup



384 Silicon Drift Detector
for a total active area of 246 cm²
The thickness of 450 µm ensures a high collection efficiency for X-rays of energy in the 5-12 keV range



SIDDHARTA-2 Scientific Goal

Kaonic deuterium as the missing input for low-energy K^-N interaction studies

First measurement ever of the kaonic deuterium X-ray transition to the ground state (1s level), determining the strong-interaction induced shift and width.

From level shift and width to K^-N scattering lengths

The kaonic hydrogen and deuterium observables provide complementary constraints on the isospin-dependent K^-N scattering lengths.

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

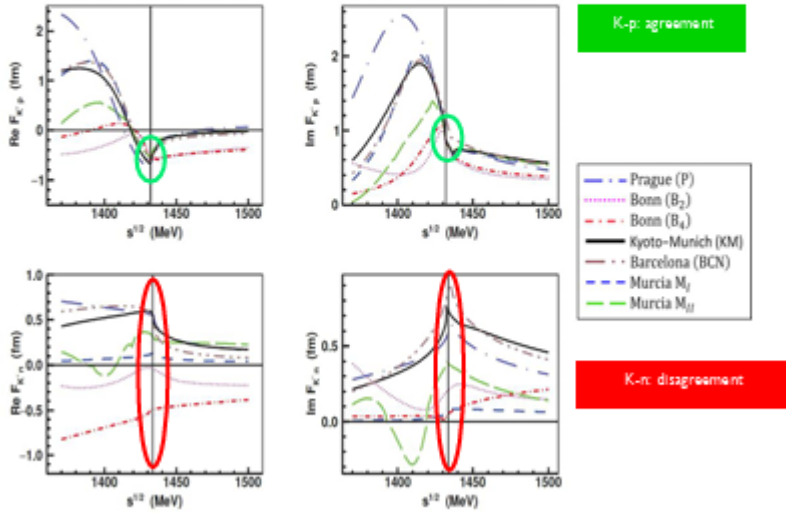
(μ_c reduced mass of the K^-p system, α fine-structure constant)

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

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

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

Combined analysis of the kaonic deuterium and kaonic hydrogen measurements to determine the isospin-dependet $\overline{KN}$ scattering lengths



Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

completely solve Isospin-dependent K-N scattering length

The road to the first Kaonic Deuterium measurement



Manti S., et al. Phys. Rev. A 113, 022815 (2026)
Sgaramella F., et al. Phys. Lett. B 865 139492(2025)
Sgaramella F., et al. J. Phys. G: Nucl. Part. Phys. 51 (2024) 055103
Bosnar D., et al. NIM A 1069 (2024) 169966
Sgaramella F., et al. Eur. Phys. J. A (2023) 59:56
Sirghi D., et al. J. Phys. G: Nucl. Part. Phys. 49 (2022) 055106

Data Taking Summary

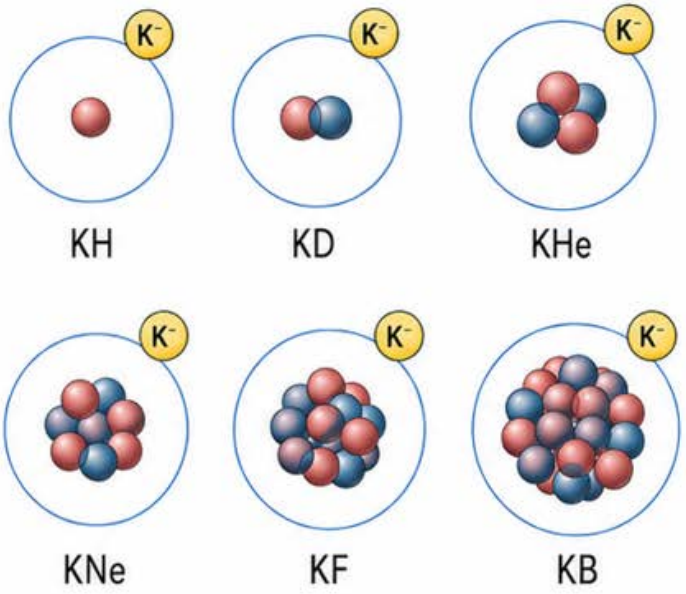
SIDDHARTA-2: kaonic atoms measurements (2023–2024)

- **Initial calibration and optimization**
  - *Kaonic neon*: int. lumi ~ 125 pb^{-1} (April 2023)
- **Kd Run-1: int. luminosity 196 pb^{-1} (May–July 2023)**
  - *Kaonic helium-4*: final calibration of the setup, int. lumi ~ 40 pb^{-1} (July 2023)
- **Kaonic neon calibration**
  - *Kaonic neon*: int. lumi ~ 36 pb^{-1} (Sept 2023)
- **Kd Run-2: int. luminosity 344 pb^{-1} (October–December 2023)**
  - *Kaonic hydrogen*: final calibration of the setup, int. lumi ~ 26 pb^{-1} (Dec 2023)
- **Kaonic hydrogen calibration**
  - *Kaonic hydrogen*: int. lumi ~ 70 pb^{-1} (Jan 2024)
- **Kd Run-3: int. luminosity 435 pb^{-1} (February–April 2024)**
  - *Kaonic hydrogen*: final calibration of the setup, int. lumi ~ 150 pb^{-1} (April 2024)
- **Kd Low density run: int. luminosity 200 pb^{-1} (May–July 2024)**

To investigate yield as function of density

- **Post Kd calibration run (July 2024)**
  - 20 pb^{-1} with solid target (*KF*; *KB* as test measurements)

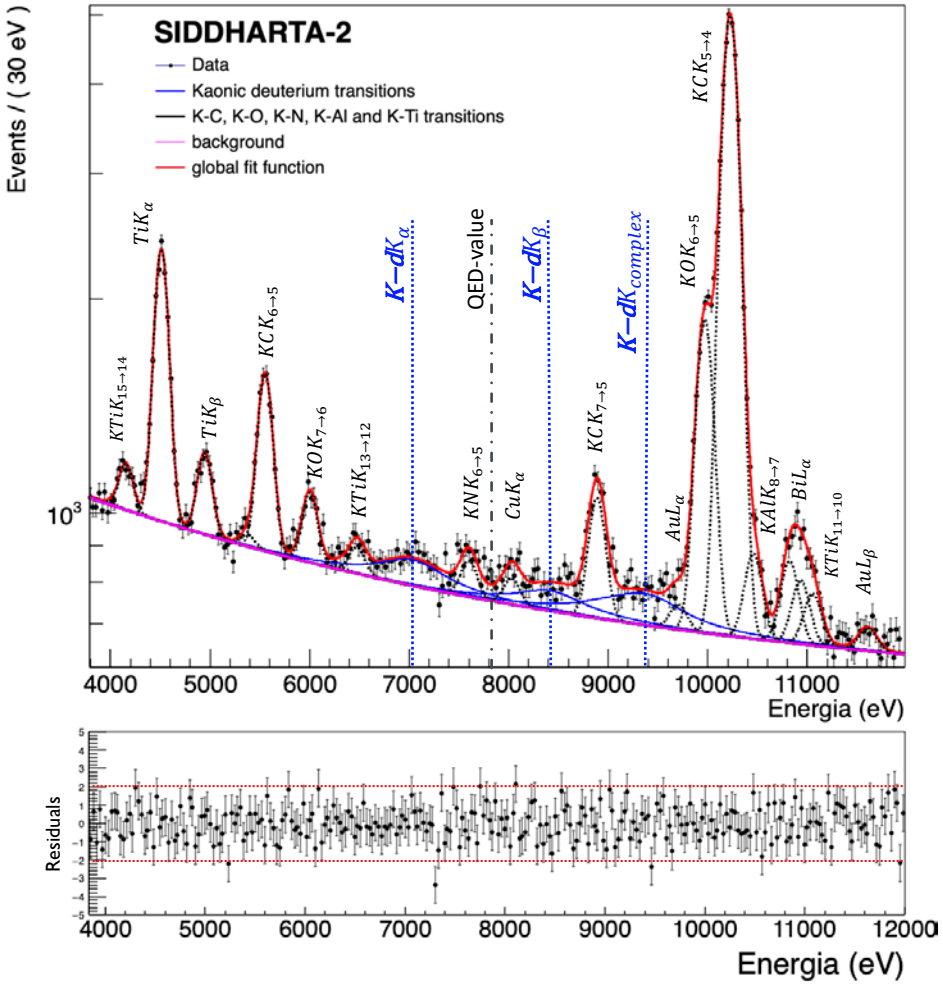
Measured kaonic atoms



Total integrated luminosity
good on Kd for physics:

815 pb^{-1} (delivered 975 pb^{-1})
+ 200 pb^{-1} low density run

Kaonic Deuterium Results

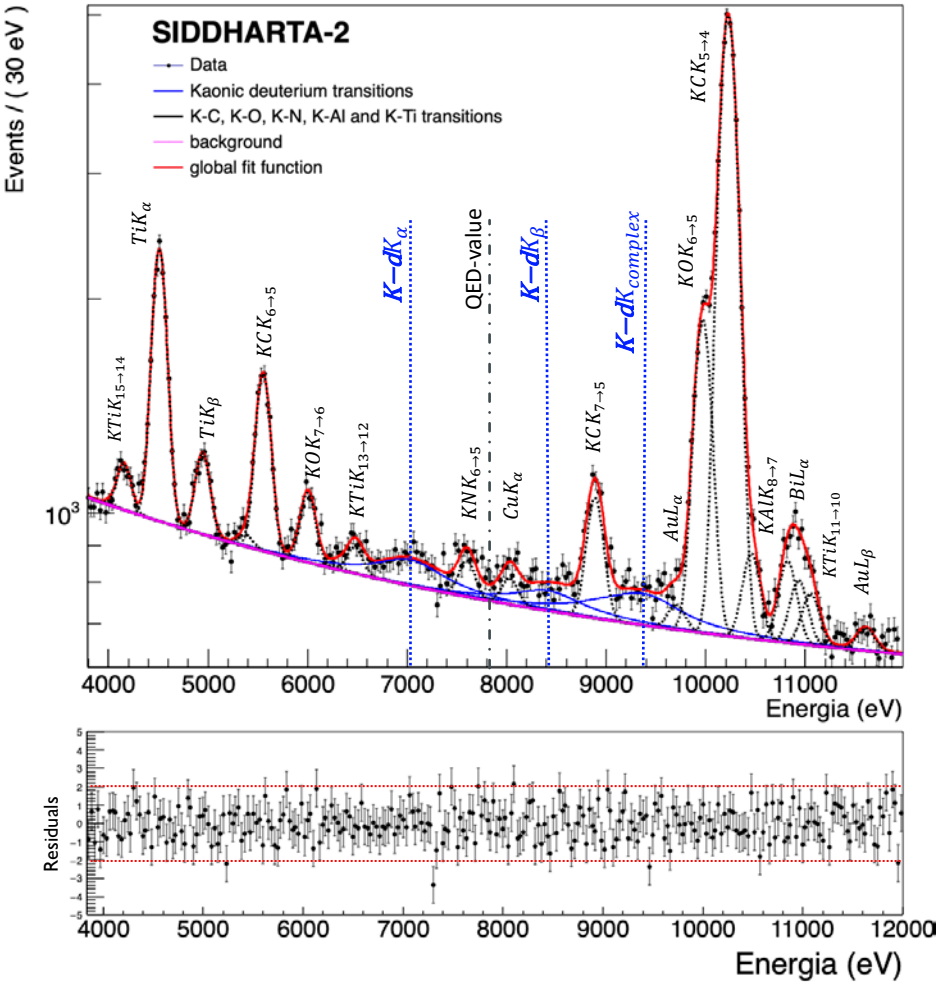


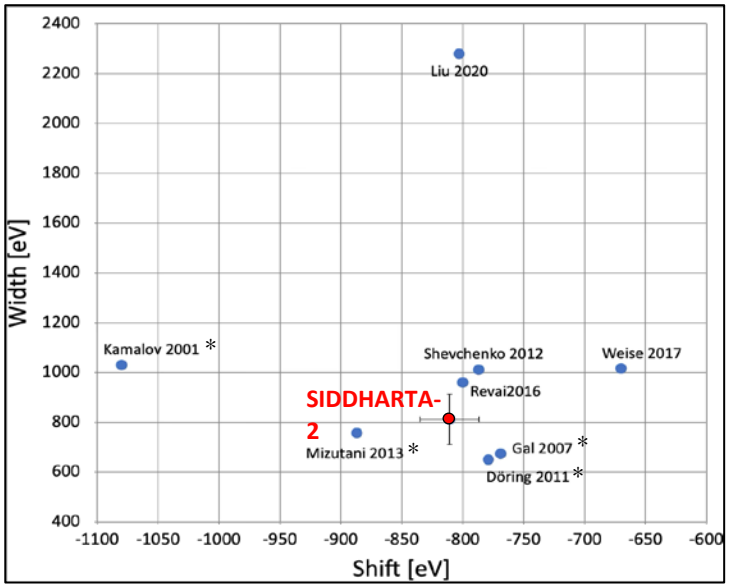
$$\varepsilon_{1s} = -810.9 \pm 24.5(\text{stat}) \pm 2.1(\text{syst}) \text{ eV}$$

$$\Gamma_{1s} = 812 \pm 97(\text{stat}) \pm 33(\text{syst}) \text{ eV}$$

- Negative shift: repulsive-type strong-interaction effect
- Large width: strongly absorptive antikaon–deuteron interaction

Kaonic Deuterium Results





* The energy shift and width are extracted from scattering length using the Deser-Trueman formu

the achieved experimental precision ➡ clear discrimination among competing theoretical approaches

provide the first direct experimental constraint on the K^-d system at threshold energy

$$\varepsilon_{1s} = -810.9 \pm 24.5(\text{stat}) \pm 2.1(\text{syst}) \text{ eV}$$

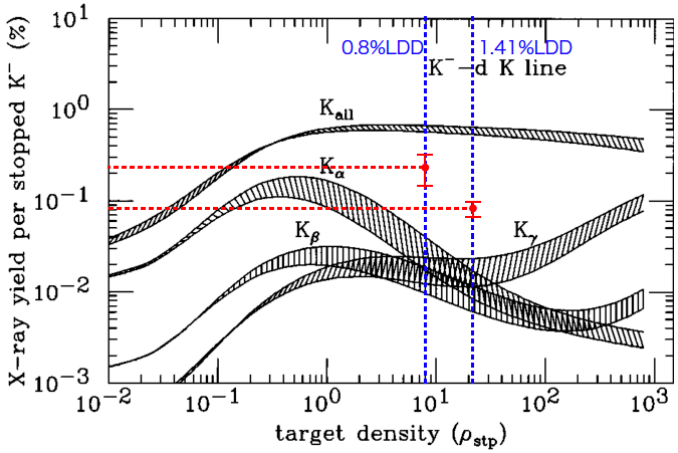
$$\Gamma_{1s} = 812 \pm 97(\text{stat}) \pm 33(\text{syst}) \text{ eV}$$

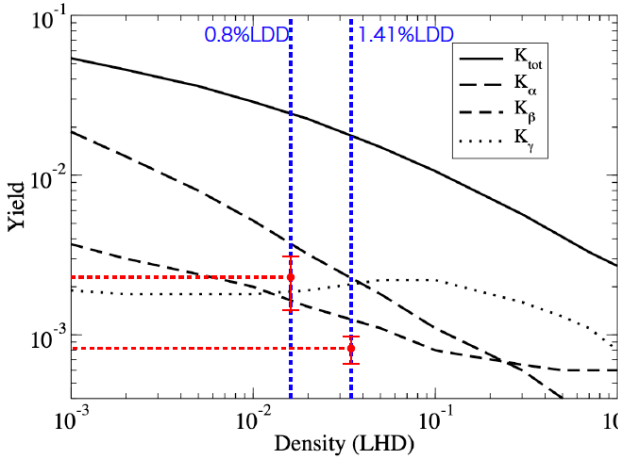
Targeted precision achieved!

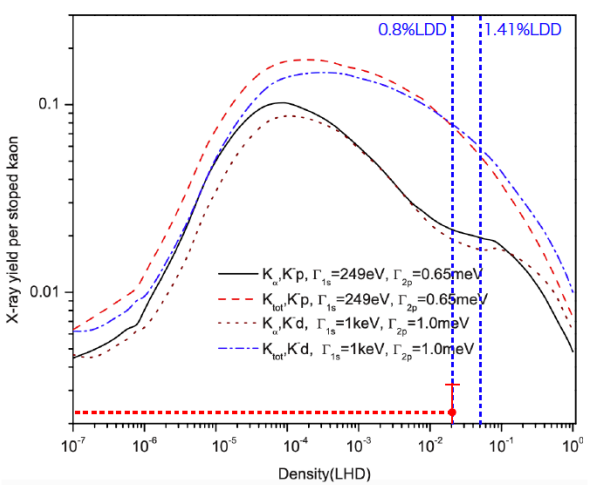
- **Preliminary Kd Spectrum published in Progress in Particle and Nuclear Physics (PPNP) article on kaonic atoms (IF17.9)**
- **Kd 1s Energy Shift and Width to Physical Review Letters**

Kaonic Deuterium Results: X-ray yield

- **Various cascade models predict completely different K-d X-ray yield values and different density dependencies of the target**
- **The combined analysis of 1.4% and 0.8% LDD kaonic deuterium yields offers a decisive test to discriminate between competing cascade models**







- A comparison with three cascade models shows that none fully reproduces the data, although **the Jensen model is closest**
- **This first experimental input provides essential constraints for future theoretical developments** (**publication in preparation**).

This demonstrates how important these measurements are, not only for studying the strong interaction, but also for improving our understanding of the atomic cascade mechanisms.

Kaonic Deuterium: Next Steps

1 **X-ray yield**

Evaluate the **kaonic deuterium X-ray yield** from high- and low-density runs.

article

2 **K^-d scattering length**

Evaluate the **kaonic deuterium scattering length** in collaboration with theoreticians.

article

3 **Combined KH + KD analysis**

Use kaonic hydrogen and deuterium together to determine the **isospin-dependent antikaon–nucleon scattering lengths** and constrain theory (in collaboration with theoreticians)

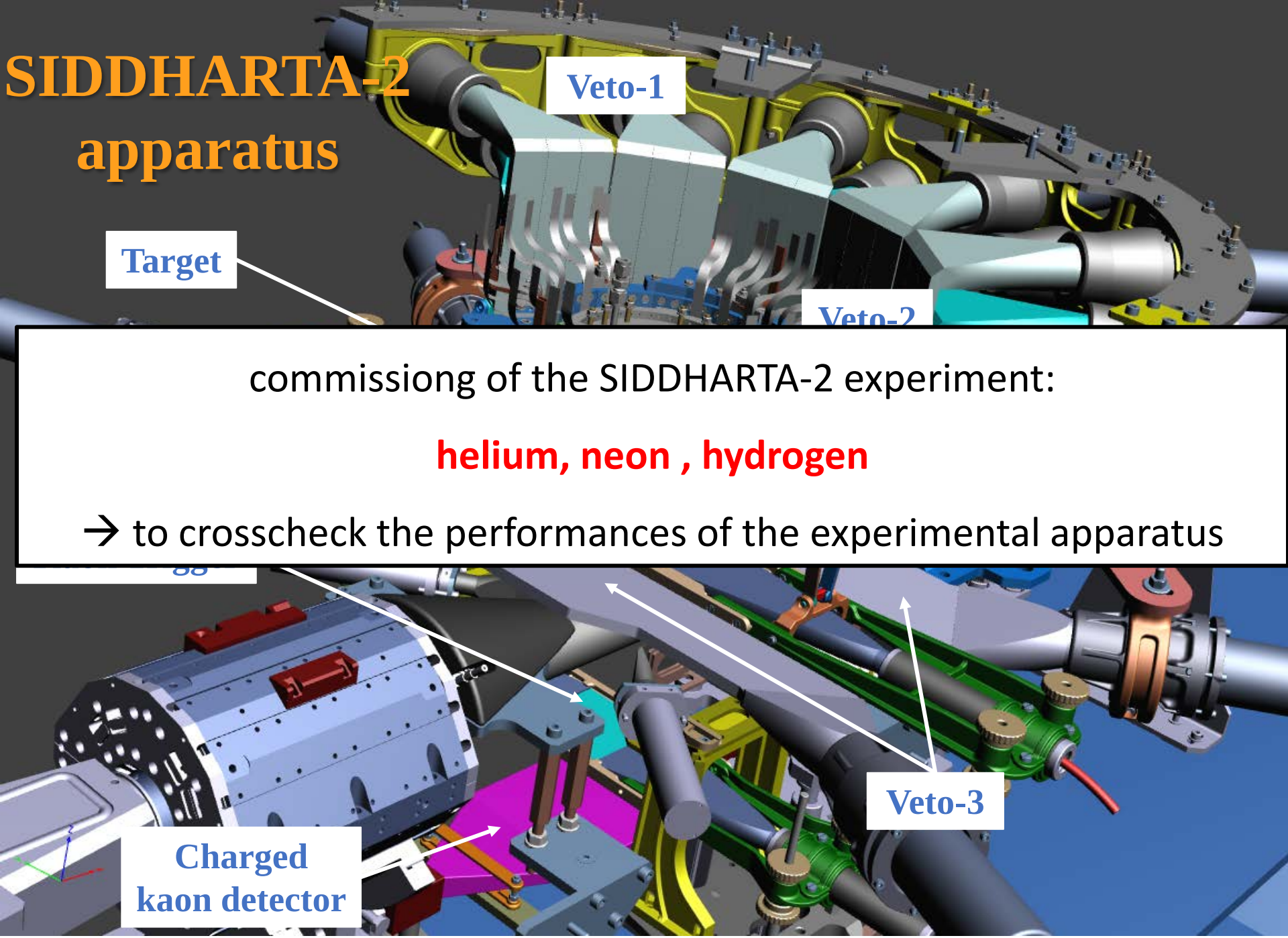
article(s)

4 **Model discrimination**

Reach enhanced precision to **disentangle competing theoretical models** of low-energy QCD in the strangeness sector.

Goal: turn the first kaonic deuterium spectroscopy into quantitative constraints on **K^-N dynamics at threshold.**

SIDDHARTA-2 apparatus



commissiong of the SIDDHARTA-2 experiment:

helium, neon , hydrogen

→ to crosscheck the performances of the experimental apparatus

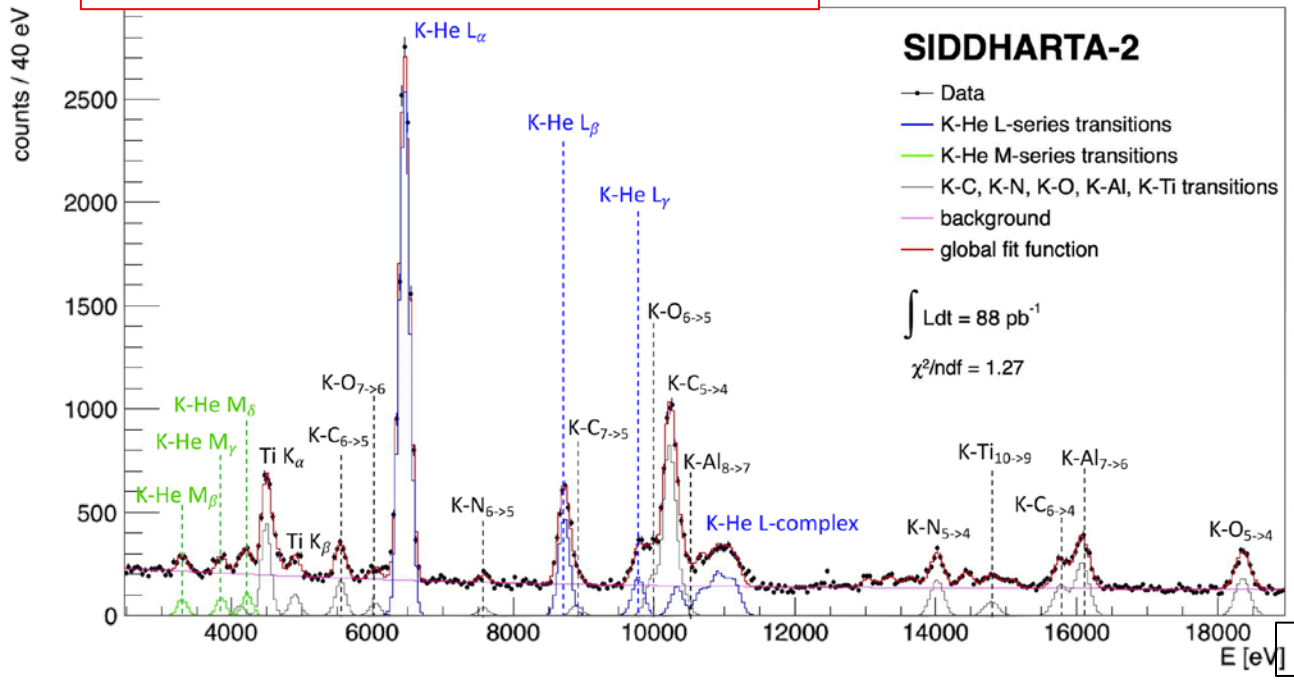
The Kaonic ^{4}He measurement (2021-2022)

- Very precise measurement of kaonic helium-4 Lα in gas: 2p level energy shift and width
- First observation of kaonic helium-4 M-series transition (n→3d)
- First Measurement of high-n transition in kaonic carbon – nitrogen – oxygen and aluminium

the most precise measurement in gas!

$$\varepsilon_{2p} = E^{exp}_{3d\to 2p} - E^{e.m}_{3d\to 2p} = -1.9 \pm 0.8\,(stat) \pm 2.0\,(sys)\ eV$$
$$\Gamma_{2p} = 0.01 \pm 1.60\,(stat) \pm 0.36\,(sys)\ eV$$

→ *no sharp effect of the strong interaction on the 2p level*



new data to enrich the kaonic atoms transitions database

Transition	Energy [eV]
K^-C (6→5)	5546.0 ± 5.4 (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)	6014.8 ± 8.4 (stat) ± 2.0 (syst)
K^-O (6→5)	9965.1 ± 6.9 (stat) ± 2.0 (syst)
K^-O (5→4)	18361.1 ± 5.4 (stat) ± 12.0 (syst)
K^-N (6→5)	7581.1 ± 16.0 (stat) ± 2.0 (syst)
K^-N (5→4)	14008.0 ± 6.0 (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)
K^-Ti (10→9)	14790.3 ± 16.6 (stat) ± 9.0 (syst)

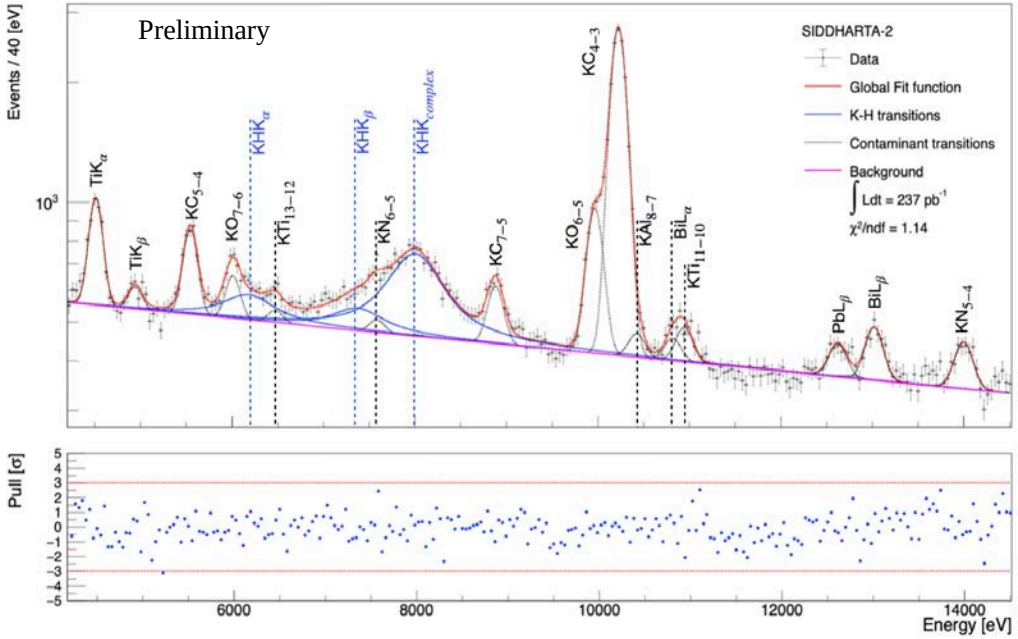
Sgaramella F., et al., 2023, Eur. Phys. J. A, 59 (3) 56

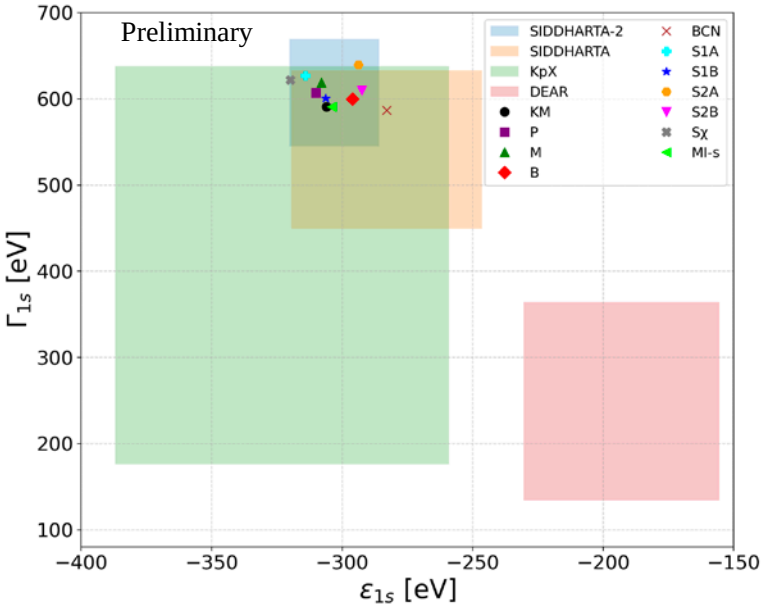
The new kaonic atoms measurements (high-n energy transitions):

- ***a new era for the antikaon-nuclei studies at low energy***
- **establish a solid basis for future dedicated kaonic atoms measurements through the whole periodic table**

A new Kaonic Hydrogen Measurement

- The most precise determination to date
- An improvement in the (ε_{1s} Γ_{1s}) parameter space by a factor-of-three with respect to SIDDHARTA
- **Impact on theoretical models describing the low-energy $\bar{K}N$ interaction and $\Lambda(1405)$**



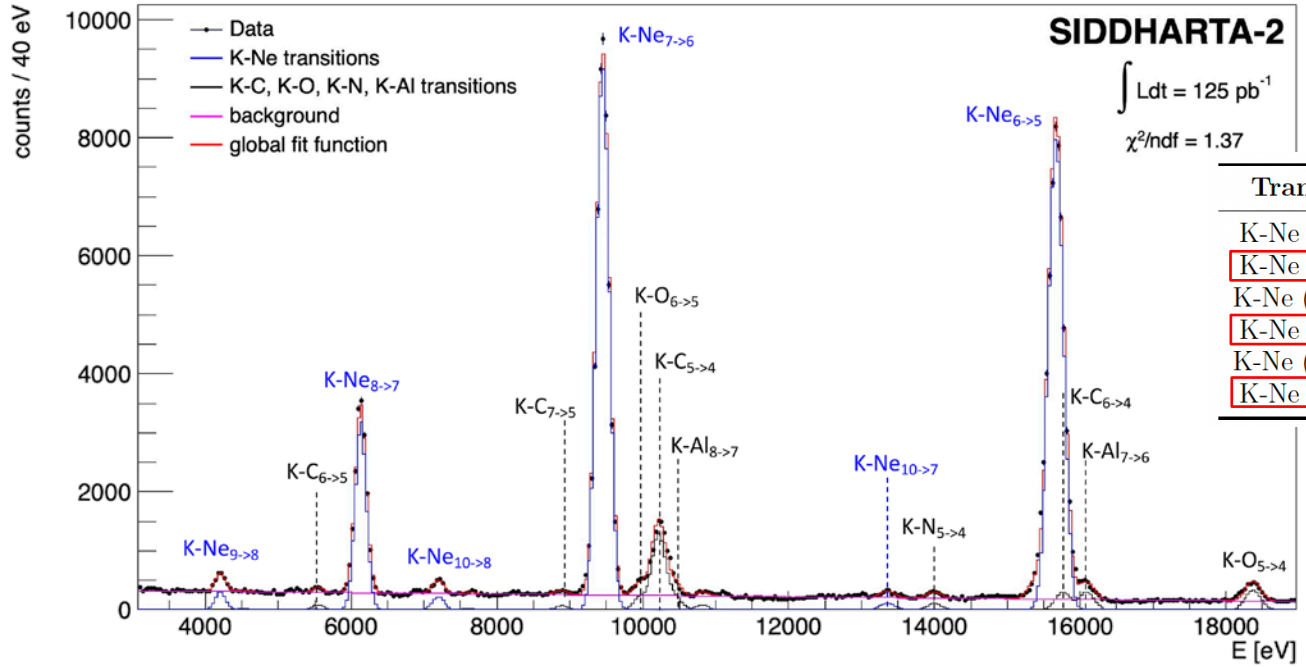


Experiment	ε_{1s} [eV]	Γ_{1s} [eV]	a_{K^-p} [fm]
SIDDHARTA-2 (this work)	-303.0 ± 17.0 (stat.) ± 2.5 (syst.)	607 ± 62 (stat.) ± 6 (syst.)	(-0.715±0.054) + i(0.905±0.091)
SIDDHARTA [20]	-283 ± 36 (stat.) ± 6 (syst.)	541 ± 89 (stat.) ± 22 (syst.)	(-0.68±0.11) + i(0.80±0.13)
KpX [18]	-323 ± 63 (stat.) ± 11 (syst.)	407 ± 208 (stat.) ± 100 (syst.)	(-0.883±0.20) + i(0.62±0.35)
DEAR [19]	-193 ± 37 (stat.) ± 6 (syst.)	249 ± 111 (stat.) ± 30 (syst.)	(-0.49±0.10) + i(0.35±0.16)

Article in preparation for PLB

The Kaonic Neon measurement (2023)

First measurement of high-n kaonic neon X-ray transitions
(sub eV statistical accuracy)



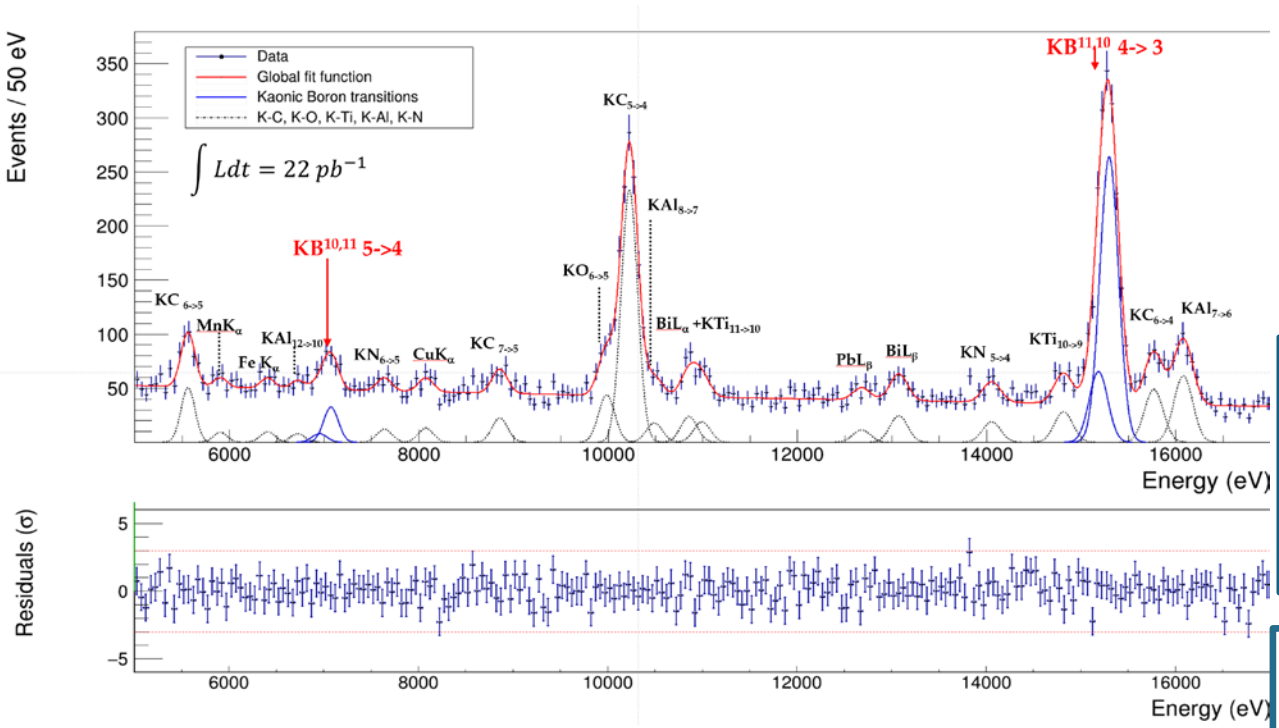
Transition	Energy [eV]
K-Ne $(9 \rightarrow 8)$	4206.35 ± 3.75 (stat) ± 2.00 (syst) eV
K-Ne $(8 \rightarrow 7)$	6130.86 ± 0.71 (stat) ± 1.50 (syst) eV
K-Ne $(10 \rightarrow 8)$	7191.21 ± 4.91 (stat) ± 2.00 (syst) eV
K-Ne $(7 \rightarrow 6)$	9450.08 ± 0.41 (stat) ± 1.50 (syst) eV
K-Ne $(10 \rightarrow 7)$	13352.20 ± 10.07 (stat) ± 3.00 (syst) eV
K-Ne $(6 \rightarrow 5)$	15673.30 ± 0.52 (stat) ± 9.00 (syst) eV

- precision measurements of high-n transitions in kaonic atoms using low-Z gaseous targets are feasible.
- **The first kaonic neon measurement** : a new refined measurement of the kaon mass and of precision tests of BSQED.→ **see talk of S.Manti**

Transition	Yield
K-Ne $(10 \rightarrow 8)$	0.010 ± 0.001 (stat) ± 0.001 (sys)
K-Ne $(9 \rightarrow 8)$	0.137 ± 0.012 (stat) ± 0.010 (sys)
K-Ne $(8 \rightarrow 7)$	0.228 ± 0.004 (stat) ± 0.011 (sys)
K-Ne $(7 \rightarrow 6)$	0.277 ± 0.002 (stat) ± 0.014 (sys)
K-Ne $(6 \rightarrow 5)$	0.308 ± 0.003 (stat) ± 0.015 (sys)

Kaonic Boron

Target: Boron, 75 mm x 50 mm, 2 mm thick, inserted bellow the vacuum window (at 5 mm)





Transition	Energy [eV]
K-^{11}B ($5 \rightarrow 4$)	$7064.62 \pm 16.93 \pm 2.00$
K-^{10}B ($5 \rightarrow 4$)	$6920.96 \pm 58.23 \pm 2.00$
K-^{11}B ($4 \rightarrow 3$)	$15293.33 \pm 4.8 \pm 5.30$
K-^{10}B ($4 \rightarrow 3$)	$15180.11 \pm 20.86 \pm 5.30$

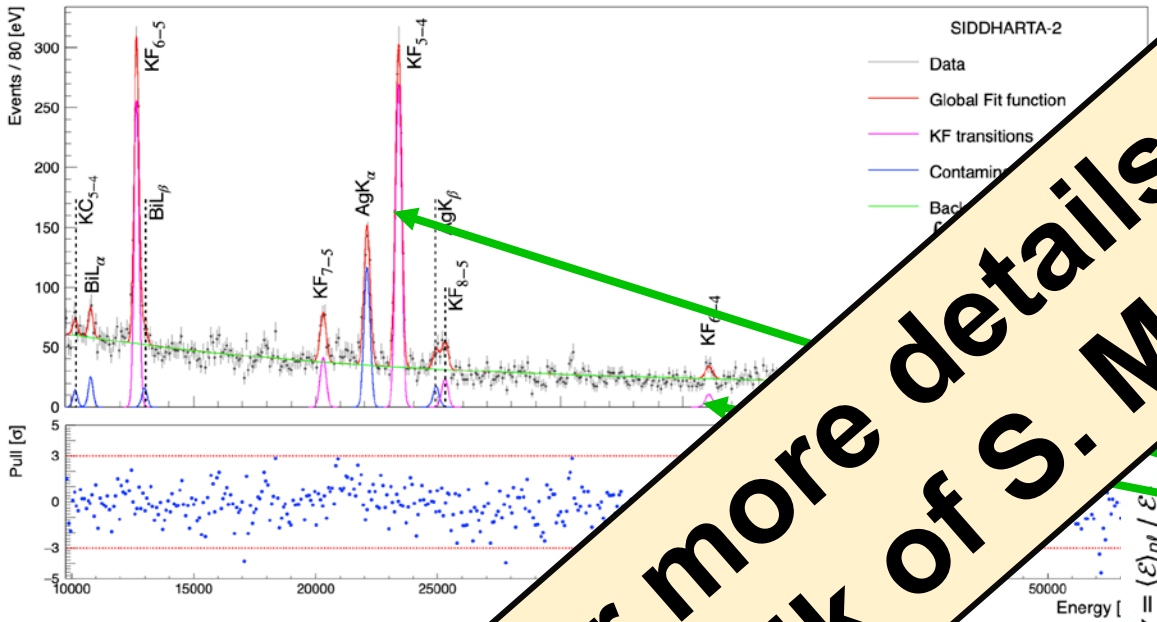
Transition	Number of events	Yield
K-^{11}B ($5 \rightarrow 4$)	127 ± 21	$0.076 \pm 0.013\ (stat)^{+0.011}_{-0.012}\ (syst.)$
K-^{11}B ($4 \rightarrow 3$)	1301 ± 64	$0.115 \pm 0.006\ (stat)^{+0.002}_{-0.005}\ (syst.)$

First experimental determination of the 5 → 4 and 4 → 3 transition yields -> new data to refine cascade models for kaonic boron and for kaonic atoms.

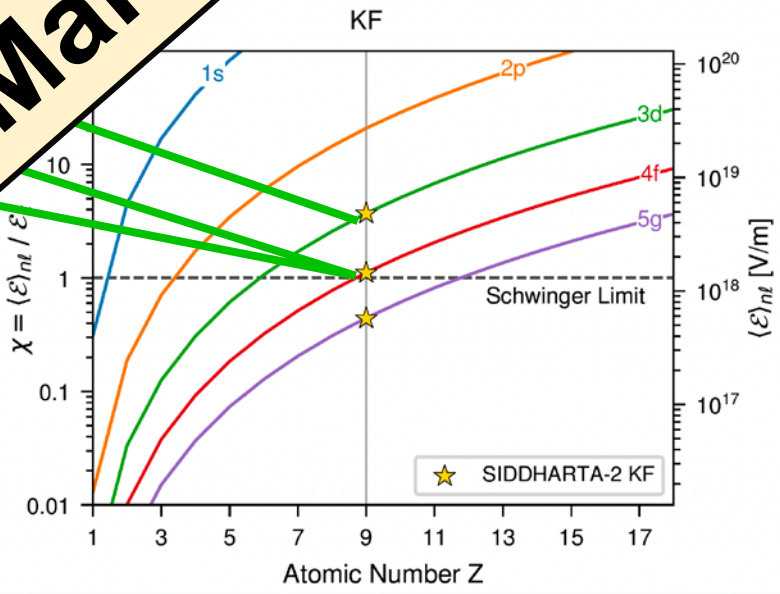
- provide **new data for the kaonic atoms database** of studying **light kaonic atoms using solid targets** -> enabling **investigations of kaon interactions with few-nucleon systems.**
- no statistically significant deviation from electromagnetic (QED) expectations.
- stringent constraints which exclude potentials producing energy shifts or widths exceeding a few eV in boron

Article submitted to J. Phys. G

Strong Field QED with Kaonic Atoms/KF



alk @ 70th
Scientific
Committee

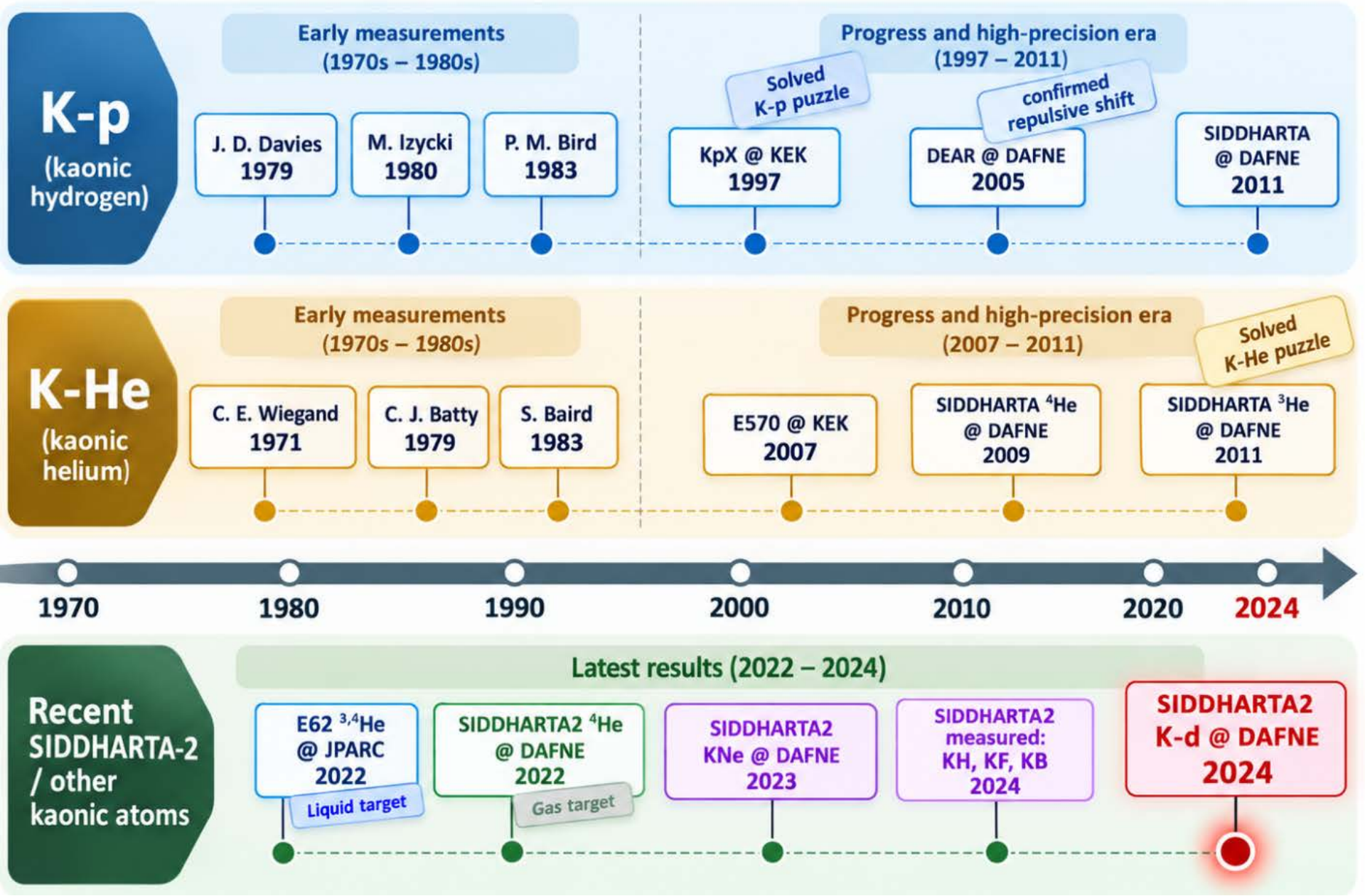


Kaonic atoms are opti… above the

Schwinger … where the Strong
Intera… ing any role

For more details: see talk of S. Manti

History of Kaonic Atoms Measurements



Beyond SIDDHARTA-2

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 measurements are the basis for all the theoretical model used for: $\bar{K}N$, $\bar{K}NN$ interaction at threshold, Kaon mass, Kaonic atoms cascade models

Available experimental information:

1. The available data on "lower atomic levels" have big uncertainties
2. For several kaonic atoms are actually unmeasured
3. Many of them are hardly compatible among each other
5. Absolute yields are unknown (except for few transitions)

All this limitations demonstrate
the need for new era of kaonic atoms 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]

The goal: not only to improve the accuracy of existing data, but also to extend the experimental database to a wider range of elements

EXKALIBUR

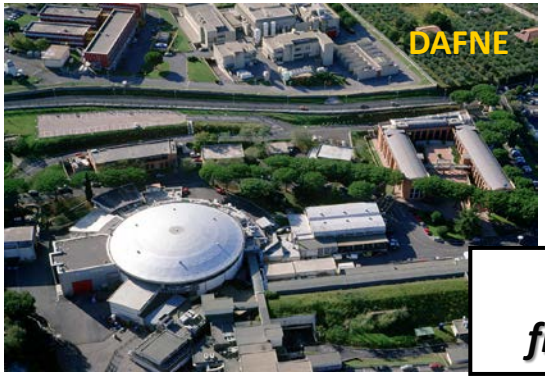
EXKALIBUR: high-precision kaonic-atom spectroscopy over a broad range of the periodic table

1.1 - High precision kaonic neon measurement
To extract the charged kaon mass with a precision of about 5 keV

BSQED and Physics beyond Standard Model

1.2 - Light kaonic atoms (LHKA)
– solid target Li, Be, B

Low energy strong interaction – kaon multi-nucleon interaction



EXKALIBUR

C. Curceanu et al., Front.in Phys. 11 (2023) 1240250

EXtensive Kaonic Atoms research: from LIthium and Beryllium to URanium



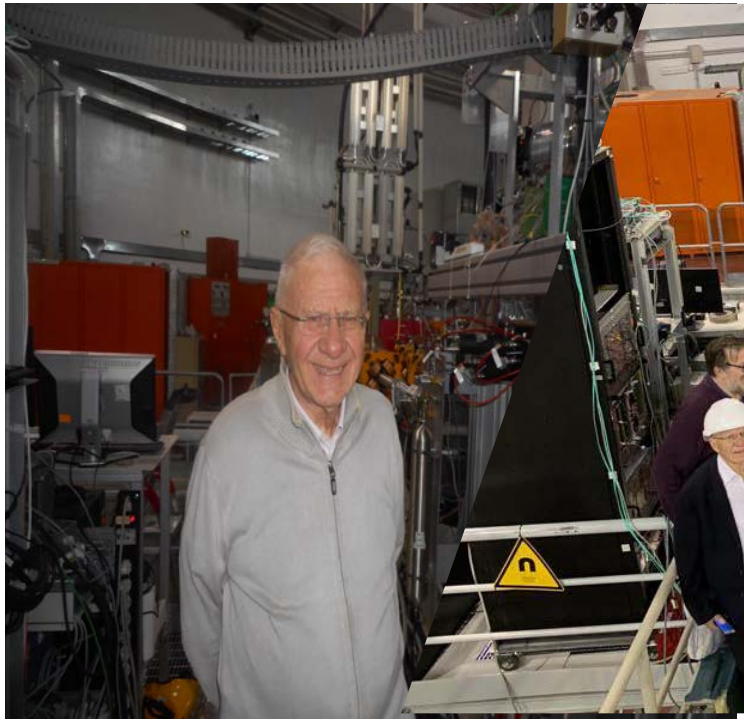
Intermediate kaonic atoms (IMKA)
In parallel we plan dedicated runs kaonic atoms such as *O, Al, S* with CdZnTe detectors
- 200 -300 pb^{-1} of integrated luminosity/target

Conclusions

- Kaonic atoms provide **a unique tool to test fundamental interactions**, in particular **low-energy strong interaction with strangeness.**
  - **The first measurement of kaonic deuterium**—awaited for more than 40 years—will significantly improve our understanding of the $\bar{K}N$ interaction.
  - A **new and more precise measurement of kaonic hydrogen**: implications for the $\bar{K}N$ interaction and the $\Lambda(1405)$
  - **Feasibility study of kaonic fluorine** opens the way to tests of **strong-field QED with kaonic atoms** and to searches for **physics beyond the Standard Model**.
  - Exploratory measurements of **kaonic neon demonstrated the feasibility of resolving the kaon mass–charge puzzle**

- These results lay the foundation for a **new era of precision kaonic atom spectroscopy at DAΦNE and J-PARC** within the **EXKALIBUR project**, aimed at exploring fundamental interactions from low-energy strong QCD to strong-field QED.

We dedicate these results to our dear friends and colleagues
Prof Carlo Guaraldo and Dr. Johann Zmeskal
who passed away in 2024. You are very much missed!







THANK YOU



THANK YOU





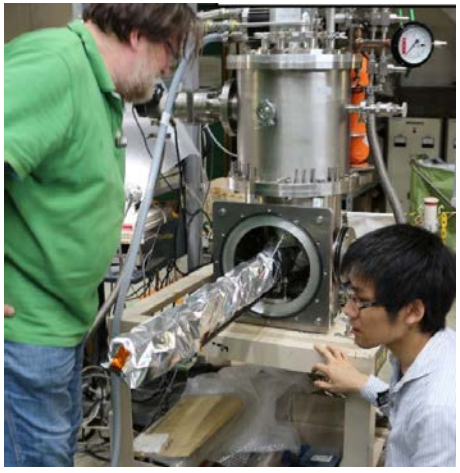












CONCLUSION

- The successful spectroscopy of kaonic deuterium opens the way to a new generation of experimental studies of low-energy QCD in the strangeness sector and provides a benchmark for theoretical descriptions of strongly interacting hadronic matter

- The last 25 years of kaonic atom precision measurements mark the modern era of kaonic atom experiments and **set new constraints on theories which deal with low-energy QCD in the strangeness sector.**

- The future of this sector will further enhance our understanding of *"strangeness physics"* in the non-perturbative regime of QCD, with implications ranging from particle and nuclear physics to astrophysics, contributing to a deeper knowledge of how nature works.

SPARES


THANK YOU!

Kaonic Atoms as Precision Probes: Experimental Challenges

2. Target Systems

Breakthrough in the signal intensity of light kaonic atoms

Lightweight gaseous high-density cryogenic targets
replaced liquid hydrogen, avoiding the drastic reduction of X-ray yields due to the **Stark mixing effect.**

General requirements for target systems

- **high-purity gas target systems** to avoid kaon losses due to the Stark effect
- **cryogenic temperature** for stable and efficient atomic cascade conditions
- **reduced material budget** in front of the X-ray detectors for optimum X-ray detection
- **thin target walls** facing the X-ray detectors; geometry adapted to each kaon source

Design priorities

- **Purity** — minimize Stark losses
- **Temperature** — cryogenic gas target
- **Transparency** — thin entrance/ window walls
- **Geometry** — matched to kaon source

Target design directly affects X-ray yield, background, and achievable precision.

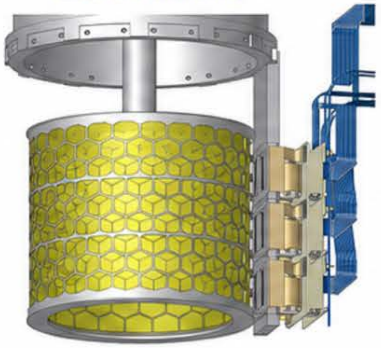
Representative Cryogenic Target Systems

SIDDHARTA, SIDDHARTA-2 and E57

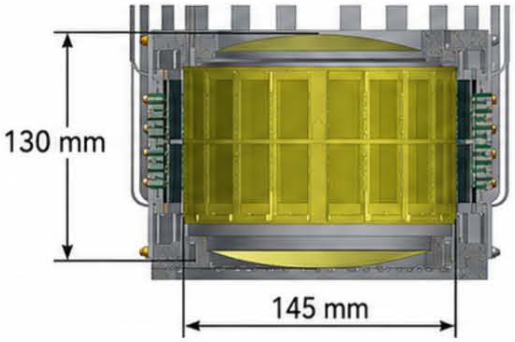
Parameter	SIDDHARTA	SIDDHARTA-2	E57
Active target volume (cm^3)	2400	**2100**	540
Target diameter (cm)	13.7	**14.5**	6.0
Working temperature (K)	20–25	**25–30**	25–30
Working pressure (MPa)	0.10	**0.25**	0.5
Gas density	1.8%[a]	**3%**[b]	4%[b]
Burst pressure (MPa)	0.40	**0.65**	0.80
Kapton entrance window (μm)	125	**125**	125
Kapton side wall (μm)	75	**140**	140

[a] Gas density as a fraction of the liquid hydrogen density (0.0708 g/cm^3).
[b] Gas density as a fraction of the liquid deuterium density (0.164 g/cm^3).

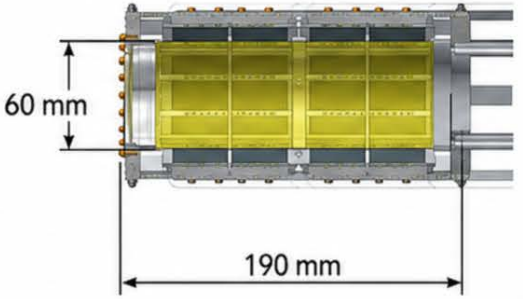
SIDDHARTA



SIDDHARTA-2



E57



Target design evolves with source conditions, density requirements, and X-ray detection constraints.

Kaonic Atoms as Precision Probes: Experimental Challenges

3. High-Performance X-ray Detectors

Progress in X-ray detector technology enabled higher precision, improved energy resolution and timing capability for modern kaonic-atom measurements: to measure weak signal of kaonic atoms over a large background.

Experiment	KpX 1998	DEAR 2005	E570 2007	SIDDHARTA 2009	SIDDHARTA-2, E57	E62
Detector	Si(Li)	CCD	SDD-KETEK	SDD-JFET	SDD-CUBE	TES
Effective area (mm^2)	200	724	1 × 100	3 × 100	8 × 64	~ 23
Thickness (mm)	5	0.03	0.26	0.45	0.45	0.003
Energy resolution @ 6 keV	410	150	190	160	170	5
Drift time (ns)	200	–	375	800	800	–

Modern SDD arrays: large active area and timing capability

TES: extreme energy resolution (~5 eV at 6 keV)

The new technologies and kaon beams: experiments which measured, with unprecedented precision, a series of kaonic atoms.

Kaonic Atoms as Precision Probes: Experimental Challenges

3. High-Performance X-ray Detectors

Progress in X-ray detector technology enabled higher precision, improved energy resolution and timing capability for modern kaonic-atom measurements.

Experiment	KpX 1998	DEAR 2005	E570	ARTA-2, E57	E62
Detector	Si(Li)	CCD		SDD-CUBE	TES
Effective area (mm^2)	200			8 × 64	~ 23
Thickness (mm)	5		0.45	0.45	0.003
Energy resolution @ 6 keV			160	170	5
Drift time (ns)		375	800	800	–

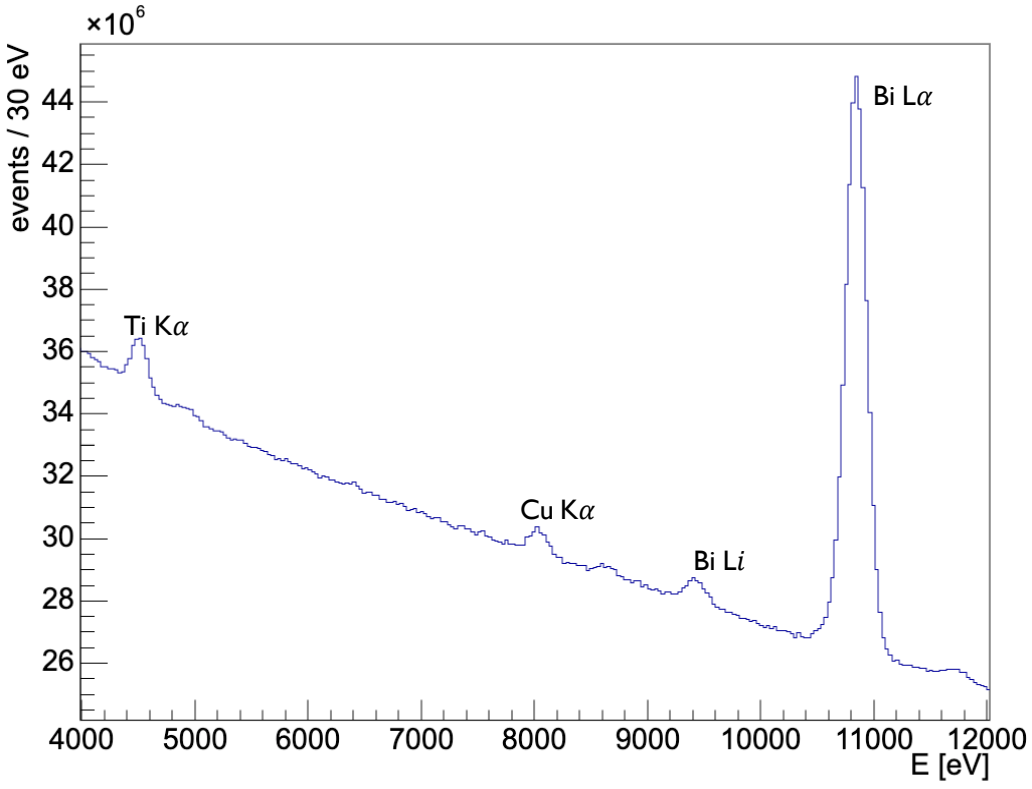
For more details: see talk of F. Sirghi

Modern SDD arrays: large active area and timing capability

TES: extreme energy resolution (~5 eV at 6 keV)

Kaonic deuterium analysis

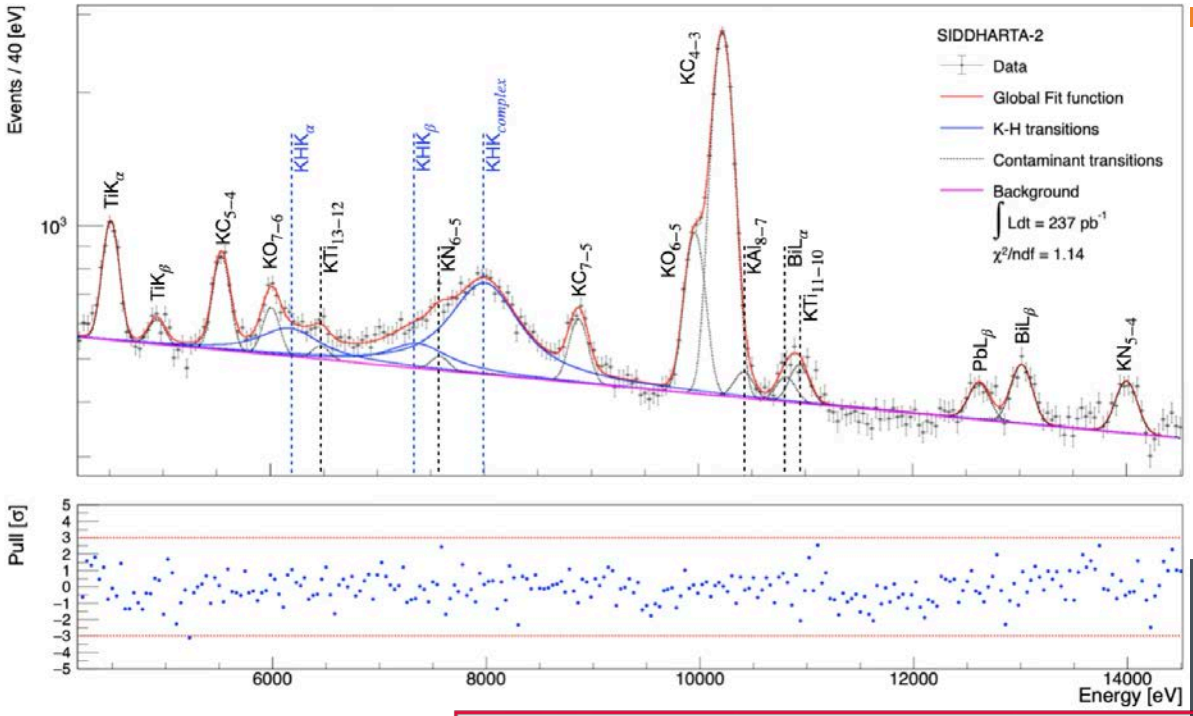
Inclusive energy spectrum: the continuous background and the fluorescence peaks are due to the electromagnetic (asynchronous) and hadronic (synchronous) background



- Electromagnetic (asynchronous) background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect → Kaon Trigger and SDDs drift time

-Hadronic (synchronous) background: associated to kaon absorption on materials nuclei, or to other Φ decay channels. It can be considered a hadronic background.
-Spectra contamination by Xray fluorescence or by X-rays produced in higher transitions of other kaonic atoms, formed in the setup materials → Veto systems

MEASUREMENT



(about 250 pb^{-1})

Article in preparation for PLB

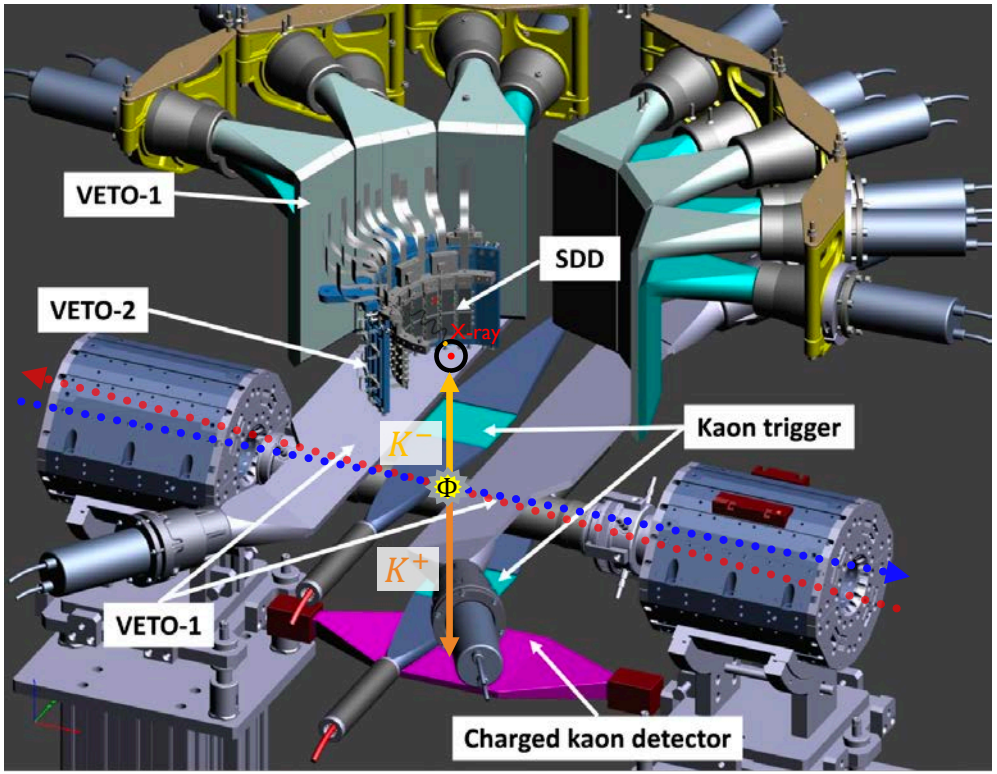
$$\begin{cases} \varepsilon_{1s} = -303 \pm 17\,(\text{stat}) \pm 2.5\,(\text{syst})\,eV \\ \Gamma_{1s} = 607 \pm 62\,(\text{stat}) \pm 6\,(\text{syst})\,eV \end{cases} \qquad \begin{cases} \mathcal{R}e[a_{K^-p}] = -0.715 \pm 0.054\,fm \\ \mathcal{I}m[a_{K^-p}] = 0.905 \pm 0.091\,fm \end{cases}$$

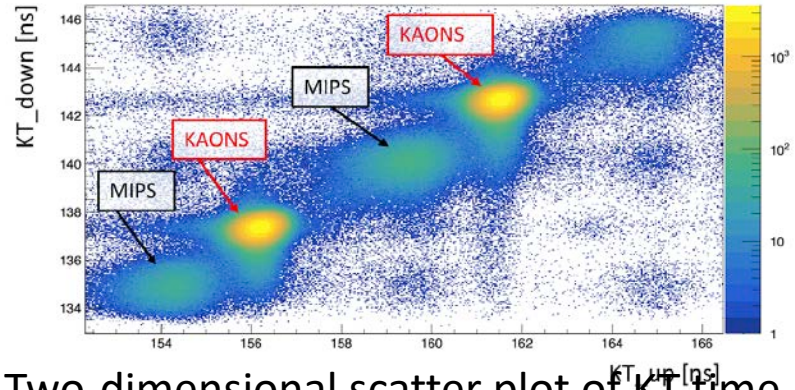
Experiment	ε_{1s} [eV]	Γ_{1s} [eV]	a_{K^-p} [fm]
SIDDHARTA-2 (this work)	-303.0 ± 17.0 (stat.) ± 2.5 (syst.)	607 ± 62 (stat.) ± 6 (syst.)	(-0.715±0.054) + i(0.905±0.091)
SIDDHARTA [20]	-283 ± 36 (stat.) ± 6 (syst.)	541 ± 89 (stat.) ± 22 (syst.)	(-0.68±0.11) + i(0.80±0.13)
KpX [18]	-323 ± 63 (stat.) ± 11 (syst.)	407 ± 208 (stat.) ± 100 (syst.)	(-0.883±0.20) + i(0.62±0.35)
DEAR [19]	-193 ± 37 (stat.) ± 6 (syst.)	249 ± 111 (stat.) ± 30 (syst.)	(-0.49±0.10) + i(0.35±0.16)

- represent the most precise determination to date.
- impact on theoretical models describing the low-energy antiKN interaction
- the achieved accuracy: more precise determination of the complex K− p scattering length

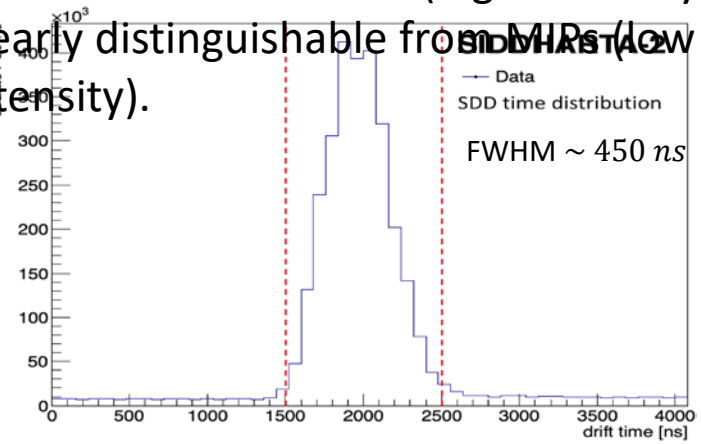
Kaonic deuterium analysis

The trigger is generated by the coincidence of 2 back-to-back scintillators. The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs). ToF analysis can efficiently discriminate the Kaons from MIPs!



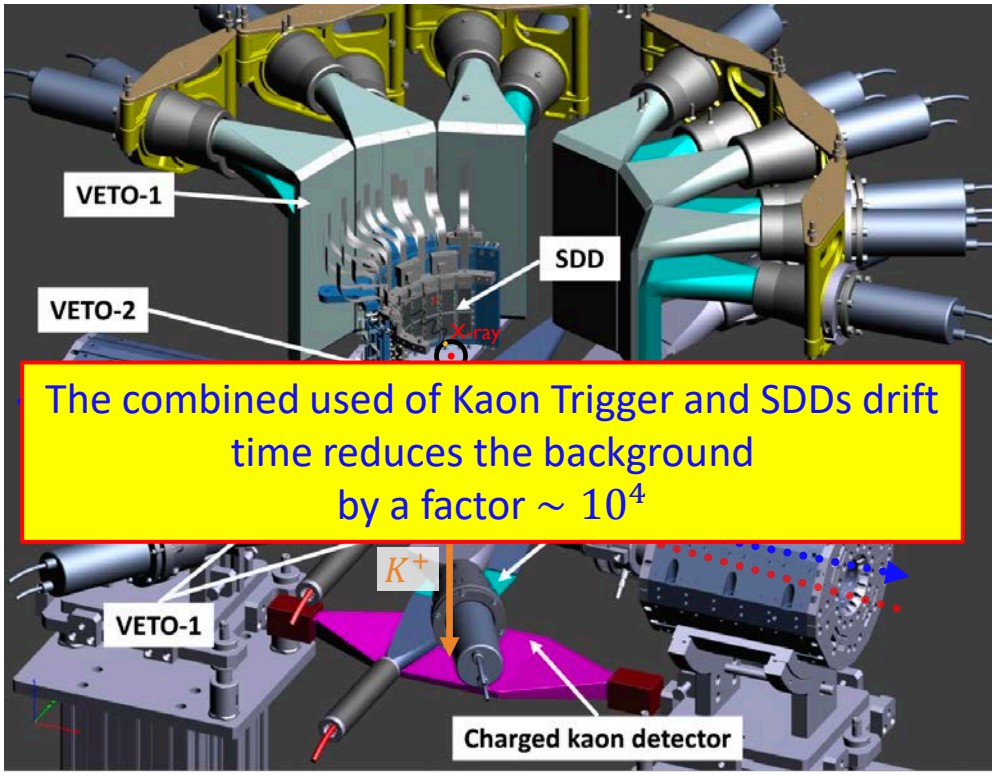


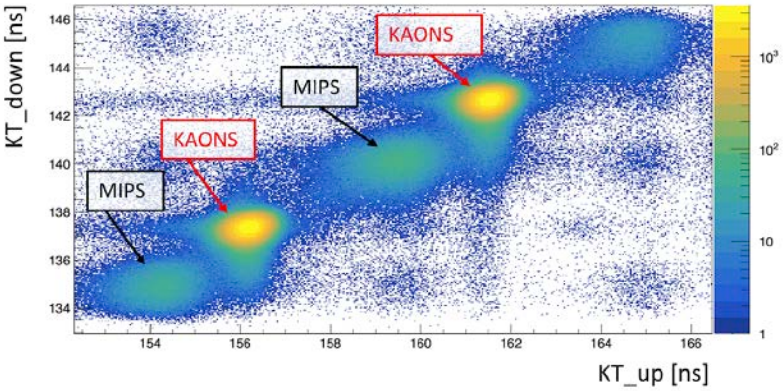
Two-dimensional scatter plot of KT time distributions. The coincidence events related to kaons (high intensity) are clearly distinguishable from MIPs (low intensity).

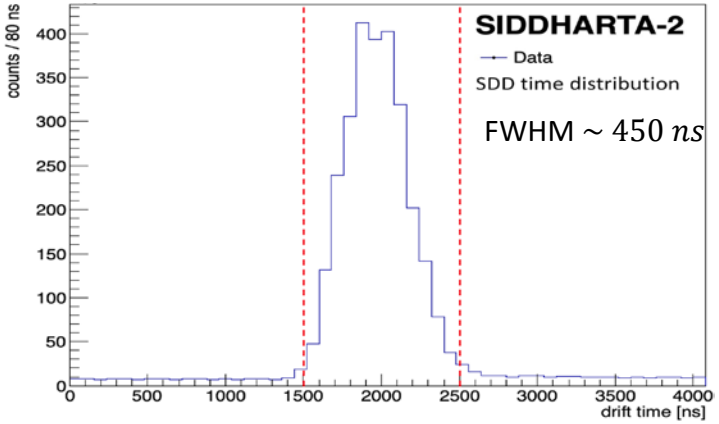


Kaonic deuterium analysis

The trigger is generated by the coincidence of 2 back-to-back scintillators. The ToF is different ($\sim 2\ ns$) for Kaons, m(K)~ 500 MeV/c^2 and light particles originating from beam-beam and beam-environment interaction (MIPs). ToF analysis can efficiently discriminate the Kaons from MIPs!

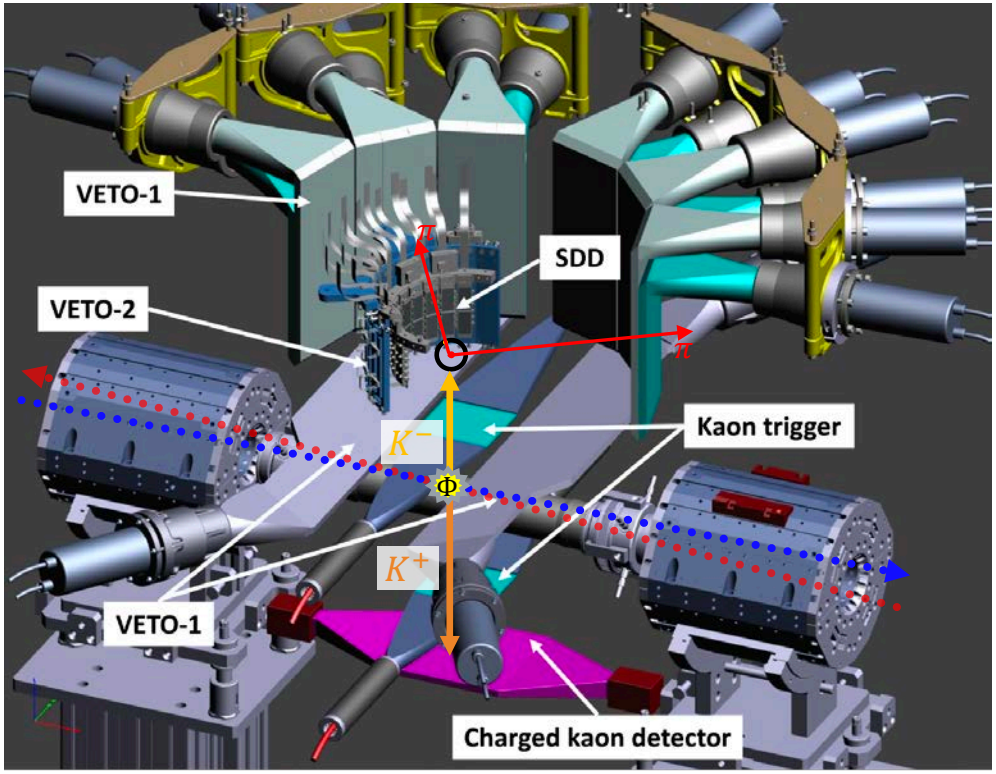






Kaonic deuterium analysis

The combined use of the veto systems further reduces the background by a factor of 3



Veto-1 (fiducial volume selection): to select the events occurring in the gas target, rejecting the X-ray background corresponding to K- stopped in the solid elements of the setup.

Veto-2 (charged particle rejection): 48 plastic scintillator read by SiPMs to distinguish X-ray from charged particle by topological correlation with the SDD.

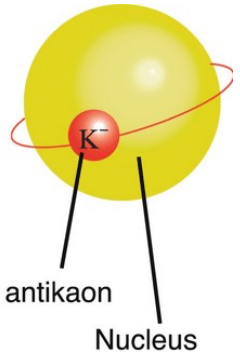
Charged kaon detector: distinguishes K^+ from K^- by exploiting their different interaction mechanisms with matter.

Beyond SIDDHARTA-2: EXKALIBUR

The measurement for the **first EXKALIBUR module** were selected based on two criteria:
Feasibility with **minimal modifications/addings** of the already existent SIDDHARTA-2 setup and within a reduced timescale

Impact: i.e. the **maximal scientific outcome:**

Kaonic Neon -> charge kaon mass (precision goal 5-7 keV)



EXtensive
Kaonic
Atoms research: from
LIthium and
Beryllium to
URanium

Precision measurements along the periodic table at DAΦNE for:

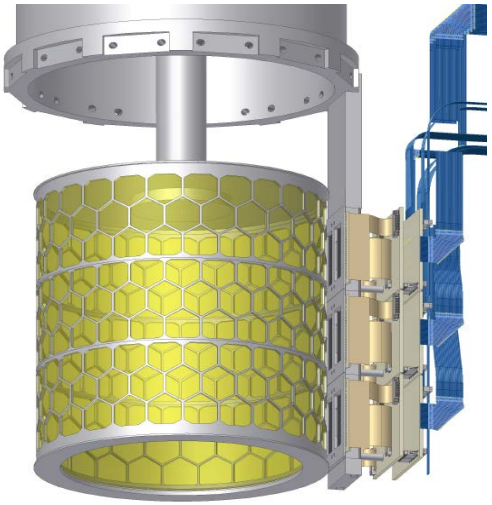
- **Selected light kaonic atoms (LHKA) – Li, Be, B**
- **Selected intermediate and heavy kaonic atoms (IMKA) – Al, C, O, S, Pb**

Dedicated runs with different types of detectors: CZT detectors, SDDs

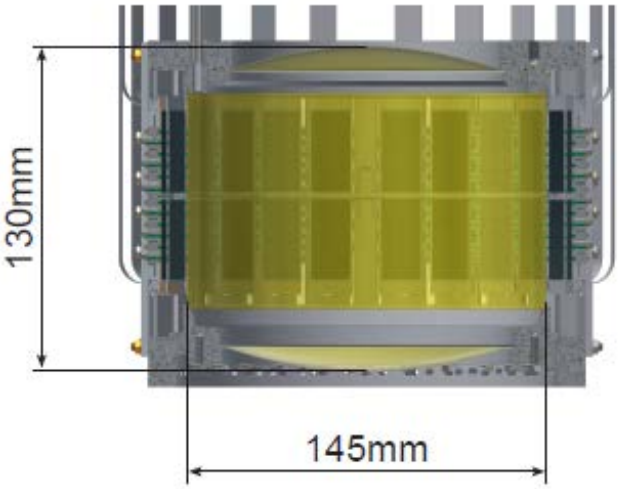
	SIDDHARTA	SIDDHARTA-2	E57
Active target volume (cm^3)	2400	2100	540
Target diameter (cm)	13.7	14.5	6.0
Working temperature (K)	20–25	25–30	25–30
Working pressure (MPa)	0.10	0.25	0.5
Gas density	1.8%[a]	3%[b]	4%[b]
Burst pressure (MPa)	0.40	0.65	0.80
Kapton entrance window (μm)	125	125	125
Kapton side wall (μm)	75	140	140

[a]Gas density as a fraction of the liquid hydrogen density (0.0708 g/cm^3).
[b]Gas density as a fraction of the liquid deuterium density (0.164 g/cm^3).

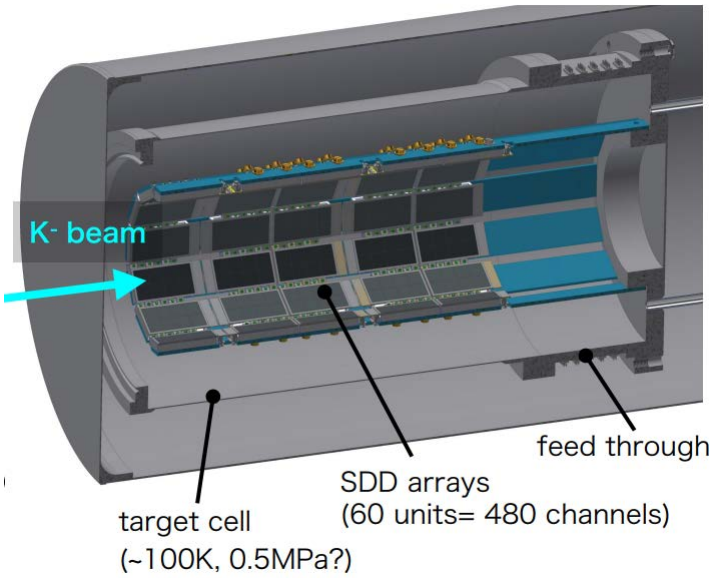
SIDDHARTA



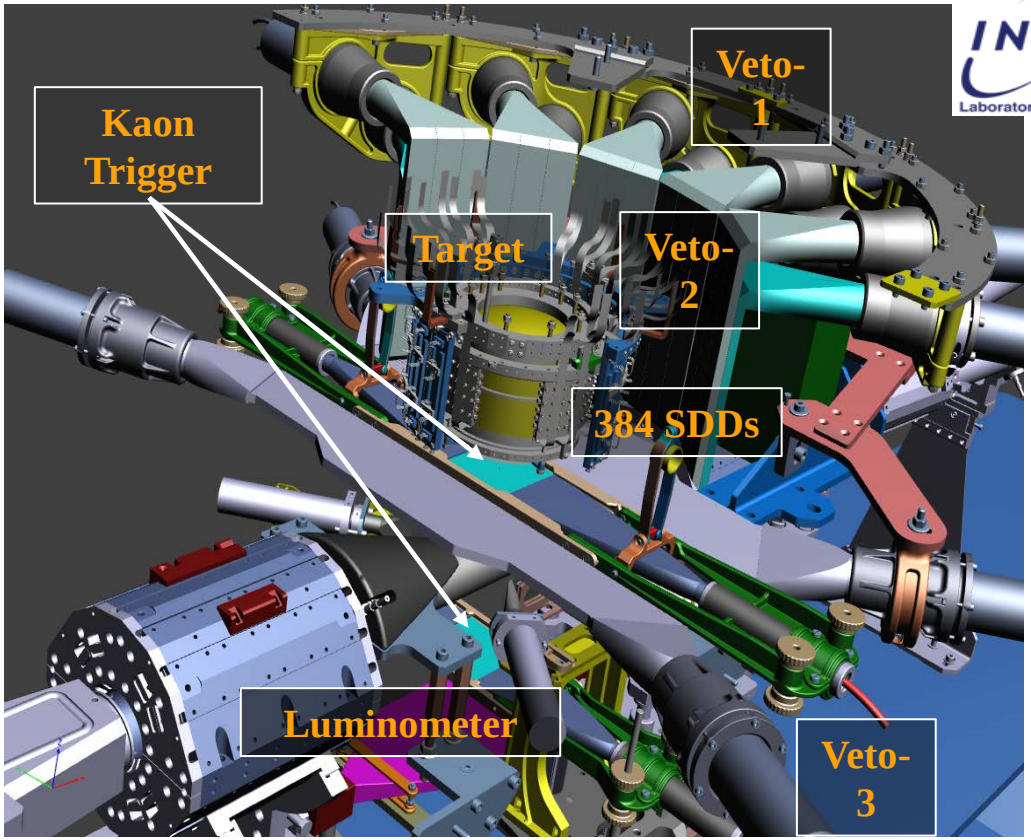
SIDDHARTA-2



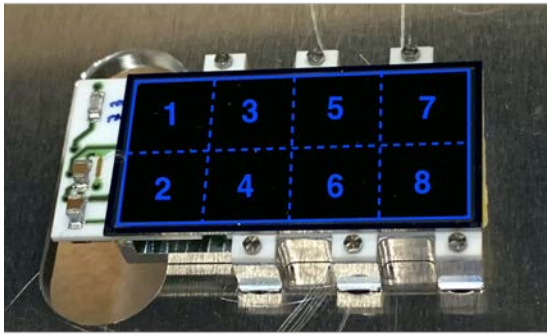
E57 –updated strategy



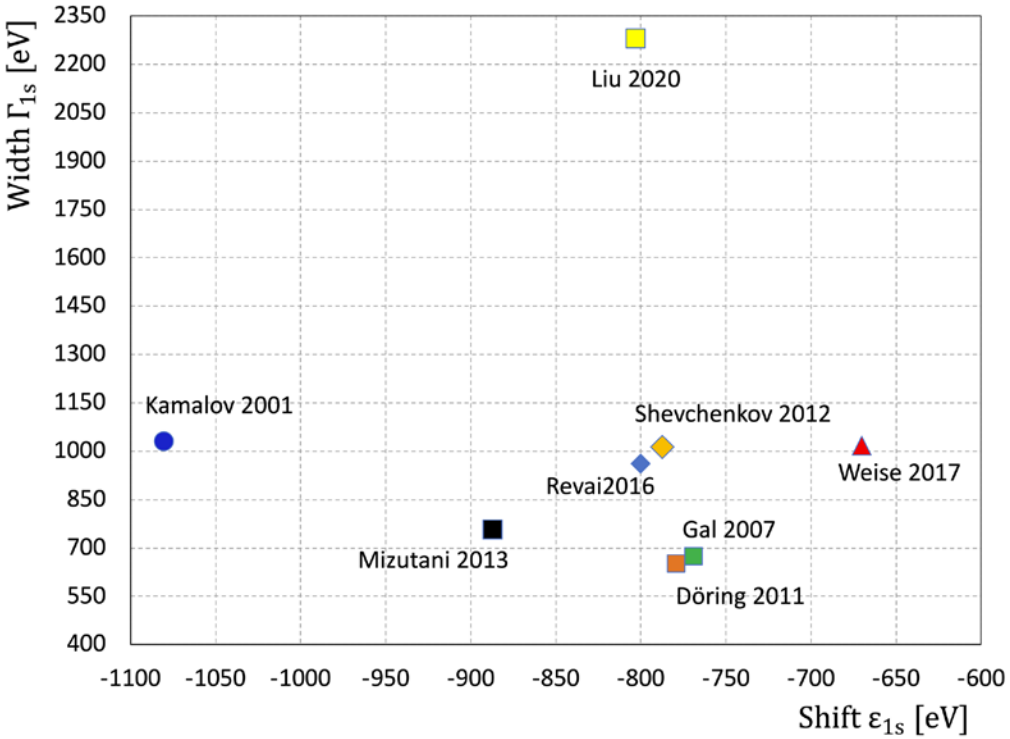
The SIDDHARTA-2 setup



48 Silicon Drift Detector arrays with 8 SDD units (0.64 cm^2) for a total active area of 246 cm^2
The thickness of 450 µm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV



SIDDHARTA-2: Kaonic deuterium measurement (2023-2024)



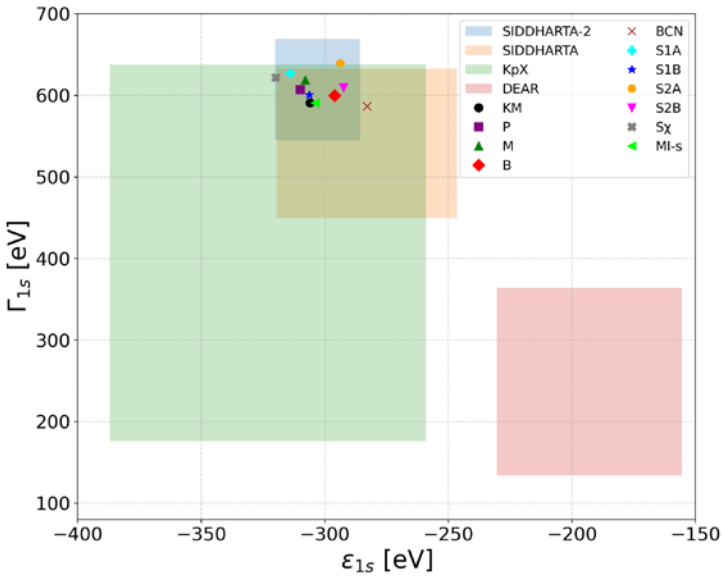
Theoretical predictions for the kaonic deuterium 1s level shift and width

"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 $\bar{K}N$ interaction and their complete independence from all other kinds of measurements which bear on this interaction".

R.H. Dalitz (1982)

New Kaonic Hydrogen measurement

[*Article in preparation for PLB*]



- A more precise measurement of KH improves the precision of KN potentials
- Useful to clarify the subthreshold extrapolation together with the nature of the Λ(1405)
- Resonant state in the I=0 channel, sensitive to a_{Kp} almost insensitive to a_{KN}
- Critical for KD: more accurate 2-body amplitude input yields **more reliable 3-body calculations**

A New Measurement of Kaonic Hydrogen X-rays #1

SIDDHARTA Collaboration • M. Bazzi (Frascati) et al. (May, 2011)

Published in: *Phys.Lett.B* 704 (2011) 113-117 • e-Print: 1105.3090 [nucl-ex]

pdf DOI cite claim reference search 438 citations

Experiment	ε_{1s} [eV]	Γ_{1s} [eV]	a_{K^-p} [fm]
SIDDHARTA-2 (this work)	-303.0 ± 17.0 (stat.) ± 2.5 (syst.)	607 ± 62 (stat.) ± 6 (syst.)	(-0.715±0.054) + *i*(0.905±0.091)
SIDDHARTA [20]	-283 ± 36 (stat.) ± 6 (syst.)	541 ± 89 (stat.) ± 22 (syst.)	(-0.68±0.11) + *i*(0.80±0.13)
KpX [18]	-323 ± 63 (stat.) ± 11 (syst.)	407 ± 208 (stat.) ± 100 (syst.)	(-0.883±0.20) + *i*(0.62±0.35)
DEAR [19]	-193 ± 37 (stat.) ± 6 (syst.)	249 ± 111 (stat.) ± 30 (syst.)	(-0.49±0.10) + *i*(0.35±0.16)

65

Why Kaonic Atoms?

Particle and Nuclear Physics
to low-energy strong interactions in systems containing strangeness
QCD at low energy limit
Chiral symmetry • Lattice QCD

Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 547

Fundamental Physics
high-lying transitions used for precision tests of **Bound-State QED • New Physics**

The modern era of light kaonic atom experiments
Rev. Mod. Phys. 91 (2019) 025006

Kaonic atoms
Kaon–nuclei interactions
(scattering and nuclear interactions)

Dark Matter and BSM
New hadronic forces • Exotic systems

Probing new hadronic forces with heavy exotic atoms (2025)
On self-gravitating strange dark matter halos around galaxies

Astrophysics
Dense matter • Neutron-star EOS

The equation of state of dense matter: stiff, soft, or both?
Astron. Nachr. 340 (2019) 189

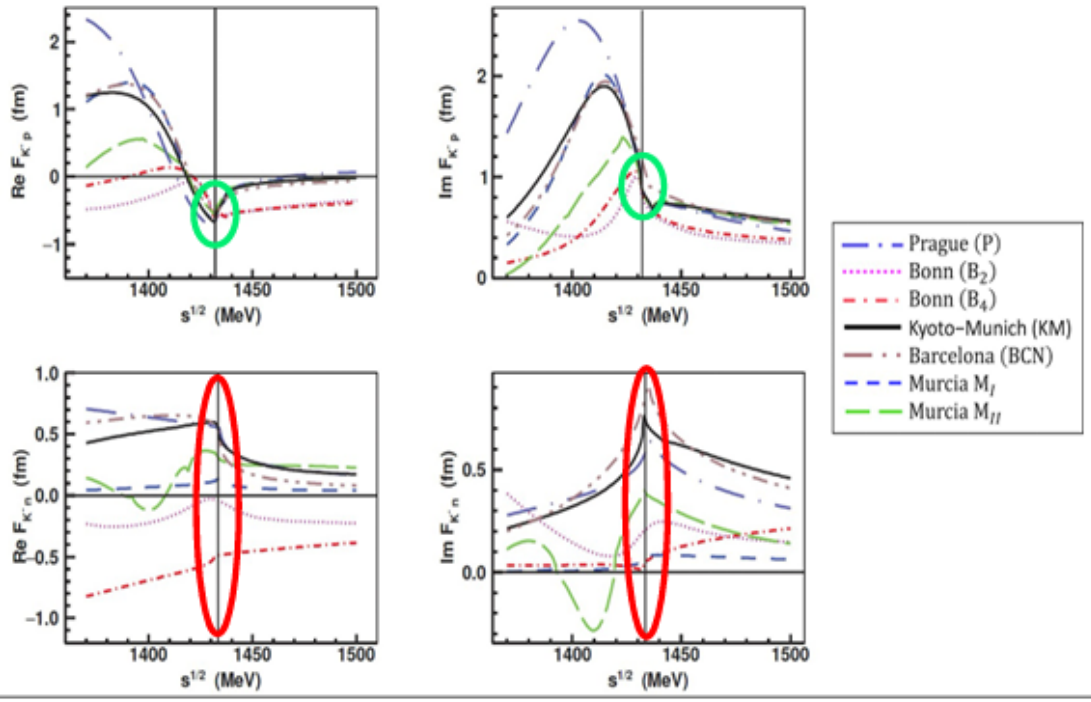
Kaonic Deuterium analysis: next steps

The combined analysis of kaonic deuterium and hydrogen will have implications in nuclear, particle and astrophysics, providing experimental inputs to solve the discrepancy between the theoretical prediction for K-n scattering amplitudes

K-p and K-n scattering amplitudes

K-p: agreement

K-n: disagreement



Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

Experimental challenges towards K^-d

- X-ray yield: K^-p ~ 1 %

  K^-d ~ 0.1 %

- 1s state width: K^-p ~ 540 eV

  K^-d ~ 800 – 1000 eV

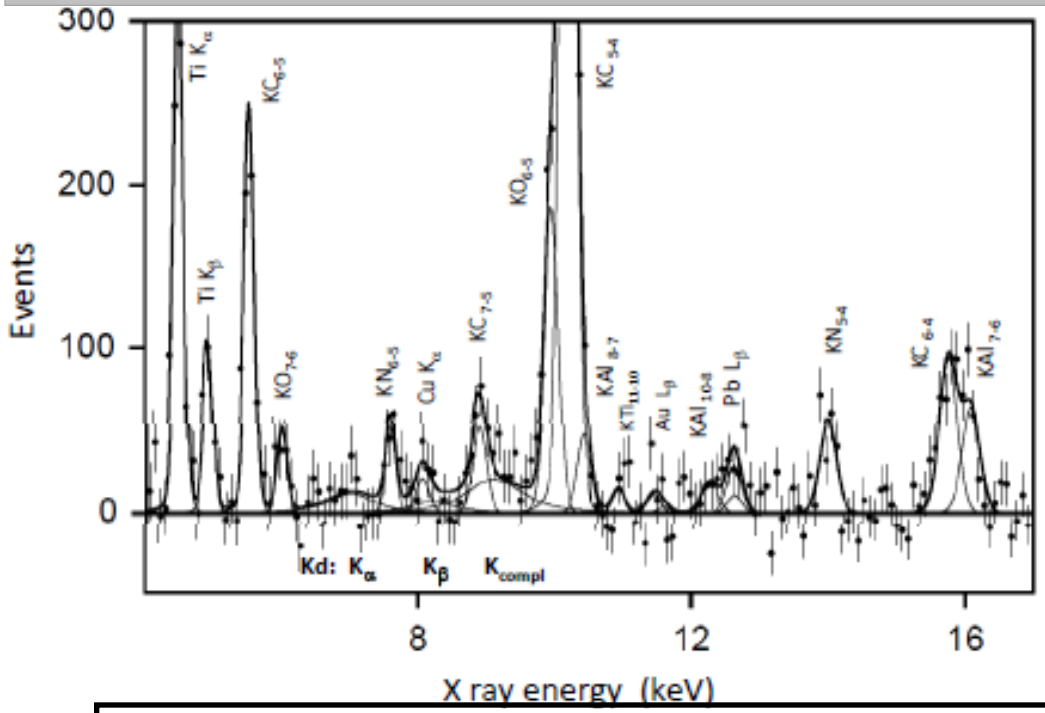
BG sources: asynchronous BG → timing
synchronous BG → spatial correlation

The kaonic deuterium measurements at DAΦNE and at J-PARC require:

- a large area x-ray detector, with good energy and timing resolution
- stable working conditions, even in the high accelerator
- dedicated veto detector system, to improve by at least 1 order of magnitude the signal-to-background ratio, as compared to the kaonic-hydrogen measurement performed by SIDDHARTA.
- dedicated cryogenic lightweight gaseous target system

SIDDHARTA Kd exploratory measurement

First exploratory measurement for Kd



$Y(K_{tot}) = 0.0077 \pm 0.0051$

Kd K_α yield $Y(K_\alpha) = 0.0019 \pm 0.0012$

Yield of a factor about 10 smaller then the KH yield, estimated to be 1 to 2 % for K_α.

an enhancement by one order of magnitude of the signal-to background ratio is required for SIDDHARTA-2.

Experimental challenges towards K^-d

- X-ray yield: K^-p ~ 1 %

  K^-d ~ 0.1 %

- 1s state width: K^-p ~ 540 eV

  K^-d ~ 800 – 1000 eV

BG sources: asynchronous BG → timing
synchronous BG → spatial correlation

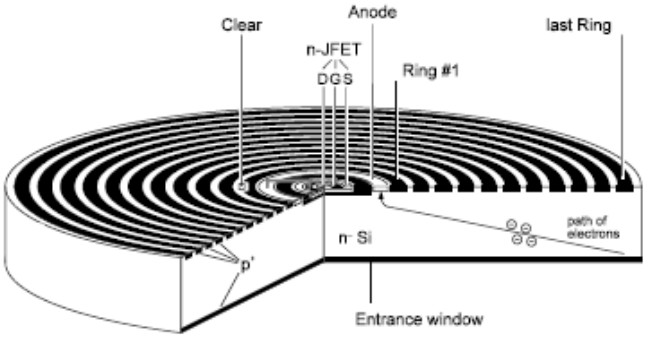
The kaonic deuterium measurements at DAΦNE and at J-PARC require:

- a large area x-ray detector, with good energy and timing resolution
- stable working conditions, even in the high accelerator
- dedicated veto detector system, to improve by at least 1 order of magnitude the signal-to-background ratio, as compared to the kaonic-hydrogen measurement performed by SIDDHARTA.
- dedicated cryogenic lightweight gaseous target system

New SDD detectors for SIDDHARTA-2 and E57

difference with respect to the SDDs in SIDDHARTA:

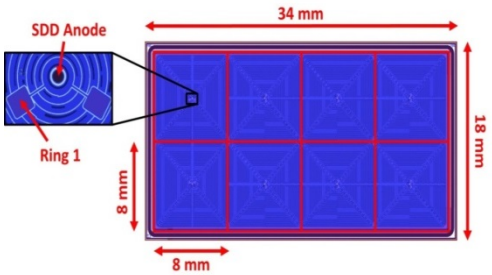
- the change of the preamplifier system from the JFET structure on the SDD chip to a complementary metal-oxide semiconductor integrated charge sensing amplifier CUBE), able to operate at very low temperatures (below 50 K) (standard SDD technology)
- reduction of the single element size (from 10 × 10 to 8 × 8 mm2)

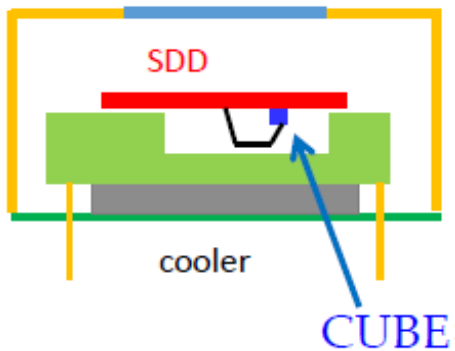




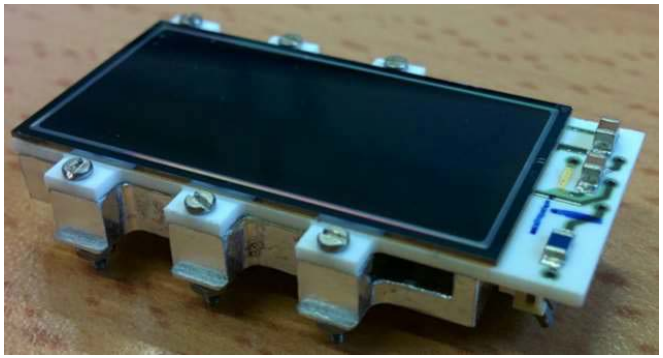
radiation entrance window

Better drift time of 300 ns compared to the SDDs in SIDDHARTA (~800 ns)





Monolitic 4x2 SDD array - single unit



SDD characteristics:

- area/cell = 64 mm^2
- total area = 512 mm^2
- T = - 100°C
- drift time < 500 ns

Lightweight cryogenic target: SIDDHARTA-2 and E57

Main component of both cells :

- cylindrical wall, two layers of 50 μm thick Kapton foils glued together with a two component epoxy glue, with an overlap of 10 mm
- achieving a total thickness of the order of (140 ± 10) μm w
- an x-ray transmission of 85% at 7 keV.

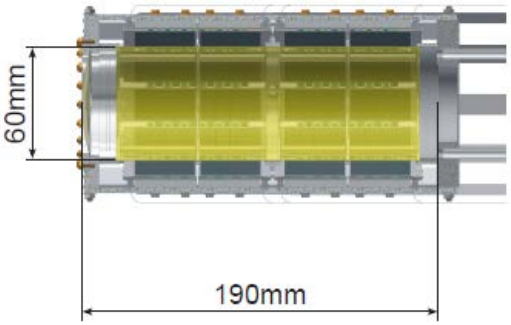
The final dimensions of the target cells depend on the machine used.

- **DAΦNE, SIDDHARTA-2:** low momentum monochromatic kaons (127 MeV/c) → **low thickness degrader**, few mm plastic for kaon st**opping efficiency of almost 100%.**
- **J-PARC, E57** : kaons momentum of 660 MeV/c → kaon carbon degrader with a thickness of ~400 mm to achieve a **kaon stop efficiency of ~2%.**
- The gas density for SIDDHARTA-2 and E57 : 3% and 4% of the liquid deuterium density,

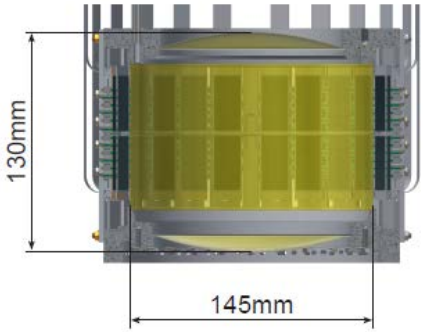
Therefore, the dimensions of the target cells are quite different

- for SIDDHARTHA-2 the diameter145 mm, height 130 mm,
- for E57 the diameter 60 mm, length 190 mm

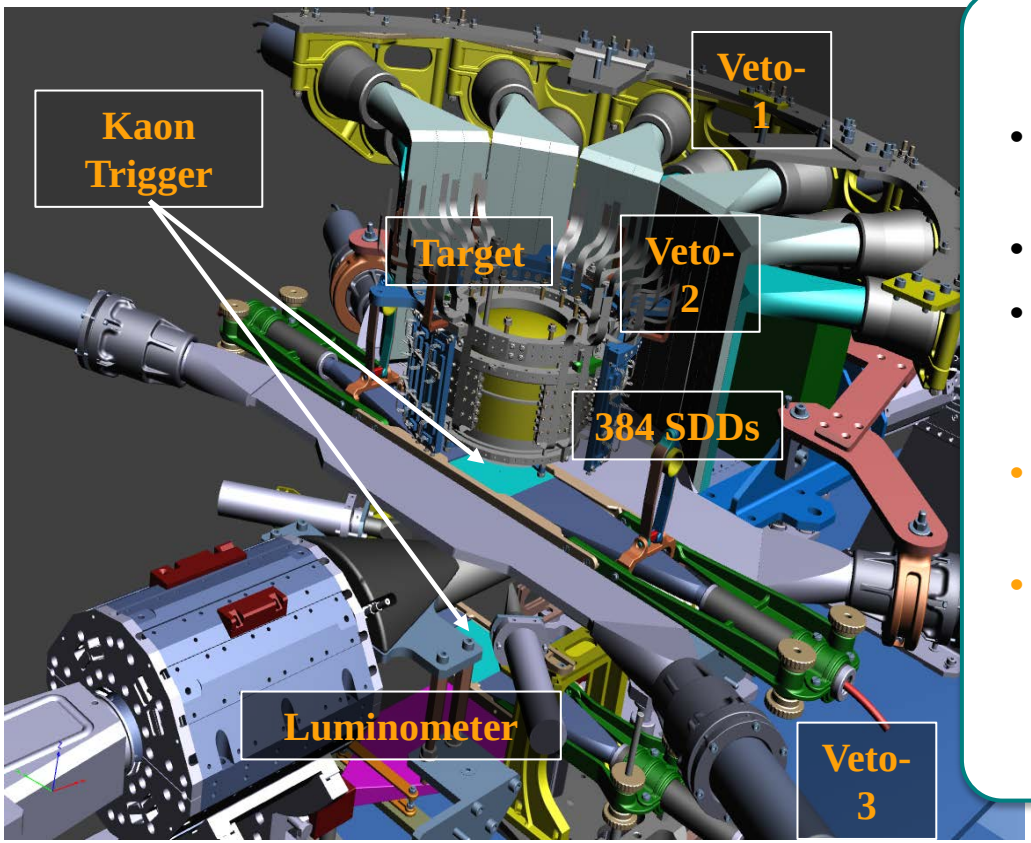
E57



SIDDHARTA-2



The SIDDHARTA-2 setup



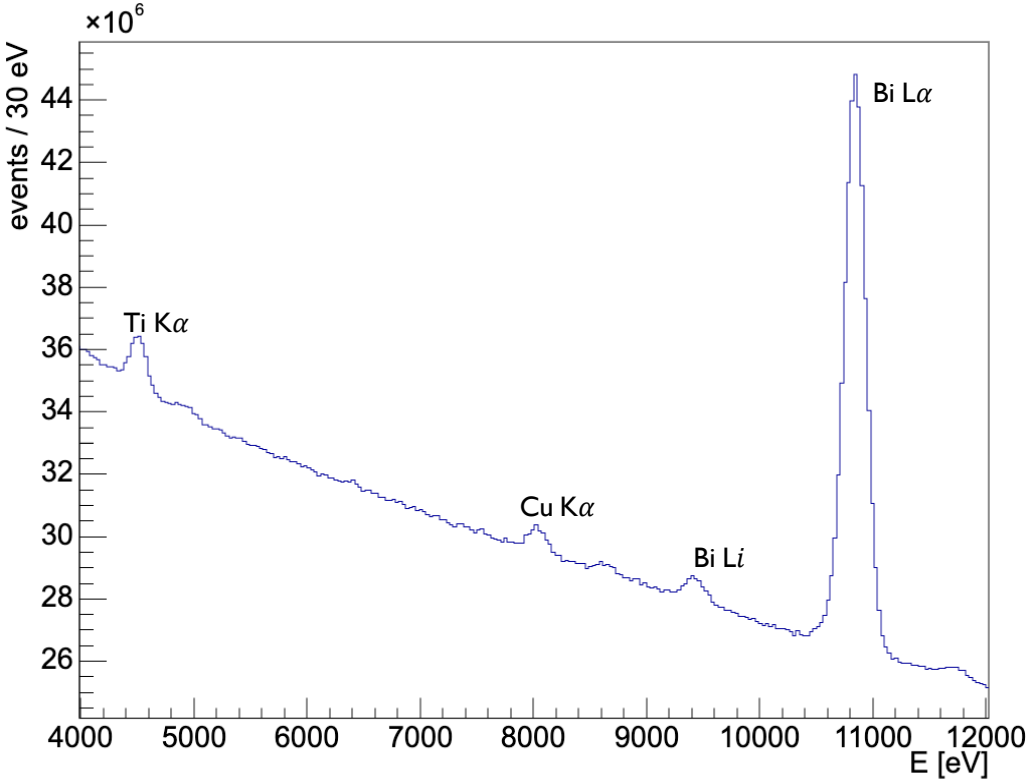
Key upgrades

- New generation of **Silicon Drift Detectors** and read-out electronics
- SDD active area **2 times larger**
- SDD **time resolution 450 ns** (instead of 800 ns in SIDDHARTA), **background rejection improved by a factor of 2**
- **New trigger, lead shielding and DAΦNE optics**: **background reduced by a factor of 3**
- **3 veto systems** for hadronic background suppression: **background reduced by an additional factor of 2**

74

Kaonic deuterium analysis

Inclusive energy spectrum: the continuous background and the fluorescence peaks are due to the electromagnetic (asynchronous) and hadronic (synchronous) background



The high continuous background contribution prevents to directly observe the kaonic deuterium signal

- Electromagnetic (asynchronous) background: the electromagnetic shower produced in the accelerator pipe (and other setup materials) invested by e-/e+ lost from the beam overlaps the signal; the loss rate in the interaction region reaches few MHz. The main contribution comes from Touschek effect → Kaon Trigger and SDDs drift time

-Hadronic (synchronous) background: associated to kaon absorption on materials nuclei, or to other Φ decay channels. It can be considered a hadronic background.
-Spectra contamination by Xray fluorescence or by X-rays produced in higher transitions of other kaonic atoms, formed in the setup materials → Veto systems

Kaonic Deuterium: next steps

- Evaluation of the **kaonic deuterium X-ray yield** (high and low density runs) **-> article**
- Evaluation of the **kaonic deuterium scattering length** (in collaboration with theoreticians) **-> article**
- **Combined analysis of kaonic hydrogen and deuterium to determine the isospin dependent antikaon-nucleon scattering lengths (in collaboration with theoreticians) and implication for theory -> article(s)**
- **Necessary enhanced precision: to disentangle between models**

76

K-p

K-He

1970

J. D. Davies 1979

M. Izycki 1980

P. M. Bird 1983

C. E. Wiegand 1971

C. J. Batty 1979

S. Baird 1983

1980

Solved K-p puzzle

Significant improvement!

KpX @ KEK 1997

2000

Solved K-He puzzle

E570 @ KEK 2007

confirmed repulsive shift

DEAR @ DAFNE 2005

2010

SIDDHARTA ^{4}He @ DAFNE 2009

SIDDHARTA ^{3}He @ DAFNE 2011

SIDDHARTA @ DAFNE 2011

2022

E62 ^{3,4}He @ JPARC 2022

Liquid target

Gas target

SIDDHARTA2 ^{4}He @ DAFNE 2022

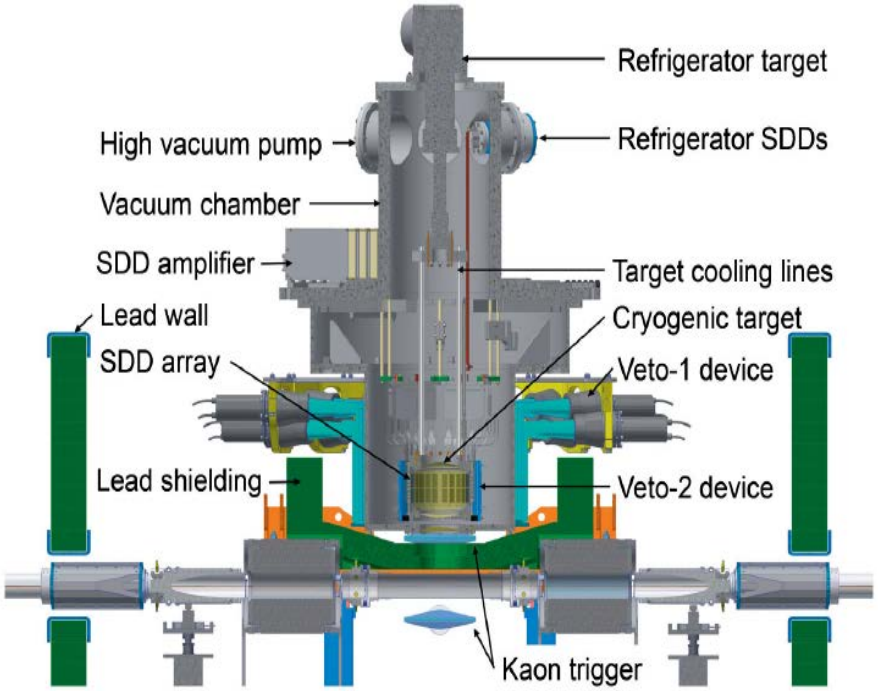
SIDDHARTA2 KNe @ DAFNE 2023

SIDDHARTA2 K-d @ DAFNE 2024

2024

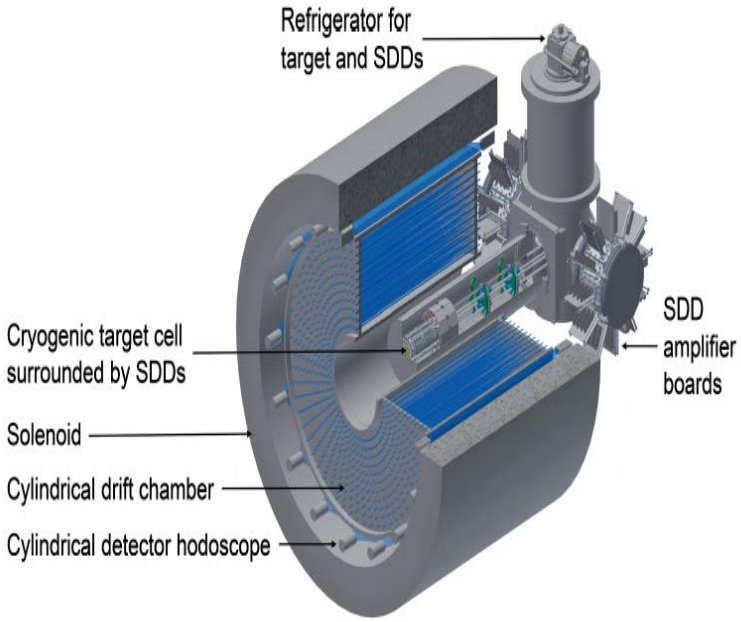
SIDDHARTA2 measured: KH, KF, KB

SIDDHARTA-2



SIDDHARTA – 2, installed in DAΦNE from April 2019, ready to start to take data for kaonic deuterium: 2020

E57



E57
data for kaonic deuterium: 2022 (?)

Why Kaonic Atoms?

Particle and Nuclear Physics
QCD at low energy limit
Chiral symmetry • Lattice QCD

Kaonic Atoms to Investigate Global Symmetry Breaking
Symmetry 12 (2020) 547

Fundamental Physics
Bound-State QED • New Physics

The modern era of light kaonic atom experiments
Rev. Mod. Phys. 91 (2019) 025006

Kaonic atoms
Kaon–nuclei interactions
(scattering and nuclear interactions)

Dark Matter and BSM
New hadronic forces • Exotic systems

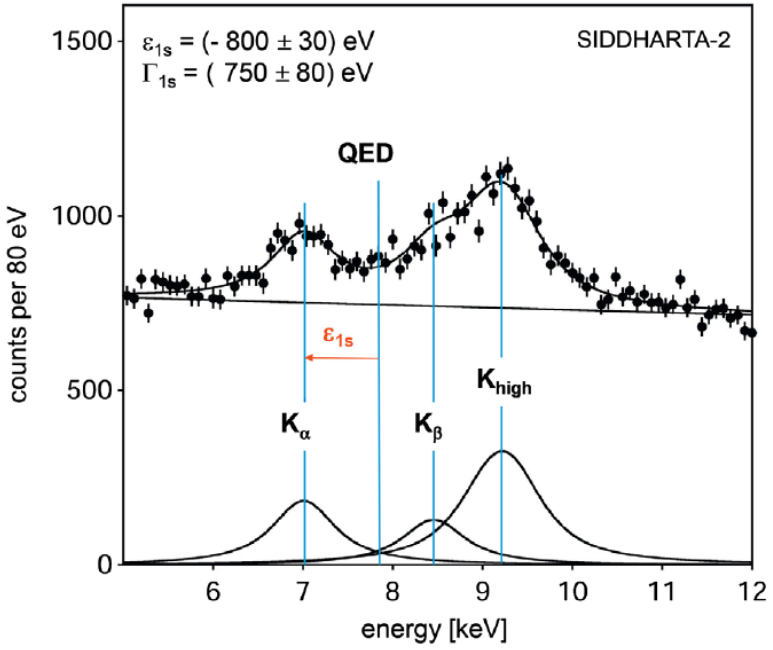
Probing new hadronic forces with heavy exotic atoms (2025)
On self-gravitating strange dark matter halos around galaxies

Astrophysics
Dense matter • Neutron-star EOS

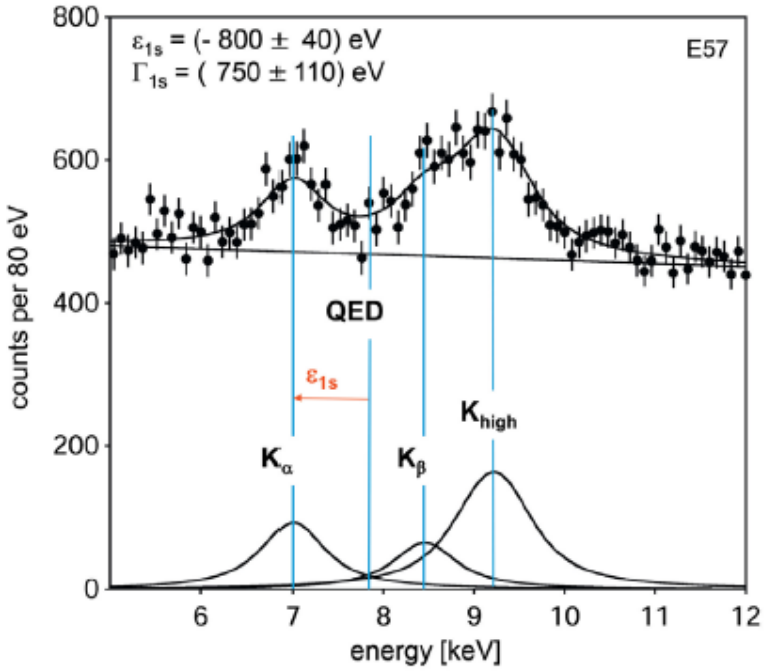
The equation of state of dense matter: stiff, soft, or both?
Astron. Nachr. 340 (2019) 189

The Monte Carlo simulations for kaonic deuterium

SIDDHARTA-2



E57



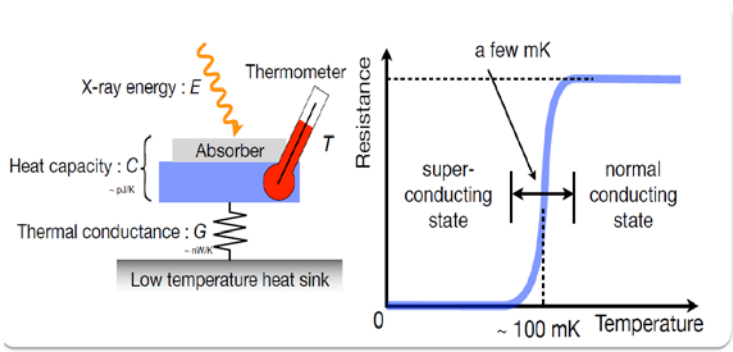
KH results:

ε_{1S}= −283 ± 36(stat) ± 6(syst) eV

Γ_{1S}= 541 ± 89(stat) ± 22(syst) eV

Transition-Edge-Sensor microcalorimeters (E62) experiment

- A new type of detector technology has been developed: the **transition edge sensors**, for extreme precision x-ray measurements.
- work on a calorimeter principle, based on a phase transition in a superconducting material, achieving **unprecedented energy resolution: 2 eV @ 6 keV.**
- will be used to perform measurements of kaonic atom transitions with **sub-eV precision** (2 eV for SDD , for energy resolution 150 eV @6 keV) which are important to fully understand the strong interaction between kaons and nuclei.

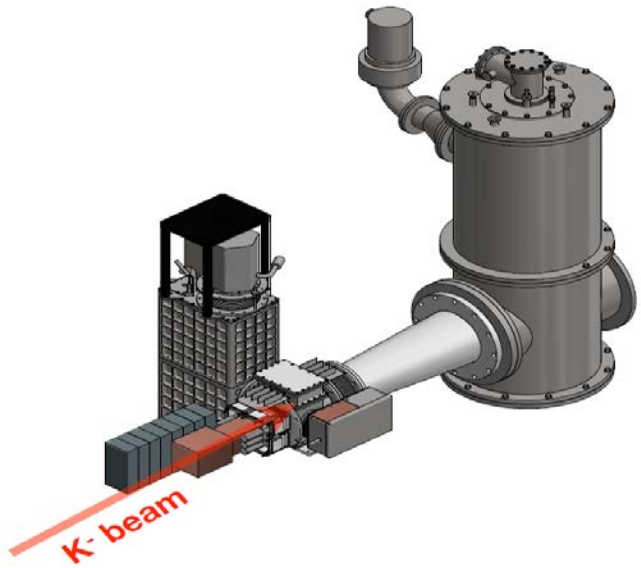


✓ Excellent energy resolution ~2 eV FWHM@ 6 keV

✓ Wide dynamic range possible

E62: K⁻He 3d-2p

sub-eV precision (ΔE_{2p})
to distinguish "deep" or "shallow" potential



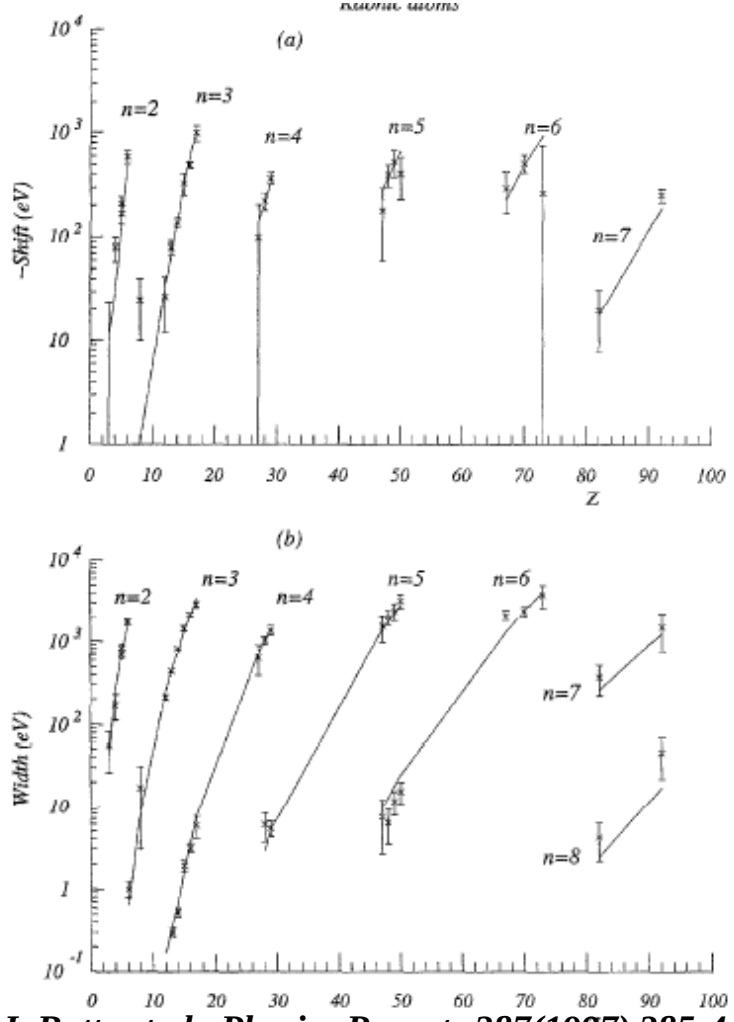
CONCLUSIONS

The last 20 years of kaonic atom precision measurements mark the modern era of kaonic atom experiments and set new constraints on theories which deal with low-energy QCD in the strangeness sector.

The future of this sector will further boost a deeper understanding of the "strangeness physics" in the nonperturbative regime of QCD, with implications from particle and nuclear physics to astrophysics, for better knowledge of the way in which nature works

Kaonic atom data (Z≥3)

The shift and widths of kaonic atom X-ray energy have been measured using targets with atomic numbers from Z=1 to Z-92, which provide very important quantities for understanding the antiKN strong interaction.



C.J. Batty et al., Physics Reports 287(1997) 385-445

Kaonic atom data (Z≥3)

Used for studies of $K^{bar}N$ interaction

Optical model

$$2\mu V_{\mathrm{opt}}^{(2)}(r) = -4\pi\left(1+\frac{\mu}{m}\right)b_0\rho(r).$$

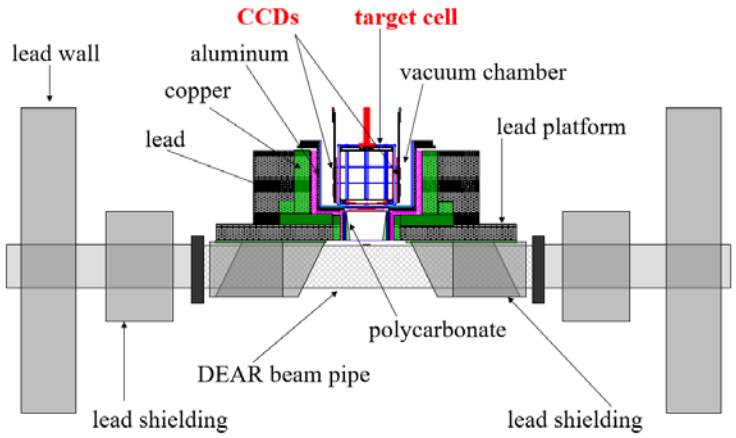
Experimental X-ray data of shift & width: Well fitted with optical potentials

Expected shift of K-4He 2p state: ΔE ~ 0 eV

There are discrepancies for:

- **Kaonic Hydrogen (Z=1)**
- **Kaonic Helium (Z=2)**

DEAR at DAΦNE (2002–2005)



Scientific aim

Precision measurement of the

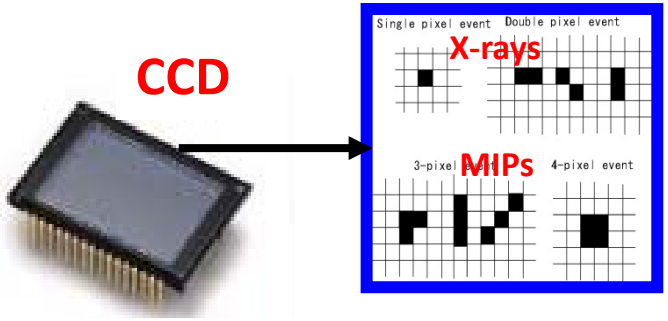
shift and width of the Kα line of kaonic hydrogen and kaonic deuterium

Advantages:

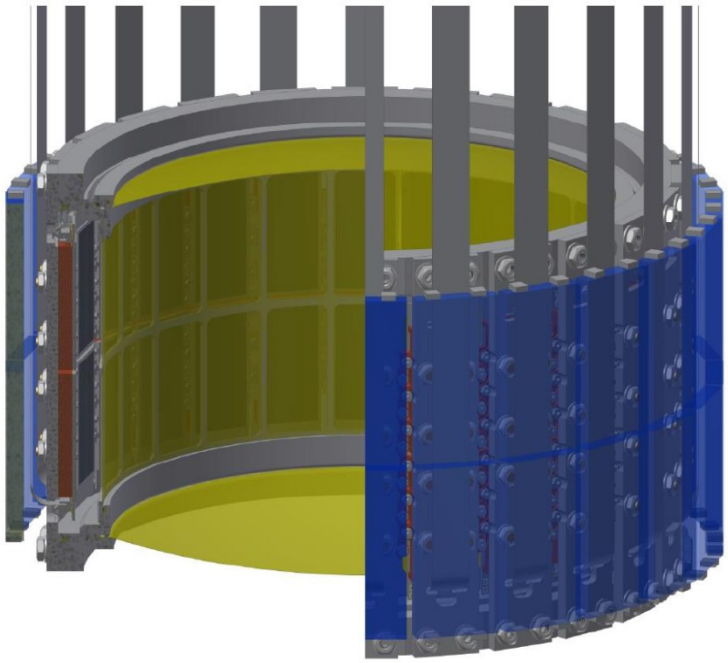
- Monochromatic low-energy K^- (~127 MeV/c ; Δp/p = 0.1%) → Φ → $K^- K^+$ (49.2%)
- Low density gas target(25 K, 2 bar) (higher yields of the atomic state in gaseous over the liquid one→ Stark effect)
- 16 Charge Coupled Device (CCD) as detector (FWHM@6 keV = 150 eV), large area 116 cm^2, pixel analysis for background reduction

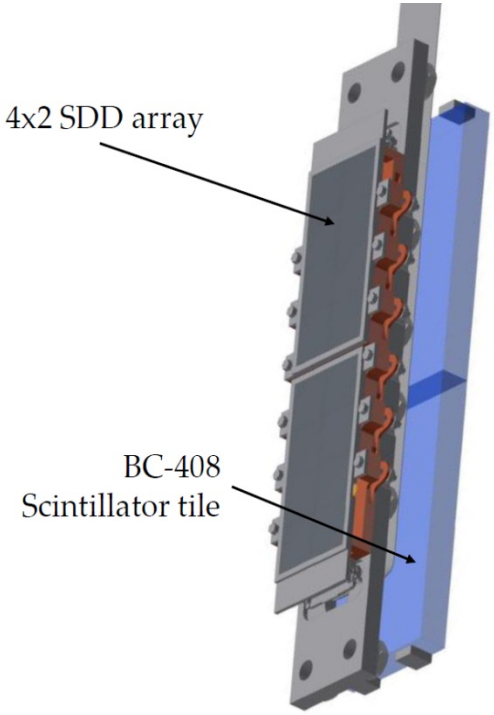
Disadvantages:

- identification of a signal (≈ 6.4 keV) withy very small yield (1% for KH) over a huge background



The 4 x2 SDD array around the target cell

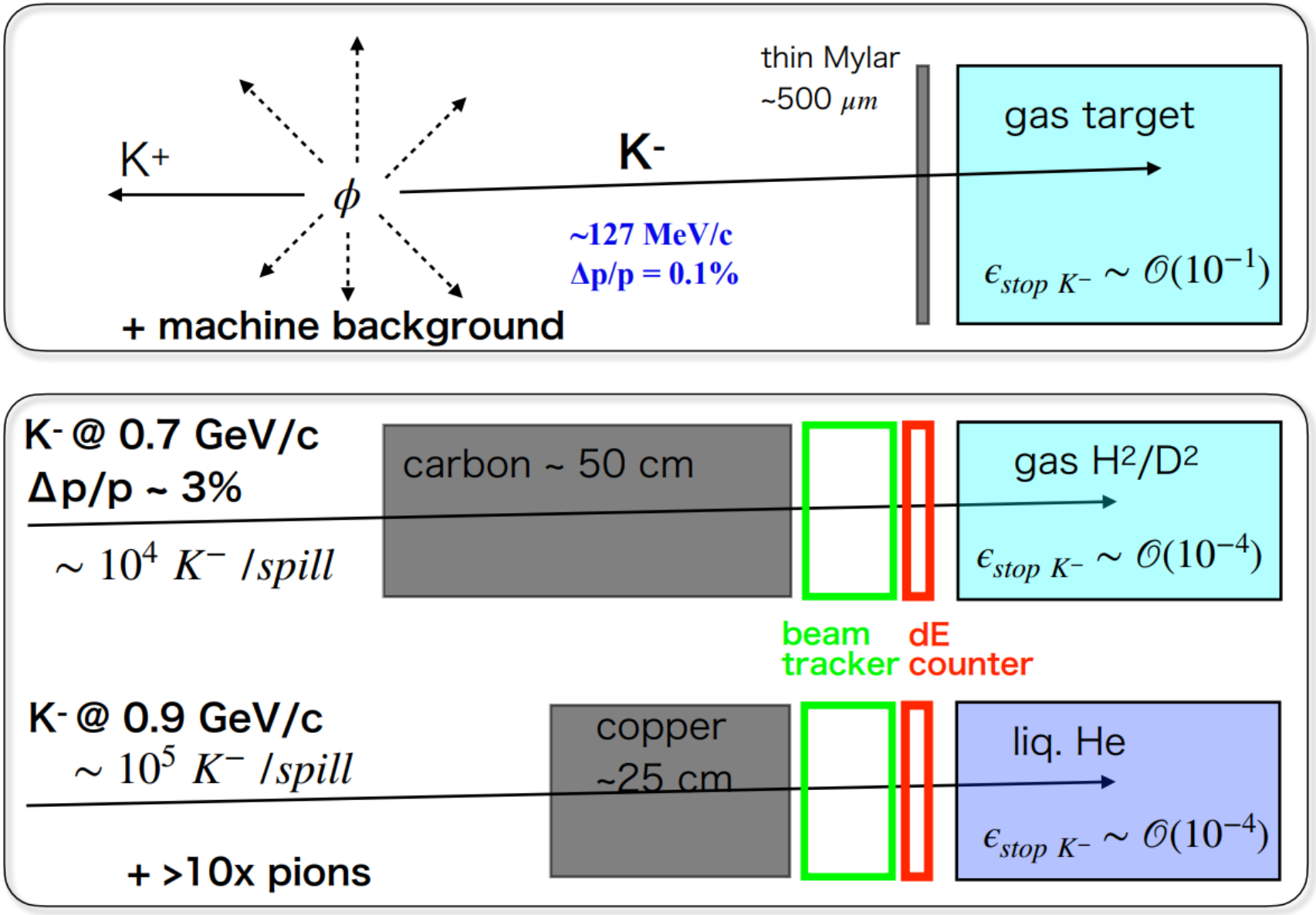




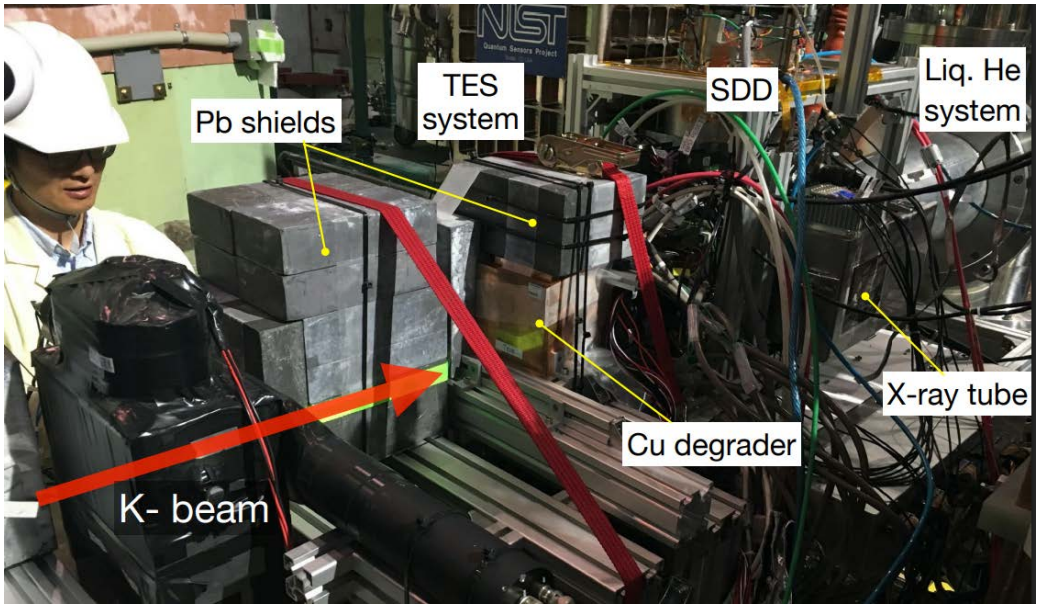
The new advance technology will allow to setup a cryogenic target detector system with an efficient detector packing density,
covering a solid angle for stopped kaons in the gaseous target of ~ 2π.

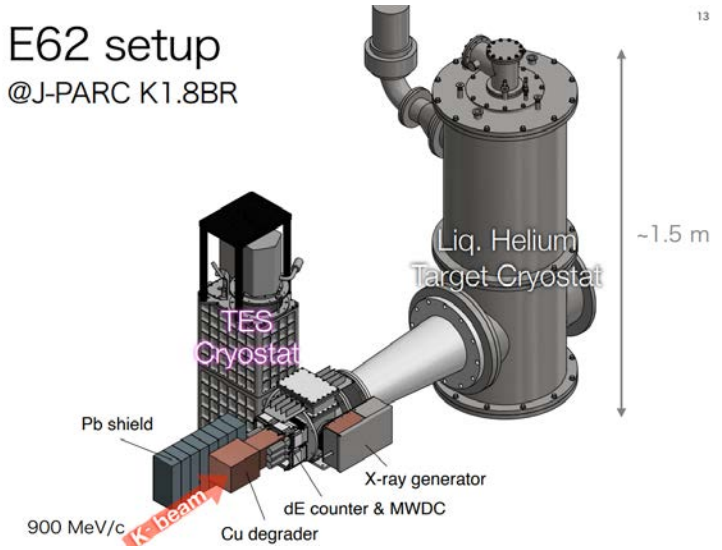
48 monolithic SDD arrays will be around the target with a total area of about 246 cm^2

DAΦNE vs. J-PARC

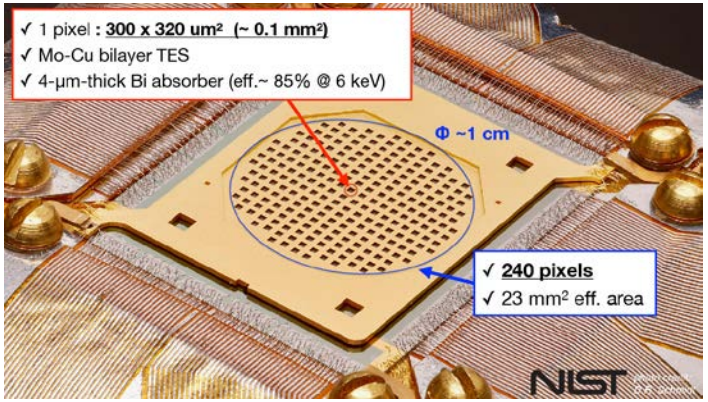


E62 experiment J-PARC (2022)





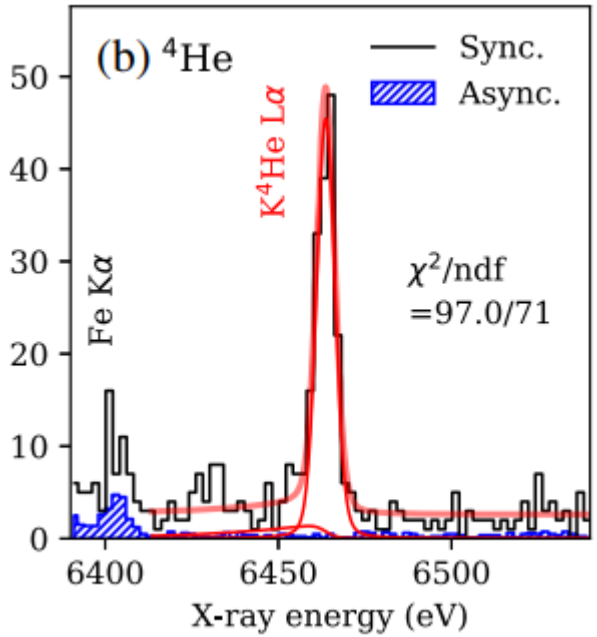
- **TES: transition edge sensors**, for extreme precision x-ray measurements.
- work on a calorimeter principle, based on a phase transition in a superconducting material, achieving **unprecedented energy resolution: 2 eV @ 6 keV.**



$K^{3,4}$He results by E62 (2022)

Kaonic 4-Helium

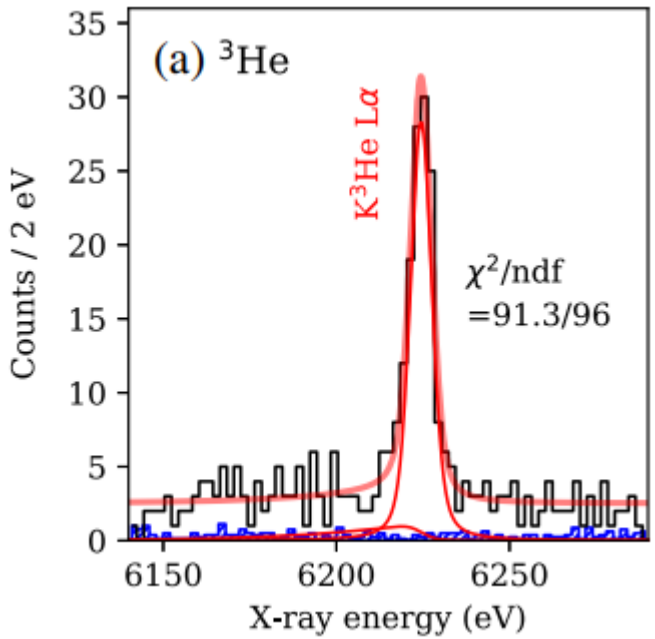
$$E_{3d\to 2p}^{K^{-4}\mathrm{He}} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV}$$



$$E_{3d\to 2p}^{K^{-4}\mathrm{He}} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV}$$
$$\Gamma_{2p}^{K^{-4}\mathrm{He}} = 1.0 \pm 0.6(\mathrm{stat}) \pm 0.3(\mathrm{syst})\ \mathrm{eV}$$

Kaonic 3-Helium

$$E_{3d\to 2p}^{K^{-3}\mathrm{He}} = 6224.5 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}$$



$$E_{3d\to 2p}^{K^{-3}\mathrm{He}} = 6224.5 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{eV}$$
$$\Gamma_{2p}^{K^{-3}\mathrm{He}} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{eV}$$

Phys. Rev. Lett. 128 (2022) 112503

Liquid target for ^{3,4}He