Workshop on Fundamental Physics with Exotic Atoms

The physics of kaonic atoms in the last 25 years

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INFN-LNF

on behalf of SIDDHARTA-2 collaboration

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LNF-INFN, Frascati, Italy

We dedicate these results to
Prof. Carlo Guaraldo and Dr. Johann Zmeskal
whose contributions and passion for exotic atom research continue to inspire us.

The modern era of light kaonic atoms experiments,
the precision era, covers the last twenty-five years.

Breakthroughs in technological developments
which allowed performing
a series of long-awaited precision measurement

↓

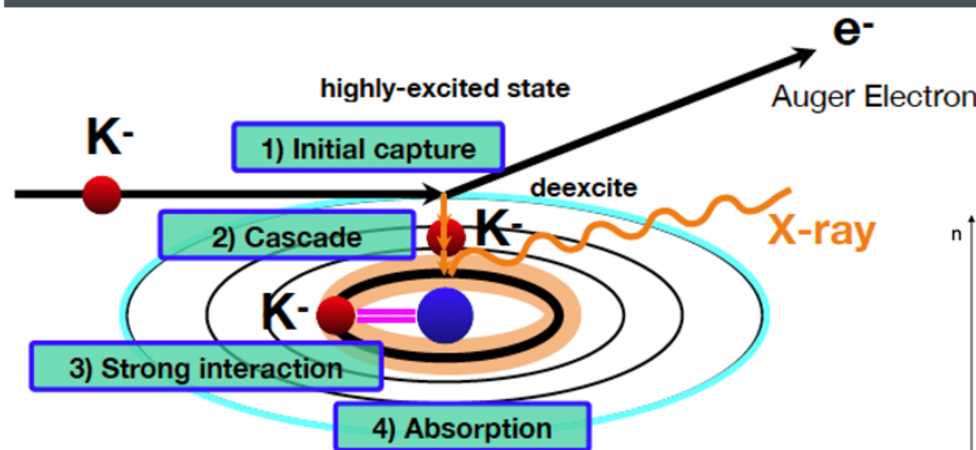
Better understanding of the strong interaction
between anti-K & nucleus at low energy limit

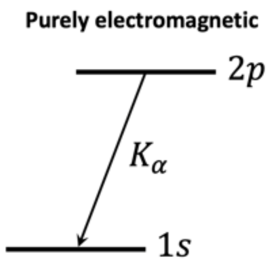
↓

Motivation for kaonic atoms experiments

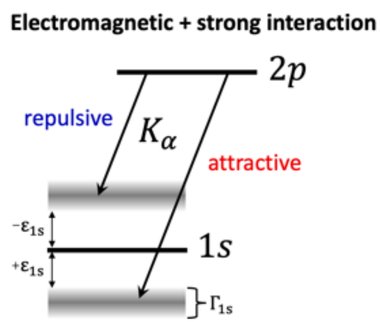
Kaonic Atoms X-ray Spectroscopy

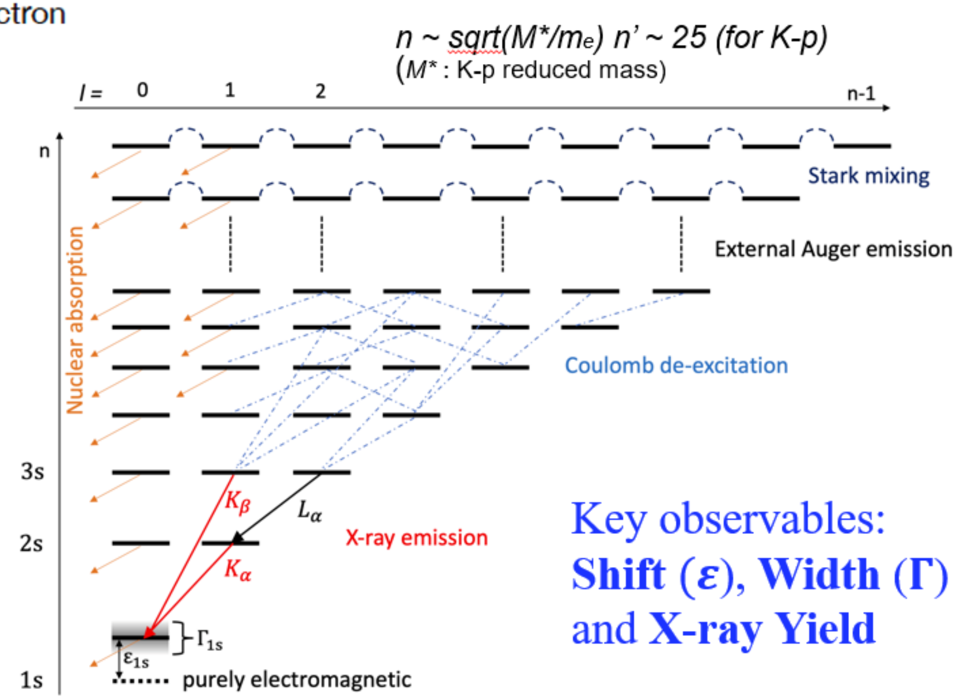
Kaonic atom formation





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





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

Importance of kaonic atoms studies

Atomic binding energies of light systems the keV range →tens of MeV in the low-energy scattering experiments

	m (MeV/c^2)	μ (MeV/c^2)	B_{1s} (keV)	r_B (fm)	Accessible interaction
ep	0.511	0.511	13.6×10^{-3}	53 000	Electroweak
μp	105.7	95.0	2.53	279	Electroweak
πp	139.6	121.5	3.24	216	Electroweak + strong
Kp	493.7	323.9	8.61	81	Electroweak + strong
$\bar{p}p$	938.3	469.1	12.5	58	Electroweak + strong

Kaonic atoms: the 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

- **Explicit and spontaneous chiral symmetry breaking (mass of nucleons)**
- **Dense baryonic matter structure**
- **Neutron (strange?) stars EOS**

Light kaonic atoms

- Kaonic hydrogen isotopes $\rightarrow$ basic low energy parameters: antikaon –nucleon scattering lenghts
- Kaonic deuterium $\rightarrow$ antikaon –neutron system
- Other light kaonic atoms $\rightarrow$ how to construct the antikaon-nucleus interaction from the elementary reactions

Light exotic atoms are formed almost "electron-free"
high-precision measurements,
due to the absence of electron screening effect

Breakthrough in the technologies for kaonic atoms studies:
1. Antikaons sources

Availability of the new kaon beams with excellent characteristics for the studies of kaonic atoms:

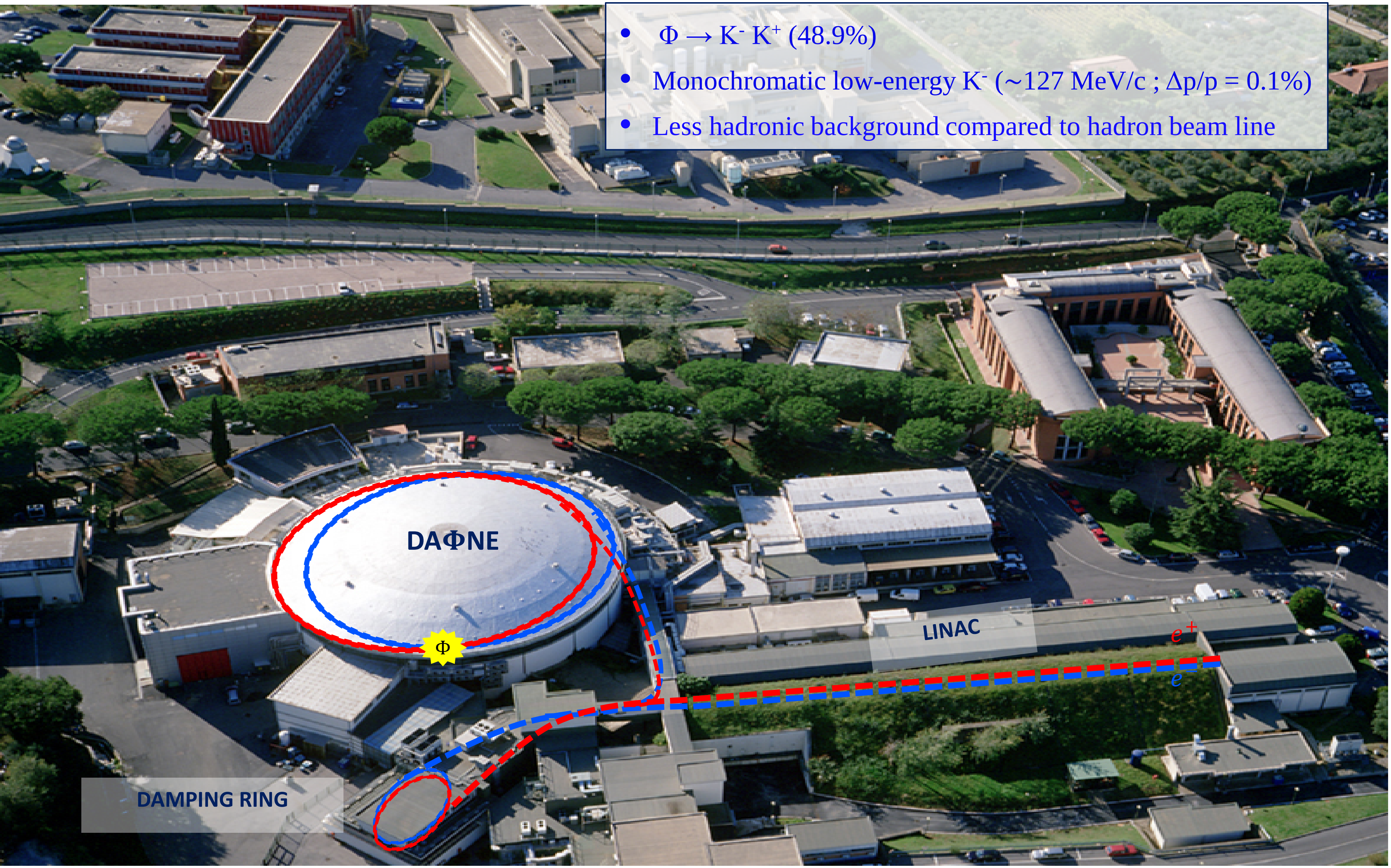
first necessary ingredient towards the progress in kaonic atoms studies in the modern era.

New technological developments in the accelerators delivering kaon beams:

1. DAΦNE collider at LNF-INFN
2. kaon extracted beams in Japan, firstly at KEK and then at J-PARC

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



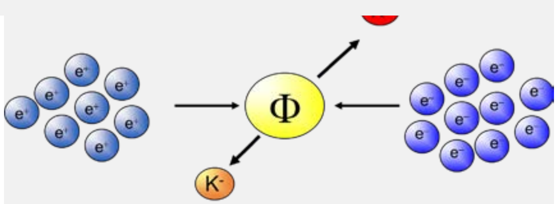
DAΦNE: low-momentum kaon beam

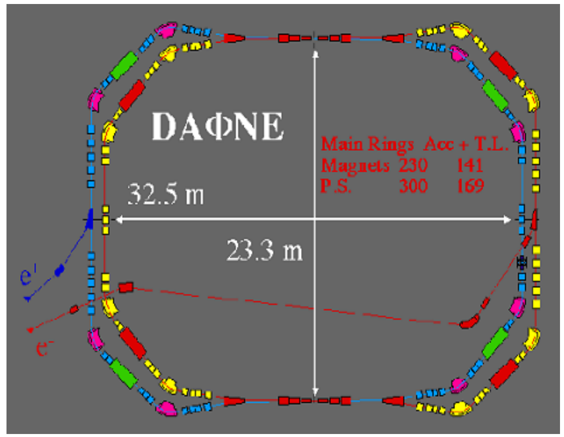
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

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

mass $m = 1019.413 \pm .008$ MeV

width $\Gamma = 4.43 \pm 0.06$ MeV





- $e^+ e^-$ 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

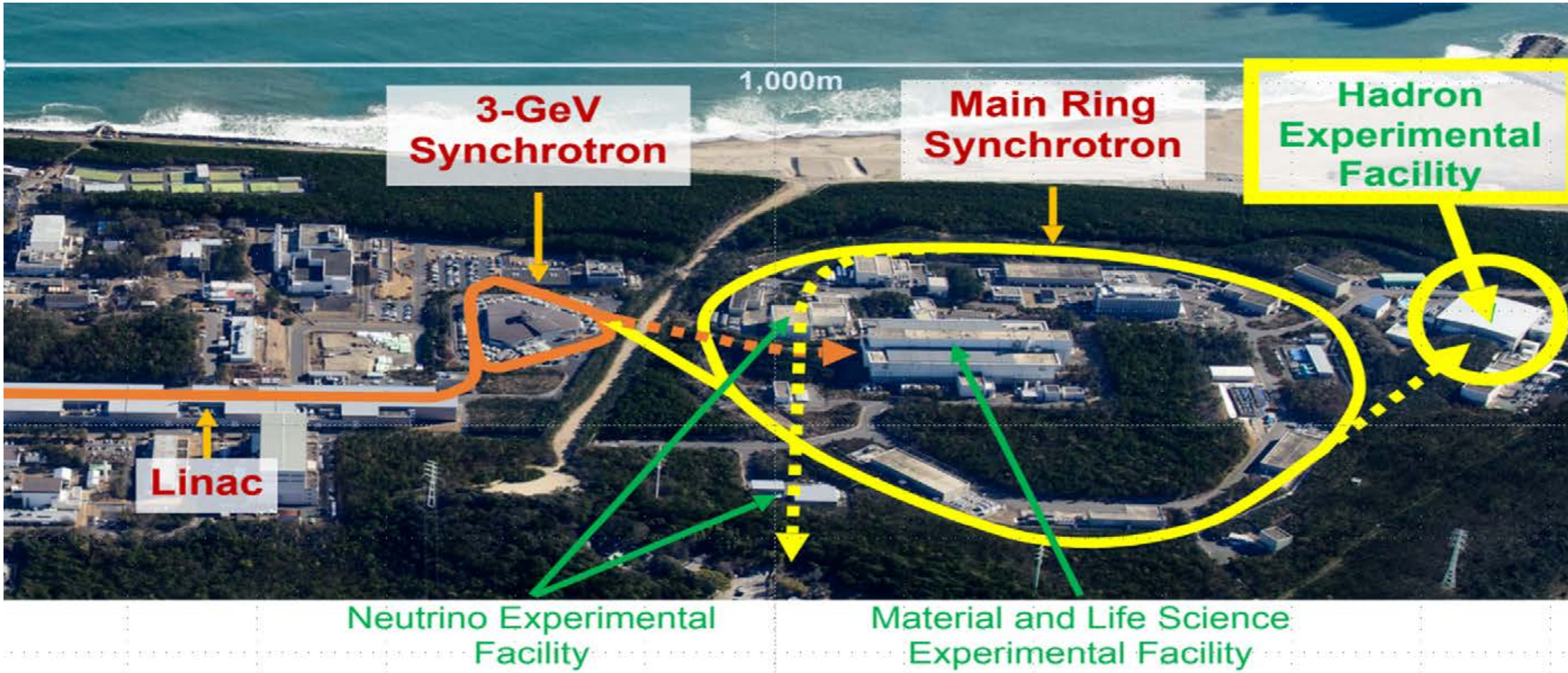
Best low momentum K^- factory in the world

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-mometum kaon beam

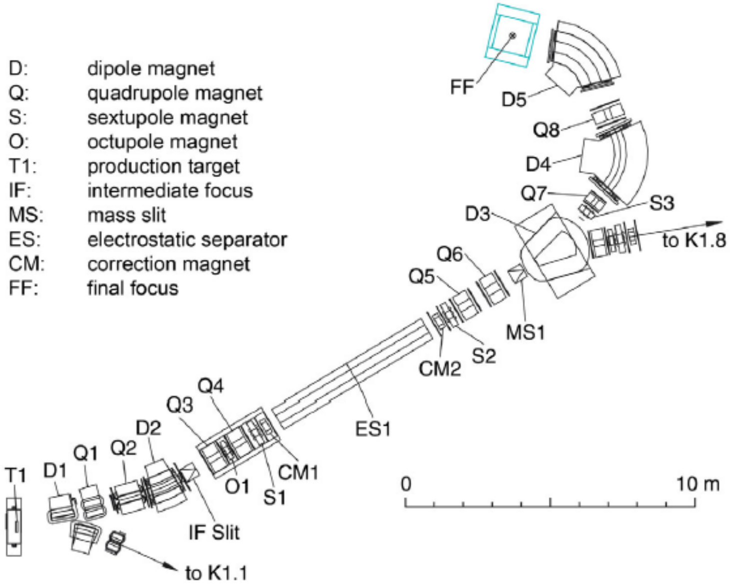


J-PARC consists of a series of world-class proton accelerators and experimental facilities using high-intensity proton beams.

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-mometum kaon beam

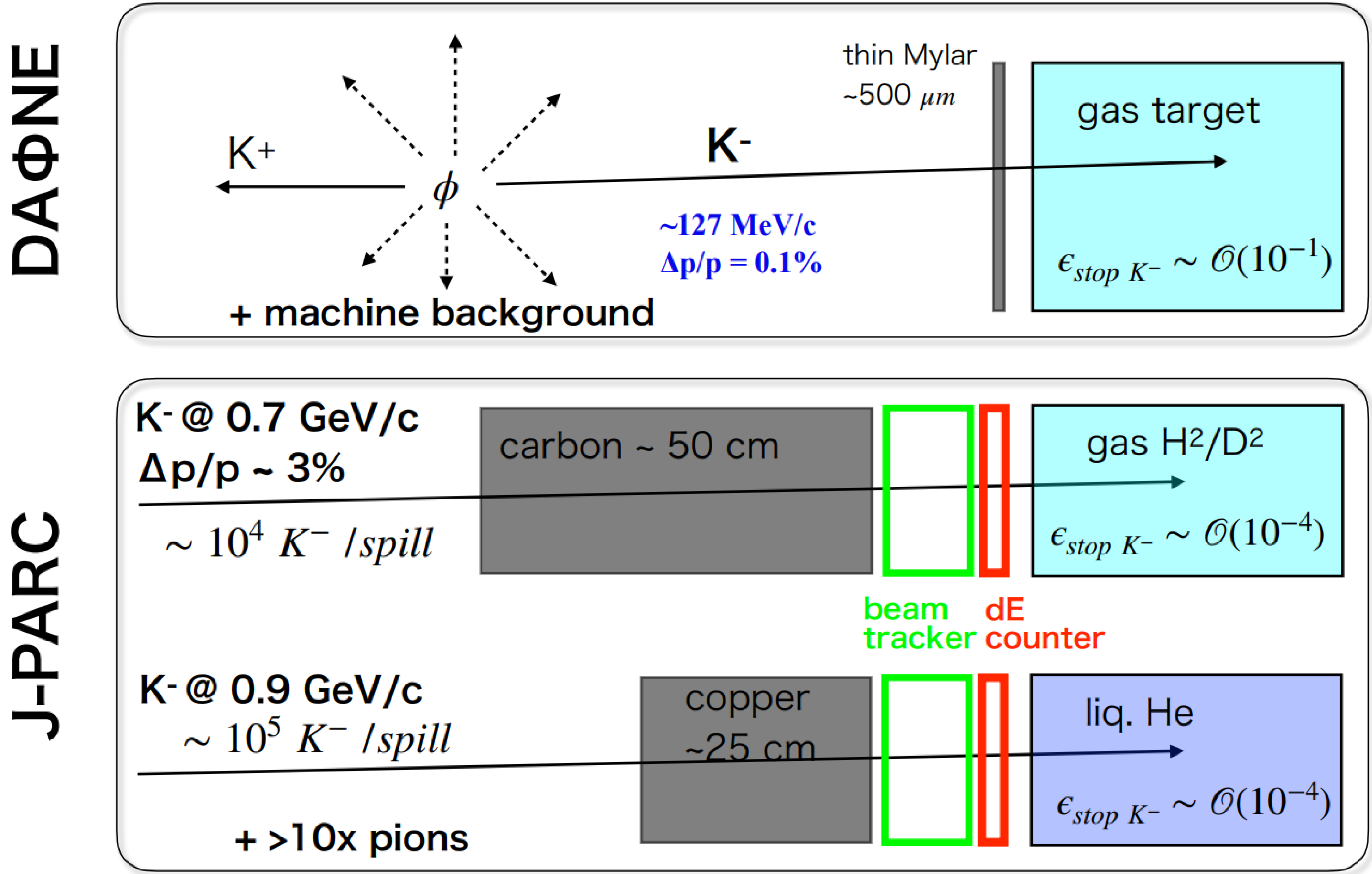
Main kaon beam lines K1.8 and K1.8BR were constructed at the Hadron Hall using primary protons from the J-PARC 50 GeV synchrotron (MR) (up to now, only 30 GeV primary proton beam are produced).



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

DAΦNE vs. J-PARC



Breakthrough in the technologies for kaonic atoms studies:
2. Target systems

Breakthrough in the intensity of the signals of light kaonic atoms:

- **cryogenic pressurized hydrogen gas targets, instead of liquid hydrogen, avoiding the drastic reduction of the X-ray yields due to the Stark mixing effect.**

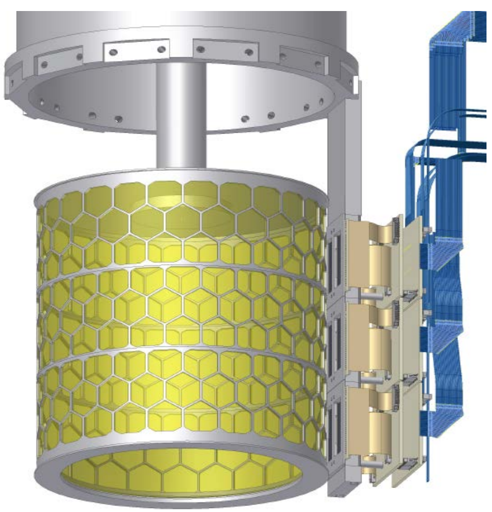
General requirements for the target systems for research on kaonic light atoms

- **high purity gas target systems**, to avoid kaon losses due to the Stark effect
- **cooled to cryogenic temperature**.
- to be designed for optimum X-ray detection **by reducing the material budget in front of the X-ray detector**.
- according to the different kaon sources, the shapes of the target systems are quite different, but in common for all cells is the request for **thin target walls**, facing the X-ray detector.

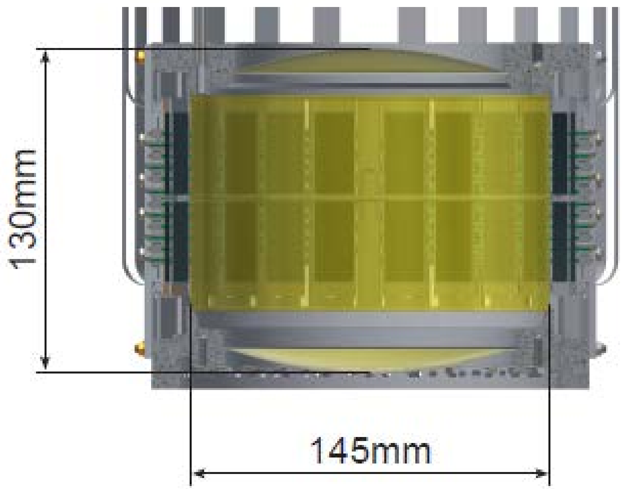
	SIDDHARTA	SIDDHARTA-2	E57
Active target volume (cm^3)	2400	2100	540
Target diameter (cm)	13.7	14.5	6.0
Working temperature (K)	20–25	25–30	25–30
Working pressure (MPa)	0.10	0.25	0.5
Gas density	1.8%[a]	3%[b]	4%[b]
Burst pressure (MPa)	0.40	0.65	0.80
Kapton entrance window (μm)	125	125	125
Kapton side 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 ($0.164\ g/cm^3$).

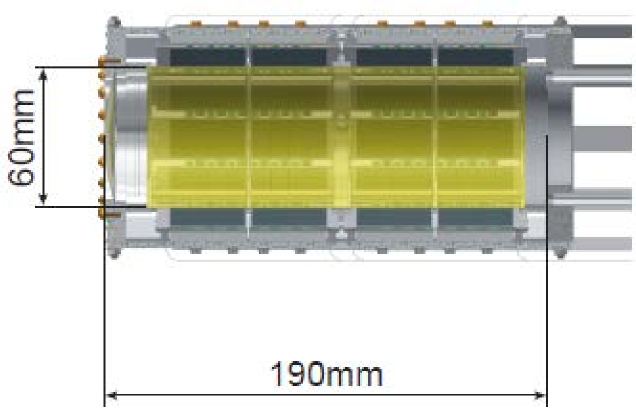
SIDDHARTA



SIDDHARTA-2



E57



Breakthrough in the technologies for kaonic atoms studies:
3. High performance X-ray Detectors

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 (mm2)	200	724	1 × 100	3 × 100	8 × 64	~ 23
Thickness (mm)	5	0,03	0,26	0,45	0,45	0,003
Energy resolution @ 6KeV	410	150	190	160	**170**	**5**
Drift time (ns)	200	-	375	800	**800**	**-**

Breakthrough in the technologies for kaonic atoms studies:

3. X-ray Detectors

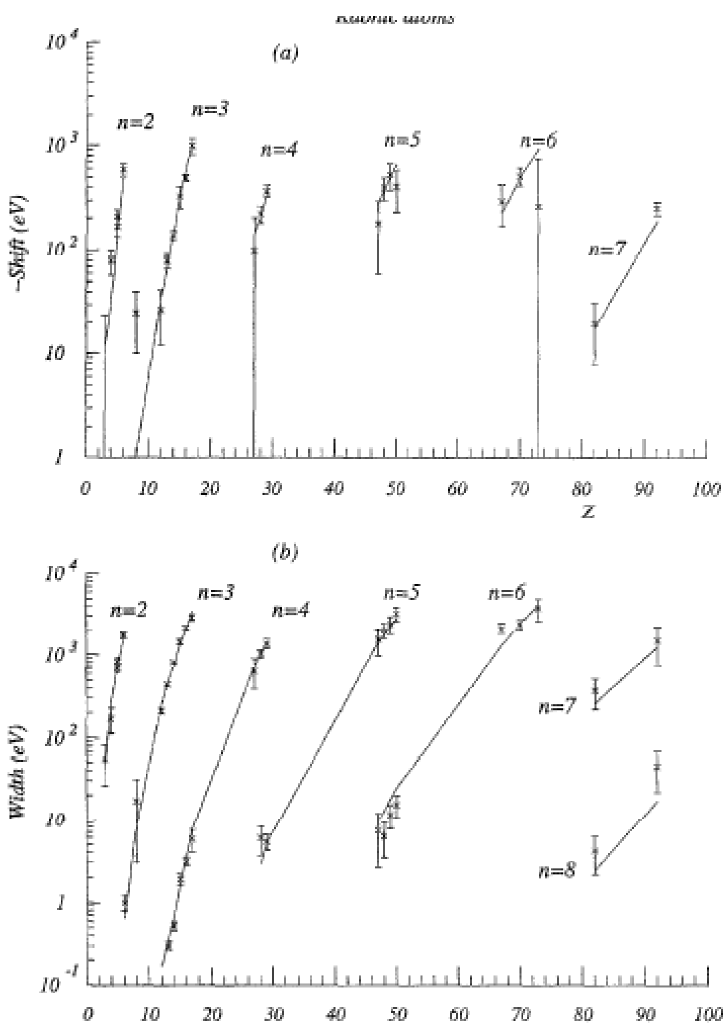
Experiment	KpX 1998	DEAR 2005	E570 2007	SIDD[illegible]TA	SIDDHARTA2, E57	E62
Detector	Si(Li)	CCD	SD[illegible]	[illegible]	**SDD-CUBE**	**TES**
Effective area (mm2)	200	[illegible]	[illegible]	[illegible] × 100	8 × 64	~ 23
Thickness (mm)	[illegible]	[illegible]	[illegible],26	0,45	0,45	0,003
Energy resolution @ 6KeV	4[illegible]	[illegible]150	190	160	**170**	**5**
Drift time (ns)	200	-	375	800	**800**	**-**

For more details:
see talk of F. Sirghi

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.

Kaonic atom data (Z≥3)
Used for studies of $K^{bar}N$ interaction



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

Optical model

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

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

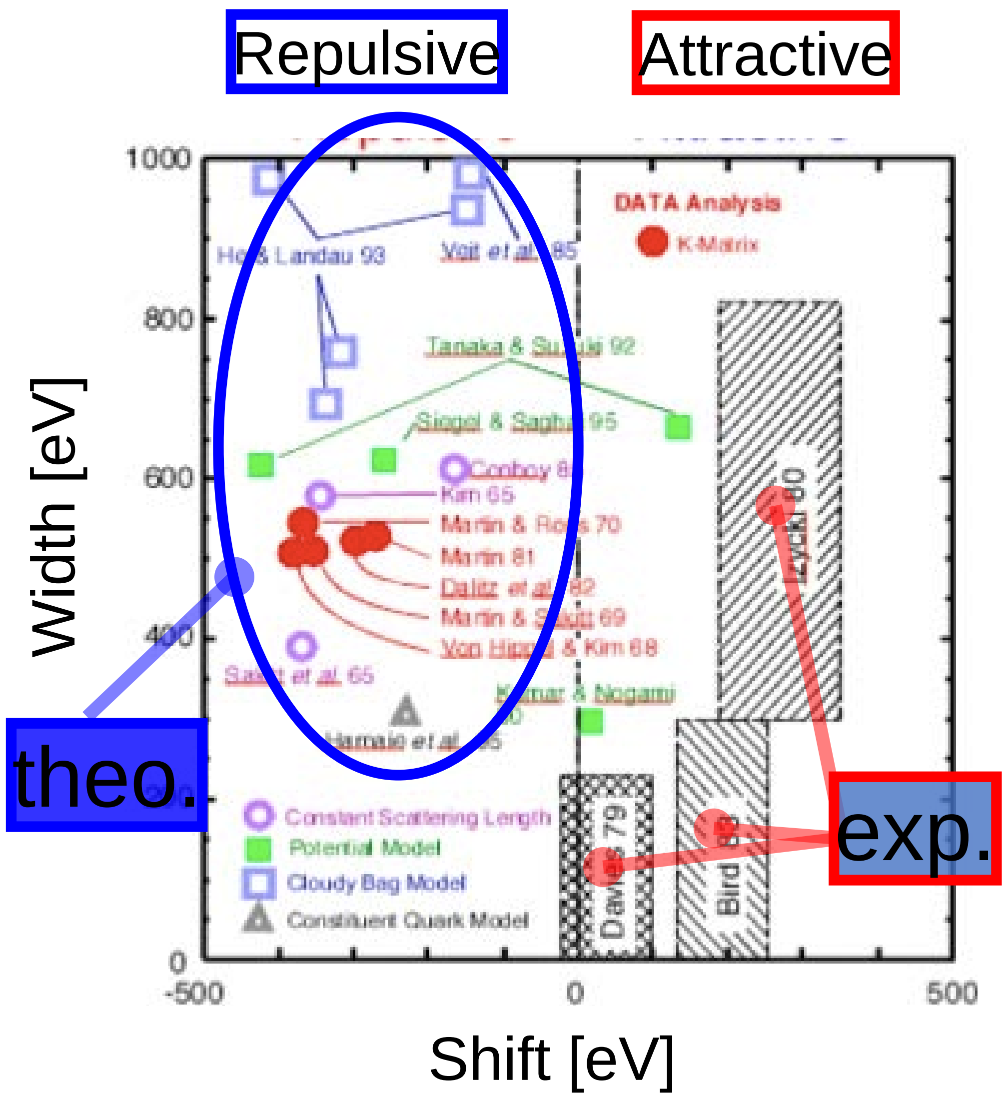
Expected shift of K-4He 2p state:
ΔE ~ 0 eV

There are discrepancies for:

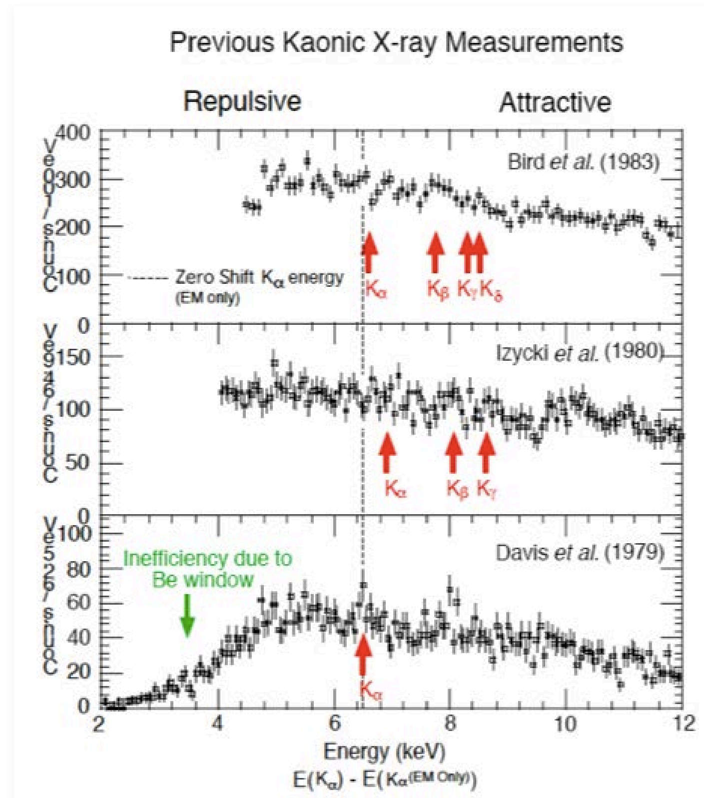
Kaonic Hydrogen (Z=1)

Kaonic Helium (Z=2)

70-80's: Kaonic hydrogen puzzle



past 3 exp.



Liquid Hydrogen target

Si(Li) as X-ray detector

Kaonic Helium atoms

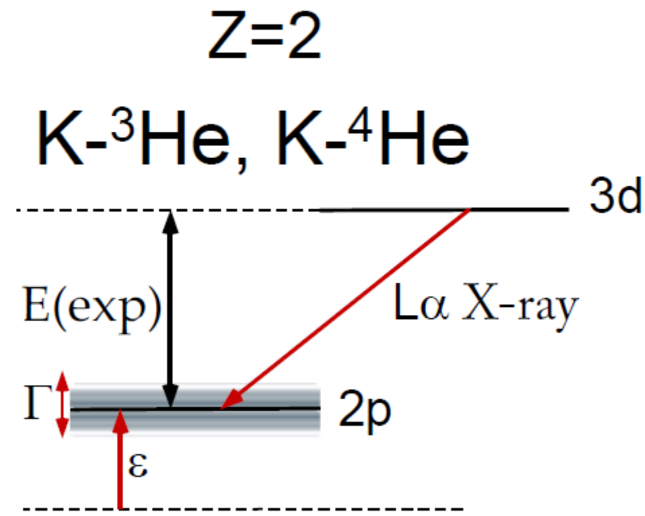
$$\varepsilon = E_{3d\to 2p}(\text{exp}) - E_{3d\to 2p}(\text{e.m.})$$

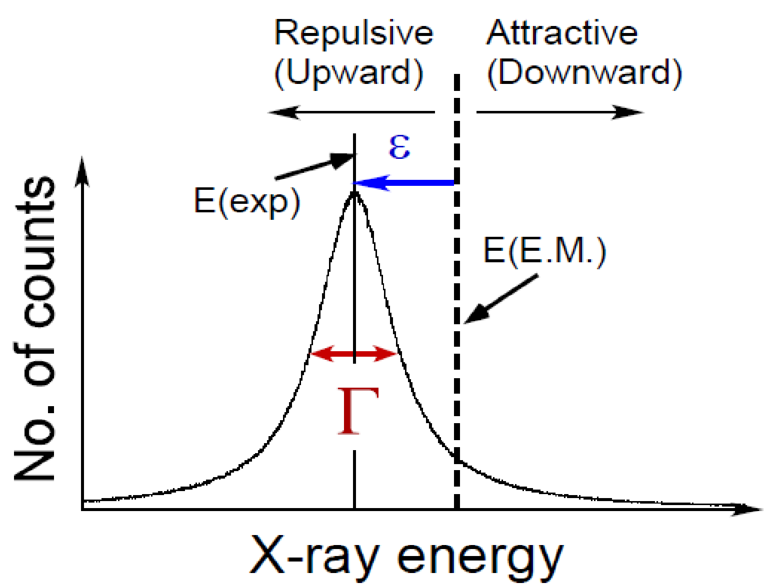
The most suitable transition to observe the strong interaction effects

Most kaons are absorbed without radiative transition to *1s* state.

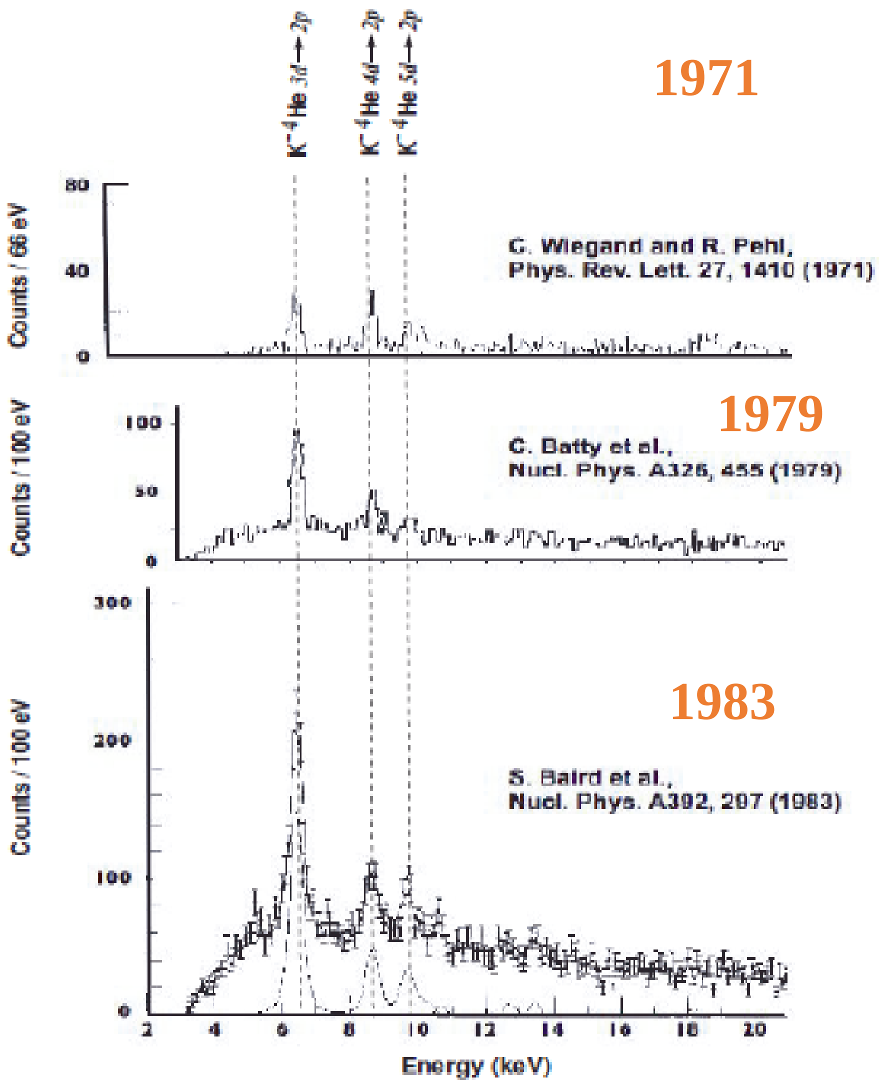
$$E(e.m.) \approx -\frac{1}{2}\mu c^2 (Z\alpha)^2 \cdot \left[\frac{1}{n_i^{\,2}} - \frac{1}{n_f^{\,2}}\right]$$

$$\varepsilon = E(\text{exp}) - E(e.m.)$$
$$\varepsilon < 0\,(\text{repulsive})$$
$$\varepsilon > 0\,(\text{attractive})$$



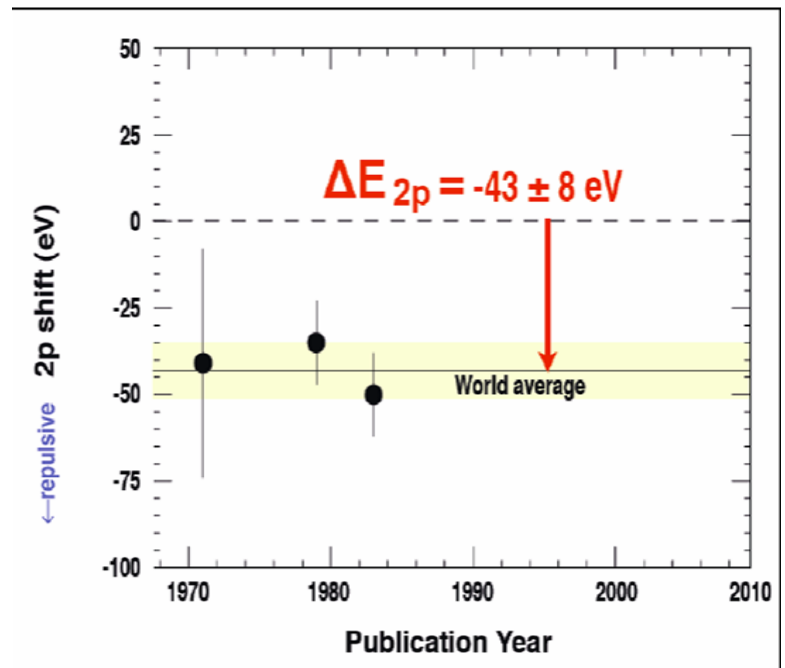


Kaonic helium atom data (Z=2)



ΔE_{2p}(eV)	Γ_{2p} (eV)
-41±33	-
-35±12	30±30
-50±12	100±40
-43±8	55±34

Average of above



Kaonic helium atoms theoretical values

There are two types of theories compared to the experimental results:

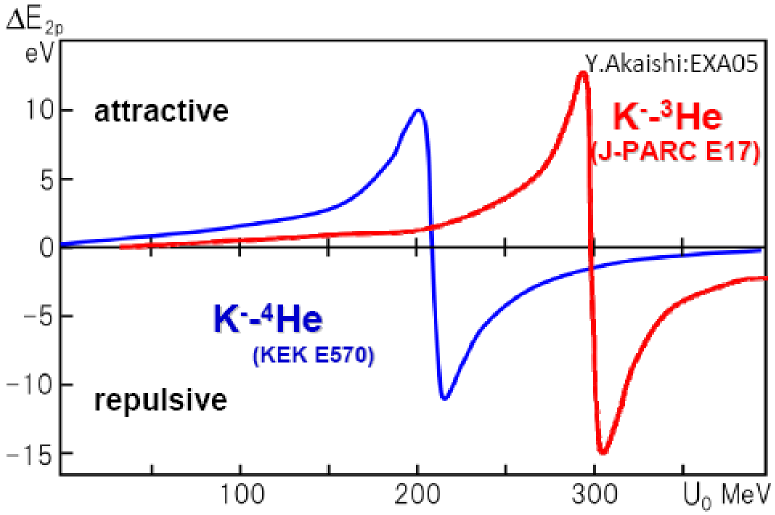
Optical-potential model:

(theoretical calculations based on kaonic atom data)

Recent theoretical calculations:

Akaishi-Yamazaki model of deeply-bound kaon-nucleus states

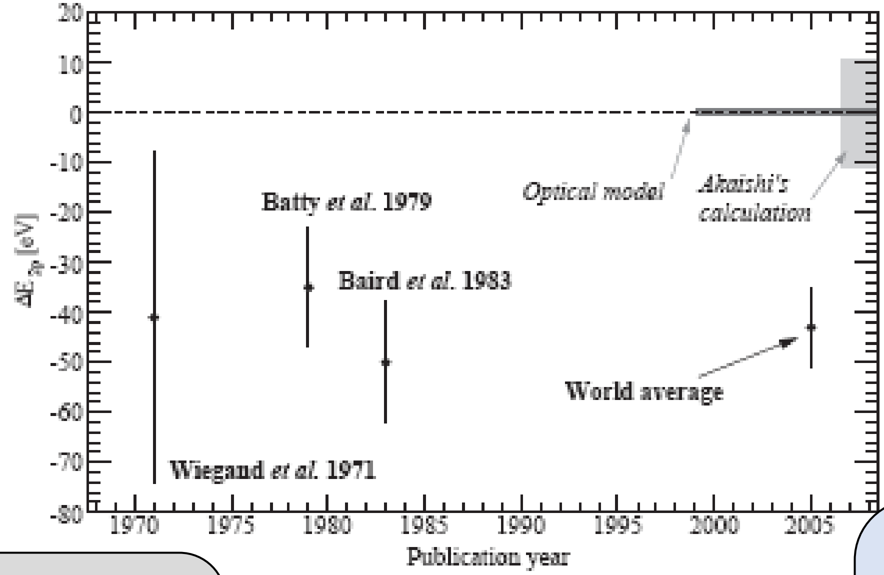
Shift (eV)	Ref.
-0.13±0.02	Batty, NPA508 (1990) 89c
-0.14±0.02	Batty, NPA508 (1990) 89c
-1.5	Akaishi, Porc. EXA05



Tiny shift ($\Delta E_{2p} \approx 0$ eV)

Predicts a possible maximum shift: ΔE_{2p} of ± 10 eV

What is Kaonic helium puzzle?



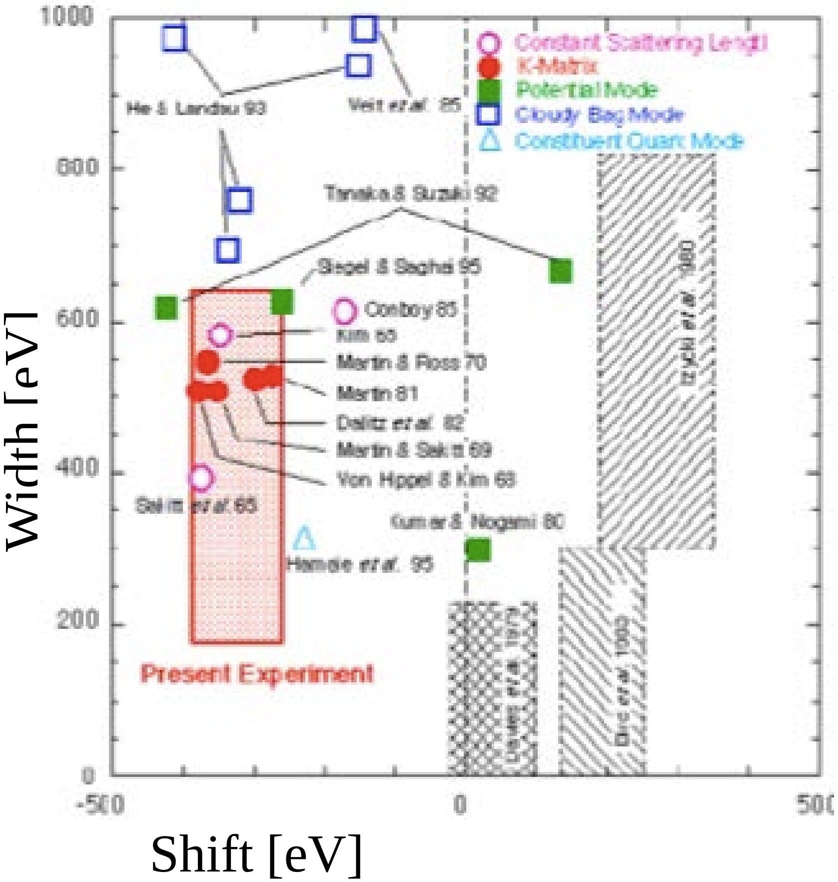
Experiment:
Large shift
(ΔE2p ≈ 40 eV)

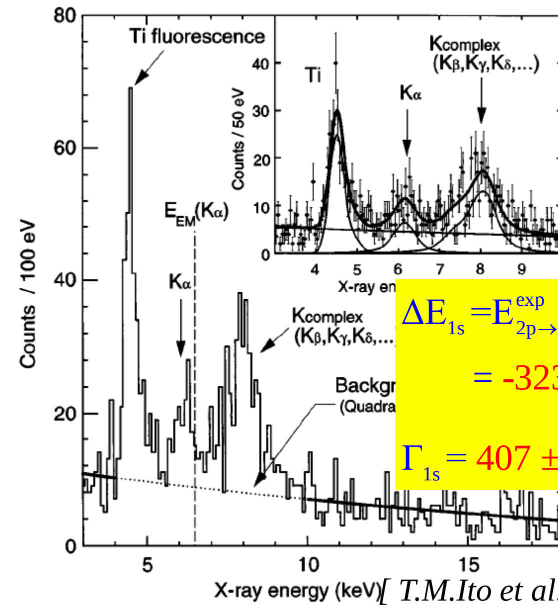
Theory:
ΔE2p ≈ 0 eV
or
< ± 10 eV

Need new precise measurements using the advanced technologies!!

98's: solving Kaonic hydrogen puzzle
(KpX experiment)

Repulsive type **Attractive**





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

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

$\Delta E_{1s} = E^{exp}_{2p\to 1s} - E^{E.M.}_{2p\to 1s}$

$= -323 \pm 63(stat.) \pm 11(syst.)$ eV

$\Gamma_{1s} = 407 \pm 208$ (stat.) ± 100 (syst.) eV

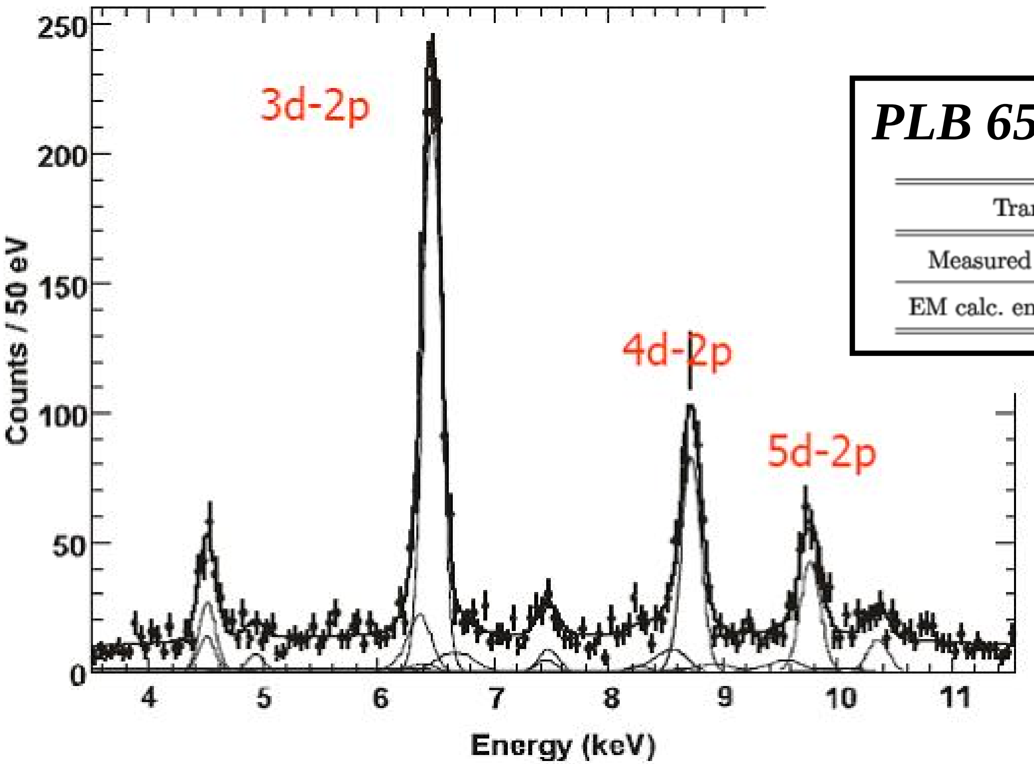
***Gas target (100K, 4 atm)**

*** 60 Si(Li) detector (each one of 200 mm^2)**

***Hadron beamline**

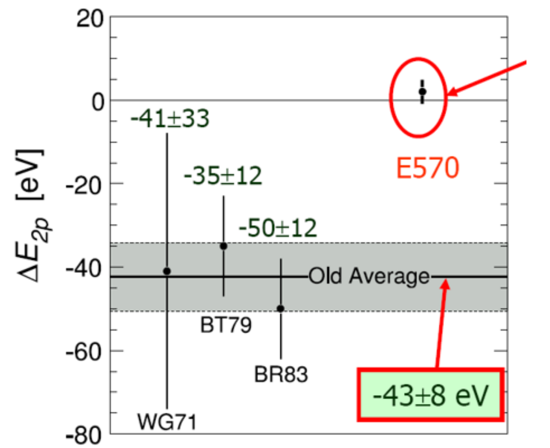
Kaonic hydrogen puzzle solved

2007: solving K^4He puzzle
(E570 (KEK) experiment)



PLB 653 (2007) 387

Transition	$3d \to 2p$	$4d \to 2p$	$5d \to 2p$
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



K^4He 3d→2p: 1500 events

3x higher statistics
2x better Energy resolution
6x better S/N

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

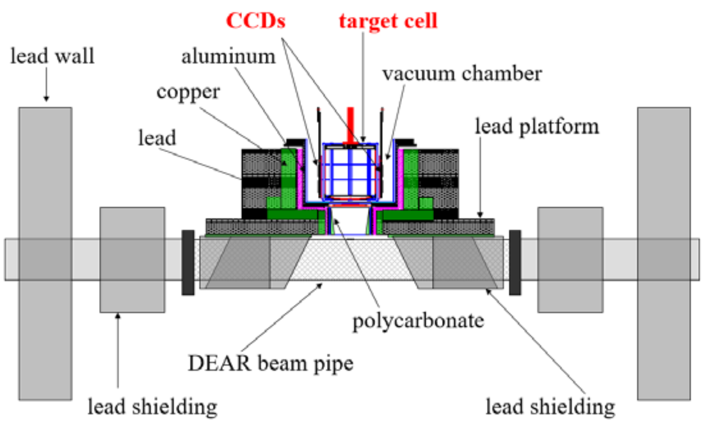
Liquid target for ^4He
SDD detectors

Kaonic hydrogen puzzle
Kaonic helium puzzle
Solved!

↓

Confirmation of the results of KpX and E570
to completely solve the hydrogen and helium puzzle!
Need precise measurements!

DEAR (DAFNE Exotic Atom Research)
(2002-2005)



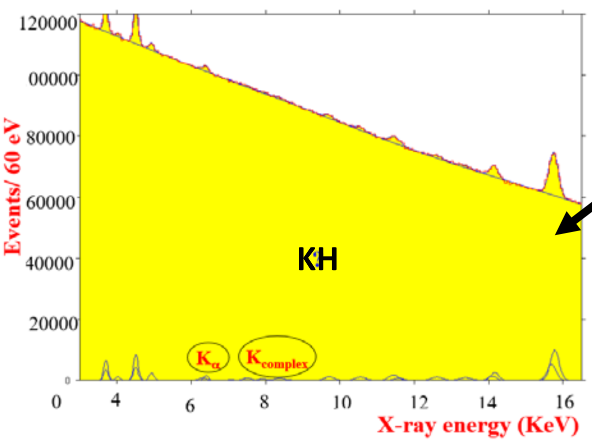
Scientific aim:
precision measurement of the shift and of the width of the K_α line of kaonic hydrogen and kaonic deuterium

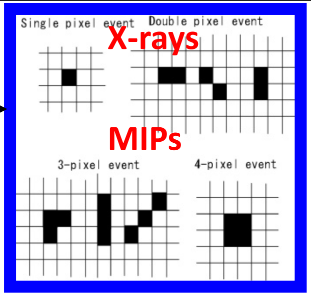
Advantages:

- 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:

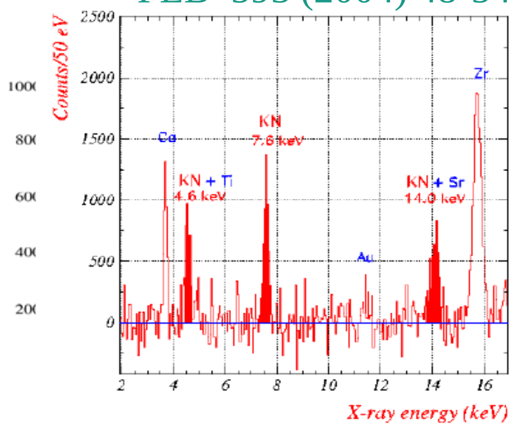
- identification of a signal (≈ 6.4 keV) withy very small yield (1% for KH) over a huge background





DEAR outcomes

PLB 593 (2004) 48-54



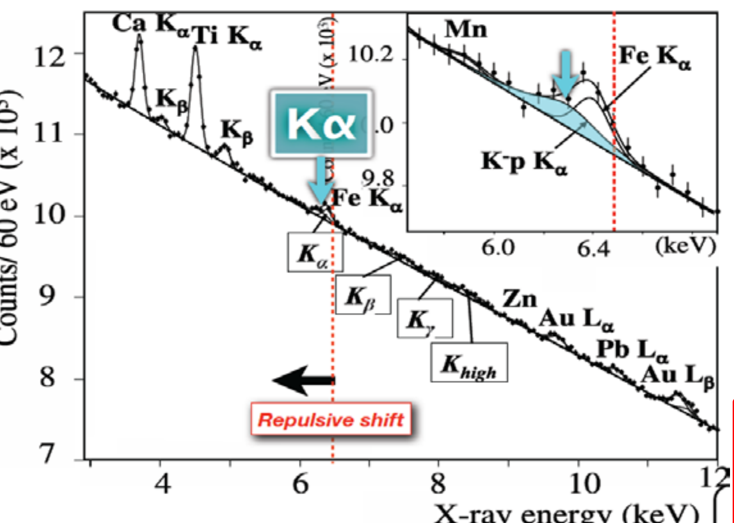
1. Kaonic Nitrogen: first kaonic atom at DAFNE

First determination **of the yield of 3 Kaonic Nitrogen X-ray transitions**

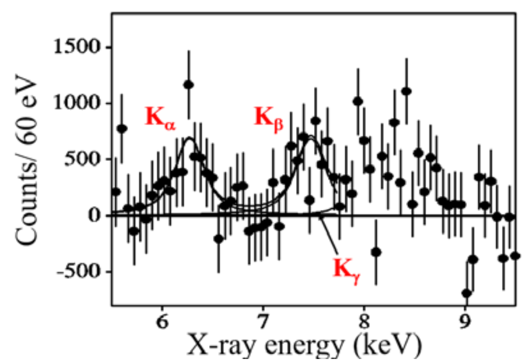
KN 7 → 6 (4.6 keV): (41.5 +/- 8.7 +/- 4.1)%
KN 6 → 5 (7.6 keV): (55.0 +/- 3.9 +/- 5.5)%
KN 5 → 4 (14.0 keV): (57.4 +/- 15.2 +/- 5.7)%

inputs for the cascade calculations for exotic atoms

2. Kaonic Hydrogen



G. Beer et al., PRL 94 (2005) 212302



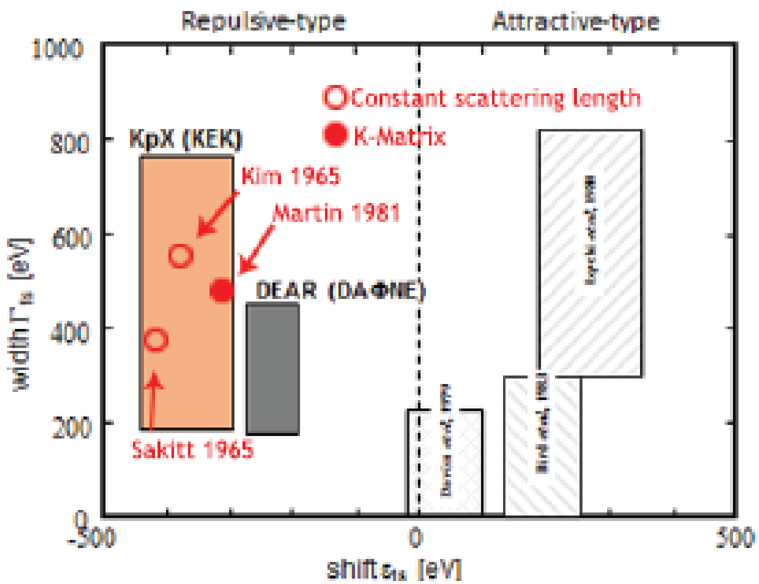
- **represents the best measurement performed on Kaonic Hydrogen up to now**
- **confirms repulsive character of K- p interaction**

$$\varepsilon = -193 \pm 37(stat.) \pm 6(syst.) eV$$

$$\Gamma = 249 \pm 111(stat.) \pm 39(syst.) eV$$

No deuterium measurements due to the too much high background: S/B =1/70

Kaonic hydrogen results (DEAR)



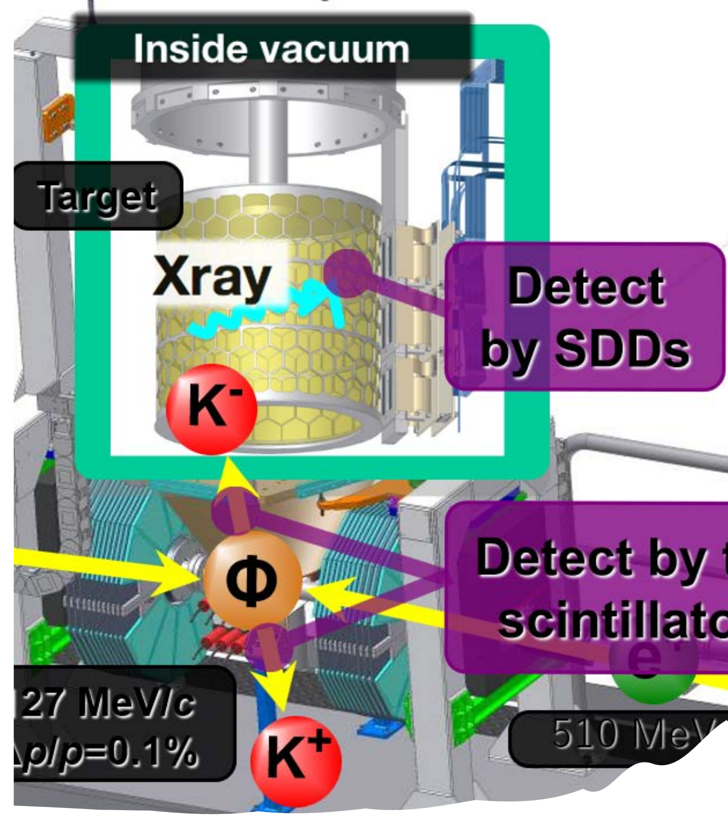
- **The DEAR results were consistent with the KEK measurement within 1σ of their respective errors.**
- **The repulsive-type character of the K-p strong interaction was confirmed.**
- **the uncertainty of the DEAR results was about twice smaller than that KEK values.**
- **DEAR observed the full pattern of kaonic hydrogen K-lines, clearly identifying Kα, Kβ and Kγ lines**

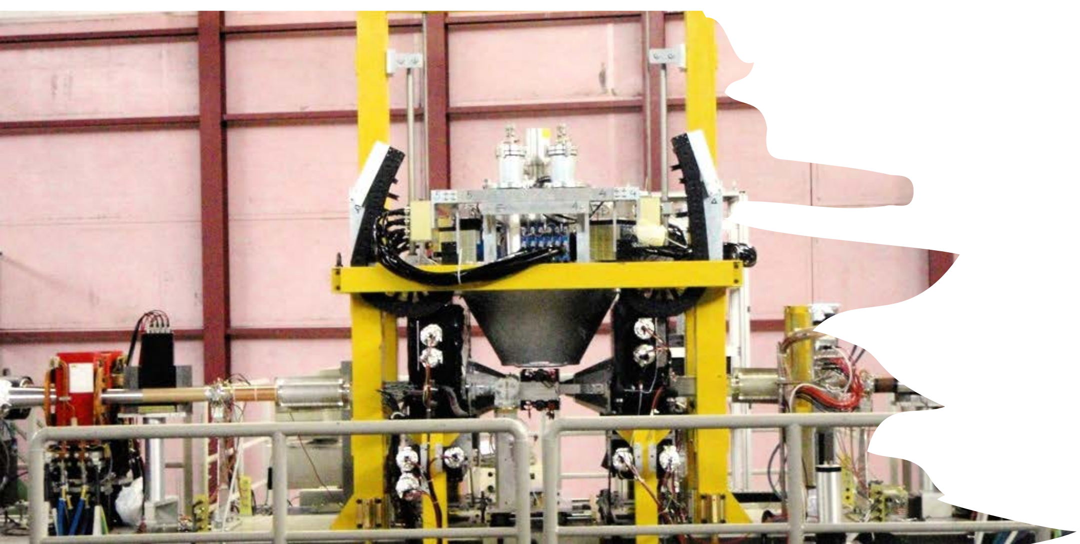
BUT

what we are aiming for is:

precision measurement of kaonic hydrogen 1s level shift;

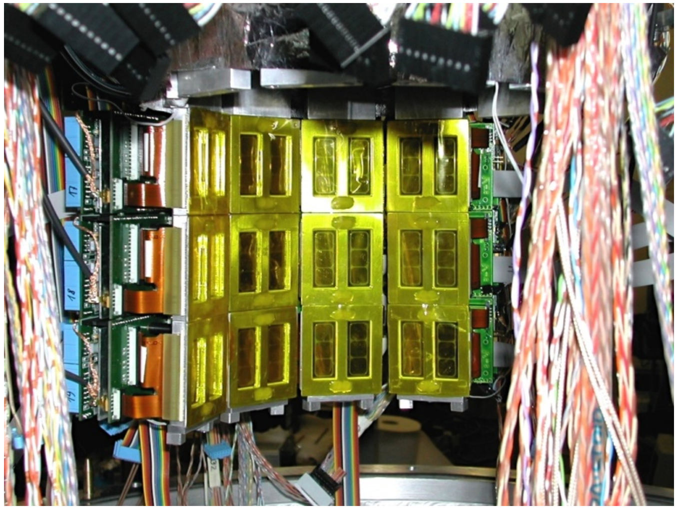
first measurement of kaonic deuterium



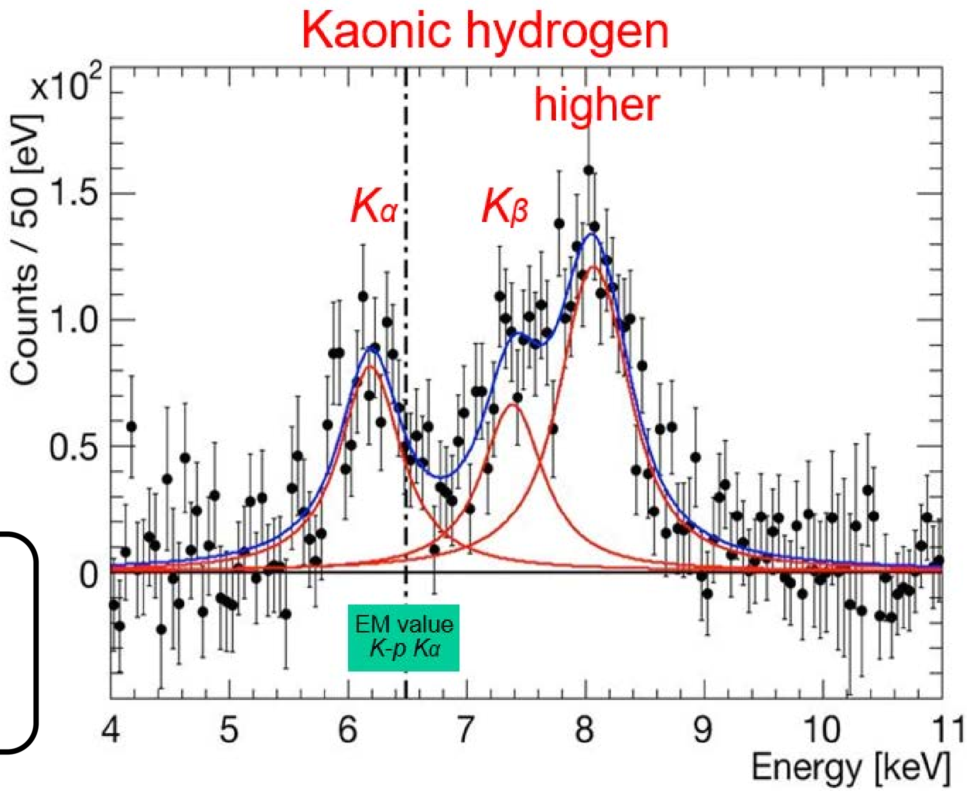


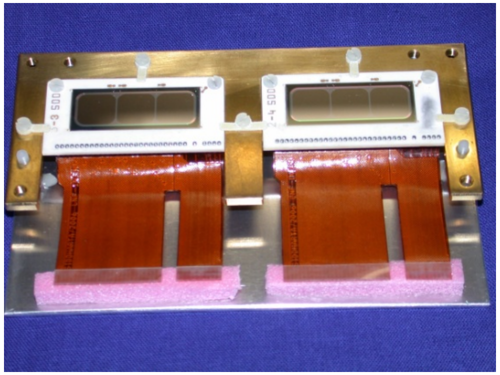
SIDDHARTA
(2007-2009)

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)



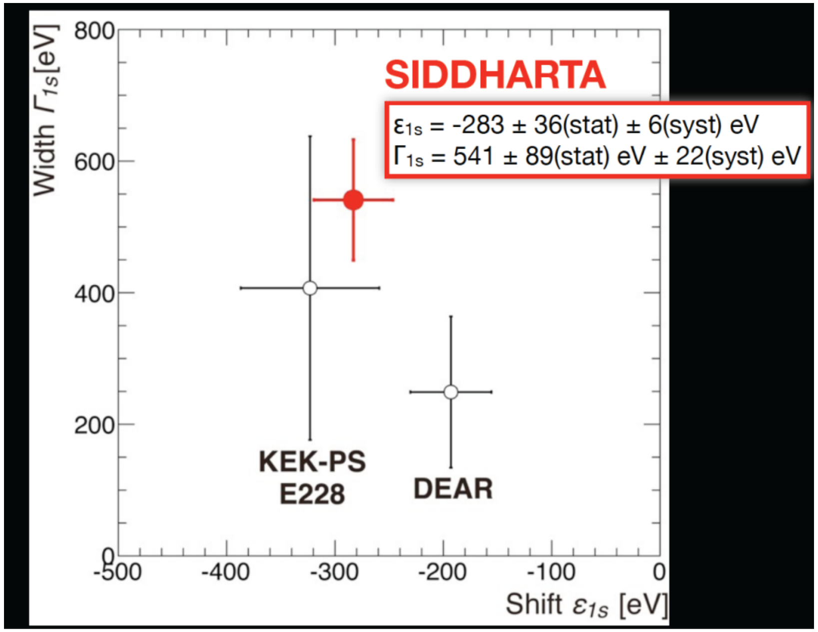


$\varepsilon_{1S} = -283 \pm 36(\text{stat}) \pm 6(\text{syst})$ eV
$\Gamma_{1S} = 541 \pm 89(\text{stat}) \pm 22(\text{syst})$ eV

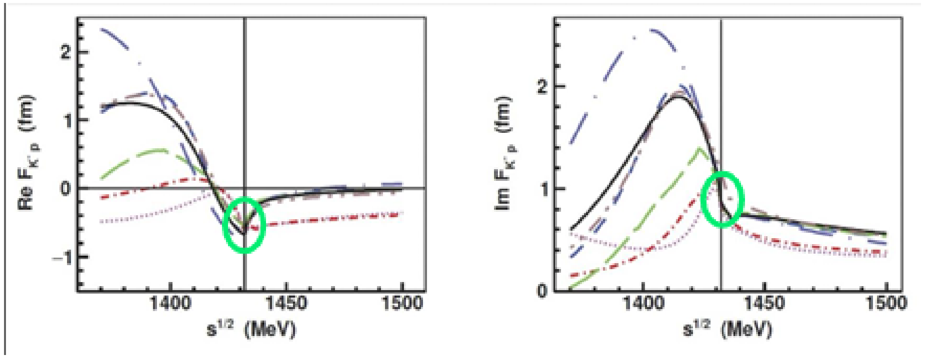
most reliable and precise measurement ever

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



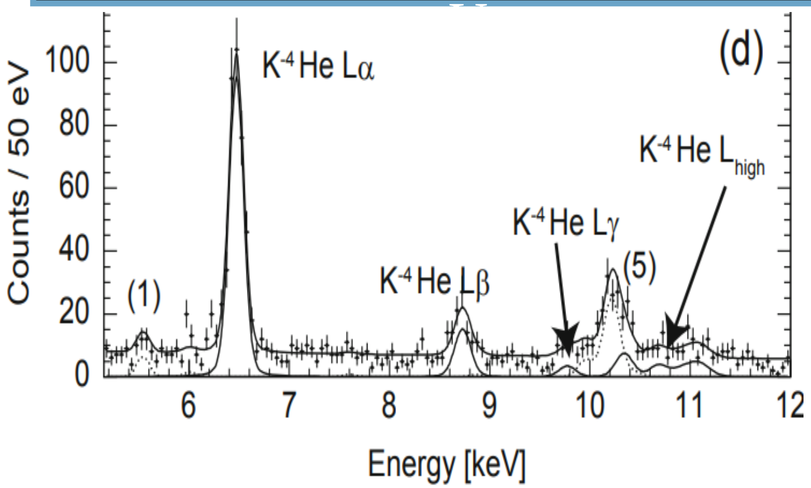
Ciepl y, A. et al. From KN interactions to K-nuclear quasi-bound states. AIP Conf. Proc. 2249, 030014 (2020).

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.)



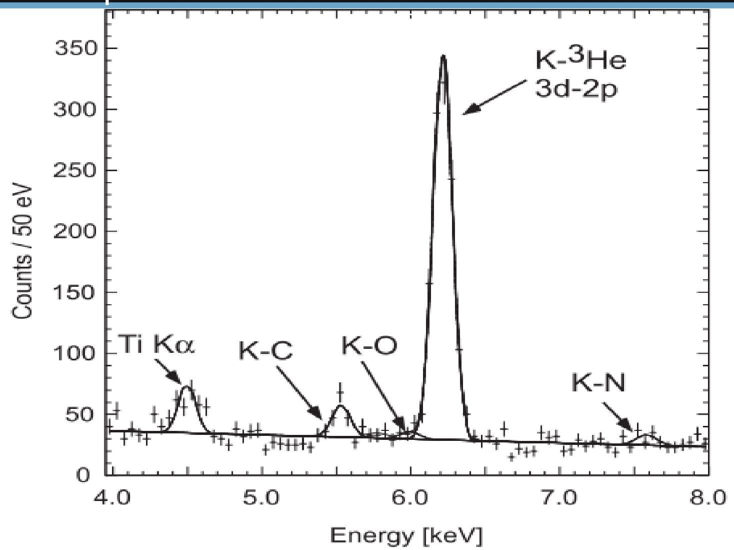
$$\Delta E_{2p} = +5 \pm 3(sta) \pm 4(sys)\ \text{eV}$$

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.)

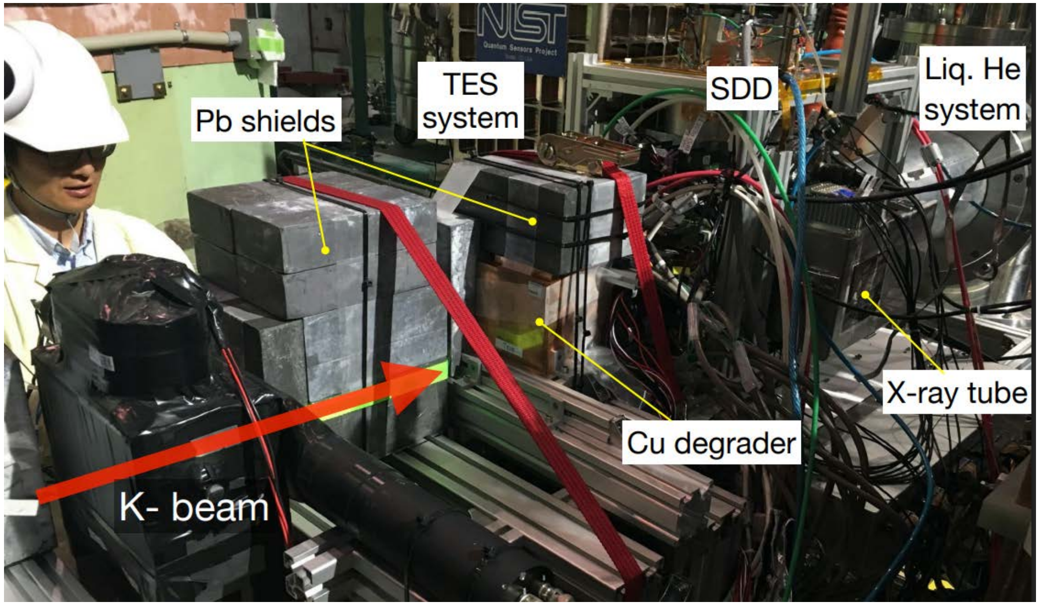


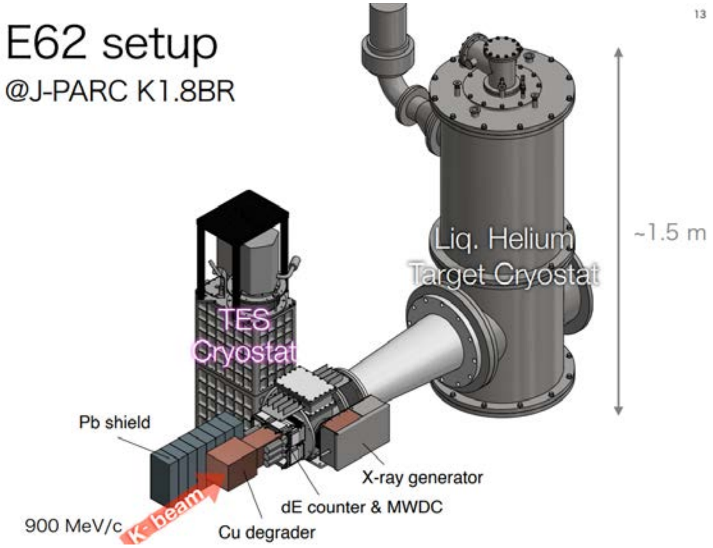
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

Phys. Lett. B 697 (2011) 199

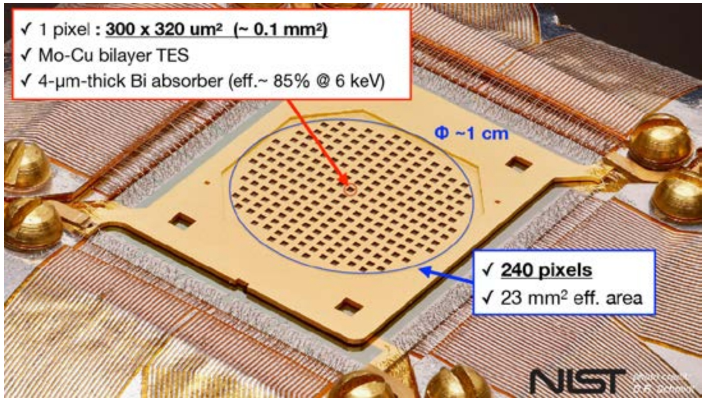
first time for ^3He

E62 experiment J-PARC (2018)





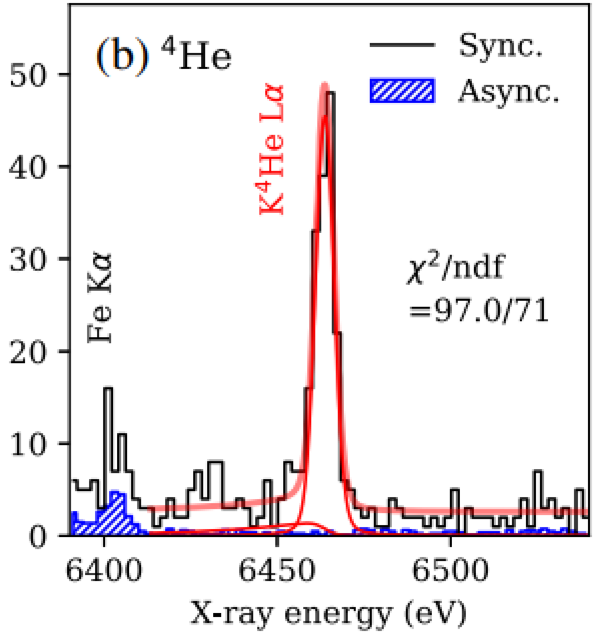
- **TES: transition edge sensors**, for extreme precision x-ray measurements.
- work on a calorimeter principle, based on a phase transition in a superconducting material, achieving **unprecedented energy resolution: 2 eV @ 6 keV.**



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

Kaonic 4-Helium

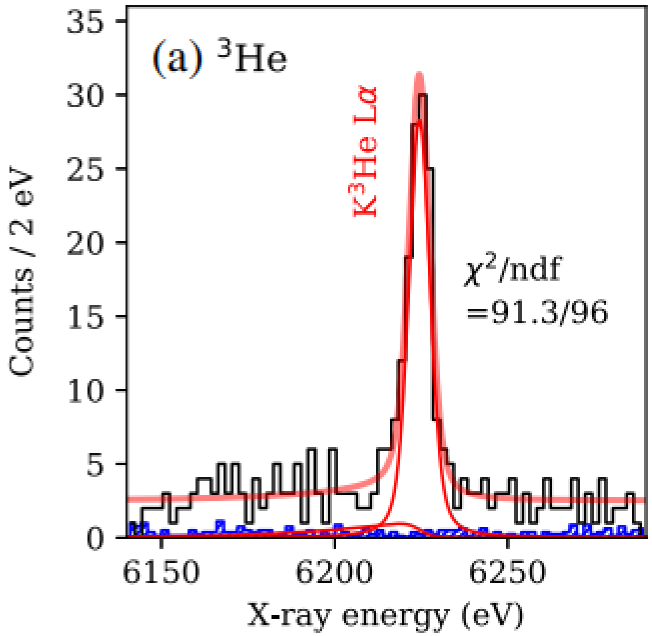
$$E_{3d\to 2p}^{K^-{}^4\mathrm{He}} = 6463.7 \pm 0.3(\mathrm{stat}) \pm 0.1(\mathrm{syst})\ \mathrm{eV}$$



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

Kaonic 3-Helium

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



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

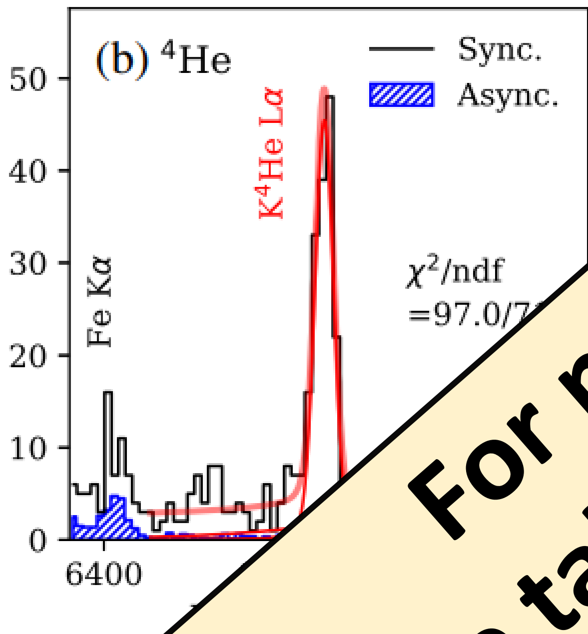
Phys. Rev. Lett. 128 (2022) 112503

Liquid target for $^{3,4}He$

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

Kaonic 4-Helium

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

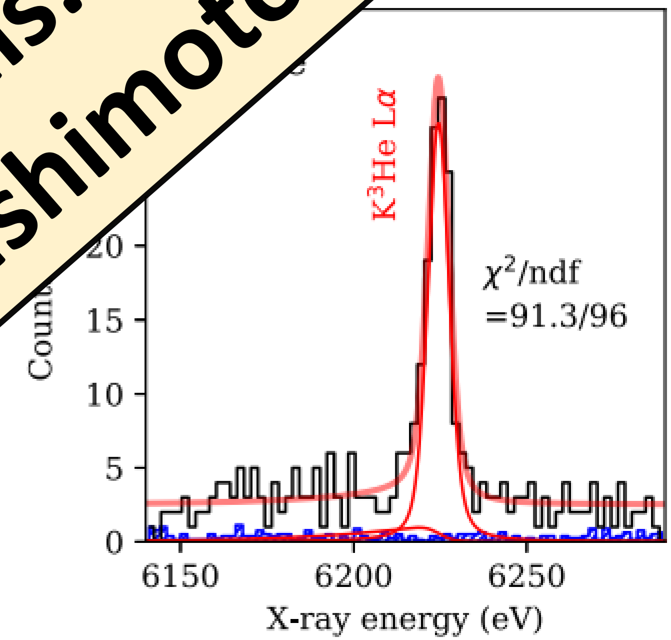


$E_{3d\to 2p}^{K^- {}^4He} = 64$ … (syst) eV

$\Gamma_{2p}^{K^- {}^4He} = 1.0 \pm$ … 3(syst) eV

… 3-Helium

… tat) $\pm\, 0.2(\mathrm{syst})$ eV,



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

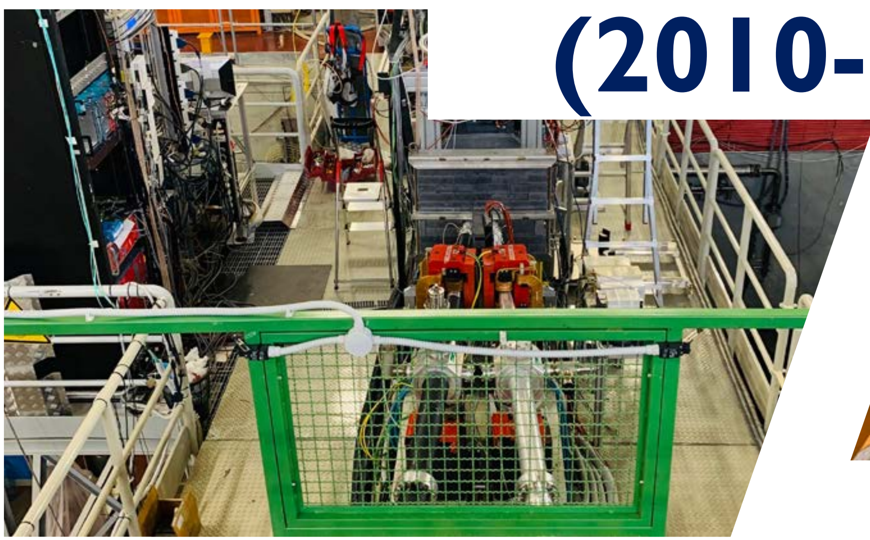
$\Gamma_{2p}^{K^- {}^3He} = 2.5 \pm 1.0(\mathrm{stat}) \pm 0.4(\mathrm{syst})$ eV

For more details: see talk of T. Hashimoto

Phys. Rev. Lett. 128 (2022) 112503

Liquid target for $^{3,4}He$

SIDDHARTA-2 (2010-2024)



SIDDHARTA-2 Scientific Goal

To perform the *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.

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

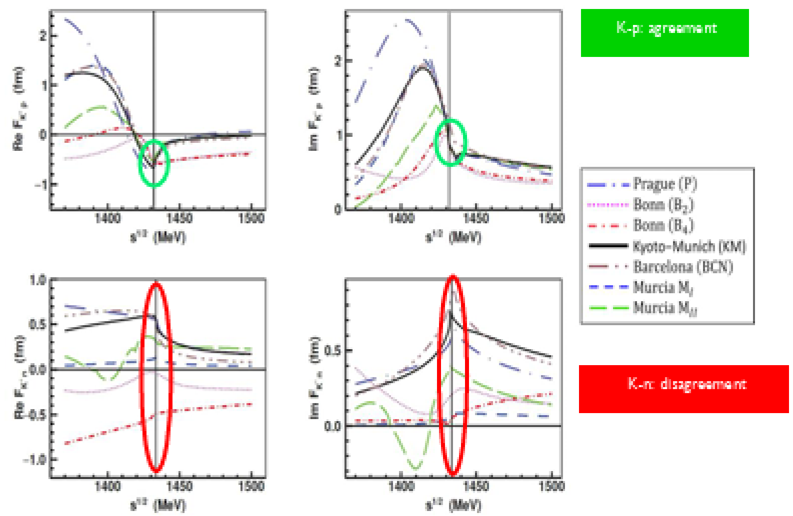
(μ_c reduced mass of the K^-p system, α fine-structure constant)

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

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

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

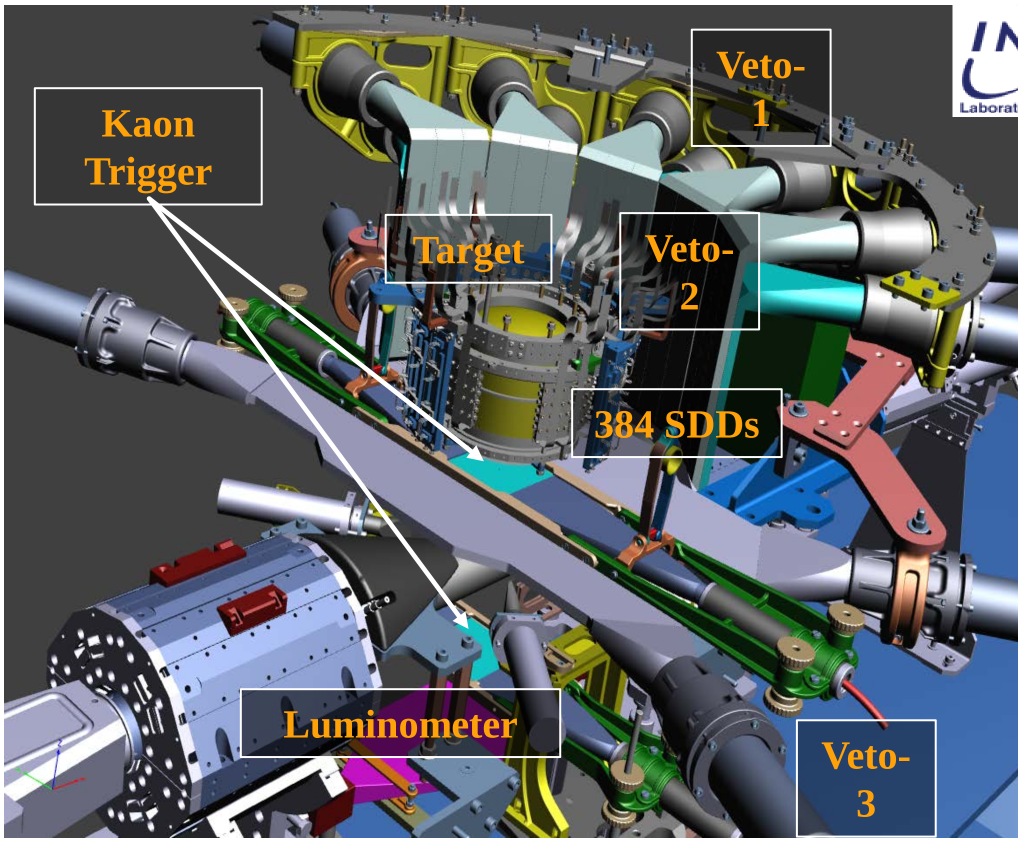
Combined analysis of the kaonic deuterium and kaonic hydrogen measurements to determine the isospin-dependet $\overline{K}N$ scattering lengths



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 SIDDHARTA-2 setup



New generation of Silicon Drift Detectors and read-out electronics

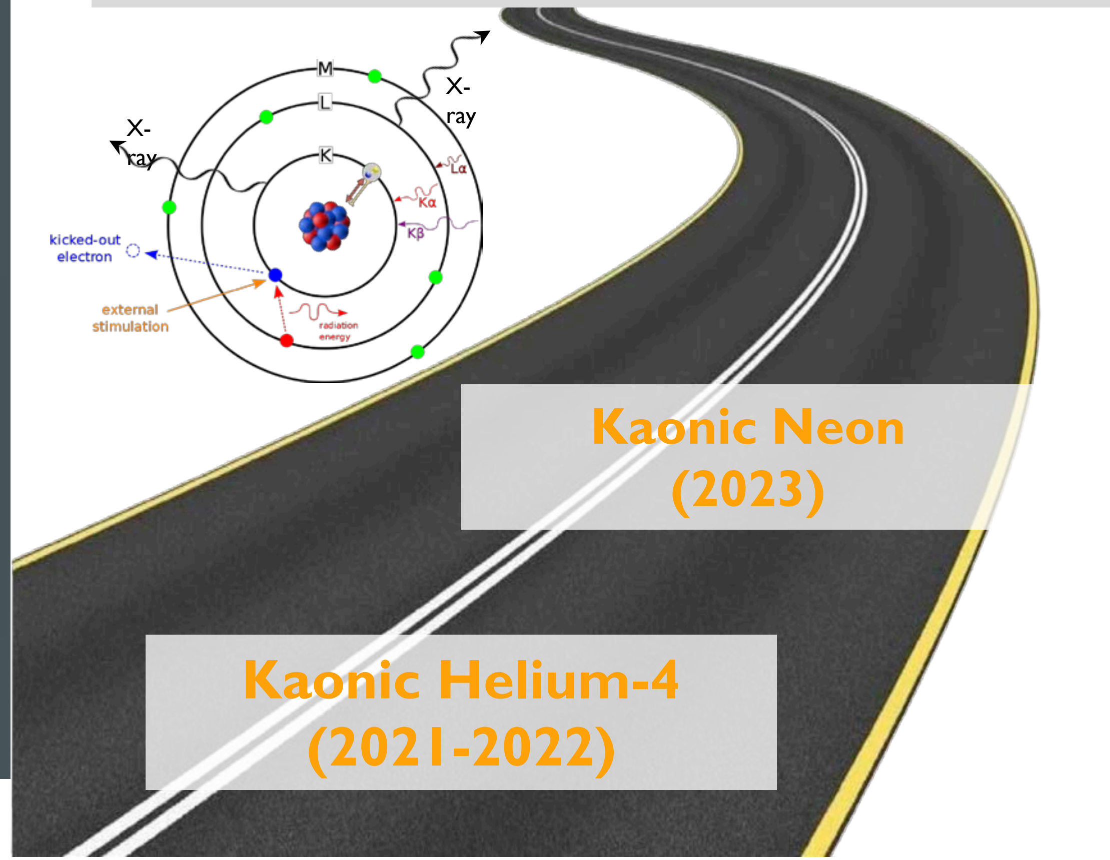
- Active area 2 times larger
- SDDs drift time 450 ns (instead of 800 ns as in SIDDHARTA) → e.m. background rejection improved by a factor of 2

The thickness of 450 µm ensures a high collection efficiency for X-rays of energy between 5 keV and 12 keV

- 3 veto system for hadronic background suppression
- New vacuum chamber and lead shield design for better background reduction

THE ROAD TO THE FIRST KAONIC DEUTERIUM MEASUREMENT

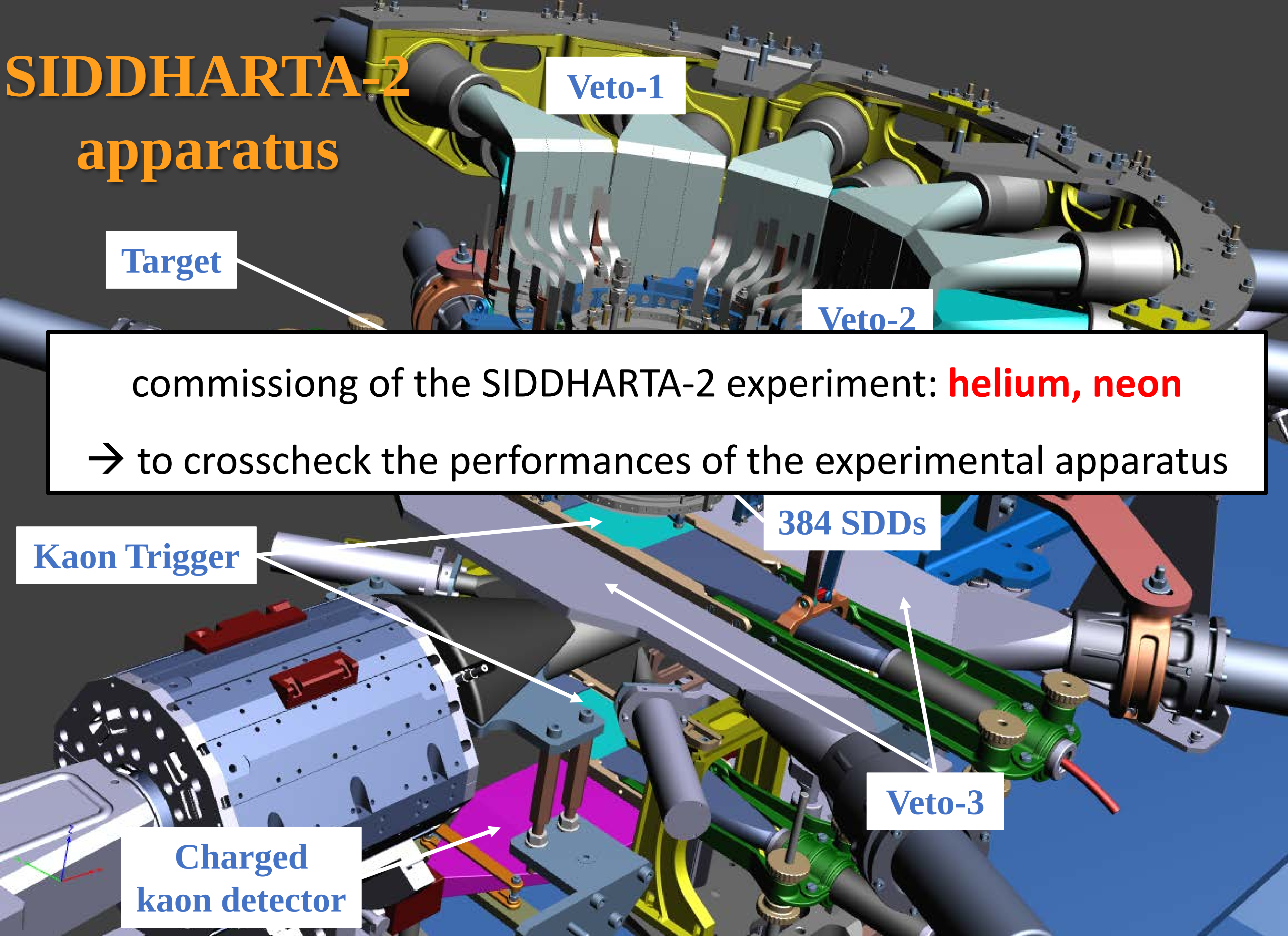
First kaonic deuterium measurement (2023 -2024)



Kaonic Neon (2023)

Kaonic Helium-4 (2021-2022)

SIDDHARTA-2 apparatus



commissiong of the SIDDHARTA-2 experiment: **helium, neon**

→ to crosscheck the performances of the experimental apparatus

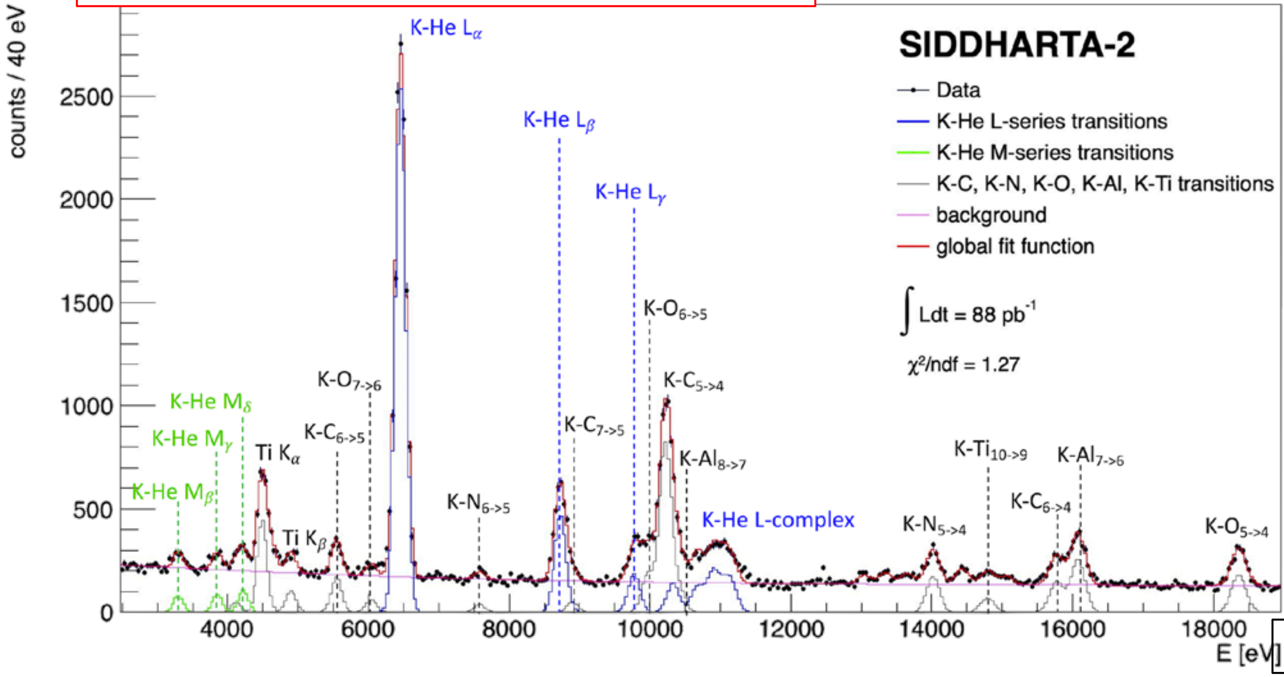
The Kaonic ^{4}He measurement (2021-2022)

- 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!

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

→ *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)

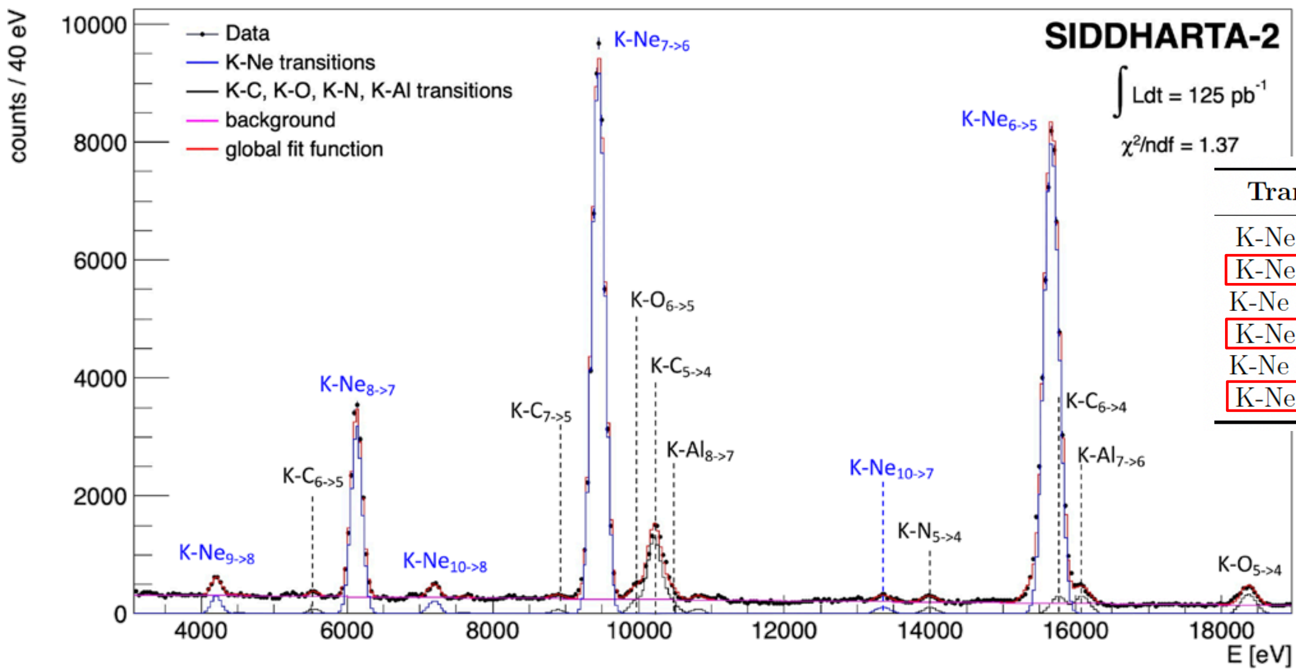
Sgaramella F., et al., 2023, Eur. Phys. J. A, 59 (3) 56

The new kaonic atoms measurements:

- ***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**

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 → 8)	4206.35 ± 3.75 (stat) ±2.00 (syst) eV
K-Ne (8 → 7)	6130.86 ± 0.71 (stat) ±1.50 (syst) eV
K-Ne (10 → 8)	7191.21 ± 4.91 (stat) ±2.00 (syst) eV
K-Ne (7 → 6)	9450.08 ± 0.41 (stat) ±1.50 (syst) eV
K-Ne (10 → 7)	13352.20 ± 10.07 (stat) ±3.00 (syst) eV
K-Ne (6 → 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**

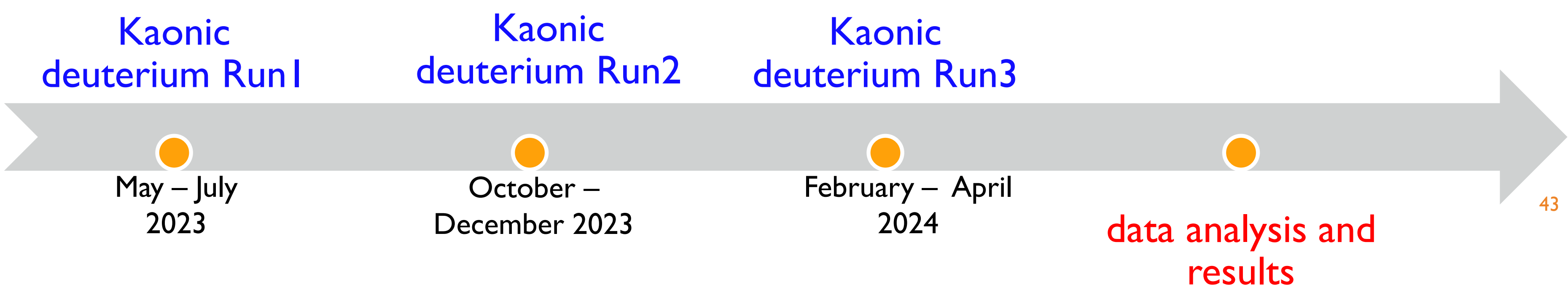
Transition	Yield
K-Ne (10 → 8)	0.010 ± 0.001 (stat) ± 0.001 (sys)
K-Ne (9 → 8)	0.137 ± 0.012 (stat) ± 0.010 (sys)
K-Ne (8 → 7)	0.228 ± 0.004 (stat) ± 0.011 (sys)
K-Ne (7 → 6)	0.277 ± 0.002 (stat) ± 0.014 (sys)
K-Ne (6 → 5)	0.308 ± 0.003 (stat) ± 0.015 (sys)

The first kaonic deuterium measurement (2023-2024)

The SIDDHARTA-2 collaboration aims **to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state with similar precision as K-p !**

- **First run** with SIDDHARTA-2 optimized setup for **200 pb^{-1}** integrated luminosity: May – July 2023
- **Second run** - October – December 2023: **345 pb^{-1}**
- **Third run** 2024 - February – April 2024: **435 pb^{-1}**

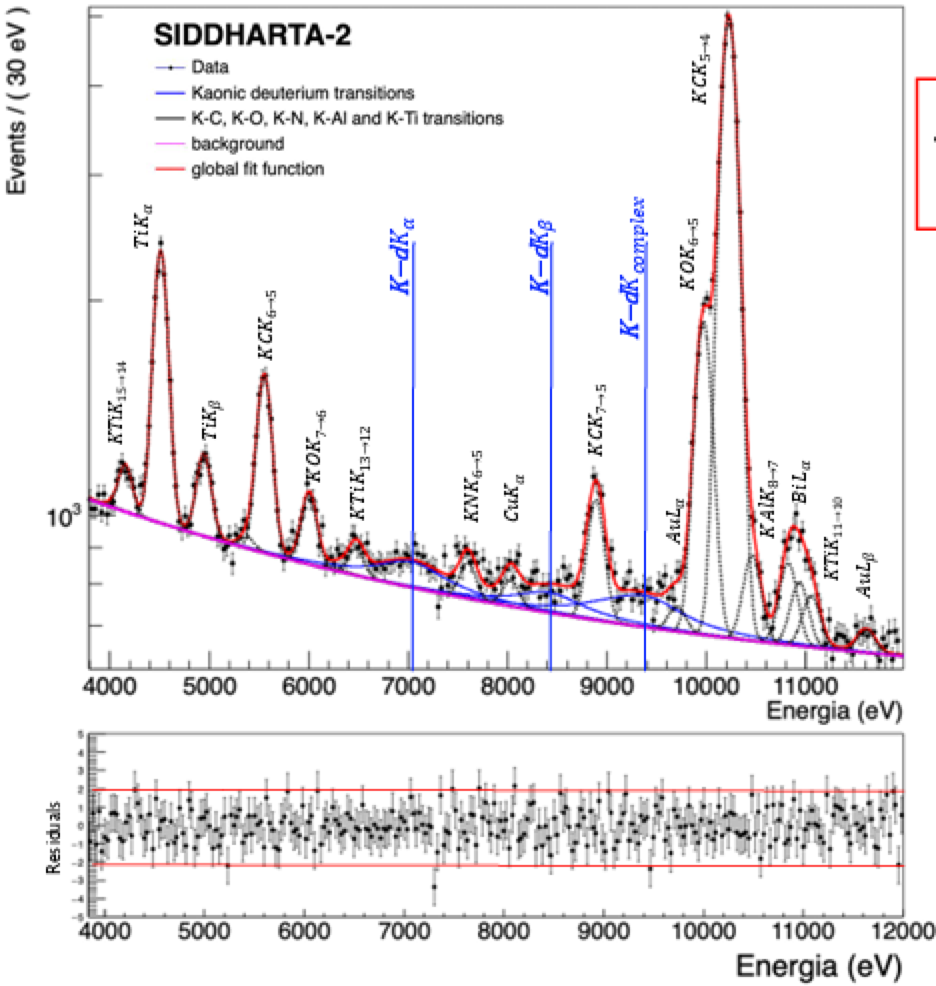
Total integrated luminosity of 980 pb^{-1}



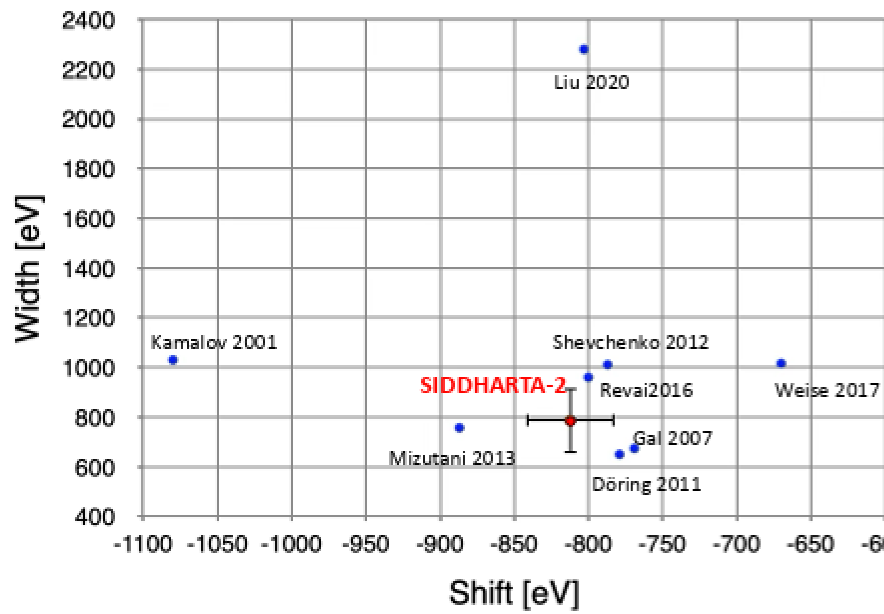
Kaonic Deuterium Results

$$\varepsilon_{1s} = E^{exp}_{2p\to 1s} - E^{QED}_{2p\to 1s} = 7021.9 - 7834.0 = -812.1 \pm 29.8(stat) \pm 2.1(syst)\ \text{eV}$$

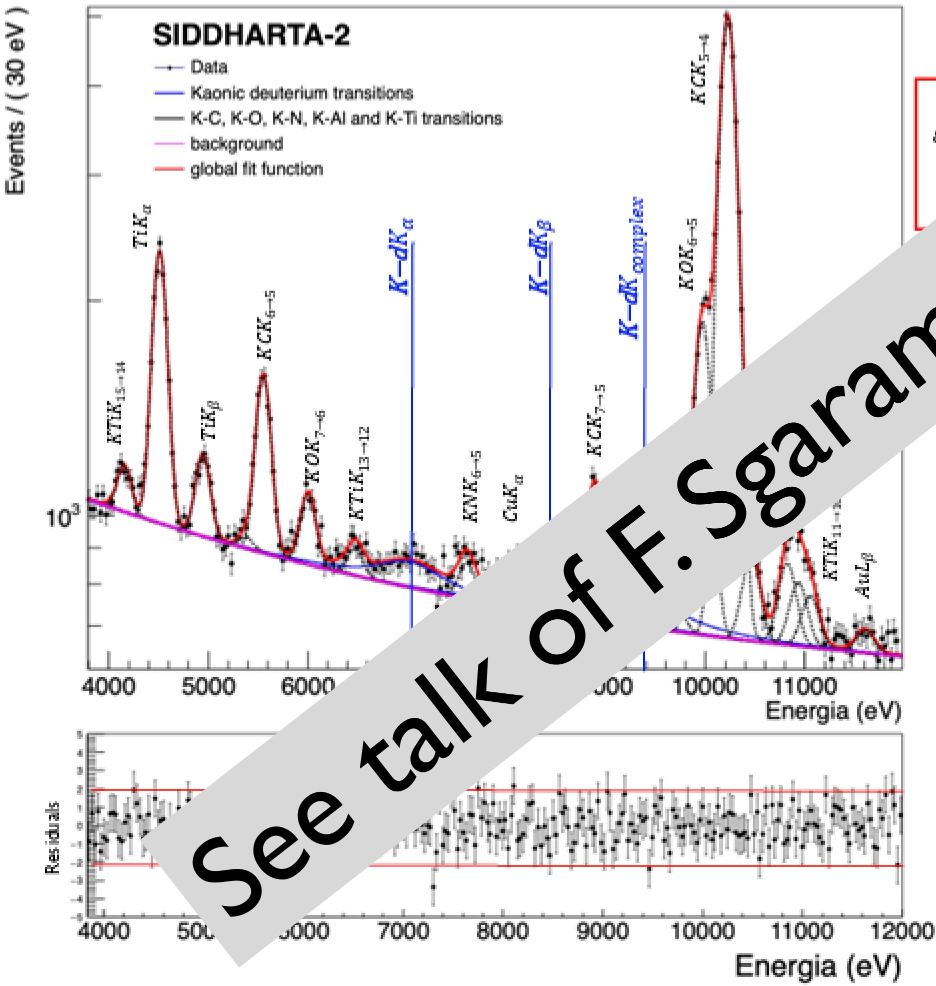
$$\Gamma_{1s} = 787 \pm 126(stat) \pm 33(syst)\ \text{eV}$$



Targeted precision achieved!



Kaonic Deuterium Results

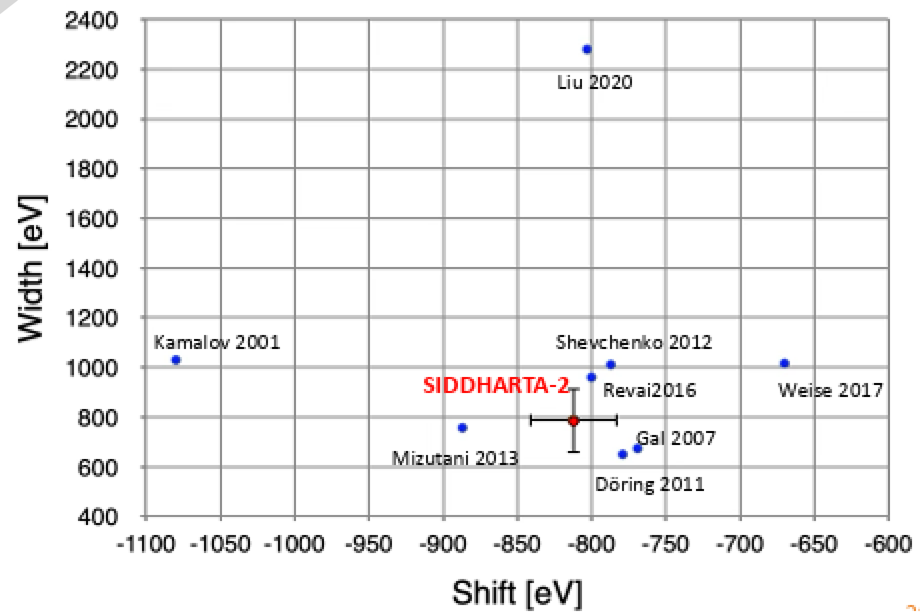


See talk of F. Sgaramella

$\varepsilon_{1s} = E^{exp}_{2p \to 1s} - E^{QED}_{2p \to 1s} = 7021.9 - 7834.0 = -812.1 \pm 29.8(stat) \pm 2.1(syst)$ eV

$\Gamma_{1s} = 787 \pm 126(stat) \pm 33(syst)$ eV

Targeted precision achieved!



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

confirmed repulsive shift

Significant improvement!

KpX @ KEK 1997

DEAR @ DAFNE 2005

SIDDHARTA @ DAFNE 2011

2000

2010

Solved K-He puzzle

E570 @ KEK 2007

SIDDHARTA ^{4}He @ DAFNE 2009

SIDDHARTA ^{3}He @ DAFNE 2011

2022

E62 ^{3,4}He @ JPARC 2022

Liquid target

Gas target

SIDDHARTA2 ^{4}He @ DAFNE 2022

SIDDHARTA2 KNe @ DAFNE 2023

2024

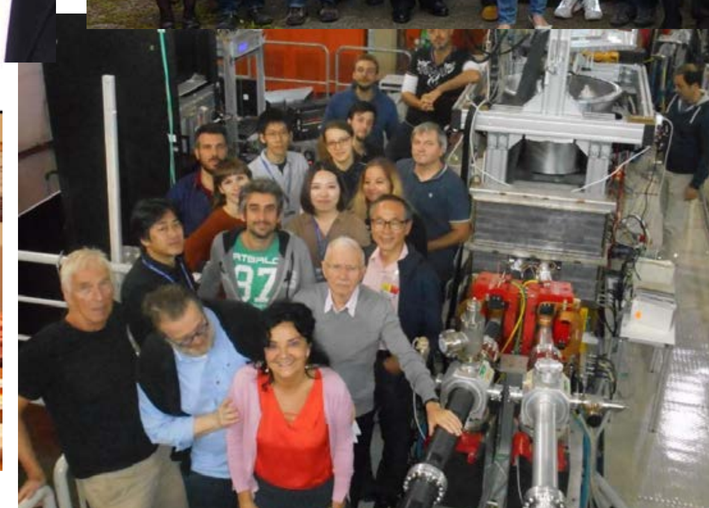
SIDDHARTA2 K-d @ DAFNE 2024

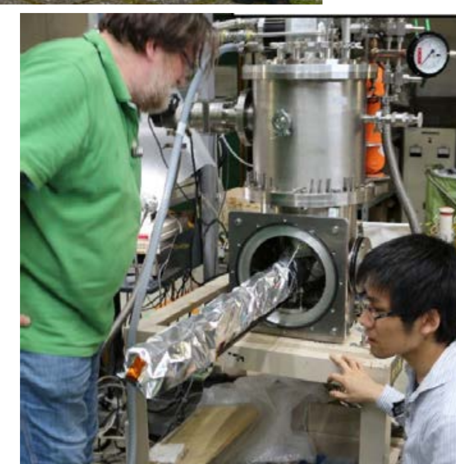
CONCLUSION

- 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.

More than 25 years of friendship and work together





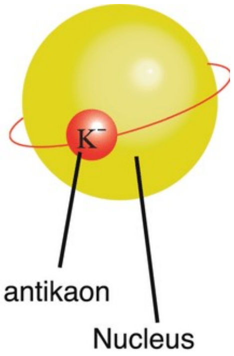
THANK YOU!

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**

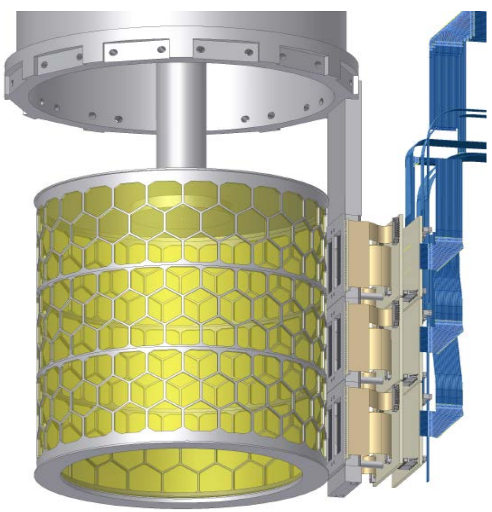
Dedicated runs with different types of detectors: CZT detectors, SDDs

	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

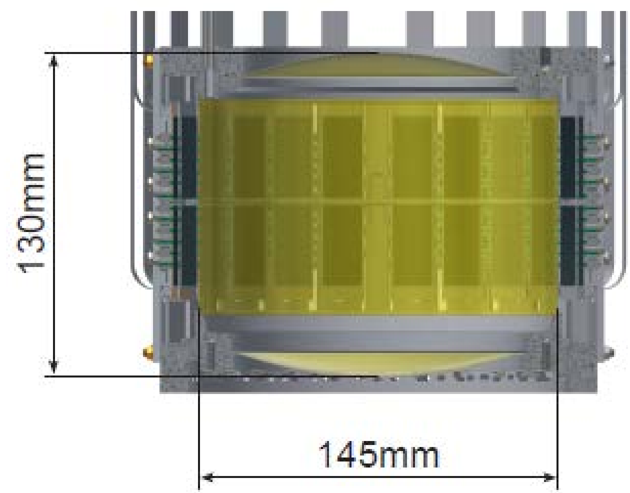
[a]Gas density as a fraction of the liquid hydrogen density (0.0708 g/cm^3).

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

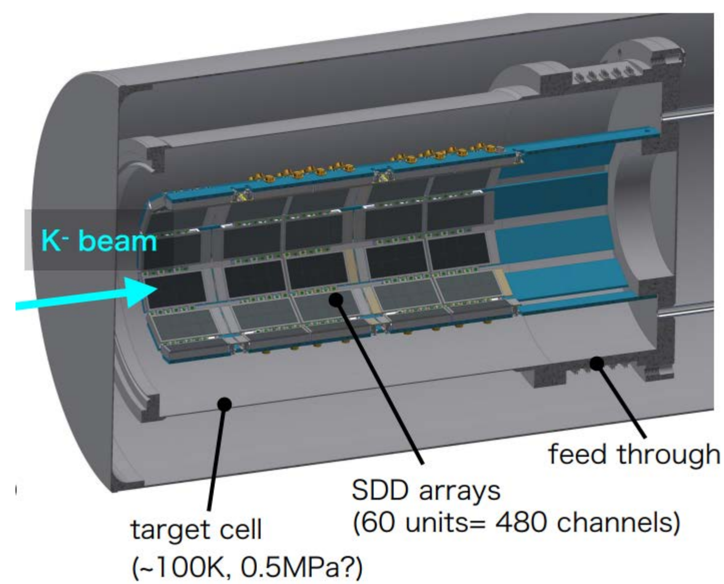
SIDDHARTA



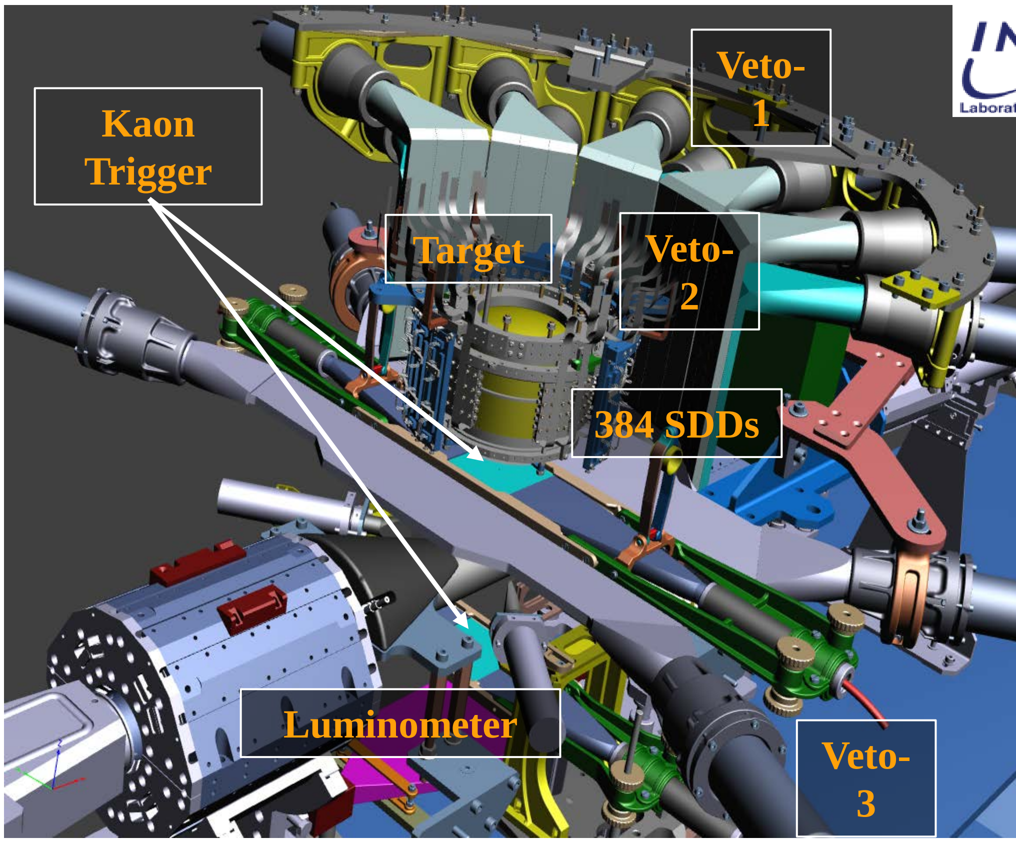
SIDDHARTA-2



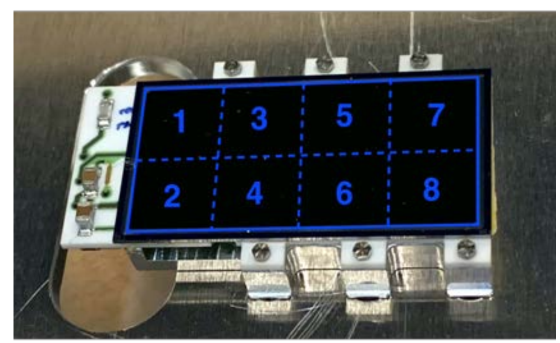
E57 –updated strategy



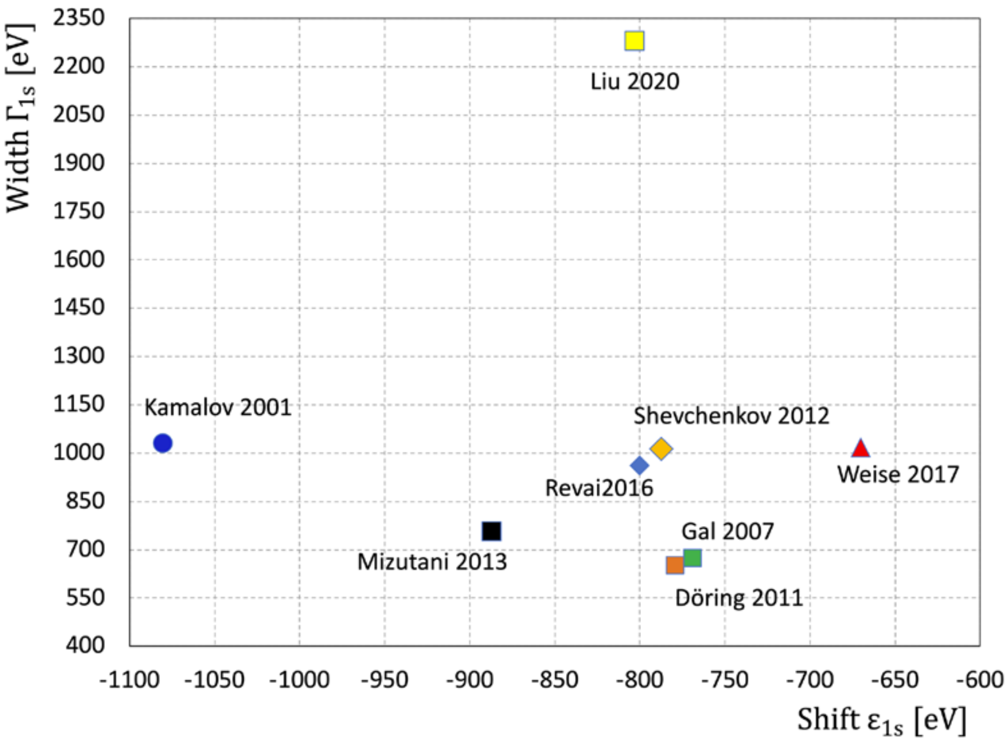
The SIDDHARTA-2 setup



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)

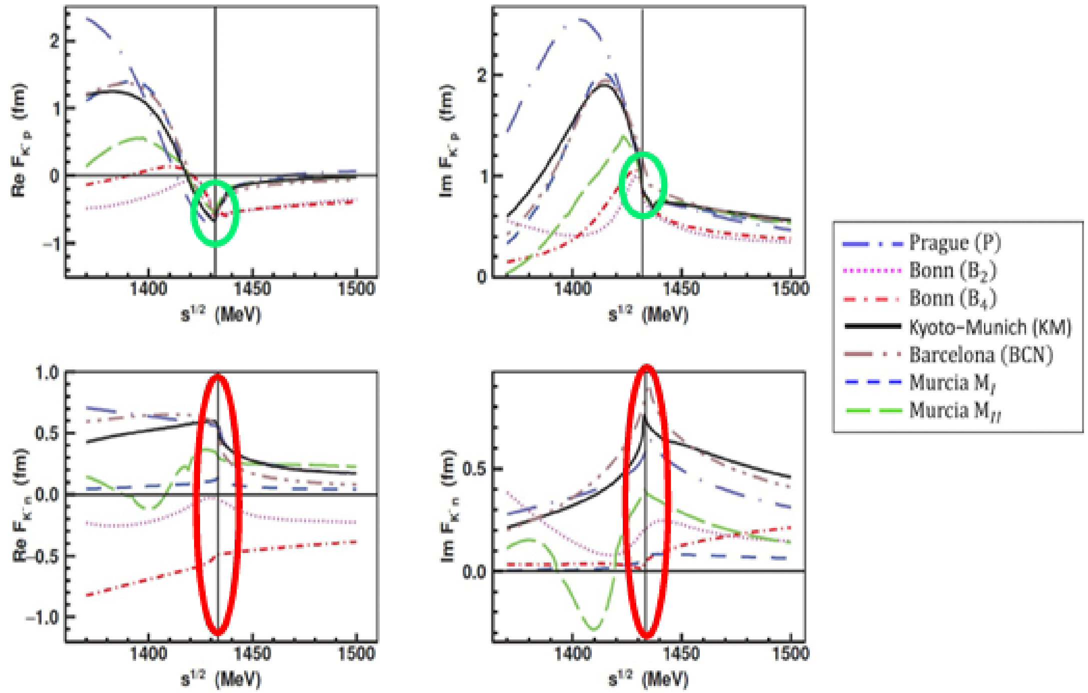
Kaonic Deuterium analysis: next steps

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

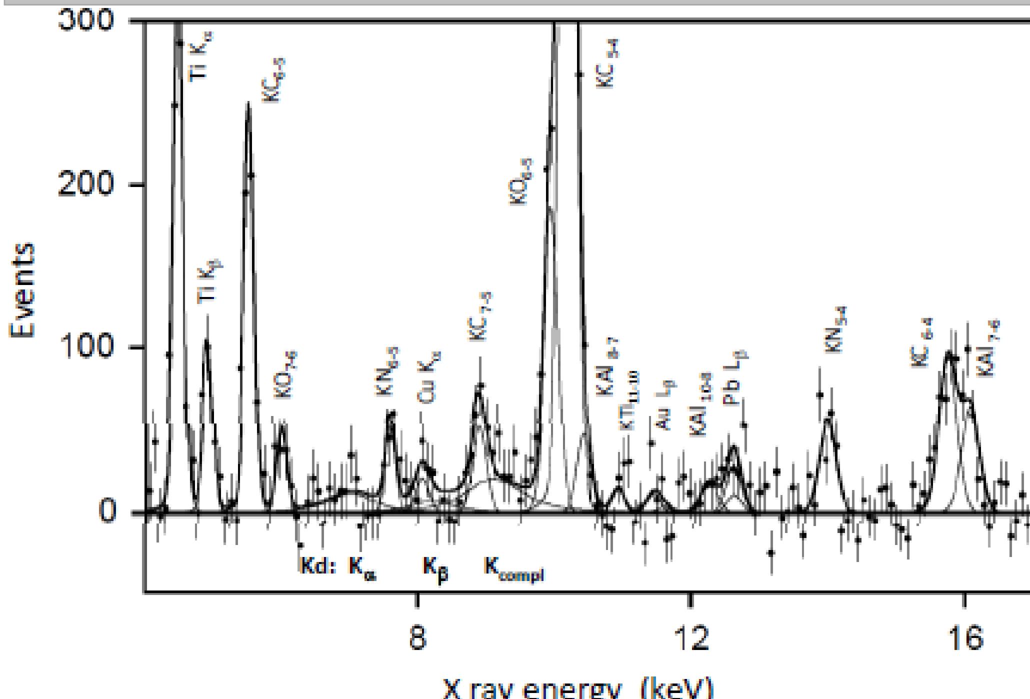
BG sources: asynchronous BG → timing
synchronous BG → spatial correlation

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

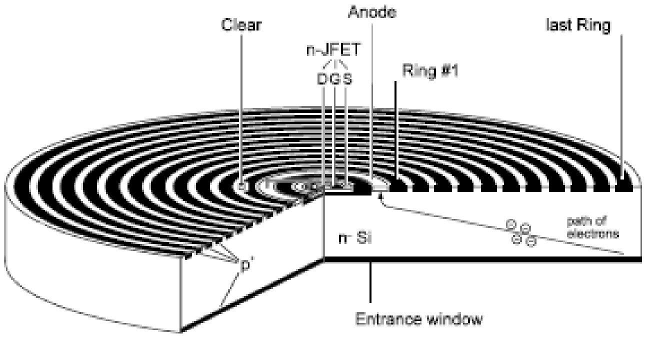
The kaonic deuterium measurements at DAΦNE and at J-PARC require:

- 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

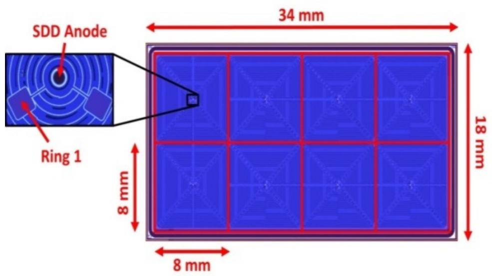
New SDD detectors for SIDDHARTA-2 and E57

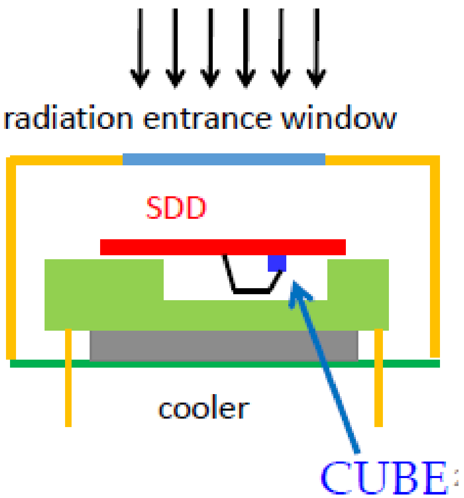
difference with respect to the SDDs in SIDDHARTA:

- 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)

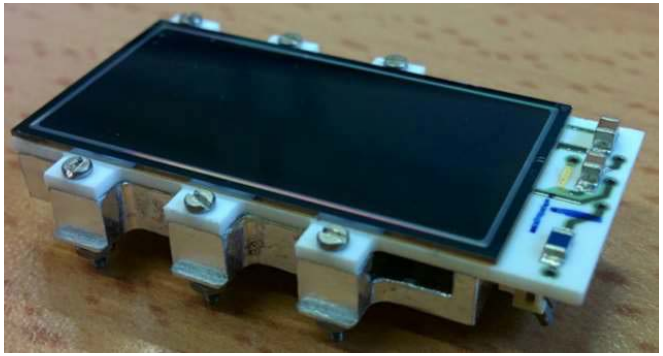


Better drift time of 300 ns compared to the SDDs in SIDDHARTA (~800 ns)





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.

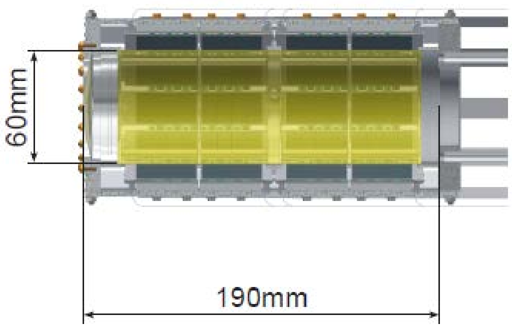
The final dimensions of the target cells depend on the machine used.

- **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,

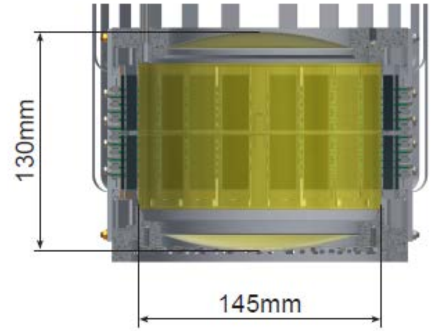
Therefore, the dimensions of the target cells are quite different

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

E57

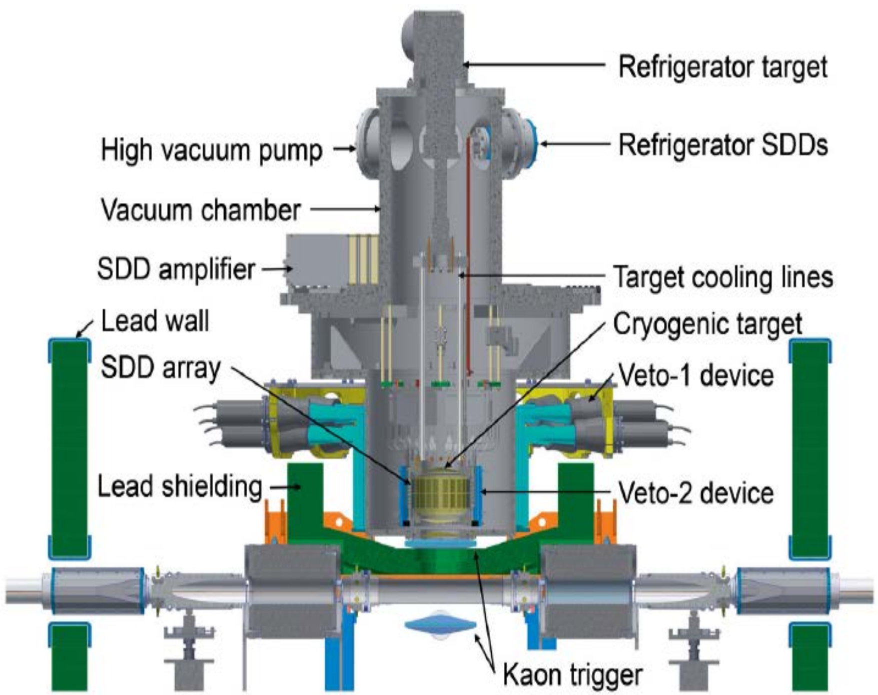


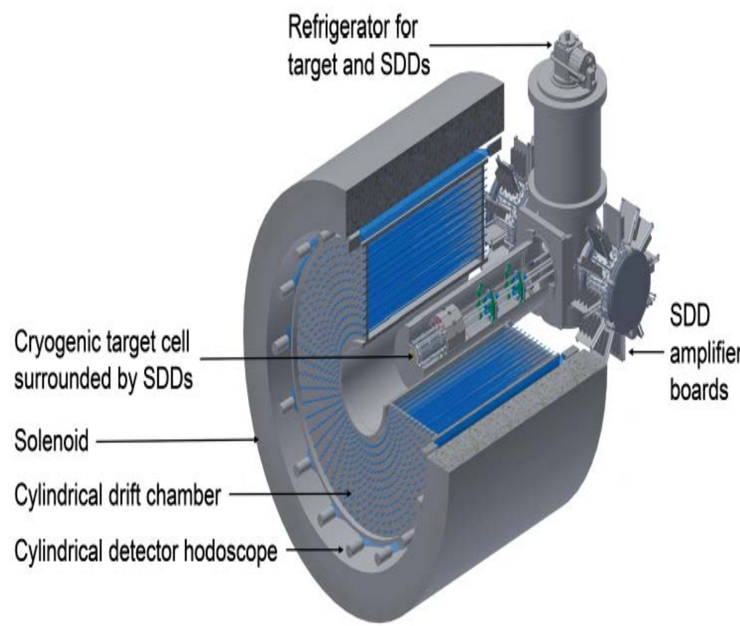
SIDDHARTA-2



SIDDHARTA-2

E57



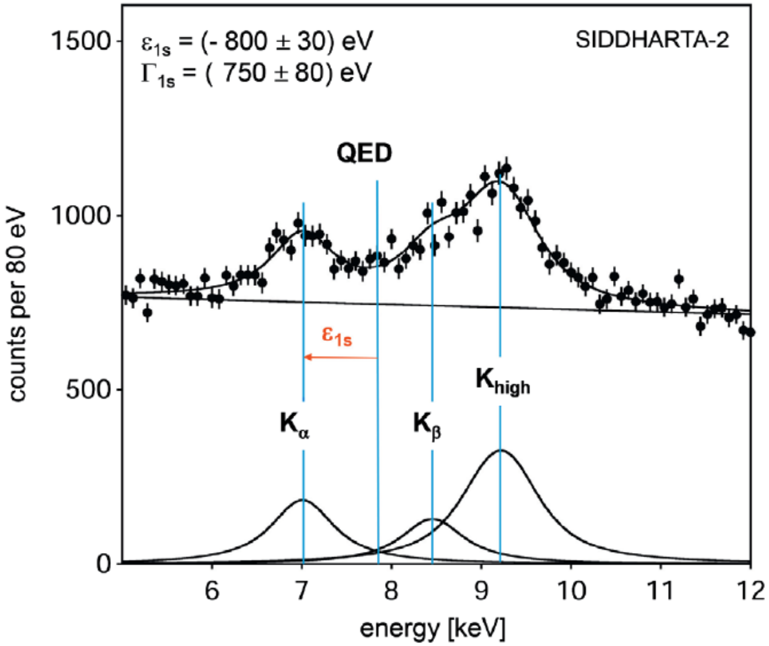


SIDDHARTA – 2, installed in DAΦNE from April 2019, ready to start to take data for kaonic deuterium: 2020

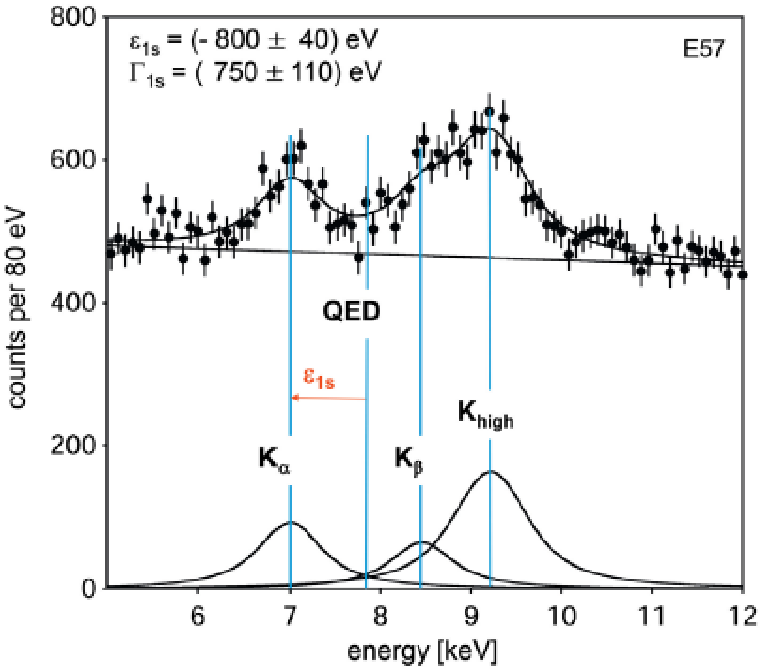
E57
data for kaonic deuterium: 2022 (?)

The Monte Carlo simulations for kaonic deuterium

SIDDHARTA-2



E57



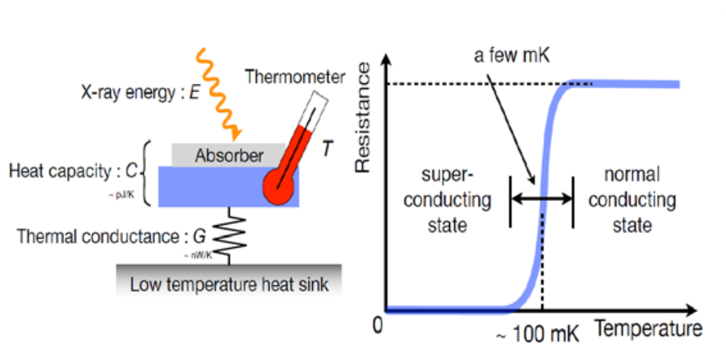
KH results:

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.

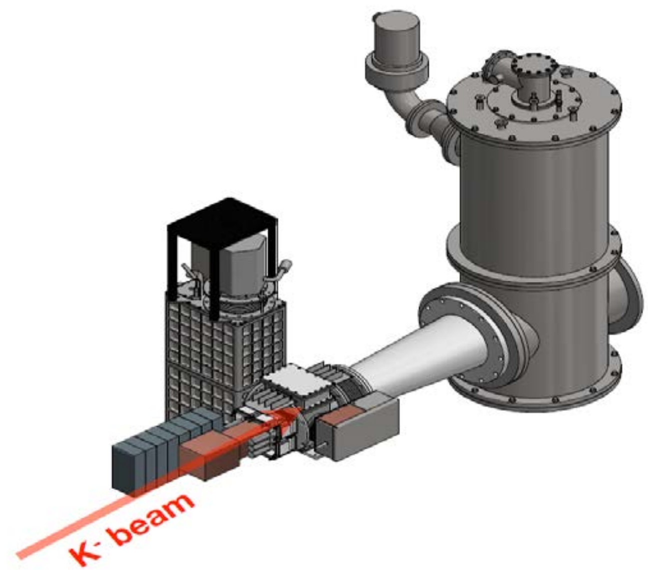


✓ Excellent energy resolution ~2 eV FWHM@ 6 keV

✓ Wide dynamic range possible

E62: K$^-$He 3d-2p

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

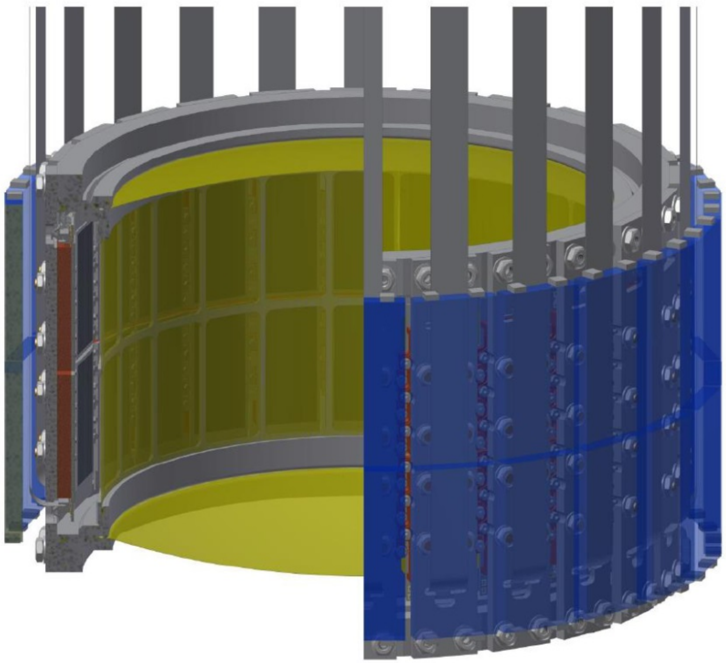


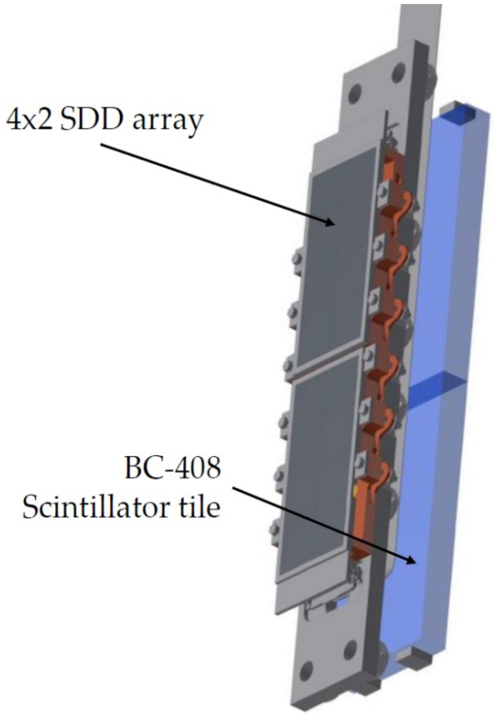
CONCLUSIONS

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

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