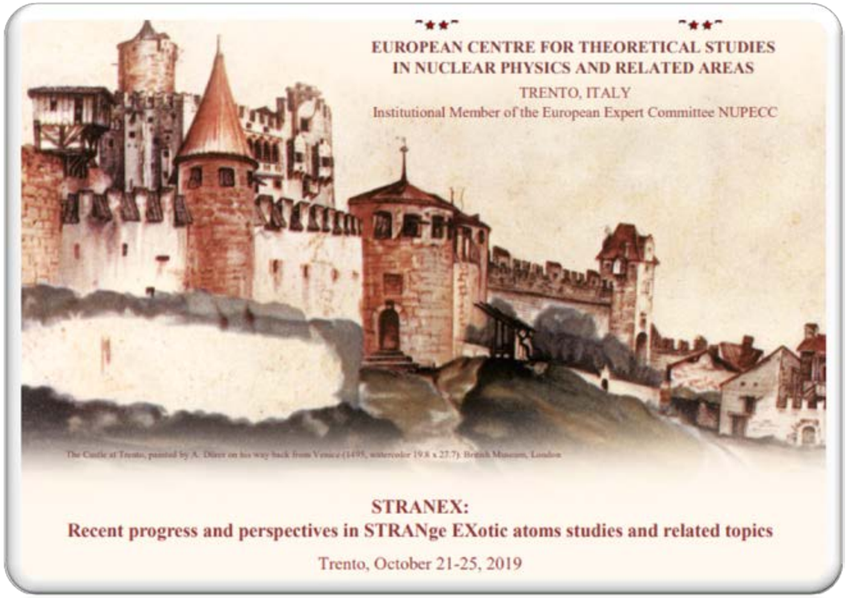
STRANEX: Recent progress and perspectives in STRANge EXotic atoms studies and related topics



The physics of kaonic atoms in the last 20 years

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INFN-LNF

on behalf of SIDDHARTA/SIDDHARTA-2 collaborations

21-25 October 2019
Trento, Italy

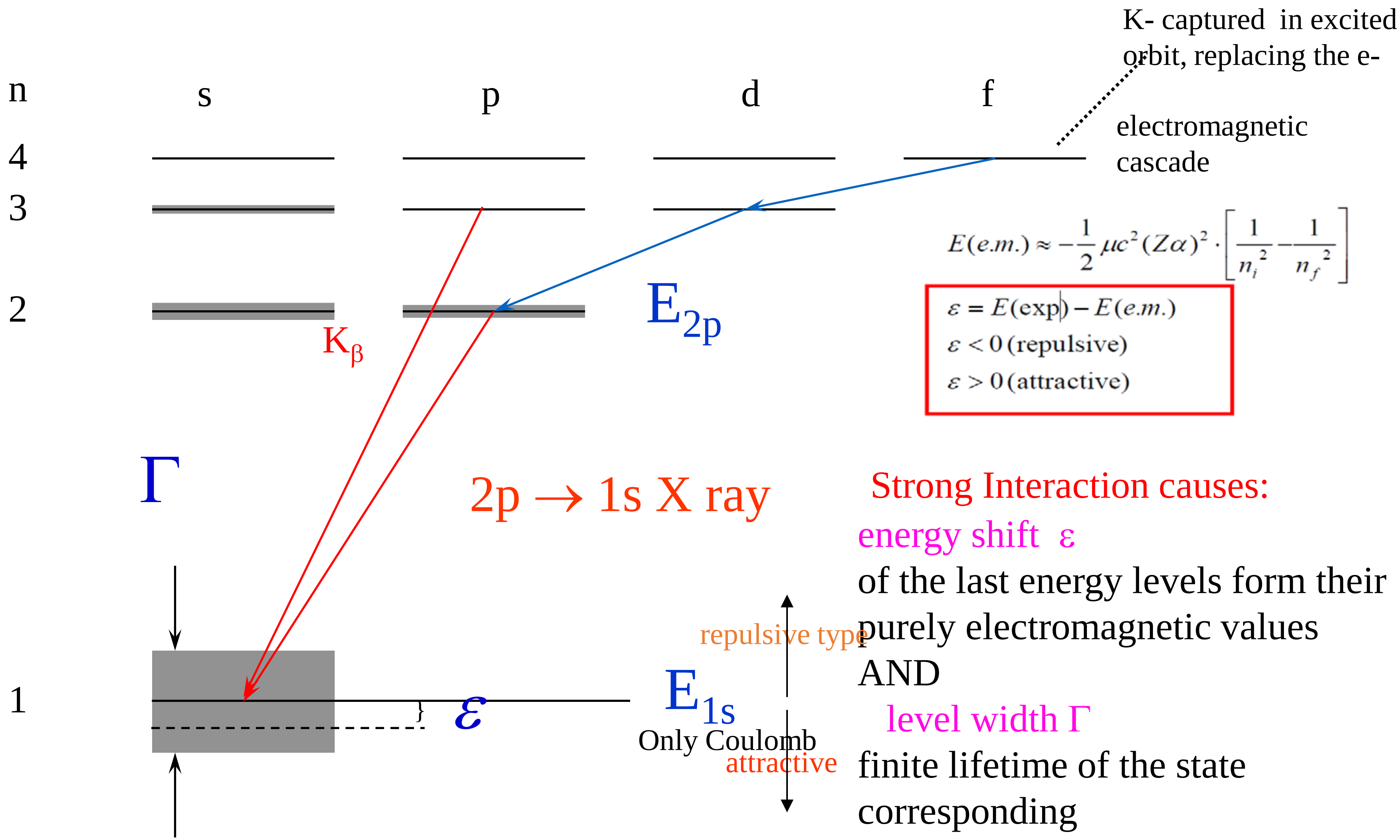
The modern era of light kaonic atoms experiments,
the precision era, covers the last twenty years.

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 Hydrogen atoms



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

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

Strong Interaction causes:

energy shift ε

of the last energy levels form their purely electromagnetic values

AND

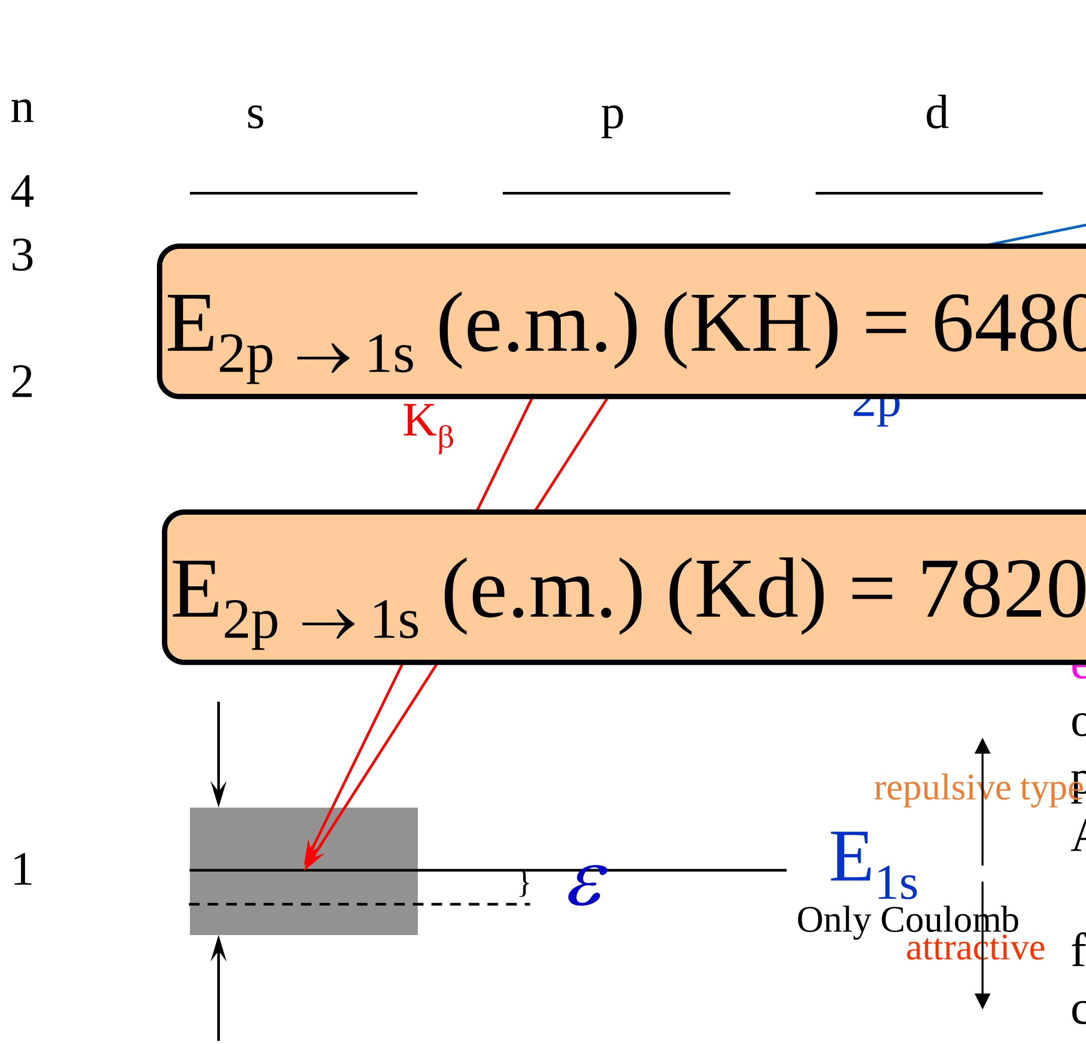
level width Γ

finite lifetime of the state corresponding

to an increase in the observed level width

$$\varepsilon = E_{2p \to 1s}(\exp) - E_{2p \to 1s}(e.m.)$$

Kaonic Hydrogen atoms



$$E_{2p \rightarrow 1s}\ (\text{e.m.})\ (\text{KH}) = 6480 \pm 1\ \text{eV}$$

$$E_{2p \rightarrow 1s}\ (\text{e.m.})\ (\text{Kd}) = 7820 \pm 1\ \text{eV}$$

$\left[\frac{1}{n_i^2} - \frac{1}{n_f^2}\right]$

$\varepsilon < 0$ (repulsive)

$\varepsilon > 0$ (attractive)

es:

energy shift ε

of the last energy levels form their purely electromagnetic values

AND

level width Γ

finite lifetime of the state corresponding to an increase in the observed level width

$$\varepsilon = E_{2p \rightarrow 1s}\ (\text{exp}) - E_{2p \rightarrow 1s}\ (\text{e.m.})$$

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

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

Observable in light kaonic atoms (Deser formula)

Deser-type relation (including the isospin-breaking corrections) connects shift ε_{1s} and width Γ_{1s} to the real and imaginary part of $a_{K\text{-}p}$

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-p}[1 - 2\alpha\mu(\ln\alpha - 1)a_{K-p} + \ldots]$$

A similar formula holds for $a_{K\text{-}d}$

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K-d}[1 - 2\alpha\mu(\ln\alpha - 1)a_{K-d} + \ldots]$$

The connection between the scattering lengths $a_{K\text{-}p}$ and $a_{K\text{-}d}$ and the s-wave $\bar{K}N$ isospin dependent (I=0,1) isoscalar a_0 and isovector a_1 scattering length:

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

$$a_{K-n} = a_1$$

$$a_{K-d} = \frac{4[m_N + m_K]}{[2m_N + m_K]} Q + C$$

$$Q = \frac{1}{2}[a_{K-p} + a_{K-n}] = \frac{1}{4}[a_0 + 3a_1]$$

C, includes all higher-order contributions, namely all other physics associated with the K^-d three-body interaction.

Fundamental inputs of low-energy QCD effective theories.

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

The availability of the new kaon beams with excellent characteristics for the studies of kaonic atoms was the first necessary ingredient towards the progress in kaonic atoms studies in the modern era.

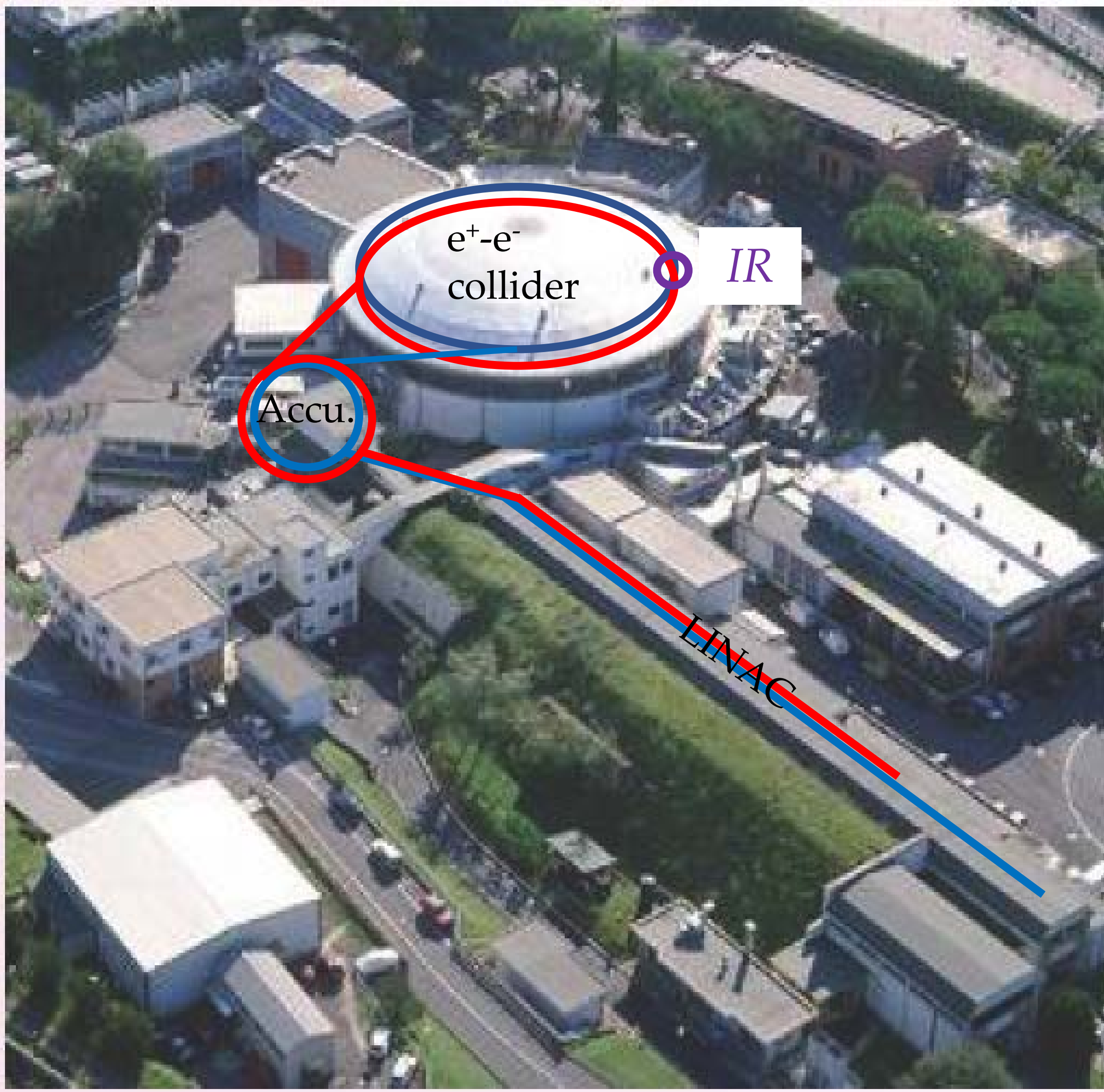
New technological developments in the accelerators delivering kaon beams:

1. DAΦNE collider at LNF-INFN

2 kaon extracted beams in Japan, firstly at KEK and then at J-PARC

DAΦNE accelerator, since 1998:

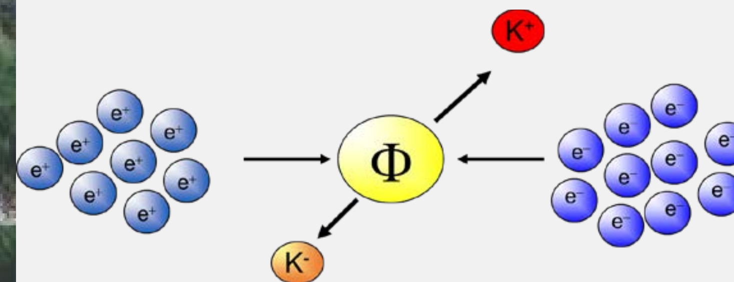
The Double Annular Φ factory for Nice Experiments



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



Φ produced via e^+e^- collision

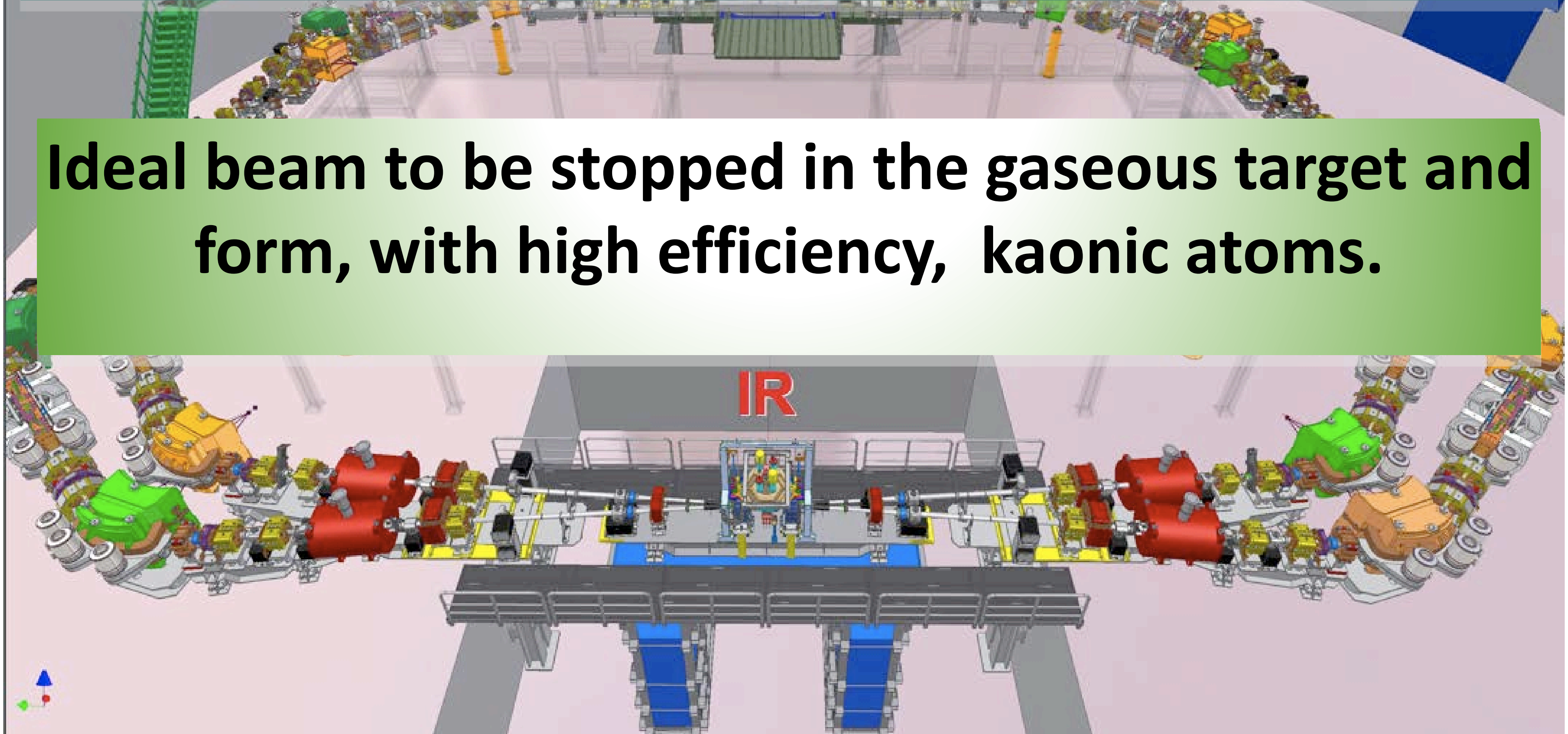
$\sigma(e^+e^- \rightarrow \Phi) \sim 5\ \mu b$

→ monochromatic kaon beam (127 MeV/c)

DAΦNE: low-momentum kaon beam

- $\Phi \rightarrow K^- K^+$ (49.1%)
- monochromatic low-energy K (~127MeV/c)

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



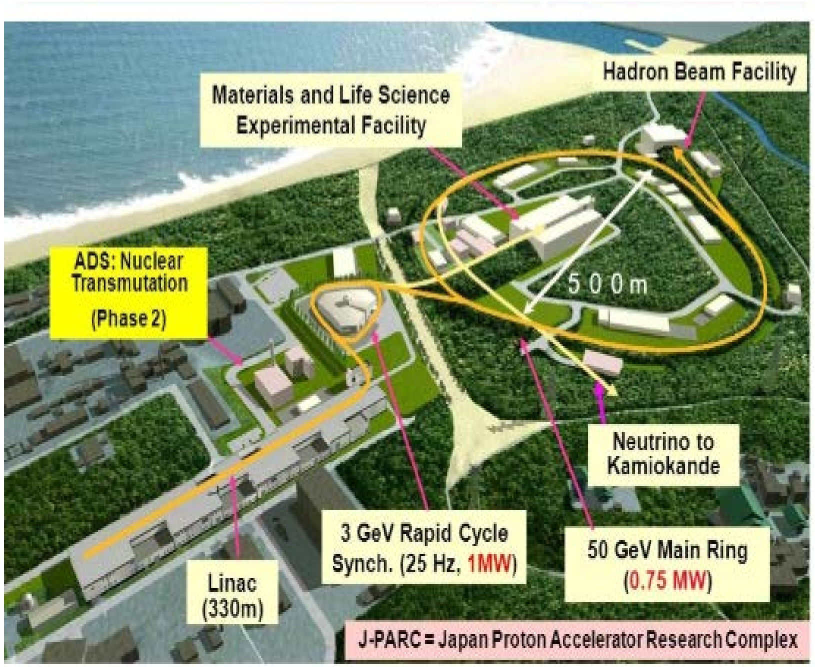
DAΦNE: low-momentum kaon beam

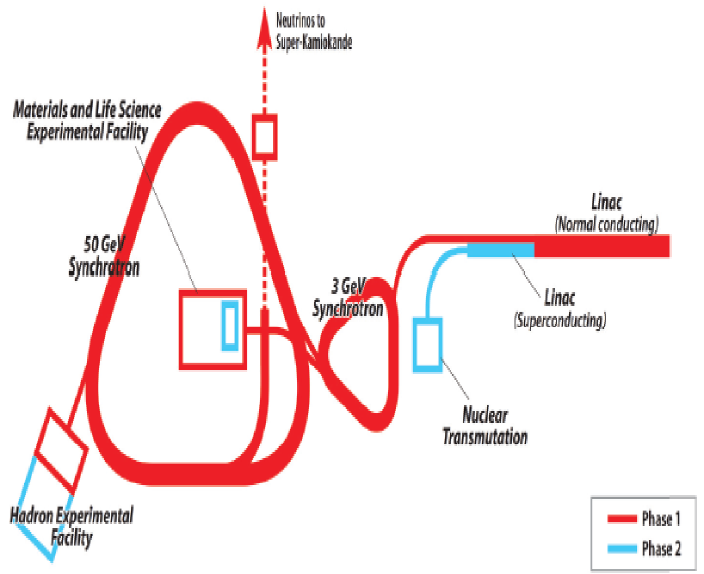
- $\Phi \rightarrow K^- K^+$ (49.1%)
- monochromatic low-energy K (~127MeV/c)

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

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



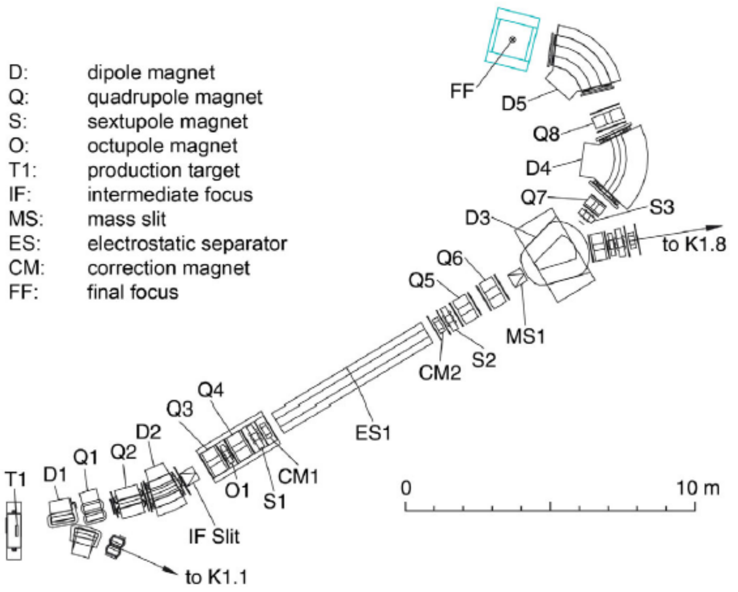


J-PARC consists of a series of world-class proton accelerators and experimental facilities using high-intensity proton beams.

J-PARC Is 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

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

Breakthrough in the intensity of the signals of K-levels hydrogen transitions:

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

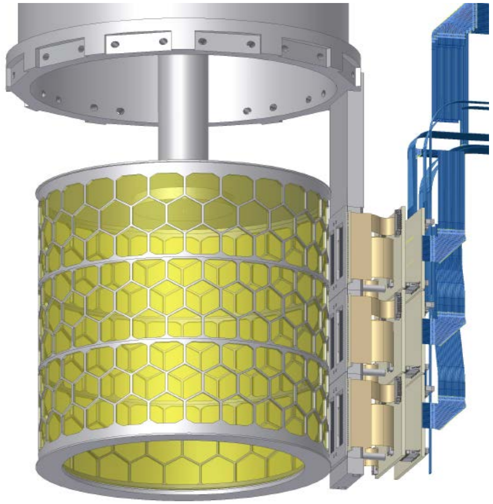
General requirements for the target systems for research on kaonic hydrogen isotopes

- **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.

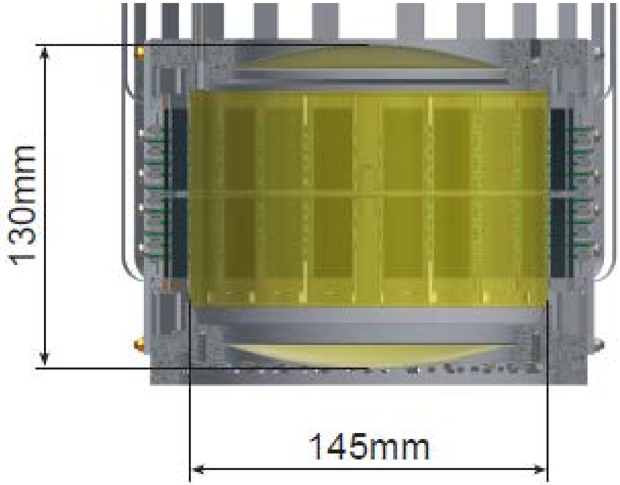
	SIDDHARTA	SIDDHARTA-2	E57
Active target volume (cm^3)	2400	2100	540
Target diameter (cm)	13.7	14.5	6.0
Working temperature (K)	20–25	25–30	25–30
Working pressure (MPa)	0.10	0.25	0.5
Gas density	1.8%[a]	3%[b]	4%[b]
Burst pressure (MPa)	0.40	0.65	0.80
Kapton entrance window (μm)	125	125	125
Kapton side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

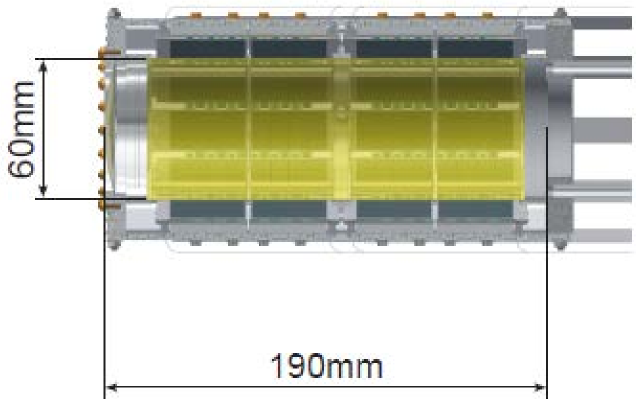
SIDDHARTA



SIDDHARTA-2



E57



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

Experiment	**KpX 1998**	**DEAR 2005**	**E570 2007**	**SIDDHARTA 2009**	**SIDDHARTA-2, E57**
Detector	**Si(Li)**	**CCD**	**SDD-KETEK**	**SDD-JFET**	**SDD-CUBE**
Effective area (mm2)	200	724	1 × 100	3 × 100	8 × 64
Thickness (mm)	5	0,03	0,26	0,45	0,45
Energy resolution @ 6KeV	410	150	190	160	**140**
Drift time (ns)	200	-	375	800	**300**

The experimental results in the last 20 years

Experiments which measured, with unparalleled precision:

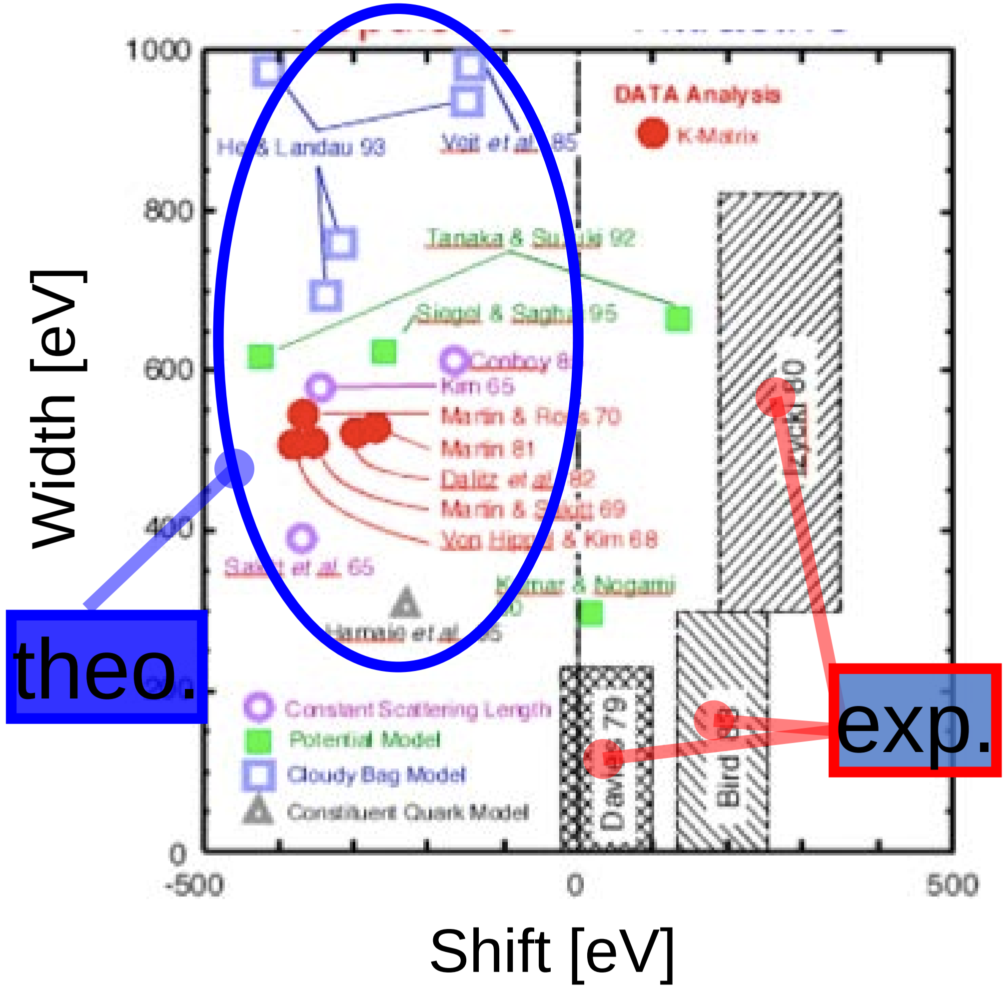
- **kaonic-hydrogen transitions**, solving the **kaonic-hydrogen puzzle**, in a series of measurements performed first at KEK, the KpX experiment, then at DAΦNE, DEAR and SIDDHARTA
- **Other light kaonic atoms** were also measured with high precision, such as **kaonic helium-4**, also in this case solving the inconsistencies resulting from old experiments**, kaonic helium-3** (the first measurements ever)
- **Other low-Z kaonic atom transitions** (**kaonic nitrogen, kaonic kapton**, etc), which contributed to the understanding of the atomic cascade processes in kaonic atoms.
- **Exploratory first measurement of the kaonic deuterium**

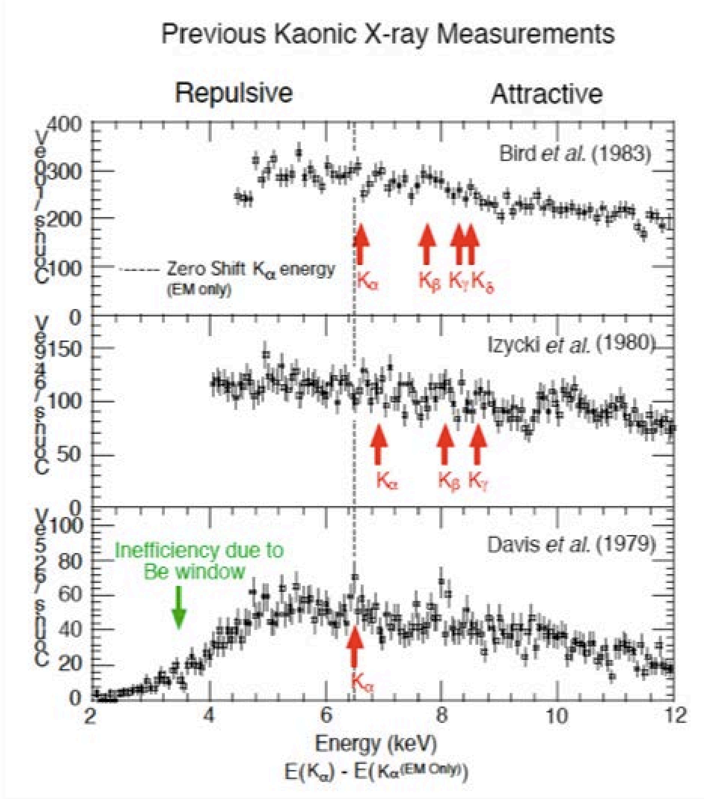
70-80's: Kaonic hydrogen puzzle

Repulsive

Attractive

past 3 exp.



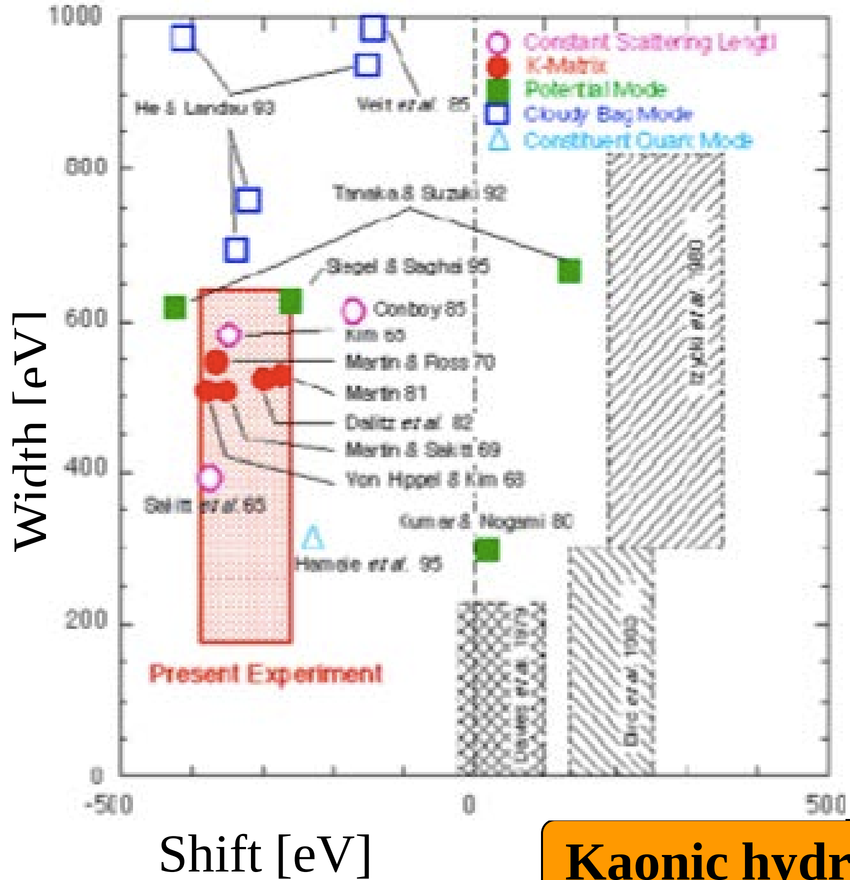


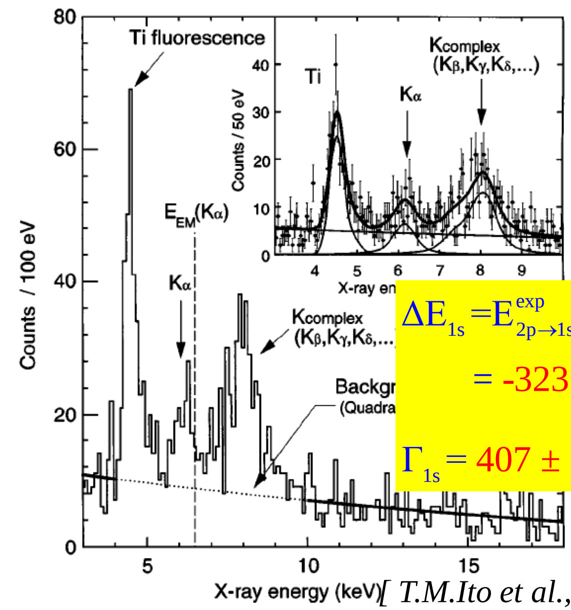
Liquid Hydrogen target

Si(Li) as X-ray detector

98's: solving Kaonic hydrogen puzzle

Repulsive type **Attractive**





$\Delta E_{1s} = E^{exp}_{2p\to1s} - E^{E.M.}_{2p\to1s}$

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

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

[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.

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

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

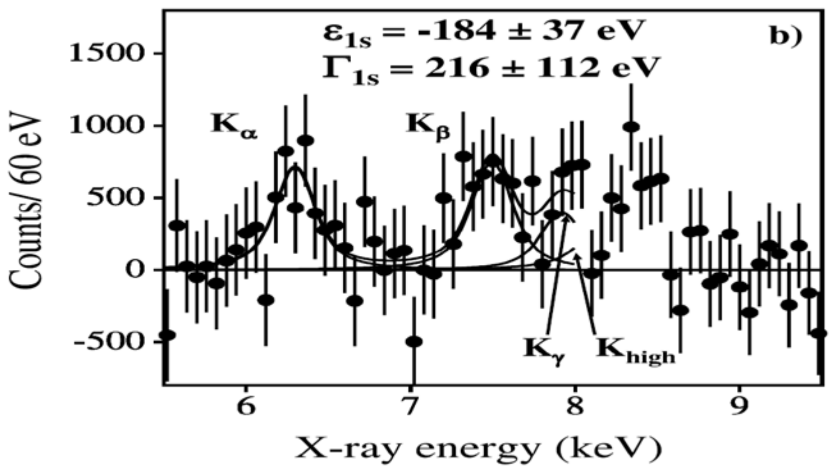
***Hadron beamline**

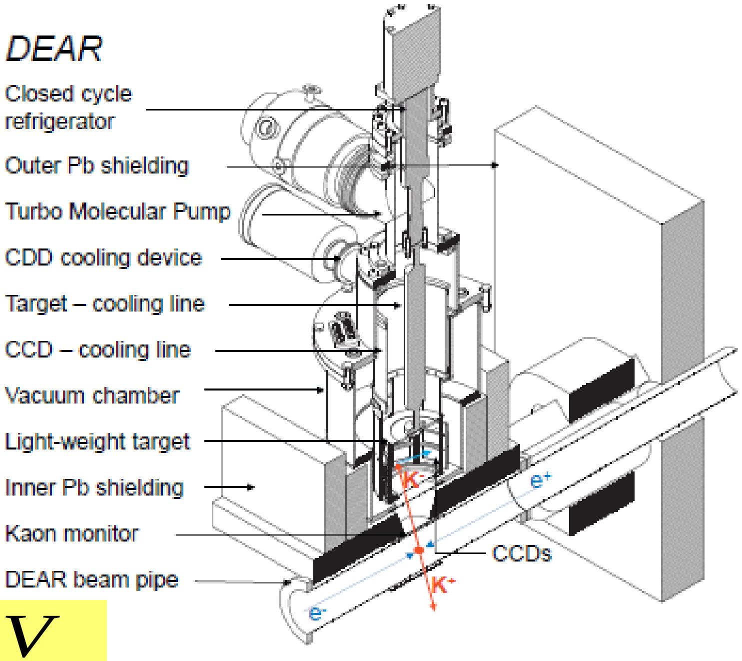
Kaonic hydrogen puzzle solved

↓

Need a precise measurement!

DEAR results (2002-2005)





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

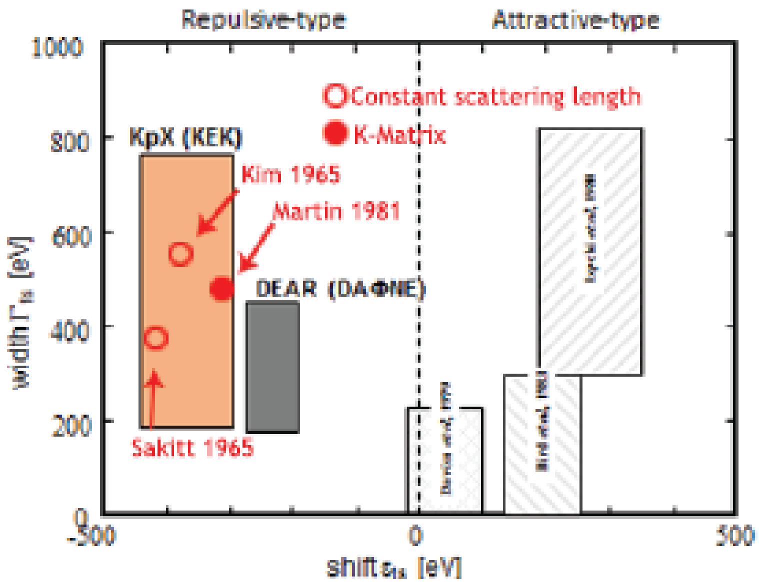
$$\Gamma = 249 \pm 111(stat.) \pm 39(syst.)eV$$

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

Confirming repulsive character of K- p interaction

- **Gas target (25 K, 2 bar)**
- **16 CCD used as X-ray detector with a total area of 116 cm^2**
- **Good energy resolution (140eV @ 6 keV)**
- **No time resolution**

Kaonic hydrogen results



- 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

SIlicon Drift Detector for Hadronic Atom Research by Timing Applications

SIDDHARTA Collaboration

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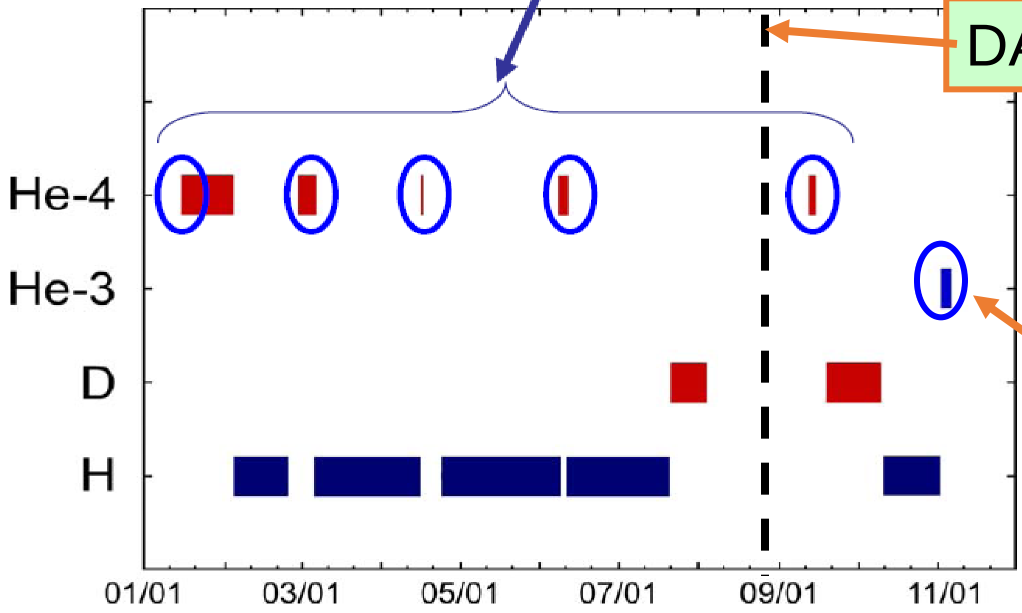
[i] *Excellence Cluster Universe, Tech. Univ. München, Garching, Germany*

SIDDHARTA data taking campaign: ended in November 2009

K-He4 data without Fe source



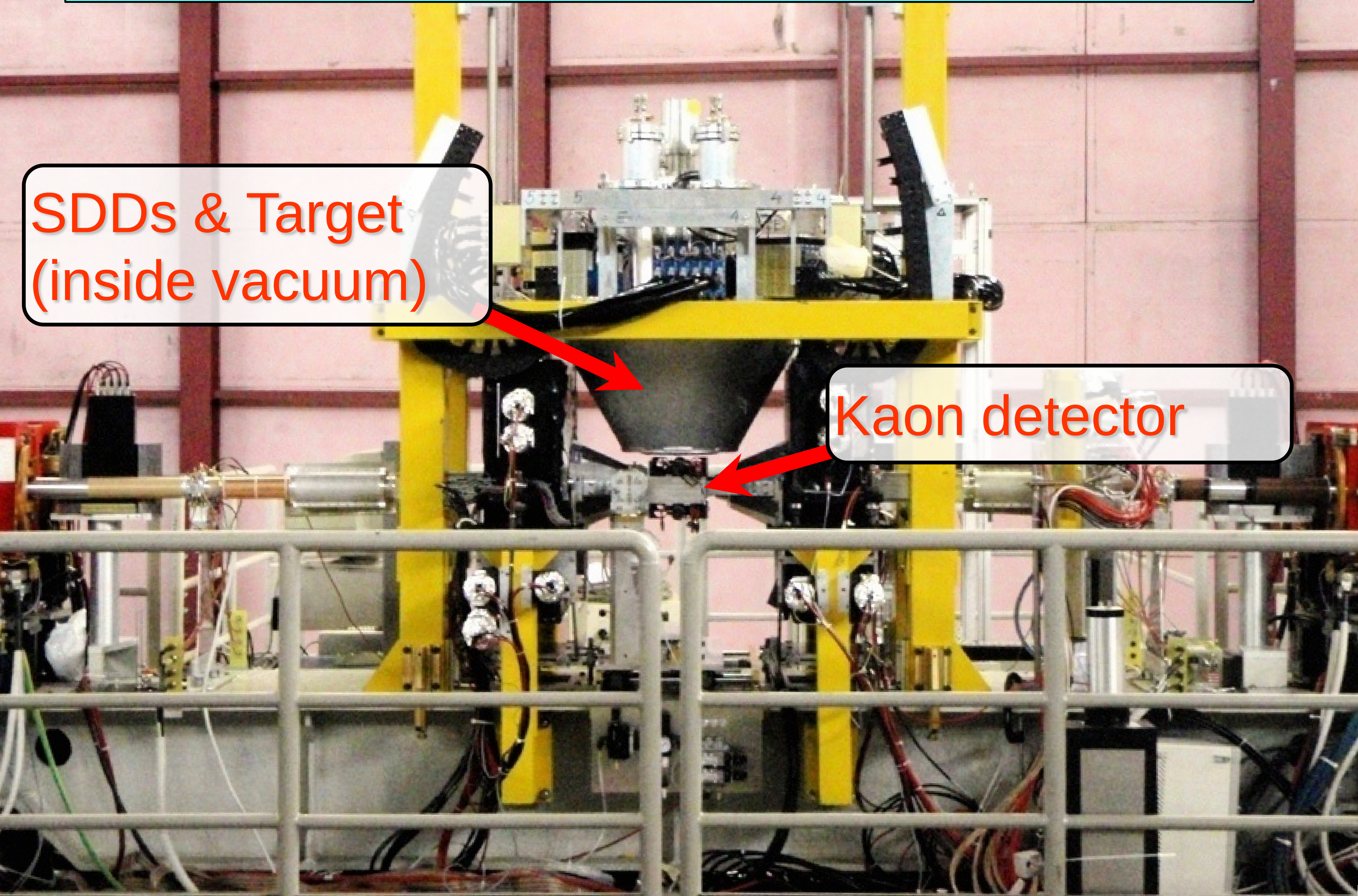
DAΦNE shutdown in Summer

New alignment of setup
→Improve S/N ratio

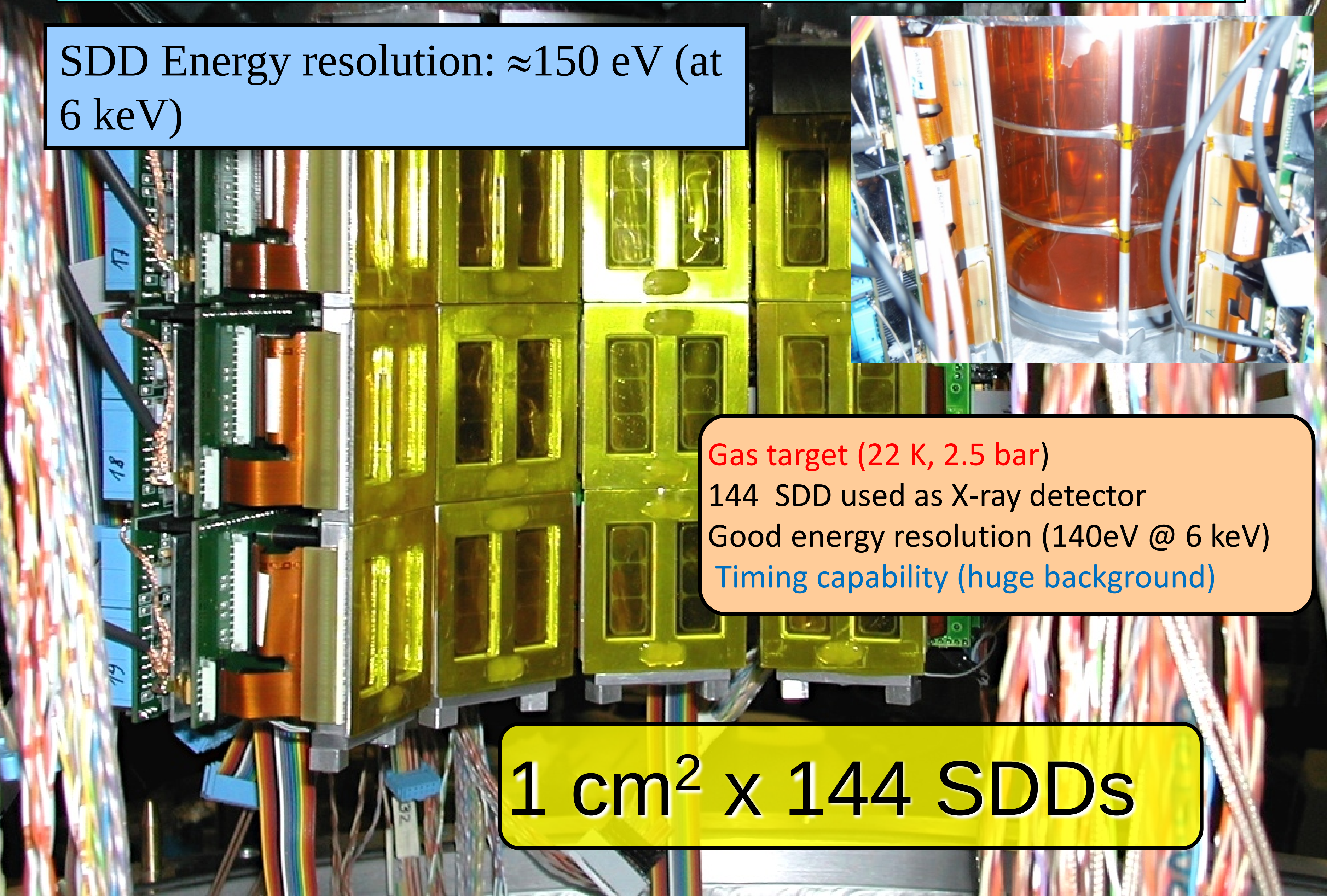
K-He3 data (~4days)

SIDDHARTA performed
kaonic atoms transitions measurements
on the upgraded DAΦNE collider

SIDDHARTA setup



Silicon Drift Detector - SDD



SDD Energy resolution: ≈150 eV (at 6 keV)

Gas target (22 K, 2.5 bar)
144 SDD used as X-ray detector
Good energy resolution (140eV @ 6 keV)
Timing capability (huge background)

$1\ cm^2$ x 144 SDDs

SIDDHARTA results:

- Kaonic Hydrogen: 400pb^{-1}, most precise measurement ever,Phys. Lett. B 704 (2011) 113, Nucl. Phys. A881 (2012) 88; Ph D

- Kaonic deuterium: 100 pb^{-1}, as an exploratory first measurement ever, Nucl. Phys. A907 (2013) 69; Ph D

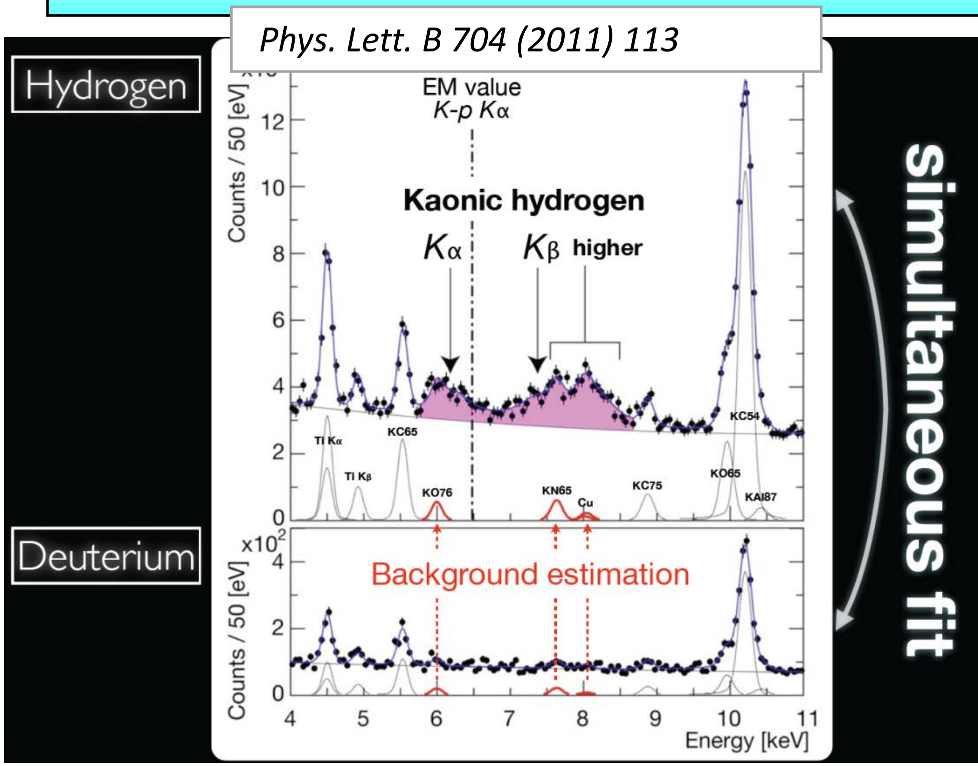
- Kaonic helium 4 – first measurement ever in gaseous target; published in Phys. Lett. B 681 (2009) 310; NIM A628 (2011) 264 and Phys. Lett. B 697 (2011);; PhD

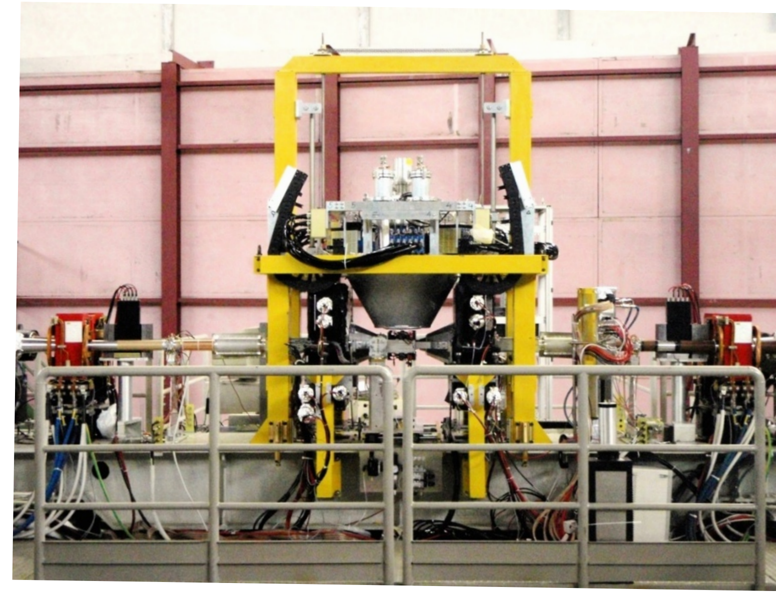
- Kaonic helium 3 – 10 pb^{-1}, first measurement in the world, published in Phys. Lett. B 697 (2011) 199; Ph D

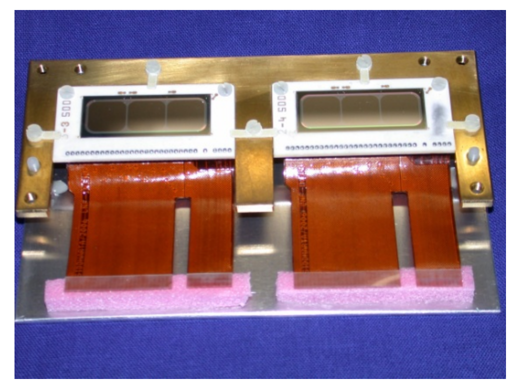
- Widths and yields of KHe3 and KHe4 - Phys. Lett. B714 (2012) 40; kaonic kapton yields – Nucl. Phys. A916 (2013) 30; yields of the KHe3 and KHe4 –EPJ A(2014) 50; KH yield – Nucl. Phys. A954 (2016) 7.

SIDDHARTA – important TRAINING for young researchers

SIDDHARTA results: KH (2009)







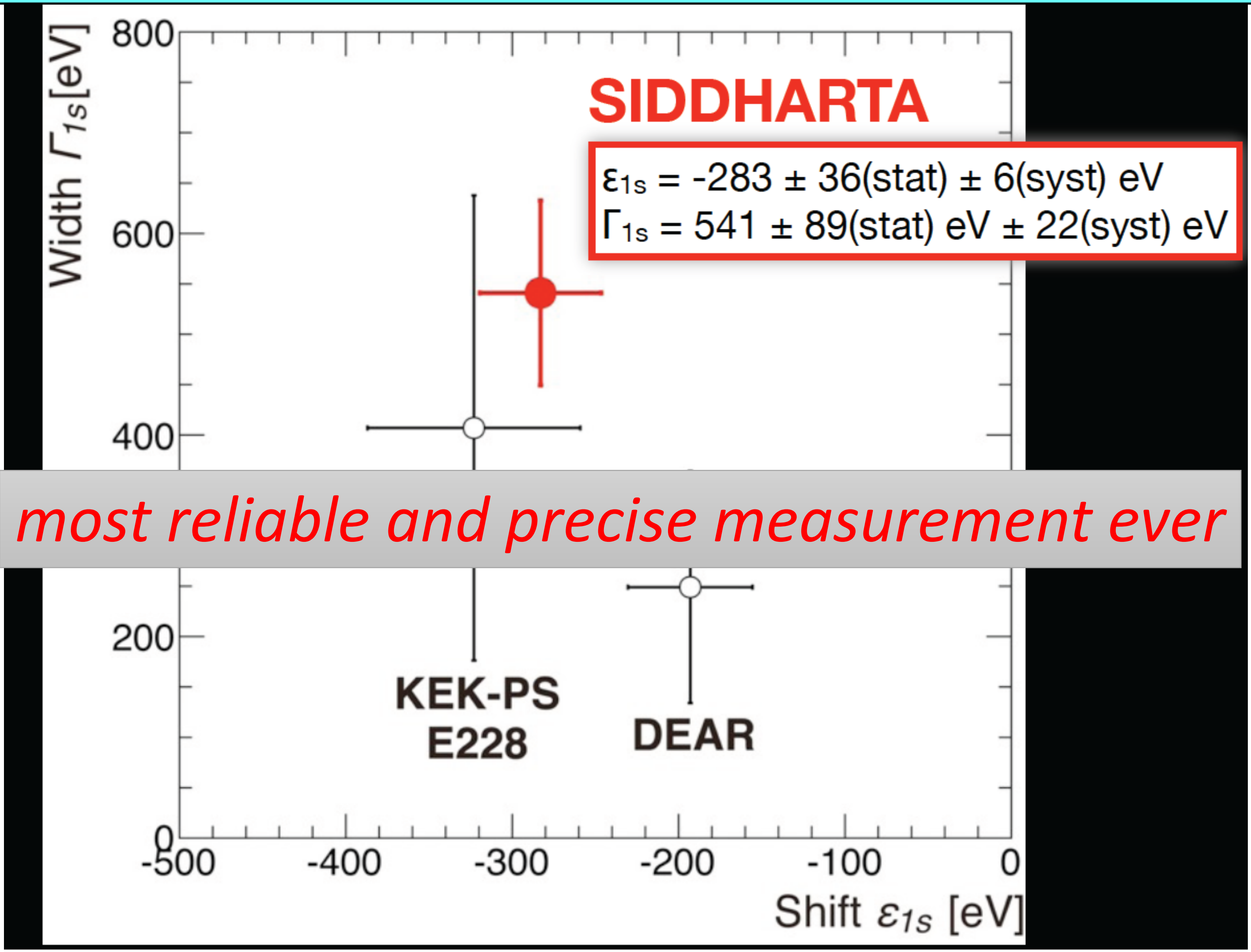
ε_{1S}= −283 ± 36(stat) ± 6(syst) eV

Γ_{1S}= 541 ± 89(stat) ± 22(syst) eV

Gas target (22 K, 2.5 bar)
144 SDD used as X-ray detector
Good energy resolution (140eV @ 6 keV)
Timing capability (huge background)

Drastically improved S/B ratio

SIDDHARTA results: KH (2009)



most reliable and precise measurement ever

Kaonic Helium measurements SIDDHARTA

In the framework of the SIDDHARTA experiment we have performed:

- the measurements related with the **Kaonic helium transition to the 2p level (L-lines)**
  - **for first time in a gaseous target for ^{4}He**
  - **for the first time ever for $K^{3}He$**

Kaonic Helium atoms

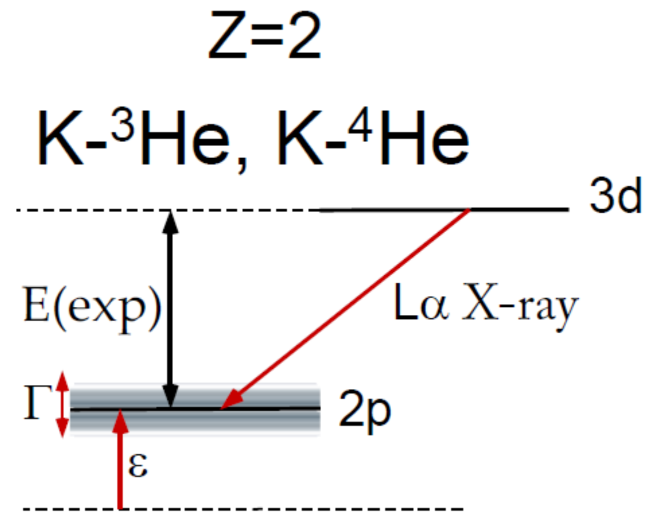
$$\varepsilon = E_{3d \to 2p}(\text{exp}) - E_{3d \to 2p}(\text{e.m.})$$

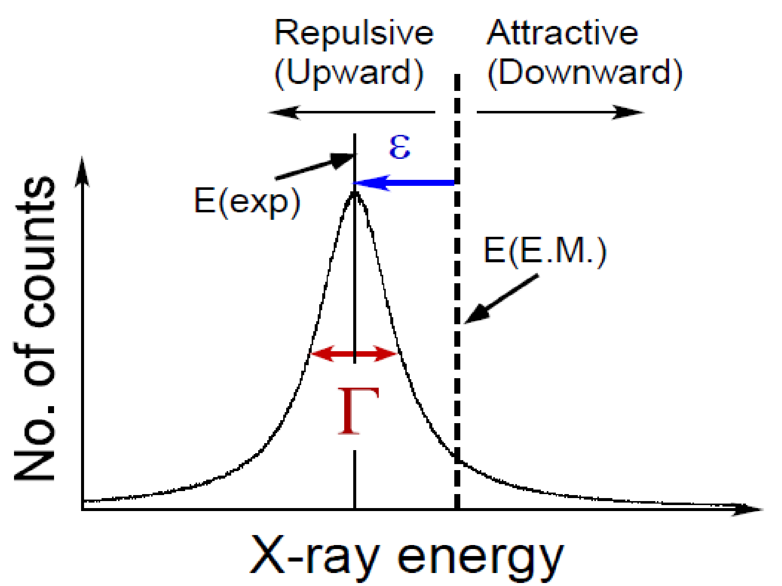
The most suitable transition to observe the strong interaction effects

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

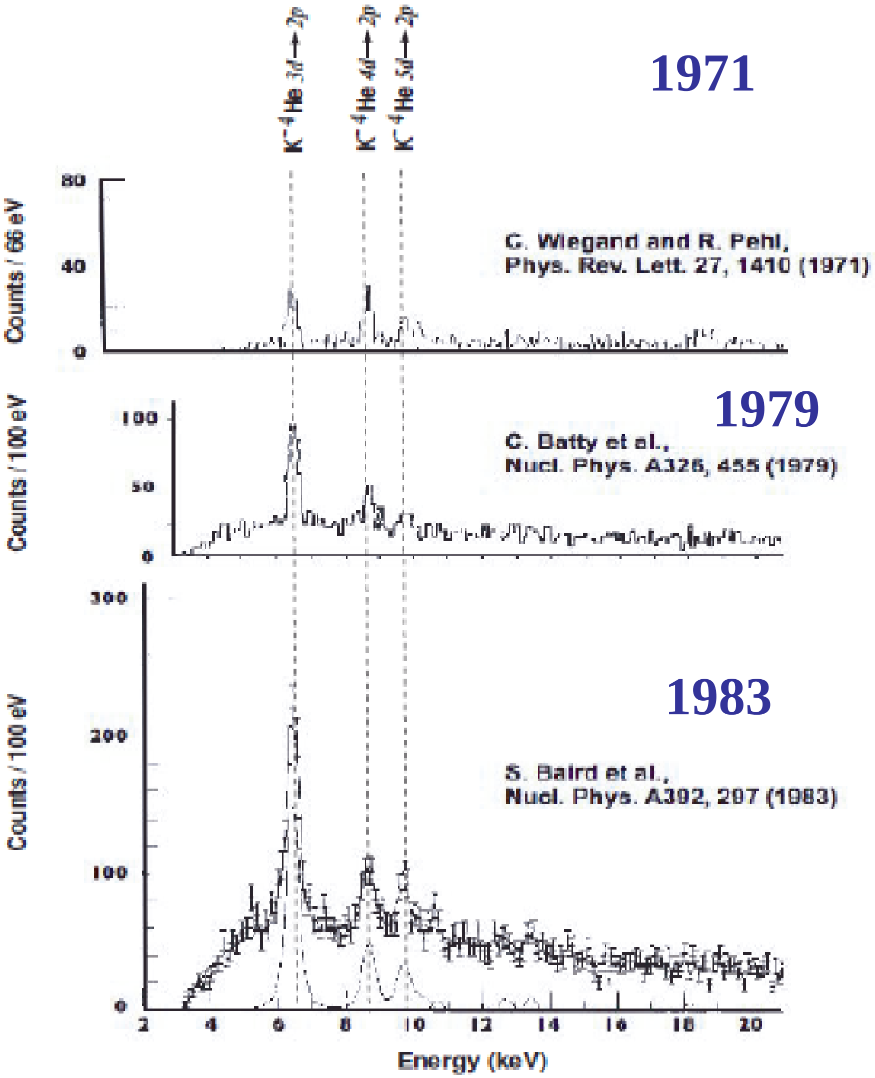
$$E(e.m.) \approx -\frac{1}{2}\mu c^2 (Z\alpha)^2 \cdot \left[\frac{1}{n_i^2} - \frac{1}{n_f^2}\right]$$

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



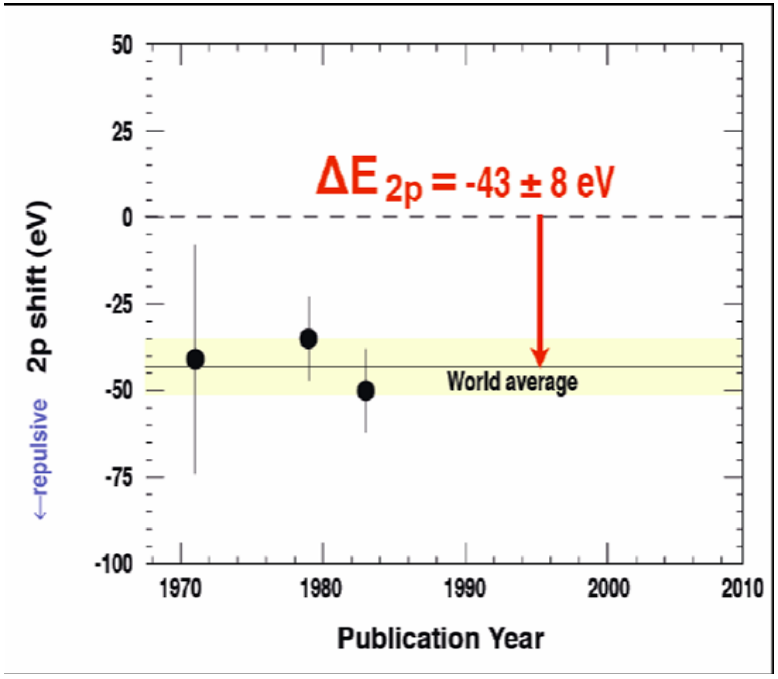


Kaonic helium atom data (Z=2)



Average of above

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



Kaonic helium atoms theoretical values

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

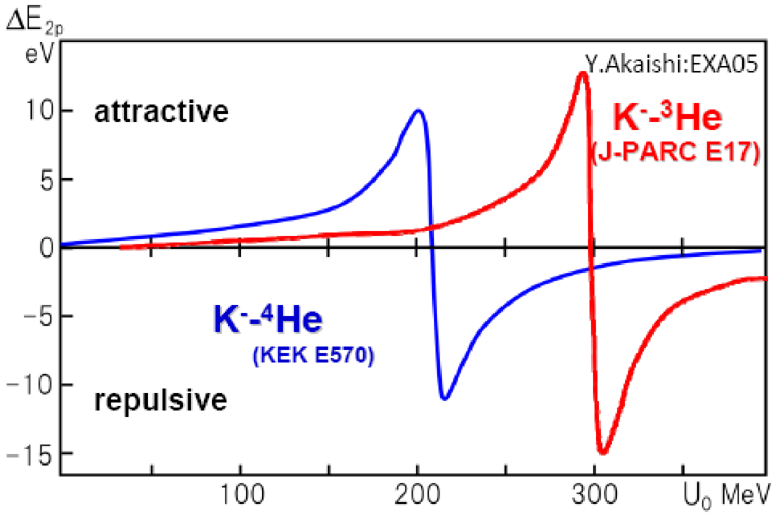
Optical-potential model:

(theoretical calculations based on kaonic atom data)

Recent theoretical calculations:

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

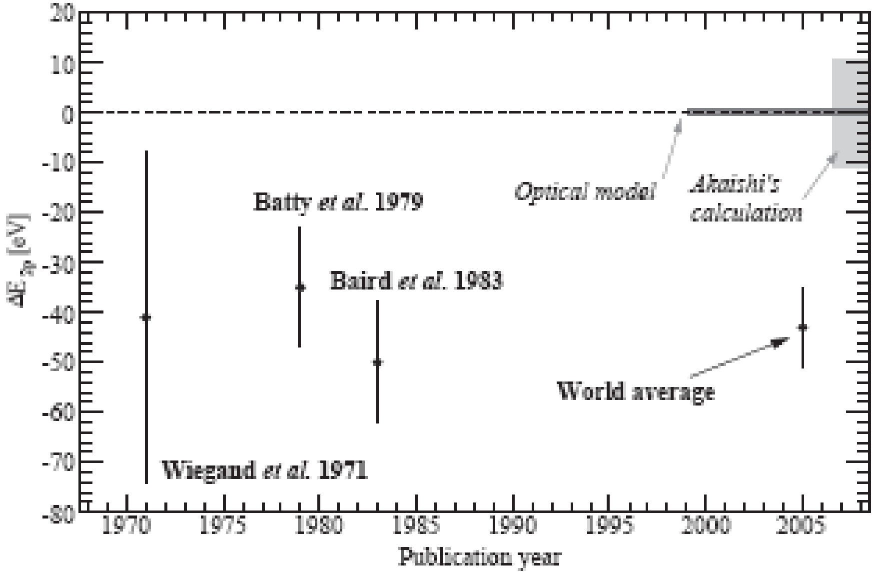
Shift (eV)	Ref.
-0.13±0.02	Batty, NPA508 (1990) 89c
-0.14±0.02	Batty, NPA508 (1990) 89c
-1.5	Akaishi, Porc. EXA05



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

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

What is Kaonic helium puzzle?

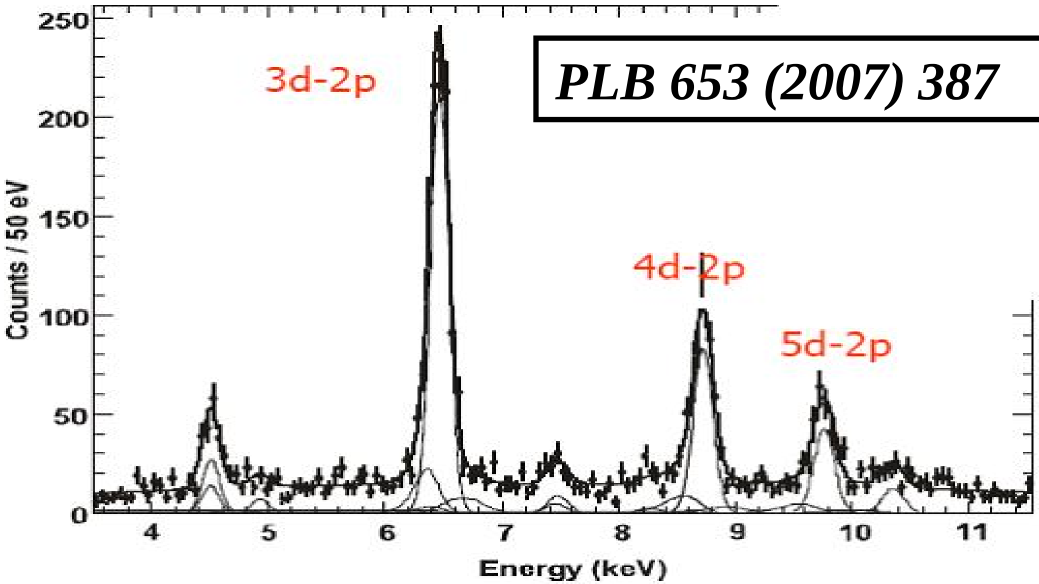


Experiment:
Large shift
(ΔE2p ≈ 40 eV)

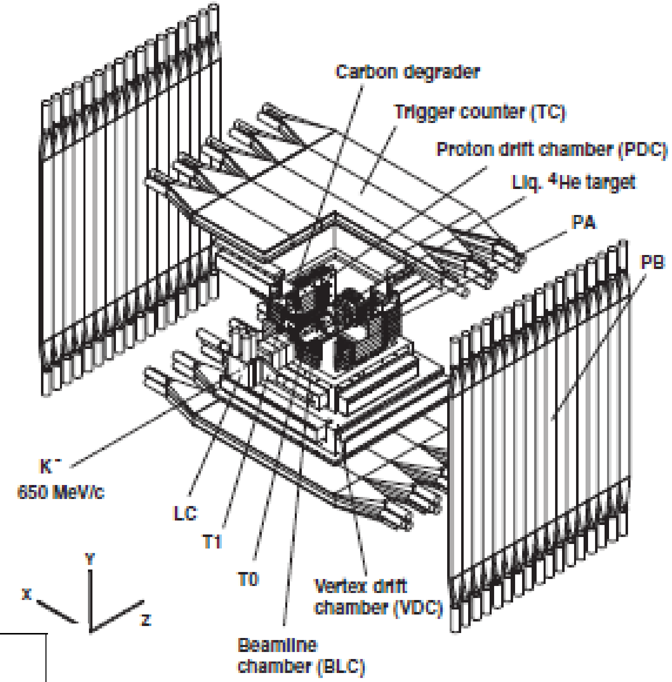
Theory:
ΔE2p ≈ 0 eV
or
< ± 10 eV

Need a new $K^{-4}He$ X-ray measurement!

New K⁴He results by KEK PS E570



PLB 653 (2007) 387



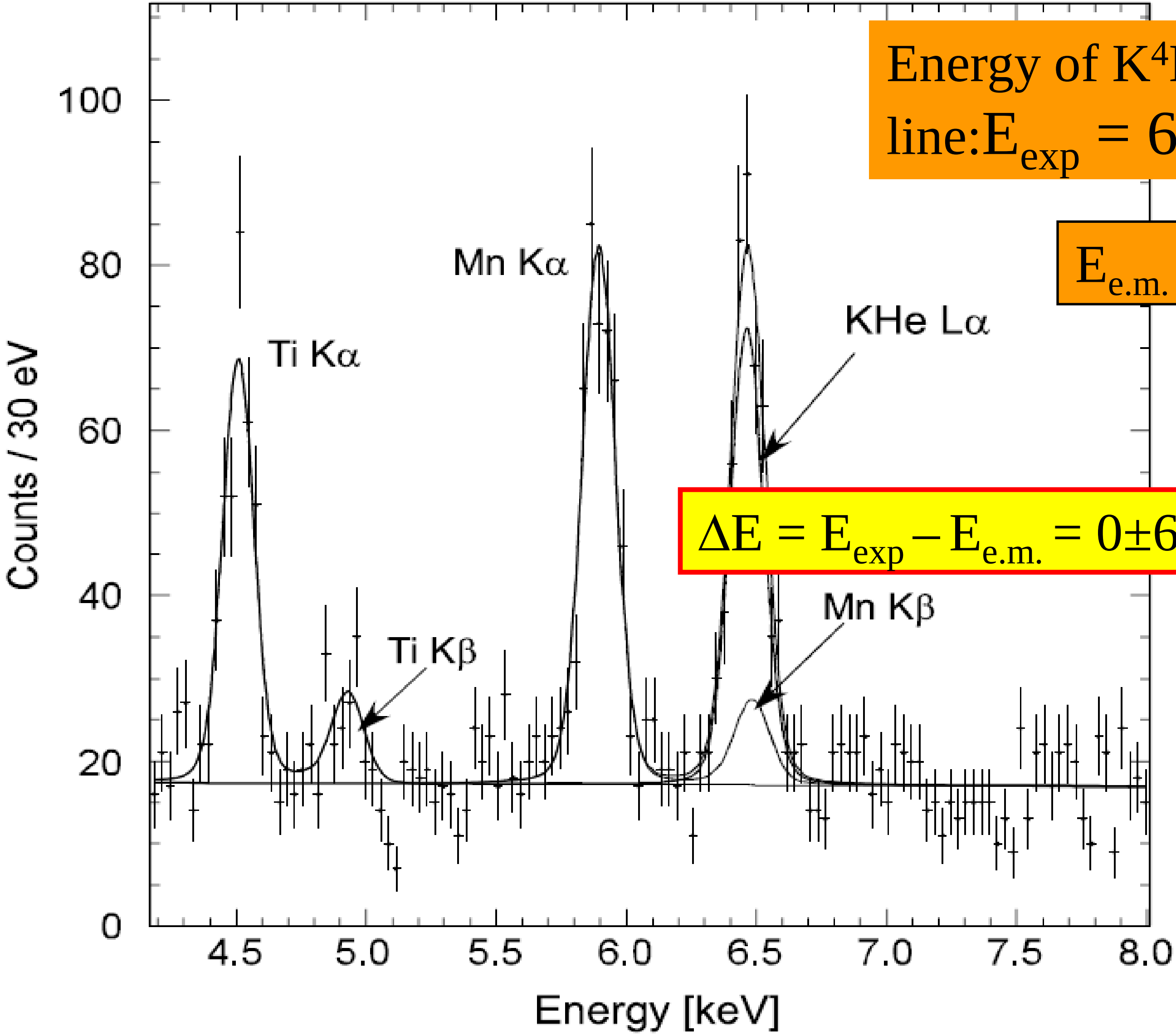
Transition	$3d \to 2p$	$4d \to 2p$	$5d \to 2p$
Measured energy (eV)	6466.7 ± 2.5	8723.3 ± 4.6	9760.1 ± 7.7
e.m. calc. energy (eV)	6463.5	8721.7	9766.8

K^4He 3d→2p: 1500 events

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

ΔE_{2p} =2±2(stat.)±2(syst.) eV)

SIDDHARTA results: K-^{4}He



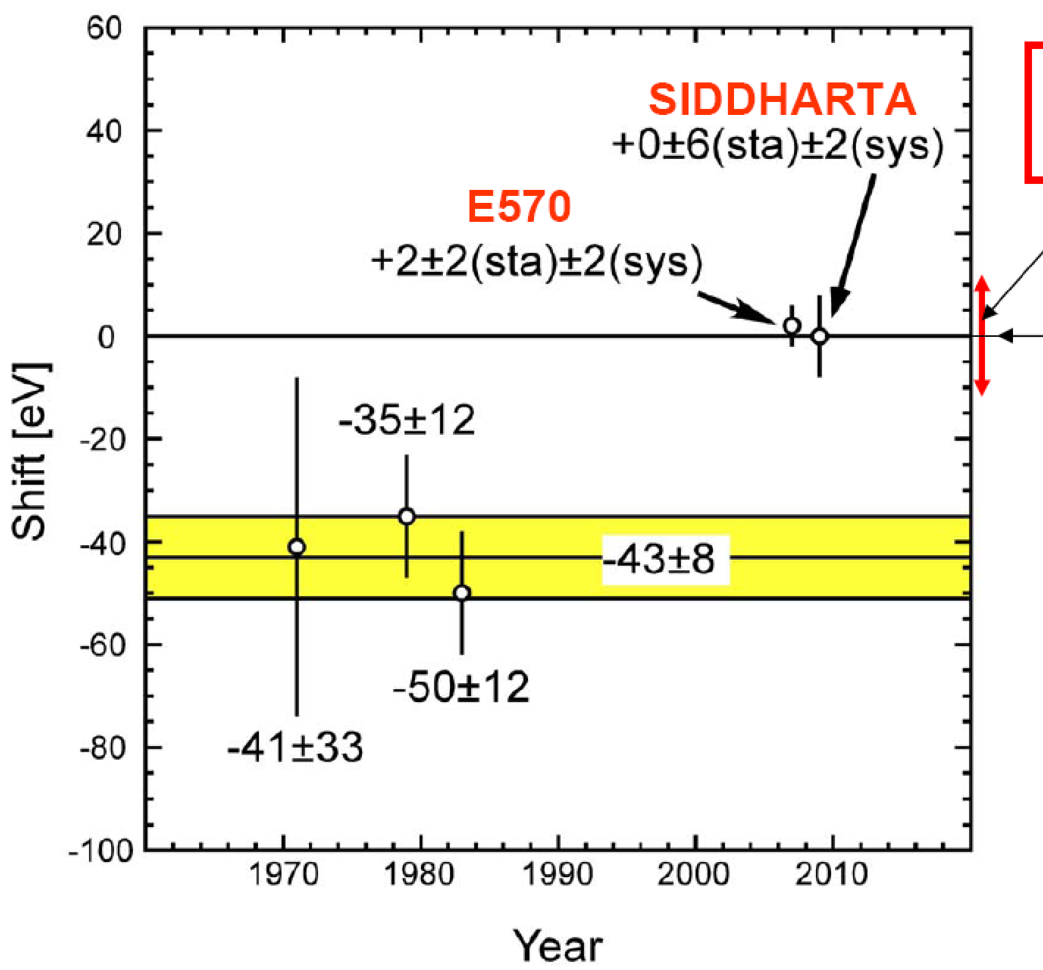
Energy of K^{4}He L_α (3d→2p) line: E_{exp} = 6463.6±5.8 eV

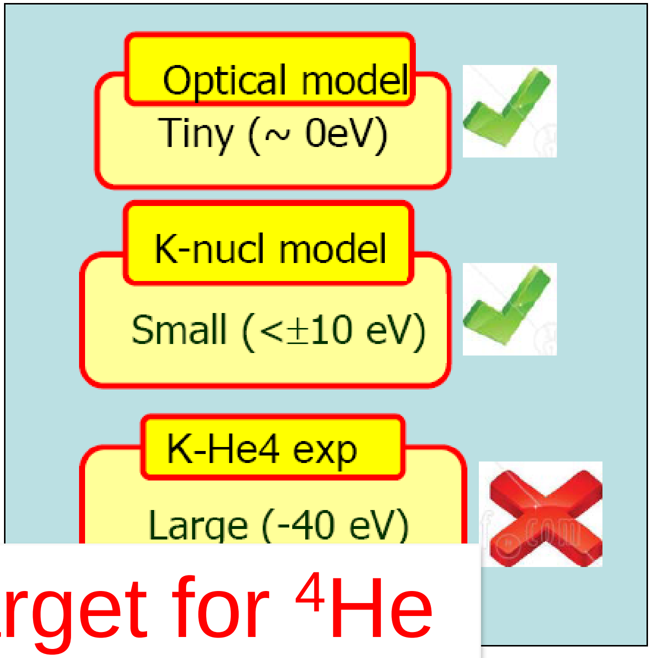
$E_{e.m.}$ = 6463.5±0.2 eV

$\Delta E = E_{exp} - E_{e.m.}$ = 0±6(stat) ±2(syst) eV

PLB 681 (2009) 310

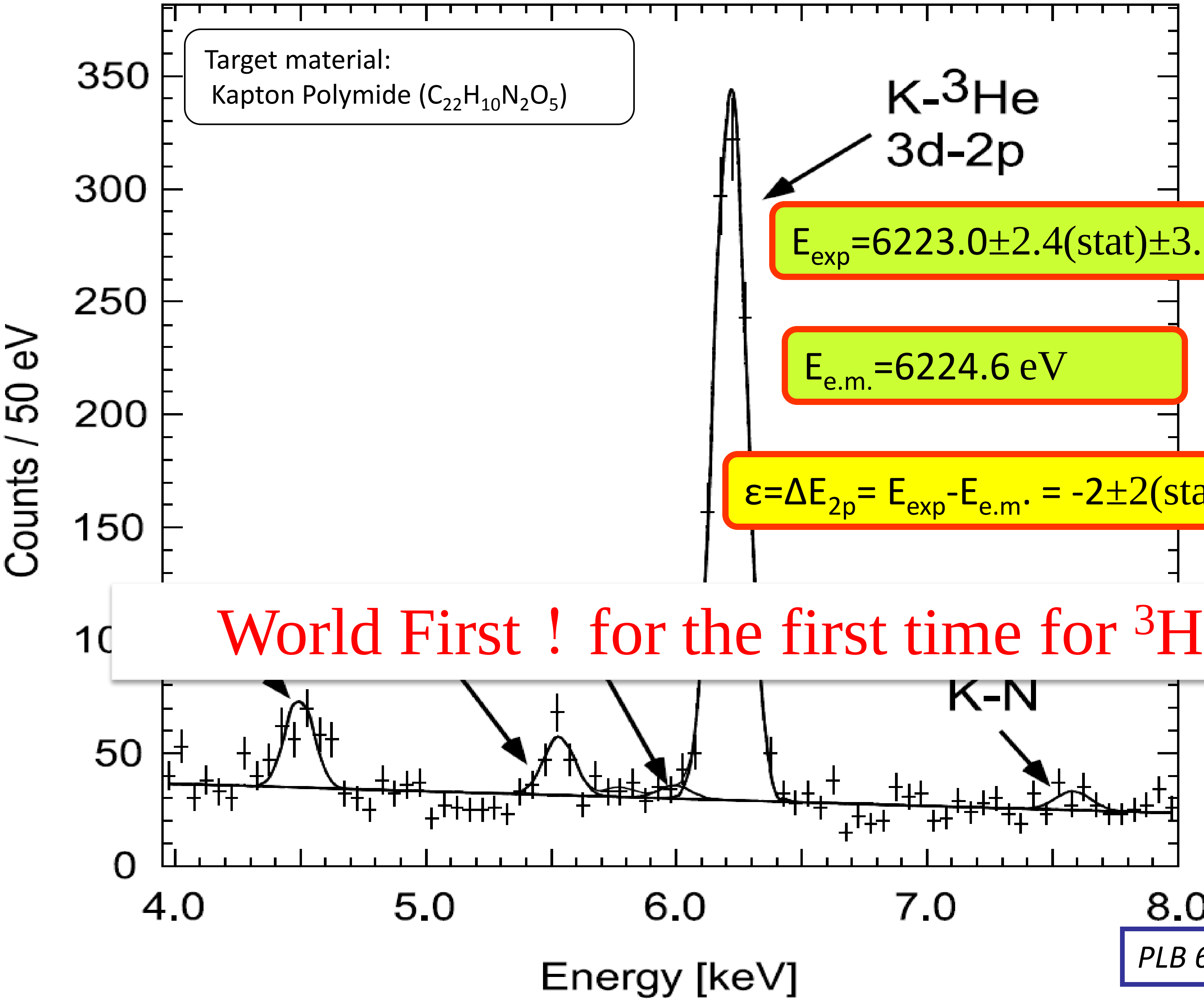
Summary of the K-^{4}He shifts





for first time in a gaseous target for ^{4}He

SIDDHARTA results: K-^{3}He



E_{exp}=6223.0±2.4(stat)±3.5(syst.) eV

$E_{e.m.}$=6224.6 eV

$\varepsilon = \Delta E_{2p} = E_{exp} - E_{e.m.}$ = -2±2(stat)±4(syst)

World First！for the first time for ^{3}He

PLB 697 (2011) 199

SIDDHARTA results: K-^{3}He and K-^{4}He

- **The shifts and the widths of kaonic helium-3 and helium-4 He**

$$K^{-3}\mathrm{He}: \varepsilon_{2p} = -2 \pm 2(\mathrm{stat}) \pm 4(\mathrm{syst})\ \mathrm{eV},$$

$$K^{-4}\mathrm{He}: \varepsilon_{2p} = +5 \pm 3(\mathrm{stat}) \pm 4(\mathrm{syst})\ \mathrm{eV},$$

$$K^{-3}\mathrm{He}: \Gamma_{2p} = 6 \pm 6(\mathrm{stat}) \pm 7(\mathrm{syst})\ \mathrm{eV},$$

$$K^{-4}\mathrm{He}: \Gamma_{2p} = 14 \pm 8(\mathrm{stat}) \pm 5(\mathrm{syst})\ \mathrm{eV}.$$

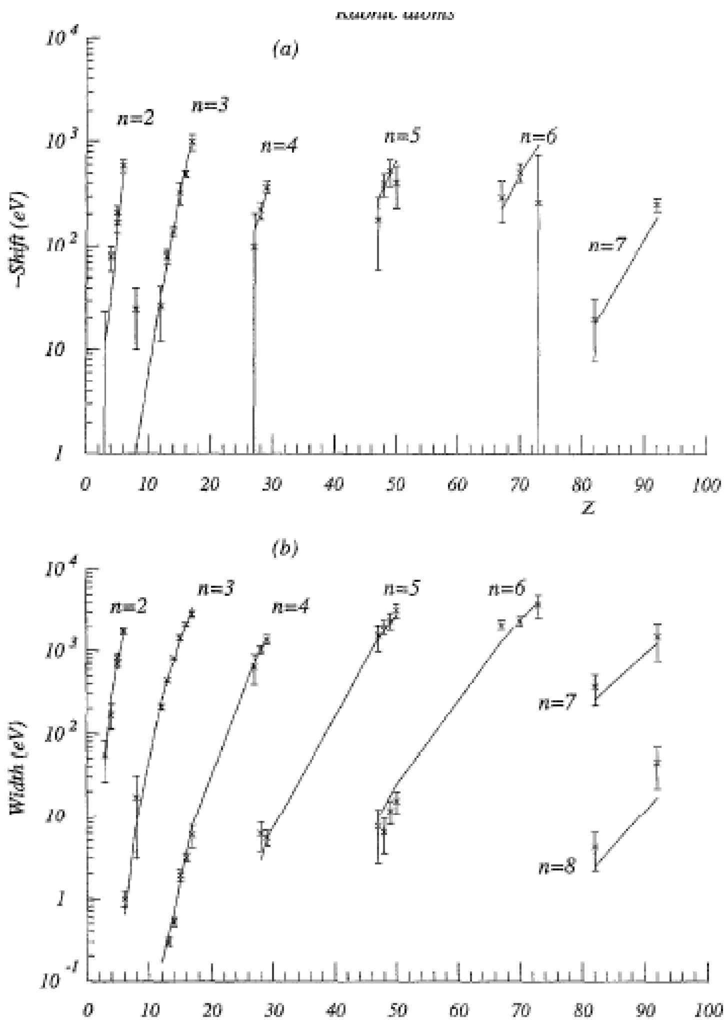
- **Absolute x-ray yields of kaonic helium-3 and helium-4 He (SIDDHARTA gaseous targets)**

Transition	helium-3 (0.96 g/l)	helium-4 (1.65 g/l)	helium-4 (2.15 g/l)	helium-4 (liquid)	helium-4 (liquid)
L_α $(3d \to 2p)$	$25.0^{+6.7}_{-5.8}$	$23.1^{+6.0}_{-4.2}$	$17.2^{+2.6}_{-9.5}$	9.2 ± 2.4	8.9 ± 4.5
L_β $(4d \to 2p)$	$3.6^{+1.3}_{-0.7}$	4.2 ± 1.1	$3.1^{+0.6}_{-1.6}$	5.2 ± 1.3	2.3 ± 1.2
L_γ $(5d \to 2p)$	$1.3^{+0.5}_{-0.4}$	1.3 ± 0.6	$0.7^{+0.3}_{-0.5}$	2.4 ± 0.7	1.6 ± 0.8
L_{high}	5.2 ± 2.1	$6.9^{+2.0}_{-1.9}$	$4.1^{+1.1}_{-2.1}$	...	0.4 ± 0.3

- the yields of Lα x rays in gas are about twice as high as those in liquid (~9%).
- the yields of the Lβ and the Lγ are similar in gas and in liquid.
- the intensities of the Lhigh lines in gas are higher than those in liquid.
  Yield differences :related to the density dependence of the cascade processes, such as the molecular Stark effect

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

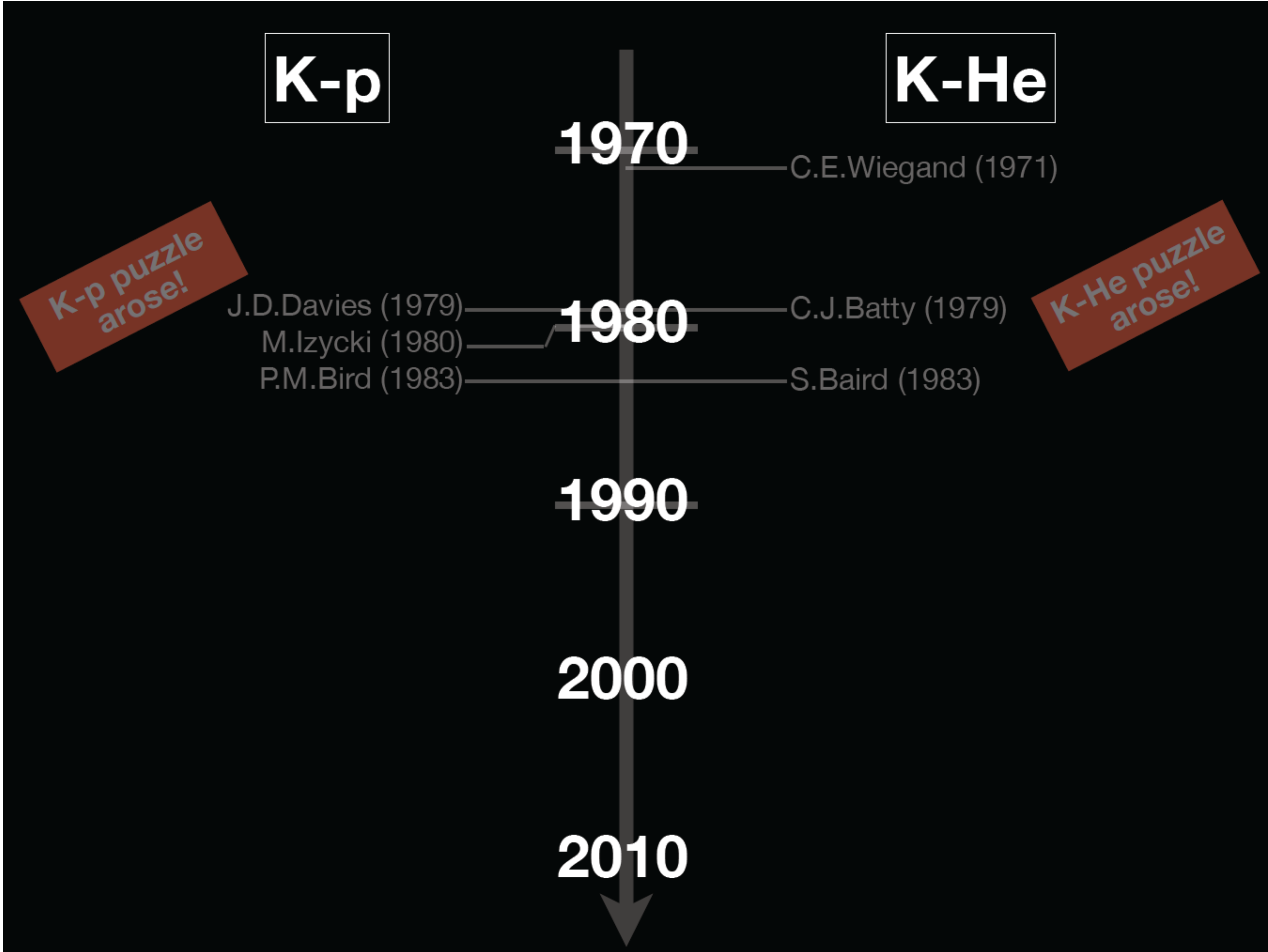
$$2\mu V_{\rm opt}^{(2)}(r) = -4\pi \left(1 + \frac{\mu}{m}\right) b_0 \rho(r).$$

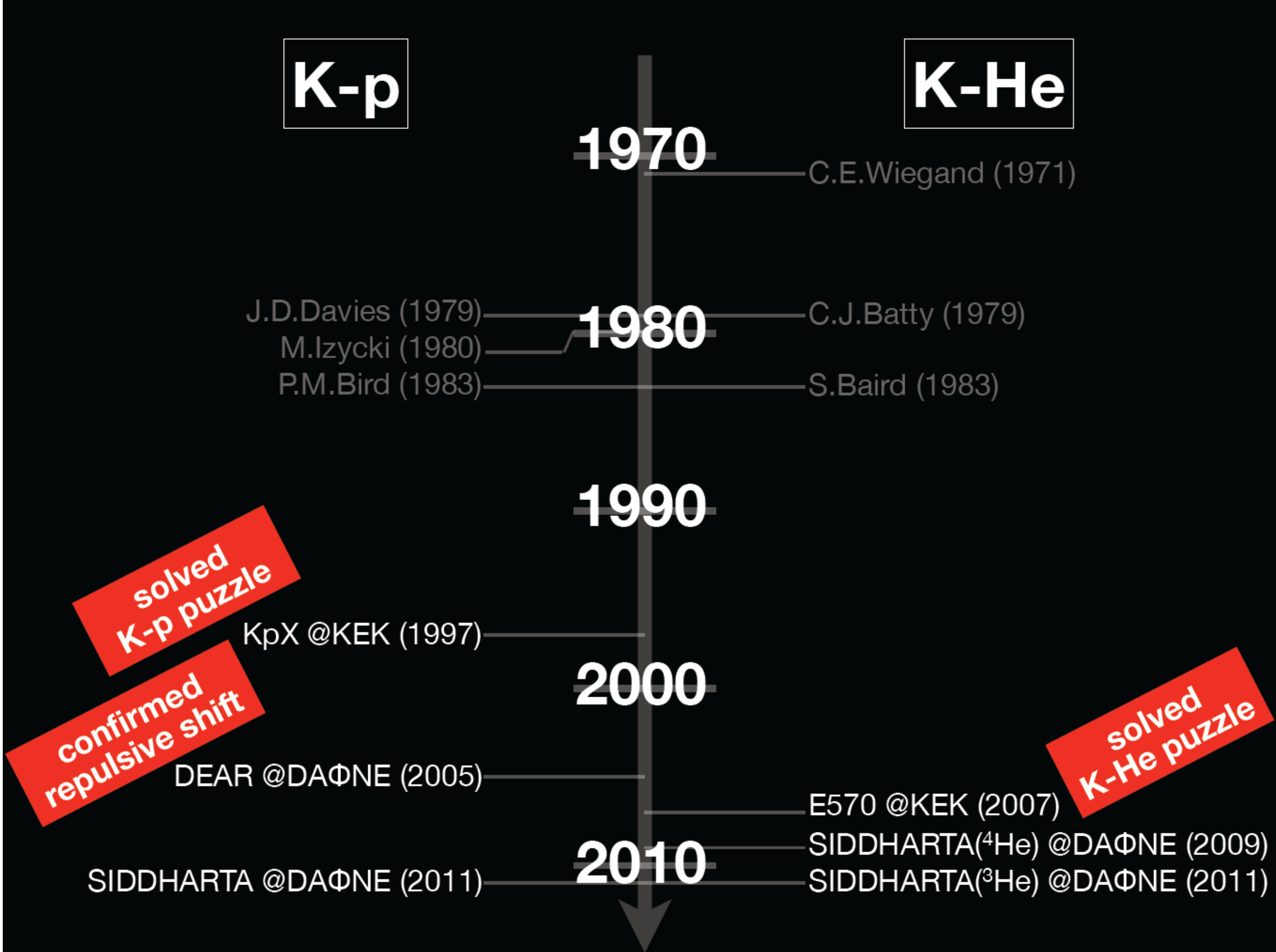
Experimental X-ray data of shift & width:
Well fitted with optical potentials

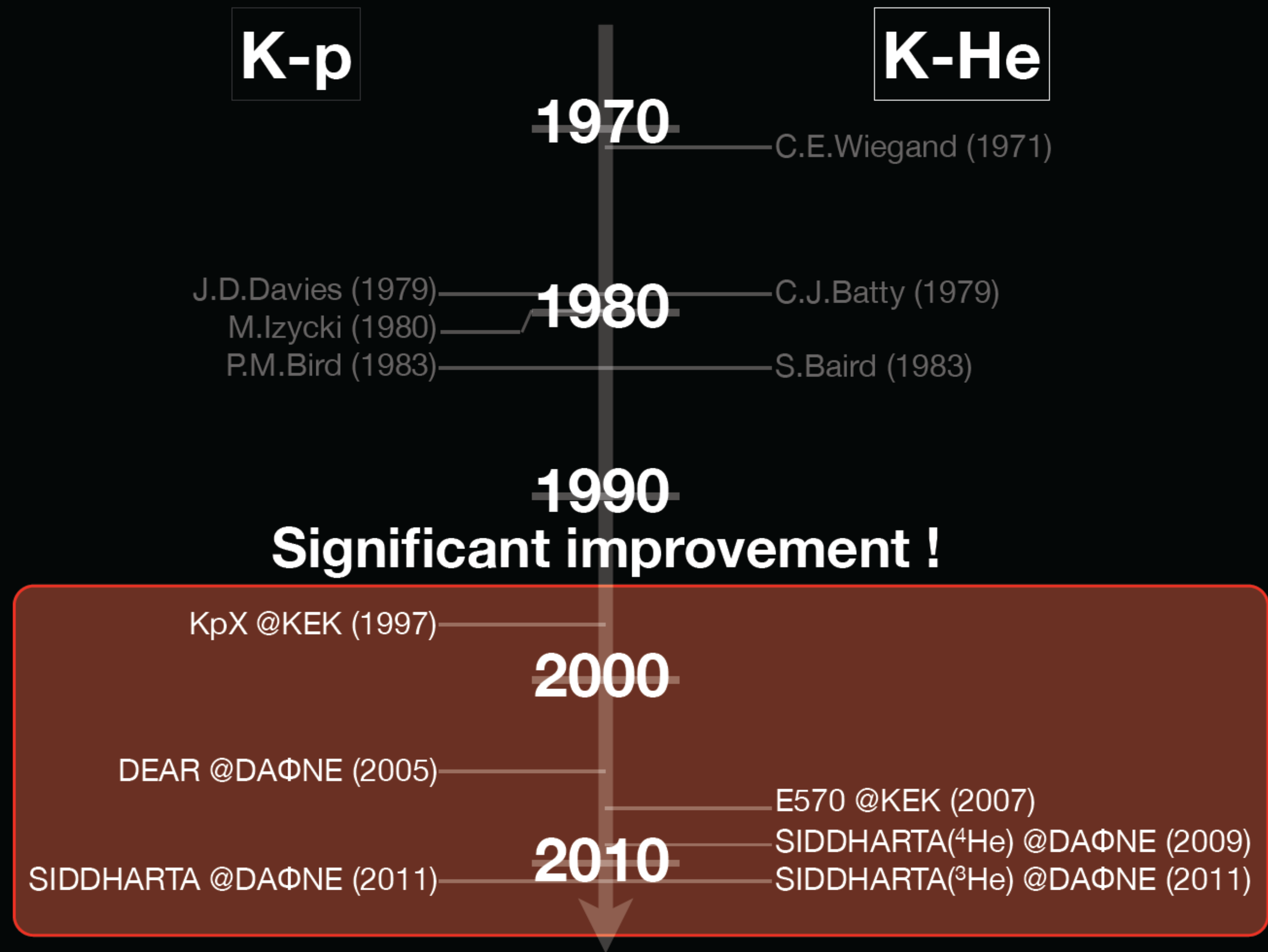
Expected shift of K-4He 2p state:
ΔE ~ 0 eV

There are discrepancies for:

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


K-p
K-He
1970
C.E.Wiegand (1971)
K-p puzzle arose!
K-He puzzle arose!
J.D.Davies (1979)
1980
C.J.Batty (1979)
M.Izycki (1980)
P.M.Bird (1983)
S.Baird (1983)
1990
2000
2010


K-p
K-He
1970
C.E.Wiegand (1971)
J.D.Davies (1979)
1980
C.J.Batty (1979)
M.Izycki (1980)
P.M.Bird (1983)
S.Baird (1983)
1990
solved K-p puzzle
KpX @KEK (1997)
2000
confirmed repulsive shift
DEAR @DAΦNE (2005)
solved K-He puzzle
E570 @KEK (2007)
SIDDHARTA(4He) @DAΦNE (2009)
2010
SIDDHARTA @DAΦNE (2011)
SIDDHARTA(3He) @DAΦNE (2011)


K-p
K-He
1970
C.E.Wiegand (1971)
J.D.Davies (1979)
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1980
M.Izycki (1980)
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S.Baird (1983)
1990
Significant improvement !
KpX @KEK (1997)
2000
DEAR @DAΦNE (2005)
E570 @KEK (2007)
SIDDHARTA(⁴He) @DAΦNE (2009)
2010
SIDDHARTA @DAΦNE (2011)
SIDDHARTA(³He) @DAΦNE (2011)

K-p | **K-He**

STILL MISSING!!!

the measurement of the kaonic deuterium

the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions

Significant improvement !

SIDDHARTA-2 at DAΦNE

E57 at J-PARC

E570 @KEK (2007)

SIDDHARTA(^{4}He) @DAΦNE (2009)

2010

SIDDHARTA @DAΦNE (2011)

SIDDHARTA(^{3}He) @DAΦNE (2011)

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

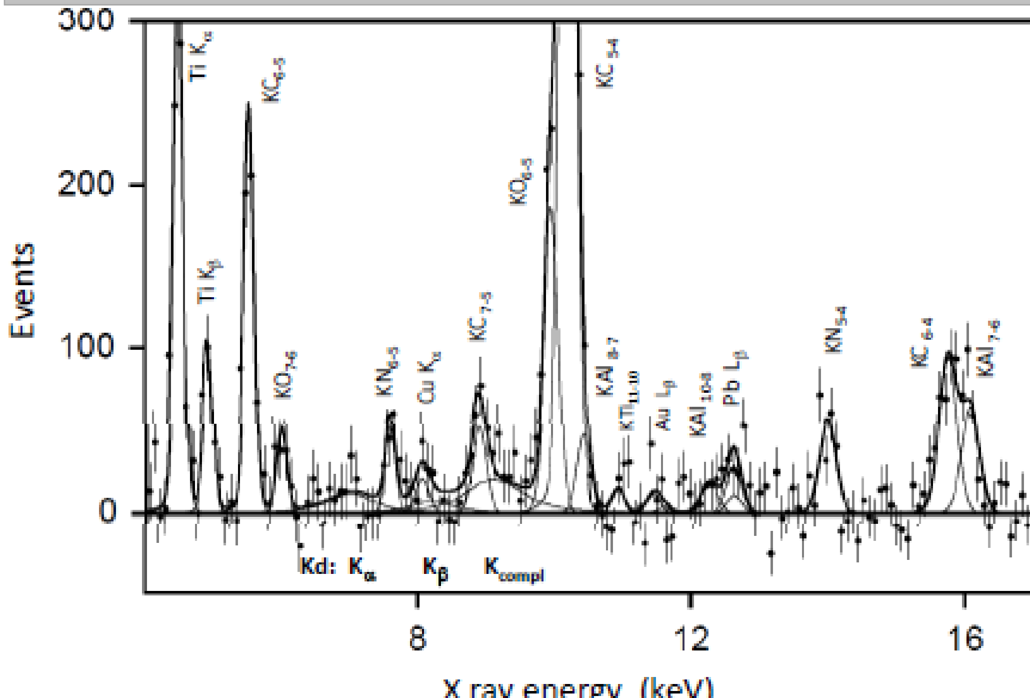
BG sources: asynchronous BG → timing
synchronous BG → spatial correlation

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

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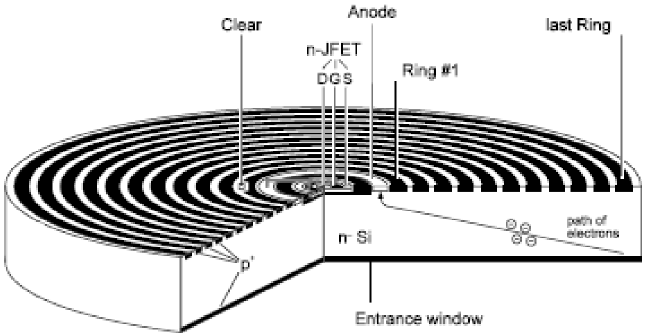
- dedicated cryogenic lightweight gaseous target system

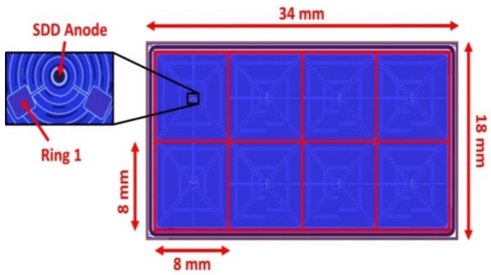
New SDD detectors for SIDDHARTA-2 and E57

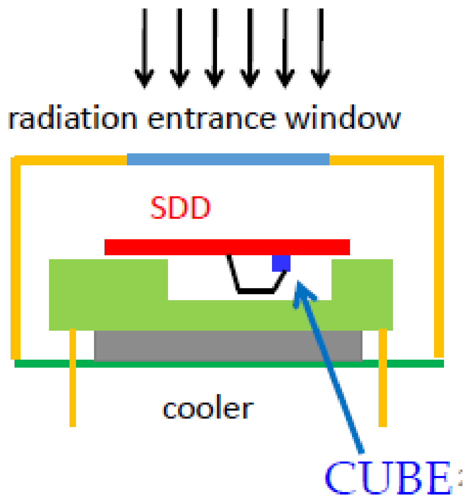
difference with respect to the SDDs in SIDDHARTA:

- 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)

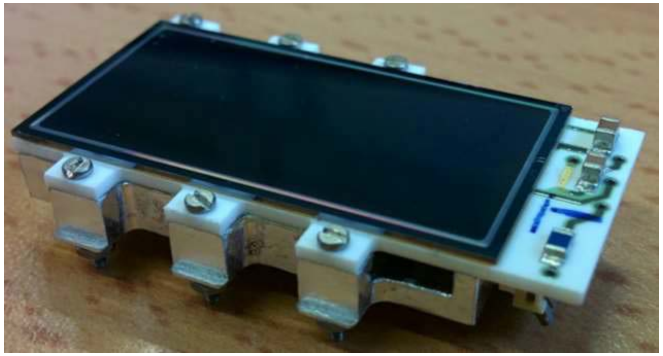


Better drift time of 300 ns compared to the SDDs in SIDDHARTA (~800 ns)





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.

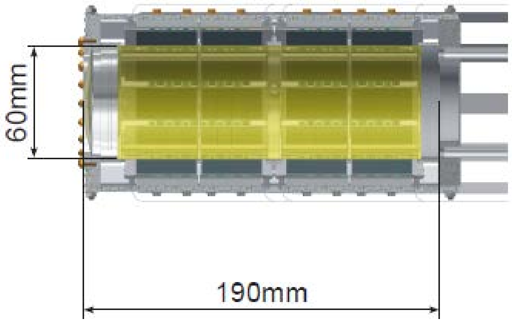
The final dimensions of the target cells depend on the machine used.

- **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,

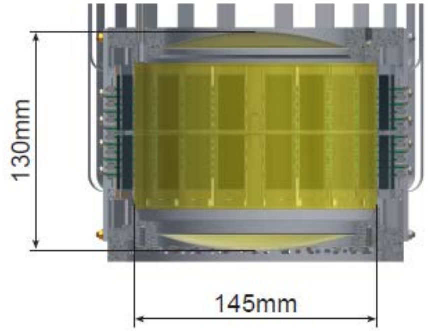
Therefore, the dimensions of the target cells are quite different

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

E57

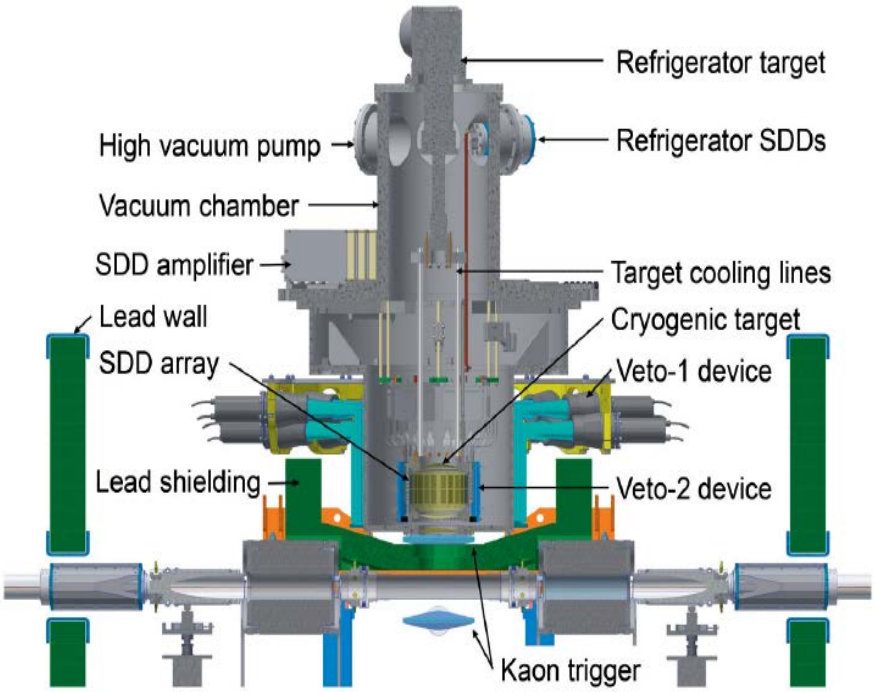


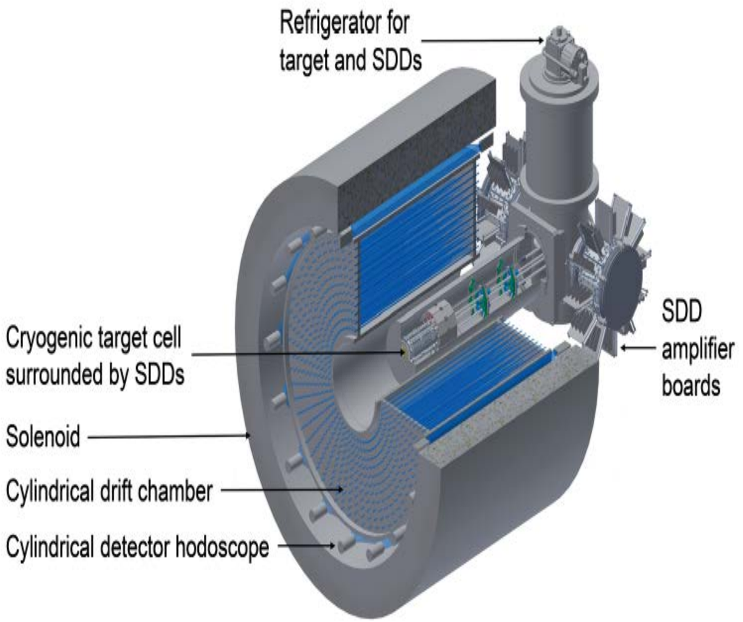
SIDDHARTA-2



SIDDHARTA-2

E57



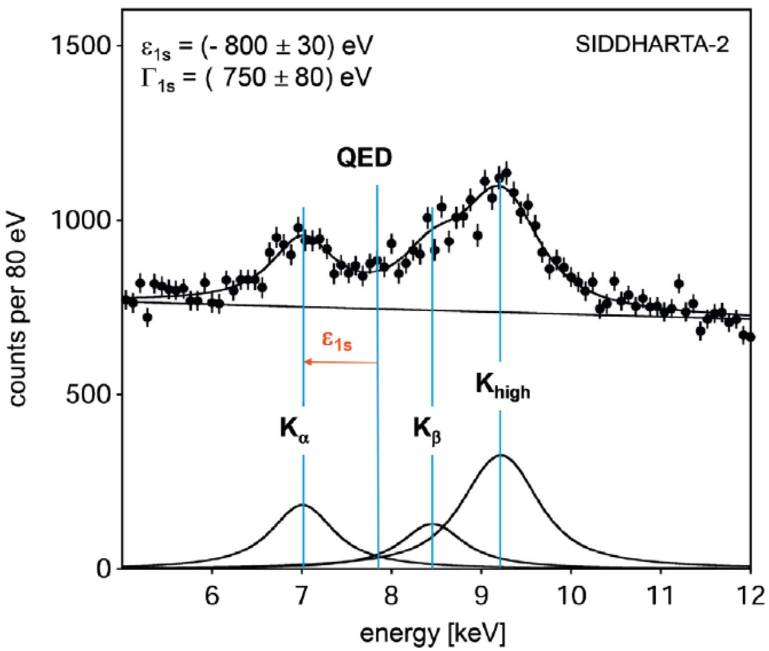


SIDDHARTA – 2, installed in DAΦNE from April 2019, ready to start to take data for kaonic deuterium: 2020

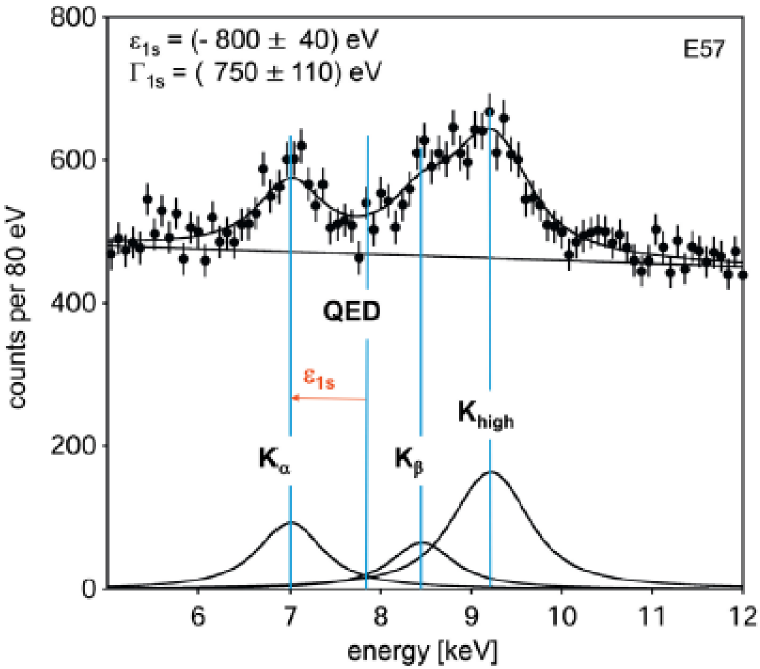
E57
data for kaonic deuterium: 2022 (?)

The Monte Carlo simulations for kaonic deuterium

SIDDHARTA-2



E57



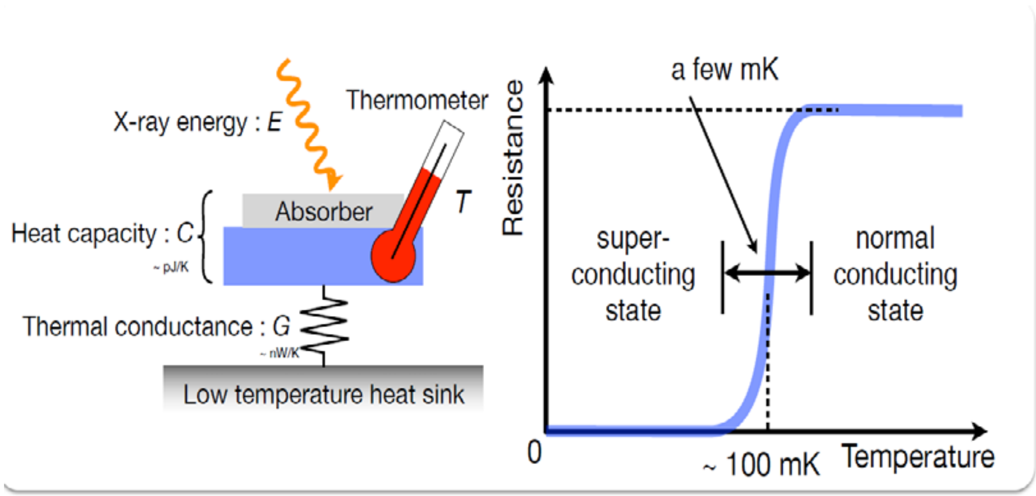
KH results:

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.

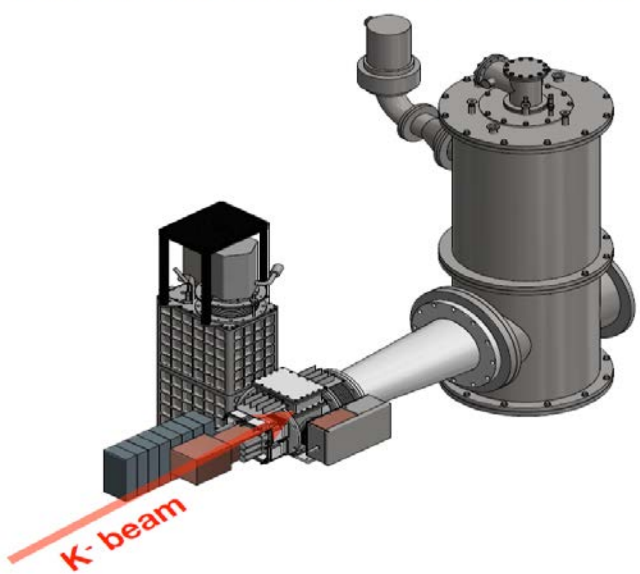


✓ Excellent energy resolution ~2 eV FWHM@ 6 keV

✓ Wide dynamic range possible

E62: K^-He 3d-2p

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

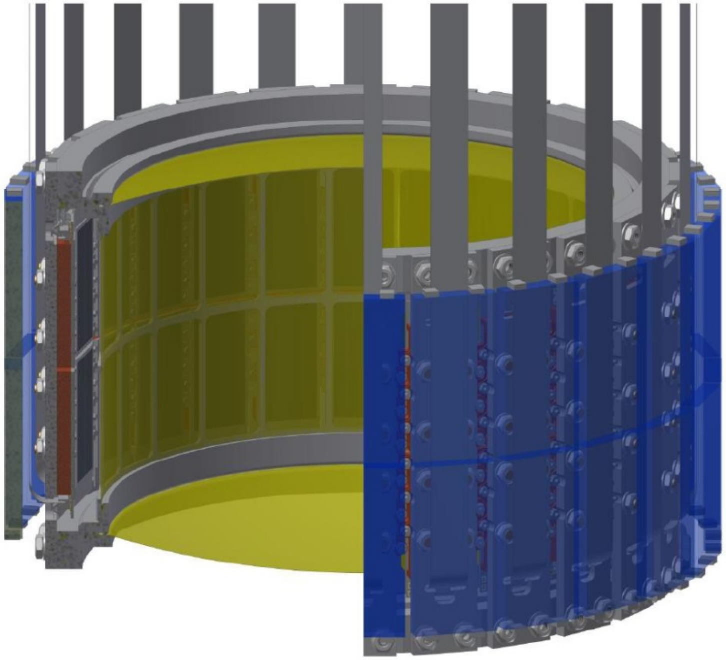


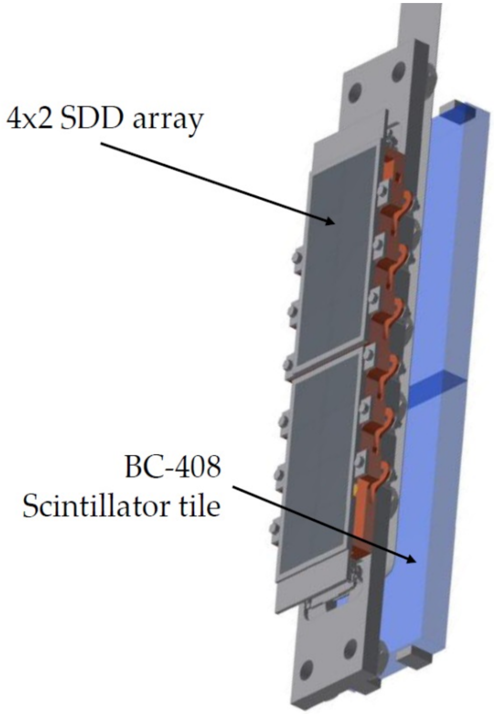
CONCLUSIONS

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