X-rays of light kaonic atoms: SIDDHARTA and future

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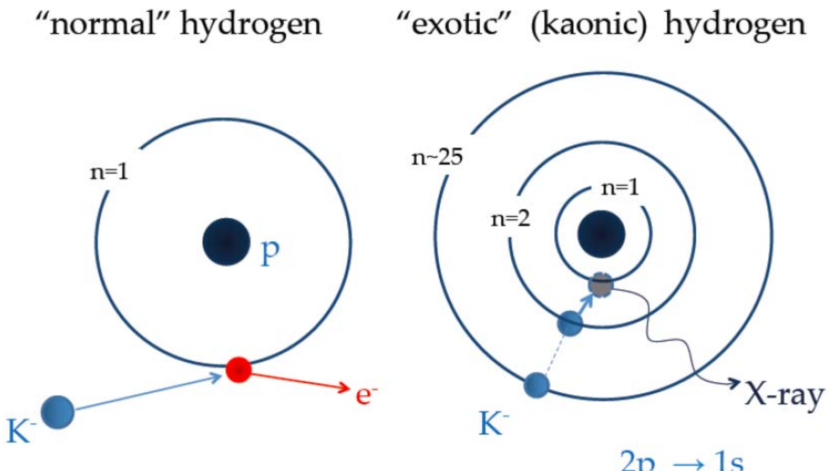
On behalf of: **The SIDDHARTA collaboration**

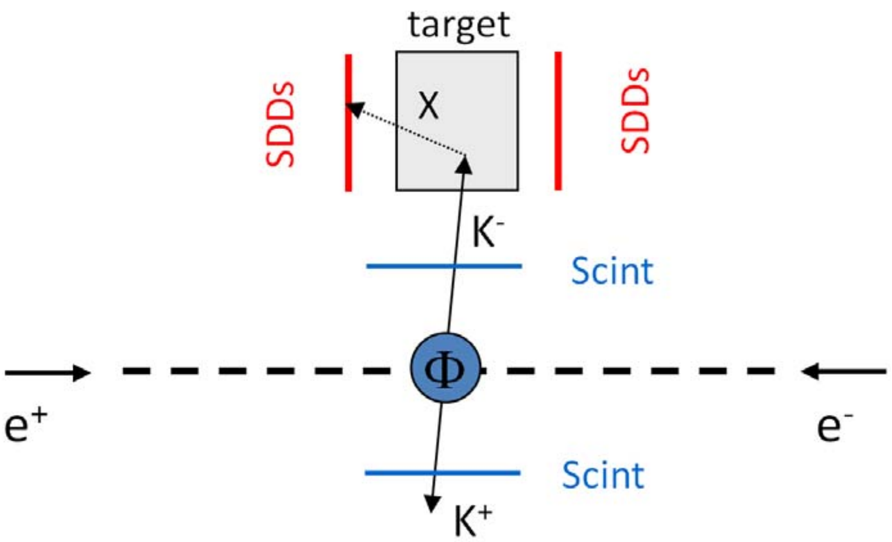
2015 European Nuclear Physics Conference

Kaonic atoms X-rays



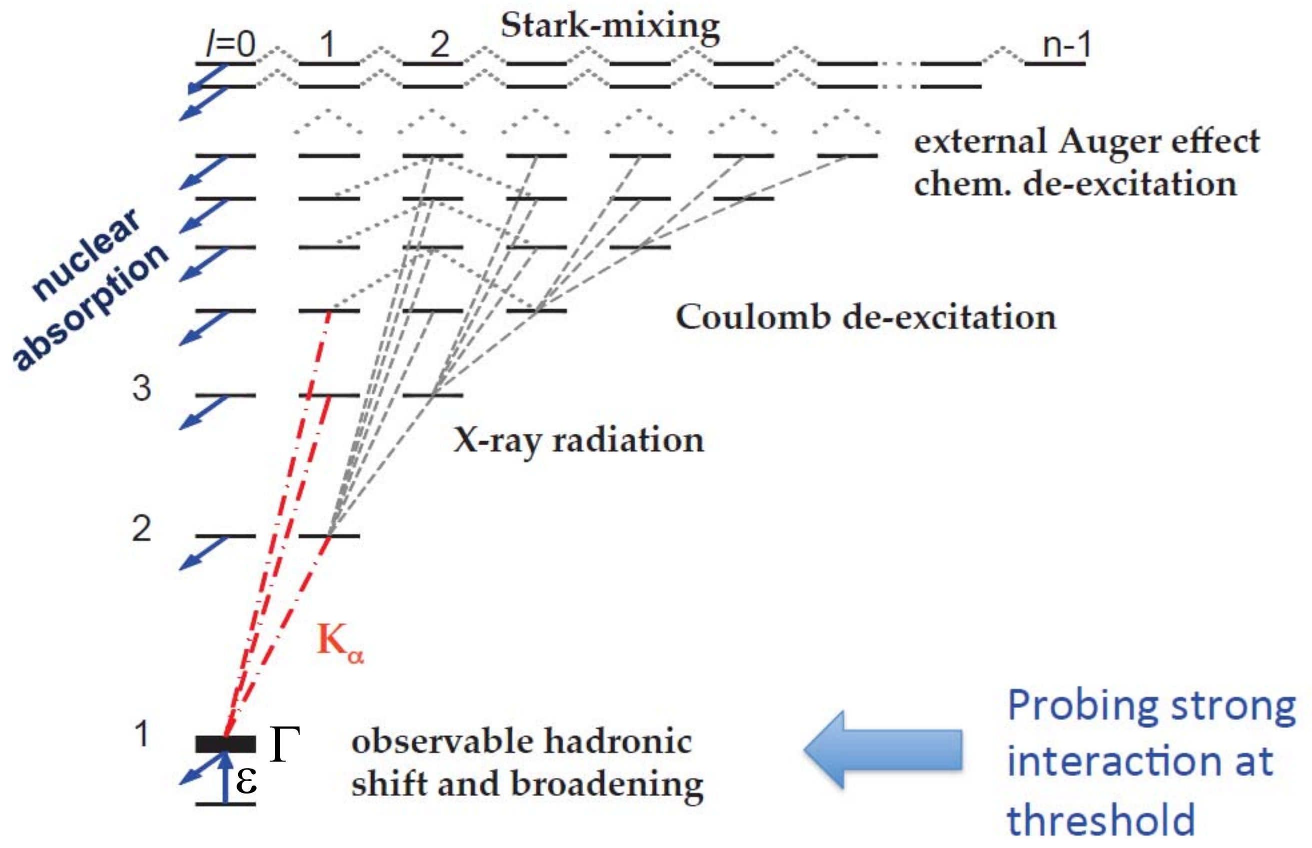
$$n \approx \sqrt{\frac{m_{\rm red}}{m_e}} \cdot n_e$$

SIDDHARTA experiment at DAFNE:
(.. e+ e- collider tuned to the energy of the Φ resonance, Frascati)



Kaonic atoms X-rays

Goal: learn about antikaon-nucleon interaction at lowest energies
Technique: measure the shift and broadening of X-ray transition energies in light kaonic atoms.
The lowest states are measureably affected by the strong interaction between the kaon and the nucleus. ε, Γ connect to theories in low energy QCD



Theory and experiment

Kp, Kd, KHe ..bound electromagnetically, binding well known
Strong interaction (mediated by QCD) $\rightarrow$ modifies binding
$\rightarrow$ causes absorption

if ‚small perturbation'
$\rightarrow$ energy shift and width can be related to T-matrix elements at threshold
(Deser type formulas)

Decription of antikaon nucleon interaction: chiral effective field theory

ChEFT $\leftrightarrow$ scattering data
ChEFT $\leftrightarrow$ *atomic X ray data*
ChEFT $\leftrightarrow$ *energy, width of resonances*

.. needs input from experimental data
.. aims at accomodating *all* experimental evidence

Test validity of the *description of the antikaon-nucleon interaction* at low energies

Scattering lengths

Deser-type relation [1)] connect the observables shift ε_{1s} and width Γ_{1s} of transitions to the ground-state with the real and imaginary part of the scattering length a (μ_C reduced mass of the K^-d system, α finestructure constant, similar relation for K^-p):

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

$$\begin{aligned} a_{K^-p} &= \frac{1}{2}[a_0 + a_1] \\ a_{K^-n} &= a_1 \\ a_{K^-d} &= \frac{4[m_N + m_K]}{[2m_N + m_K]}Q + C \\ Q &= \frac{1}{2}[a_{K^-p} + a_{K^-n}] = \frac{1}{4}[a_0 + 3a_1] \end{aligned}$$

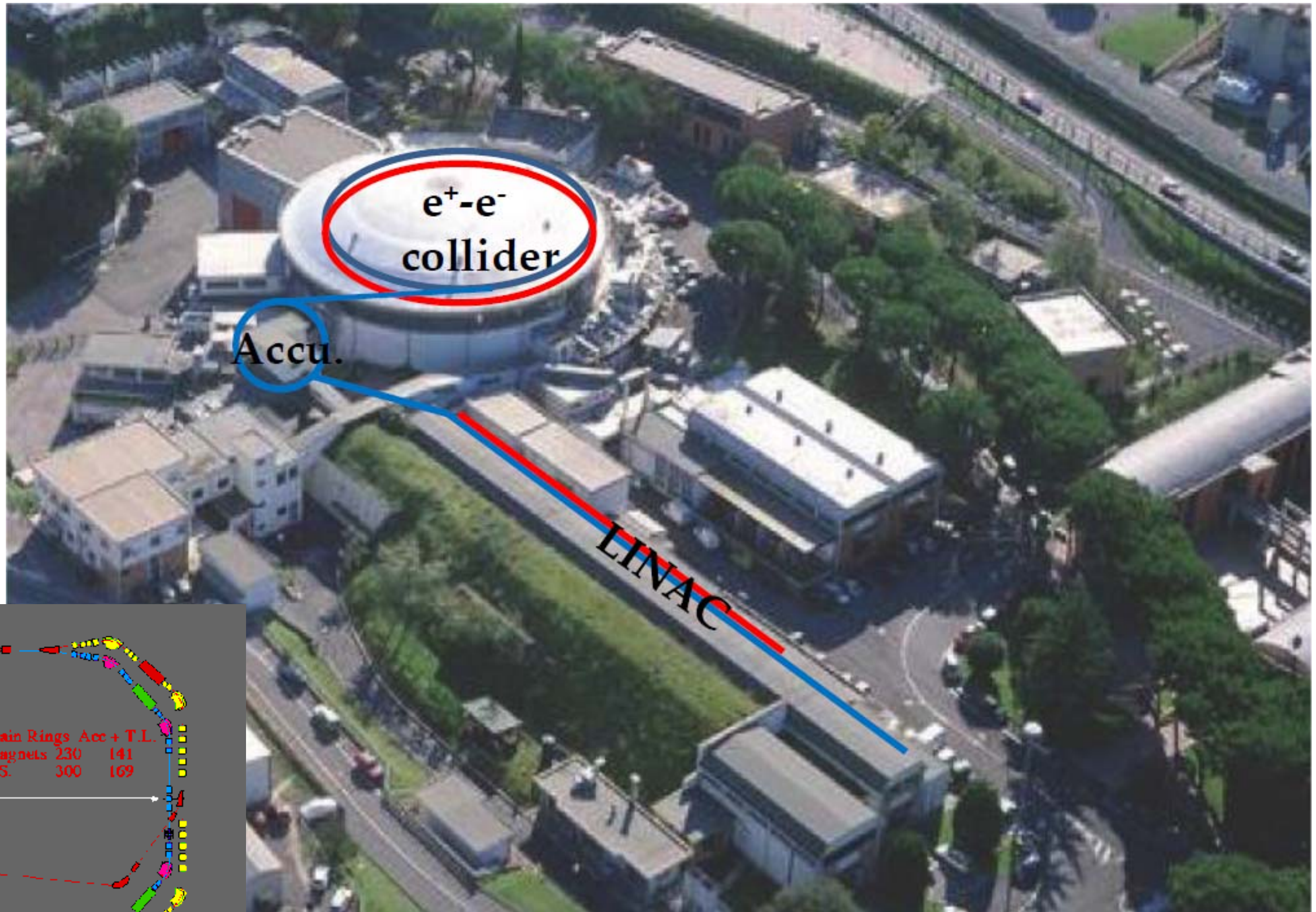
$\mathbf{a_{K\text{-}p}}$ and $\mathbf{a_{K\text{-}d}}$ are linear combination of the $\bar{K}N$ isospin scattering lengths a_0 and a_1. To extract a_0 and a_1, both scattering lengths $\mathbf{a_{K\text{-}p}}$ and $\mathbf{a_{K\text{-}d}}$ are needed (contain different combination of a_0 a_1)

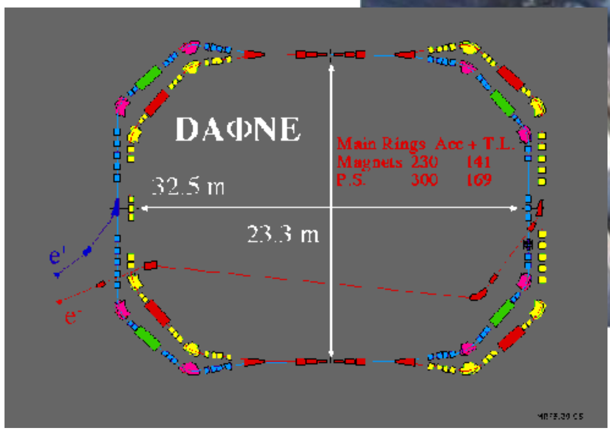
[1)] U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order in isospin breaking
Note: sign-reversed definition of the shift

D A Φ N E

... „Double Annular Phi-factory for Nice Experiments“

at Laboratory Nazionali di Frascati dell‘INFN





Experimental setup SIDDHARTA 2009

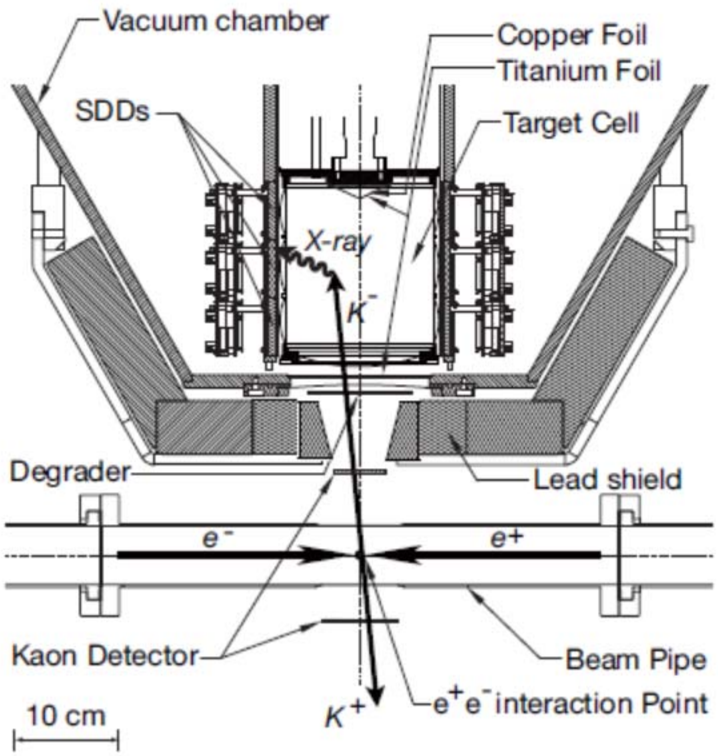
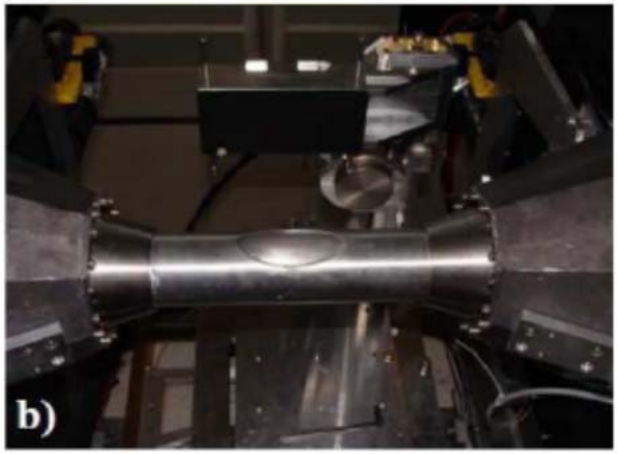


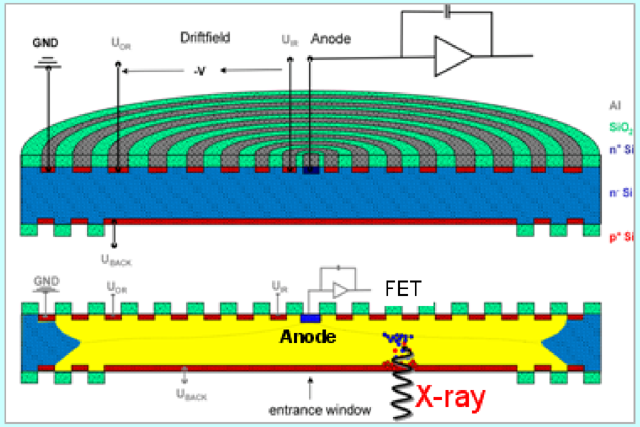
Figure 1: A schematic view of the SIDDHARTA setup installed at the e^+e^- interaction region of DAΦNE.



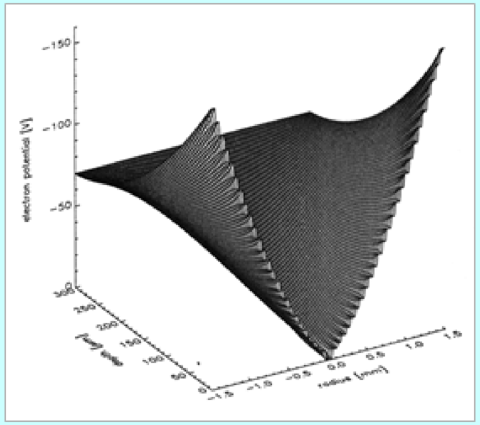
SIDDHARTA X ray detectors

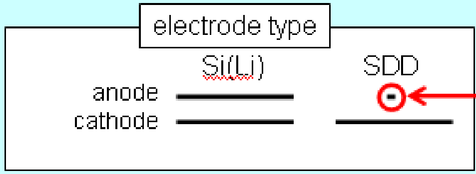
SDD (Silicon Drift Detector)

Schematic drawing



potential distribution





$Q = CV$
$= (\varepsilon_0 S / d)\, V$

Small capacitance

The small capacitance results in a large amplitude and a short rise time of the signal

Compared to conventional photodiodes SDDs can be operated at higher rates and have better energy resolution.

I3 Hadron Physics EU FP6 –
Joint Research Activity: **SIDDHARTA** - in cooperation with LNF, MPG, PNSensor, Politecnico Milano, IFIN-HH.

A lateral field makes the produced charge drift to the collecting anode.

different from standard electronic devices:

- double sided structure
- not passivated
- large area chips
- arrangement of bond pads in the center

Data analysis

Data aquisition:

- ***energies*** and detector numbers of X ray hits
- event id-number, time-tag

if a kaontrigger happend: - the ***time correlation*** between X-ray and kaon
- the kaon detector parameters

Analysis tasks:

- periodically calibrate the >100 individual detectors (**gain alignment**), discard ‚bad' ones

- determine the energy resolution (**response shape**) of the summed detectors

- **fit** the spectrum with signal-components, background lines and continous background

Background:

„Beam background" Touschek- Babha- and *beam-gas*-scattering,
stray high-energy $e^{\pm}$ => e.m. **showers. not correlated** to charged kaon pairs**:**
(1) „accidentals"

μ, π, e from K decay; **Λ, π,..** from K^- absorption, kaonic X rays from K^- wallstops
=> *synchronous background* – has trigger signal
(2) kaonic X-ray lines
(3) continous kaon correlated background

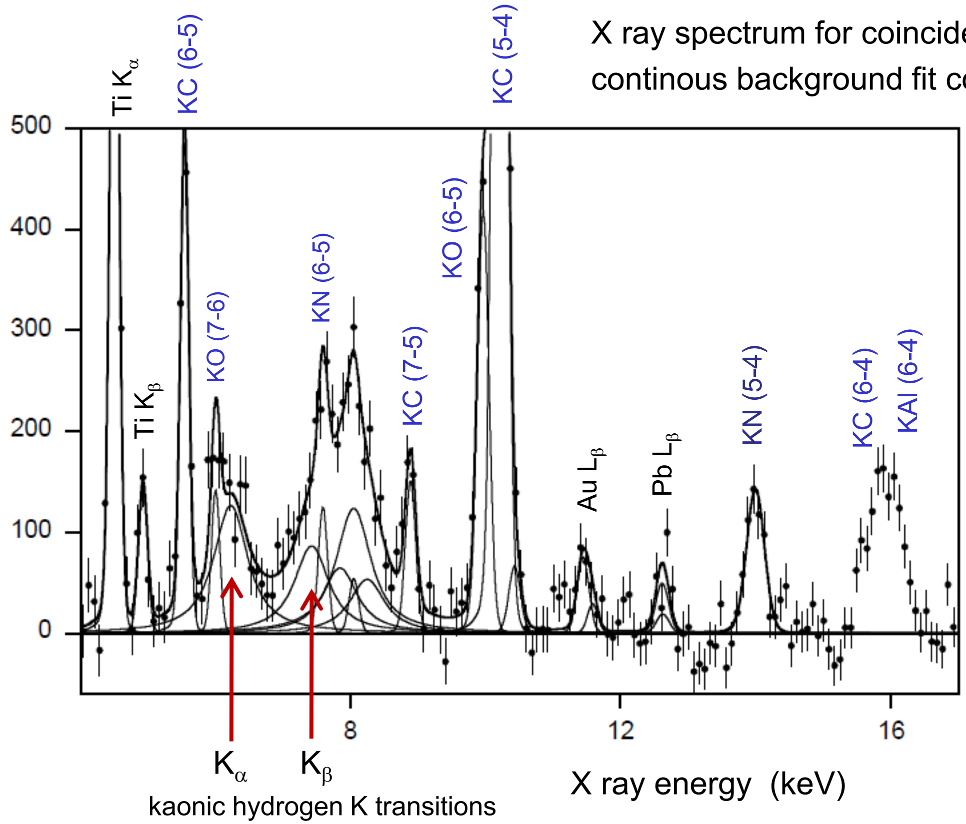
Fit of the KH data

Transition	unshifted energy (keV)
KH (2-1)	6.480
KH (3-1)	7.677
KH (4-1)	8.096
KH (5-1)	8.299
KH (6-1)	8.395
KH (7-1)	8.458
...	...
KH (inf.)	8.634

background lines

Transition	Energy
KC (6-5)	5.545
KC (5-4)	10.200
KC (6-4)	15.759
KC (7-5)	8.888
KO (7-6)	**6.007**
KO (6-5)	9.969
KN (6-5)	**7.596**
KN (5-4)	13.996
Cu K_{α}	**8.04**

X ray spectrum for coincidence time-gate.
continous background fit component is subtracted



kaonic hydrogen:
shift= -283 +- 36 +- 6 eV width = 541 +- 89 +- 22 eV

SIDDHARTA collaboration, "A new measurement of kaonic hydrogen X-rays", Physics Letters B 704 (2011), p. 113

SIDDHARTA results applied

Chiral SU(3) theory of antikaon-nucleon interactions with improved threshold constraints
Y. Ikeda, T. Hyodo and W. Weise, Nucl. Phys. A881 (2012) 98-114.

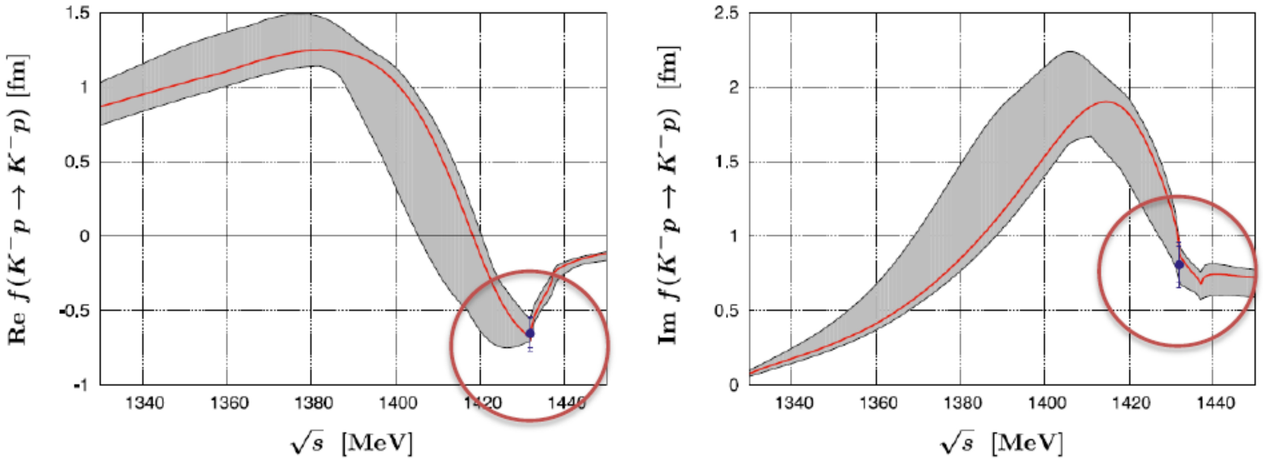
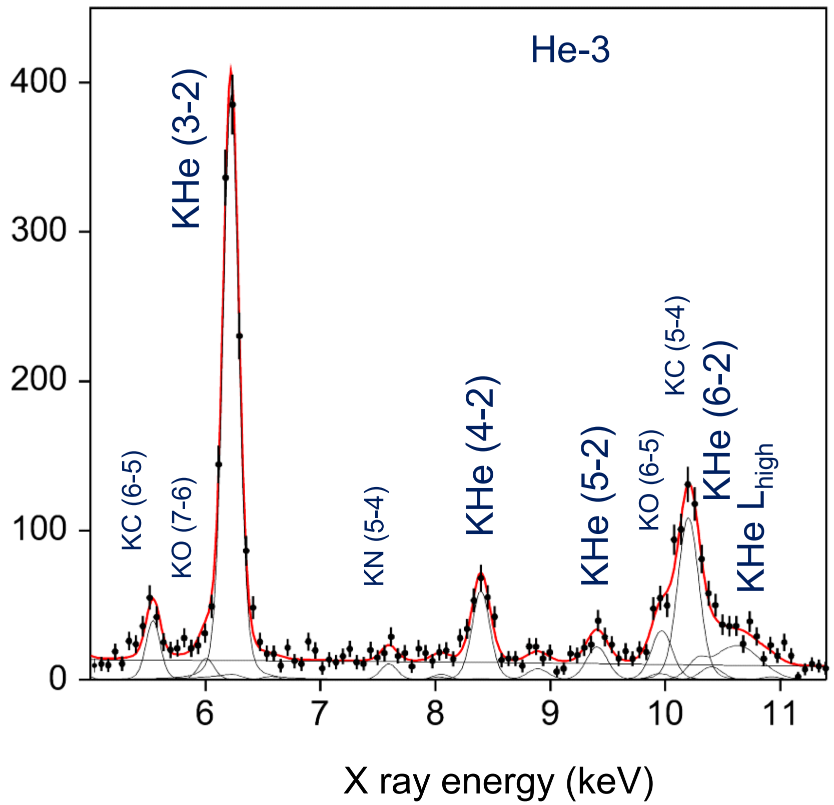
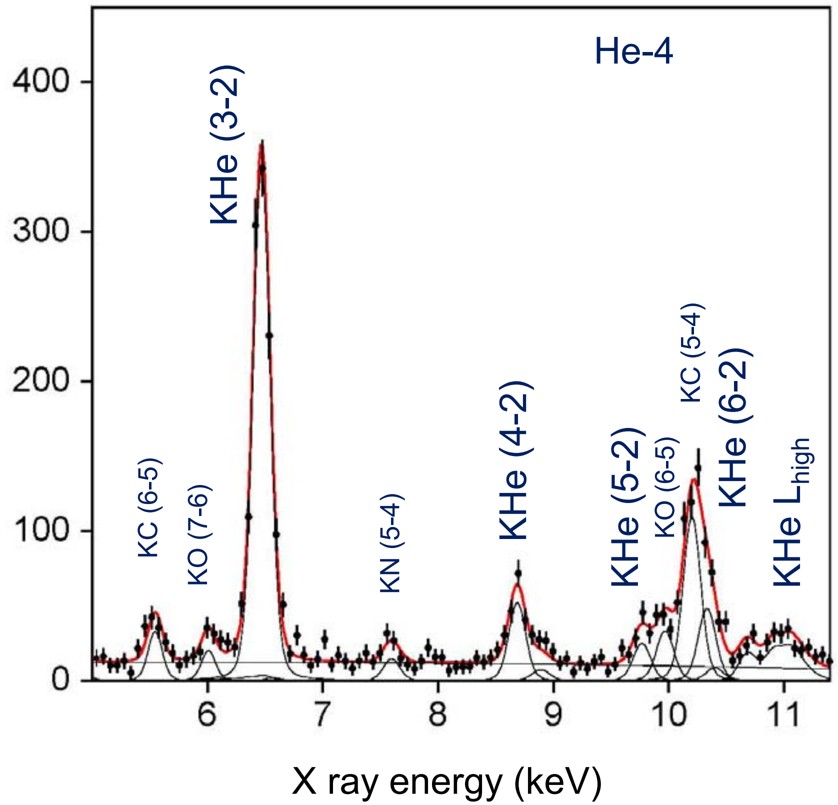


Fig. 4. Real part (left) and imaginary part (right) of the $K^-p \to K^-p$ forward scattering amplitude obtained from the NLO calculation and extrapolated to the subthreshold region. The empirical real and imaginary parts of the K^-p scattering length deduced from the recent kaonic hydrogen measurement (SIDDHARTA [15]) are indicated by the dots including statistical and systematic errors. The shaded uncertainty bands are explained in the text.

Kaonic helium spectra from SIDDHARTA

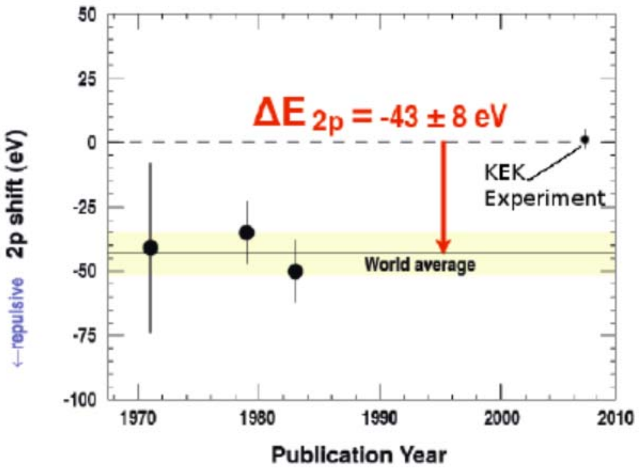
L-series lines prominently seen !





note S/B !

Kaonic helium



Summary of experimental results on the kaonic helium 4 L-series X-ray transition shift

SIDDHARTA confirmed the KEK KHe4 result and was the first maesurement of KHe3

308 *SIDDHARTA Collaboration / Nuclear Physics A 914 (2013) 305–309*

Table 1
Energy shifts (ΔE_{2p}) and widths (Γ_{2p}) of the kaonic helium ^{3}He and ^{4}He $2p$ states.

Target	ΔE_{2p} (eV)	Γ_{2p} (eV)	Ref.
^{4}He	-41 ± 33	–	Wiegand et al. [1]
^{4}He	-35 ± 12	30 ± 30	Batty et al. [2]
^{4}He	-50 ± 12	100 ± 40	Baird et al. [3]
^{4}He	-43 ± 8	55 ± 34	Average of above [3,4]
^{4}He	$+2 \pm 2$ (stat.) ± 2 (syst.)	–	Okada et al. [12]
^{4}He	0 ± 6 (stat.) ± 2 (syst.)	–	SIDDHARTA [8]
^{4}He	$+5 \pm 3$ (stat.) ± 4 (syst.)	14 ± 8 (stat.) ± 5 (syst.)	SIDDHARTA [9,10]
^{3}He	-2 ± 2 (stat.) ± 4 (syst.)	6 ± 6 (stat.) ± 7 (syst.)	SIDDHARTA [9,10]

SIDDHARTA results

Table 1. Compilation of SIDDHARTA results. The errors given in this table are the sum of the statistical and the systematic component; in case of asymmetric errors, the larger one is quoted here. The upper limits of the yields are for CL 90%. The yields for H and He are preliminary values. Gas densities: H: 14.5 ρ_{STP}, D: 13.9 ρ_{STP}), ^{3}He: 5.38 ρ_{STP}, ^{4}He: 9.24 ρ_{STP}. For kaonic carbon etc. see [6].

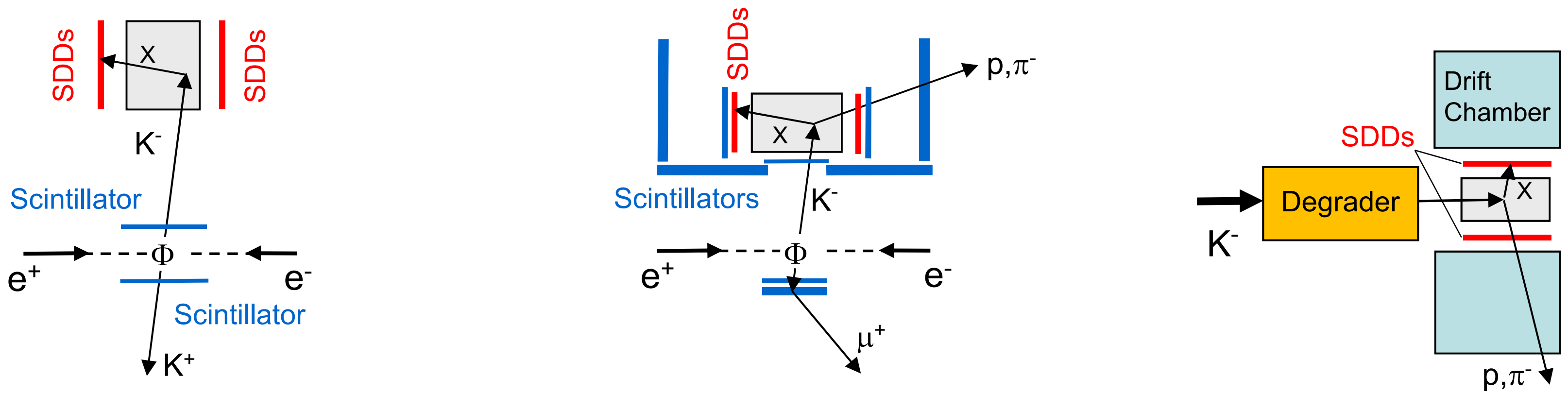
	shift [eV]	width [eV]	transition yields in % per stopped K^-	ref.
H	ϵ_{1s}= -283±42	Γ_{1s}= 541±111	Y(K_{tot})= 4.5±1.2 Y(K_α)= 1.2±0.4	[7–9]
D			Y(K_{tot}) < 1.43 Y(K_α) < 0.39	[10]
^{3}He	ϵ_{2p}= -2±6	Γ_{2p}=6±13	Y(L_α)= 25.0±6.7	[11, 13, 14]
^{4}He	ϵ_{2p}= 5±7	Γ_{2p}=14±13	Y(L_α)= 23.1±6.0	[12–14]

[6] (SIDDHARTA Collaboration), Nucl. Phys. A **916**, 30 (2013)
[7] (SIDDHARTA Collaboration), Phys. Lett. B **704**, 113 (2011)
[8] (SIDDHARTA Collaboration), Nucl. Phys. A **881**, 88 (2012)
[9] (SIDDHARTA Collaboration), Eur. Phys. J. Web of Conferences **66**, 09016 (2014)
[10] (SIDDHARTA Collaboration), Nucl. Phys. A **907**, 69 (2013)
[11] (SIDDHARTA Collaboration), Phys. Lett. B **697**, 199 (2011)
[12] (SIDDHARTA Collaboration), Phys. Lett. B **681**, 310 (2009)
[13] (SIDDHARTA Collaboration), Phys. Lett. B **714**, 40 (2011)
[14] (SIDDHARTA Collaboration), Eur. Phys. J. A **50**, 91 (2014)

Experimental schemes for future Kd

for a Kd yield ~ 1/10 of Kp yield and Kd width up to 2 times Kp width we need
~ <u>20 times reduction</u> of background to get similar S/B as in kaonic hydrogen
~ 600 pb^{-1} to get 1500 events in Kd (2-1) if efficiency of the setup is doubled

SIDDHARTA | SIDDHARTA-2 | Kd.J-PARC



SIDDHARTA-2 at DAFNE

changed ***geometry and gas-density:***

closer, doubled gas density, upper kaon trigger DIRECTLY in front of target, smaller then entry window

added ***kaon livetime detector*** for K^{+-} discrimination:

identify K^+ by delayed secondaries (τ_K=12.8 ns)

added surrounding ***scintillators:***

„active shielding", anticoincidence during SDDs time window (~500 ns), except
coincidence during „gas-stop-time (~ 5 ns, K^- absorption secondaries) , but not „behind X ray hit" (MIPS veto)

SDDs operated at lower temp. to improve timing resolution, make use of drift-time/risetime correlation

SIDDHARTA-2 at DAFNE

600 pb^{-1} => with 8 pb^{-1} per day ~75 days

1.5e6 $K^{\pm}$ per pb^{-1}
=> 1.5e7 $K^{\pm}$ per day ~ isotropically
p = 127 MeV/c

Target stops: ~ 2 % per kaonpair (gas 3% dens.)
due to solid angle. Intrinsic ~ 100%
=> *18e6 stops*

SDDs: 144 cm^2 devices from SIDDHARTA
active/module = 0.22
possibly: 246 cm^2 new SDDs from Milano /FBK

source

low energy kaons

tracking not necessary

preparation in advanced state

... at J-PARC

at 30 kW proton beam,
35 days

at p = 0.7 GeV/c
~ 40e7 kaons per day

Target stops for 5% dens.
~ 0.6e-3 per beam kaon => *7.8e6 stops*

SDDs: 246 cm^2 new devices from Milano /FBK
active/module = 0.84

beam

high energy kaons
>90% lost in degrader, wide energy range at entering target
in the target: absorption in flight relevant

tracking
fiducial volume cut

feasibility study, *proposal submitted*

Proposed Kd at J-PARC

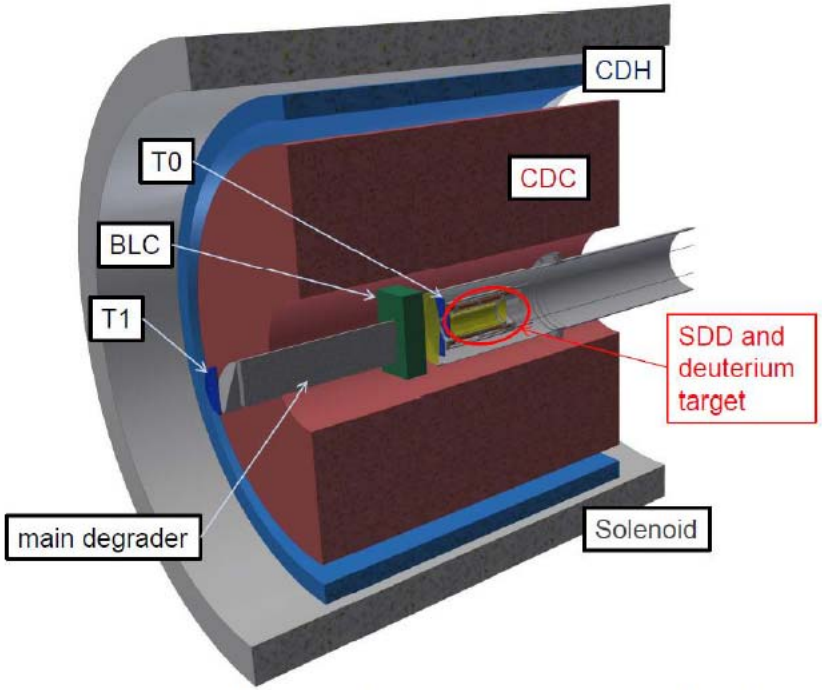


Figure 8: Sketch of the proposed setup for the kaonic deuterium measurement

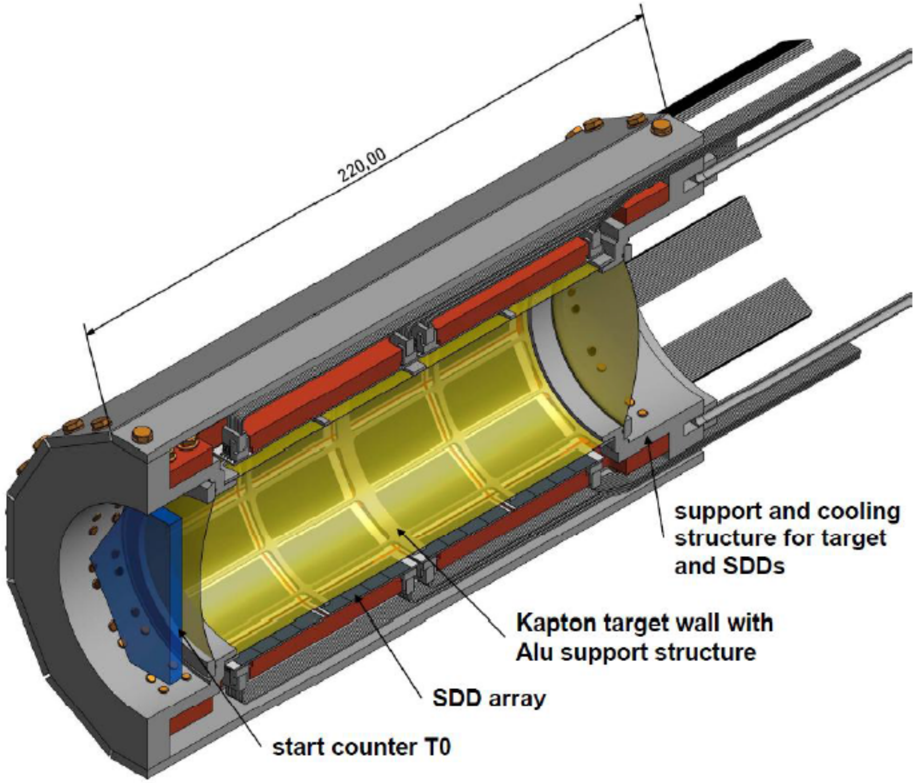
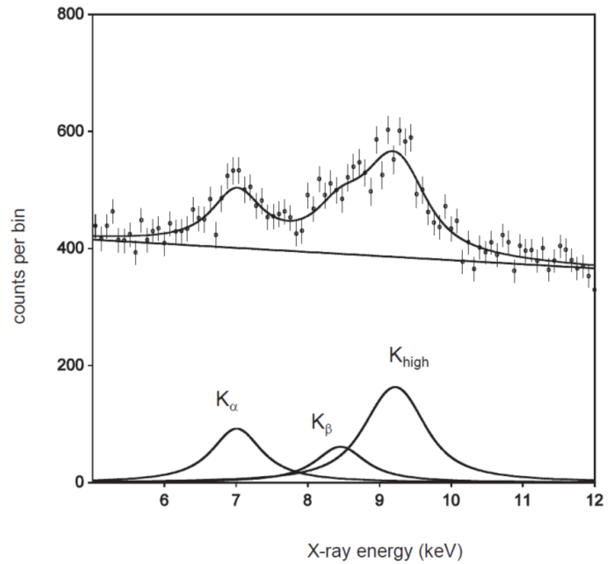


Figure 11: Design of the cryogenic target and X-ray detector system. The target cell, with a diameter of 65 mm and a length of 160 mm, is closely surrounded by SDDs, about 5 mm away from the target wall.

Achievable precision

events kaonic deuterium $K\alpha$	S/B „ampl/ BGlevel“	precision of shift result (eV)	precision of width result (eV)	experiment 600 pb^{-1} at DAFNE resp. 100 shifts with 40 kW p-beam at J-PARC
1500	1 : 3	47	123	SIDDHARTA-2
3000	1 : 3	32	83	SIDDHARTA-2 using the new SDDs
1500	1 : 5	70	160	J-PARC
2000	10 : 3	12	24	kaonic hydrogen test (few days)

Monte Carlo test spectrum with relative yield distribution similar to kaonic hydrogen.
1500 Kd $K\alpha$ events
Fit with free intensities



Summary and Outlook

Results on shift, width and yields from measurements of kaonic He-3, He-4, C and hydrogen **(K^-p)** published. Strong impact for K^- N theory !

K^-d first experiment, exploratory measurement, signal hints, significance ~ 2σ
upper limit for K-series yield published.

Proposed extension of the experimental program: **SIDDHARTA-2**
with improved technique - measure Kd shift and width, other light atoms, Kp $\rightarrow \gamma\ \Lambda^*$
Preparations under way. *Timescale: „after KLOE experimental period“ ... 2017 ?*

„Plan B“: Kd experiment at J-PARC, proposal submitted.

future: microcalorimeter detectors with few eV resolution at 6 keV


at SIDDHARTA-2 meeting Sept 11, 2014