X-rays of light kaonic atoms: SIDDHARTA and future

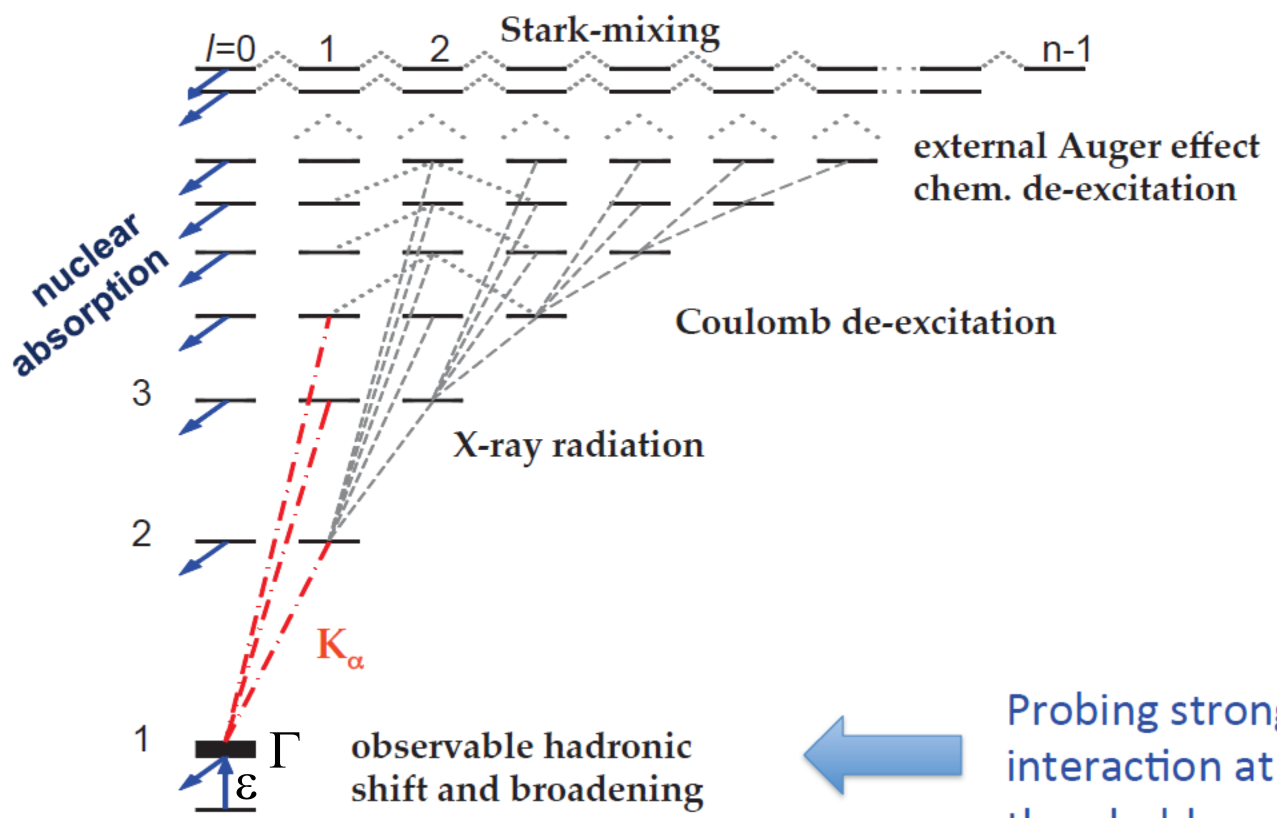
Michael Cargnelli, Stefan Meyer Institute, Austrian Academy of Sciences, Vienna

On behalf of: **The SIDDHARTA collaboration**

"Strangeness in Nuclei and in Neutron Stars"
workshop Pisa 2015-05-20/21

X-ray transitions in kaonic atoms

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



Probing strong interaction at threshold

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):

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

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

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

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

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

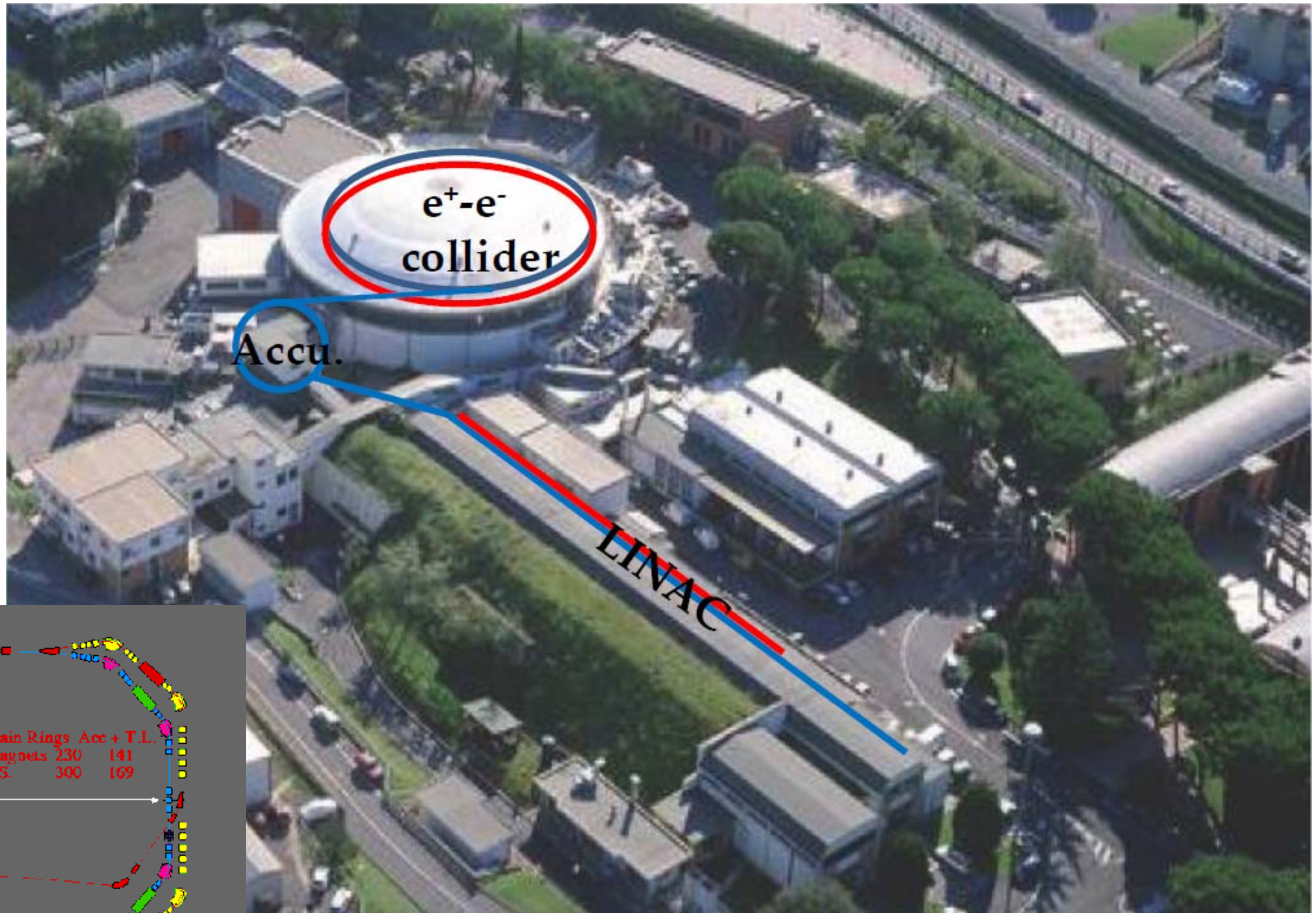
$\mathbf{a_{K-p}}$ and $\mathbf{a_{K-d}}$ are linear combination of the $\bar{K}N$ isospin scattering lengths a_0 and a_1. To extract a_0 and a_1, both scattering lengths $\mathbf{a_{K-p}}$ and $\mathbf{a_{K-d}}$ are needed (contain different combination of a_0 a_1)

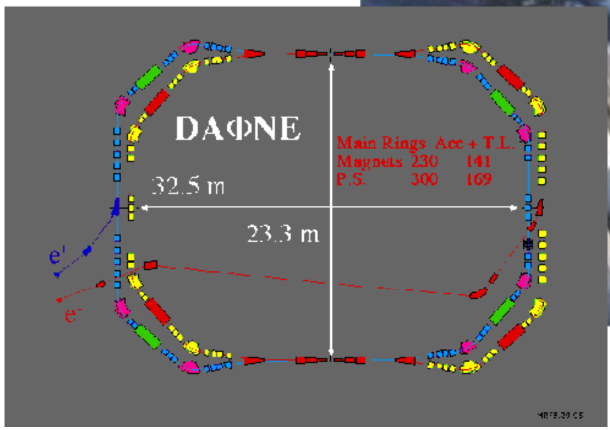
[1)] U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349
next-to-leading order in isospin breaking
Note: sign-reversed definition of the shift

D AΦN E

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

at Laboratory Nazionali di Frascati dell‘INFN





Experimental setup SIDDHARTA 2009

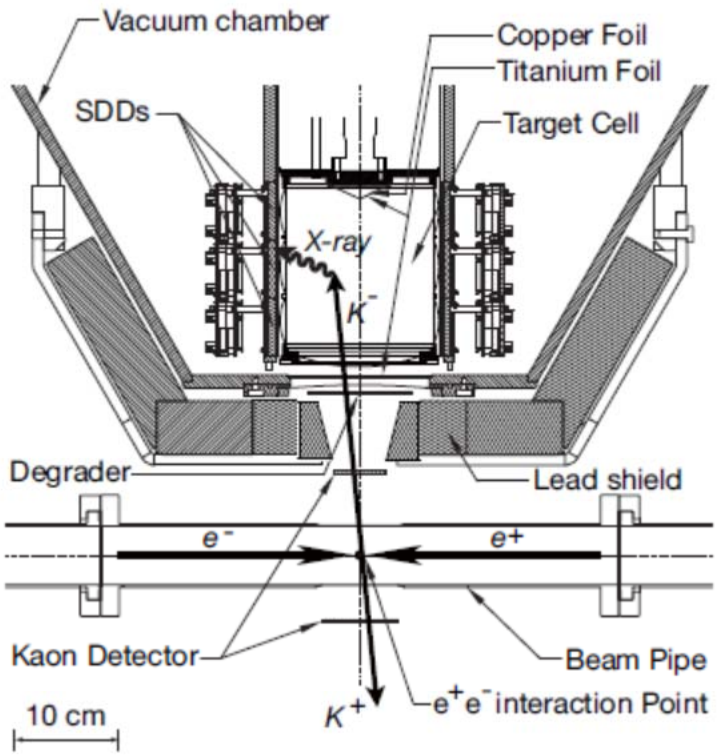
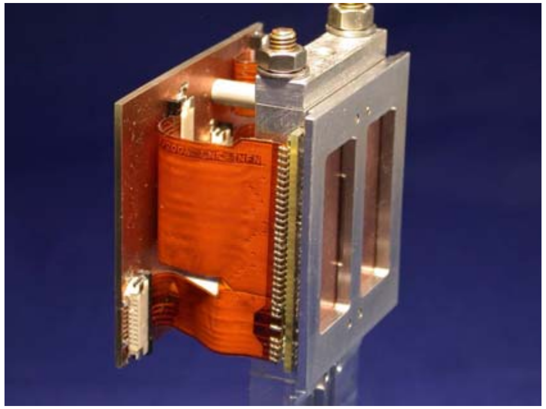
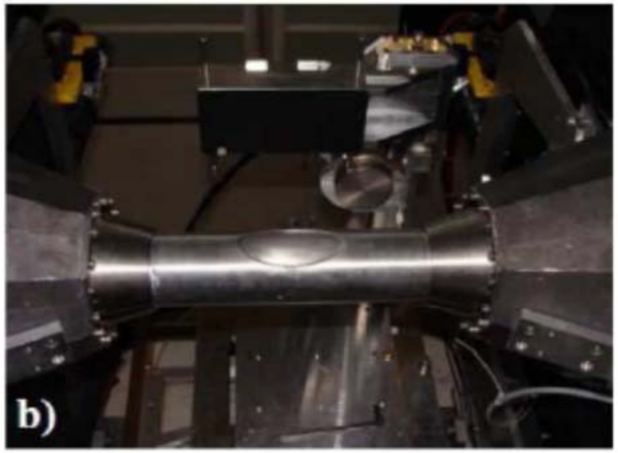


Figure 1: A schematic view of the SIDDHARTA setup installed at the e^+e^- interaction region of DAΦNE.

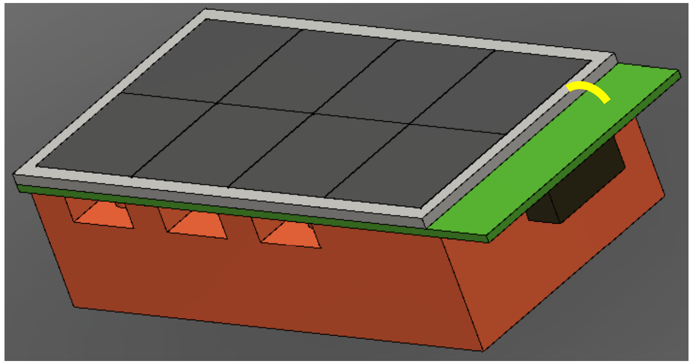


SDD module, 6 x 1 cm^2
24 modules => 144 detectors



Newly developed SDDs by Federatione Bruno Kessler (Trento) and Politecnico Milano for future Kd experiments at DAFNE or J-PARC

- monolithic array of 2x4 SDDs
- area single SDD = 8x8mm^2
  (driven by drift time considerations)
- square shape
- 1mm dead area at chip periphery
- operating temperature = 20K-30K
- ceramic: as large as SDD chip, with only one additional strip for bonding and connector
- mounting, cooling: ceramic glued to a cupper frame (or alternative solutions under study)

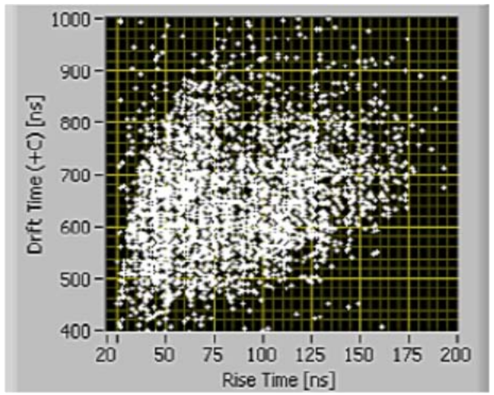


- 6,12 cm^2 chip area
- 5,12 cm^2 active area

Improving the timing resolution:

Measurement of the correlation between the drifttime and the risetime of the newly developed SDDs.

By using the rise-time information, the hit time at the SDDs may be determined more precisely (correcting for the varying drift times) Currently studied...



SIDDHARTA experimental data

-***energies*** and detector numbers of hits on SDDs (mostly overflow events from MIPS tracks)

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

Data analysis tasks:

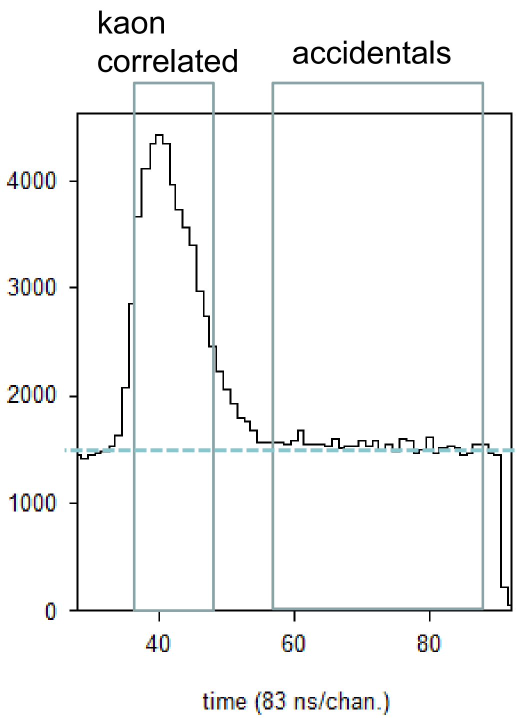
- periodically calibrate the 144 individual detectors (gain alignment), discard ‚bad' ones
- determine the energy resolution (response shape) of the summed detectors
- fit the spectrum with signal-components, background lines and continous background

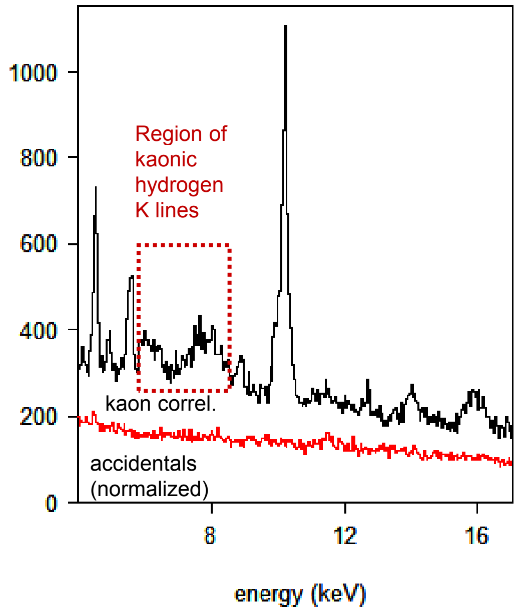
The radiation environment leads to **large charge** in Si (dE > 150 keV at 0.5 mm thickness)

„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

Kaonic hydrogen X-ray data





K correlated background:

decay secondaries from K^+, K^-
K^- absorption secondaries
K^- kaonic X-rays, wallstops, gasstops

total background: accidental+hadronic

electromagnetic showers resulting from lost e^+ e^-

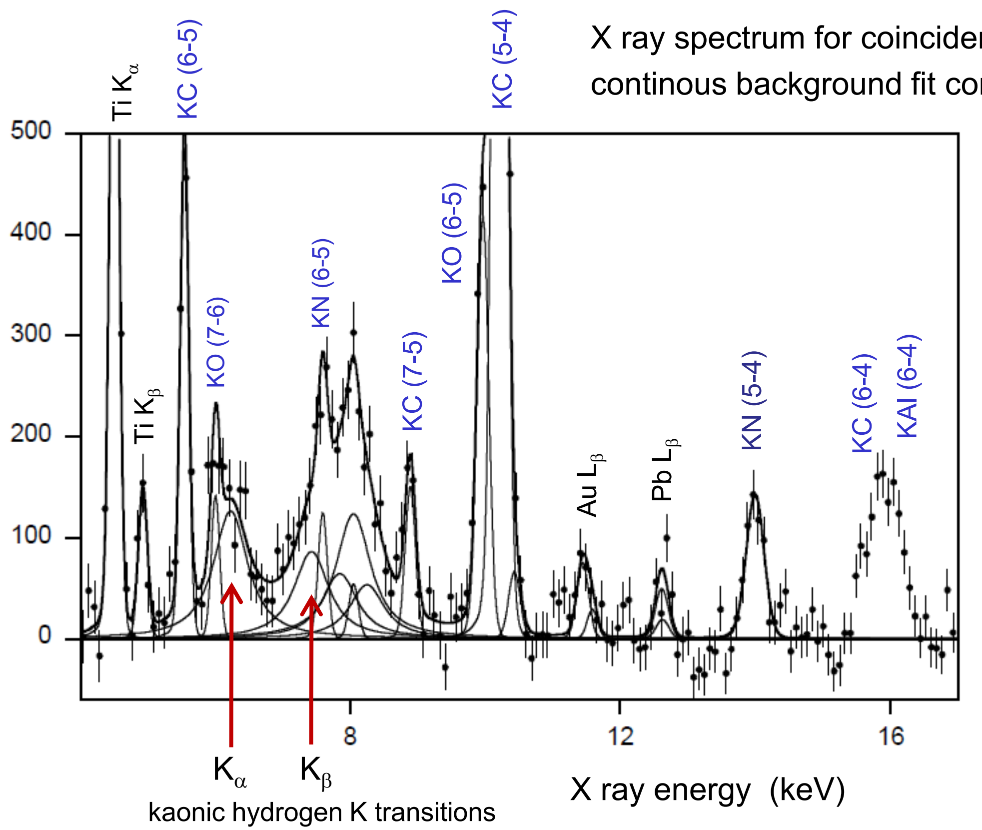
Fit of the KH data

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

Example of the impact of SIDDHARTA

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.

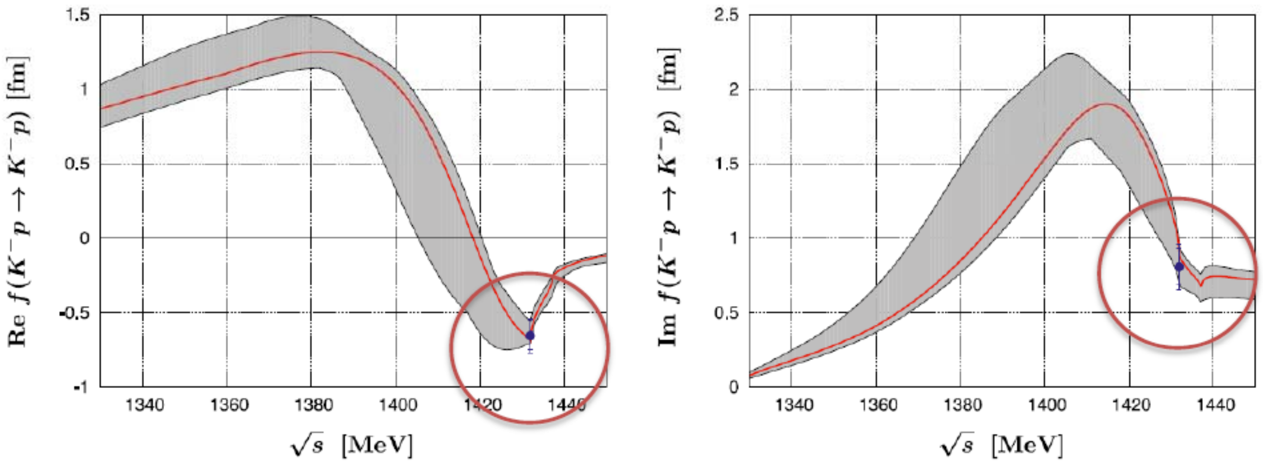
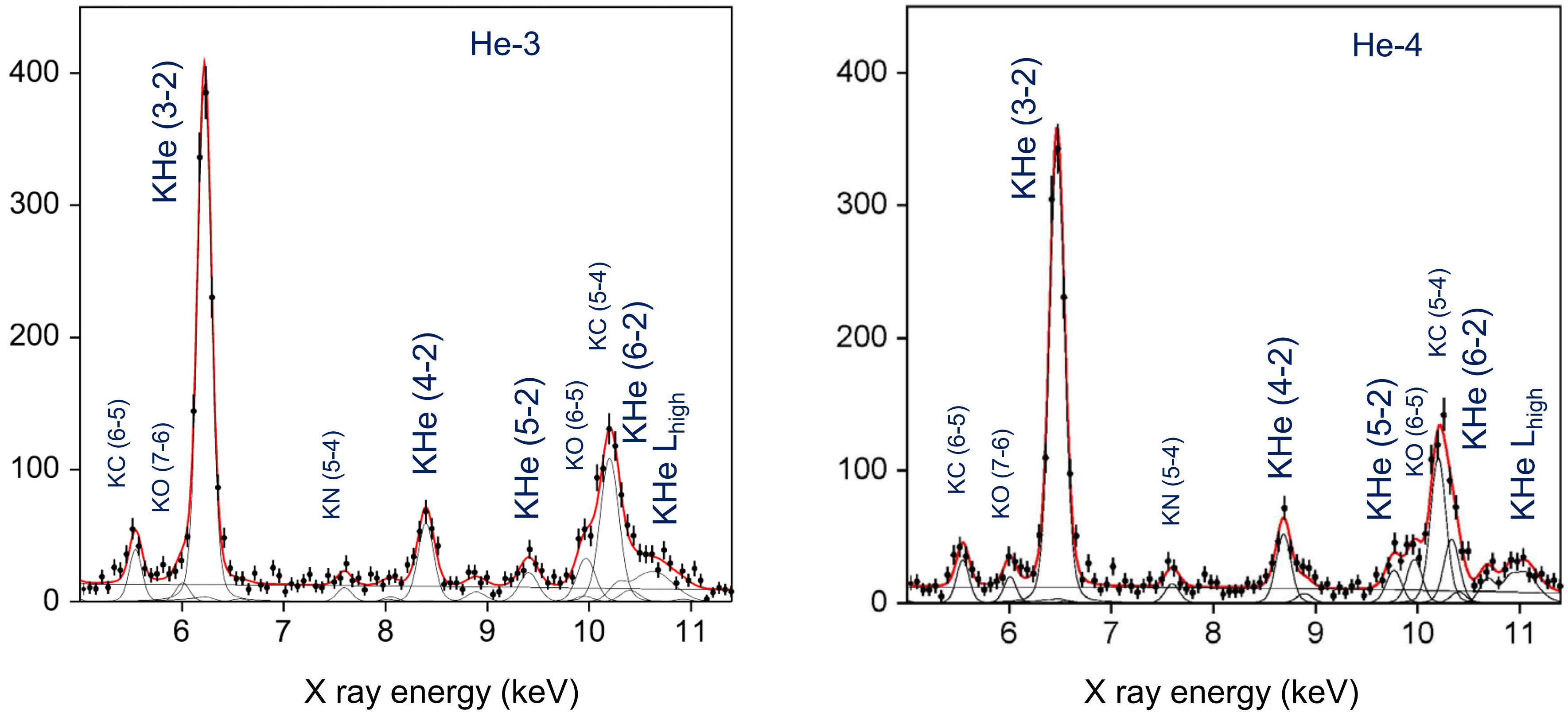


Fig. 4. Real part (left) and imaginary part (right) of the $K^-p \to K^-p$ forward scattering amplitude obtained from the NLO calculation and extrapolated to the subthreshold region. The empirical real and imaginary parts of the K^-p scattering length deduced from the recent kaonic hydrogen measurement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

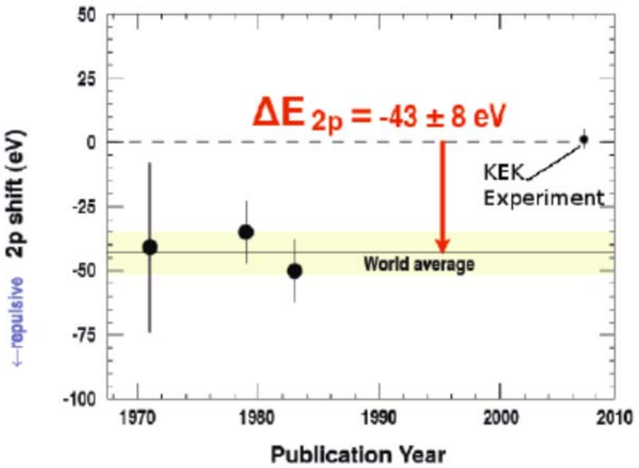
Kaonic helium spectra from SIDDHARTA

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]

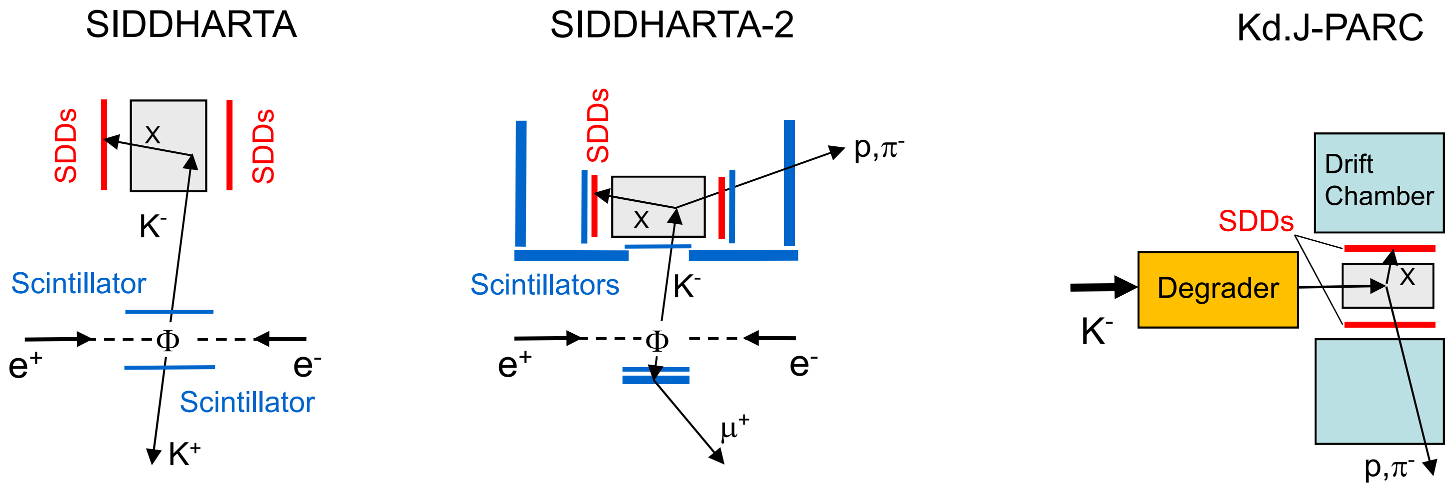
SIDDHARTA results

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 experiments



SIDDHARTA-2 at DAFNE

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

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)

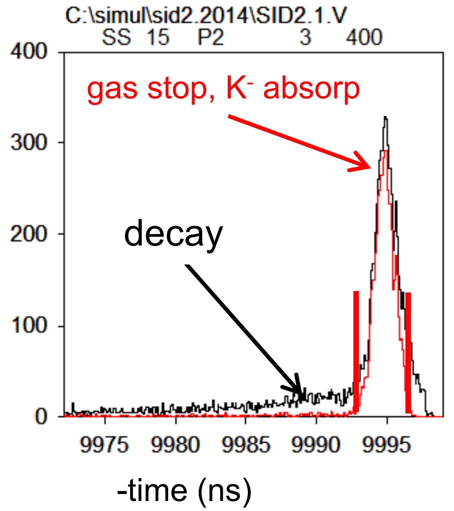
added surrounding ***scintillators:***
„active shielding“, anticoincidence during SDDs time window (~500 ns), except
coincidence during „gas-stop-time (~ 5 ns, K^- absorption secondaries) , not „behind X ray hit“

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

SIDDHARTA-2 at DAFNE: background reduction (Monte Carlo study)

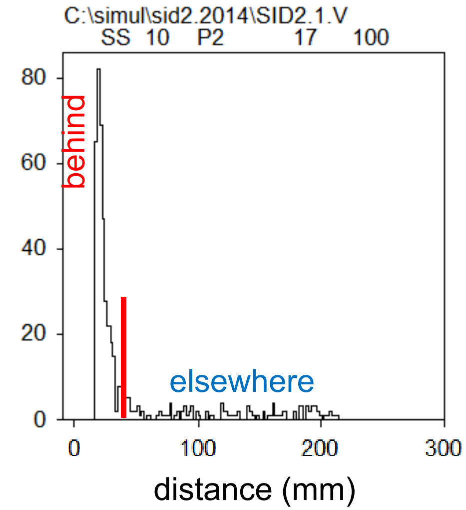
arrival times of MIPS at the vertical scintillators
timeresolution of each det.: 0.5 ns FWHM

gas-stop
timing

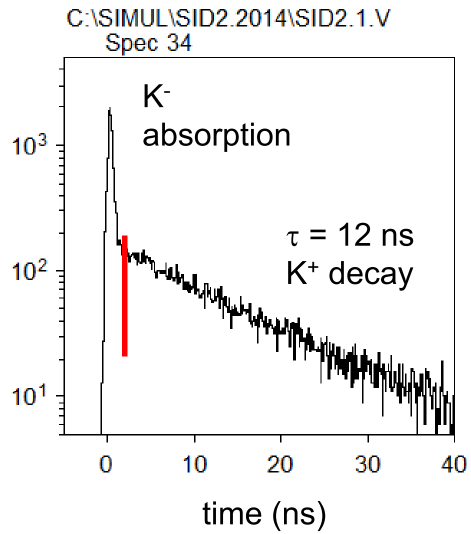


topological correlation of low energy signals.
distance SDD to MIPS-veto counter

MIPS-veto



K^+ livetime



time correlation between lower triggerscintillator
and last hit on kaonstopper
timeresolution of each detector: 0.5 ns FWHM

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

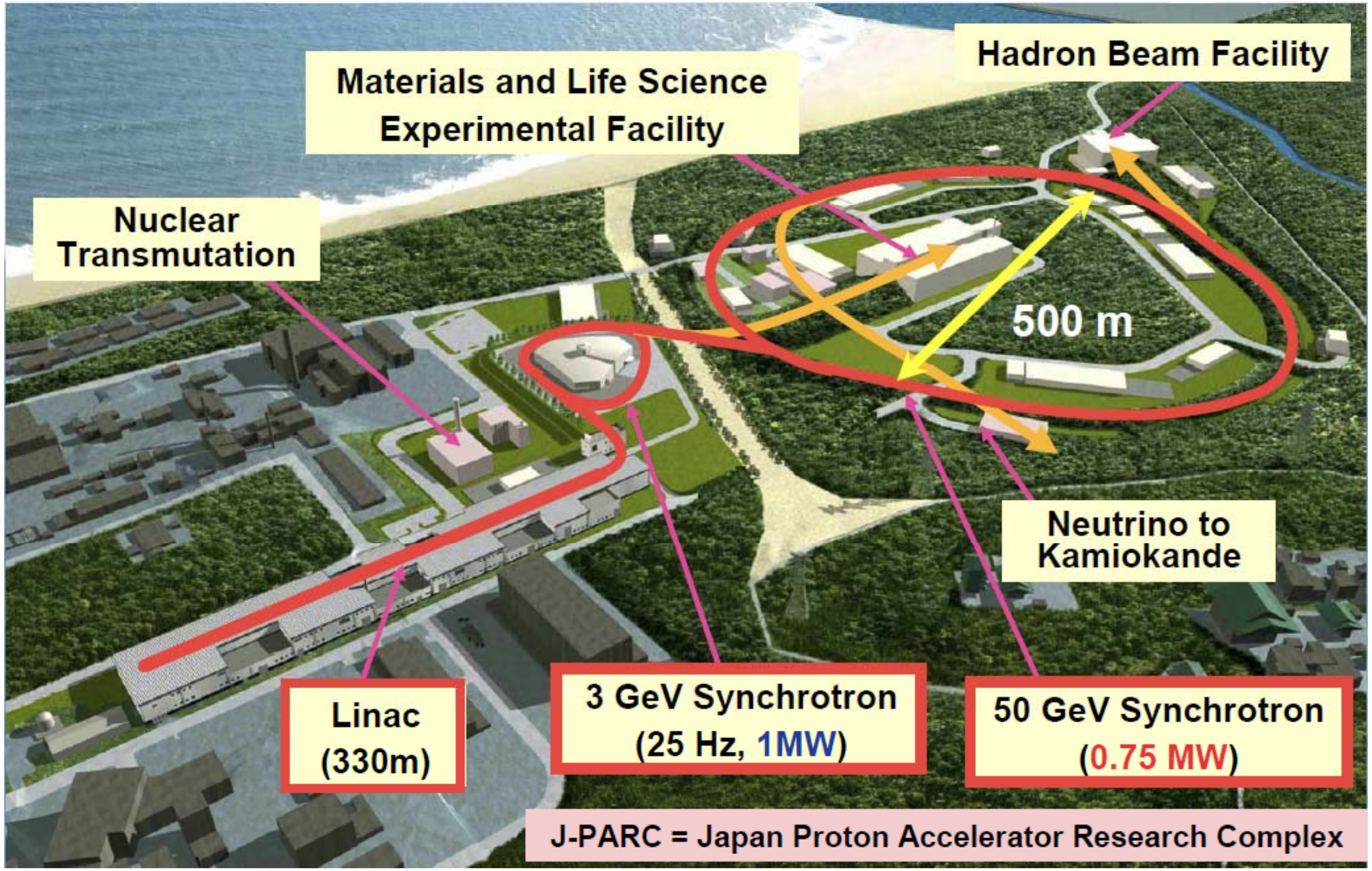
high energy kaons
>90% lost in degrader, wide energy range at entering target
in the target: absorption in flight relevant

tracking
fiducial volume cut

feasibility study, *proposal submitted*

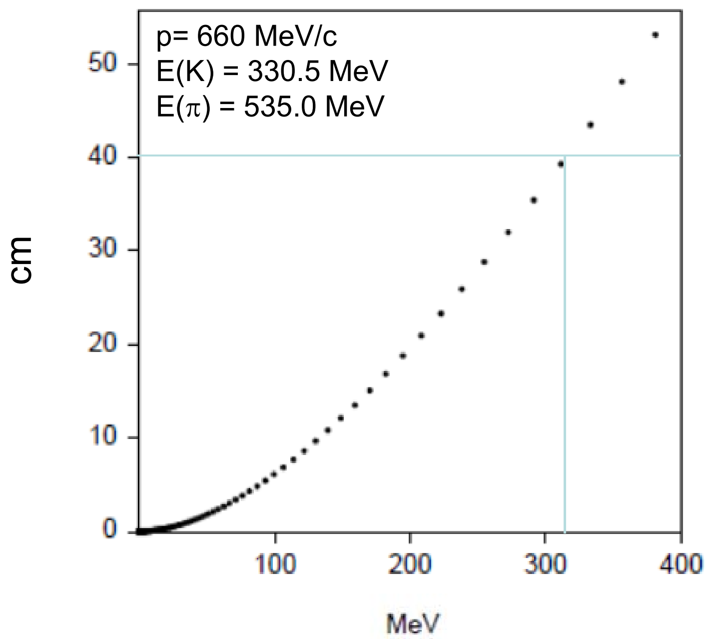
J-PARC

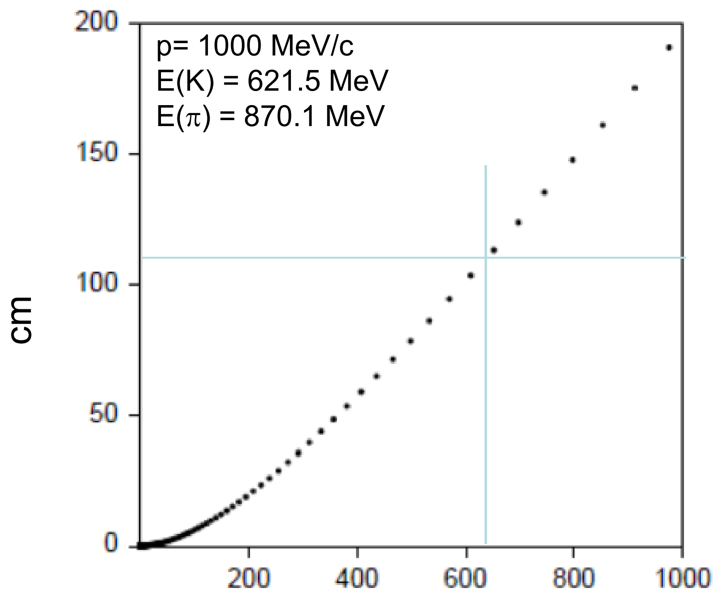
Located in Tokai, Ibaraki,



from the talk of Masaharu Sato (E17 collaboration) given at ECT* Trento 2012:

K^- mean range in carbon (from GEANT tables):





J-PARC K1.8BR beamline
Beam-spot:

PTEP
Prog. Theor. Exp. Phys. 2012, 02B009 (16 pages)
DOI: 10.1093/ptep/pts038

Secondary charged beam lines at the J-PARC hadron experimental hall

Keizo Agari[1], Shun Enomoto[2], Hiroyuki Fujioka[3], Yuya Fujiwara[4], Tadashi Hashimoto[4], Ryugo S. Hayano[4], Toshihiko Hiraiwa[3], Erina Hirose[1], Masaharu Ieiri[1], Youichi Igarashi[1], Masami Iio[1], Jun Imazato[1], Kentaro Inoue[2], Yosuke Ishiguro[3], Kenta Itahashi[5], Masahiko Iwasaki[5,6], Yohji Katoh[1], Shingo Kawasaki[2], Akio Kiyomichi[7], Hiroshi Kou[6], Michifumi Minakawa[1], Ryotaro Muto[1], Tomofumi Nagae[3], Megumi Naruki[1], Hiroyuki Noumi[8], Hiroaki Ohnishi[5], Haruhiko Outa[5], Yuta Sada[3], Fuminori Sakuma[5], Masaharu Sato[4], Yoshinori Sato[1], Shin'ya Sawada[1], Hexi Shi[4], Yoshihisa Shirakabe[1], Yoshihiro Suzuki[1], Hitoshi Takahashi[1], Toshiyuki Takahashi[1], Minoru Takasaki[1], Kazuhiro H. Tanaka[1], Makoto Tokuda[6], Akihisa Toyoda[1], Kyo Tsukada[9], Mifuyu Ukai[9], Hiroaki Watanabe[1], Takeshi O. Yamamoto[9], and Yutaka Yamanoi[1]

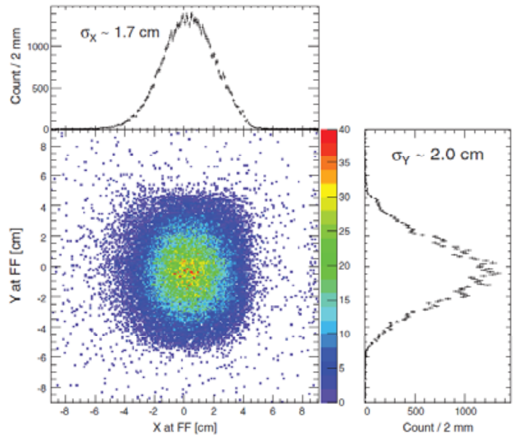
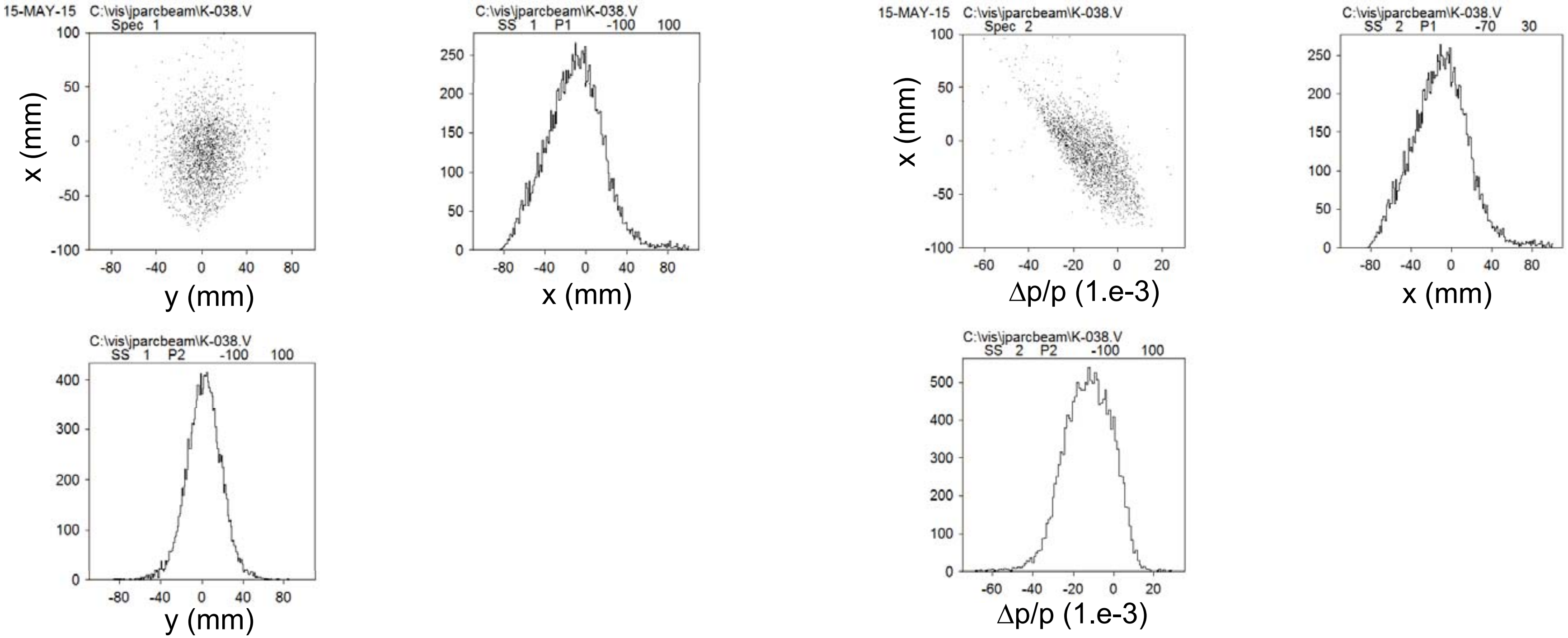


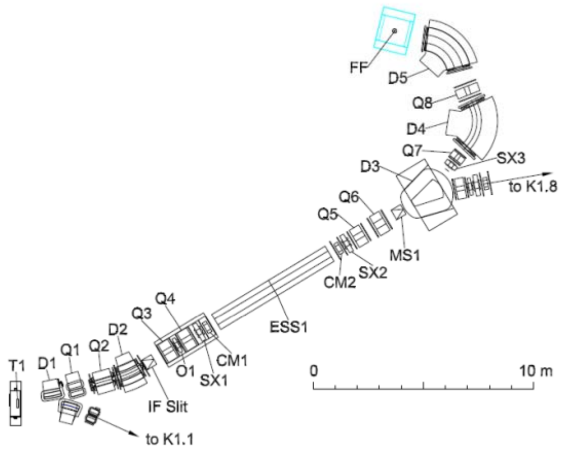
Fig. 11. Beam profile at the final focus point reconstructed by the wire drift chamber.

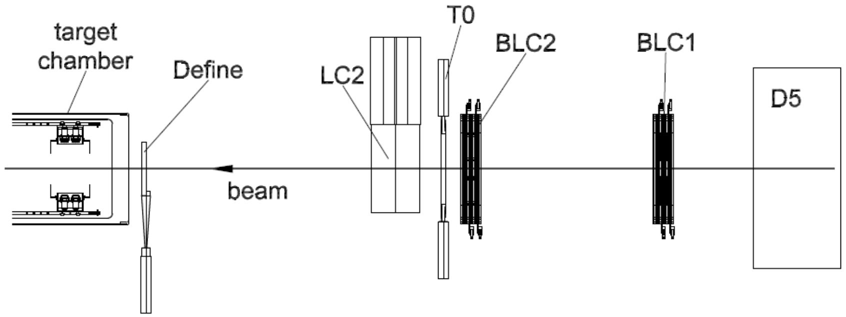
Beamprofile data from a recent measurement at K1.8BR:

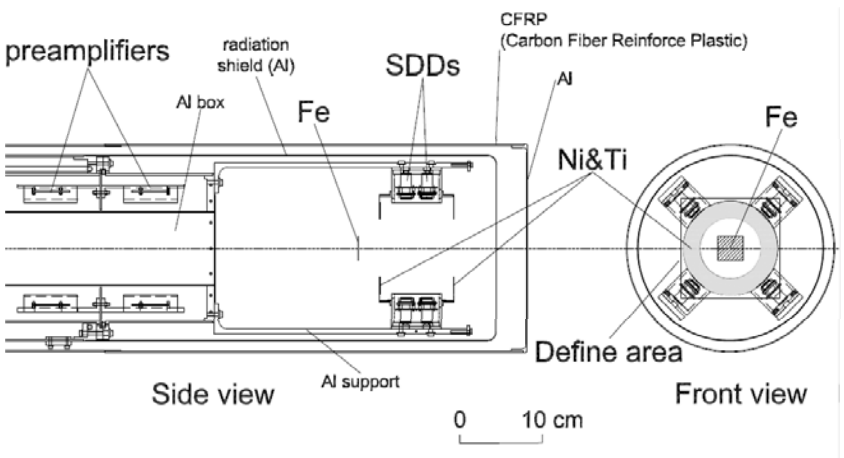


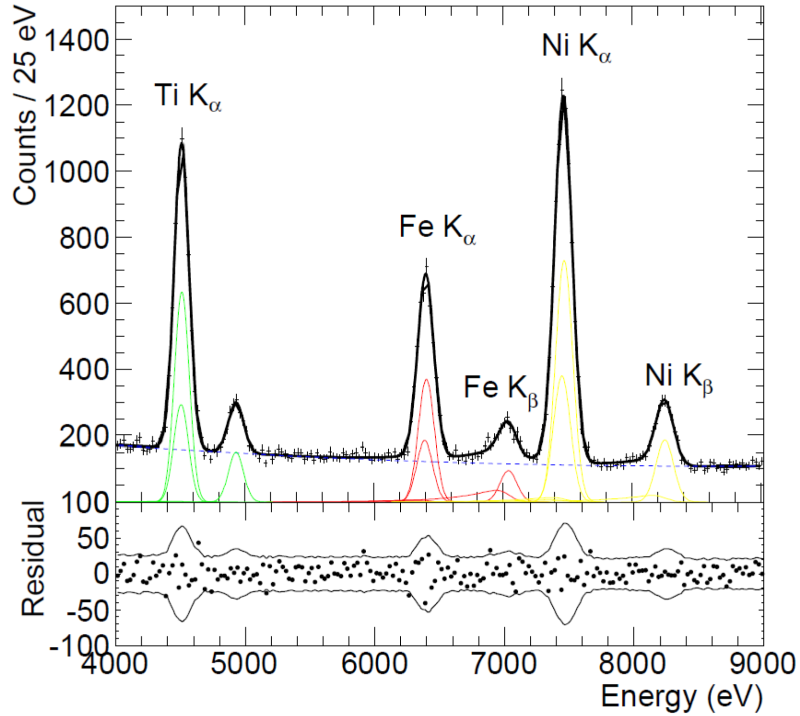
Measurements at K1.8BR at 0.9 GeV/c,
no degrader, no target, 8 cm^2 SDDs

From the thesis of T. Hashimoto, 2011



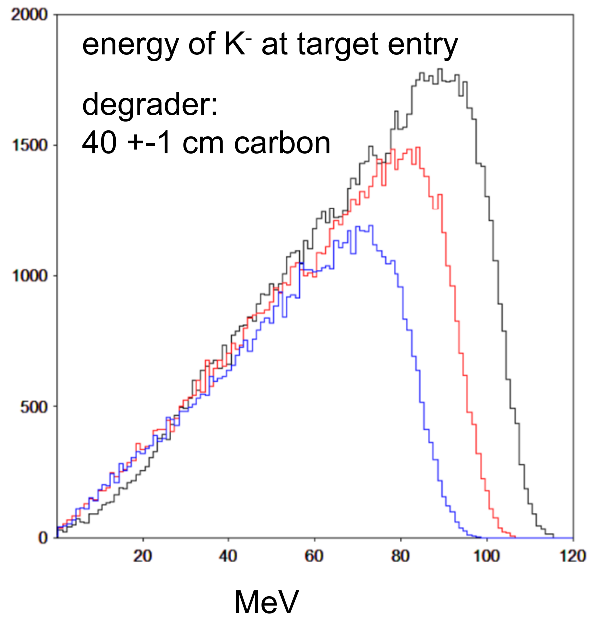


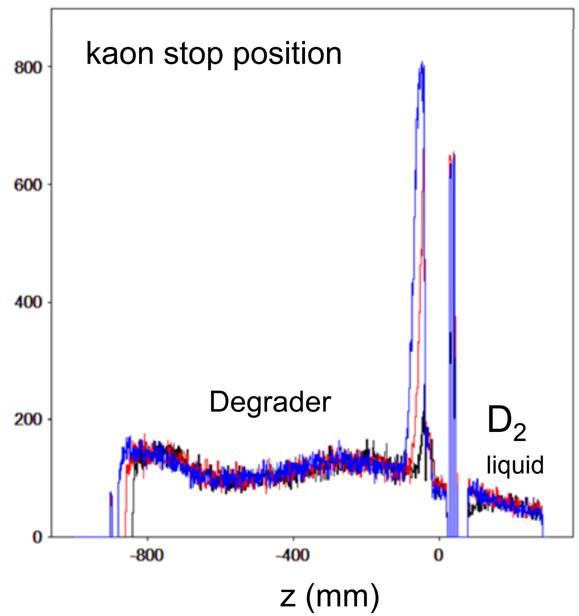


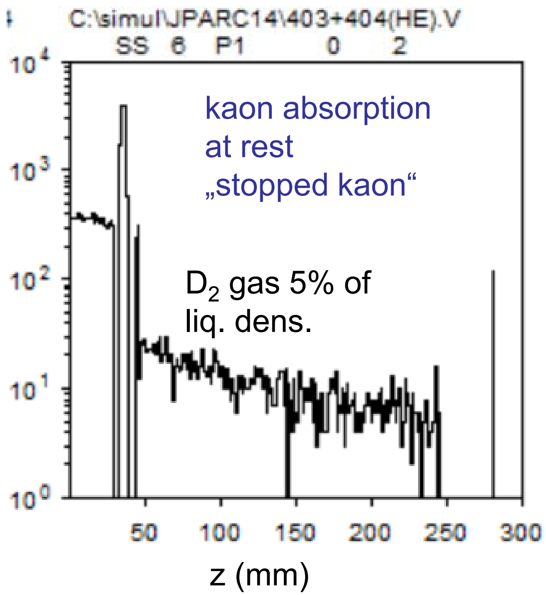


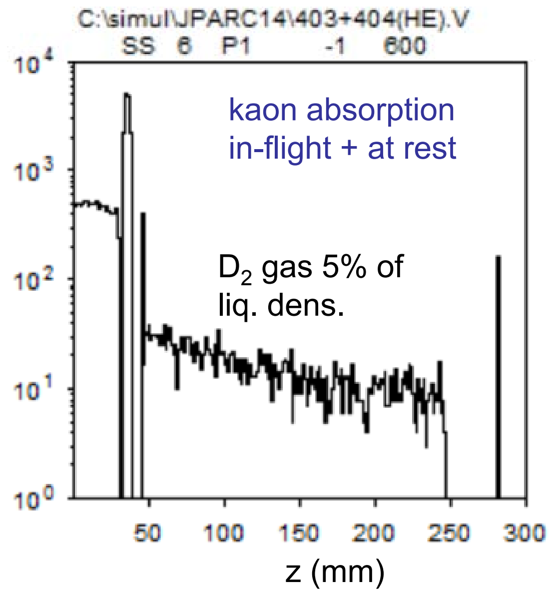
The background derived from this fig.
is approx. **1.7e-6** /keV /cm^2 /K,π

Simulation of kaon stopping,   degrader optimization









Background sources

decay in flight: $\mu^- \nu$ 63.5%, $\pi^- \pi^0$ 21.2 %, $\pi^- \pi^+ \pi^-$ 5.6%, $\pi^0 e^- \nu$ 4.8%
absorption: in flight or at rest

1-nucleon absorption
total probability = (1 – w2N)

$K^- N$ reaction	Subsequent decay mode	Finally produced particles	ratio (%)
$\Sigma^+ \pi^-$	$\Sigma^+ \rightarrow \pi^0 p$; $\pi^0 \rightarrow 2\gamma$	$\pi^- 2\gamma p$	11.1
	$\Sigma^+ \rightarrow \pi^+ n$	$\pi^- \pi^+ n$	11.1
$\Sigma^- \pi^+$	$\Sigma^- \rightarrow \pi^- n$	$\pi^- \pi^+ n$	10.0
$\Sigma^0 \pi^0$	$\Sigma^0 \rightarrow \Lambda \gamma$; $\Lambda \rightarrow \pi^- p$	$\pi^- 3\gamma p$	7.6
	$\Sigma^0 \rightarrow \Lambda \gamma$; $\Lambda \rightarrow \pi^0 n$; $\pi^0 \rightarrow 2\gamma$	$5\gamma n$	7.6
$\Lambda \pi^-$	$\Lambda \rightarrow \pi^- p$	**$2\pi^-$ p**	14.2
	$\Lambda \rightarrow \pi^0 n$; $\pi^0 \rightarrow 2\gamma$	$\pi^- 2\gamma n$	14.2
$\Sigma^0 \pi^-$	$\Sigma^0 \rightarrow \Lambda \gamma$; $\Lambda \rightarrow \pi^- p$	$2\pi^- \gamma p$	5.4
	$\Sigma^0 \rightarrow \Lambda \gamma$; $\Lambda \rightarrow \pi^0 n$	$\pi^- 2\gamma n$	5.4
$\Sigma^- \pi^0$	$\Sigma^- \rightarrow \pi^- n$	$\pi^- 2\gamma n$	10.8

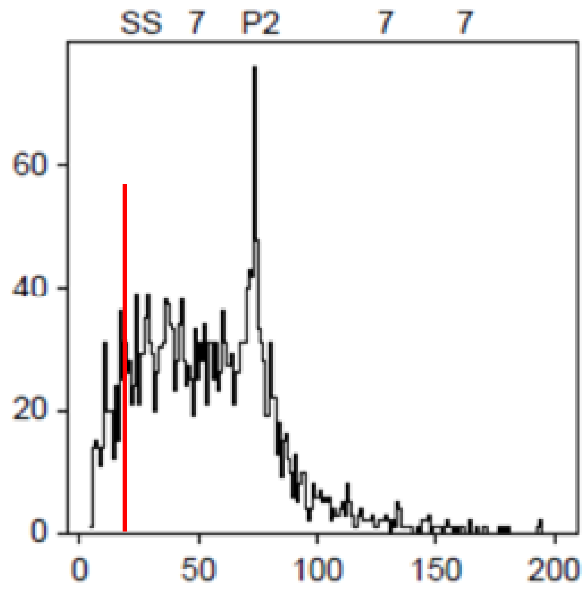
2-nucleon absorption:
total probability = w2N

$K^- d$ reaction products	Subsequent decay modes	Finally produced particles
$\Sigma^+ \pi^- n$	$\Sigma^+ \rightarrow \pi^0 p$; $\pi^0 \rightarrow 2\gamma$	$\pi^- 2\gamma p n$
	$\Sigma^+ \rightarrow \pi^+ n$	$\pi^- \pi^+ n n$
$\Sigma^- \pi^+ n$	$\Sigma^- \rightarrow \pi^- n$	$\pi^- \pi^+ n n$
$\Sigma^0 \pi^0 n$	$\Sigma^0 \rightarrow \Lambda \gamma$; $\Lambda \rightarrow \pi^- p$	$\pi^- 3\gamma p n$
	$\Lambda \rightarrow \pi^0 n$; $\pi^0 \rightarrow 2\gamma$	$5\gamma n n$
$\Lambda \pi^- p$	$\Lambda \rightarrow \pi^- p$	**$2\pi^-$ p p**
	$\Lambda \rightarrow \pi^0 n$; $\pi^0 \rightarrow 2\gamma$	$\pi^- 2\gamma n p$
$\Sigma^0 \pi^- p$	$\Sigma^0 \rightarrow \Lambda \gamma$; $\Lambda \rightarrow \pi^- p$	$2\pi^- \gamma p p$
	$\Lambda \rightarrow \pi^0 n$	$\pi^- 2\gamma n p$
$\Sigma^- \pi^0 p$	$\Sigma^- \rightarrow \pi^- n$; $\pi^0 \rightarrow 2\gamma$	$\pi^- 2\gamma n p$
Y* N		
$\Lambda^* n$	$\Lambda^* \rightarrow \Sigma^+ \pi^-$ $\Sigma^+ \rightarrow \pi^+ n$ $\Sigma^+ \rightarrow \pi^0 p$ $\pi^0 \rightarrow 2\gamma$ $\Lambda^* \rightarrow \Sigma^- \pi^+$ $\Sigma^- \rightarrow \pi^- n$ $\Lambda^* \rightarrow \Sigma^0 \pi^0$ $\Sigma^0 \rightarrow \Lambda \gamma$ $\Lambda \rightarrow \pi^- p$ $\Lambda \rightarrow \pi^0 n$	$\pi^- \pi^+ n n$ $\pi^- 2\gamma p n$ $\pi^- \pi^+ n n$ $\pi^- 3\gamma p n$ $5\gamma n n$

„vanishing kaon“:
Vertex from K^- × 1 outgoing charged

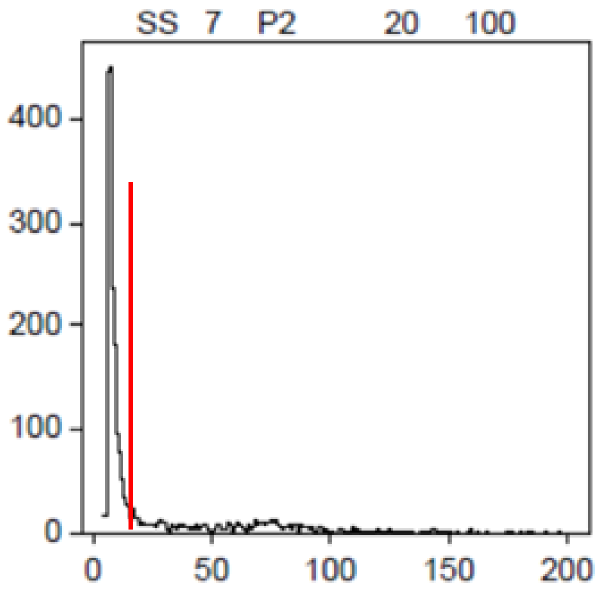
Correlation of dE in SDDs vs. distance of SDDposition from mips track

signal (at 7 keV)



distance to mips track (mm)

background in ROI



distance to mips track (mm)

Proposed Kd experiment at J-PARC

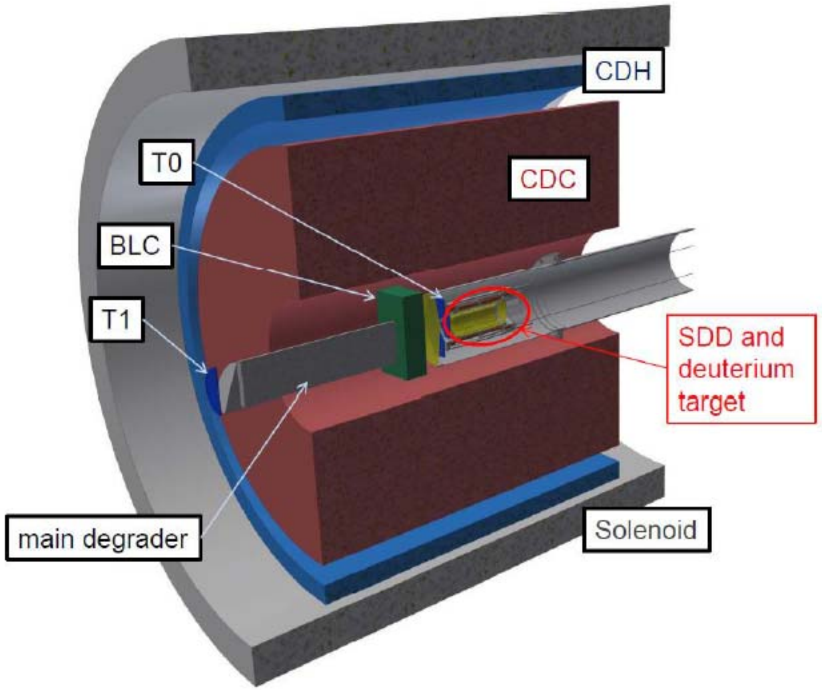


Figure 8: Sketch of the proposed setup for the kaonic deuterium measurement

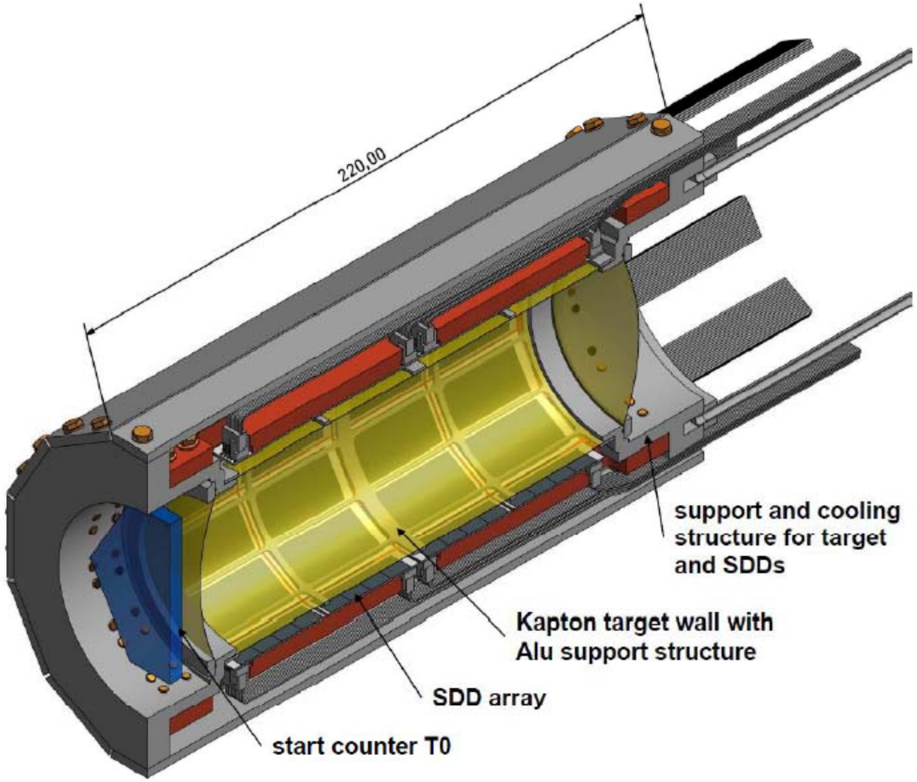
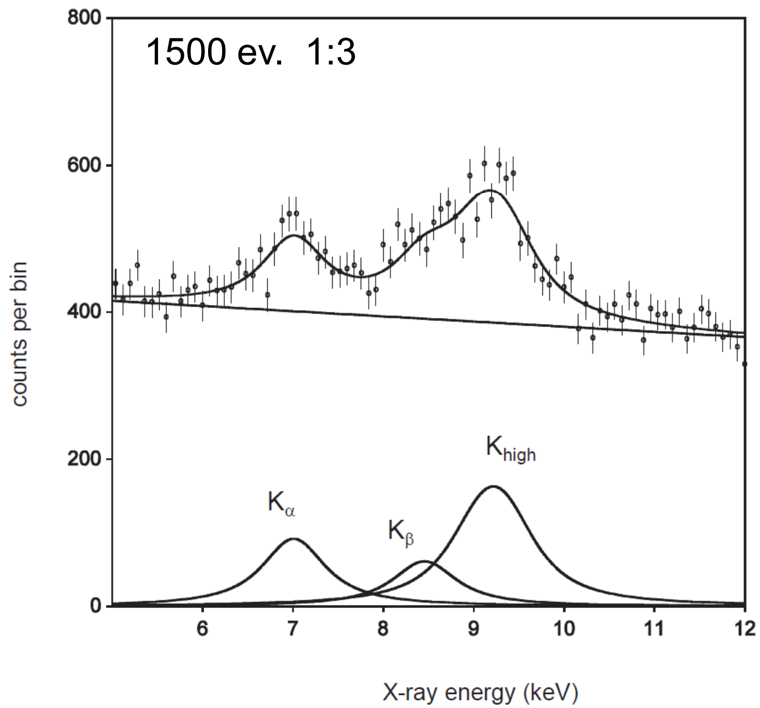


Figure 11: Design of the cryogenic target and X-ray detector system. The target cell, with a diameter of 65 mm and a length of 160 mm, is closely surrounded by SDDs, about 5 mm away from the target wall.

Achievable precision

events kaonic deuterium $K\alpha$	S/B	precision of shift result (eV)	precision of width result (eV)	experiment $600\ pb^{-1}$ at DAFNE resp. 100 shifts with 30 kW p-beam at J-PARC
1500	1 : 3	47	123	DAFNE
3000	1 : 3	32	83	DAFNE, new SDDs
1500	**1 : 5**	**70**	**160**	**J-PARC, new SDDs**
2000	10 : 3	12	24	DAFNE hydrogen (few days)



test spectrum with relative yield distribution similar to kaonic hydrogen. $y(K\alpha) = 1.e{-3}$
Fit with free intensities, parametrized K_{high} shape

sum(signal) / sum(bg in FWHM of signal) e.g. 1:5
ampl.(signal) / bg-level => 1:7

Summary and Outlook

SIDDHARTA: 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: SIDDHARTA-2 with improved technique to measure Kd shift and width. Preparations well under way. *Timescale at DAFNE still unclear (**might be as late as 2018**)*

Kd experiment at J-PARC: Monte Carlo studies, developmet of experimental setup, **proposal submitted** (100 shifts at 30 kW p-beam, beamtime 2016/17?)

New possibilities due to microcalorimeter detectors with few eV resolution at 6 keV, Proposal for J-PARC

HadronPhysics

HadronPhysics2 Study of Strongly Interacting Matter

LEANNIS

FWF

at SIDDHARTA-2 meeting Sept 11, 2014