Kaonic deuterium X-ray experiments - SIDDHARTA and plans for LNF and J-PARC

Michael Cargnelli, SMI

Advanced studies in the low-energy QCD in the strangeness sector
and possible implications in astrophysics
Dedicated to the memory of Paul Kienle
19-21 June 2013, LNF-INFN

SIDDHARTA-2 at DAFNE

with 10 pb^{-1} per day

1.5e6 $K^{\pm}$ per pb^{-1}
=> 1.5e7 $K^{\pm}$ per day ~ isotropically
p = 127 MeV/c E= 16 MeV

Target stops: ~ 2 % per kaonpair (gas)
due to solid angle. Intrinsic ~ 100%

SDDs: 144 cm^2 existing from SIDDHARTA
active/module = 6 / 27.5 = 0.22

low energy kaons
no tracking

preparation in advanced status

SIDDHARTA-2J at J-PARC

at 30 kW beam power

40e7 kaons per day
p = 660 MeV/c E= 331 MeV

430e7 kaons per day
p = 1000 MeV/c E= 535 MeV

Target stops:
~ 1 % per kaon (660 MeV/c, liquid)
~ 0.03 % per kaon (660 MeV/c, gas)
~ 0.046 % per kaon (1000 MeV/c liquid)

SDDs: 342 cm^2 new devices from Milano
active/module = 9x0.8x0.8 / 3x3 = 0.64

high energy kaons
tracking

feasibility study, planned letter of intent to J-PARC

KEK E570: KHe Lα line: after fiducial volume cut: signal/backgr ~ 25 : 1 (hadronic+beam backgr.)

yield in liq. He ~ 10 % yield Kα in D2 gas ~ 0.1 %

... 0.25 : 1 = 1 : 4

FWHM ~ 200 eV FWHM ~ 800 eV => 1: 16

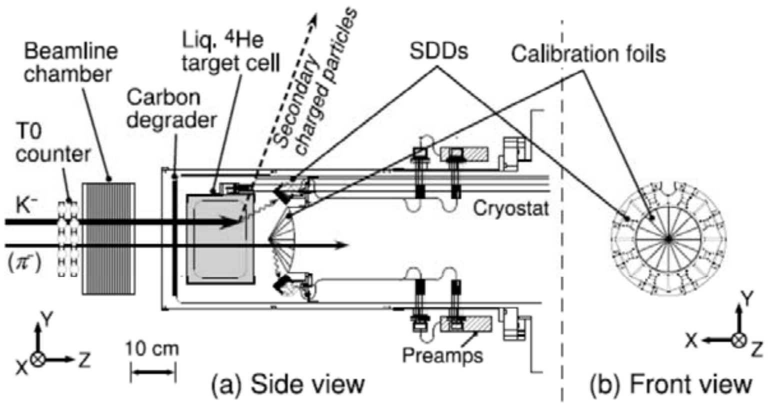


Figure 1: (a) A schematic side view of the E570 setup around the cylindrical target with the x-ray detection system. (b) A front view of the silicon drift detector (SDD) assembly. Eight SDDs are mounted on holders tilted at a 45 degree angle to the beam center in an annular-shaped pattern. Fan-shaped high-purity titanium and nickel foils are put alternately on a cone-shaped support located on the beam axis.

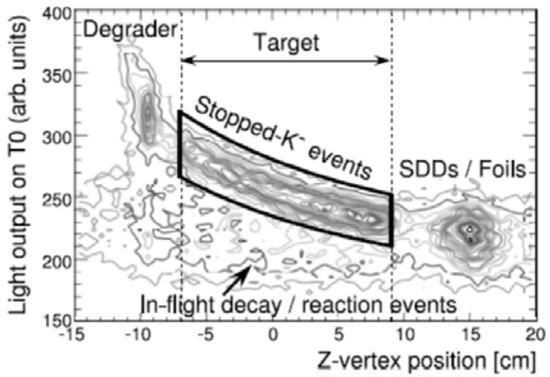


Figure 2: A typical density plot between the z-coordinate of the reaction vertex and the light output on T0, used to reject in-flight kaon decay/reaction events.

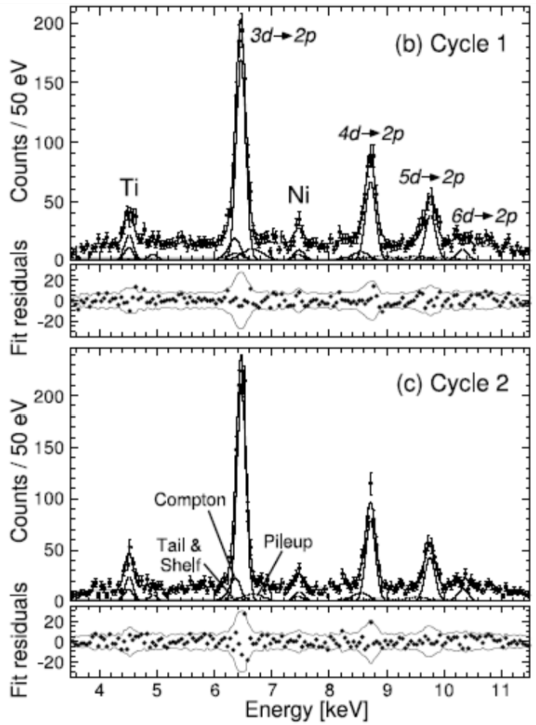


Figure 3: (a) A typical x-ray spectrum for self-triggered events which provides high-statistics energy-calibration information. (b)(c) Measured x-ray spectra for stopped-K^- events obtained from the runs in October 2005 (cycle 1) and December 2005 (cycle 2) respectively. A fit line is also shown for each spectrum, along with individual functions of the fit. The fit residuals are shown under each spectrum, with thin lines denoting the $\pm 2\sigma$ values of the data, where σ is the standard deviation due to the counting statistics.

KpX: PRL 78(16)3067 1997, Phys. Rev. C 58, 2366 (1998)
beam: 600 MeV/c, X-ray detectors: 45 (60) SiLi with 200 mm^2 each => 90 cm^2 total

hydrogen at 1.32 % LHD „two-charged-pion-tag" $K^-\pi \Rightarrow \Sigma^\pm \pi^{-+}$ $\Sigma^\pm \Rightarrow n\, \pi^\pm$
Kp $K\alpha$ line: after fiducial volume cut: signal/backgr ~ 1 : 1 (hadronic+beam backgr.)
yield in H2 gas ~ 1 % yield in D2 gas ~ 0.1 %
FWHM ~ 500 eV FWHM ~ 1000 eV => 1: 20

The average kaon intensity and the *K/π* ratio, both after the carbon degrader, were 8000 per spill and 1/90,respectively. The spill duration was 2 s and the repetition rate was 1 spill per 4 s.

=> 2 kHz after degrader, ~ 20 kHz before degrader (4 times higher than JPARC near future expectation !)

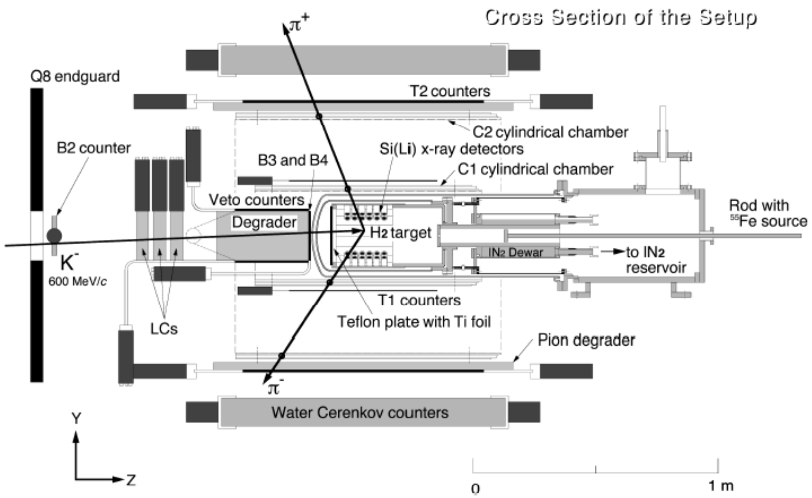


FIG. 1. Experimental apparatus (cross section). Negative kaons of 600 MeV/*c* were slowed down in the carbon degrader and brought to rest in the hydrogen gas target, forming kaonic hydrogen atoms. The timing of the incoming beam was determined by the B2 counter. Three Lucite Čerenkov counters served for *K/π* separation. X rays from kaonic hydrogen atoms were detected with the Si(Li) x-ray detectors placed in the hydrogen volume. The two layers of scintillation counter arrays (T1 and T2), the two cylindrical MWPCs (C1 and C2), and the water Čerenkov counter array surrounding the target served to detect two charged pions from K^-p absorption to select appropriate events.

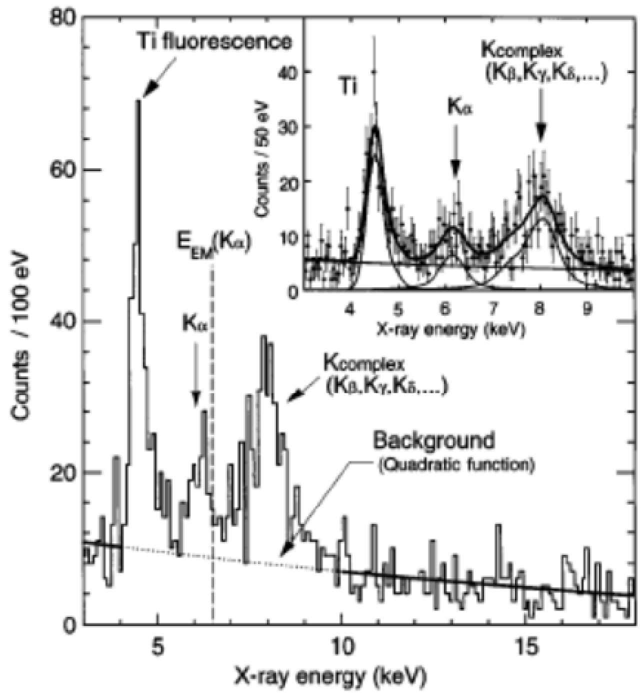


FIG. 3. Kaonic hydrogen x-ray spectrum. The inset shows the result of peak fitting and the components.

Expected shift and width

Compilation of predicted K^- d scattering lengths a_d and corresponding experimental values ε_{1s} and Γ_{1s} calculated from eq. 1. (see below), except for [5] where the shift and width are given in the paper explicitly (They differ slightly for "one-pole" and "two-pole" structure of Λ(1405) an averaged value is inserted in this table).

a_d [fm]	ε_{1s} [eV]	Γ_{1s} [eV]	Reference
-1.58 + *i* 1.37	- 887	757	Mizutani 2013 [4]
-1.48 + *i* 1.22	- 787	1011	Shevchenko 2012 [5]
-1.46 + *i* 1.08	- 779	650	Meißner 2011 [1]
-1.42 + *i* 1.09	- 769	674	Gal 2007 [6]
-1.66 + *i* 1.28	- 884	665	Meißner 2006 [7]

=>
shift = 800
width = 800
used in simulation

Modified Deser formula next-to-leading order in isospin breaking (Meißner, Raha, Rusetsky 2004 [3])
(μ_c reduced mass of K^-d, α finestructure constant)

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

[1] M. Döring, U.-G. Meißner, Phys. Lett. B 704 (2011) 663.
[3] U.-G. Meißner, U.Raha, A.Rusetsky, Eur. phys. J. C35 (2004) 349.
[4] T. Mizutani, C. Fayard, B. Saghai, K. Tsushima, arXiv:1211.5824[hep-ph] (2013).
[5] N.V. Shevchenko, Nucl. Phys. A 890-891 (2012) 50-61.
[6] A. Gal, Int. J. Mod. Phys. A22 (2007) 226
[7] U.-G. Meißner, U. Raha, A. Rusetsky, Eur. phys. J. C47 (2006) 473

Estimated signal rate   Kd-jparc

EFFICIENCY FOR 346 CM^2 AREA SDDs   (10 x 6 modules of 9 x 0.64 cm^2 each => 346 cm^2) situated at diameter= 9.2 cm.

Target cell: windowless, diameter= 9.2 cm, length= 20 cm   Or: with windows, diameter = 8 cm

The simulations starts with 660 MeV/c kaons (E_k = 330.6 MeV) with momentum bite as measured. Kaons and pions are degraded in a carbon block, pass plastic scintillators and enter the target. The kaons decay, can be absorbed in flight or be stopped and then absorbed. If stopped, a 7.0 keV X-ray is generated with yield 100%. The X ray attenuation in the deuterium and in the 75 μm Mylar exit window is calculated at tracking.

Efficiency per beam kaon, applying a longitudunal fiducial-volume-cut: dE * z-vertex zvertex from kaontrack * piontrack

660 MeV/c, ρ = 0.05 liq.dens ε = $\mathbf{0.2\times10^{-3}}$ × Kd-X-yield × efficiency-of-tagging

660 MeV/c, ρ = liq. dens ε = $\mathbf{4.0\times10^{-3}}$ × Kd-X-yield × efficiency-of-tagging

1000 MeV/c, ρ = liq. dens ε = $\mathbf{0.13\times10^{-3}}$ × Kd-X-yield × efficiency-of-tagging

EXPECTED BEAM

From „Sakuma: The K1.8BR spectrometer system at J-PARC": the intensity of the 1.0 GeV/c K- beam is expected to be 2e6 per spill (6 seconds repetition) .... at 270 kW (30 GeV, 9 microA proton beam)

Jan 2013: 1 kW proton beam „1e4 per pulse" 6s extrapolated by the authors to 2.7e5 at 27 kW (=> 0.5e5 Hz)

Tatsuno using the Sanford/Wang formula: „In the near future, about 30kW power will be available, then the intensity will also increase 240k/spill @1.0GeV/c. So, the expected K- intensity will be 30k/spill @660MeV/c with opening slits. This means **5k Hz kaons** (0.4G kaons per day) are available."

660 MeV/c .... 0.4×10^9 kaons per day

1000 MeV/c .... 4.3×10^9 kaons per day

Kd K_α yield: $Y_{gas} = 10^{-3}$ $Y_{liq} = 10^{-4}$

tracking efficiency ε_{tr} **= 0.7**

660 MeV/c, ρ = 0.05   R = $0.4 \times10^9 \times 0.2 \times10^{-3} \times 10^{-3} \times 0.7$ = 66 events per day   1780 per month

660 MeV/c, ρ = 1   R = $0.4 \times10^9 \times 4.0 \times10^{-3} \times 10^{-4} \times 0.7$ = 112 events per day   3360 per month

1000 MeV/c, ρ = 1   R = $4.3 \times10^9 \times 0.13 \times10^{-3} \times 10^{-4} \times 0.7$ = 39 events per day   1170 per month

Note: signal intensity will depend on the cuts finally used, this depends on the background suppression techniques

obtainable precision

extraction of shift and width

Fit components representing the signal:

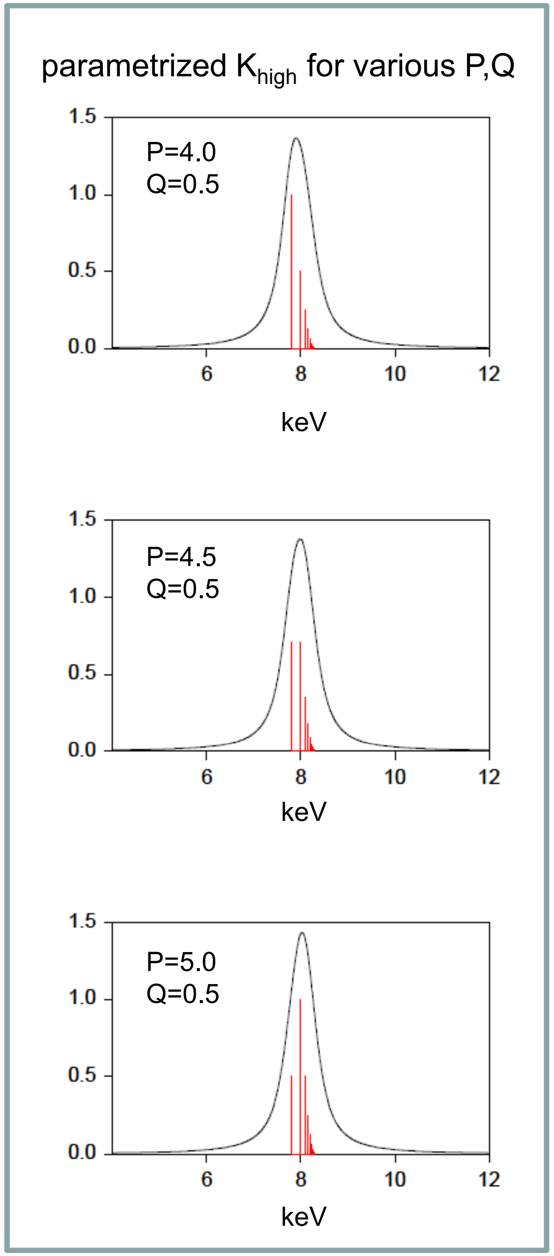
Voigt functions for K_α, K_β, K_{high}

I_{high} total intensity of K_{high}

K_{high} shape parametrisation by 2 params (P,Q)

$y(i \rightarrow 1) = Q^{\,abs(i-P)}$ $\quad i = 4,5,....$

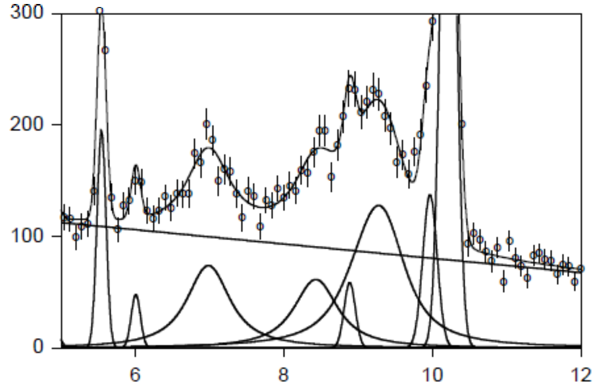
Fit parameters: $\boldsymbol{\varepsilon, \Gamma, I_\alpha, I_\beta, I_{high}, P, Q}$



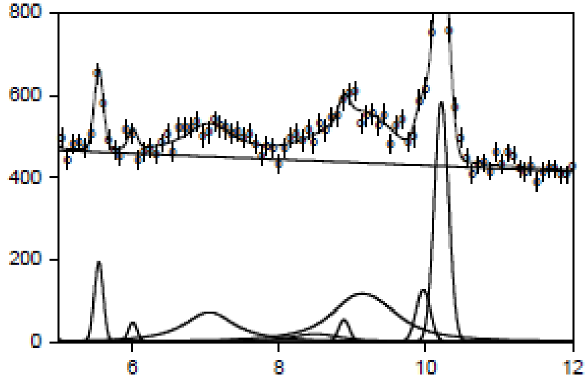
obtainable precision

deuterium,   30 days

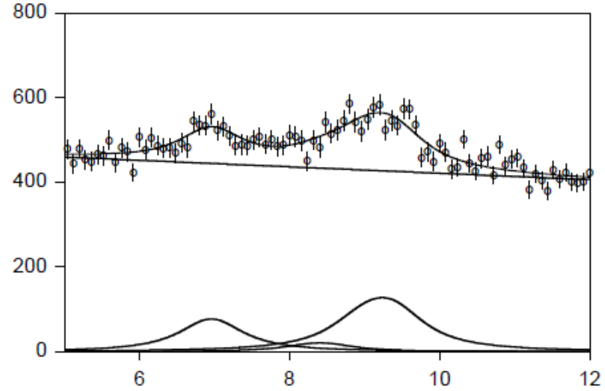
1000 ev. in Kd Ka
sigma(shift) = 30, 42, 37 => 36
sigma(width) = 79, 108, 119 => 102



1000 ev. in Kd Ka
sigma(shift) = 68, 102, 52 => 74
sigma(width) = 203, 231, 192 => 209

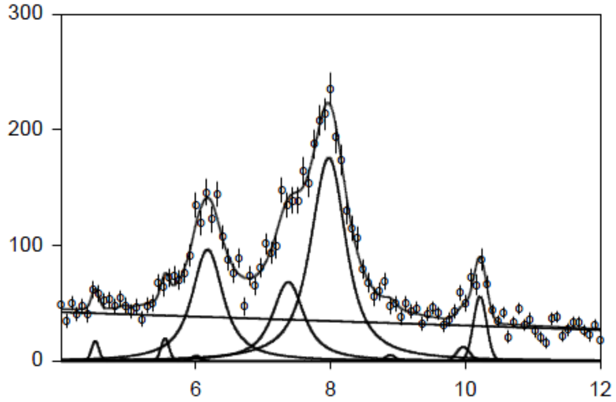


1000 ev. in Kd Ka
sigma(shift) = 71, 93, 71 => 78
sigma(width) = 227, 209, 185 => 207

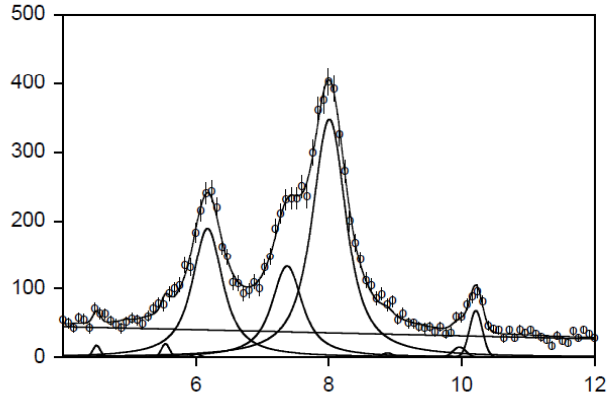


hydrogen,   3 days

1000 ev. in Kp Ka
sigma(shift) = 16, 18, 17 => 17 eV
sigma(width) = 35, 36, 37 => 36 eV



2000 ev. in Kp Ka
sigma(shift) = 10
sigma(width) = 22



Input for Monte Carlo simulation

Beam: position, momenta, directions of the incoming kaons
(cases: 660 MeV/c central value, 1.0 GeV/c, (440 MeV/c)

Degrader: dimensions, material, position relative to beamspot

(Beam telescope detectors)

(Collimator)

Target cell: dimensions, position, window materials (entry, exit, lateral or „windowless“)

Target filling: density (cases: 3% (5%) gas, liquid)

X-ray detectors (energy range: 4-400 keV possible?),

Tracking detectors for vertex reconstruction: acceptance, spatial precision

Accidental background rate, X-ray detector time resolution

J-PARC beam properties

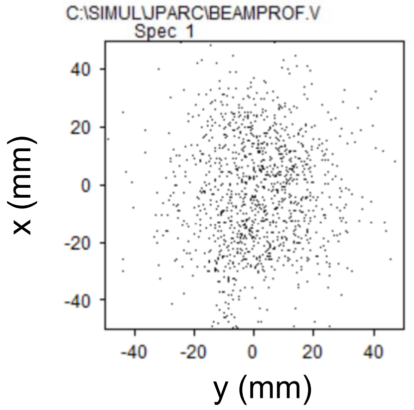
(2013/04/16 14:00), Fuminori Sakuma wrote:
Dear Ishiwatari-san,

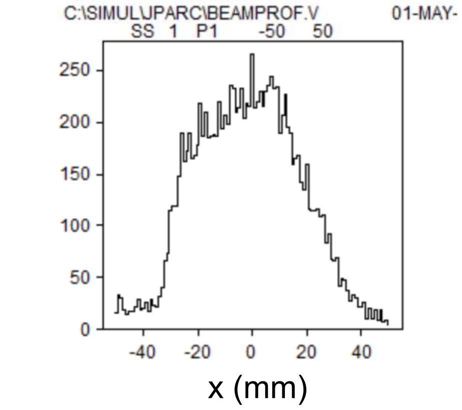
Attached please find 1.0 GeV/c K- data sample @ BLC2 (FF-130cm)
analyzed by Hashimoto-san. Details of the sample are following:

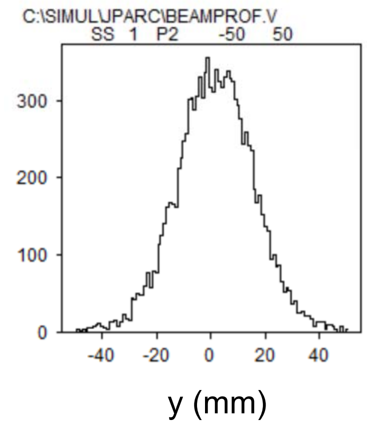
RUN#: RUN#43(2012 Jun.), run0021
condition: -1.0GeV/c, K-trigger,
kaons are selected by Time-of-Flight (BHD-TOF)
format: x[cm], dx[tan], y, dy, dp/p[%] <-- @ BLC2 (FF-130cm)

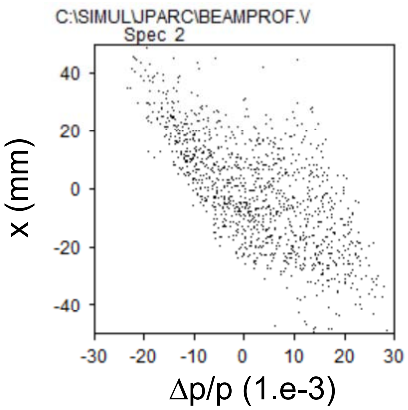
Please check the data sample. As for Q1/Q2, Hashimoto-san reported the
analysis-results in E15-meeting as an attached file (see p.6).

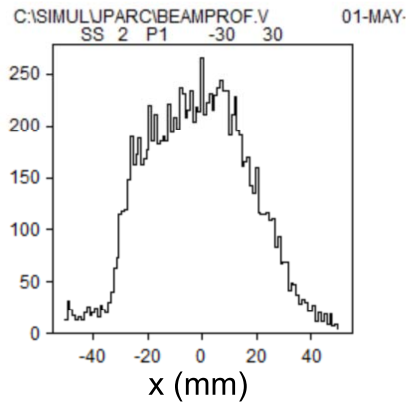
Best regards,
fuminori

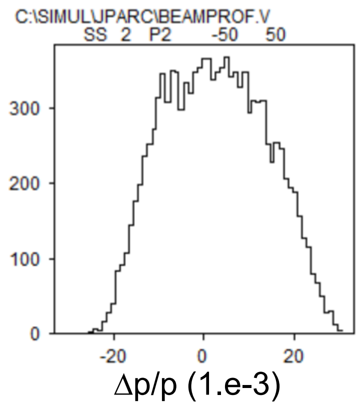


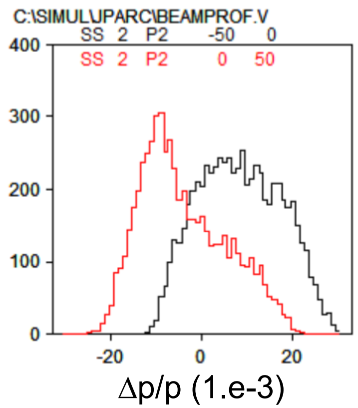






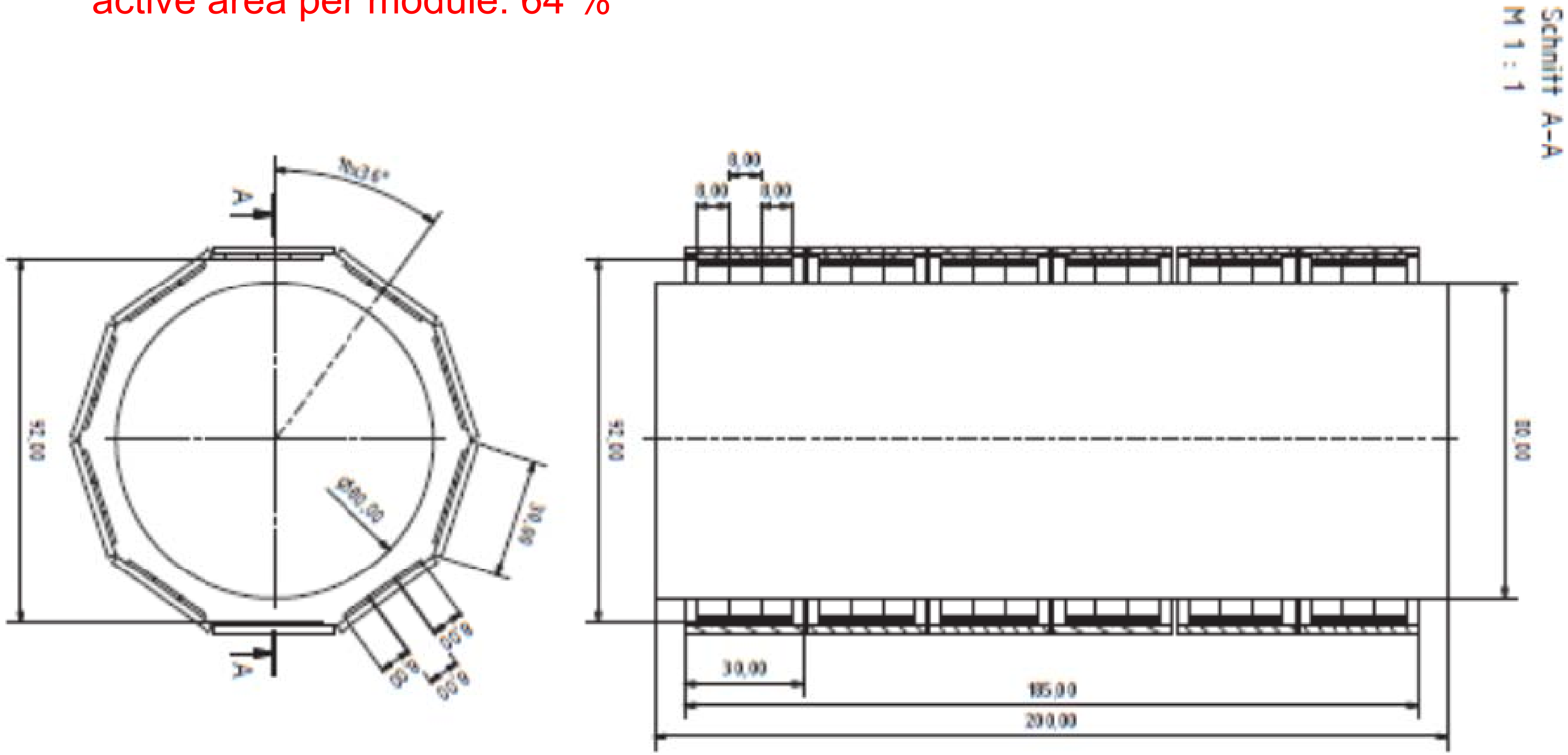




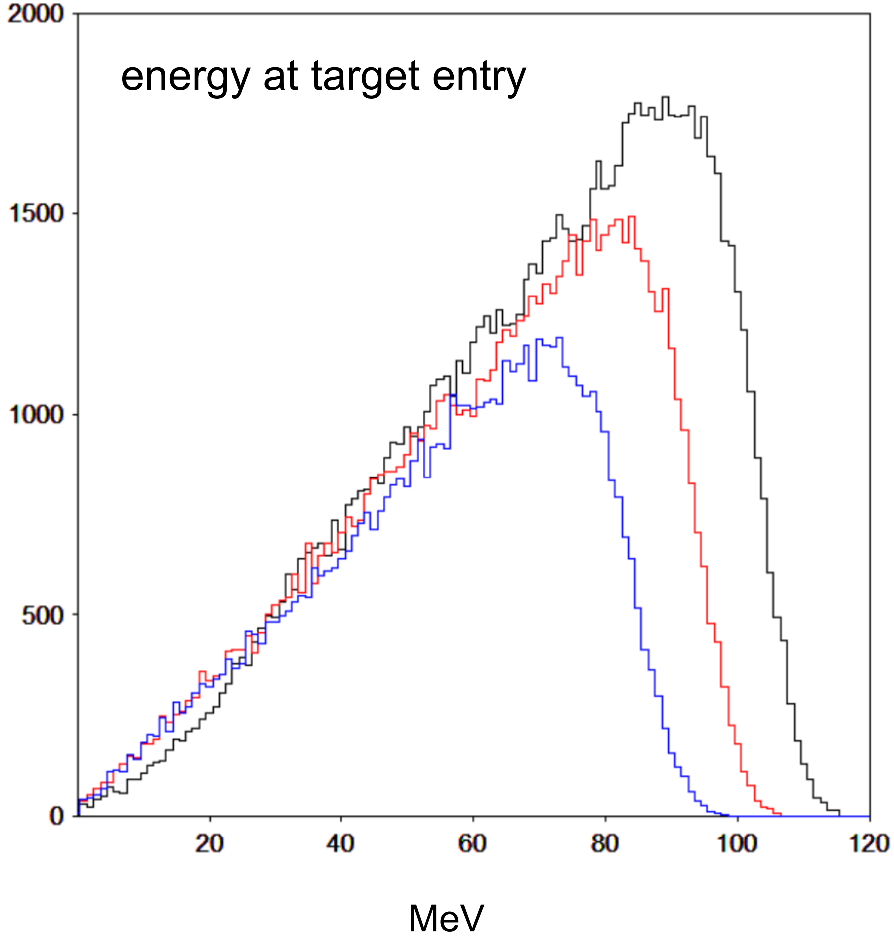


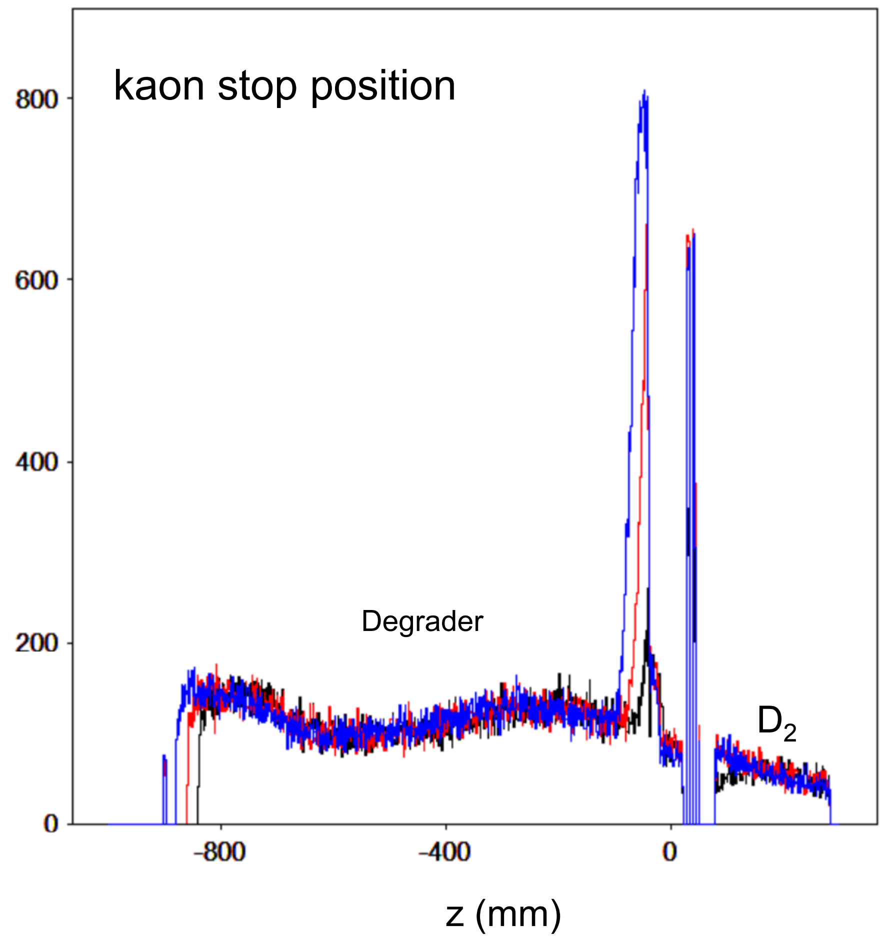
Draft for target cell + detectors   setup (SMI 2013-03)

new SDDs: 1 module consists of 9 pcs. of 0.8x0.8 cm^2
Target volume surrounded by 10 x 6 modules
$\Rightarrow$ total 345.6 cm^2 active area
active area per module: 64 %



degrader: +-1 cm carbon



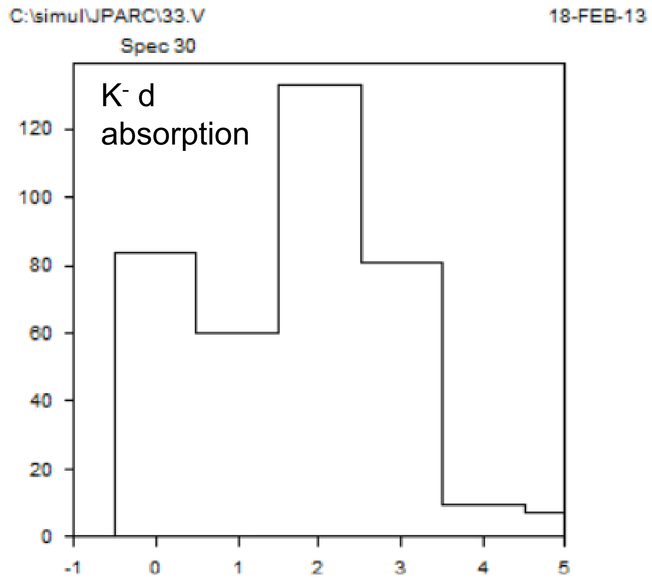


K^- absorption in deuterium

taken from GEANT4 code

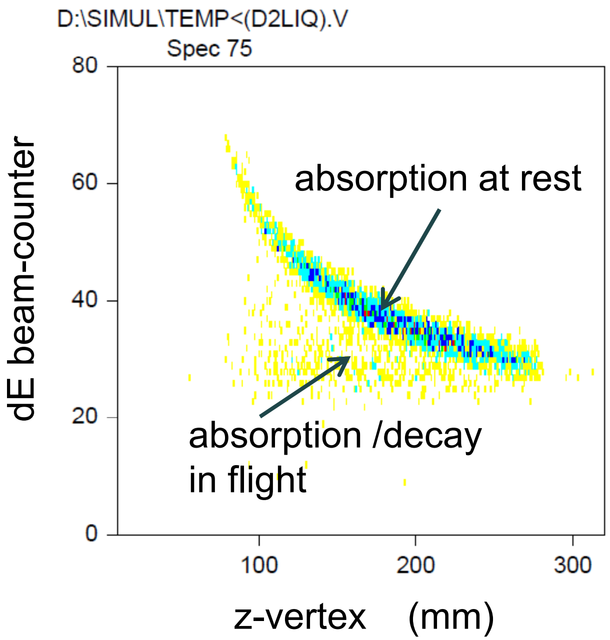
K^-N reaction products	Subsequent decay mode	Finally produced particles	Branching ratio (%)
$\Sigma^+ \pi^-$	$\Sigma^+ \rightarrow \pi^0\ p;\ \pi^0 \rightarrow 2\gamma$	$\pi^-\ 2\gamma\ p$	11.1
$\Sigma^+ \pi^-$	$\Sigma^+ \rightarrow \pi^+\ n$	$\pi^-\ \pi^+\ n$	11.1
$\Sigma^- \pi^+$	$\Sigma^- \rightarrow \pi^-\ n$	$\pi^-\ \pi^+\ n$	10.0
$\Sigma^0 \pi^0$	$\Sigma^0 \rightarrow \Lambda\ \gamma;\ \Lambda \rightarrow \pi^-\ p$	$\pi^-\ 3\gamma\ p$	7.6
$\Sigma^0 \pi^0$	$\Sigma^0 \rightarrow \Lambda\ \gamma;\ \Lambda \rightarrow \pi^0\ n;\ \pi^0 \rightarrow 2\gamma$	$5\gamma\ n$	7.6
$\Lambda \pi^-$	$\Lambda \rightarrow \pi^-\ p$	$2\pi^-\ p$	14.2
$\Lambda \pi^-$	$\Lambda \rightarrow \pi^0\ n;\ \pi^0 \rightarrow 2\gamma,\ \pi^0 \rightarrow 2\gamma$	$\pi^-\ 4\gamma\ n$	14.2
$\Sigma^0 \pi^-$	$\Sigma^0 \rightarrow \Lambda\ \gamma;\ \Lambda \rightarrow \pi^-\ p$	$2\pi^-\ p$	5.4
$\Sigma^0 \pi^-$	$\Sigma^0 \rightarrow \Lambda\ \gamma;\ \Lambda \rightarrow \pi^0\ n$	$\pi^-\ 2\gamma\ n$	5.4
$\Sigma^- \pi^0$	$\Sigma^- \rightarrow \pi^-\ n$	$\pi^-\ 2\gamma\ n$	10.8

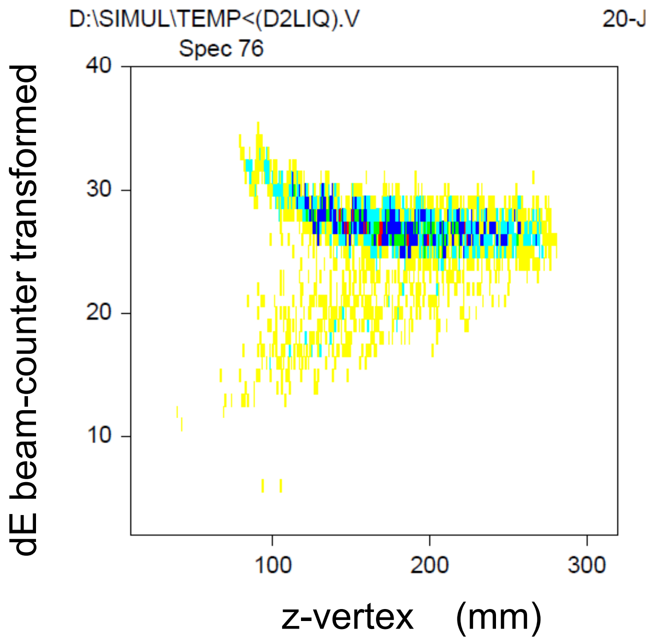
Monte Carlo results
Kaon stops in gas: 378
with charged multiplicity > 0: 294
with charged multiplicity > 1: 225
with charged multiplicity > 2: 101

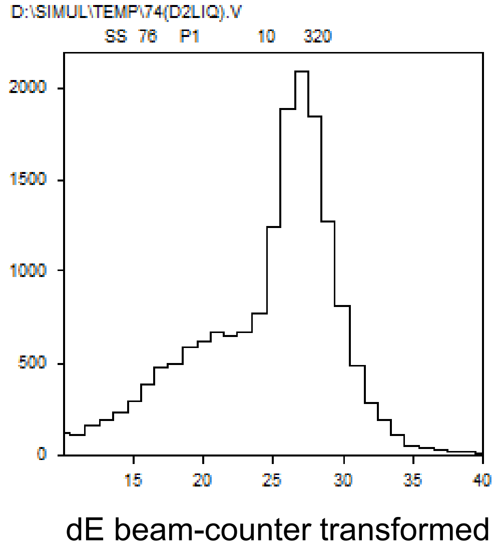


multiplicity of charged secondaries

fiducial volume derived from vertex reconstruction

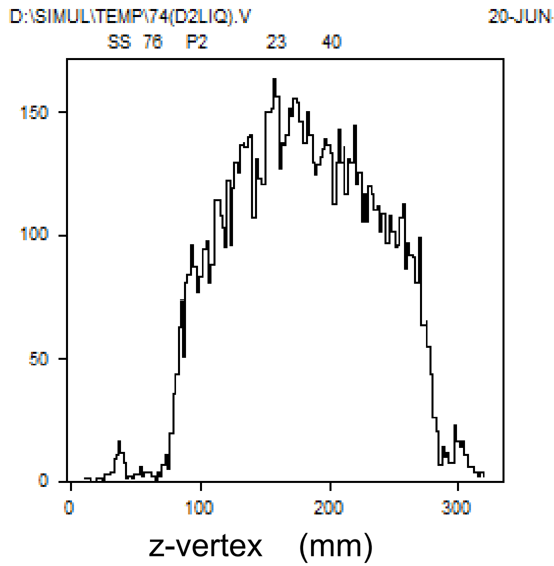






discriminates against
- Kabsorption BG from wallstops
- Kaonic X-rays from wallstops

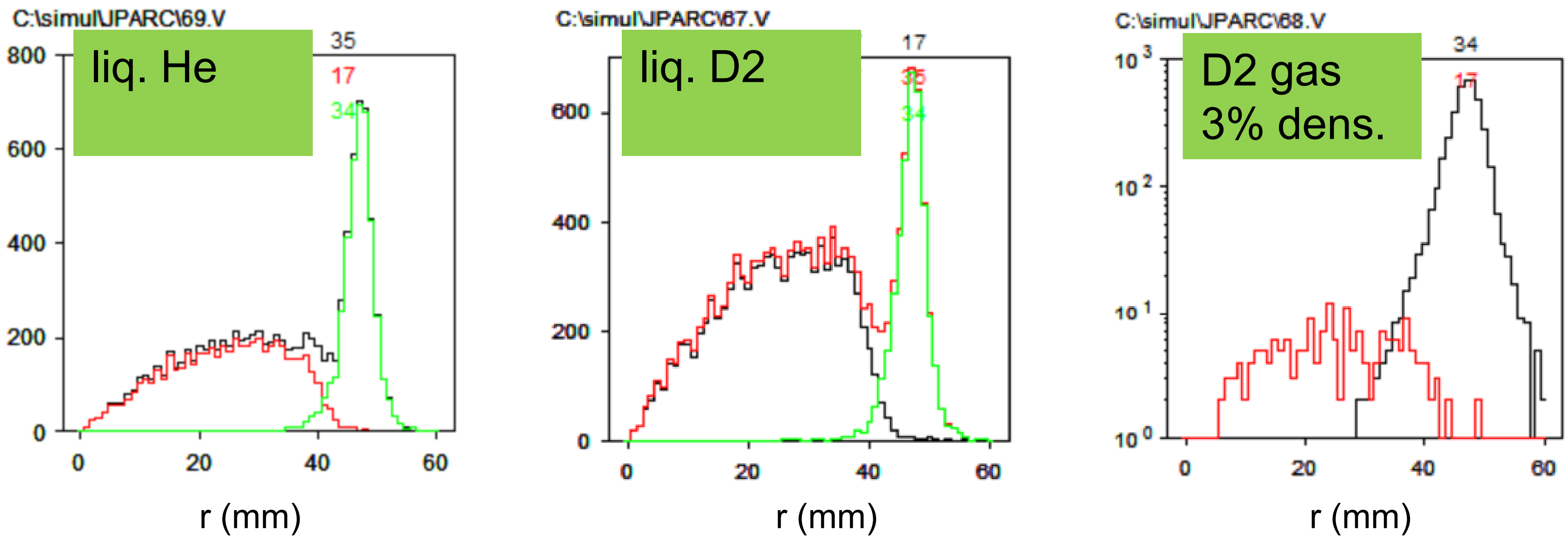
- in flight reactions if dE vs. z-vertex



fiducial volume cont‘d

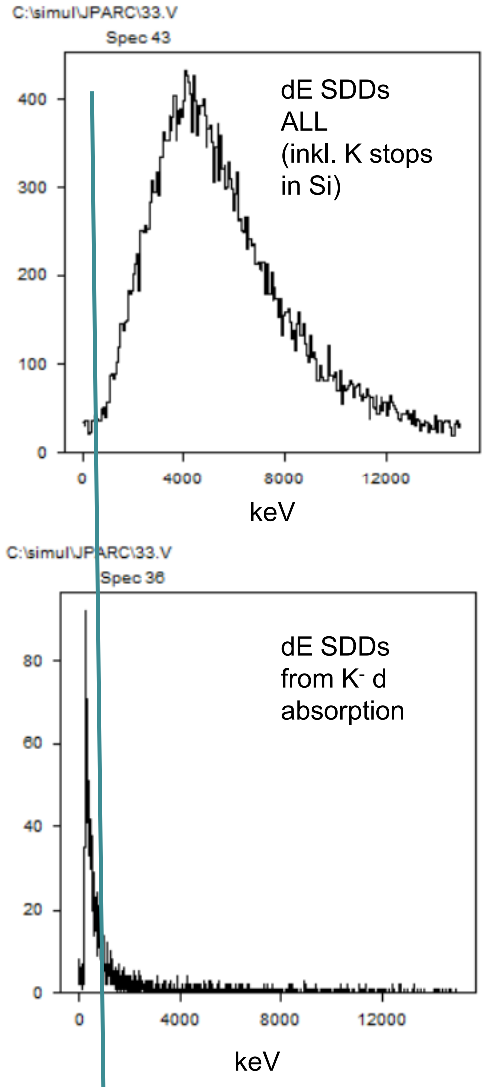
background from target stops => gas target prefered
.... wall stops => liquid target prefered

radial position of reconstructed vertex

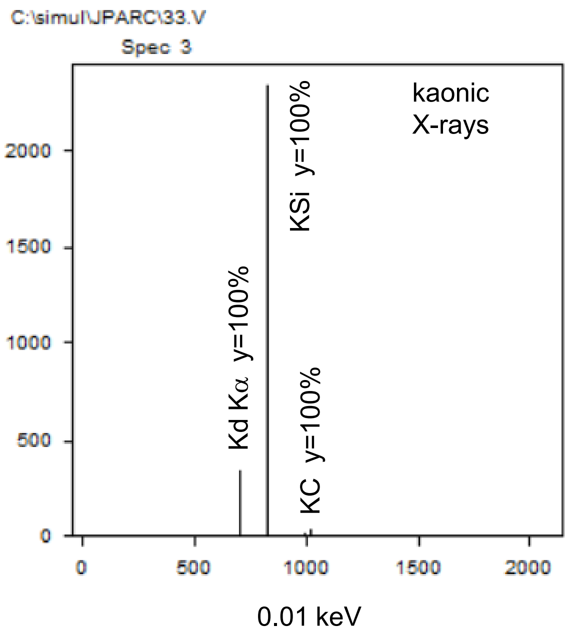


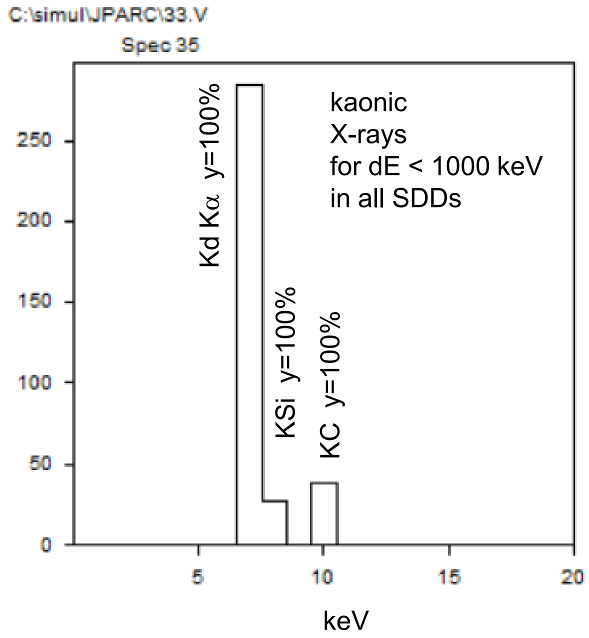
BG from kaon stops in SDDs

effective discrimination if threshold can be set above the pion dE



ρ = 0.03 liq. dens.





Conclusions

Kd X-ray measurement looks feasible in reasonable beamtime (30 days)

We intend to submit a letter of intent

What still has to be worked out besides financial issues:

- actual background at 1.8BR: measurement? realistic simulation needs input
- shielding possibilities
- liquid vs. gastarget scenario
- windowless target: advantage, drawbacks

besides the Kd K-series: Kp as test measurement, L-lines (windowless)

Thank You!

Kd yields from theory (1)

Frascati Physics Series Vol. XXXVI (2004), pp.
DAΦNE 2004: PHYSICS AT MESON FACTORIES – Frascati, June 7-11 , 2004
Selected Contribution in Plenary Session

ATOMIC CASCADE IN KAONIC HYDROGEN AND DEUTERIUM

T.S. Jensen
Laboratoire Kastler–Brossel, ENS et UPMC, Paris, France

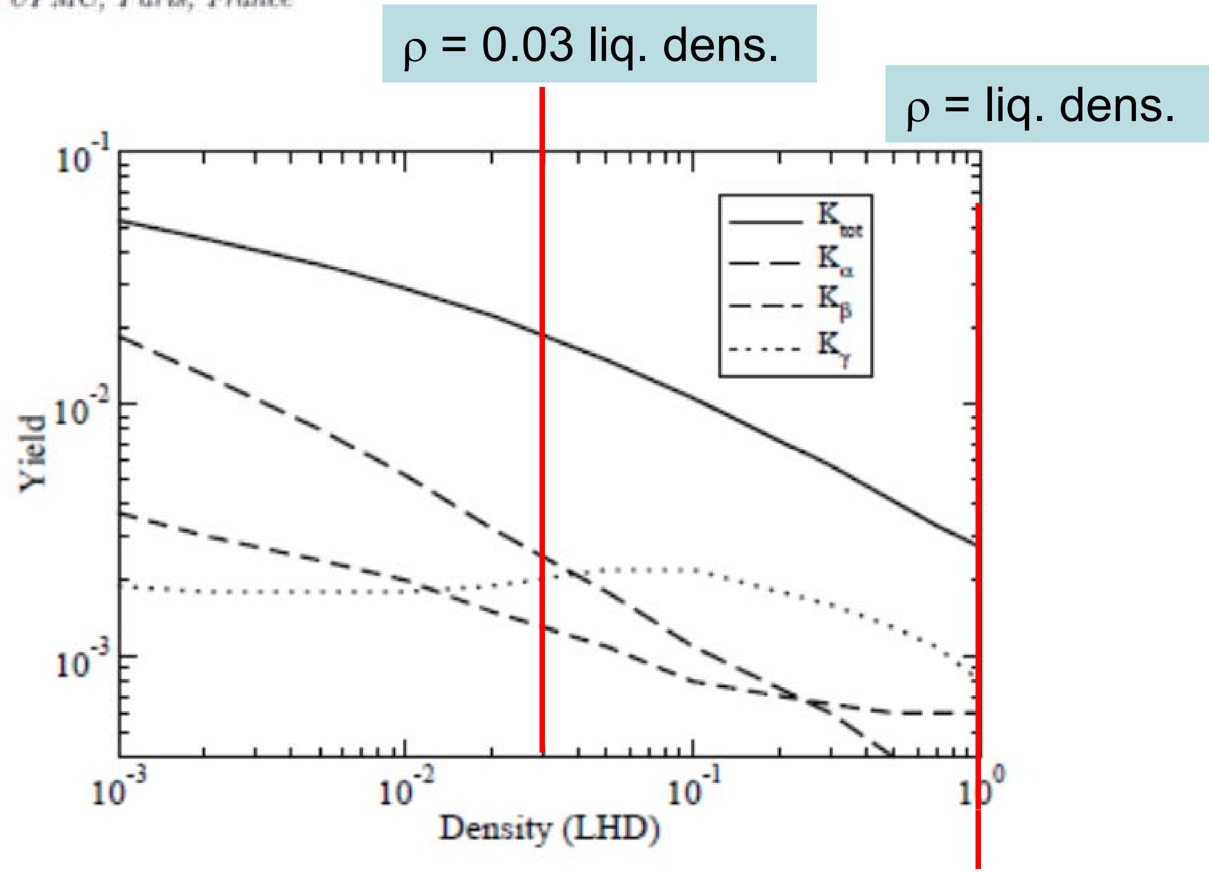


Figure 2: *The density dependence of the K x–ray yields in kaonic deuterium.*

Kd yields from theory (2)

PHYSICAL REVIEW C VOLUME 53, NUMBER 1 JANUARY 1996

Cascade calculation of K^--p and K^--d atoms

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Y. Akaishi
Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan

(Received 15 September 1995)

X-ray yields of K^--p and K^--d atoms are calculated as a function of the target density in
optimum condition for experiments. The dependence of the yields on the energy level shif
width due to the strong interaction is systematically investigated.

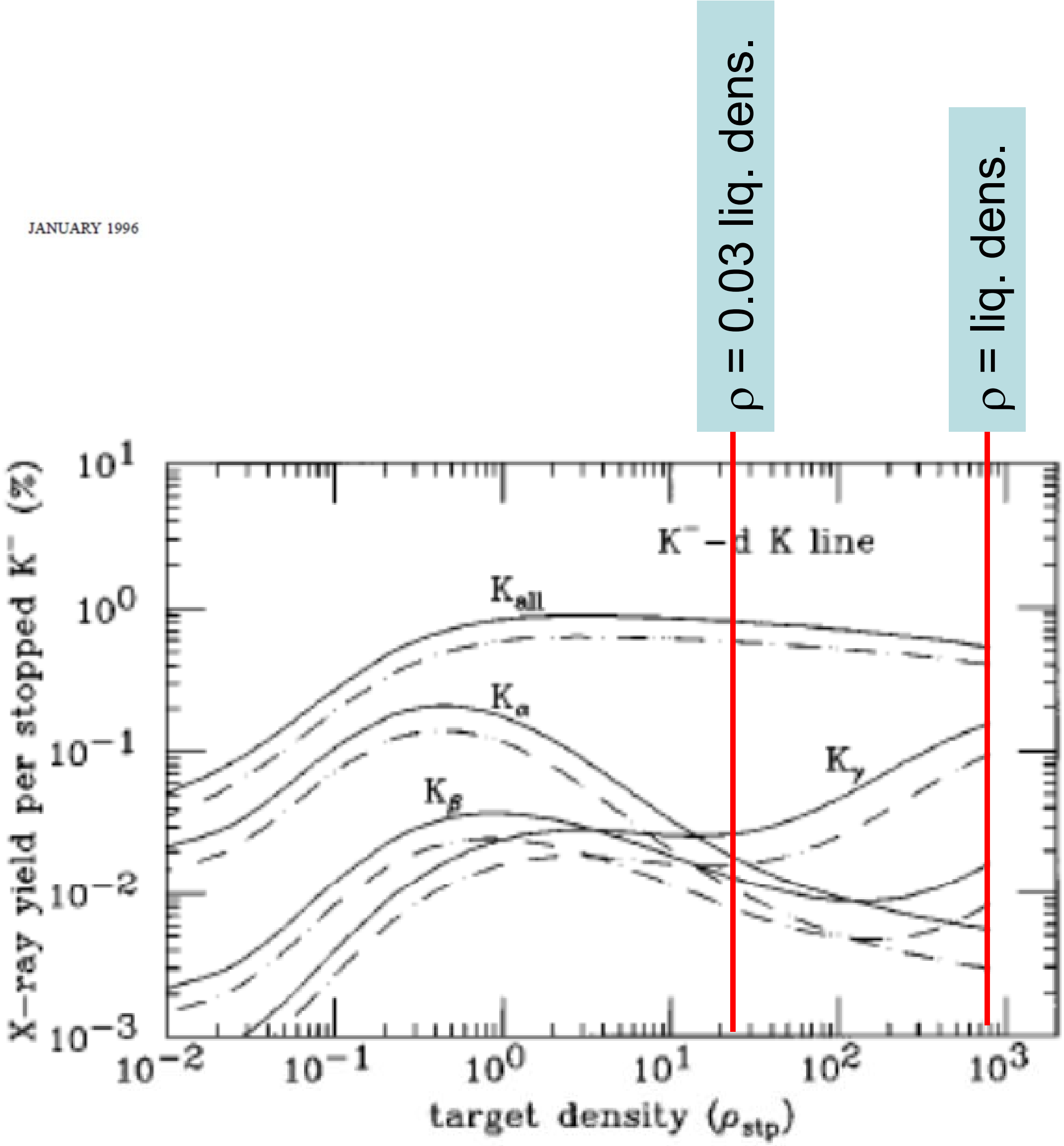

FIG. 10. Density dependence of K^--d atom x-ray yields with varying the strong-interaction parameters. The solid lines are the case of Martin's K matrix + Fermi average + binding effect. The dashed lines are for Batty's optical potential.

Kd yields from theory (3)

PHYSICAL REVIEW C **84**, 064314 (2011)

Energy-level displacement of excited *np* states of kaonic deuterium in a Faddeev-equation approach

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We calculate the energy-level displacement of the excited *np* state of kaonic deuterium in terms of the *p*-wave scattering length of K^-d scattering. We solve the Faddeev equations for the amplitude of K^-d scattering in the fixed-center approximation and derive the complex *p*-wave scattering length of K^-d scattering in terms of the *s*-wave and *p*-wave scattering lengths of $\bar{K}N$ scattering. The estimated uncertainty of the complex *p*-wave scattering length is of about 15%. For the calculated width $\Gamma_{2p} = 10.203$ meV of the excited $2p$ state of kaonic deuterium we evaluate the yield $Y_{K^-d} = 0.27\%$ of x rays for the K_α emission line of kaonic deuterium. Using the complex *s*-wave and *p*-wave scattering lengths of $\bar{K}N$ scattering, calculated in B. Borasoy, R. Nißler, and W. Weise [Eur. Phys. J. A **25**, 79 (2005)] and W. Weise and R. Härtle [Nucl. Phys. A **804**, 173 (2008)], we get the width $\Gamma_{2p} = 2.675$ meV of the excited $2p$ state and the yield $Y_{K^-d} = 1.90\%$ of x rays for the K_α emission line of kaonic deuterium. The results obtained in this paper can be used for planning experiments on the measurements of the energy-level displacement of the ground state of kaonic deuterium, caused by strong low-energy interactions.

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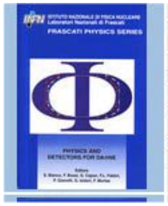
Kd yields from theory (4)



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THEORY OF CASCADE PROCESSES IN KAONIC ATOMS OF HYDROGEN ISOTOPES

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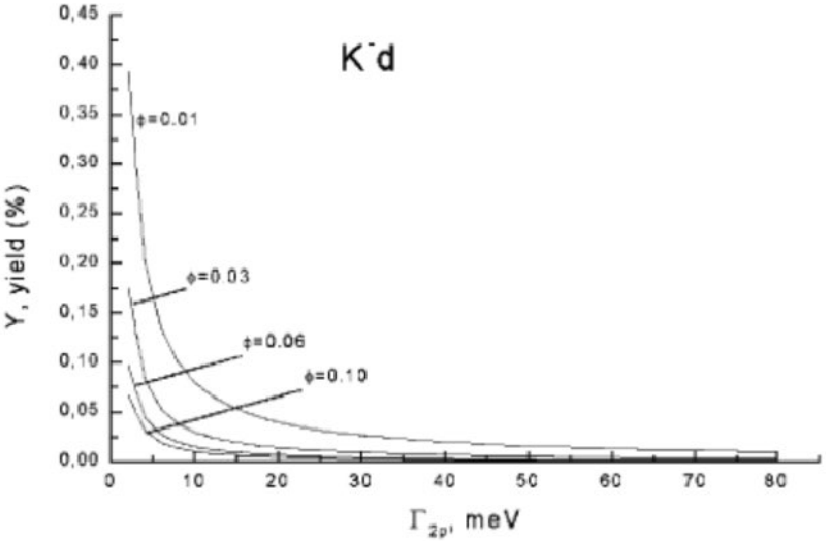


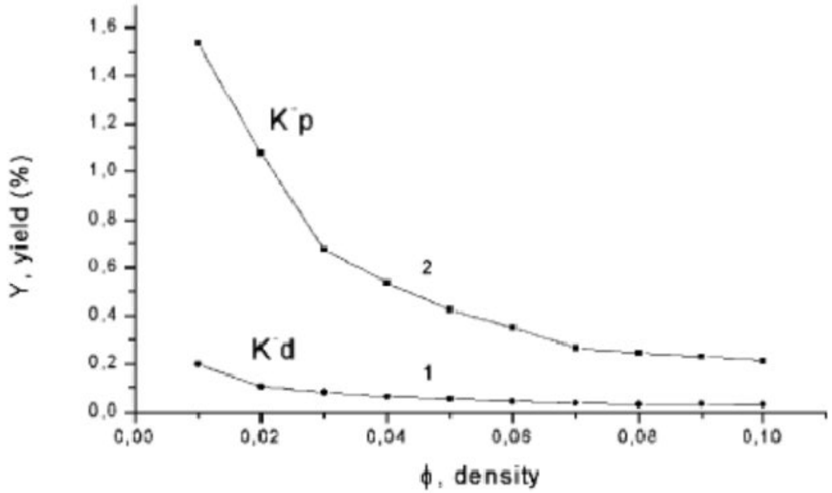
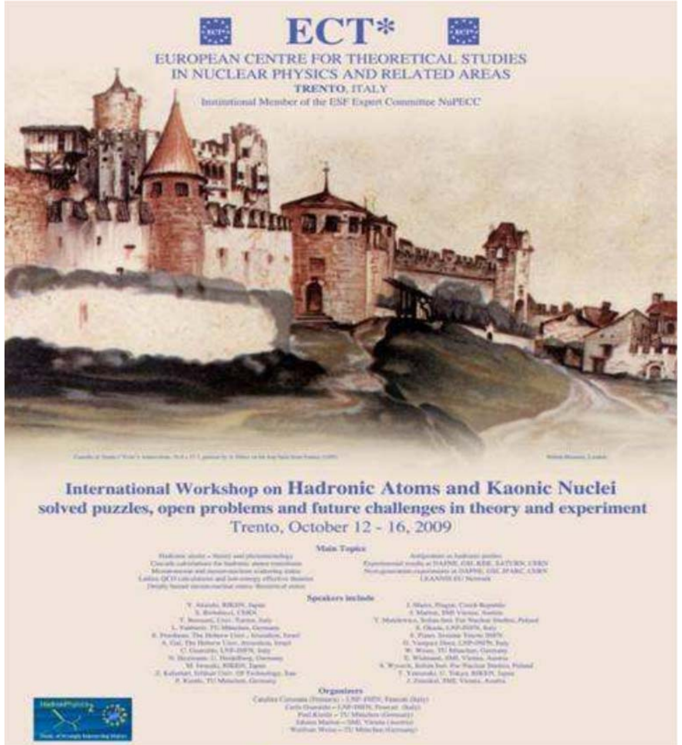


FIG. 9.

Kd yields from theory (5)



Quantum–classical calculations of cascade transitions in hadronic hydrogen atoms

M.P. Faifman, L.I. Men'shikov

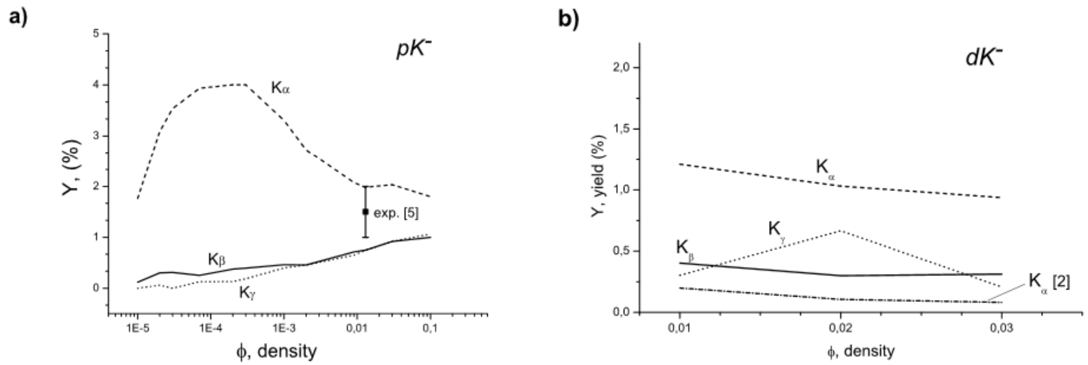


Figure 1: The K_α, K_β and K_γ -yields in kaonic atoms as function of density reduced to the liquid hydrogen density. a) The yields for pK^- atoms calculated with the nuclear capture width in the $2p$-state Γ_{2p} =2 meV [4]; b) The dK^- atom yields for the nuclear capture width Γ_{2p} =4 meV [2].

Our calculating scheme allows to obtain as well the other basic cascade characteristics which are needed for the detailed analysis of the DEAR/SIDDHARTA experimental data.

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