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Letter of Intent
for J-PARC

Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium

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Abstract

The antikaon-nucleon ($K^{bar}N$) interactions close to threshold provide crucial information of the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD. In this context the importance of the kaonic deuterium X-ray spectroscopy has been well recognized, but no experimental results were obtained up to now due to the difficulty of the measurement. Based on the development of new X-ray detectors and on the availability of the intense kaon beam line K1.8BR at J-PARC the proposed experiment will provide the strong-interaction level shift and width of the kaonic deuterium 1s state with most stringent constraints on the antikaon-nucleon interaction, promising a breakthrough for this field.

We propose to measure the shift and width of the kaonic deuterium 1s state with an accuracy of 60 eV and 140 eV, respectively. These results obtained at J-PARC together with the kaonic hydrogen data (KpX at KEK, DEAR and SIDDHARTA at DAΦNE), will allow to determine both values of the isospin I=0 and I=1 antikaon-nucleon scattering lengths.

Making use of the existing E15 apparatus at J-PARC upgraded with a newly developed X-ray detector system and based on the experience gained due a first test measurement of kaonic deuterium with SIDDHARTA, we have designed an experimental setup for a kaonic deuterium measurement at J-PARC. Detailed Monte Carlo studies were performed to investigate the background suppression factors with this new setup. With a beam power of 30 kW within 30 days of beam time we could demonstrate the feasibility to determine the shift and width of the kaonic deuterium atom 1s state with the aimed accuracy: shift = 60 eV and width = 140 eV.

1 Physics Motivation

1.1 Introduction

The antikaon-nucleon (K^{bar}-N) interactions close to threshold provide crucial information of the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD. Experimental investigations in this field have been performed over many years, like scattering experiments, determination on K^-p decay channels and branching ratios, and X-ray spectroscopy of kaonic atoms [1]. Theoretical investigations based on the experimental results have been performed [2-13], but these approaches are very complicated due to the presence of the $\Lambda(1405)$ resonance located just below the K^-p threshold. At present, there are no lattice QCD calculations of antikaon-nucleon scattering lengths, although a theoretical framework has been recently proposed [14]. Therefore, further experiments with more precise data and a first measurement of kaonic deuterium X-rays are necessary. In particular, the kaonic atom X-ray data provide the most precise values of the antikaon-nucleon scattering at threshold energy.

The K^-p interaction is now well understood from the recent results of kaonic hydrogen obtained from KpX [15] at KEK, DEAR [16] and finally from SIDDHARTA at DAΦNE [17] and the theoretical calculations based on this result [18, 19]. A milestone was the KpX experiment solving the long standing kaonic hydrogen sign puzzle and used for the first time fiducial volume cuts for background suppression.

Although the importance of the kaonic deuterium X-ray spectroscopy has been well recognized since more than 30 years [20], no experimental results were obtained so far due to the difficulty of the X-ray measurement. ***"The necessity to perform measurements of the kaonic deuterium ground state observables is justified by the fact that, unlike the case of pionic atoms, the measurement of only the kaonic hydrogen spectrum does not allow – even in principle – to extract independently both s-wave K^{bar}-nucleon scattering lengths a_0 and a_1."***, quoting from U.-G. Meisser [21]. The kaonic deuterium X-ray measurement represents the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions today.

With this proposal, using as input the experience gained with the SIDDHARTA experiment (kaonic hydrogen X-rays determined with up to now highest precision and a first exploratory measurement of kaonic deuterium), we have evaluated the possibility to perform a kaonic deuterium X-rays measurement. The expected result of the kaonic deuterium X-ray measurement at J-PARC together with those of SIDDHARTA will provide the most stringent constraints of the antikaon-nucleon interaction, promising a breakthrough in this field.

The data of kaonic hydrogen and deuterium are also indispensable for applying unitarized chiral perturbation theory, accounting for the $\Lambda(1405)$ resonance to kaon-hadronic systems in dense matter. There are several indications for K^- quasi-bound states in few-body nuclear systems by FINUDA [22] at DAΦNE and

DISTO [23] at SATURNE. In addition with E15 [24] a search for a $K^{-}pp$ bound system is ongoing at J-PARC, giving urgency to the precise measurements in the kaonic atom systems.

1.2 Present state-of-the-art

Recently, the most precise values of the strong-interaction shift and width of the kaonic hydrogen 1s state were obtained by the SIDDHARTA experiment [17]. The result of the pioneering KpX experiment together with DEAR and SIDDHARTA are shown in figure 1.

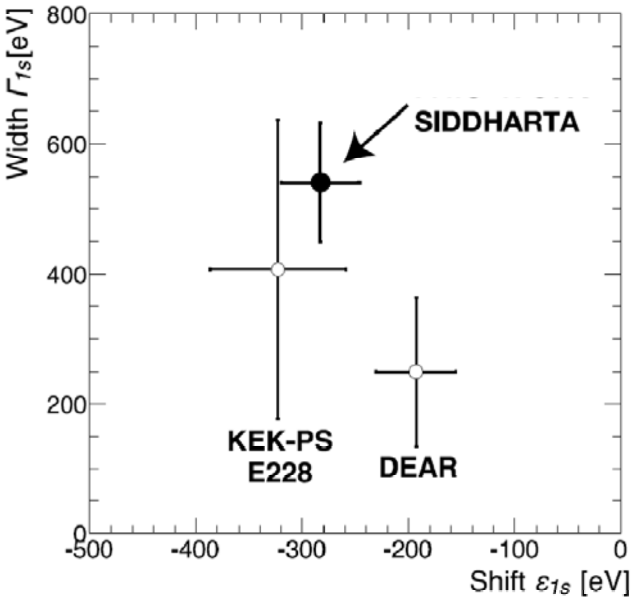

Figure 1: Comparison of experimental results for the strong-interaction shift and width of the kaonic hydrogen 1s state.

Alternating with the SIDDHARTA data taking of kaonic hydrogen a first exploratory measurement of kaonic deuterium was performed [25].

The analysis of the kaonic deuterium data delivered a 1.7 σ hint of a signal (see figure 2), if the values for shift and width of the K-series transitions are taken from theory: shift = –800 eV and width = 750 eV. The upper limits for the yield of the K-series transitions were derived in this analysis: $Y(K_{tot}) < 0.0143$ and $Y(K_{\alpha}) < 0.0039$ (CL 90%).

The experimentally determined shift and width are related to the *s*-wave scattering lengths at threshold [1]. Because of the isospin conservation, only the average value of the isospin *I=0* and *I=1* scattering lengths (*a0* and *a1*) was obtained from the kaonic hydrogen measurement. In order to determine the isospin dependent scattering lengths, the measurement of the shift and width of the kaonic deuterium 1*s* state is definitely needed [18-21, 26-28].

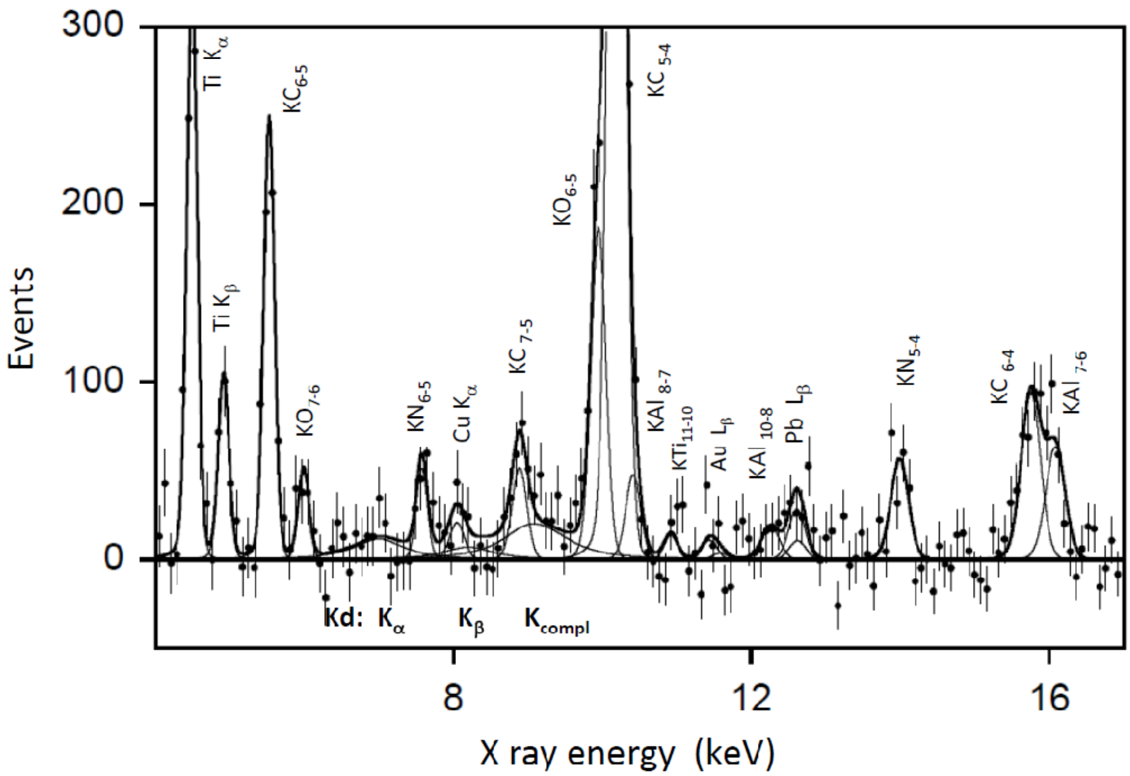

Figure 2: Example of a fit of kaonic deuterium X-ray lines using theoretical estimated values for shift -800 eV and width 750 eV (taken from [25], figure 2).

On the theoretical side there are many recent publications, giving quite consistent values of the shift and width for the kaonic deuterium 1s state (see table 1).

a_{K^-d} [fm]	ϵ_{1s} [eV]	Γ_{1s} [eV]	ref.
-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]

Table 1: Compilation of predicted K^-d scattering lengths $a_{K\text{-}d}$ and corresponding experimental quantities ε_{1s} and Γ_{1s} (taken from [25], table1).

2 Experimental method

The proposed experiment is based on the experience gained with Silicon Drift Detectors (SDDs) at KEK with the E570 [29] experiment and the use of charged particle tracking for background reduction already developed for the KpX experiment E228 [15] at KEK. In addition the studies performed for E17 [30] at J-PARC to measure kaonic helium-3 were used as input for the Monte Carlo simulation described in paragraph 4. Finally the results obtained from an exploratory measurement of kaonic deuterium with SIDDHARTA [25] were used to confine the input values, for X-ray yield, shift and width, used for the Monte Carlo studies in this LoI.

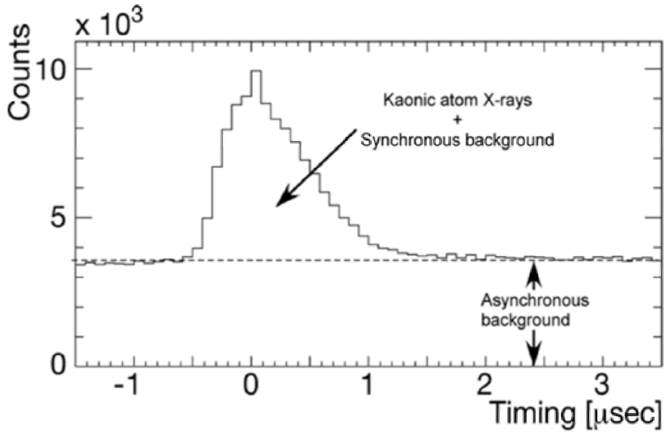

Figure 3: Drift time distribution of the SIDDHARTA SDDs at a temperature of 170 K; the measured drift time (FWHM) is approx. 700 ns.

The experimental challenge of the proposed experiment is the very small kaonic deuterium X-ray yield and the difficulty in doing X-ray spectroscopy in the high radiation environment of an accelerator. It is therefore crucial to control and improve the signal-to-background ratio for a successful observation of the kaonic deuterium X-rays. There are two types of background sources; correlated (synchronous) and uncorrelated (asynchronous) to the incoming K^-.

The asynchronous background originates from the production target. This background can be suppressed by additional shielding and better timing of the SDD itself. The broadening of the peak in figure 3 corresponds to the drift time distribution of charges in the SDDs, which depends (besides the shape) on the working temperature of the SDDs. Running the SDDs at a temperature of 120 K (compared to 170 K as shown in figure 3) reduces the drift time to 200 ns for this type of large area SDDs (1 cm^2).

Another possibility, which is under evaluation now, is to collect the charge of the "holes" on the backplane, which will lead to a drift time below 10 ns.

The synchronous background originates from secondary particles generated by the decays and reactions of kaons (kaon absorption in the target gas or in the walls). These background events can be suppressed by charged particle tracking, determining the stopping point of the kaons within the target. Therefore the excellent tracking capability of the E15 apparatus is essential for the proposed measurement.

2.1 E570 – Kaonic helium measurement at KEK

For the E570 [29] experiment at KEK (see figure 4) eight silicon drift detectors (SDDs) produced by KETEK GmbH [31] were used as X-ray detectors, each with an effective area of 1 cm^2 and 260 μm-thick active layer. The electrons produced by an X-ray hit in the SDDs are drifting radially toward the central anode where they are collected. The small anode size (and hence small capacitance) is essential to realize the good energy resolution of ~190 eV (FWHM) at 6.4 keV, about twice better than that of the Si(Li) detectors used in the previous experiments. The reduced active layer thickness, less than 1/10 of the previously used Si(Li) detectors, helps to reduce continuum background caused by Compton scattering inside the detector.

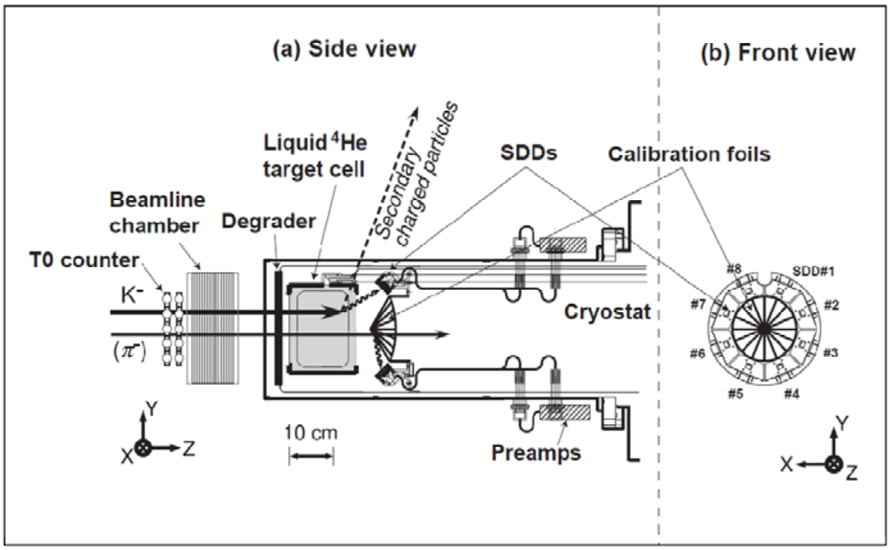

Figure 4: (a) A schematic side view of the E570 setup around the cylindrical target with the X-ray detection system. (b) A front view of the SDD assembly. Eight X-ray detectors were mounted on holders tilted at a 45 degree angle to the beam centre in an annular-shaped pattern. Fan-shaped high-purity titanium and nickel foils are put alternately on a cone-shaped support located on the beam axis (figure 2 from [29]).

Another important feature of the E570 experiment was the possibility to perform fiducial volume cuts. The kaon-reaction vertex was reconstructed from an incident kaon track and an outgoing secondary charged particle track. The secondary charged particles were emitted from kaon absorption on the nucleus. To reduce background it was required that the kaon-reaction vertices should be within the target. This requirement ensured the X-rays detected in coincidence with the secondary charged particles were emitted from the target.

The experiment E570 clearly shows the excellent capability of SDDs for X-ray spectroscopy of kaonic atoms in the environment of an accelerator. In addition the fiducial volume cut technique developed at the KpX experiment has proven to be very efficient to suppress background events originating from the wall and has to be applied as well in the proposed kaonic deuterium X-ray measurement.

2.2 E17 experiment at J-PARC

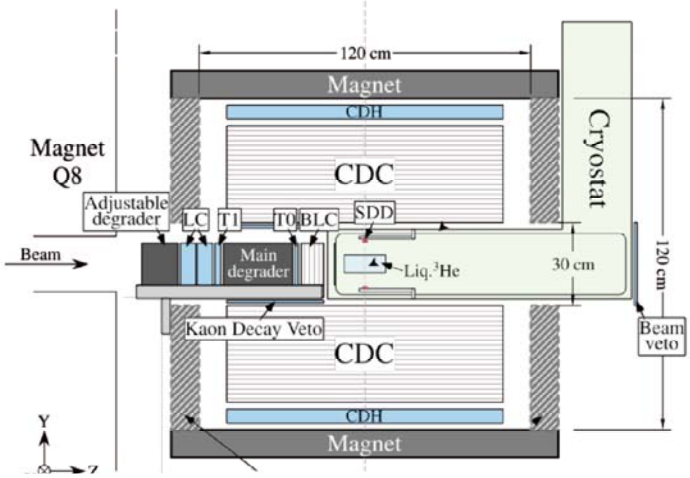

Figure 5: E17 setup, using part of the K1.8BR spectrometer.

The experiment E17 [30] at J-PARC proposed to measure the strong-interaction shift of 3d → 2p X-rays of kaonic helium-3 atoms with a precision better than 2 eV (setup figure 5). The result of E17 together with that for kaonic helium-4 atoms measured by the E570 collaboration [29], will provide crucial information on the isospin-dependent K^{bar}-nucleus strong interaction at the low energy limit.

In the simulations done by E17 it was assumed that the background originates from hits of charged particles and high energy γ-rays, which partly come from accidental beam particles, and partly from coincident secondary particles emitted after K^- absorption in helium-3. An estimate based on the experience gained in the KEK E570 experiment was done. The results are summarized in table 2.

	KEK E570	J-PARC E17
Time Resolution ΔT (ns)	130	220
SDD Efficiency ϵ_{SDD} (%/all SDDs)	0.13	0.95
SDD Single Hit rate F_{SDD} (s^{-1})	105	50
SDD OR / spill	210	100
spill length (s)	2	2
Spill duty factor D_{spill}		0.3
Continuum BG / 50 eV /2000 KHeL_α	25	18 (estimation)
from kaon absorption	14	14 (estimation)
from beam	11	4 (estimation)

Table 2: Comparison of the experimental conditions at KEK (E570) and J-PARC (E17). Background counts for KEK E570 were evaluated by using timing and energy spectra. Time resolution and SDD OR / spill for J-PARC E17 are measured values in the beam commissioning in November 2010.

We used the background evaluation done by the E17 collaboration as input for the Monte Carlo studies in this LoI. Essential for a further reduction of the beam uncorrelated background will be the improvement of the SDD timing from about 200 ns to around 10 ns, which is currently under investigation.

2.3 Results of an exploratory measurement with SIDDHARTA

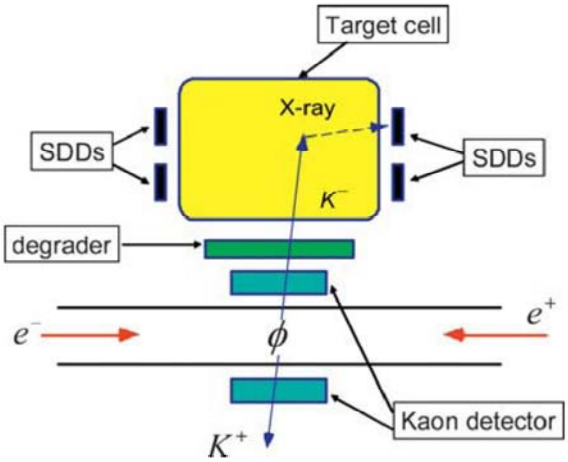

Figure 6: Drawing of the SIDDHARTA experimental setup.

A first exploratory measurement of kaonic deuterium was performed in the SIDDHARTA experiment, alternating with the kaonic hydrogen X-ray measurements [25]. In figure 6 a sketch of the experimental setup is shown. The back-to-back correlated charged kaon pair (K^+K^-) emitted from the $\phi(1020)$ decay (with a branching ratio of about 50%) was detected by the two scintillators mounted above and below the beam pipe at the interaction point (``kaon detector''). The charged kaons were stopped in the gas, after passing through the scintillator and degrader. X-rays from kaonic atoms were detected by large-area ($1 cm^2$) Silicon Drift Detectors (SDDs), installed around the target cell, with a total area of 144 cm^2.

Further development of large area Silicon Drift Detectors for X-ray spectroscopy was based on the SIDDHARTA SDDs. The new SDDs have a much better ratio of active to total area and could be closer packed around the target cell, achieving a much better solid angle.

3 Proposed experimental setup

The proposed kaonic deuterium experiment will use the excellent features of the K1.8BR kaon beam line together with the K1.8BR spectrometer. We plan to upgrade the spectrometer with a cryogenic deuterium target surrounded by SDDs with a total area of 300 cm² (450 single elements) for X-ray detection.

3.1 K1.8BR spectrometer

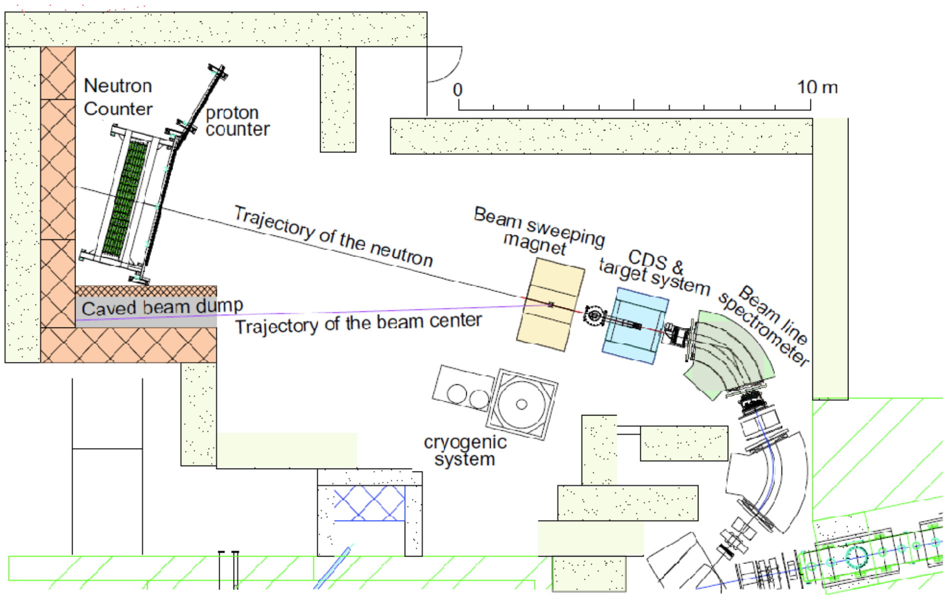

Figure 7: The J-PARC K1.8BR spectrometer. The setup consists of a beam line spectrometer, a cylindrical spectrometer system (CDS), a beam sweeping dipole magnet, a caved beam dump equipped with beam monitor hodoscopes, a neutron counter made of an array of plastic scintillation counters equipped with charged veto counters and a proton counter hodoscopes.

The K1.8BR multi-purpose spectrometer [32] (see figure 7) has quite unique feature for our needs, namely a large acceptance cylindrical spectrometer system (CDS), consisting of a cylindrical drift chamber (CDC) for charged particle tracking, essential for efficient background reduction for the proposed study of kaonic deuterium X-rays. The cylindrical drift chamber, with a diameter of 1060 mm and length of 950 mm, is surrounded by a cylindrical detector hodoscope (CDH) to trigger on decay particles.

These parts of the experimental setup will be utilized for the proposed experiment to be upgraded with a cryogenic target system and a novel X-ray detector system with a total area of 300 cm², with excellent energy resolution (better than 150 eV at 6 keV) and improved timing capability, in the order of 10 ns.

Finally, the kaonic deuterium setup will be similar to the E17 experimental setup (as shown in figure 5). The beam counter and degrader will be used together with the cylindrical spectrometer system, while the target and SDD system will be replaced.

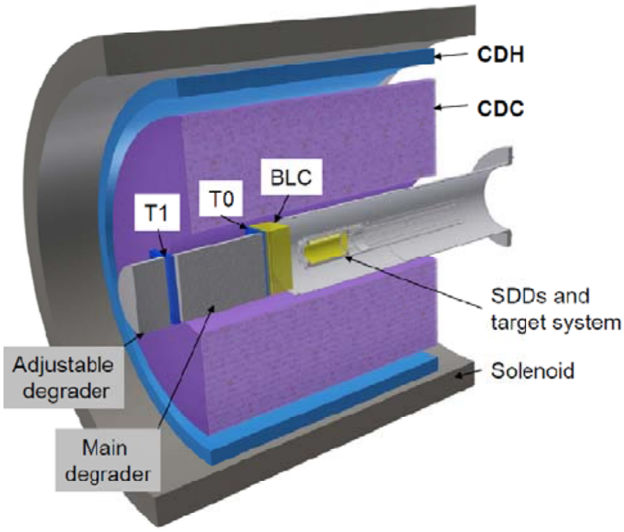

Figure 8: Sketch of the proposed setup for the kaonic deuterium measurement

The proposed setup (figure 8) will allow the tracking of the incoming kaons with segmented plastic scintillators as start counter (T1, T0) and the beam line chamber (BLC) for tracking. The produced charged particles due to kaon absorption on the nucleus will be tracked by the large cylindrical drift chamber (CDC), while the cylindrical detector hodoscope (CDH) is used as trigger.

Excellent tracking capability is essential for the efficient background suppression as described in the next paragraph (Monte Carlo studies).

3.2 Silicon Drift Detector (SDD) upgrade and cryogenic deuterium target

We plan to use new SDD chips, which were developed in collaboration by Fondazione Bruno Kessler – FBK and Politecnico di Milano in Italy.

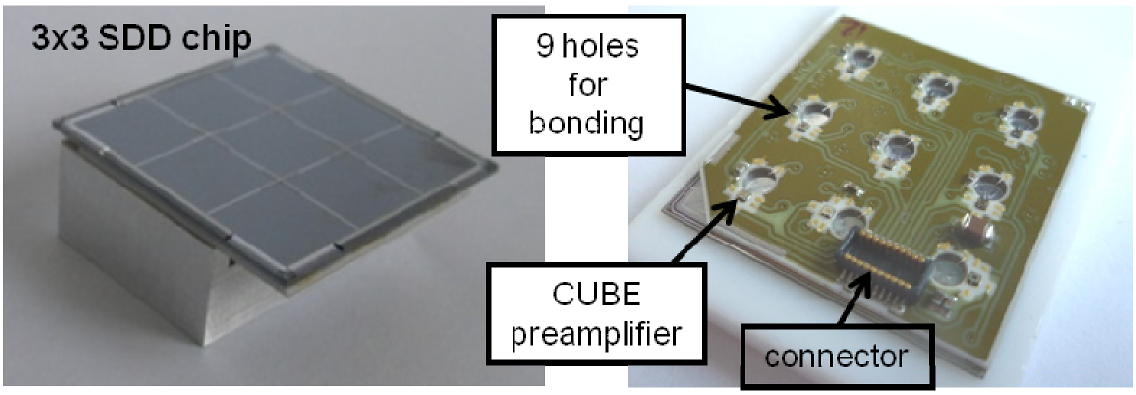

Figure 9: Monolithic array of 3x3 SDDs each 8x8 mm² (left); backside of the SDD array mounted on a print board with preamplifier chip (CUBE) for detector segment (right).

Monolithic arrays with 9 detector segments with a total area of 5.76 cm² (see figure 9) are perfectly suited for the proposed experiment. For these SDDs special preamplifier chips (CUBE), were developed.

First test measurements were performed successfully. For example an stability test running for 72 hours, performed at a SDD temperature of 120 K, achieved an energy resolution of 130 eV at 6 keV (see figure 10). The drift time at this working temperature is around 200 ns.

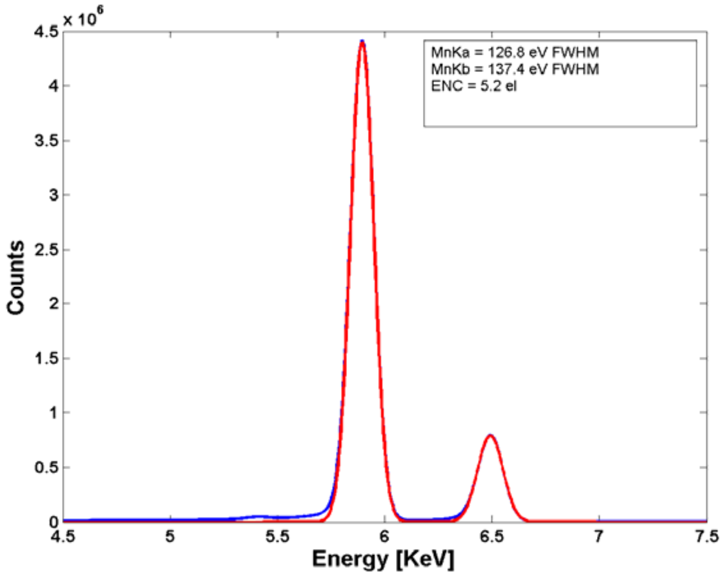

Figure 10: Test of a single cell at a temperature of 100 K, measured for 72 hours using a Fe-55 source. The MnK$_\alpha$ is determined with FWHM of 127 eV.

With some small modification, by taking the timing signal from the back-plane of the SDD chip, it should be possible to obtain 10 ns timing, which is an essential factor to further suppress the beam related background.

The cryogenic target cell will be made of a 75μm Kapton body with a diameter of 80 mm and a length of 200 mm, with reinforcement rings made out of aluminium. The cooling and mounting structure of the SDDs is used, in addition, to reinforce the target cell in longitudinal direction. The working temperature of the target cell is around 25 K with a maximum pressure of 0.35 MPa. With these parameters a gas density of 5% liquid deuterium density (LDD) will be achieved.

Finally 50 monolithic SDD arrays will be structured close together around the target cell, with a total area of 300 cm^2 containing 450 readout channels (see figure 11).

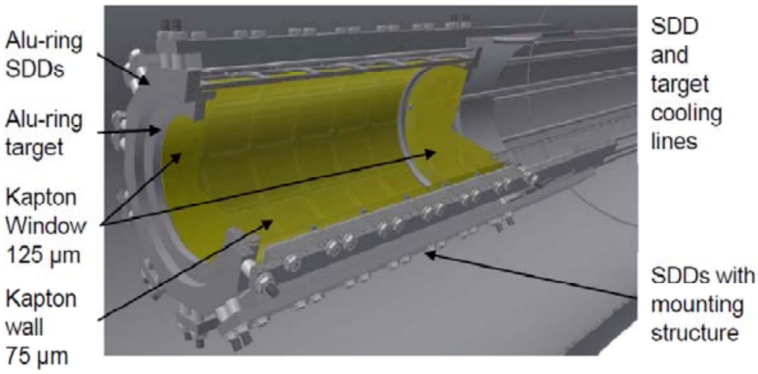

Figure 11: Design of the cryogenic target and X-ray detector system. The target cell with a diameter of 80 mm and a length of 200 mm is closely surrounded by SDDs, about 5 mm away from the target wall.

What is essential for the success of the proposed experiment will be the newly developed SDDs attached to the CUBE preamplifier chips, with the possibility to build a device with an excellent ratio of active to total area of 85%, which allows a high packing density around the target cell to cover a large solid angle of about 2π. And, the additional feature of these SDDs to achieve a timing capability in the order of 10 ns, while keeping the excellent energy resolution of the device, is important for the necessary background reduction.

4. Monte Carlo studies

4.1 Degrader optimisation, kaon stopping distribution

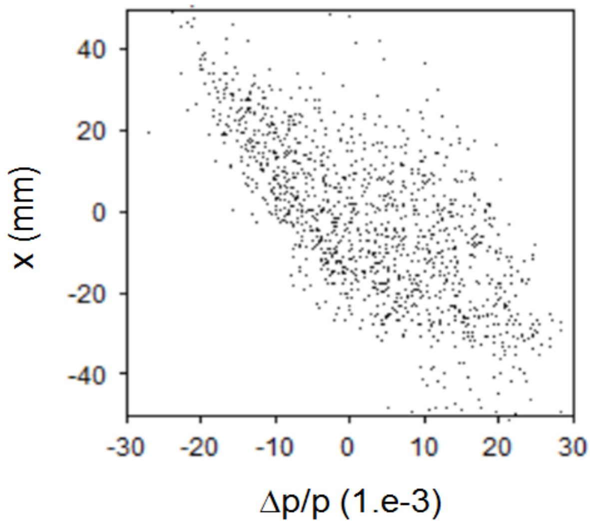

Figure 12: Momentum deviation versus lateral position

The kaon beam properties were taken from a measurement at the K1.8 BR in June 2012 with a kaon momentum of 1000 MeV/c (see figure 12).

For the use as kaon degrader several materials (carbon, polyethylene and iron) were compared in the simulation. The highest stopping rates were obtained with a carbon degrader of about 40 cm thickness.

In table 3 the optimised results for the carbon degrader thicknesses are summarised for gas and liquid targets. Kaons with a central momentum of 660 MeV/c were assumed in the simulation. A prism shaped additional degrader was used to compensate the position dependence of the momentum (see figure 12).

degrader thickness [cm]	kaon target stops per beam kaon ($x10^{-3}$)	target density
40	0.43	0.03
40	0.70	0.05
39	15.0	1

Table 3: Kaon stopping density in gaseous and liquid targets, optimised for carbon degrader. The target density is given relative to the liquid deuterium density (LDD).

In figures 13 and 14 the results of the optimisation of the kaon stopping density in gaseous and liquid deuterium targets are shown, respectively.

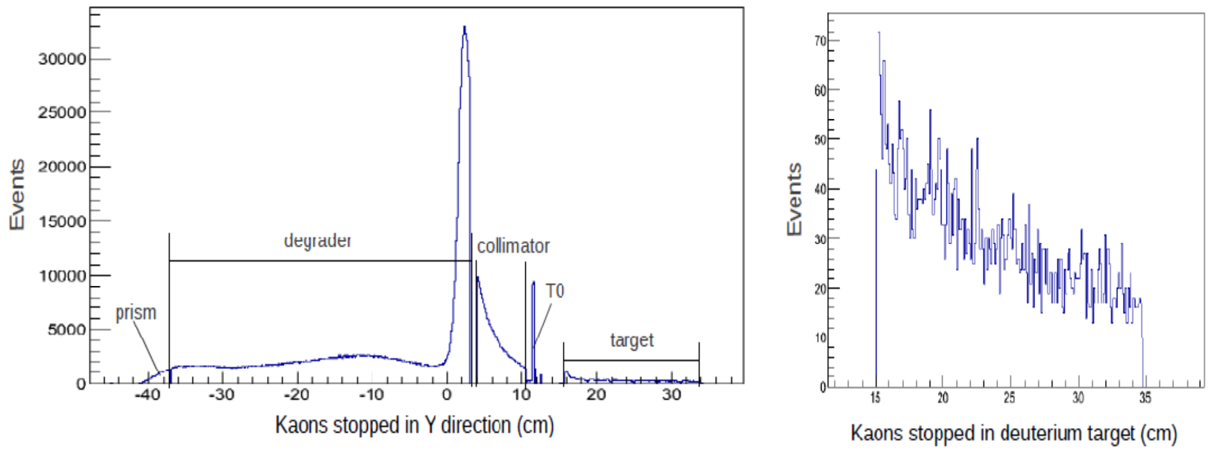

Figure 13: Kaon stopping distribution from degrader to target (left); kaon stops in the deuterium gas target, with a density of 5% LDD (right).

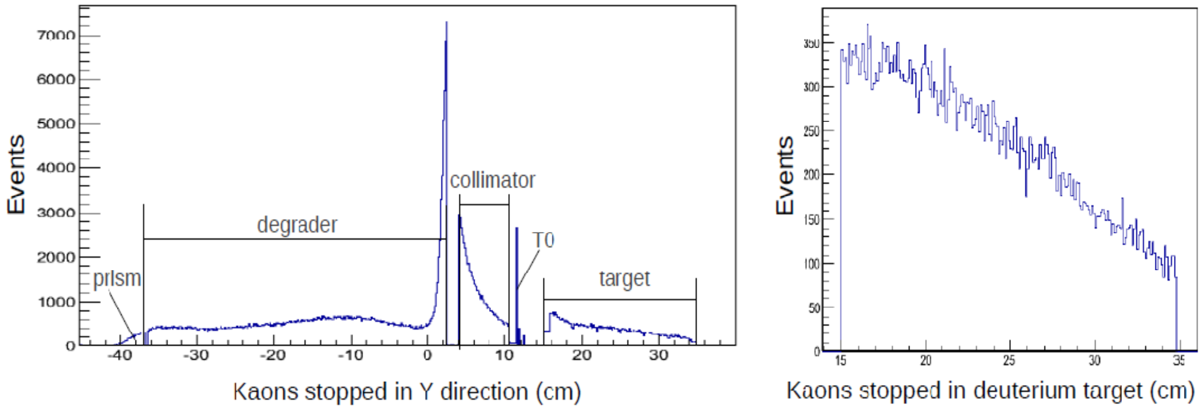

Figure 14: Kaon stopping distribution from degrader to target (left); kaon stops in the liquid deuterium target (right).

4.2 X-ray yields, cascade calculations

The most recent cascade calculations for kaonic deuterium are shown in figure 15, where the X-ray yields per stopped kaon for K_α-, K_β- and K_γ-transitions in a wide density range were calculated.

As input in our Monte Carlo simulation we used a K_α-yield of 0.1% for the gas targets and 0.01% for the liquid target, which are between the calculated values of Koike [33] and Jensen [34].

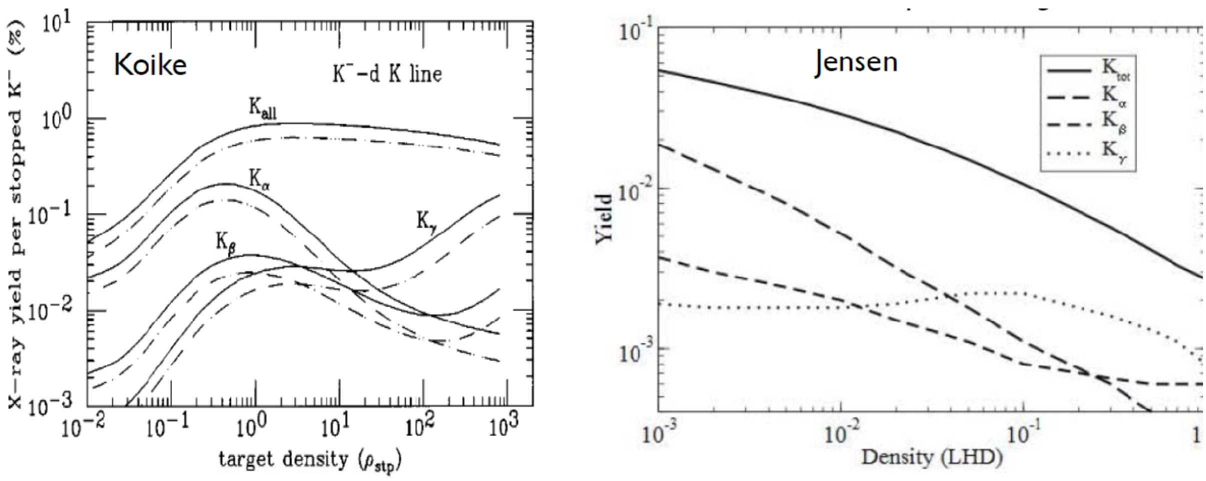

Figure 15: Kaonic deuterium cascade calculations, for the X-ray yield of K_α, K_β, K_γ and K_{tot}; [33] (left), [34] (right).

4.3 X-ray events and background suppression

We have simulated the kaonic deuterium X-ray spectrum, assuming a 30 kW beam power and 30 days of data taking with an X-ray detector of 300 cm^2 active area. The yield ratios of the K_α:K_β:K_{total} transitions were taken from the kaonic hydrogen data, with an assumed K_α yield of 10^{-3} for the gaseous target and 10^{-4} for the liquid target. For the strong interaction induced shift and width theoretical prediction (see table 1) were used: shift = -800 eV and width = 750 eV.

If one only demands that a signal coming from a "good" kaon was detected in the beam counter located after the degrader, the beam correlated background is by far too high to extract a kaonic X-ray signal (figure 16, left). Using the vertex cut method (successfully used with E570 at KEK and planned as well for E17 at J-PARC) with a defined volume inside the target, 5 mm away from the walls and a charged particle veto for tracks passing through or nearby SDDs, one could clearly see a drastic improvement in the signal to background ratio.

For a gas density of 5% the estimated signal to background ratio (integral) is 1:3 (see figure 16, right), with a statistical significance of the K_α line of ~10 sigma.

Fitting a set of simulated data we extracted the shift and width with a precision of 60 eV and 140 eV, respectively.

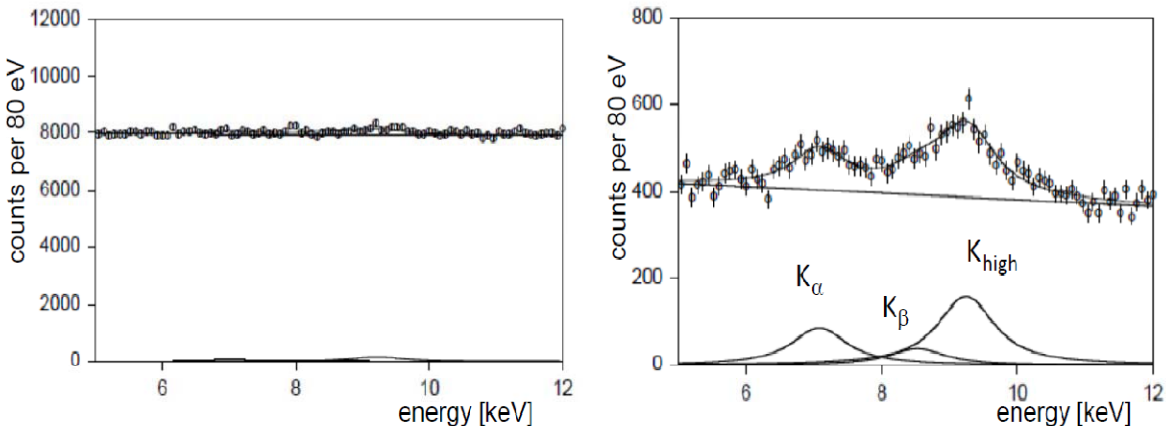

Figure 16: Simulated kaonic deuterium x-ray spectrum, assuming a 30 kW beam power, 30 days of data taking and a detector area of 300 cm². Left: Demanding only appropriate K⁻ signal on the beam counter after the degrader. Right: Beam counter condition same as before, but additionally vertex cut (fiducial volume 5 mm off the walls) and charged particle veto for tracks passing SDDs.

In table 4 the results of the simulation for 2 gas target conditions and for a liquid target are summarised.

density rel. to LDD	events for 30 days	Signal/BG	shift error [eV]	width error [eV]
0.03	902	1:4	--	--
0.05	1476	1:3	56	139
1	3333	1:7	65	162

Table 4: The signal to background ratio is calculated by the sum of K_α events divided by the sum of the background event in a region corresponding to the FWHM of the K_α peak. The simulated kaonic deuterium X-ray spectra were fitted and the precision in the determination of the shift and width are displayed in the last two columns.

5. Summary

We have shown that for a 30 kW proton beam power with a momentum of 660 MeV/c about 4.5 x 10^8 kaons per day can be expected entering the degrader. Assuming this kaon intensity and rejecting the kaon correlated background using various cuts, especially a fiducial volume cut and a charged particle veto, it will be possible to achieve a signal to background ratio of 1:3 for the kaonic deuterium K_α-line with a target gas density of 5%.

Uncorrelated background is estimated to be negligible, since the unprecedented timing resolution of the new SDD electronics scheme (~ 10 ns) reduces it to a marginal level.

Within 30 days of beam time, using a gas density of 5% LDD, we will be able to collect 1500 K_α events, which will allow a determination of the strong interaction induced shift and width of the 1s state of kaonic deuterium with a precision of 60 eV and 140 eV, respectively.

To achieve the goals of the proposed experiment further studies of the SDDs are necessary:

First tests of the new SDD arrays with a modified CUBE preamplifier chip will be performed to extract a timing signal from the back-plane within 2013. A drift time of ~ 10 ns is expected for a 500 μm thick SDD wafer.

In addition the performance of these SDD arrays in a high magnetic field (approx. ~ 1 Tesla) will be studied. Similar SDDs have been tested successfully in a magnetic field of ~0.3 Tesla.

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