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A New Silicon Drift Detector System for Kaonic Atom Measurements

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Abstract. The kaonic deuterium measurement at J-PARC and DAΦNE will provide a piece of information still missing to the antikaon-nucleon interaction close to threshold, providing valuable information to answer one of the most fundamental problems in hadron physics today - to the yet unsolved puzzle of how the hadron mass is generated. For this a new X-ray detector system has been developed to measure the shift and width of the 2p → 1s transition of kaonic deuterium with a precision of 60 eV and 140 eV, respectively.

1. Introduction

The antikaon-nucleon interaction close to threshold provides crucial information on the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD. Several dedicated experiments on kaonic hydrogen spectroscopy performed at KEK [1], DEAR [2] and most recently the SIDDHARTA experiment [3] at DAΦNE yielded important information for theoretical calculations (see [4, 5]) of K^-p interactions. However, even though the importance of a kaonic deuterium measurement has well been recognised, it has not yet been carried out due to the immense difficulty of the experiment.

Similar to the kaonic hydrogen measurement, the kaonic deuterium measurement will detect the energy shift of the 1s ground state induced by the strong interaction as well as the broadening of the ground state level caused by nuclear absorption. With the new experimental results and the results obtained from the SIDDHARTA experiment, the isospin dependent ($I = 0$ and $I = 1$) antikaon-nucleon scattering lengths can be determined, ensuring a breakthrough in this field.

2. K^-d Apparatus for J-PARC

The experimental challenge of the kaonic deuterium measurement is the very small kaonic deuterium X-ray yield and the difficulty to perform X-ray spectroscopy in the high radiation environment of an extracted beam. Therefore, it is crucial to improve the X-ray detection efficiency, as well as to control and improve the signal-to-background ratio for a successful observation of the kaonic deuterium X-rays. The experimental setup consists of three main parts:

- the lightweight cryogenic deuterium target cell filled with gaseous deuterium,
- recently developed Silicon Drift Detectors (SDDs),
- and the charged particle tracking system of the K1.8BR spectrometer [6].

The lightweight cryogenic target cell is 200 mm long and has a diameter of 65 mm. The walls of the cell are made of two layers of 50 μm Kapton foil, glued together with epoxy, resulting in a total thickness of 130 μm to withstand a pressure of 0.35 MPa at a temperature of 29 K. The optimal gas density has been determined by a Monte Carlo (MC) study to be in the order of 5 % of the liquid deuterium density with the criterium to stop enough kaons coming from the K1.8BR beam at J-PARC and still ensure that enough kaons reach the ground state, which is inversely proportional to the gas density (Stark effect).

The main requirements for the newly developed SDDs, besides the quest for a stable performance, mainly in terms of peak stability and latch-up performance in a high radiation environment, are given by a MC simulation:

- The energy and drift time resolution should be in the order of 200 eV at 8 keV and of 300 ns at 120 K, respectively.
- The design of the detector device should allow an efficient, dense arrangement of the SDD arrays around the target cell with an active to total area ratio of ~ 70 %.

The drift time is defined as the time an electron needs to reach the anode depending on the position where the X-rays hit the detector. In total 48 SDDs will be used. They are connected to 24 shaping amplifier boards outside the vacuum chamber. One amplifier can boost and shape the signal of two SDD arrays. To compensate for differences of SDD units, every amplifier board provides manual settings of trigger and reset thresholds. Due to the special layout of the K1.8BR multi-purpose spectrometer inside a magnet (which will also be used for the E57 experiment "Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium at J-PARC") a line-driver has been developed with enough power to overcome the large distance between SDDs and amplifier boards. The K1.8BR multi-purpose spectrometer has very unique features, namely a large acceptance cylindrical spectrometer system (CDS), consisting of a cylindrical drift chamber (CDC) for charged particle tracking and a cylindrical detector hodoscope (CDH) surrounding the CDC. These components are essential for the kaonic deuterium X-ray measurement for an efficient background reduction. A schematic picture of the target and detector system for the K^-d experiment is shown in figure 1.

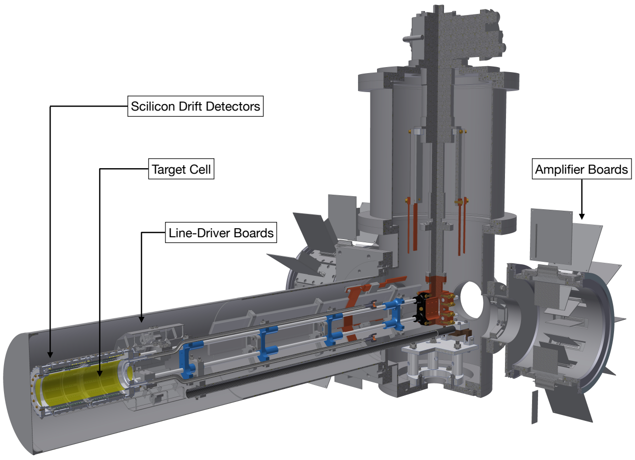

Figure 1. The target and SDD system for the kaonic deuterium measurement at J-PARC.

2.1. Newly Developed Silicon Drift Detectors

New SDD arrays were developed at FBK together with Milano Politecnico, LNF-INFN and SMI for the kaonic deuterium experiments E57 and SIDDHARTA-2. 48 SDD arrays will be arranged around the target cell. One SDD array consists of eight single SDD units, each with an active area of $8 \times\ 8$ mm^2. Due to the special layout of the SDD arrays with only a dead area margin of 1 mm and a special layout of the support structure the dead area of the total detector system could be minimised. This increases the active to total area of the detector compared to the previously used SDDs in the SIDDHARTA experiment from 20 % to the order of 70 %. Figure 2 shows the layout of one SDD array including the channel numeration and the dimensions.

A significant improvement compared to the previously used SDDs is the change of the preamplifier system from a JFET structure, implemented close to the anode of the SDD chip, to a CMOS preamplifier (CUBE) mounted on the ceramic carrier directly connected to the anode [7]. This makes the SDDs almost independent of the applied bias voltages as well as on temperature fluctuations, increasing their stability. Thus, they should only show minimal fluctuations of peak position and energy resolution (a few eV for both), guaranteeing an efficient summing of 384 SDD channels. This allows the determination of the K^-d peak position with a precision of 60 eV and of the width with a precision of 140 eV. An additional advantage of the CMOS system is the better latch-up performance, making the SDDs robust against high event rates up to 100 kHz. Furthermore, a better drift time can be achieved with the newly developed SDDs (300 ns at 100 K compared to 800 ns of previous SDDs), essential for further background reduction.

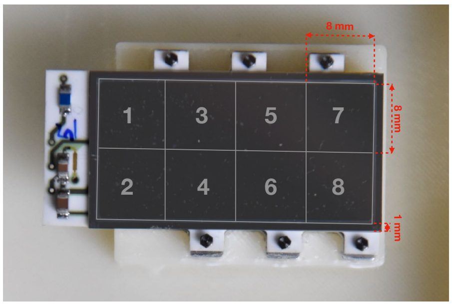

Figure 2. The layout of the Silicon Drift Detectors used for the kaonic deuterium experiments E57 and SIDDHARTA-2.

3. Recent SDD Tests at the Stefan Meyer Institute

First test measurements of stability and energy resolution have shown that the requirements needed for a successful $K^{-}d$ experiment are fulfilled and have been reported in [8]. The complete characterisation of the SDDs including the determination of the drift time and the crosstalk behaviour, as well as a more precise evaluation of the energy resolution is given in the following paragraphs.

3.1. Drift Time Measurement

One of the most important test measurements was to determine the drift time of the newly developed SDDs. To do so, a simple test arrangement was set up, using a Sr-90 source, which is a $\beta-$emitter (with maximum electron energies of 546 keV and 2280 keV), a 21 μm copper foil and a thin plastic scintillator with a thickness of 1 mm. The electrons passing the scintillator might produce fluorescence X-rays, and therefore the timing signal of the scintillator was used as a time stamp for signals (which include produced Cu K_α X-rays and electrons from the Sr-90 source) detected by the SDD array. Dedicated MC studies and a test measurement with a previous SDD type have shown that the difference in drift times between signals produced by X-rays and electrons is smaller than the error bar, and is thus negligible. Therefore, in this drift time analysis signals originating from both Cu X-rays as well as overflow events (electrons) have been included to get a high statistic. The time difference between the scintillator and one channel of the SDD array was determined with a Time-to-Digital-Converter (TDC) of the type V1290 (CAEN). A drift time of 500 ns at a temperature of T = 155 K has been achieved (see figure 3). Regarding measurements performed at LNF with the same type of SDDs in the temperature range from 100 to 210 K, a drift time of 300 ns was achieved at a temperature of 100 K (the SMI measurement of 500 ns at 155 K fits within the error bar).

3.2. SDD Energy Resolution

Furthermore, the energy resolution of one SDD array has been evaluated at a temperature of T ∼150 K, including the full detection chain:

- starting with the CUBE preamplifier (directly mounted on the SDD-ceramic board),
- a 200 mm long Kapton cable (connecting the SDD with the line-driver board),
- the line-driver board (a simple broadband 1:1 amplifier to allow for longer cable length),
- a 1500 mm flat-band cable (between line-driver and vacuum feedthrough), and

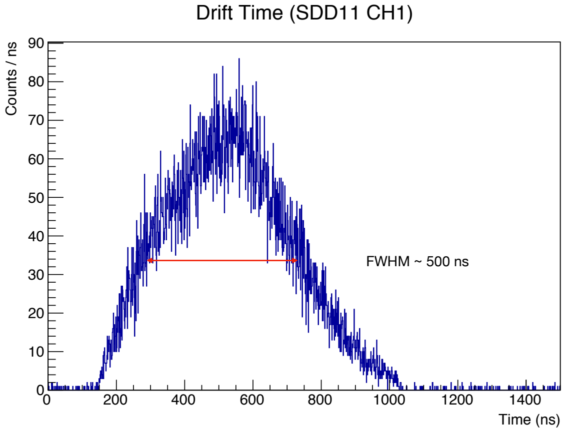

Figure 3. Drift Time measurement of one SDD channel at T =155 K. The figure shows the time difference between the timing signal of the scintillator and the SDD array.

- the vacuum feedthrough with the amplifier board directly connected on the outside of the vacuum chamber.

To partly resemble the high background of the K1.8BR beam line at J-PARC a Sr-90 source has been used with an additional Cu foil placed beneath it to produce Cu X-rays with a time stamp as described in the previous section. Data has been taken for a time span of five days with an Analog-to-Digital-Converter (ADC) of the type V785 (CAEN).
The energy calibration has been achieved by subtracting the ADC pedestal (FWHM = (8.74 ± 0.01) ADC channel at (75.70 ± 0.01) ADC channel) from the Cu K_α peak, leading to a value of the K_α peak of (1297.64 ± 0.21) ADC channel. By dividing the literature value from [9] of the Cu K_α peak (taking the weighted average of $K_{\alpha,1}$ and $K_{\alpha,2}$ results in 8041.1 eV) with the experimentally obtained ADC channel value, one gets a conversion factor of (6.197 ± 0.001) eV/ch.
Representatively, the result for channel 4 of SDD No. 18 can be seen in figure 4, providing an energy resolution of the Cu K_α peak at (1373.34 ± 0.21) ADC channel of FWHM = (31.27 ± 0.22) ADC channel, which corresponds to FWHM = (193.78 ± 3.25) eV. The achieved energy resolution fulfils the necessary requirement (energy resolution at 8 keV of < 200 eV) for the E57 experiment.

3.3. Crosstalk Evaluation

Lastly, the crosstalk probability between all eight SDD cells of SDD No. 18 has been evaluated for the same data sample that has been used for the determination of the energy resolution. It was expected that a splitting of charge will mainly occur if an X-ray hits the border between two SDD cells (see SDD layout, figure 2).
Representatively, crosstalk events between channel 7 and channel 5 can be seen in figure 5. Only events above an ADC channel value of 500 (approx. 3 keV) have been included in the analysis. The charge splitting of the Cu K_α peak (meaning events with a total energy of $\sim$ 1373 ADC channel of both SDD cells) is shown by the red circle. As the Cu K_α peaks of channel 7 and channel 5 hold approximately 12,000 events each, and the number of crosstalk events in this case amounts to $\sim$ 60 events, it is indicated that $\sim$ 0.25 % of the charge at (8.0 ± 0.5) keV is split between neighbouring channels, which could be recovered by a detailed offline analysis.

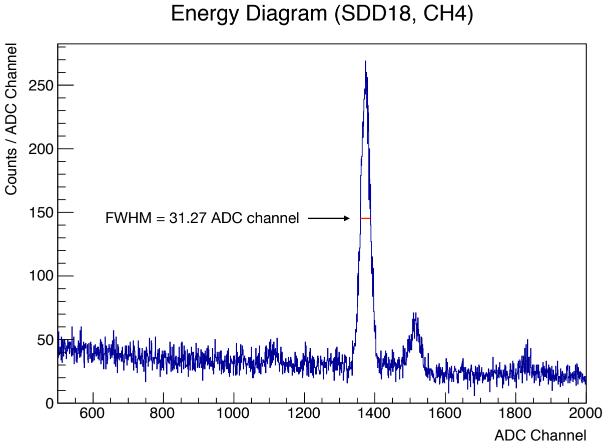

Figure 4. Energy resolution measurement of one SDD channel at T ~150 K.

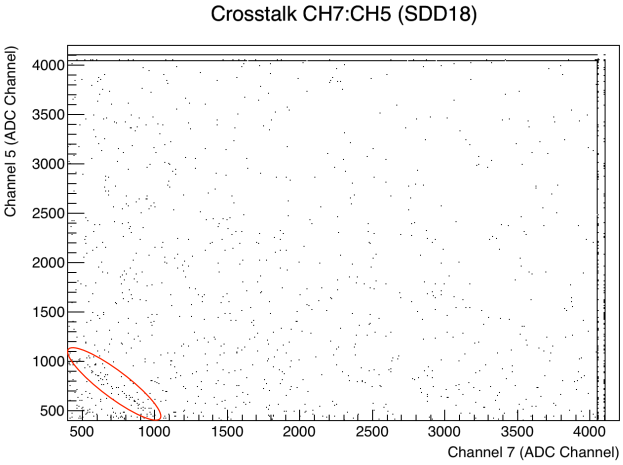

Figure 5. Crosstalk events between channel 7 and channel 5 of SDD No. 18. The red circle indicates the charge splitting for the Cu K_α peak.

A more detailed crosstalk evaluation includes the study of an overflow event (event with an energy higher than 4000 ADC channel, corresponding to an energy higher than 24.8 keV) in one SDD cell, because overflows will be the most likely background event under real conditions at J-PARC. As an example the following condition has been studied: An overflow event detected by channel 7 has been compared with signals detected in coincidence with all other channels. The coincidence channel values have been divided into four different energy regions (see table 1):

(i) The probability for a signal between the trigger threshold and the beginning of the region of interest, where the Cu K_α peak is expected. This corresponds to an energy region from 3.1 to 7.8 keV and is presented in column 2.

(ii) The probability for a signal with an energy in the region of interest, around the Cu K_α peak. This corresponds to an energy region from 7.8 to 9.3 keV and is displayed in column

3.

(iii) The probability for a signal from the end of the region of interest close to the overflow peak. This corresponds to an energy region from 9.3 to 24.7 keV and is given in column 4.

(iv) The probability for an overview signal. This corresponds to an energy above 24.8 keV and is presented in column 5.

The number of overflow events for channel 7 amounts to 2.9 $\times 10^6$. As can be seen in table 1, the fraction of detected signals below overflows in the other channels are in the order of a few times 10^{-4}. Furthermore, the probability in the region of interest has been determined to stay below 0.02 % for non-neighbouring channels, while for neighbouring channels a value below 0.05 % is achieved.

This crosstalk evaluation can be extended to the crosstalk expectation for the E57 experiment, as the region of interest of the kaonic deuterium K-lines lies between 5 to 9 keV, and this energy region is covered by the first two energy regions (column 2 and 3 of table 1). Even though the number of crosstalk events seems to be small, the crosstalk events in the region of interest are higher if a charged particle was passing through one of the cells distributing charge in the undepleted bulk of the silicon beneath the depleted region, which will diffuse not only to neighbouring cells. For the K^-d experiment the whole SDD array will thus be discarded. A dedicated MC simulation has shown that this will reduce the background by almost a factor of 3, and result in a signal reduction of approximately 5 %.

The most probable case of crosstalk events is shown in column 5, namely if channel 7 is detecting an overflow event and in addition, one of the other channels shows an overflow event in coincidence with channel 7, too. This case is in the order of 4 to 6 % for the neighbouring channels 5 and 8, 2 % for channel 6 (only one of their corners lying close together), and between 1 to 2 % for the remaining channels. The chances of detecting simultaneous overflow events between cell 7 and cell 1 are higher than expected (as they are completely separated by other SDD cells) and might result from the fact that on the connector, which is mounted on the ceramic board, both signal lines are running next to each other without ground line in between. Therefore, this result might origin from electronic crosstalk rather than from crosstalk on the SDD itself. For the kaonic deuterium measurement these events are not a problem, as they are far above the region of interest, and this SDD array will be neglected in the final analysis.

Table 1. Determination of the crosstalk probability between channel 7 detecting an overflow event ($x > 4000$ ADC channel) and all other channels in different ADC Channel regions: between the trigger threshold and the region of interest, the region of interest around the Cu K_α peak, between the region of interest and the overflow peak, and the ADC channel region for an overflow event.

Channel	$500 < x < 1250$	$1250 < x < 1500$	$1500 < x < 4000$	$4000 < x$
1	0.024 %	0.015 %	0.039 %	1.841 %
2	0.025 %	0.012 %	0.037 %	0.737 %
3	0.023 %	0.014 %	0.040 %	1.449 %
4	0.024 %	0.014 %	0.039 %	1.356 %
5	0.164 %	0.045 %	0.271 %	3.870 %
6	0.039 %	0.016 %	0.054 %	2.058 %
8	0.174 %	0.050 %	0.319 %	6.331 %

4. Summary and Outlook

Satisfying performance has been achieved with all tested SDDs. The drift time of 500 ns at a temperature of 155 K is as expected, and will be determined again at lower temperatures. With an energy resolution of the Cu K_α peak in the order of 190 eV and a peak stability in the order ± 1.5 eV (see [8]) the summing of 384 channels can be guaranteed, allowing for a determination of the kaonic deuterium shift and width with a precision of 60 eV and 140 eV, respectively.
Concerning the crosstalk of one SDD array it can be said that the probability of crosstalk between a channel detecting a high energy signal and another channel detecting a signal in the region of interest is lower than 0.1 %.
The final important test of the SDD arrays has been achieved during the E62 kaonic helium experiment (together with high resolution TES detectors) at J-PARC in June 2018. Four SDDs were used to determine the X-ray yields of transitions to the He 2p-state, as well as to study the performance of the SDDs under real conditions in the environment of a hadron beam facility. The first analysis of the data have confirmed that the new SDDs are working without problem (concerning their stability and their energy and time resolutions) in the environment of an accelerator.

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References

[1] Iwasaki M *et al.* 1997 *Phys. Rev. Lett.* **78** 3067
[2] DEAR Collaboration 2005 *Phys. Rev. Lett.* **94** 212302
[3] SIDDHARTA Collaboration 2011 *Phys. Lett.* **B 704** 113
[4] Ikeda Y, Hyodo T and Weise W 2011 *Phys. Lett.* **B 706** 63
[5] Mai M and Meißner U−G 2013 *Nucl. Phys.* **A 900** 51
[6] Agari K *et al.* 2012 Prog. Theor. Exp. Phys. 02B011
[7] Bertuccio G *et al.* 2015 Journal of Instrumentation **10** P01002
[8] Trippl C, Zmeskal J *et al.* 2018 *EPJ Web of Conferences* **181** 01035
[9] Thompson A *et al.* 2009 *X-Ray Data Booklet* (Berkeley, CA: Lawrence Berkeley National Laboratory)