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A New Silicon Drift Detector For Kaonic Deuterium Measurements

On behalf of the E57 collaboration at J-PARC

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Abstract. The interaction of antikaons with nucleons and nuclei in the low-energy regime is a very active research field in hadron physics. Specially, the antikaon-nucleon interaction close to threshold provides crucial information on the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD and touching one of the fundamental problems in hadron physic today - the still unsolved question of how hadron masses are generated. To study this problem, we have developed a new X−ray detector system and constructed an experimental apparatus to measure the kaonic deuterium 1s ground state shift and width with an accuracy of 60 eV and 140 eV, respectively.

1 Introduction

For kaonic hydrogen atoms a detectable energy shift of the 1s ground state has been found induced due to the strong interaction, as well as an observable energy broadened ground state level, caused by nuclear absorption. Measuring these observables kaonic hydrogen atoms offer the unique possibility to determine s−wave antikaon−nucleon scattering lengths at almost zero energy. Although the importance of a kaonic deuterium X−ray measurement has been well recognised, no experimental results have yet been obtained due to the difficulty of such a measurement. A determination of the isospin dependent (I=0 and I=1) antikaon−nucleon scattering lengths will be only possible by combining the result of the kaonic hydrogen and deuterium measurements. This combined result will provide the most stringent constraints on the antikaon−nucleon interaction at low energy, promising a breakthrough for this field.

1.1 State-of-the-art

The K^-p interaction is well understood from the recent results of kaonic hydrogen obtained from KpX [1] at KEK, DEAR [2] and finally from SIDDHARTA [3] at DAΦNE and the theoretical calculations based on these results [4], [5]. A milestone was the KpX experiment solving the long standing kaonic hydrogen puzzle (the old kaonic atom experiments were in contradiction with scattering data and theory). Although the importance of kaonic deuterium X−ray spectroscopy has been well recognised for more than 30 years (R.H. Dalitz [6]), no experiments have been performed so far due to the difficulty of the X−ray measurement.

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"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 antikaon−nucleon scattering lengths a_0 and a_1.", quoting from U.−G. Meisser [7]. We have now designed and constructed an apparatus which will allow us to measure the kaonic deuterium X−ray spectrum at J-PARC [8].

2 K⁻d Apparatus for J-PARC

The K⁻d setup consists of three main parts: The **Cryogenic Target Cell**, which will be filled with gaseous deuterium, is surrounded by 48 newly developed **Silicon Drift Detectors** (SDDs) connected to 24 **Amplifier Boards**, which are stationed outside of the vacuum chamber. In Figure 1 the setup is shown schematically. The distance between SDDs and amplifier boards is due to the dimensions of the E15 setup inside a magnet, in which the K⁻d apparatus will be placed.
For detailed information on Silicon Drift Detectors see chapter 3.

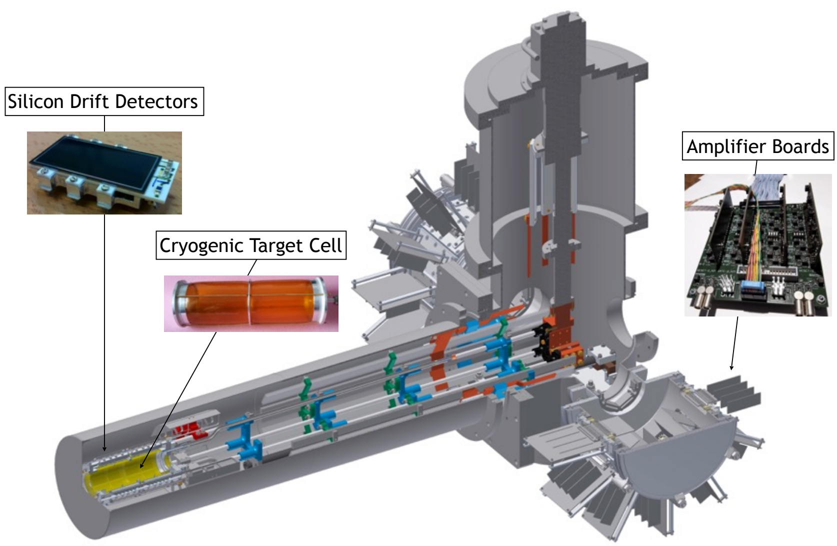

Figure 1. Schematic setup of the E57 Experiment at J-PARC

Kaons, which come from the K1.8BR beam at J-PARC, are stopped inside the cryogenic target cell and form kaonic deuterium atoms. The target cell, with dimensions of 65 mm in diameter and 200 mm in length, is cooled down to 29 K and is able to withstand a pressure of 0.35 MPa. The walls of the target cell are made of two layers of a 25 μm thick Kapton foil and the cell has been tested successfully to withstand a pressure up to 0.7 MPa. To achieve a good stopping rate of kaons, but still keep the X-ray yield (the probability that the kaon reaches the 1s ground state, which is inverse proportional to the gas density) as high as possible an optimal gas density has been found by performing a dedicated MC simulation to be in the order of 5% of the liquid deuterium density. Therefore, the wall of the lightweight

cryogenic target cell have been constructed as thick as necessary to safely hold a target pressure of 5% gas density, but still thin enough to provide sufficiently high transition for K_α photons, in the order of 70-80% at 6 keV.
The amplifier boards are arranged on two sides outside of the vacuum chamber. The amplification is performed in two steps: Firstly, a single amplification is done, and secondly, in addition to the amplification the shaping of the signal is carried out. Typically, the shaping time of the signal can be set between 1 to 5 μs. Furthermore, the adjustment of trigger and reset thresholds are necessary as differences of individual SDD channels have to be compensated.
Due to the large distance between the SDDs and amplifier boards in the final setup at the J-PARC accelerator, a line-driver has been developed to connect the SDD arrays inside the vacuum chamber with the amplifier boards stationed outside of it. The line-driver is a 1 : 1 amplifier with low power consumption, placed closely to the SDDs, and is connected via a one metre cable to the amplifier boards outside the vacuum chamber. For all tests performed at the Stefan Meyer Institute the configuration for the final measurement has been used.

3 Newly developed Silicon Drift Detectors

The main requirements for newly developed Silicon Drift Detectors are:

- Optimised active to total area ratio in the order of 80% (compared with 20% of the previously used SDDs)
- Drift time less than 300 ns at low temperatures (compared with 800 ns of the previously used SDDs)
- Robust against high charge load (better letch up performance)
- Peak stability better than ± 5eV
- Energy resolution better than 180 eV
- High rate capability 20 kHz

A dedicated Monte Carlo simulation (using Geant 4) has shown that with this assumption a K^-d experiment at J-PARC will be feasible. The requirements for peak stability, energy resolution and high rate capability are similar as for the former used SDDs. An optimised active to total area will allow an efficient packing density around the target cell increasing the detection efficiency, while the reduced drift time is essential for additional background reduction. The more simple design without FET of the newly developed SDDs, but with a small CMOS preamplifier chip (CUBE) mounted in close vicinity to the anode, will reduce the letch up probability drastically. In addition, a lower working temperature of the new SDDs will reduce the drift time to 300 ns at about 100 K. For the final setup the working temperature of the SDD should be as low as 50 K.

3.1 SDD Layout

The detection area around the target cell will be covered by 48 Silicon Drift Detector modules. One SDD array consists of eight square SDD units, each providing an active detection area of 8×8 mm^2. Thus, the complete active area of the detectors adds up to 246 cm^2. Due to the special design of the layout, the dead area of one SDD array is minimised, with only a margin of 1 mm on all four sides of the array. Another advantageous feature of the new Silicon Drift

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Detectors is the special layout of the support structure. With the small bulges on two opposite sides of the SDD the arrangement of the SDD arrays around the target cell is simplified and additionally reduces the dead area of the detector.
As usual, three different voltages have to be applied to provide the electric field which forces the electrons to the collection anode and the holes to the back.
The newly developed Silicon Drift Detectors are directly connected to a CUBE preamplifier on the support structure. Compared to the previously used JFET structure of the SDD chip, the now used CMOS is not as dependent on the applied voltages and shows less changes due to temperature fluctuations. This means that both peak position as well as energy resolution (width) should show fluctuations of only a few eV. This is necessary to allow the summation of almost 400 SDD channels for the determination of the $K^{-}d$ peak position in the order of 50 eV and the peak width in the order of 100 eV.
A high intrinsic efficiency for X-rays in the energy range from $5 - 15$ keV is provided due to a small thickness of the SDD arrays of 450 μm, which makes them also less sensitive to MIPs compared to e.g. HP Ge detectors. It is necessary for the SDDs to cope with high count rates up to 100 kHz in combination with readout electronics, and to have a high yield of active to total area.

3.2 SDD tests at the Stefan Meyer Institute

Several test measurements have been performed at the Stefan Meyer Institute, including tests on stability as well as dependence on the applied voltages. The test setup is shown below (Figure 2). It is important to emphasise that the setup uses the same distances as in the final setup at J-PARC for all tests, including the line-driver element and the one metre long cable.

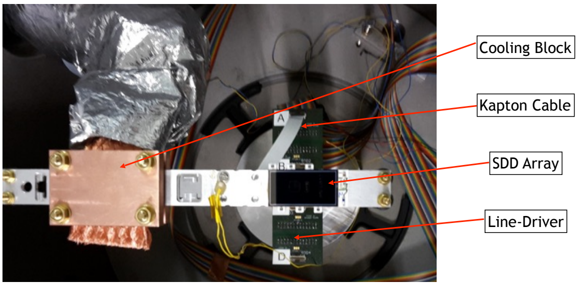


Figure 2. Test setup of the E57 experiment at the Stefan Meyer Institute including the cooling block, one single SDD array and the line-driver

The first tests have been dedicated to improve the energy resolution of the SDDs. For the energy calibration a Fe-55 source with an additional titanium foil has been used to produce characteristic X-Rays. In Figure 3 the energy calibration of one SDD unit (channel 2) can be seen. The first two peaks of the spectrum correspond to the Ti K_α and the Ti K_β transitions;

the third and fourth peak are the Mn K_α and the Mn K_β lines.
At a temperature T = (165 ± 2) K an energy resolution FWHM = (152.59 ± 0.45) eV has been achieved.

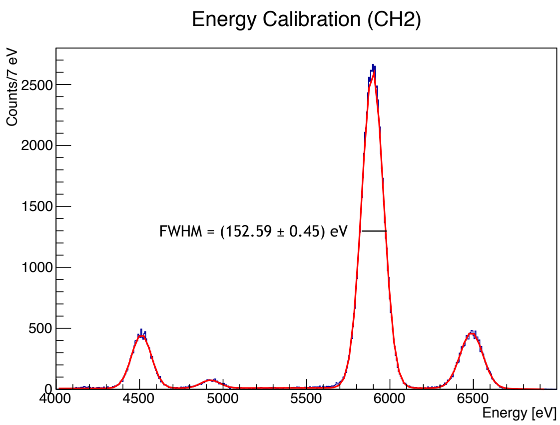
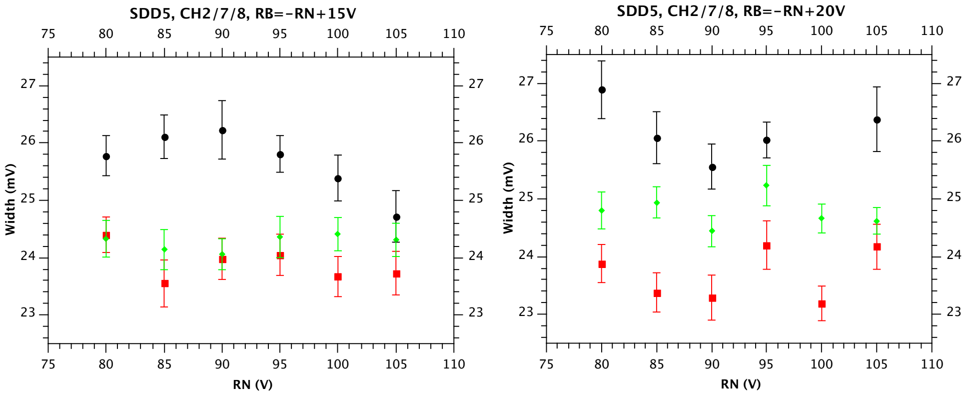


Figure 3. Energy calibration of one SDD channel (channel 2) obtained with a Fe-55 source and an additional Ti foil.

The second test measurement was performed to determine the voltage configuration applied to the SDDs to be able to achieve the best energy resolution. For this the voltage applied to the innermost ring, R_1, was set to be constant on $R_1 = -16.0$ V; the voltage applied to the outermost ring, R_N, and the back voltage, R_B, have been varied in steps of 5 V, always keeping a difference of 15 V and 20 V between R_N and R_B. The result can be seen in Figure 4 . There is very little change between the different configurations. However, the best value for the width for all channels was achieved for a voltage supply of $R_N = -90.0$ V and $R_B = -70.0$ V.



(a) (b)

Figure 4. Voltage configuration of three SDD channels (black = CH2, red = CH7, green = CH8) with different R_B to R_N interval.

Finally, to determine the stability of the Silicon Drift Detectors when operating, the Mn K_α drift and width has been analysed over a period of almost seven days. The data has been divided into packages of eight hours, showing an insignificant variation of the Mn K_α width in the order of ±0.2 ADC channel (Figure 5). The same is true for the Mn K_α peak, which varied only in the order of ±0.25 ADC channel (= ±1.0 eV). Both results indicate very good stability of the SDD over a long period of time and therefore ensure the excellent performance of the SDDs during the experiment to determine the K-d peak position and peak width.

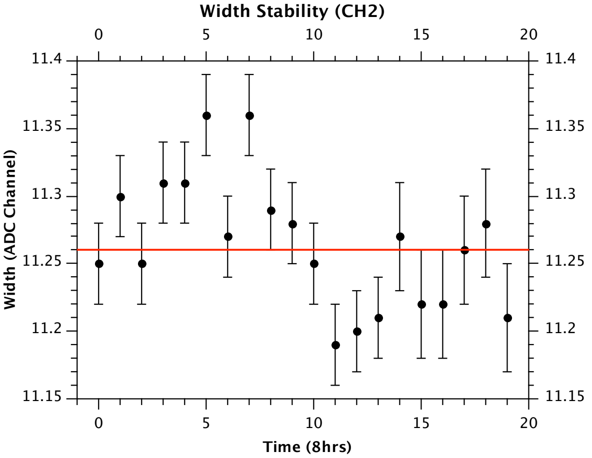


Figure 5. Width Stability of the Mn K_α width of one SDD channel (channel 2). The red line indicates the average width of the data sample corresponding to 148.0 eV with fluctuations of ±1.0 eV.

4 Summary and Outlook

Most of the requirements described in the first paragraph of chapter 3 have been successfully tested. The SDDs provide a good peak (and width) stability in the order of ± 1 eV as well as an energy resolution of 160 eV, which is better than necessary, but will help in adding up all 384 channels for the kaonic deuterium measurement.
To be able to reach temperatures of around 50 K, the cooling system has to be changed. This will reduce the drift time to 200 - 300 ns, thus reducing the background events drastically.
Furthermore, a time resolution (drift time) measurement will be performed. Using a Sr−90 source (an electron emitter) placed in front of a scintillator a start signal will be produced, and the time difference between the scintillator and the SDD will be measured.
Finally, more than 40 SDDs still have to undergo testing to check their functioning and stability. Nevertheless, considering the good measurements performed until now, we are very optimistic to reproduce these positive results.

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