

Performance Evaluation of Silicon Drift Detectors for a Precision X-ray Spectroscopy of Kaonic Helium-3

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Abstract. We are preparing Silicon Drift Detectors (SDDs) for a precision spectroscopy of kaonic helium-3 $3d \rightarrow 2p$ x-rays (~ 6.2 keV) at J-PARC (E17, DAY-1). Since we need to operate SDDs and their preamplifiers in a cryogenic system, their low-temperature behavior was investigated. The optimal operational temperatures were found to be 110 - 130 K and over 270 K for SDDs and preamplifiers, respectively. In such condition, energy resolution is around 150 eV (FWHM) with 5.9 keV x-rays and time resolution is around 400 ns (FWHM). We also investigated the effect of different incident angles to verify our calibration method in E17. Although response function depends on incident angle, Mn $K\alpha$ peak positions differ at most 0.5 eV equivalent. Further basic studies of SDDs are ongoing toward the physics run planned in 2011.

1. Introduction

Kaonic atoms are K^- -nucleus Coulomb bound systems, whose energy level shifts and widths can provide the unique information on \bar{K} -nucleus strong interaction at threshold energy [1]. Recently, the use of Silicon Drift Detectors (SDDs) are becoming popular for their x-ray spectroscopies, especially with low Z number targets [2, 3].

In our case, 8 SDDs manufactured by KETEK [4] will be used for a spectroscopy of kaonic helium-3 x-rays at the K1.8BR beam line in the J-PARC hadron facility (E17, DAY-1) [5–7]. We aim to determine the absolute energy of $3d \rightarrow 2p$ x-rays (~ 6.2 keV) with a precision better than 2 eV so as to distinguish ~ 0 eV $2p$ shift calculated with an optical model [1] from a possible large shift (<15 eV) predicted in connection with deeply bound kaonic nuclei by Akaishi [8].

To assure such high precision, a careful optimization of the operation condition and deep understanding of the detector response are essential. In KEK and J-PARC, we are performing various measurements for this purpose. In this paper, the measurements studying SDD low-temperature behavior and the effect of different incident angle will be described, following an explanation of an SDD.

2. Silicon Drift Detector

Silicon Drift Detector (SDD) is a state-of-the-art semiconductor detector based on the principle of side-ward depletion introduced by Gatti and Rehak [9]. When it is customized for x-ray spectroscopies, concentric ring-shaped p^+ junction stripes are placed on one side of an SDD as well as small n^+ ohmic substrate contact in their center acting as a collecting anode. The opposite surface is made of a non-structured p^+ junction as a homogeneous radiation entrance window. When proper reverse-bias voltages are applied, high-resistivity n-type silicon is fully depleted side-ward and at the same time electron drift field to a collecting anode are created along both axial and radial direction. Thus, all the electrons induced by an x-ray injection are collected to the small anode.

As a result, an SDD has advantages such as i) good energy resolution, ii) large effective area, iii) thin active layer which suppresses the Compton background, iv) sub- μ s time resolution. A comparison with previously-used x-ray detectors for spectroscopies of kaonic atoms is summarized in Table 1.

Table 1. Comparison of x-ray detectors used for kaonic x-ray measurements.

Detector	Si(Li)	CCD	SDD(KEK)	SDD(E17)
Effective area (mm^2)	200	724	100	100
Thickness (mm)	5	0.03	0.26	0.45
Energy resolution (FWHM) @ 6 keV (eV)	410	170	185	<150
Time resolution (FWHM) (ns)	290	-	430	~ 400
References	[10–12]	[13–15]	[2]	this paper

3. SDD basic study

3.1. Measurement method

In J-PARC E17, SDDs are placed near the target for larger acceptance. Their preamplifiers are also operated in a cryogenic target system because they should be as close as SDDs to minimize cable length for better resolutions. In addition, both SDDs and preamplifiers should be surrounded by liquid-nitrogen-cooled materials for a minimal thermal effect to the liquid helium-3 target. Then, proper thermal insulators such as teflon washers and Kapton tapes are installed to heat up only SDDs and preamplifiers themselves.

We realized such conditions also in our test cryostat like Fig. 1 and detailed studies of SDDs and their preamplifiers are performed therein. An SDD can be exposed to checking sources outside the vacuum through mylar window. An ^{55}Fe source (Mn $K\alpha \sim 5.9$ keV) was used to

check energy resolution and to study response function. In a time resolution measurement, a PIPS (Passivated, Implanted, Planar Silicon) detector [16] was placed between an SDD and a ^{90}Sr source to measure the timing difference of electron hits on an SDD and a PIPS. Time resolution of a PIPS was measured to be ~ 50 ns (FWHM), which is an order better than that of SDDs.

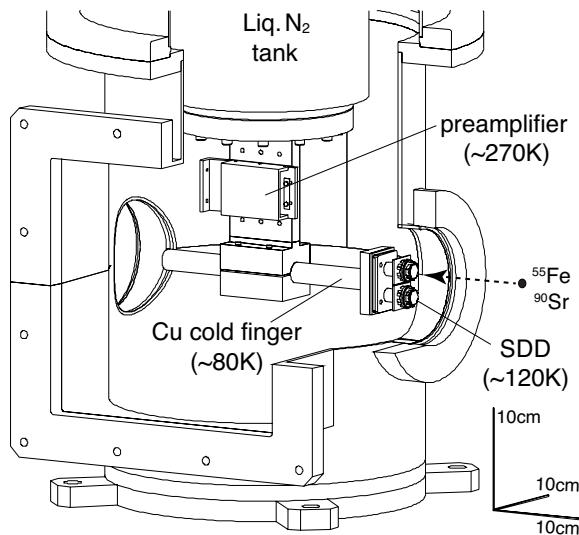


Figure 1. Schematic view of the test cryostat.

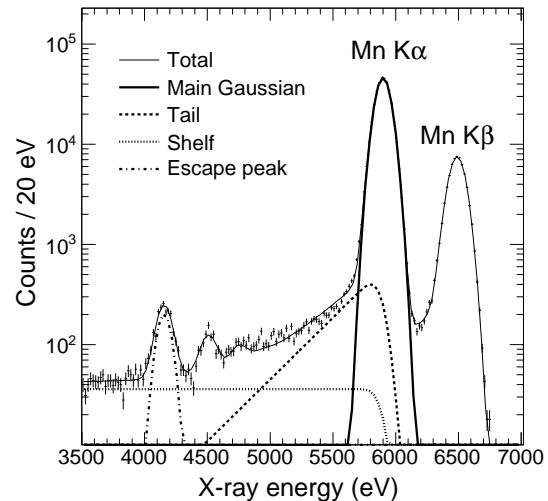


Figure 2. Typical ^{55}Fe spectrum. The resolution is ~ 150 eV (FWHM) at 5.9 keV.

3.2. Response function

There are many empirical studies on the response function of conventional Si(Li) detectors [17]. Based on these studies, we defined the response function of our SDDs.

For a main peak, a *Gaussian* is used instead of a Voigtian because natural widths of characteristic x-rays are much smaller than detector resolution. *Tail* and *Shelf* are considered to be caused by incomplete charge collection, and escapes of a silicon K x-ray result in *Escape peak*.

Figure 2 shows a typical ^{55}Fe spectrum fitted with the response function described above. Titanium contamination is also considered here just for better chi-squares. We may improve our spectral fitting introducing radiative Auger electron peaks, satellite peaks (in charged particle-induced case) and tail structure particularly caused by the Compton scattering in the mylar window etc.. These may have effect to absolute peak position and the absolute strength of *Tail* component. However, these are unnecessary for our present interests; energy resolution, relative peak position and relative intensities of each component in various conditions.

3.3. Preamplifier temperature

We succeeded in operating our preamplifiers in a vacuum chamber. However, when they are mounted on a support cooled with liquid nitrogen, we need to heat up them at least over 200 K, otherwise they may be broken.

At temperatures between 240 K and 290 K, we found energy resolutions are stable and Mn $K\alpha$ peak positions moves 0.5 eV equivalent every 1 K change. The instability of the peak positions is not a problem because we can control the temperature with < 1 K stability and in-situ energy calibration compensates gain fluctuations in the E17 experiment.

The most severe constraint on preamplifiers' temperatures are related to a *reset* mechanism. We usually need $\sim 300 \mu\text{s}$ VETO after *reset* to wait the baseline to be stable. At lower temperatures than a threshold around 260 K, however, the VETO time we need suddenly become much longer. It means preamplifiers should be kept at $> 270 \text{ K}$ including some safety margin.

3.4. SDD temperature

Our SDDs are designed for the use at room temperature with an integrated Peltier cooling element and their low-temperature behaviors were not known well before.

Measured energy and time resolution dependence on SDD temperatures are shown in Fig. 3. It shows energy resolution gets worse at temperatures lower than 130 K. Below 100 K, sometimes we cannot obtain x-ray signals. Usually, semiconductor detectors are operated in a low temperature ($< 150 \text{ K}$) to suppress the current noise caused by thermally excited carriers and the frequent *reset* caused by leakage current. However, the performance of an FET is known to become poor at such low temperatures. Our result may be explained such behavior of an integrated-FET on the SDD.

Time resolution becomes better as the temperature decreases. It can be well explained temperature dependence of electron mobility in silicon. We calculated electron mobilities in SDDs from the measured time resolutions assuming the drift time from the outer-most ring to center anode corresponds to the resolution (FWHM), that is,

$$\mu_e = \frac{L^2}{FWHM \times (V_{last} - V_{center})} \quad (1)$$

where, μ_e is electron mobility, L is drift length from the outer-most ring to the center anode, $FWHM$ is measured time resolution, V_{last} and V_{center} are applied voltages to the outer-most ring and inner-most ring, respectively. Figure 4 shows they are consistent with well-known data.

We also found Mn $K\alpha$ peak position moves $\sim 0.5 \text{ eV}$ equivalent every 1 K change, which is mainly due to the temperature dependence of electron-hole pair creation energy [18].

Considering both energy and time resolution dependence on temperature, we conclude 110 K - 130 K is optimal operational temperature for the SDD. Further fine tuning will be done in the final setup.

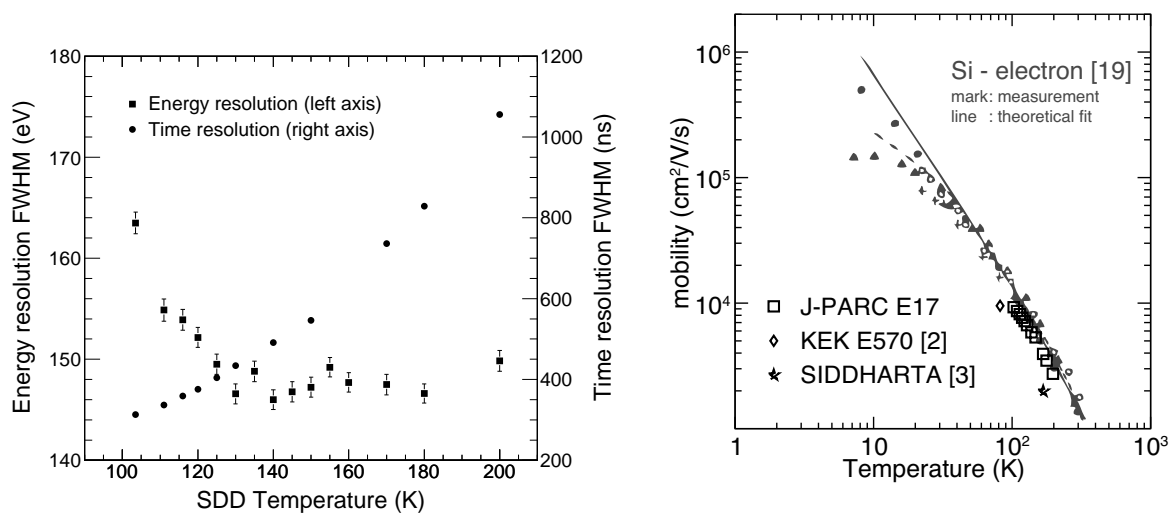


Figure 3. SDD temperature dependence of energy (square) and time (circle) resolutions.

Figure 4. Estimated electron mobilities in SDDs are compared to the previous measurements [19].

3.5. X-ray incident angle

In J-PARC E17, characteristic x-rays induced by the incident beam (mainly contaminating pions in the kaon beam) on pure titanium and nickel foils will provide an in-situ energy calibration. In addition, their spectrum will be used to estimate some parameters in the response function of kaonic helium-3 x-rays. However, there is a large difference in the incident-angular distribution between kaonic helium x-rays and characteristic x-rays as shown in Fig. 5.

To study the effect of the incident angle on an SDD, we measured the ^{55}Fe spectrum with various incident angles at the test cryostat, changing source position outside the vacuum chamber. We found the ratios of *Tail area*, *Shelf height* and *Escape peak area* to the main *Gaussian area* become larger with a larger incident angle (Figure 7). Considering larger incident-angle x-rays through an effectively thicker surface, our measurement implies most of energy losses occur at the surface of a detector.

To investigate the peak position difference between different incident-angle x-rays, which is found to be much smaller than a gain drift, we need an in-situ energy calibration. Keeping the position of nickel and titanium foils as well as a ^{90}Sr source for the calibration, an ^{55}Fe source was moved to be incident angles of 0 and 60 degrees. Although present statistics is not enough and the analysis is preliminary, Mn $K\alpha$ peak positions differ at most 0.5 eV equivalent in these two spectra (Figure 6).

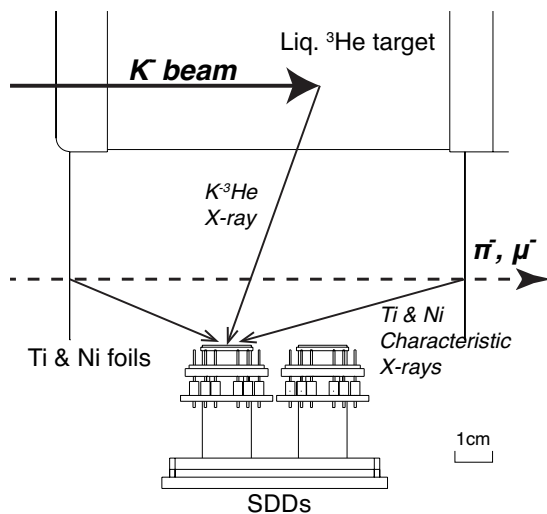


Figure 5. Schematic view around the target in J-PARC E17.

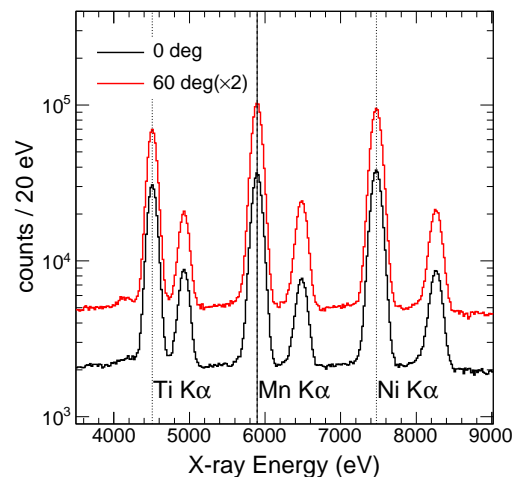


Figure 6. Comparison of two different incident angle spectra. Their energies are calibrated by characteristic x-rays of titanium and nickel.

4. Summary and Outlook

SDD low-temperature behavior was investigated and optimal operational condition for the SDD system was established. For our experiment, the optimal operational temperatures of SDDs are 110 K - 130 K and those of our preamplifiers are over 270 K. In such condition, we can achieve energy resolution around 150 eV (FWHM) with 5.9 keV x-rays and time resolution around 400 ns (FWHM).

We are also performing various studies to obtain a low-background spectrum and to determine absolute energy as accurate as possible from an obtained spectrum. They include the studies of linearity of the system, long-term stability, pileup rejection and response function dependence

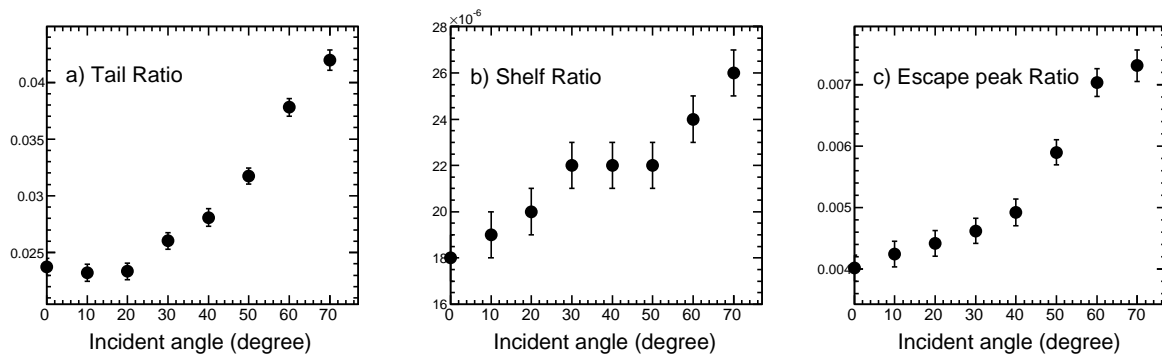


Figure 7. Incident-angle dependence of a) *Tail* area ratio, b) *Shelf* height ratio, c) *Escape peak* area ratio to *Main Gaussian* area.

on rate, incident energy, angle and position. In this paper, only the incident-angle measurement was described. We found energy-loss-originated components in the response function become larger with larger incident angle. However, Mn $K\alpha$ peak positions with different incident angles (0 and 60 degrees) differ at most 0.5 eV equivalent.

The development of the SDD and liquid helium-3 target system is also going steadily at J-PARC K1.8BR experimental area. We will perform an SDD commissioning in the coming autumn, especially to check detection rates of SDDs in a realistic beam and yields of characteristic x-rays for the energy calibration. Then, the physics run of E17 starts in 2011.

Acknowledgments

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