

## STUDIES OF THE LINEARITY AND STABILITY OF SILICON DRIFT DETECTORS FOR KAONIC ATOMS X-RAY SPECTROSCOPY\*

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The SIDDHARTA-2 experiment at the DAΦNE collider aims to perform precision measurements of kaonic atoms X-ray spectroscopy for the investigation of the antikaon–nucleon strong interaction. To achieve this

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goal, novel large-area Silicon Drift Detectors (SDDs) have been developed. These devices have special geometry, field configuration, and readout electronics that ensure excellent performance in terms of linearity and stability. The paper presents preliminary results for the linearity determination and stability monitoring of the SDDs system during the measurement of kaonic deuterium carried out in the summer of 2022.

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## 1. Introduction

The Silicon Drift Detectors (SDDs) [1, 2] combine the silicon  $p$ - $n$  junction response to ionizing radiation with an innovative electronic field design [3]. These devices play a key role in high-precision X-ray spectroscopy of light exotic atoms [4] due to their low electronic noise, good energy resolution, and high rate capability [5]. In particular, their excellent capabilities are exploited to extract the shift ( $\epsilon$ ) and width ( $\Gamma$ ) of atomic levels caused by the strong antikaon–nucleon interaction [6]. Experimental studies of light kaonic atoms provide a unique tool to investigate the non-perturbative quantum chromodynamics (QCD) in the strangeness sector [7, 8].

After the successful data-taking campaign of the SIDDHARTA (Silicon Drift Detectors for Hadronic Atom Research by Timing Application) experiment in 2009, resulting in the most precise measurement of the kaonic hydrogen ( $\bar{K}p$ ) fundamental level shift ( $\epsilon$ ) and width ( $\Gamma$ ) [9], the SIDDHARTA-2 Collaboration implemented several updates of the apparatus to perform the analogous, more challenging kaonic deuterium ( $\bar{K}d$ )  $2p \rightarrow 1s$  transition measurement [10]. The experimental facility is located at the DAΦNE collider [11] of the Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Frascati (INFN-LNF) in Italy.

The SDD detector, used in the experiment, is composed of a fully depleted  $n^-$  silicon cylindrical bulk, double-sided by  $p^+$  silicon doped electrodes [1, 2]. On one side, a layer of  $p^+$  concentric ring strips is biased with a negative voltage through an internal divider, while on the opposite side, a metalized non-structured  $p^+$  layer forms the radiation entrance window (see Fig. 1). The electrons produced by the absorbed radiation are focused by the radial drift field to the small  $n^+$  anode, placed in the center of the structured side and connected to the dedicated front-end electronics.

New monolithic large-area SDD arrays have been developed by Fondazione Bruno Kessler, together with Politecnico di Milano, INFN-LNF in Italy and the Stefan Meyer Institute (SMI) in Austria, to perform high-precision kaonic deuterium spectroscopy [3, 7]. The 450  $\mu\text{m}$  thick SDD array consists of a  $2 \times 4$  matrix of square cells (0.64  $\text{cm}^2$  area for each single unit), mounted on an alumina carrier. The signals coming from the

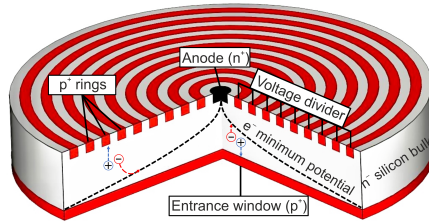


Fig. 1. Schematic layout of a cylindrical SDD. The dotted lines represent the drift field inside the bulk. Figure adapted from Ref. [12].

detectors are buffered by a CMOS low-noise charge sensitive preamplifier (CUBE [13]), directly connected to the  $n^+$  anode, then processed by a dedicated analog SDD front-end readout ASIC (SFERA [14]), and are digitized by an analog-to-digital converter (ADC, model NI-PCI 6115).

The SIDDHARTA-2 experimental apparatus [6, 10] consists of 48 SDD arrays, resulting in a total of 384 readout channels, and a luminometer built with plastic scintillators, based on J-PET technology [15–19]. As shown in Ref. [7], the precision on the evaluation of the shift and the width of the kaonic deuterium  $1s$  level is about 30 eV and 80 eV, respectively. Thus, the required precision of the SDD linearity is 10 eV in the energy region of interest (4–12 keV). Moreover, studies of the stability of the SDD system are mandatory to achieve the planned high-precision measurement of kaonic deuterium X-rays by keeping the systematic error within a few eV.

## 2. Linearity characterization

The SDD detector chain linearity studies were performed with an X-ray tube exciting a target made of high-purity titanium and copper strips [12]. Figure 2 (a) shows a typical spectroscopic response of a single SDD unit at  $-145^\circ\text{C}$ , irradiated by fluorescence emission from the target strips, activated by the X-ray tube operated at 25 kV and  $50 \mu\text{A}$ . Together with the titanium (Ti) and copper (Cu) lines, the Mn  $K_\alpha$  and Fe  $K_\alpha$  (produced by the excitation of other components of the setup) are also visible.

The spectral response of silicon detectors is predominantly described by a Gaussian function for each X-ray peak, with a low-energy tail due to the incomplete charge collection at the anode, and electron–hole recombination. Thus, the shape of the peaks was modeled taking into account the intrinsic Gaussian statistical spread and the tail effect [20–22].

The fit function (red curve in Fig. 2 (a)) reproduces the fluorescence lines coming from the target. The various contributions to the overall fit function are also shown. A constant plus an exponential function describes the background. The Ti  $K_\alpha$ , Fe  $K_\alpha$ , and Cu  $K_\alpha$  peaks were exploited to evaluate

the linearity of the detectors, due to their higher signal-to-background ratio. The positions of these peaks were determined as the centroids of Gaussians from the overall fit and plotted as a function of the tabulated energy values [23], and a straight line was used to interpolate the points (see Fig. 2 (b)). The slope of the fit function (in eV/channel) gives the gain parameter value of the spectrum.

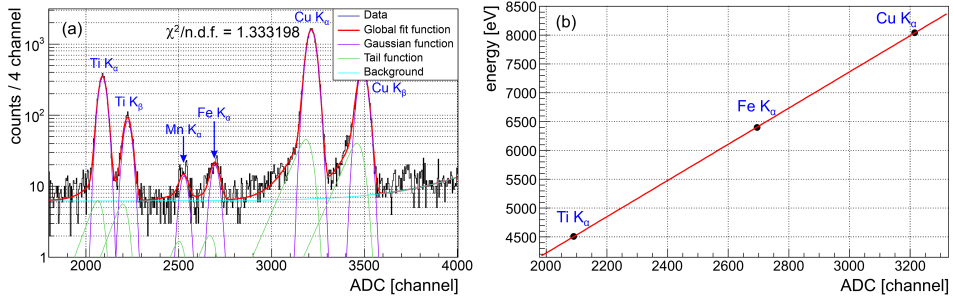


Fig. 2. (a) A fitted fluorescence spectrum for a single SDD in arbitrary ADC units. Red line shows the overall fit function consisting of a sum of Gaussian (violet line) and tail functions (green line) for each peak, together with a constant plus an exponential function to describe the background (cyan line). (b) Linear fit of the experimental  $K_{\alpha}$  peak positions as a function of the known energies of transitions.

The final energy spectrum is shown in Fig. 3 (a). The difference between each  $K_{\alpha}$  experimental calibrated point ( $P_i^{\text{exp}}$ ) with respect to its corresponding theoretical value ( $P_i^{\text{label}}$ ) was used for the evaluation of the system linearity

$$R_i = P_i^{\text{label}} - P_i^{\text{exp}}. \quad (1)$$

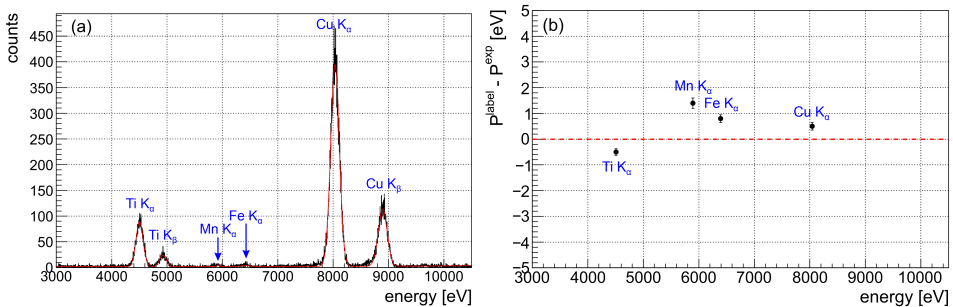


Fig. 3. (a) Calibrated energy spectrum of the single SDD. (b) Difference between each  $K_{\alpha}$  experimental calibrated point ( $P_i^{\text{exp}}$ ) with respect to its corresponding theoretical value ( $P_i^{\text{label}}$ ).

The distribution in Fig. 3 (b) shows that the peak energies differ from the theoretical values by less than 1.5 eV, setting the linear response  $\frac{\Delta E}{E}$  of the SDD below  $10^{-3}$ .

### 3. Stability

Another important aspect of the SDD system that needs to be monitored during high-precision measurements is its long-term stability, since it is a possible source of systematic error in the experiment. During the kaonic deuterium test measurement period, which took place in June–July 2022, 12 calibration runs were performed. For each SDD, fluctuations over time of the Cu  $K_\alpha$  peak position were used to control the stability (see Fig. 4 (a)). During the measurements in June 2022, the fluctuations of the Cu  $K_\alpha$  position were about 0.5 channels, which corresponds to  $\sim 1.5$  eV, and are comparable with the residuals evaluated during the analysis in Section 2. However, the deviation of the peak position in the last two runs of July was larger (within  $\sim 1.5$  channels, corresponding to  $\sim 4.5$  eV), which is related to more unstable beams condition during the measurement.

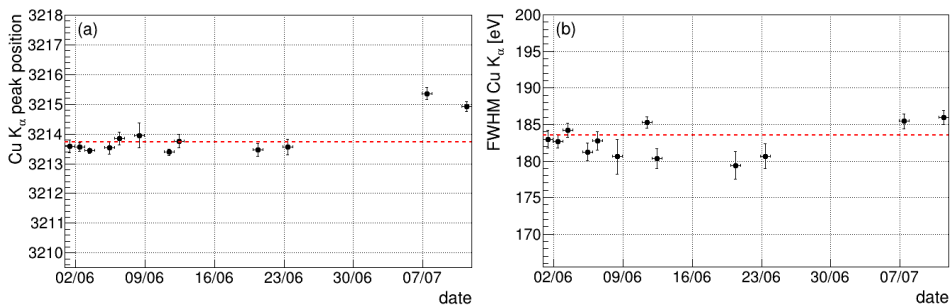


Fig. 4. (a) The position of the Cu  $K_\alpha$  peak (in arbitrary ADC units) as a function of time for a typical SDD. (b) Width stability of the Cu  $K_\alpha$  line.

The energy resolution reflects its accuracy in determining the energy of the incoming radiation. For the SDD, the Full Width at Half Maximum (FWHM) of the peak depends on the energy of the incoming photons, and on the electronic noise of the system [24]. Figure 4 (b) shows the FWHM (in eV) of the Cu  $K_\alpha$  line as a function of time for a typical SDD unit. The width of the peak varies by about  $\pm 2.5$  eV.

Both results indicate very good stability of the SDDs throughout the experiment, thus providing an excellent opportunity to accurately determine the position of the kaonic deuterium peak, as well as the peak width.

## 4. Conclusions

The SIDDHARTA-2 Collaboration has developed a new Silicon Drift Detector (SDD) system for the measurement of the kaonic deuterium X-ray transitions to the ground state. The experimental setup has been installed at the DAΦNE collider of the INFN-LNF. The linearity and stability of the SDDs were monitored during the kaonic deuterium test run, and their performance is described in this work. The results show that the detectors are stable within a few eV and the linearity of the system is below the required precision in the energy region of interest. Following the 2022 kaonic deuterium test run, a full measurement will be performed in 2023 to extract for the first time the strong interaction effects in this exotic atom.

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