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Silicon Drift Detectors' Spectroscopic Response during the SIDDHARTA-2 Kaonic Helium Run at the DAΦNE Collider

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Abstract: A large-area silicon drift detectors (SDDs) system has been developed by the SIDDHARTA-2 collaboration for high precision light kaonic atom X-ray spectroscopy at the DAΦNE collider of Istituto Nazionale di Fisica Nucleare—Laboratori Nazionali di Frascati. The SDDs' geometry and electric field configuration, combined with their read-out electronics, make these devices suitable for performing high precision light kaonic atom spectroscopy measurements in the background of the DAΦNE collider. This work presents the spectroscopic response of the SDDs system during the first exotic atoms run of SIDDHARTA-2 with kaonic helium, a preliminary to the kaonic deuterium data taking campaign. The SIDDHARTA-2 spectroscopic system has good energy resolution and a 2 µs timing window which rejects the asynchronous events, scaling the background by a factor of 10^{-5}. The results obtained for the first exotic atoms run of SIDDHARTA-2 prove this system to be ready to perform the challenging kaonic deuterium measurement.

Keywords: X-ray precision spectroscopy; kaonic atoms; SIDDHARTA-2

1. Introduction

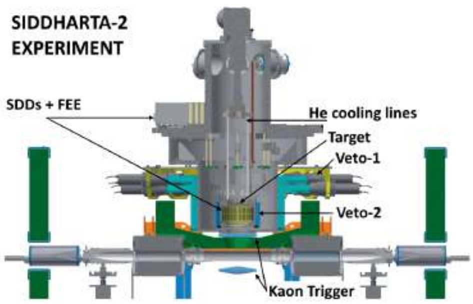
Silicon drift detector (SDD) technology [1,2] combines the silicon p–n junction reverse bias properties with an innovative electronic field design, resulting in low electric noise and high-rate devices able to perform high precision X-ray measurements for a wide range of applications [3–7]. Among these, the SDDs' excellent spectroscopic performances are used for light kaonic atom X-ray spectroscopy to accurately determine shifts (ϵ) and widths (Γ) of the atomic levels caused by the $\bar{K}$N strong interaction. These measurements allow one to probe the non-perturbative quantum chromodynamics (QCD) in the strangeness sector, with implications extending from particle and nuclear physics to astrophysics [8–11]. In 2009, the SDDs technology was employed for the first time by the SIDDHARTA collaboration [12], at the DAΦNE collider [13,14] of Istituto Nazionale di Fisica Nucleare—Laboratori Nazionali di Frascati (INFN-LNF), achieving the most precise measurements of the K^-H fundamental level shift (ϵ) and width (Γ). Nowadays, the SIDDHARTA-2 collaboration is ready to perform the analogous, more challenging kaonic deuterium (K^-d) 2p→1s transition measurement. Monte Carlo simulations [10], based on theoretical calculations [15,16] and considering one order of magnitude lower yield with respect to the SIDDHARTA K^-H measurement [17], predicted precision of about 30 eV and 80 eV for the extracted shift and width determination, respectively. Furthermore, the signals corresponding to the kaonic deuterium K-transitions are expected to be within 4000–12,000 eV, perfectly matching with the SDDs' high quantum efficiency (above 85% for 450 µm thick silicon bulk).

To achieve this unprecedented and ambitious goal, the SIDDHARTA-2 collaboration developed a SDDs system dedicated to kaonic deuterium X-ray spectroscopy measurements. This work presents the SIDDHARTA-2 experimental apparatus and the SDDs system's X-ray spectroscopy response during the first phase of the kaonic helium data taking campaign, prior to the difficult kaonic deuterium measurement.

2. The SIDDHARTA-2 Experiment

The SIDDHARTA-2 setup is presently installed at the DAΦNE collider of INFN-LNF. Figure 1 left shows the cross-sectional view of the experimental apparatus. The target cell, made by a high purity aluminum structure and Kapton walls, operates at a temperature of around 30 K and a pressure of 0.4 MPa (equivalent to 3% liquid hydrogen density, LHD), to optimize the kaon stopping efficiency and the X-ray yield. The 48 SDDs arrays placed around the target cell cover an X-ray detection area of 245.8 cm^2. The veto system [18,19], made of plastic scintillators placed externally (Veto-1) and internally (Veto-2) on/in the vacuum chamber all around the setup, rejects the radiation generated by K^-'s interactions with the materials of the experimental apparatus. The plastic scintillators below and above the beam pipe (kaon trigger) are used to suppress the electromagnetic background, providing a trigger to the SDDs given by the K^-–K^+ coincidence signals.

The SIDDHARTA-2 GEANT4 simulation (Figure 1 right), takes as input parameters the theoretical calculations [15,16] and a yield of 0.1% for the K_α transition of kaonic deuterium extrapolated from the SIDDHARTA run in 2009 [17]. It allows the optimization of each single element of the SIDDHARTA-2 experimental apparatus and estimates that the precisions by which both ϵ_{1s} and Γ_{1s} are expected to be measured in a run of 800 pb^{-1} are comparable to those obtained by SIDDHARTA for the kaonic hydrogen measurement.



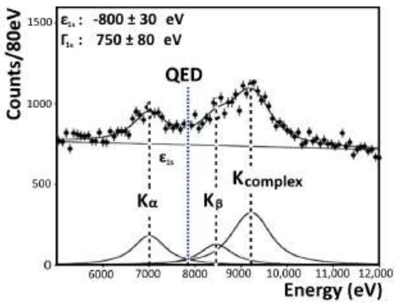


Figure 1. (**Left**): SIDDHARTA-2 cross-sectional view. (**Right**): Kaonic deuterium Monte Carlo simulation (parameters inputs are ϵ_{1s} = −800 eV, Γ_{1s} = 750 eV and yield = 0.1%) for integrated luminosity of 800 pb^{-1}.

In order to perform a challenging kaonic deuterium high precision X-ray spectroscopic measurement, a new monolithic SDDs system has been developed by Fondazione Bruno Kessler, Politecnico di Milano, INFN-LNF (Italy), and the Stefan Meyer Institute (Austria), in the framework of the SIDDHARTA-2 collaboration. The active surface for each 450 µm thick SDDs 2×4 matrix array is 5.12 cm^2 (active/total surface ratio of 0.75). Each device is screwed on a high purity aluminum support, and the thermal contact with the target cell is optimized to keep the device temperature stable at 170 K, improving their energy and timing resolutions. The gear–wheel ceramic carrier structure closely packages the SDDs arrays around the target cell, optimizing the geometrical efficiency. The silicon bulk is glued on an alumina carrier, providing the polarization to the SDD units and housing the CMOS low-noise charge sensitive preamplifier (CUBE) bonded close to the SDD n^+ anode, maximizing the gain/noise ratio within the 16 keV energy range. The array is coupled to the dedicated preamplifier (CUBE) and analog processing (SFERA—SDDs front-end readout ASIC) integrated electronics [20,21] for the X-ray signal processing chain, which consists of fast and slow shaper lines with programmable parameters, and provides the amplitude and the timing information of the X-ray events. In detail, the analog signal corresponding to the detected X-ray is filtered by a 2 µs 9th order semi-Gaussian shaping stage, minimizing the electronic noise contribution. Then, the maximum value of the peak is held by the peak stretcher circuit and put at disposal of the multiplexer output to be digitized by an analog-to-digital converter (ADC, model NI-PCI 6115). Lastly, a National Instrument package manages the external logic and stores all the event data. The SIDDHARTA-2 SDDs system's performances were investigated and optimized in the laboratory [22,23] and then tested in the hard environment of the DAΦNE collider [24], revealing good performances in terms of stability, linear conversion, and energy and timing resolutions. All these features make these devices suitable for performing high precision kaonic atom X-ray spectroscopy, even with the high background of the particle collider.

Lastly, a luminosity monitor placed on the horizontal side of the beam pipe (normal with respect to the kaon trigger) continuously monitors the number of kaons and the background generated for e^+–e^- collisions (see [25] for details). This device is fundamental for monitoring the beam quality, especially during the machine optimization phase preliminary to the SIDDHARTA-2 data taking campaign, providing online feedback on the luminosity and background.

During the DAΦNE collider e^+–e^- commissioning, the SIDDHARTA-2 experimental apparatus was installed in a reduced configuration called SIDDHARTINO, with all SIDDHARTA-2 functionalities but housing a reduced number of SDDs units (8 arrays instead of 48). SIDDHARTINO was running on DAΦNE from January 2021 to July 2021. After reaching a satisfactory beam quality from the machine in terms of kaons delivered over machine background, the SIDDHARTINO data taking campaign concluded with the K^-He^4 L_α X-ray transition measurement.

3. Results and Discussion

The SIDDHARTA-2 SDDs system X-ray response was evaluated during the K^-He^4 data taking campaign, prior to the kaonic deuterium measurement. The total SDDs-calibrated spectrum, corresponding to 10 pb^{-1} of luminosity acquired by the experiment, is shown in Figure 2. Thanks to the combination of the linear response at the level of a few eV with an energy resolution compatible to that of common silicon device technology (see [22,24]), it is possible to precisely describe the overall SIDDHARTINO energy response within the SIDDHARTA-2 ROI in terms of background and spurious elements contamination.

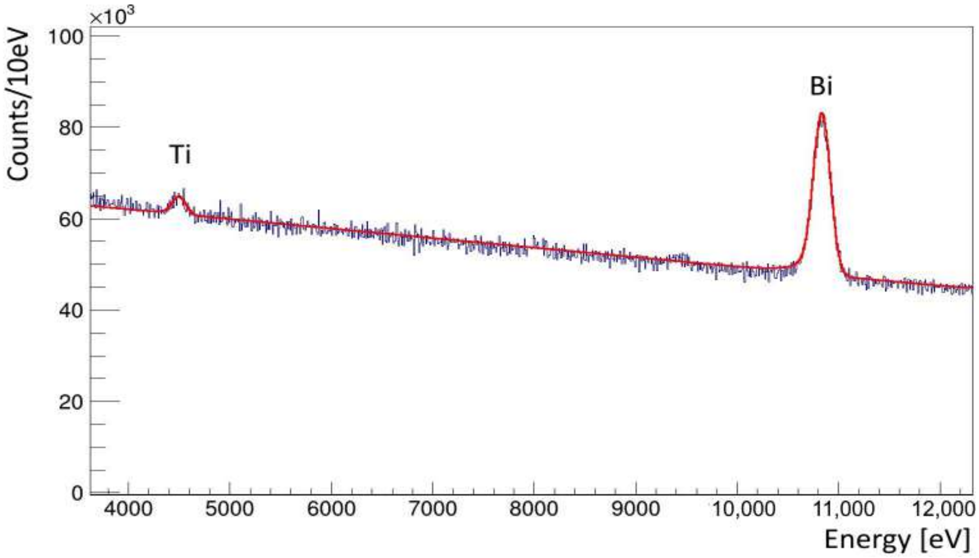


Figure 2. Total SIDDHARTINO spectrum for 10 pb^{-1} of acquired luminosity. The fit (red) consists of two Gaussian functions for the fluorescence peaks and a first grade polynomial to interpolate the background. The measured FWHM of the Ti K_α line was 144 ± 4 eV.

A fit, consisting of two Gaussian functions for the fluorescence peaks and a linear decreasing polynomial for the background, was used to describe the acquired spectrum. The two visible fluorescence peaks are due to the beams products' interactions with the components of the experimental apparatus: the titanium K_α peak at 4509 eV was generated by the titanium foil at the top of the target cell, and the bismuth L_α fluorescence line at 10,838 eV was due to the emission from the SDDs ceramics (close to the Silicon wafer). Except for the Ti K_α and Bi L_α peaks, no other invasive spurious elements were detected over the smooth, linearly decreasing background. During the kaonic helium data taking campaign, the titanium and bismuth signals were used to rapidly check the SDDs system's linearity.

Figure 3 left shows the 2D plot of the time-to-digital conversion (TDC) coincidence signals detected on the scintillators placed, respectively, at the top (TDC1+TDC2) and the bottom (TDC3+TDC4) of the beam pipe. On the diagonal, we observe a high intensity region corresponding to the kaons distributions (red circle) generated by the decay of the Φ mesons, well separated from the signals due to the particles lost from e^+–e^- bunches (Minimum Ionizing Particles, MIPs). On the right, the projection in time of the diagonal elements is also presented. The red distribution corresponds to the kaons' timing response, and it allows one to select the events associated with the kaons. The machine background, in terms of kaons/MIPs, and the total luminosity acquired, was also evaluated.

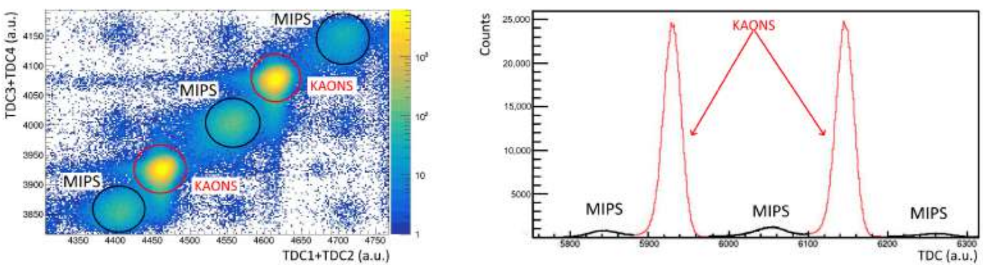


Figure 3. Kaon trigger distributions. (**Left**): 2D plot of the TDC's coincidence detected at the top (TDC1 and TDC2) and bottom (TDC3 and TDC4) of the beam pipe. (**Right**): projection on the time coordinates of the 2D plot diagonal; the red distribution refers to the kaons' coincidences.

The coincidence signals of the scintillators placed on the vertical side of the beam pipe provide the trigger to the experiment. Thus, it was also fundamental to exploit the

SDDs system's timing response in order to disentangle the kaonic helium signal from the asynchronous electromagnetic background of the measurement. The SDDs system timing response, referring to the events associated with a kaon, is shown in Figure 4. The correlation between the energy and timing response for each event detected in the energy range from 4000 to 12,000 eV for a time interval up to 8 μs is shown on the left. The kaonic helium signal (distribution confined by the dotted lines around 6400 eV) can be clearly seen within the X-ray events. The histogram on Figure 4-right reports the projection on the drift time axis of the kaonic helium events' distribution. The plot clearly evidences the timing response of the SDDs system for the selected energy region, allowing one to define a cut of 2 μs (from 1.3 μs to 3.3 μs) to reject the asynchronous electromagnetic background.

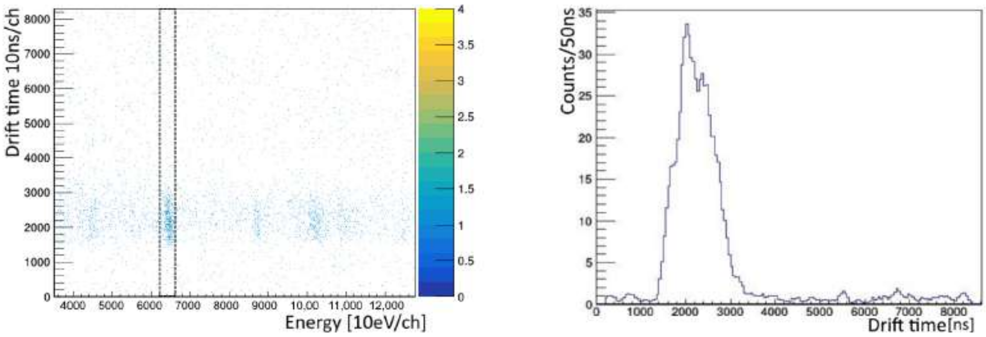


Figure 4. SIDDHARTA-2 SDDs system timing response. (**Left**): Energy vs. drift time 2D plot given by the coincidence between the signals on the SDDs and kaon trigger for each kaon detected. In between the dotted lines, the energy selection around the K^-He^4 L_α peak, from 6200 to 6700 eV. (**Right**): SDDs' timing distribution of the events with energy within 6200 to 6700 eV.

The calibrated spectrum of triggered events obtained after the 2 μs SDDs timing window selection, for the subset of 10 pb^{-1}, is shown in Figure 5. The spectrum cleaned by the asynchronous background clearly shows the K^-He^4 L_α peak at around 6400 eV. Few satellites peaks were generated by the K^- interaction with the elements of the setup (Kapton target wall generated K^-C and K^-N lines, whereas the K^-Ti peak was from the K^- interaction with the a titanium plate placed at the top of the target cell). The background of the measurement is smooth and flat, scaled by a factor 10^{-5} with respect to the one shown in Figure 2.

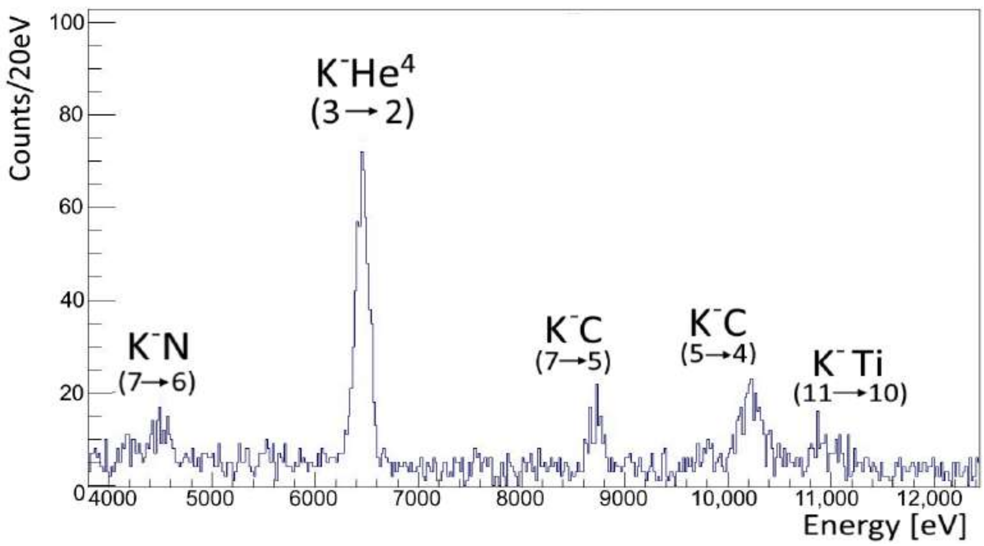


Figure 5. Calibrated SIDDHARTINO spectrum for 10 pb^{-1} of luminosity acquired after a timing selection procedure. Spectrum obtained applying a 2 μs timing cut to SIDDHARTINO triggered events.

Overall, the present work evaluated for the first time the SDDs system's performances during a real kaonic atom X-ray measurement at DAΦNE, proving this technology to be ready to perform the ambitious kaonic deuterium run.

4. Conclusions

The SIDDHARTA-2 collaboration developed a silicon drift detectors (SDDs) system dedicated to ambitious shift (ϵ) and width (Γ) measurements of the K^-d $2p \rightarrow 1s$ transition. The SIDDHARTA-2 setup was installed at the DAΦNE collider of INFN-LNF in the reduced (SDDs) configuration, called SIDDHARTINO, during the machine beam optimization concluded by the K^-He^4 data taking campaign in July 2021. The SIDDHARTA-2 X-ray system response was evaluated during the first exotic kaonic atom run of the SIDDHARTA-2 experiment. It was proved that the SDDs system is suitable and ready to perform the unprecedented and ambitious K^-d measurement, thanks to the asynchronous events rejection, which scaled the background by a factor 10^{-5} for the selected data sample. Furthermore, the X-ray response was expressed as a linear and stable energy response within a few eV, and a good energy resolution [22–24] was preserved. The SIDDHARTA-2 data taking campaign is scheduled for 2021–2022.

Meanwhile, the collaboration is already developing new 1 mm thick SDDs technology dedicated to the measurement of heavier kaonic atoms to explore higher energy intervals with respect to the SIDDHARTA-2 interval, with the aim of obtaining additional fundamental information for the non-perturbative QCD in the strangeness sector.

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