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Main Features of the SIDDHARTA-2 Apparatus for Kaonic Deuterium X-Ray Measurements

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Abstract. The low-energy, non-perturbative regime of QCD can be studied directly by X-ray spectroscopy of light kaonic atoms. The SIDDHARTA-2 experiment, located at the DAΦNE collider, aims to measure the $2p \rightarrow 1s$ transition in kaonic deuterium for the first time to extract the antikaon-nucleon scattering lengths. This measurement is impeded, inter alia, by the low $K^{-}d$ X-ray yield. Hence, several updates have been implemented on the apparatus to increase the signal-to-background ratio, which are discussed in detail in this paper: a lightweight gas target cell, novel Silicon Drift Detectors for the X-ray detection with excellent performance, and a veto system for active background suppression. The experiment has undergone a first preparatory run during DAΦNE's commissioning phase in 2021, concluding with a successful kaonic helium measurement.

1 Scientific Motivation

Light kaonic atoms provide a unique key to study the antikaon-nucleon interaction at threshold and hence to access the low-energy, non-perturbative regime of the strong interaction at zero relative energy. In kaonic hydrogen and deuterium systems, the kaon interacts via the strong interaction with the nucleons, which induces a shift in energy as well as a broadening

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of the kaonic atom ground state. Through measurements of the K_α transition in these light kaonic atoms, the $1s$ shift ϵ_{1s} and width Γ_{1s} can be observed. A combination of the results for kaonic hydrogen and kaonic deuterium allows to extract the isospin-dependent antikaon-nucleon scattering lengths a_0 and a_1, which provide crucial constraints for the prevalent theoretical models. An overview of the experimental work on kaonic atoms is given in [1].

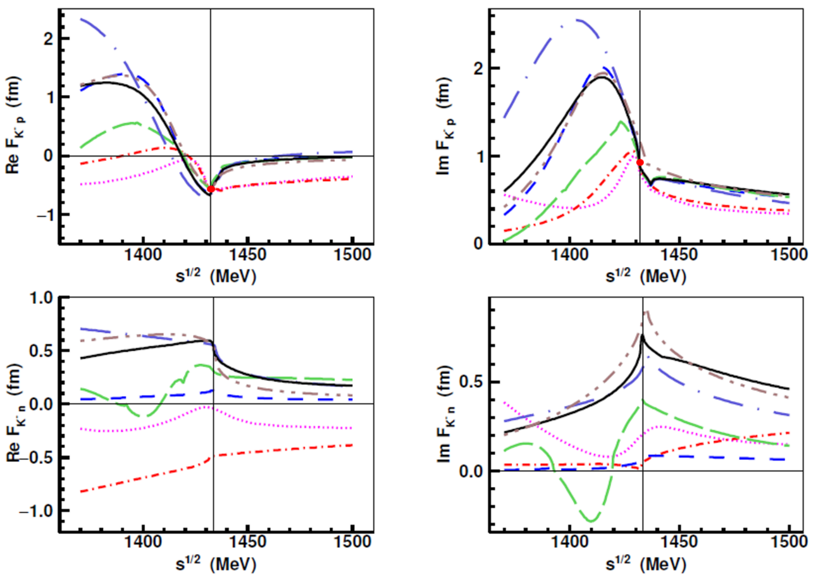

Figure 1. The elastic scattering amplitudes for the K^-p (*top*) and K^-n (*bottom*) cases given by different chiral models: Bonn (dotted and dot-dashed) [4], Murcia (dashed and long-dashed) [5], Prague (dot-long-dashed) [3], Barcelona (dot-dot-dashed) [6], and Kyoto-Munich (continuous) [2]. *From [7].*

Fig. 1 shows calculations from different chiral effective models [2–6] for the elastic scattering amplitudes for the proton and neutron case, respectively [7]. For the antikaon-proton calculations, the successful kaonic hydrogen measurement performed by the SIDDHARTA collaboration in 2009 [8] provided a significant constraint on the parameters of the models describing the real and imaginary part of the K^-p elastic scattering amplitudes to reproduce the SIDDHARTA data points (Fig. 1 top panels). Therefore, the SIDDHARTA-2 collaboration now aims to provide the same constraint for the K^-n case by measuring the $2p \rightarrow 1s$ transition in kaonic deuterium.

The SIDDHARTA-2 experiment is located at the DAΦNE collider at Laboratori Nazionali di Frascati (LNF) in Italy. The challenge of the K^-d measurement is the low expected kaonic deuterium X-ray yield of $Y_{K_\alpha} < 0.0039\%$ [9], as well as the broad ground state width as compared to kaonic hydrogen. Therefore, the experimental apparatus has undergone several updates to improve the signal-to-background ratio by at least one order of magnitude, which is crucial for the K^-d measurement. These updates include:

- a luminosity monitor to study the beam and background conditions,
- a lightweight, cryogenic gaseous target cell,
- 48 arrays of newly developed monolithic Silicon Drift Detectors (SDDs) for the detection of X-rays,
- and a dedicated veto system.

2 The SIDDHARTA-2 Apparatus

The SIDDHARTA-2 apparatus was installed at the DAΦNE collider in April 2019. A schematic drawing of the apparatus is shown in Fig. 2 including all the main components. The target cell is shown in yellow, surrounded by the X-ray detectors and inner layer of the veto system. Outside of the vacuum chamber, the outer layer of veto detectors is shown. A luminosity monitor, the luminometer, is installed close to the interaction point [10]. Due to the special feature of DAΦNE producing the Φ mesons almost at rest, the charged kaons are emitted back-to-back, and can be detected in coincidence using the kaon trigger to suppress asynchronous background.

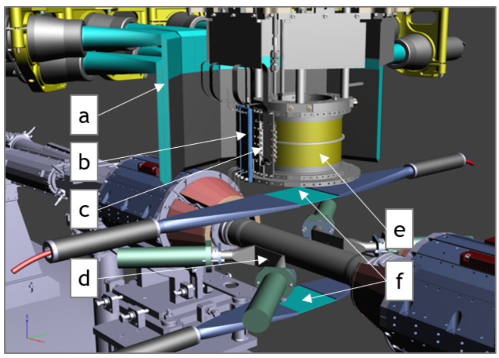

Figure 2. Schematic drawing of the SIDDHARTA-2 apparatus with the veto systems (a, b), X-ray detectors (c), luminosity monitor (d), target cell (e) and kaon trigger (f).

2.1 The Target Cell

Since X-ray losses due to the Stark effect severely aggravate the measurements in light kaonic atoms, the target gas density has to be optimised to strike a balance between a sufficiently high kaon stopping power and minimal X-ray losses. Therefore, the working parameters of the SIDDHARTA-2 target cell are a temperature of 30 K and a deuterium density of 1.5% liquid density (LDD). For a 90% transmission of 8 keV X-rays to the X-ray detectors, the sidewalls are made from two layers of 50 μm Kapton foils glued together with epoxy adhesive, resulting in a total thickness of $\sim$ 150 μm. The target cell with a height of 120 mm and a diameter of 144 mm is shown in Fig. 3.

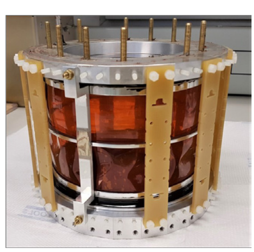

Figure 3. The lightweight SIDDHARTA-2 target cell with Kapton sidewalls and the mounting structures for the SDDs.

2.2 The Silicon Drift Detectors

The X-ray detection system of SIDDHARTA-2 consists of 48 arrays of newly developed SDDs. Each array features eight cells of 8×8 mm^2 (Fig. 4 left panel), resulting in a total of 384 read-out channels and a total active area of 246 cm^2. In comparison to the SDDs used for the kaonic hydrogen measurement in SIDDHARTA, the new detectors have been structurally updated. Before, an *n*-channel JFET was implemented directly on the anode structure of the SDD. For SIDDHARTA-2, however, a preamplifier based on a MOSFET technology, called CUBE, is implemented on the ceramic carrier structure of the SDD close to the anode (Fig. 4 *right*). This update allows for a lower operational temperature of the SDDs and a more stable operation at high rates, as well as lower drift times (~ 400 ns) and an improved energy resolution. Thanks to the geometry of the ceramic carrier, a solid angle of ~ 2π is achieved.

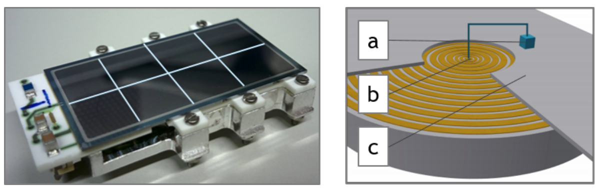

Figure 4. *Left:* An SDD array with eight read-out channels. The geometry of the ceramic holding structure enables a compact arrangement of detectors around the target cell. *Right*: Schematic of an SDD chip with the CUBE (a) mounted on the ceramics (c), directly connected to the anode (b).

The SDDs were characterized at LNF and Stefan Meyer Institute, Vienna, in terms of their stability, linearity, timing performance and energy resolution [11–13]. Calibration measurements were performed, using an Fe-55 source activating a Ti foil. A typical calibration spectrum is shown in Fig. 5, were the characteristic X-ray lines for Ti (K_α peak at 4.5 keV) and Mn (K_α peak at 5.9 keV) are clearly visible. The Ca K_α peak at 3.7 keV (yellow) originates from the surrounding setup materials. The bottom panel of Fig. 5 shows the fit residuals. For 6 keV X-rays, an energy resolution of approximately 145 eV was measured at a temperature of 120 K.

2.3 The Veto Systems

The SIDDHARTA-2 experiment is equipped with a two-stage veto system to actively suppress the synchronous background. The purpose of the outer layer of the veto system, the Veto-1, is the distinction between signals originating from kaon stops in the target gas, and kaon stops in the surrounding materials. Since the stop of a kaon in a solid is much faster than in gas, timing information can be used to make this distinction. Therefore, a time resolution of the time delay with respect to the kaon trigger smaller than 1 ns (FWHM of the peak) has to be achieved. The Veto-1 system consists of twelve units of $(260 \times 110 \times 10)$ mm^3 plastic scintillators read out by photomultipliers (PMTs). To achieve the required time resolution despite the limited space around the vacuum chamber, mirrors and light guides are used to read out the scintillators on both ends (Fig. 6). In this way, a time resolution of (746 ± 53) ps (FWHM) is achieved [14].

The inner layer of the veto system, the Veto-2, is mounted directly behind the SDDs and is dedicated to the suppression of signals originating from minimum ionizing particles (MIPs) produced in the final kaon absorption on the nucleons. A background event in the X-ray region of interest can be produced should the MIPs traverse the SDDs on the edge of their

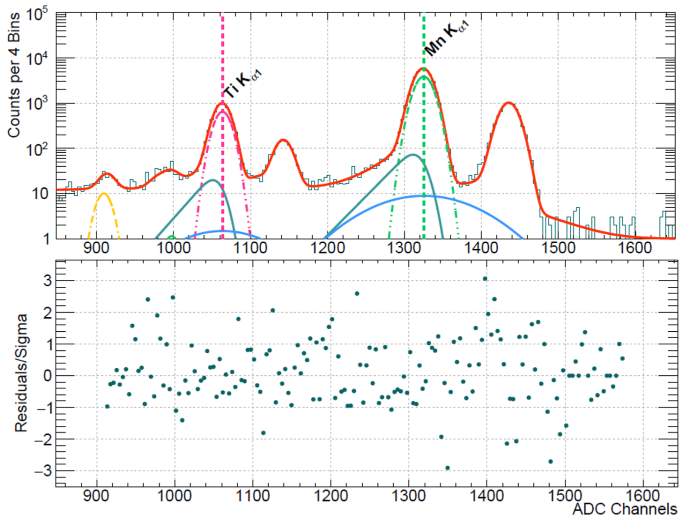

Figure 5. *Top:* Fitted SDD calibration spectrum obtained with an Fe-55 source and Ti foil. *Bottom:* Residuals from the fit of the calibration spectrum.

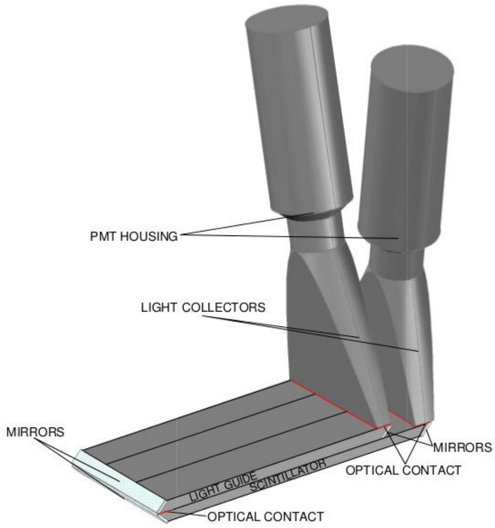

Figure 6. Detector unit of the Veto-1 system: A plastic scintillator, read out on both ends with PMTs using light guides. *From [14].*

active area. The spatial correlation between hits in the X-ray detectors and the Veto-2 system enables the rejection of these events [15]. The Veto-2 system consists of 24 detector units, each composed of four $(50 \times 12 \times 5)$ mm^3 plastic scintillators with Silicon Photomultiplier (SiPM) read-out. One of these units is shown in Fig. 7. Additionally, two pulsed LEDs are implemented per unit, allowing for an in-situ calibration of the Veto-2 detectors and for monitoring their performance, e.g. in terms of possible radiation damage.

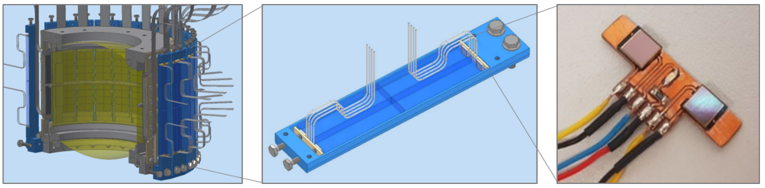

Figure 7. *Left:* Target cell surrounded by the SDDs, with the Veto-2 system mounted directly behind. *Middle:* Veto-2 detector unit consisting of four plastic scintillators read out by SiPMs. *Right:* The zoom shows the SiPMs in detail, with the LED for calibration in the middle.

3 Status of the Experiment

To establish the optimal working conditions for the SIDDHARTA-2 experiment, a run with a reduced setup, called SIDDHARTINO, was performed in 2021 during the commissioning operations of DAΦNE. With only eight out of the 48 SDD arrays installed, the optimal conditions for the SIDDHARTA-2 experiment were established. During this phase, the performance of all components of the setup, i.e. the luminometer, kaon trigger, cooling system, degrader, target cell and SDDs, was thoroughly checked. Moreover, the background conditions were studied - a crucial step for the planned deuterium measurement. During the entire SIDDHARTINO run, the online feedback provided by the luminosity monitor was vital in assessing the quality of the beam and the level of background.
In the summer of 2021, the commissioning phase was concluded with a ^{4}He run, for an integrated luminosity of 30.9 pb^{-1}. Data were collected for different ^{4}He gas densities (0.75% and 1.5% liquid He density) and various degrader configurations. A preliminary calibrated spectrum obtained with the ^{4}He target for 9.3 pb^{-1} is shown in Fig. 8. A 2.5 μs coincidence with the kaon signals registered by the kaon trigger was required. The kaonic ^{4}He L_α peak is clearly visible at 6.4 keV; additional peaks are present due to the interaction of the kaons with the setup materials.

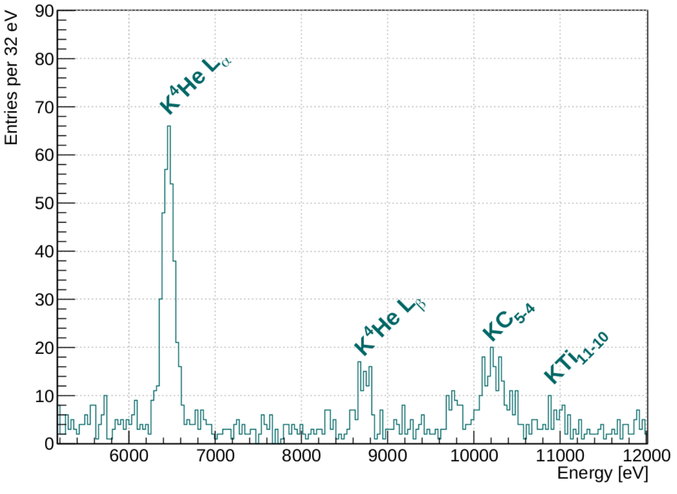

Figure 8. Preliminary calibrated spectrum obtained during the SIDDHARTINO run with ^{4}He for an integrated luminosity of 9.3 pb^{-1}.

After the successful conclusion of the SIDDHARTINO run, the full SIDDHARTA-2 setup will be installed, including full veto systems as well as all 48 SDD arrays. The collaboration aims to collect a total integrated luminosity of 800 pb^{-1} of kaonic deuterium data in 2022, split into two runs of 300 pb^{-1} and 500 pb^{-1}, respectively.

4 Conclusion and Future Perspectives

The experimental apparatus of SIDDHARTA-2 has been updated from the SIDDHARTA experiment to sufficiently increase the signal-to-background ratio for a successful kaonic deuterium measurement. The main updates include a lightweight gas target cell, new monolithic Silicon Drift Detectors and an active two-stage veto system for background suppression. All of these components were characterised and their performances were proven suitable for the planned kaonic deuterium measurement. A first successful run with kaonic ^{4}He was performed with a reduced setup during the DAΦNE commissioning phase. The full setup is currently under installation, and the kaonic deuterium run will be performed in 2022. In parallel, new proposals following the K^-d measurement by SIDDHARTA-2 are already in preparation. These include not only the development of new detectors, for example Cd(Zn)Te or High Purity Germanium detectors, but also the exploration of other elements like Be, B, or Pb, as well as taking advantage of the ultra-high precision of Highly Annealed Pyrolitic Graphite (HAPG) spectrometers.

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