Kaonic atoms with SIDDHARTA-2 at the DAΦNE collider

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Abstract. The most important information still missing in the field of the low-energy antikaon-nucleon interactions studies is the experimental determination of the hadronic energy shift and width of kaonic deuterium. This measurement will be performed by the SIDDHARTA-2 experiment, installed at the DAΦNE collider and presently in data taking campaign. The precise measurement of the shift and width of the 1s level with respect to the purely electromagnetic calculated values, generated by the presence of the strong interaction, through the measurement of the X-ray transitions to this level, in kaonic hydrogen, was performed by the SIDDHARTA collaboration, the kaonic deuterium is underway by SIDDHARTA-2. These measurement will allow the first precise experimental extraction of the isospin dependent antikaon-nucleon scattering lengths, fundamental quantities for understanding low-energy QCD in the strangeness sector. The experimental challenge of the kaonic deuterium measurement is the very small X-rays yield, the even larger width (compared to kaonic hydrogen), and the difficulty to perform X-rays spectroscopy with weak signals in the high radiation environment of DAΦNE. It was, therefore, crucial to develop a new apparatus involving large-area X-rays detector system, to optimize the signal and to control and by improve the signal-to-background ratio by gaining in solid angle, increasing the timing capability, and as well implementing additional charge particle tracking veto systems.

1 Introduction

SIDDHARTA-2 represents a state-of-the-art experiment designed to perform dedicated measurements of kaonic atoms, which are particular atomic configurations composed of a negatively charged kaon and a nucleus. Investigating these exotic atoms provides an exceptional means to comprehend the strong interactions in the non-perturbative regime involving strangeness [1]. This research has far-reaching implications, going from nuclear and particle physics to the field of astrophysics [2–4]. The DAΦNE electron-positron collider, of the INFN National Laboratory of Frascati (INFN-LNF) in Italy, is being used to study the strong force and the interactions of particles containing strange quarks (strangeness) at low energies [5]. This facility generates low-momentum kaons (approximately 127 MeV/c) that are nearly monochromatic, originating from the decay of the ϕ-resonance produced by electron-positron annihilation. The good quality of this kaon source, coupled with significant evolution in fast spectroscopic X-ray detector systems, has led to significant advancements in the study of strangeness. The pioneering DEAR [6] and SIDDHARTA [7–9] experiments played an essential role in this field. These experiments achieved the most precise measurements of X-rays transitions to the ground state in kaonic hydrogen, the first of kaonic helium-3 and high precision kaonic helium-4, transitions to the 2p level measurements. At present, the SIDDHARTA-2 experiment is configured to undertake the

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challenging task of measuring kaonic deuterium transitions to the ground state, which has not yet been measured due to an expected lower yield and larger width with respect to kaonic hydrogen [10]. To perform this challenging measurement, the collaboration developed a completely new apparatus wich is described in Section 2. The recently preliminary results from SIDDHARTA-2 during the DAΦNE commissioning phase are also included. The future perspectives and respectively conclusions are presented in Section 3 and Section 4.

2 The SIDDHARTA-2 experiment and its qualification at DAΦNE

The main goal of the SIDDHARTA-2 experiment is to perform the first measurement ever of the strong interaction induced shift and width on the fundamental level of kaonic deuterium. Measuring transitions in kaonic deuterium present several experimental challenges. Firstly, the X-ray yield from kaonic deuterium is very low, at least one order of magnitude less than the equivalent transition for hydrogen [11]. Secondly, the even larger width adds complexity to the measurement process. Thirdly, the difficulty to perform precise X-ray spectroscopy in the high radiation environment of the DAΦN machine delivering kaons. To address these challenges, the SIDDHARTA-2 apparatus employs various strategies to enhance the signal-to-background ratio (S/B) by at least one order of magnitude compared to the SIDDHARTA $K^{-}p$ measurement. The first approach involves the use of a lightweight, gaseous target cell to efficiently create kaonic atoms. Secondly, a novel X-ray detection system in the form of Silicon Drift Detectors (SDDs) was developed [11–14]. Thirdly, a multi-stage veto system was implemented to actively suppress synchronous background noise.

2.1 The SIDDHARTA-2 apparatus

Figure 1 shows the layout of the SIDDHARTA-2 setup installed at the DAΦNE collider at INFN-LNF. A cylindrical vacuum chamber is placed above the Interaction Point (IP) of the interaction region wich contains the target cell. The cryogenic cylindrical target is made of 150 μm kapton walls and high purity aluminium frame to ensure an efficient cooling. The target can be filled with different gas types to perform studies beyond the kaonic deuterium measurement. The cooling system permit to cool the gas down to 20 K, while the pressure can be tuned up to 1.4 bar to optimize the kaons stopping efficiency and to perform studies at different densities. The target is surrounded by 384 Silicon Drift Detectors (SDDs), covering an active area of 246 cm^2. The SDDs have been developed by Fondazione Bruno Kessler (FBK) in collaboration with INFN-LNF, Politecnico of Milano and the Stefan Meyer Institute (SMI), specifically for performing kaonic atoms measurements. The good energy and time resolution ($\Delta E/E < 10^{-3}$ and time resolution in the range of 300–400 ns) as well as the excellent linear response of the SDD system are key features for addressing the kaonic deuterium measurement [12–14].

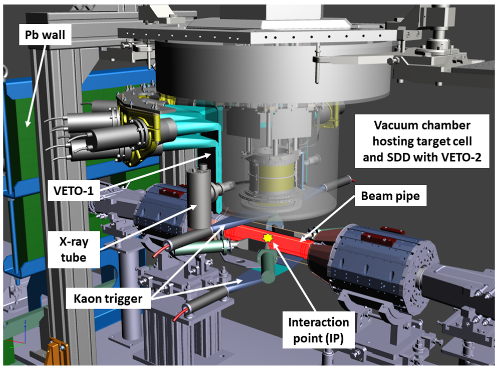

Figure 1. Schematic view of the SIDDHARTA-2 experimental apparatus installed at the interaction point of the DAΦNE collider.

A Kaon Trigger detector (KT), consisting of two plastic scintillators read by photomultipliers (PMTs), placed above and below the $e^{+}e^{-}$ interaction region, is used to detect the back-to-back $K^{+}K^{-}$, providing the trigger to the experiment [cite]. A trigger signal is defined by the coincidence of the two scintillators and allows to drastically suppress the electromagnetic background, asynchronous with the kaons production, caused by particles lost by the DAΦNE's beams and resulting in electromagnetic showers. The KT uses the Time Of Flight (ToF) information to identify the kaons directed towards the target cell during the offline analysis of the data. A luminosity monitor [15] is installed on the two sides of the beam pipe to measure the luminosity and monitor the background in real time.

In addition, special veto systems are foreseen for the SIDDHARTA-2 apparatus, in order to reduce the hadronic background (Fig. 2). The hadronic background is related to the K^{+} decay and the K^{-} nuclear absorption resulting in the emission of particles (MIPs), mostly pions, which could release a signal in the SDDs, synchronous with the KT signal.

The Veto-1 system [16] consists of an outer barrel of 24 scintillators surrounding the vacuum chamber, read by PMTs. It is used to suppress fluorescence X-rays produced by the kaons directly stopped in the target entrance window or in the setup materials. Once a K^{-} is captured by the gas atoms of the target, the atomic cascade process initiates, with radiative and non-radiative transitions, until the kaon is absorbed by the nucleus with the consequent emission of pions. The emitted pions have enough energy to pass through the SDDs and reach the Veto-1 system. The same process occurs for pions generated by kaons absorbed by other various materials of the setup. Based on the relatively long time that a kaon needs slow down and to stop in the target gas before it gets absorbed, compared to the short time in a solid material, one can realize a veto counter by using this time-related information.

The Veto-3 system serves the purpose of excluding fluorescence X-rays resulting from the direct stop of kaons, either within the entrance window of the target or inside the

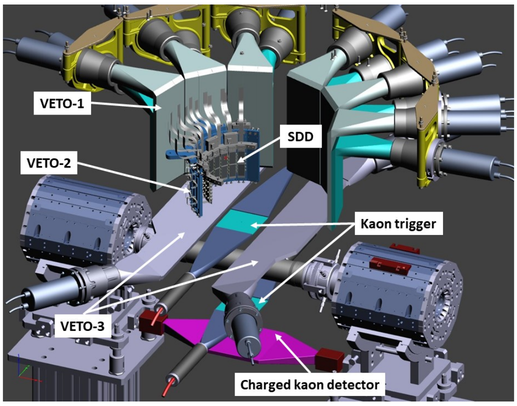

Figure 2. The veto systems foreseen for SIDDHARTA-2: Veto-1 system - outer barrel of scintillator counters surrounding the vacuum chamber; Veto-2 system - inner ring of plastic scintillation tiles (SciTiles) placed at a short distance behind the SDD's; Veto-3 system - a pair of plastic scintillators custom-shaped to fit smoothly into the available space below the vacuum chamber.

vacuum chamber. To achieve this, a pair of plastic scintillators, the EJ-200 type which combines the two important properties of long optical attenuation length and fast timing [17], have been custom-shaped to fit smoothly into the available space below the vacuum chamber. These scintillators are equipped with dual read-out capability, employing 2 Hamamatsu R10533 PMTs at both ends [18]. The selection of these type of scintillator and PMT's used in the construction of the veto systems (Veto-1 and Veto-3), was a meticulous process, aiming to strike the best possible balance among factors such as area coverage (huge counting rates), transit time spread, gain, and noise levels. The use of the double read-out configuration is essential for our objectives.

The Veto-2 system [19] is composed by a ring of 96 plastic scintillators, placed behind the SDDs, read by silicon-photomultipliers (SiPMs). It is used to reject the high energy particles, mostly pions, which pass through the SDDs at grazing angles, releasing an energy equivalent to few keV x-ray, by considering the spatial correlations between SDDs and the hits in the scintillators.

A system composed of two X-ray tubes, type Jupiter 5000 Series at 50kV from Oxford Instruments, is employed for the in-situ calibration of the SDDs, taking advantage of the excitation of the fluorescence lines of high-purity titanium-copper (Ti-Cu) foils mounted on the target. Finally, a lead table and two lead walls complete the shielding structures used to shelter the apparatus from the particles, mostly Minimum Ionizing Particles (MIPs), lost from the e^+e^- rings.

2.2 The SIDDHARTA-2 measurements and results

The SIDDHARTA-2 experiment is performing its data taking campaign for the measurement of kaonic deuterium. The optimization phase of the collider and of the setup performances was performed, in dedicated periods, from 2021 to 2023. To optimize the setup parameters, various measurements with helium-4 and neon gas targets were realized. The choice of helium-4 and neon was dictated by the high yield of the kaonic helium-4 and kaonic neon transitions, allowing for fast tuning.

In 2021, data with a reduced setup, called SIDDHARTINO (equipped with only 1/6 of the X-rays Silicon Drift Detectors) were collected. During this measurement, the *L*-series X-rays transitions of the kaonic helium-4 exotic atom were measured. The experimental outcomes of this run represents the first important physics result of the SIDDHARTA-2 collaboration, delivering the most precise measurement of the 2p level shift and width in the gaseous target [20]. The yields of the L-series in kaonic helium-4 for the two target densities [21] were also measured, proving new data points to refine the cascade models of kaonic atoms as function of density. Moreover, using the data collected with helium-4 both in 2021 and 2022, with the full SIDDHARTA-2 setup, various high-n transitions for intermediate mass kaonic atoms were measured for the first time [22]. Kaonic carbon, oxygen, nitrogen and aluminium transitions, which occur in the setup materials, were measured by using the kaons stopped in the aluminium frames and Kapton walls of the helium target. These new kaonic atoms measurements add valuable input to the kaonic atoms transitions data base, which is used as a reference for theories and models of the low-energy strong interaction between antikaon and nuclei.

After additional improvements and optimizations of the SIDDHARTA-2 setup, in 2023 the first measurement ever of kaonic neon transitions was performed. Figure 3 shows the preliminary inclusive energy spectrum acquired by the SDDs during the neon run, for a 5 pb^{-1} sample. The spectrum shows spectroscopic peaks which are activated by the material around the detectors. The Copper is due to the setup components inside the vacuum chamber while the Bismuth is present in alumina ceramic board behind the SDDs. In addition, the high continuous background contribution makes it impossible to observe the kaonic neon signal at this stage of the data analysis.

To remove the asynchronous background, a first selection is applied using the information from the Kaon Trigger. Only the events falling in a 5 μs time window in coincidence with a trigger signal are selected. The time window width was tuned to enable the front-end electronics to process and acquire the signals. In addition to the trigger signal, the kaon detector provides information about the Time of Flight (ToF) of the particles passing through it. Since the ToF is different for kaons and Minimum Ionizing Particles (MIPs), it is possible to distinguish between triggers due to kaons with respect to accidental triggers due to MIPs (Fig. 4).

Moreover, only X-rays with a timing within the SDDs' time window are selected, so further reducing the synchronous background. The time difference between the K$^+$K$^-$ coincidence in the Kaon Trigger (up-down coincidence) and the time of the X-ray detection by SDDs is shown in the Fig. 5, where the peak corresponds to X-ray signals on the SDDs in coincidence with the Kaon Trigger, while the flat distribution is the result of the uncorrelated events. More details on the data analysis are reported in

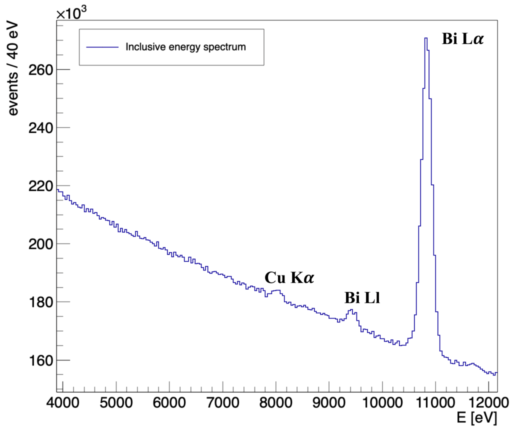

Figure 3. Kaonic neon inclusive energy spectrum using 5 pb^{-1} luminosity delivered by DAΦNE. The inclusive spectrum shows the activation of the copper and bismuth lines from the radiation emitted by the accelerator.

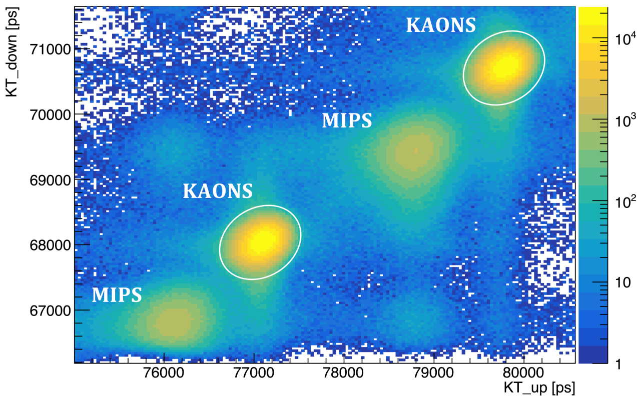

Figure 4. The Kaon Trigger 2D time distribution given by the coincidence signal detected in the two scintillators placed above and below the beam pipe. The circles shown the regions in which we can select the kaons in offline analysis.

[20]. The combined used of Kaon Trigger and SDDs drift time allow to reduce the background by a factor ∼10^5, resulting in an energy spectrum (Fig. 6) where the X-ray lines from kaonic neon are clearly seen. In Fig. 6 the preliminary final kaonic neon spectrum, after having applied the data selection described before, is shown. The kaonic neon 8→7, 7→6 and 6→5 transitions are clearly visible visible in the energy region from 6 keV to 16 keV. The Kaonic carbon line 5→4 is also present, due to kaons stopped in the Kapton walls of the target cell. This result represents the first observation of the kaonic neon lines, and their measurement is an important source of data to improve the knowledge about the kaonic neon cascade process. A refined data analysis is ongoing, for a future dedicated publication.

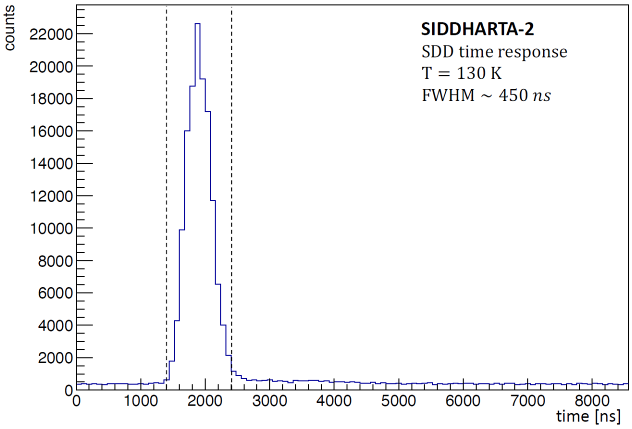

Figure 5. Distribution of the time difference between the SDD X-rays hit and the trigger signals during the SIDDHARTA-2 run. The dashed lines represent the drift time window cut used to reduce the background.

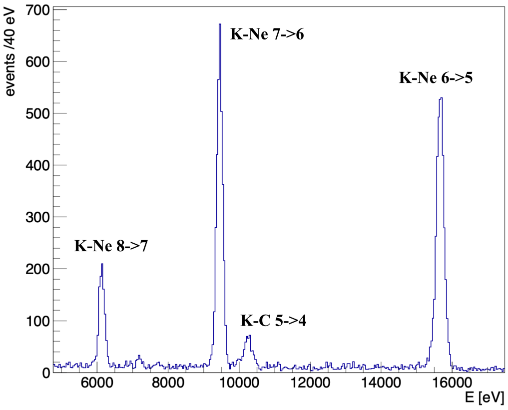

Figure 6. Kaonic neon energy spectrum after background suppression (see text) using 5 pb^{-1} delivered by DAΦNE. The kaonic neon signals are seen together with the kaonic carbon peak.

3 Future perspectives

The SIDDHARTA-2 kaonic deuterium data taking campaign is scheduled for 2023-2024. Meanwhile, the collaboration is developing a new 1 mm thick SDD technology dedicated to the measurement of light and heavier kaonic atoms to explore higher energy regions (transitions between 15 and 60 keV) with respect to the SIDDHARTA-2 one, with the aim to obtain additional fundamental information for the non-perturbative QCD in the strangeness sector. The proposed measurements are to be realized using a number of different detectors going from the 1mm thick SDDs to CdZnTe detectors [23], HPGe detectors and crystal spectrometers. The collaboration is also aiming to investigate the "kaon mass" puzzle by performing the most precise measurement of the charged kaon mass. To comply with the required precision, a series of feasibility tests are being carried out, by measuring x-rays energies of the transitions in kaonic atoms of selected solid targets (Pb and W) with the HPGe detector [24]. There are, however, a series of measurements of light kaonic atoms transitions which can already be performed with the existent SIDDHARTA-2 setup at the end of kaonic deuterium run, with a limited luminosity. The change is minimal and consists in removing the present gas target and replacing it with a conically shaped patch of solid targets (Li, Be and B), making space for additional rows of detectors in between the SDD one, as in the Fig. 7. A full program of measurements beyond SIDDHARTA-2, i.e. the EXKALIBUR project, was put forward by the collaboration [25, 26]. Monte Carlo simulations are presently being performed for the optimization of the setup, while an experimental proposal at DAΦNE was submitted.

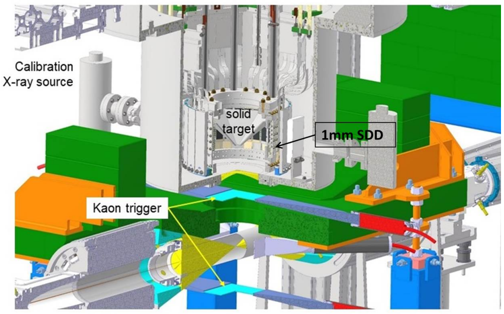

Figure 7. Schematic view of the SIDDHARTA-2 experimental apparatus for solid targets like Li, Be and B.

4 Conclusions

Kaonic atoms serve as crucial tools for gaining insights into the strong interaction at low-energy regime. Their significance covers various fields, ranging from particle and nuclear physics to astrophysics and cosmology. The DAΦNE collider at INFN-LNF stands out as the optimal source of kaons for conducting precise measurements of kaonic atoms. At present, the SIDDHARTA-2 experiment is in data taking for the measurement of kaonic deuterium wich was initiated in spring of 2023, aiming to collect 800 pb^{-1} of data. During the commissioning phase of DAΦNE, while preparing for this delicate measurement, a series of accurate measurements of transitions in kaonic helium-4 and neon were conducted. After the successful completion of the kaonic deuterium measurement, several future experiments have been proposed to take advantage of the excellent conditions offered by the DAΦNE collider.

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