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First Tests of the Full SIDDHARTA-2 Experimental Apparatus with a ^{4}He Gaseous Target

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In this paper, we present the first tests performed after the full installation of the SIDDHARTA-2 experimental apparatus on the interaction region of the DAΦNE collider at the INFN National Laboratories of Frascati. Before starting the first measurement of the kaonic deuterium $2p \to 1s$ transition, an accurate evaluation of the background rejection was required, mainly achieved with the kaon trigger system. This run, performed in the period 04–26/05/2022 with a ^{4}He gaseous target, confirmed the 10^5 order of magnitude of the rejection factor obtained with the reduced version of the setup and different machine conditions in 2021. This important outcome motivated the filling of the target cell with deuterium and the start of the measurement campaign of the kaonic deuterium $2p \to 1s$ transition.

topics: kaonic atoms, machine background reduction, time-of-flight, silicon drift detectors

1. Introduction

X-ray spectroscopy of kaonic atoms is a perfect tool for the investigation of the strong interaction in the low-energy limit [1–6]. In particular, the extraction of the K^-p and K^-d scattering lengths with isospin-breaking corrections [7, 8] is possible through the Deser–Truemann-type formulae, by combining the measurements of the strong interaction-induced shifts and widths of the 1s level both in kaonic deuterium and hydrogen. With this aim, soon after the successful measurement of kaonic hydrogen in 2009 [9] at the DAΦNE [10] collider of the INFN Laboratories of Frascati, the SIDDHARTA collaboration proposed to realize an updated version of the experimental apparatus, and it was ready to be installed on the interaction region (IR) in April 2019.

To perform both conditioning of the machine and tuning of the various components of the SIDDHARTA-2 setup, a reduced version, named SIDDHARTINO [11], with only 1/6 of the X-ray silicon drift detectors (SDD) was installed in 2019. Due to the pandemic situation, the SIDDHARTINO run only started in January 2021, and two runs with a target cell filled with ^{4}He gas at about 1.5% and 0.8% of liquid helium density were performed to optimize various setup components, as well as to provide feedback to the machine during its commissioning phase. The choice of ^{4}He was dictated by the high yield of the K ^{4}He ($3d \to 2p$) transition allowing for very fast tuning. The experimental outcomes of this run already represented the first important physics results of the SIDDHARTA-2 experiment, delivering the most precise measurement of the $2p$ level shift and width in the gaseous target [11]. In the second half of 2021, the full SIDDHARTA-2 setup was installed on the DAΦNE interaction region [12]. The increased number of SDDs, as well as the different conditions of the machine background resulting from the optimization of the instantaneous luminosity, suggested performing a second test with helium before filling the target cell with deuterium. This was indeed necessary to crosscheck the performances of the experimental apparatus in its full version, with a particular focus on the background rejection capabilities of the trigger system.

2. The SIDDHARTA-2 setup

DAΦNE is an e^+e^- collider with e^+ and e^- beams tuned at the momentum 510 MeV/c; this facility is then a world-class Φ-factory, delivering low energetic and monochromatic back-to-back K^+K^- pairs (16 MeV of kinetic energy) through the Φ-meson decay. These properties render DAΦNE the most suitable facility in the world to perform high-precision spectroscopy of kaonic atoms, which has already been evidenced by many important results achieved in 2009 by the SIDDHARTA experiment [9, 13–16].

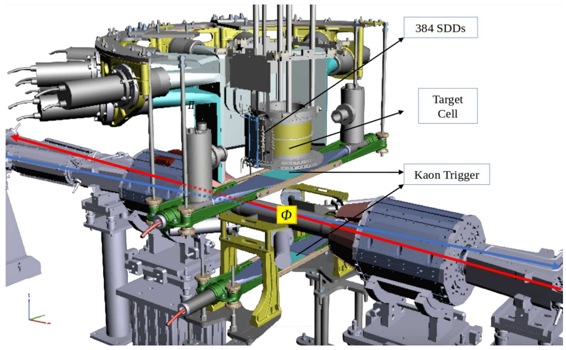

Fig. 1. The SIDDHARTA-2 setup installed on the DAΦNE interaction region at the INFN National Laboratories of Frascati.

In Fig. 1 a drawing of the SIDDHARTA-2 apparatus is shown, where the main components are highlighted. For this work, of particular interest are the target cell, SDDs, and the kaon trigger, described below.

Target cell (TC). Enclosed in a cylindrical vacuum chamber and made of a high-purity aluminum structure and a 150 μm thick Mylar wall, TC is used to store various targets. In particular, kaonic deuterium gas is planned to be stored at an equivalent density of 3% of liquid deuterium (LD).

X-ray silicon drift detectors (SDDs). X-rays emitted from the various transitions of kaonic atoms are measured by 384 fast 450 μm thick SDDs, each with a surface of 0.64 cm^2, arranged in 48 arrays (2×4 matrix), placed around the target cell for a total surface of 245.76 cm^2. Each unit is closely bonded to a C-MOS charge-sensitive amplifier (CUBE [17]) and the signals are processed by a dedicated ASIC (SFERA, [18, 19]). The SDDs system has been optimized in the laboratory and successfully tested in the heavy background of the collider [20–23]. The X-ray silicon drift detectors are, together with the target cell, placed inside a vacuum chamber where they are cooled down to −145°C.

Kaon trigger (KT). This tool, consisting of a pair of plastic scintillators read at both sides by photomultipliers (PM), is used to identify those events where a kaon pair is delivered in the vertical direction with a characteristic time of flight (ToF), ensuring that a charged kaon enters in the target cell. A dramatic reduction of the asynchronous component of the DAΦNE machine background can be then achieved with the ToF selection.

Among other components, a luminosity monitor built from plastic scintillators and based on the technology developed by J-PET for imaging of electron–positron annihilation [24–26] is used to assess the luminosity delivered by the collider [27] while two VETO systems are implemented to reduce the hadronic background [28, 29].

The kaon trigger is used to achieve a background reduction factor of the order of 10^5, defined as the ratio between the number of events after applying

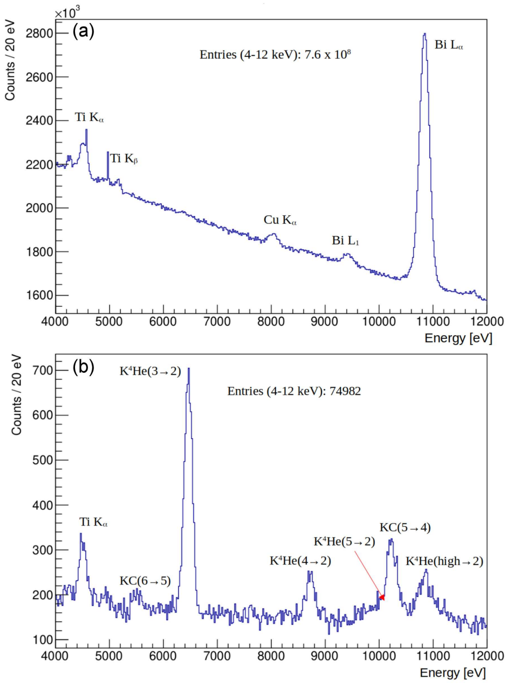

Fig. 2. (a) The total 28 pb^{-1} spectrum obtained from the sum of the individual SDDs. Fluorescence peaks from Ti, Cu and Bi are present. (b) Total spectrum after the trigger request (see text for details).

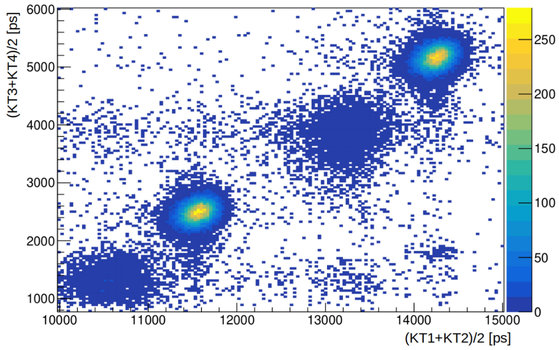

Fig. 3. Scatter plot of the mean time of the two PMs reading the upper and lower scintillators of the kaon trigger. Clusters related to kaons and MIPs are clearly visible in the double structure due to the usage of the RF/2 signal as time reference (see text for details).

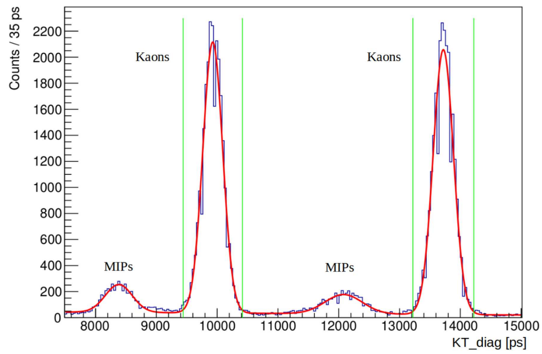

Fig. 4. Projection on the diagonal of the scatter plot of Fig. 3. The fit (red line) is used to define the acceptance windows for kaons, while the double structure is due to the usage of RF/2 as time reference (see text for details).

the trigger request and that of the raw spectrum without which signals from kaonic atoms would be impossible to be measured.

This work is focused on the tests performed immediately after the installation of the full apparatus on DAΦNE with the target ^{4}He. Confirmation of the good performances achieved in the SIDDHARTINO run is then mandatory to declare the full SIDDHARTA-2 setup ready for the kaonic deuterium measurement.

3. The kaonic helium test

The data presented in this paper were collected in the period 04–26/05/2022 and correspond to 28 pb^{-1} of integrated luminosity. SDDs were cooled down to -145°C and the density of the target corresponded to about 1.4% times that of liquid helium. All spectra are already calibrated in energy, with a procedure extensively discussed in [20].

3.1. Background suppression

In this section, the steps of analysis from the raw data collected by SDDs, to the final kaonic helium spectrum are described. The overall spectrum obtained without selection cuts is shown in Fig. 2a, where peaks due to fluorescence of various materials present in the experimental apparatus, thus not correlated in time with the beam crossing and the Φ-decay, are present.

To remove this asynchronous background, a first selection is applied using the information from KT; only triggered events where two signals are detected in coincidence by two scintillators are retained while all others are discarded. The effect of this selection is visible in Fig. 2b, where the number of events is drastically reduced and the fluorescence peaks are not visible anymore, except for that from titanium, which is present in the top of the target cell and is activated by kaons not stopping in the gas. In the triggered spectrum, the transitions of kaonic atoms formed in the Mylar walls of the target are visible.

The KT information could be also used to eliminate a part of the remaining synchronous background mainly of minimum ionizing particles (MIPs) produced in electromagnetic showers occurring within a fixed time window with the beam crossing. The two scintillators of KT allow discriminating by TOF between MIPs and kaons as shown in Figs. 3 and 4. In Fig. 3, a scatter plot of the mean timers of the two PMs reading each scintillator is

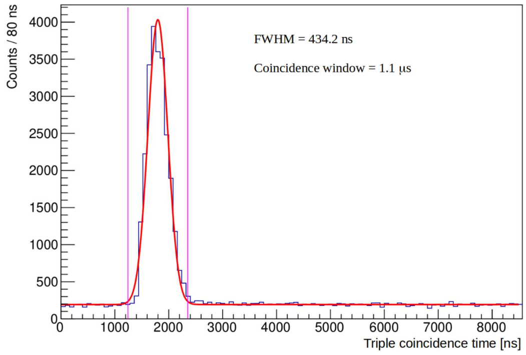

Fig. 5. Time distribution of the triple coincidence between the two KT scintillators and a hit on SDD. The peak width comes mainly from the e^- drift time towards the anodes of the X-ray detectors (see text for details).

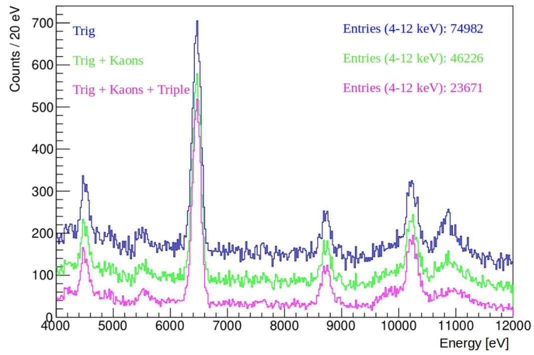

Fig. 6. Overimposed total 28 pb^{-1} spectra obtained from the sum of the individual SDDs after the trigger requirement, the kaon selection and the application of triple coincidence window.

presented, where distinct clusters corresponding to kaons (more intense) and MIPs (less intense) are visible in the double structure.

The radiofrequency (RF) of around 370 MHz of the DAΦNE collider, providing a trigger for every collision and used as a time reference by the DAQ of the experiment, cannot be handled by the most performing constant fraction discriminators (CFD), limited to working with 200 MHz, used to process it. To overcome this limitation, RF/2 is then used at a frequency of 185 MHz; as a consequence, every coincidence event in the KT discriminators can be randomly associated in time with one of the two collisions. The net result is the presence of a double structure visible both in Figs. 3 and 4. In Fig. 4, the projection of the scatter plot on the diagonal is used to perform the fit and select only the events related to kaons.

As the last step, the time information from SDDs can be exploited as well. The triple coincidence between the two scintillators of KT and a hit in one of SDDs, using the same RF/2 timestamp as reference time, is presented in Fig. 5, where the peak represents good signals while the flat background is due to accidental X-rays occurring randomly in time. The drift time of e^- towards the anode of SDD after a photon detection, typically of the order of hundreds of ns, is much larger than the time needed by the kaons to reach the target, to be then gas-moderated to form a kaonic atom and finally go through cascade emitting X-rays. For this reason, the shape of the timing distribution in Fig. 5 is mainly due to the drift time of e^- in SDDs [21]. A further selection of events can be performed by rejecting all the events lying outside the 1.1 μs window shown in Fig. 5. It has to be stressed that, with respect to -100°C of the SIDDHARTINO run, the -145°C cooling of SDDs allows for a much narrower time window than the almost 2 μs previous one, thanks to the reduction of FWHM of the triple coincidence peak from 950 to about 430 ns.

The overall effects of all these selections are presented in Fig. 6 where the spectra with only the KT flag, the further addition of the kaon selection and the triple coincidence requirement are shown in black, green and magenta, respectively. The number of events for each spectrum are reported; comparing these values with those presented in Fig. 2, a background rejection factor can be extracted as 3.1×10^{-5}. The results confirm those obtained during the SIDDHARTINO run [11].

4. Conclusions

In this paper, we presented the first tests performed after the full installation of the SIDDHARTA-2 experimental apparatus on the Interaction Region of the DAΦNE collider at the INFN National Laboratories of Frascati. The test, performed in the period 04–26/05/2022, was used to confirm the very good performance of the trigger system achieved during the SIDDHARTINO test run, performed in 2021 with a reduced number of X-ray detectors and different conditions of the accelerator [11]. This test was mandatory to assess that these new conditions as well as the larger amount of detectors were not negatively impacting the crucial background rejection factor. The outcomes of this run confirmed the 10^5 order of magnitude of the rejection factor obtained with SIDDHARTINO [11] and allows to start the first measurement of the kaonic deuterium $2p \to 1s$ transition, which will be performed in 2022 and 2023.

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