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Trigger rejection factor in the first kaonic helium run with the complete SIDDHARTA-2 setup

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Abstract. The SIDDHARTA-2 experiment aims to perform the first measurement of the kaonic deuterium 2p → 1s x-ray transition energy. Such measurement, together with the measurement of kaonic hydrogen 2p → 1s x-ray energy transition performed by the SIDDHARTA experiment in 2011, allows the determination of kaon proton and kaon neutron scattering lengths and represents a fundamental input for the low energies QCD in the strangeness sector theory. The SIDDHARTA-2 experiment is presently installed at the DAΦNE electron-positron collider at the National Laboratories of Frascati, in Italy. In May 2022, the kaonic ^4He x-ray transitions measurement was performed by the complete SIDDHARTA-2 setup, by using a gaseous target. The result of this measurement is presented in this paper, with a specific focus on the background rejection performed by the kaon trigger system.

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1 Introduction

Hadronic atoms are atomic systems in which an electron is replaced by a different negatively charged hadron, for example a pion or a kaon, bound by its electromagnetic interaction with the nucleus. The experimental research on hadronic atoms allows the study of the strong interaction in an atomic system, at low energy, and provided a large amount of data and constraints for nuclear and particle physics. Quantum electrodynamics (QED) allows a precise description of the electromagnetic properties of the kaonic atom, providing energy levels and x-ray transitions of the atomic system. However, in the innermost level of the hadronic atom, energy shifts and broadening of the atomic levels, due to the strong hadron-nucleus interaction, can be measured with x-ray spectroscopy, thus getting fundamental information on quantum chromodynamics (QCD) and strong interaction at threshold [1].
Kaonic atoms are hadronic atoms formed whenever a K^- is captured by an atom, replacing an electron in the atomic shell. The K^- contains the strange quark s. Therefore, experiments with kaonic atoms allow the investigation of the strong interaction at low-energy in the strangeness sector. In the kaonic atoms' formation, the K^- is captured in a highly excited energy level and it starts an electromagnetic cascade process until the nuclear absorption. The average lifetime of K^- is $\tau_{K^-} = 1.2 \times 10^{-8}$ s [2], whilst each of the electromagnetic cascade occurs in less than 10^{-9} s [1]. The kaon-nucleus strong interaction affects the energy orbitals of the kaonic atoms producing shifts and broadenings of the energy levels, but only for the innermost levels, these contributions become measurable. The kaonic hydrogen and kaonic deuterium offer a unique opportunity for the experimental investigation of the strong interaction between kaons and nucleons at low energies.
At low energies, the perturbative QCD models cannot be employed anymore for the description of the strong interaction among hadrons, and various phenomenological models are used. In this regime, the K^-N strong interaction is described for example with models based on Chiral Perturbation Theory (χPT). The strong coupling $\pi\Sigma$ and the resonance Λ (1405), just below the K^-N energy threshold, complicate the description of kaon-nucleon strong interaction with simple approach models in χPT [3, 4]. The state-of-art of theoretical approaches is presented with a comparative analysis in [5]. The measurement of shifts and widths of the 1s energy level in kaonic hydrogen and kaonic deuterium allows the extraction of the K^-p and K^-n scattering lengths, providing fundamental constraints for the theoretical model for the description of kaon-nucleon strong interaction at low energies [6–8].
In the last 25 years, several experiments performed the measurement of light kaonic atoms with x-ray spectroscopy. Kaonic hydrogen was investigated by the KpX experiment at J-PARC in 1997 [9], and by the DEAR experiment at the National Laboratories of Frascati (LNF) in 2005 [10]. In 2011, the SIDDHARTA experiment performed the most precise measurement of kaonic hydrogen 1s level shift and width [11]. Moreover, kaonic ^3He and ^4He measurements were performed by the E570 and the E62 experiment at J-PARC [12], in Japan, and by the SIDDHARTA experiment at LNF, in Italy [13]. In July 2022, the SIDDHARTA-2 experiment, actually installed on the Interaction Region (IR) of the DAΦNE electron-positron collider at LNF [14], started the data taking to perform the first measurement of the 1s energy level shift and width in kaonic deuterium.
In January 2021, the SIDDHARTINO experiment, a reduced version of the SIDDHARTA-2 setup with 1/6 of the x-ray Silicon Drift Detectors (SDDs), performed the best measurement of gaseous $K^{-4}He$ x-ray transitions [15]. The SIDDHARTINO $K^{-4}He$ measurement had a dual goal: to perform the tuning of the various components of the SIDDHARTA-2 setup and to provide a feedback to DAΦNE collider during its commissioning. In the second half of 2021, the installation of the SIDDHARTA-2 apparatus was completed and a new $K^{-4}He$ x-ray transitions measurement, in gas, was performed. The goal of the SIDDHARTA-2 $K^{-4}He$

measurement is to confirm the performance shown by SIDDHARTINO, in view of the kaonic deuterium measurement (2023). A background rejection factor provided by the Kaon Trigger of the same order of magnitude obtained with SIDDHARTINO (10^{-5}) was confirmed, a key ingredient for the challenging K^-d measurement.
In this paper, the SIDDHARTA-2 setup is described, and spectra of the $K^{-4}He$ x-ray atomic transitions measurement is shown. Future perspectives for the SIDDHARTA-2 kaonic deuterium measurement, are concluding the article.

2 The SIDDHARTA-2 experimental setup

Following SIDDHARTINO, the SIDDHARTA-2 apparatus was installed on the Interaction Region (IR) of the DAΦNE e^+e^- collider, at INFN-LNF, in 2021. The DAΦNE collider is a Φ factory. Electron and positron beams, both tuned at 510 MeV/c, are collided, producing Φ mesons which decay in low energy monochromatic back-to-back K^+K^- pairs (48.9% of branching ratio). The kaons are produced with a momentum of $\sim 127 MeV/c$ and a low energy spread ($\Delta p/p \simeq 0.1\%$) [14]. The DAΦNE collider is a low energy kaon source, ideal for kaonic atom measurements.
The SIDDHARTA2 experimental target is a cylindrical cell of 144 mm in diameter and 125 mm in height. The walls are made of a 2-Kapton layer 150 μm thick, placed on aluminium support (see Fig. 1). The target is filled with the gas where kaonic atoms are being formed.

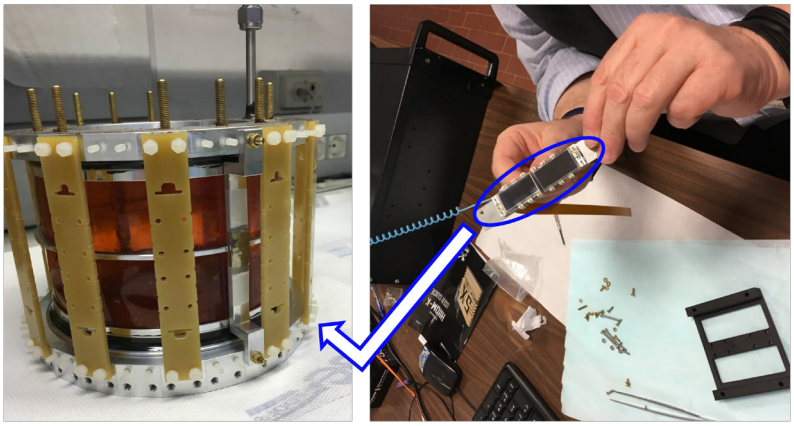

Figure 1. Picture of the SIDDHARTA2 target cell. The cylindrical target is surrounded by the SDD detector arrays for the x-ray spectroscopy.

In the SIDDHARTA-2 experiment, the cylindrical target is surrounded by 384 large area monolithic SDDs, specifically developed for the kaonic atom x-ray spectroscopy and providing a high collection efficiency (> 90%) for x-ray energies between 5 keV and 12 keV [16]. Each SDD is 450 μm thick and has an active area of 0.64 cm^2. The detectors are organized in arrays. Each array consists of 8 SDDs placed in two raws, with 4 SDD cells each (2×4 matrix), as is shown in Fig. 2.

The silicon wafer is glued on an alumina carrier providing the polarization of the SDD cells via an external voltage. Whenever an x-ray is absorbed within the silicon bulk, the generated charges are collected by a central anode. A C-MOS charge-sensitive amplifier is

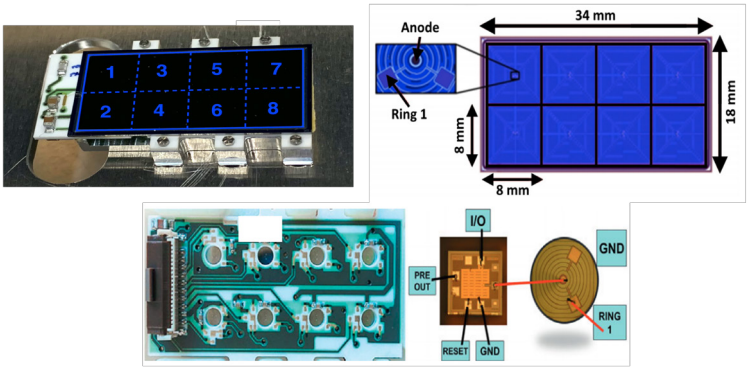

Figure 2. *Top left:* a picture of an SDD array; *Top right:* A schematic view of the SDD array; *Bottom:* schematization of the ceramic support on which the SDD cells are mounted.

closely bonded to each detector unit [17]. The signals are processed through a dedicated ASIC chip named SFERA [18, 19]. The SIDDHARTA-2 SDDs provide a resolution of $157.8 \pm 0.3(stat)^{+0.2}_{-0.2}(syst)$ eV at 6.4 keV ($K^{-4}He$ 3d $\rightarrow$ 2p transition energy) and a linearity of 2-3 eV, as tested and optimized in the commissioning phase at DAΦNE [16, 20]. In the SIDDHARTA-2 apparatus, the SDDs and the target are placed inside a vacuum chamber evacuated below 10^{-5} mbar. A closed-cycle helium refrigerator cooling system keeps the target cell cooled at about 25 K. Pressure and temperature parameters provide the best performance conditions for SDD devices and to stop kaons within the target. The SDD detectors calibration is performed *in situ* with two x-ray tubes installed outside the vacuum chamber, on the apparatus, which exciting foils of titanium and copper placed close to the detectors, inside the vacuum chamber. In the vacuum chamber, plastic scintillators read by pairs of silicon photo-multipliers (SiPMs) are placed radially outside the cylindrical target detectors for external background identification (Veto-2 system) [21, 22]. Outside the vacuum chamber, twelve plastic scintillators read by pairs of photo-multiplier tubes (PMTs), are placed radially around the target (Veto-1 system). The Veto-1 and Veto-2 systems aim to suppress the synchronous and asynchronous backgrounds coming from the pions emitted by the kaon absorption and kaon decays in kaonic atoms. A lead shielding is placed around the vacuum chamber, downstream and upstream the beam-pipe, to reduce the background from the accelerator. Moreover, two lead walls are installed and placed along the beamline in both directions, externally to the setup, to shelter the apparatus from the particles, mostly minimum ionizing particles (MIPs), mainly lost from the electron and positron rings because of the Touschek effect. A shaped Mylar degrader is placed between the target and the Interaction Point (IP) of the DAΦNE accelerator to slow down the kaons, optimizing their stopping in the target gas and the kaonic atoms formation [15]. A Kaon Trigger (KT), consisting of two pairs of plastic scintillators read by photo-multipliers placed above and below the IR, is installed in the apparatus for the identification of the K^+K^- back-to-back emitted from the decay of the ϕ meson in the IR. The KT uses the Time Of Flight (ToF) to identify the K^- directed towards the target cell, in the vertical region. The SIDDHARTA-2 luminometer (constructed based on the J-PET technology [23–25]), consisting of a pair of plastic scintillators read by photo-multipliers placed on the longitudinal plane, is installed near the IR (see Fig. 3). The SIDDHARTA-2 luminometer measures the kaons rate using the horizontal

direction [26]. A GEANT4 [27] dedicated simulation was used to optimize the geometry of the entire apparatus. A schematic drawing of the SIDDHARTA-2 setup is provided in Fig. 3.

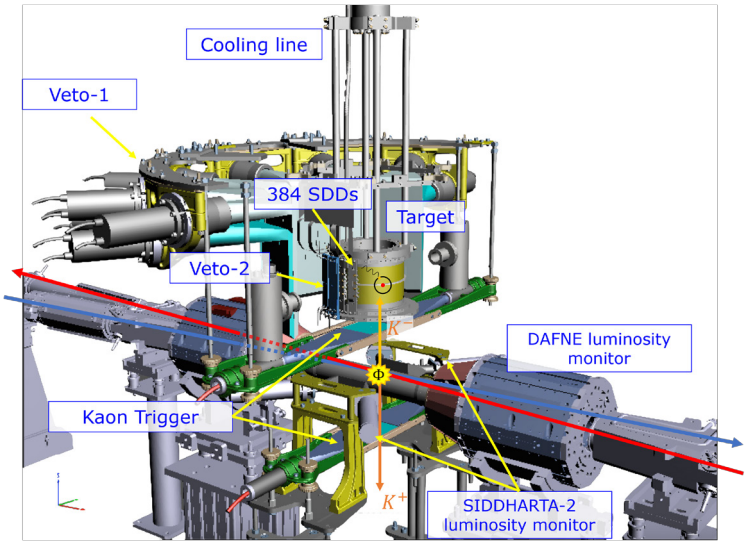

Figure 3. A schematic drawing of the SIDDHARTA-2 apparatus installed on the DAΦNE Interaction Region at the INFN National Laboratories of Frascati.

3 The Kaonic Helium 4 SIDDHARTA-2 measurement

The SIDDHARTA-2 experiment performed the $K^{-4}He$ x-ray transitions measurements in May 2022 period, collecting 28 pb^{-1} integrated luminosity aiming to characterize the full system, previous to the $K^{-}d$ data taking campaign. The ^{4}He gas in the target cell was kept to a density of about 1.4% the Liquid Helium one. The SDDs were cooled at $-145°C$. The Kaon Trigger was fundamental for the discrimination of signal events. For the asynchronous background cut, only the triggered events with signals detected in coincidence by the two scintillators were selected. The MIPs produced by the electromagnetic showers were discriminated from the kaons using the Time-of-Flight information (ToF). The final spectrum of the $K^{-4}He$ x-ray atomic transitions measurement performed by the SIDDHARTA-2 experiment is shown in Fig. 4. The background rejection factor by using the Kaon Trigger is 3.1×10^5, confirming the excellent performance measured by SIDDHARTINO [15]. The effect can be observed comparing the spectra shown in Fig. 4.

4 Conclusions and future perspectives

This paper presents the kaonic helium 4 measurement performed by the SIDDHARTA-2 experiment. The measurement is the first one performed with the complete SIDDHARTA-2 experimental apparatus installed on the Interaction Region of the DAΦNE collider at the National Laboratories of Frascati (INFN). The measurement was performed in May 2022. The results confirm the very good performance of the trigger system achieved during the SIDDHARTINO test run [15], performed in early 2021. In the specific, the crucial background

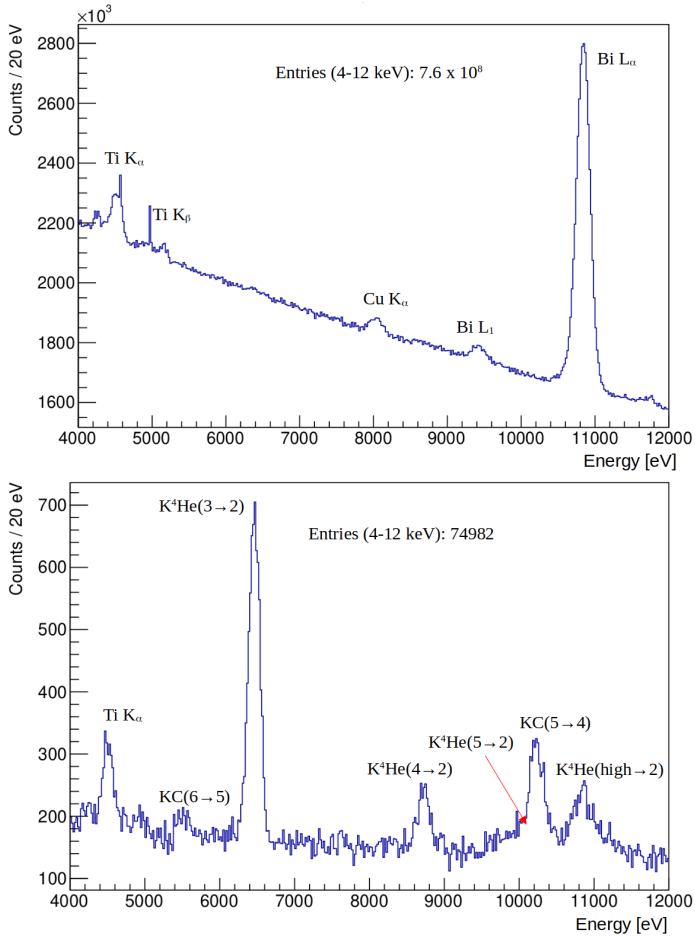

Figure 4. *Top*: The complete spectrum obtained by the SIDDHARTA-2 experiment measuring $K^{-4}He$ x-ray atomic transitions (28 pb^{-1}). Fluorescence peaks from Ti, Cu and Bi are present. *Bottom:* The final spectrum got applying the Kaon Trigger background reduction.

rejection factor is confirmed to be in the order of 10^5, thus providing optimal experimental conditions to start the first measurement of the kaonic deuterium 2p → 1s transition, which will be performed in 2023.

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