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International Conference on Kaon Physics 2022 (KAON 2022) IOP Publishing
Journal of Physics: Conference Series **2446** (2023) 012023 doi:10.1088/1742-6596/2446/1/012023

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Abstract. The SIDDHARTA-2 collaboration is aiming to perform the challenging measurement of kaonic deuterium X-ray transitions to the ground state. This will allow to extract the isospin-dependent antikaon-nucleon scattering lengths, providing input to the theory of Quantum Chromodynamics (QCD) in the non-perturbative regime with strangeness. This work describes the SIDDHARTA-2 experimental apparatus and presents the results obtained during the commissioning phase realized with kaonic helium measurements. In particular, the first observation of the kaonic helium transitions to the 3s level (M-lines), reported in this work, represents a new source of information to study the kaonic helium cascade process and demonstrates the potential of the SIDDHARTA-2 apparatus, in the view of the ambitious kaonic deuterium measurement.

Keywords: kaonic atoms, exotic atoms, SIDDHARTA-2, X-ray spectroscopy

1. Introduction

An exotic atom is an atomic system in which a negatively charged particle, different from the electron, is bound into an atomic orbit by its electromagnetic interaction with the nucleus. Exotic atoms were predicted in the 1940s [1, 2] and they were observed, for the first time, by Auger emission in photographic emulsion [3]. Up to now X-ray emissions from exotic atoms with muons [4], pions [5], kaons [6], antiprotons [7] and sigma hyperons [8] have been observed. The interest in exotic atoms, especially for the light hadronic ones, is motivated by the unique opportunity they offer to investigate quantum chromodynamics (QCD) at threshold, since the relative energy between the hadron and the nucleus is at the level of few keV. The main effect of the presence of the strong interaction between the hadron and the nucleus is a shift and a broadening of the binding energy of the atomic level with respect to the purely quantum electrodynamics (QED) calculated value. The energy shift and width of the orbital level reflect, respectively, the type of the strong interaction (repulsive or attractive) and the finite lifetime of the hadron, in the atomic orbit, due to the nuclear absorption. In the field of hadronic atoms, kaonic atoms are the ideal tool to explore the low-energy QCD in the strangeness sector with implications ranging from particle and nuclear physics [9, 10] to astrophysics [11] and dark matter [12].

In this context, after the most precise measurement of kaonic hydrogen's fundamental level energy shift and width performed by SIDDHARTA [13], the SIDDHARTA-2 collaboration aims to perform the first measurement ever of the kaonic deuterium X-ray transitions to the ground state. The analysis of the combined measurements of kaonic hydrogen and deuterium will allow to extract the isospin-dependent kaon-nucleon scattering lengths [14].

This measurement is planned to be performed in 2023. Meanwhile, as described in this paper, the SIDDHARTA-2 apparatus was installed on the DAΦNE collider, and, while the accelerator was in commissioning phase, the setup was debugged and optimized by a measurement of kaonic helium-4 transitions.

2. The SIDDHARTA-2 experiment

The SIDDHARTA-2 apparatus is currently installed at the DAΦNE collider [15] of INFN-LNF. DAΦNE (Double Annular Φ Factory for Nice Experiments) is a world-class electron-positron collider working at the center of mass energy of the ϕ resonance (1.02 GeV). K^+K^- pairs are produced via the ϕ decay with a branching ratio of 48.9 %. The charged kaons have a low momentum (127 MeV/c) and energy spread ($\sim$ 0.1 %), making DAΦNE the ideal accelerator for kaonic atoms measurements.

The SIDDHARTA-2 collaboration aims to perform the measurement of kaonic deuterium energy shift and width induced by the strong interaction, with a precision of about 30 eV and 70 eV, respectively, precision similar to the SIDDHARTA kaonic hydrogen measurement [13]. Such accuracy is fundamental to efficiently disentangle between different theoretical

approaches [16].
In order to perform the challenging kaonic deuterium measurement, a dedicated experimental apparatus has been developed to face the very small kaonic deuterium X-ray yield [17] and the difficulty to perform X-ray spectroscopy in a high radiation environment, like that of a collider.
The experiment had to take into account two different types of background sources: synchronous and asynchronous. The synchronous background is due to kaons interactions with the setup materials, nuclear absorption and decays. The asynchronous background is produced by the particles lost from the beams due to the Toushek effect and generating electromagnetic showers in the setup.
The schematic layout of the SIDDHARTA-2 setup is shown in Fig. 1. The core of the apparatus is the cylindrical target cell made of a high purity aluminium frame for thermal and mechanical support, and 150 μm thick Kapton walls with an X-ray transmission of 85% at 7 keV. The target cell can be filled with different types of gases to perform various kaonic atom measurements. The cryogenic system allows to cool the gas to 20 K, increasing its density and consequently the kaons stopping efficiency. 48 large area Silicon Drift Detectors (SDDs) arrays surround the target cell. The SDDs arrays have been developed by Fondazione Bruno Kessler (FBK), Politecnico di Milano, Stefan Meyer Institute (SMI), and Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF), specifically to perform kaonic atoms X-ray spectroscopy. Each array consists of eight square SDD cells with a thickness of 450 μm, organized in a 2×4 matrix, for a total active area of 5.12 cm^2. The SDDs system has been fully characterized, showing an excellent spectroscopic response in terms of linearity, energy and time resolutions [18, 19, 20].
A kaon detector 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^- pairs, providing the trigger to the experiment. A trigger signal is defined by the coincidence of the two scintillators and allows to drastically suppress the asynchronous background. A luminosity monitor [21] is installed on the two sides of the beam pipe to measure the luminosity and monitor the background in real time.
In addition, the apparatus is equipped with two different veto systems to further reduce the background. The veto-1 system [22] consists 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 the materials of the setup. Based on the relatively long time that a kaon needs 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 second veto system [23] is composed of 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, by

considering the spatial correlations between SDDs and the hits in the scintillators.

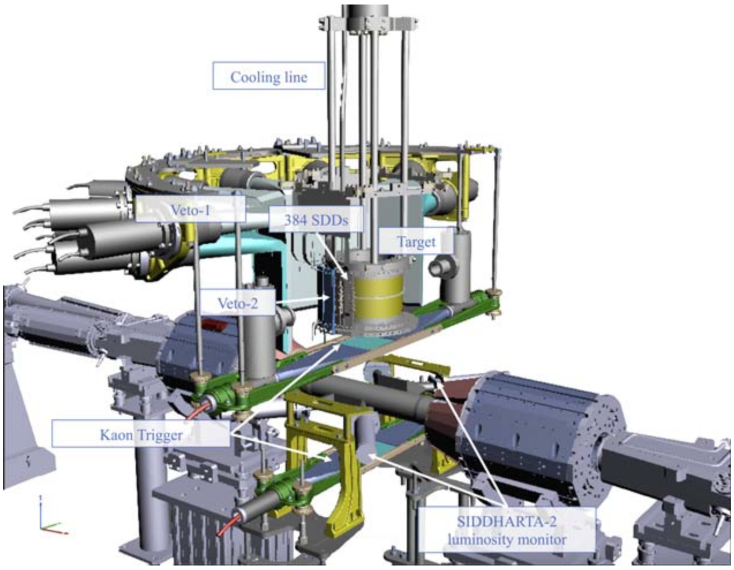

Figure 1: Schematic layout of SIDDHARATA-2 experimental apparatus

3. The kaonic helium run

In 2022 we completed the commissioning phase of the experiment, dedicated to the optimization of the detectors and veto systems in view of the kaonic deuterium run. A measurement was performed by filling the target cell with ^{4}He, since the much higher yield of helium, compared to that of the deuterium, allows to verify the performances of the apparatus much faster.
Fig. 2 shows the SDDs inclusive energy spectrum, which corresponds to the sum of the data acquired by the SDDs without any requirement. The spectrum is obtained with a data sample of 27 pb^{-1}. The presence of titanium, copper and bismuth lines is due to the activation, by particles lost by the beams, of materials around the detectors.
The background reduction takes advantage of the information provided by the SIDDHARTA-2 sub-detectors, in particular the kaon detector and the SDDs. 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. 3-left). Moreover, only X-rays with a timing within the SDDs' time window are selected, so further reducing the synchronous background (Fig. 3-right). More details on the data analysis are reported in [24].
The use of the kaon detector and the SDDs timing allow to reduce the background by a factor of 10^5. In Fig. 4 the final kaonic helium spectrum, after having applied the data selection

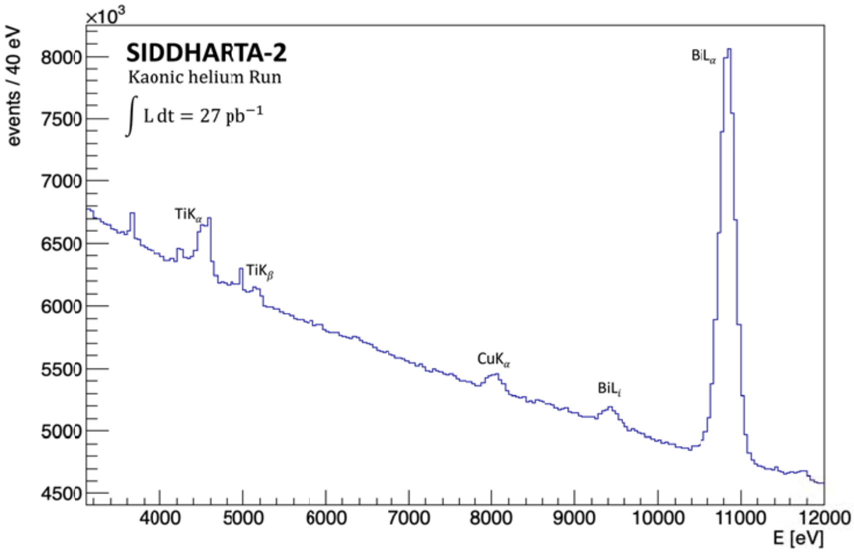

Figure 2: SIDDHARTA-2 SDDs inclusive energy spectrum using 27 pb^{-1} of data taken with the ^{4}He target.

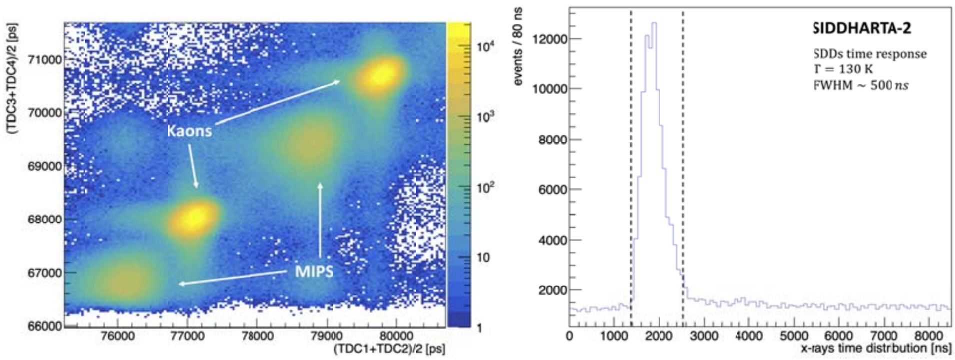

Figure 3: Left: kaon detector 2D plot given by the coincidence signal detected in the two scintillators placed above and below the beam pipe. Right: SDDs X-rays' time distribution. The dashed lines represent the time window used for the data selection.

described before, is shown. The kaonic helium L$_\alpha$ (3→2) transition together with the L$_\beta$ (4→2) and L$_\gamma$ (5→2) are clearly visible in the energy region from 6 keV to 12 keV [24]. Kaonic carbon lines are also present, due to the interaction of the kaons with the Kapton walls of the target cell. Moreover, inspecting the energy region from 3.0 keV to 5.2 keV, it is possible to note the presence of several transitions associated to the kaonic helium M-type lines (transitions to n=3). This result represents the first observation of the kaonic helium M-type lines, and their measurement is an important source of data to improve the knowledge about the kaonic helium cascade process.

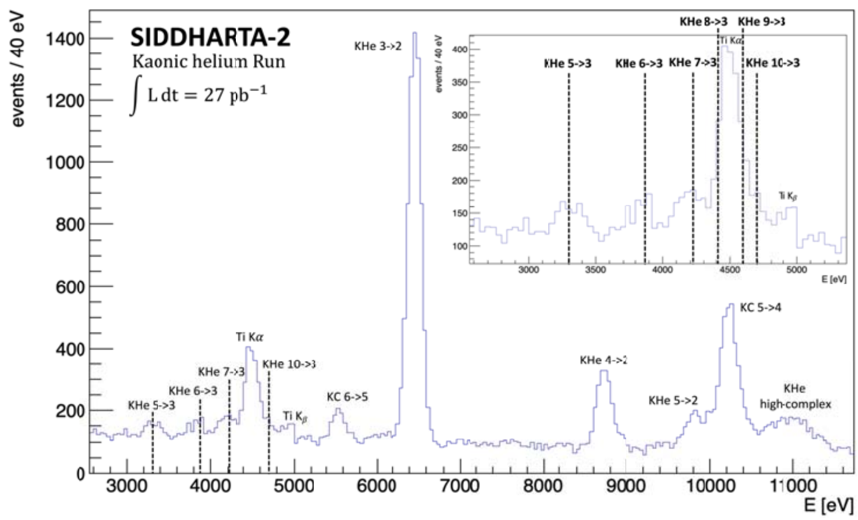

Figure 4: SIDDHARTA-2 SDDs energy spectrum using 27 pb^{-1}, after data selection.

4. Conclusion

The study of kaonic atoms is a unique tool to experimentally investigate the low-energy QCD in the strangeness sector, with implications from nuclear and particle physics to astrophysics. In this framework, the measurement of kaonic deuterium is the missing ingredient to obtain the isospin-dependent antikaon-nucleon scattering lengths. SIDDHARTA-2 aims to perform the first measurement of the kaonic deuterium X-ray transitions to the ground state in 2023.
In July 2022 we concluded the commissioning phase of the experiment by measuring the kaonic ^{4}He transitions to the n=2 energy level (L-lines) and for the first time, observed transitions to the n=3 level (M-lines). The data analysis of the M-lines is ongoing, with the goal to extract the yields and provide unique information to exotic atoms cascade calculations, which strongly need experimental input.
In conclusion, the clear measurement of the kaonic helium L-type lines combined with the first observation of the kaonic helium M-type lines demonstrate the potential of the SIDDHARTA-2 experiment to perform the challenging kaonic deuterium measurement in the coming run.

Acknowledgments

We thank C. Capoccia from LNF-INFN and H. Schneider, L. Stohwasser, and D. Pristauz-Telsnigg from Stefan Meyer-Institut for their fundamental contribution in designing and building the SIDDHARTA-2 setup. We thank as well the DAΦNE staff for the excellent working conditions and permanent support. We acknowledge support from the SciMat and qLife Priority Research Areas budget under the program Excellence Initiative—Research University at the Jagiellonian University. Part of this work was supported by the

Austrian Science Fund (FWF): [P24756-N20 and P33037-N]; the EXOTICA project of the Minstero degli Affari Esteri e della Cooperazione Internazionale, PO21MO03; the Croatian Science Foundation under the project IP-2018-01-8570; the EU STRONG-2020 project (Grant Agreement No. 824093; the EU Horizon 2020 project under the MSCA (Grant Agreement 754496); the Japan Society for the Promotion of Science JSPS KAKENHI Grant No. JP18H05402; the Polish Ministry of Science and Higher Education grant No. 7150/E-338/M/2018 and the Polish National Agency for Academic Exchange(grant no PPN/BIT/2021/1/00037).

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