

Kaonic atoms studies with the SIDDHARTA-2 experiment

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The SIDDHARTA-2 collaboration is performing research in the field of kaonic atoms spectroscopy. In this work, following an introduction on kaonic atoms and their importance for the development of low-energy strong interaction theories, the first result of the experiment (kaonic helium) is presented. This measurement was promising in the view of the main goal of the experiment, *i.e.* the first measurement of the kaonic deuterium transitions to the 1s level, important to model the kaon-nucleon interaction. In the last part of the paper future plans of the collaboration to measure new key quantities in kaonic atoms with beyond state-of-the-art radiation detectors are also presented.

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We dedicate this work to the memory of Prof. C. Guaraldo and Prof. J. Zmeskal, whose contributions were essential to the success of the kaonic atom measurements campaign at the DAΦNE collider. This work would not have been possible without them.

1. Introduction

A Kaonic Atom [1, 2] is an atomic system in which a negatively charged kaon (K^-) is captured by its electromagnetic interaction with the nucleus into an atomic orbit, thus replacing an electron. This kind of atoms provide a unique manner for experimentally probing the strong interaction between the kaon and the nucleons. When a kaonic atom is formed, the K^- is initially captured in a highly excited state; it then starts a cascade process, *i.e.* it experiences a series of both radiative and non-radiative de-excitations. The transitions to the lowest-lying energy states are characterised by the emission of X-rays. When present, the strong interaction manifests itself through two observables which can be experimentally measured: a shift (ε) of the energy level with respect to the purely electromagnetic one, and a broadening (or width) (Γ) of the level itself. In particular, for light kaonic atoms, the strong interaction happens nearly at threshold, since the relative energy between the kaon and the nucleus is of the order of the binding energy of the system, namely $O(10 \text{ keV})$, and provides unique observables in this unexplored energy region. Measurements of kaonic atoms transitions provide key quantities for theoretical models dealing with low-energy strong interaction [2] and have impact on various fields, from particle and nuclear physics to astrophysics [3] as well as cascade models. The measurement of the shift and width induced by the strong interaction to the fundamental level of Kaonic Hydrogen (KH) and of Kaonic Deuterium (KD) is particularly important: from these values the isospin-dependent scattering lengths between antikaon and nucleon can be extracted [4, 5]. Following the successful measurement of KH made by the SIDDHARTA experiment in 2009 [6], the SIDDHARTA-2 experiment [7–10] at the INFN-LNF aims to perform the first measurement of KD to provide theoretical models with crucial experimental inputs. SIDDHARTA-2 also measures higher-Z kaonic atoms, key for the understanding of the multi-body strong interaction, and performs precision tests of Quantum Electrodynamics (QED) towards a new measurement of the charged kaon mass.

2. SIDDHARTA-2 apparatus

The SIDDHARTA-2 setup is installed above the interaction point (IP) of DAΦNE [11–13]. DAΦNE is an electron-positron collider at the INFN-LNF, designed to work at the center of mass energy of the ϕ meson mass ($1.02 \text{ GeV}/c^2$). The ϕ resonances are produced almost at threshold and decay into K^+/K^- pairs with a branching ratio of 48.9%. The produced charged kaons have a momentum of $127 \text{ MeV}/c$. The experimental setup is schematically presented in Figure 1. A pair of plastic scintillators placed above and below the IP, and read by a pair of Photo-Multiplier Tubes (PMTs) each, form the Kaon Trigger (KT). The KT is able to select the kaons, via their characteristic Time-Of-Flight (TOF), which are emitted back-to-back from the ϕ decay in the IP and are directed towards the vacuum chamber, which is placed above the IP and contains the cryogenic target cell. The KT is also used to remove the background component which is asynchronous with the collisions. The kaons produced in the IP travel through the KT and the vacuum chamber window and then enter the

target cell to interact with the gas. Inside the target, the negatively charged kaons form kaonic atoms thus emitting X-rays which are detected by silicon drift detectors (SDDs) [14–18] surrounding the target. To suppress the residual background, two different veto systems are placed outside the vacuum chamber, the Veto-1 system [19], and around the SDDs, the Veto-2 system [20, 21]. More information regarding the experimental setup and its components can be found in [8].

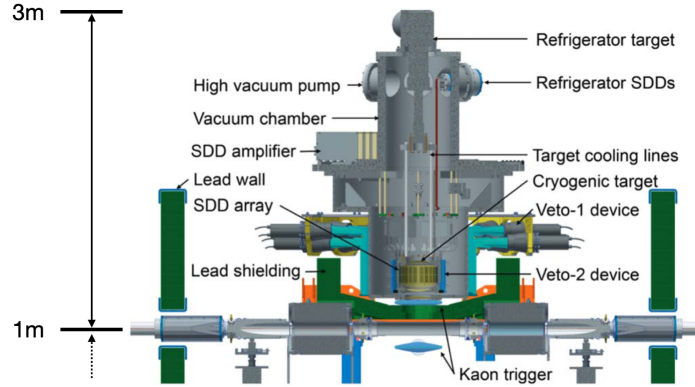


Figure 1: Schematic view of the SIDDHARTA-2 experimental setup. The whole system is installed at the e^+e^- IP in DAΦNE.

3. Preliminary results and future perspectives

The main focus of the SIDDHARTA-2 experiment is to perform the trailblazing measurement of the shift and width induced by the strong interaction on the fundamental level of kaonic deuterium. However, since the transition to the $1s$ level exhibits a severely low yield of X-rays [22], this is a challenging task. For this reason, before starting the KD data taking campaign, the setup needed to be meticulously optimized. Between March and May 2023, a characterization campaign of the experimental apparatus with a gaseous target with a much higher X-ray yield, namely Helium-4 [23], was performed. The final spectrum of this run is shown in Figure 2: after some background rejection cuts, the kaonic helium lines, together with some contaminant lines coming from the interaction of the kaons with the material of the setup, are clearly visible and were fitted to extract a new measurement of the $3d \rightarrow 2p$ (L_α) transition. The result of this study, reported in [23], excluded the presence of a large shift, in good agreement with theoretical models and previous measurements [24, 25], and proved the excellent performance of the SIDDHARTA-2 apparatus in view of the kaonic deuterium measurement, which was performed from spring 2023 to summer 2024 and whose data analysis is now ongoing. This result is also of key relevance for what regards kaon-multinucleon strong interaction. Moreover, with the same data-set, some high- n transitions of intermediate mass kaonic atoms such as Kaonic Oxygen, Kaonic Carbon and Kaonic Aluminum were also measured [26], proving the capabilities of the apparatus to measure energy transitions beyond 12 keV. The spectrum of this measurement is shown in Figure 2.

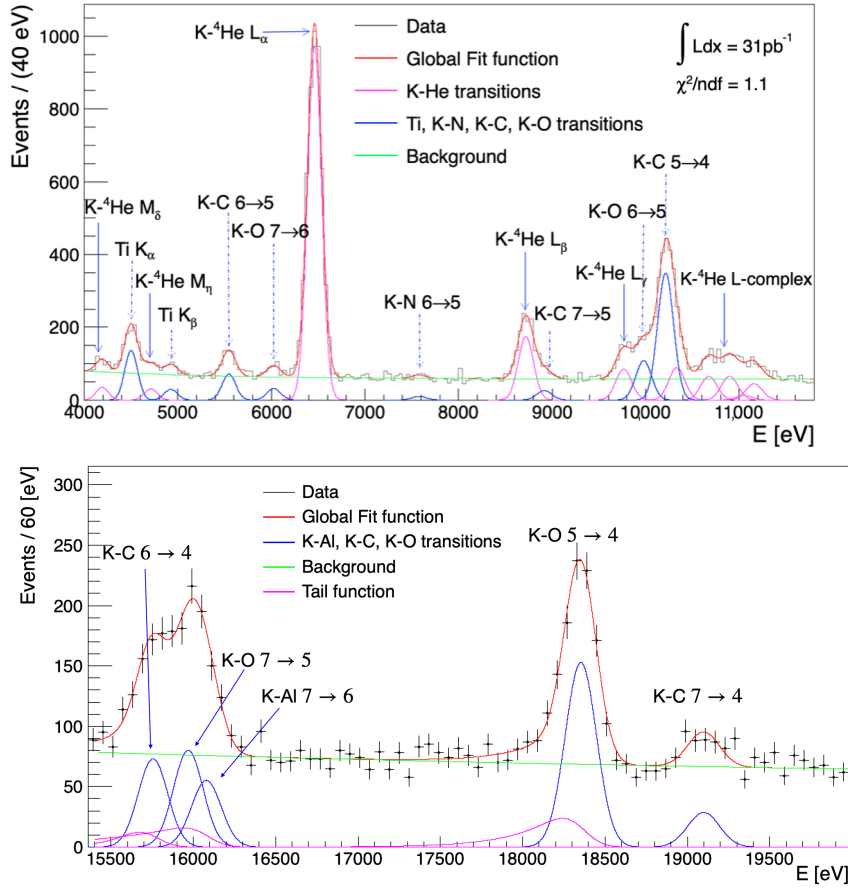


Figure 2: a) X-ray energy spectrum of the Kaonic Helium-4 run. Adapted from [23]. b) X-ray energy spectrum of the higher energy transitions. Adapted from [26].

The many-body interactions are now modeled with the data on kaonic atoms acquired between the 70's and 80's [27]. Problematic values that present wide errors or more measurements incompatible between each other (like Lithium, Boron, Aluminum and Sulfur) could be remeasured with improved precision using modern detection systems, bringing new, stringent limits to theoretical models dealing with kaon-multinucleon interaction, with a huge impact on low-energy strong interaction with strangeness. The SIDDHARTA-2 collaboration plans to measure more kaonic atoms using new 1 mm thick SDDs [28], which are now under development in collaboration with Politecnico di Milano and Fondazione Bruno Kessler, and with Cadmium Zinc Telluride (CZT) based detector systems [29–31].

The impact of kaonic atoms is not restricted only to the study of low-energy strong interaction: they can be exploited to carry out precision QED tests. One of the most forthright measurements that can be done using kaonic atoms, by measuring purely electromagnetic transition lines, is the charged kaon mass. This is still one of the open issues of the Particle Data Group (PDG) [32] which requires a definitive solution. In fact, the value of the mass of the charged kaon reported by the PDG is the result of a weighted average of the two most precise measurements which are, however, in strong disagreement with each other. Both these measurements were performed with a solid target and had

some drawbacks: in particular, the use of a solid target induces a series of possible systematic errors (like electron screening and electron refill) which are difficult to take into account. These kinds of problems are not present when using a gaseous target. Therefore, the SIDDHARTA-2 collaboration plans to perform, with a dedicated kaonic neon data taking campaign, a new measurement of the mass of the charged kaon. These measurements are part of the EXKALIBUR strategy [9], aiming to measure kaonic atoms along the periodic table.

4. Conclusions

The SIDDHARTA-2 experiment provided the most precise measurement ever for the kaonic helium $3d \rightarrow 2p$ transition [23] in a gaseous target with a relatively small (31 pb^{-1}) dataset, confirming the results obtained by the previous experiment [24]. The obtained results are encouraging for the upcoming measurement of the kaonic deuterium, the main goal of the experiment, that will bring vital experimental input to the study of the strong interaction. Beside this important goal, the collaboration is also testing and developing new technologies to reach a wider energy range (hence a higher kaonic atoms mass range) in the kaonic atoms research. New 1 mm thick SDDs [28] and a novel CZT detector system [29–31] were very successfully tested with this intent. The planned future measurements will have a huge impact in the description of the kaon-multinucleon strong interaction and in measuring the charged kaon mass, an open puzzle of modern particle physics.

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