PROCEEDINGS OF SCIENCE

Kaonic atoms measurements with the SIDDHARTA-2 experiment at DAΦNE

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Kaonic Atoms are a powerful tool to experimentally probe fundamental interactions, in particular Quantum Chromodynamics (QCD) and Quantum Electrodynamics (QED). The SIDDHARTA-2 experiment performs high-precision X-ray spectroscopy of kaonic atoms, and its main goal is to measure, for the first time, the X-ray transition to the fundamental level ($2p \rightarrow 1s$) of Kaonic Deuterium. Alongside this measurement, SIDDHARTA-2 has also measured other kaonic atoms, such as Kaonic Helium-4 and Kaonic Neon. In this paper, various results of the experiment are reported, along with the proposed target precision for the kaonic deuterium measurement and the future plans of the collaboration.

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1. Introduction

Kaonic atoms are exotic atomic systems in which one electron is replaced by a negatively charged kaon (K^-). Due to the much larger mass of the kaon compared to that of the electron, the Bohr radius of the kaonic orbitals is significantly reduced [1], bringing the K^- into proximity of the nucleus. In this regime, the strong interaction between the antikaon and the nucleus leads to measurable shifts and broadenings of the atomic energy levels, especially in the low-lying states. These modifications to the purely electromagnetic (QED) energy levels encode valuable information on the low-energy kaon-nucleus interaction, which is of fundamental importance for understanding Quantum Chromodynamics (QCD) in the non-perturbative regime and for testing effective field theories such as chiral SU(3) models [2, 3]. In particular, the shift (ε_{1s}) and width (Γ_{1s}) of the ground state in hydrogenic kaonic atoms, such as kaonic hydrogen and kaonic deuterium, are directly related to the complex scattering lengths of K^-p and K^-n systems. While kaonic hydrogen has been studied with increasing precision in past experiments (KpX [4], DEAR [5], SIDDHARTA [6]), no previous experiment had succeeded in measuring kaonic deuterium, due to the extremely low X-ray yield of the transitions [7]. This measurement is essential for disentangling the isospin components of the K^-N scattering lengths, and thus represents a cornerstone in the experimental study of hadron physics at low energies [8]. Beyond hydrogenic systems, measurement of shifts and widths on heavier kaonic atoms provides complementary information on the behavior of strong interaction at low energy with strangeness [3, 9].

On the other hand, the strong interaction plays a negligible role in high-n transitions, making precision measurements of kaonic atoms X-ray transitions ideal laboratories for tests of Bound State QED (BSQED), especially in systems with compact wavefunctions and enhanced vacuum polarization effects [10, 11]. The SIDDHARTA-2 experiment at the DAΦNE collider [12–14] is designed to exploit the unique production of low-energy kaons to perform high-precision X-ray spectroscopy of various kaonic atoms.

Section 2 presents the description of the SIDDHARTA-2 experimental apparatus; the results of the characterization run performed with a Helium-4 gaseous target and the relative measurement of Kaonic Helium, together with the most recent measurement of Kaonic Neon, which could provide a direct probe of BSQED, are reported in Section 3; Section 4 outlines the future perspectives of the collaboration; Section 5 provides the conclusions.

2. SIDDHARTA-2 apparatus

The experiment exploits the kaon beam produced by the DAΦNE electron-positron collider at the Laboratori Nazionali di Frascati (INFN-LNF) [15–17]. DAΦNE is a so-called ϕ-factory, meaning that the center-of-mass energy of the collisions is set at 1.02 GeV, corresponding to the mass of the ϕ meson, composed of a strange quark and a strange antiquark. Given the high decay rate of the ϕ meson into charged kaon pairs (48.9%), ϕ-factories are ideal machines for studying strong interactions involving strangeness in various regimes. The DAΦNE collider, as a ϕ-factory, is particularly suited for producing kaonic atoms, since the ϕ meson decays into a pair of low-momentum (127 MeV/c^2) charged kaons.

The SIDDHARTA-2 experimental setup is schematically presented in Figure 1.

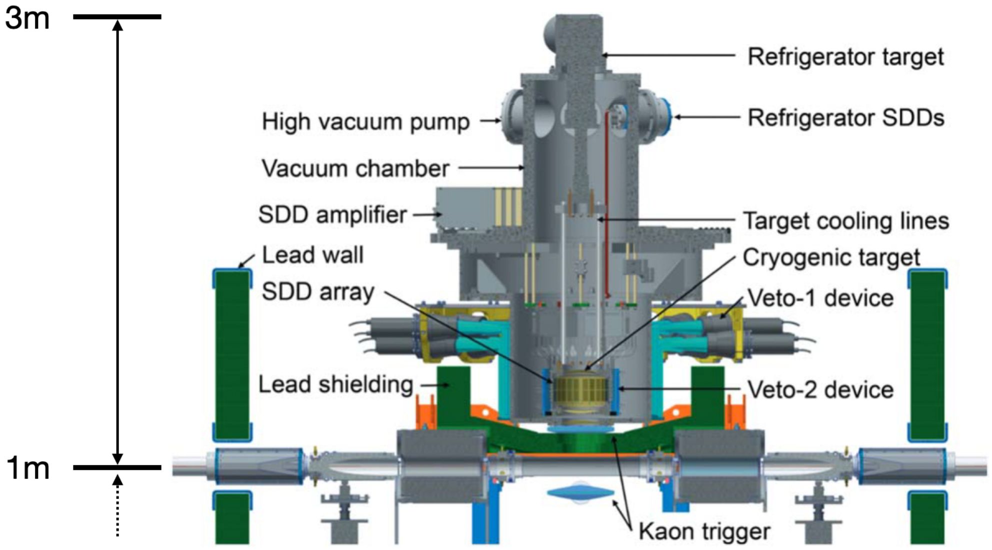

Figure 1: Schematic view of the SIDDHARTA-2 experimental setup. The whole system is installed at the e^+e^- IP in DAΦNE.

The kaon trigger (KT) system is composed of two plastic scintillators, placed above and below the Interaction Point (IP), and each is coupled to a pair of Photo-Multiplier Tubes (PMTs). This system is designed to identify kaons through their characteristic Time-Of-Flight (TOF), selecting particles produced back-to-back from the ϕ meson decay at the IP and directed towards the vacuum chamber, which hosts the cryogenic target cell. This kaon identification plays a crucial role in reducing background events associated with the collisions.

Once produced at the IP, the kaons pass through the KT and are slowed down by a mylar step-shaped degrader, a critical element inside the apparatus which is used to obtain a uniform stopping distribution of kaons inside the target cell. Kaons then travel through the vacuum chamber window before entering the target cell, where they interact with the selected gas. Inside the target, negatively charged kaons form kaonic atoms, which subsequently emit characteristic X-rays. These X-rays are detected by an array of Silicon Drift Detectors (SDDs) [18–22] surrounding the target volume.

To further mitigate residual background, two dedicated veto systems are implemented: the Veto-1 system [23], positioned outside the vacuum chamber, and the Veto-2 system [24, 25], arranged around the SDD detectors. A comprehensive description of the experimental apparatus and its components can be found in [14].

3. SIDDHARTA-2 measurements up to date

The primary goal of the SIDDHARTA-2 experiment is the first-ever measurement of the shift and width induced by the strong interaction on the fundamental level of kaonic deuterium. Due to the extremely low yield of X-rays from the $2p \to 1s$ transition [7], this measurement is particularly challenging and requires a careful optimization of the setup. To validate the performance of the apparatus under realistic conditions, a characterization run with a Helium-4 gaseous target was carried out between March and May 2023 [26], measuring the L-lines of kaonic helium, known to provide a significantly higher X-ray yield. The resulting spectrum, shown in Figure 2, displays visible kaonic helium lines, along with background contributions from kaon interactions with the experimental materials. A fit of the L_α $(3d \rightarrow 2p)$ transition yielded a new measurement consistent with previous results [27, 28] and with theoretical predictions, indicating the absence of a significant energy shift. This study confirmed the excellent performance of the experimental setup and provided essential validation for the kaonic deuterium measurement, conducted between spring 2023 and summer 2024, for which data analysis is currently ongoing. In Figure 2, the target precision (for a $\sim$ 800 pb^{-1} integrated luminosity) for the measurement of ε_{1s} and Γ_{1s} of kaonic deuterium is shown, together with some of the theoretical predictions for these values.

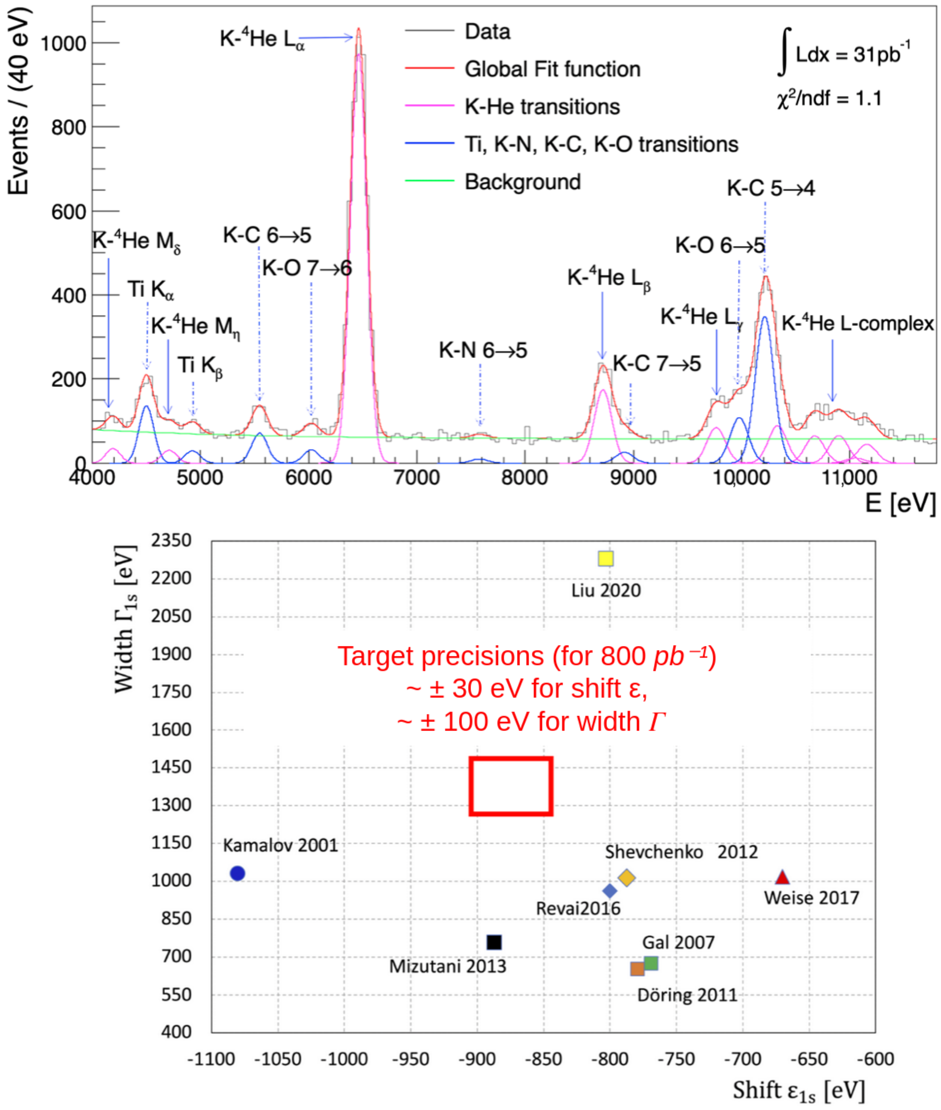

Figure 2: Above: X-ray energy spectrum of the Kaonic Helium-4 run; adapted from [26]. Below: target precision for the shift and width (red box) induced by the strong interaction on the fundamental level of kaonic deuterium, compared with some theoretical predictions [29–36].

During the 2023 run, SIDDHARTA-2 also collected data using a gaseous neon target over a total of 42 days between April and October, achieving an integrated luminosity of 125 pb^{-1}. This measurement, like the one with the Helium target, was conceived as a test aimed at optimizing both the degrader and the overall experimental setup. In particular, it allowed for the detection of several transitions within the energy region of interest for the Deuterium K-lines. The collaboration performed a high-precision measurement of kaonic neon [10], observing several high-n transitions with sub-eV statistical uncertainty. Figure 3 shows the fit to the kaonic neon spectrum. The measured energies and yields provide valuable input for the understanding of atomic cascade processes and represent one of the first experimental test towards the Bound State QED (BSQED) in strange exotic atoms. This result demonstrates the potential of kaonic atoms as a complementary testbed to muonic and antiprotonic systems for QED studies, due to their enhanced sensitivity to vacuum polarization effects and the absence of fine structure splitting in the kaonic sector [10].

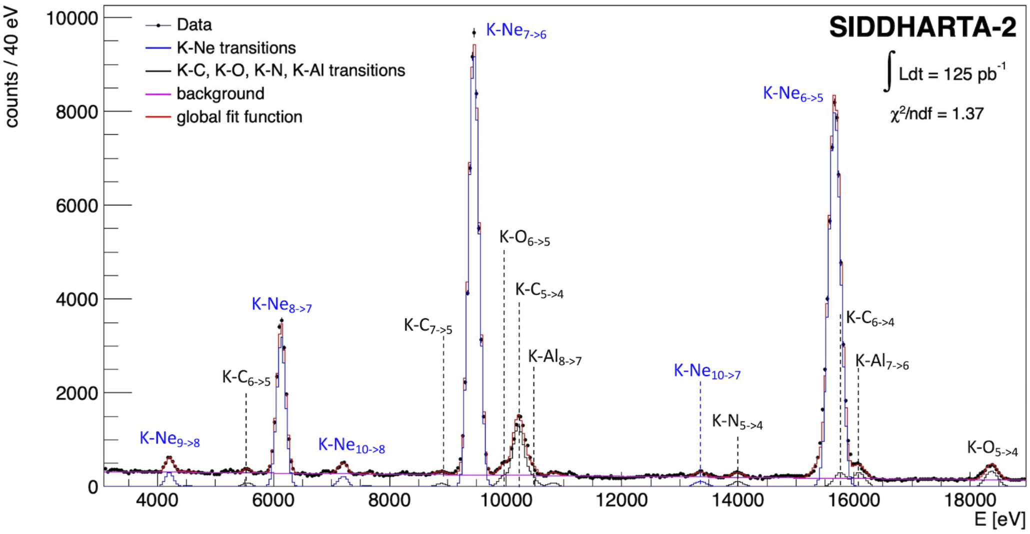

Figure 3: Fit to the kaonic neon energy spectrum; adapted from [10].

The SIDDHARTA-2 collaboration also measured transitions from kaonic atoms arising from solid elements present in the setup, namely aluminum, carbon, and oxygen. These transitions represent a background for the targeted ones, but at the same time constitute unique measurements that highlight the potential of the setup, and more generally of experiments at the DAΦNE collider, to study light and intermediate-mass kaonic atoms, with possible impact on BSQED and low-energy strong interaction models of K^-multi-N interaction [9]. In Table 1, the measurements of kaonic atoms transitions with the three mentioned nuclei are reported.

Table 1: Energies of intermediate mass kaonic atoms X-ray transitions measured by SIDDHARTA-2. Each value is reported together with the statistical and systematic uncertainty, respectively. Adapted from [37].

Kaonic Carbon		Kaonic Oxygen		Kaonic Aluminum	
Transition	Energy (eV)	Transition	Energy (eV)	Transition	Energy (eV)
7 → 5	8890.0 ± 13.0 ± 2.0	7 → 6	6016.0 ± 60.0 ± 2.0	8 → 7	10441.0 ± 8.5 ± 3.0
6 → 5	5541.7 ± 3.1 ± 2.0	6 → 5	9968.1 ± 6.9 ± 2.0	7 → 6	16083.4 ± 3.8 ± 12.0
6 → 4	15760.3 ± 4.7 ± 12.0	5 → 4	18359.4 ± 7.7 ± 12.0	-	-
5 → 4	10216.6 ± 1.8 ± 3.0	-	-	-	-

4. Future perspectives

High precision measurements of light, intermediate, and heavy mass kaonic atoms using different setups and detectors are the goal of the EXKALIBUR (EXtensive Kaonic Atoms Research: from LIthium and Beryllium to URanium) project [38], the natural successor to the SIDDHARTA-2 experiment.

The main motivation for these new measurements is that K^-multi-N interactions are still modeled based on data on kaonic atoms acquired in the 1970s and 1980s [39]. Problematic cases presenting large uncertainties or conflicting measurements (such as lithium, boron, aluminum, and sulfur) could be remeasured with improved precision using modern detection systems, providing new and more stringent constraints on theoretical models dealing with kaon–multinucleon interactions, with significant impact on our understanding of the low-energy strong interaction involving strangeness. The collaboration plans to measure higher energy kaonic atoms X-ray transitions using new 1 mm thick SDDs [40], currently under development in collaboration with Politecnico di Milano and Fondazione Bruno Kessler, and with Cadmium Zinc Telluride (CZT) based detector systems [41–43].

Moreover, one of the most relevant measurements achievable through kaonic atoms, by measuring purely electromagnetic transition lines, is the charged kaon mass. This is still one of the open issues in the Particle Data Group (PDG) [44] and requires a definitive resolution. In fact, the value of the charged kaon mass reported by the PDG is the result of a weighted average of the two most precise measurements [45, 46], which, however, are in strong disagreement with each other. Both measurements were performed with solid targets and suffered from systematic effects, such as electron screening and electron refill, which are difficult to properly account for. These systematic issues are not present when using a gaseous target. For this reason, the collaboration plans to perform a first dedicated data-taking campaign with a kaonic neon target to provide a new measurement of the charged kaon mass. These measurements are part of the EXKALIBUR strategy [38], which aims to measure kaonic atoms across the periodic table.

5. Conclusions

Kaonic atoms provide a unique experimental window into low-energy QCD, enabling the study of K^-N interactions in systems containing strangeness, and the testing of BSQED. The SIDDHARTA-2 experiment at DAΦNE has been specifically designed to perform high-precision X-ray spectroscopy of such atoms, exploiting the slow kaon production from ϕ decays.

The experiment has recently achieved important milestones. The characterization run with a Helium-4 target confirmed the excellent performance of the setup, validating the conditions for the challenging measurement of kaonic deuterium, whose data acquisition has been completed and is currently under analysis. In parallel, the first precision measurement of kaonic neon transitions has been performed, demonstrating the feasibility of sub-eV spectroscopy and opening new possibilities for BSQED studies in exotic atoms. Additional measurements on intermediate-mass kaonic atoms such as carbon, oxygen, and aluminum further extend the reach of the experiment, offering complementary insight into K^-multi-N interactions.

These results mark a significant step forward in the experimental exploration of strangeness in low-energy strong interactions and of BSQED. Future developments within the EXKALIBUR project will expand this program to a wide range of nuclear targets, aiming to build a comprehensive and systematic picture of the K^-N interaction across the periodic table.

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