INTERMEDIATE MASS KAONIC ATOMS AT DAΦNE[*]

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The SIDDHARTA-2 Collaboration aims to measure for the first time the shift and width induced on the $1s$ level of kaonic deuterium by the strong interaction. In the preliminary phase to the experiment, a test run

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[*] Presented at *Excited QCD 2024*, Benasque, Huesca, Spain, 14–20 January, 2024.

using a Helium-4 target was performed to optimize the performance of the full experimental apparatus. This preliminary study highlighted the possibility to measure transition lines coming from intermediate-mass kaonic atoms, such as kaonic carbon and kaonic aluminum. In order to measure transitions where strong interaction is manifesting at higher energies, out of the energy range of the SIDDHARTA-2 apparatus, the collaboration is testing a new detector system which exploits a novel compound semiconductor, the cadmium–zinc–telluride. Tests are now running at DAΦNE to study the performance of this detector, exploring the possibility to build a dedicated setup.

1. Introduction

Phenomenological models based on QCD [1] and on various crucial observables describe the behaviour of strong interactions in hadronic systems in the low-energy limit. An important set of these observables can be derived by studying exotic atoms [2]: systems in which a negatively-charged particle (either a lepton or a hadron) is captured in an atomic orbit, replacing an atomic electron. The exotic particle is captured in a highly excited state and then de-excites towards lower lying states by emitting radiation [3]. In this framework, kaonic atoms spectroscopy is a key experimental tool to probe the low-energy strong interaction with strangeness [4]. By measuring the shift and the width induced by the strong interaction on the lower levels, stringent constraints on the kaon-nucleon (K–N) and kaon–nuclei interactions can be set. With the recent development of precise and fast X-ray detectors, new experiments on kaonic atoms can be performed. The results of these studies give input to the phenomenological models describing the low-energy QCD with strangeness, in particular the K–N interactions as a function of the nuclear density, with important contributions in particle and nuclear physics and astrophysics (hyperon puzzle [5]).

The SIDDHARTA-2 experiment at DAΦNE [6] is presently taking data with a challenging goal: to measure for the first time the shift and the width induced by the strong interaction on the $1s$ level of kaonic deuterium. A preliminary study using a helium-4 target aiming to optimize the performance of the apparatus [7] showed how the de-excitation lines coming from some intermediate-mass kaonic atoms (such as kaonic carbon and kaonic oxigen) arising from the setup materials can be actually measured. The SIDDHARTA-2 Collaboration is now testing new technologies with the aim to set up a new, dedicated apparatus to measure the strong interaction effects on these intermediate mass kaonic atoms.

2. Experimental setup

The full SIDDHARTA-2 experimental setup was installed in the DAΦNE collider in Autumn 2022 [8]. DAΦNE is an electron–positron collider working at the center-of-mass energy of the ϕ resonance (1.02 GeV), providing, via its decay, charged K^+/K^- pairs with a branching ratio of 48.9%. The kaons are produced with a very low momentum (127 MeV/c), and can, therefore, be easily stopped inside a gaseous or solid target. The SIDDHARTA-2 experimental configuration is presented in Fig. 1, where the main elements are: the kaon trigger (KT), the Mylar degrader, the luminosity monitor [9], the cylindrical vacuum chamber that contains the cryogenic target, the Silicon Drift Detector (SDDs) [10–13], and three veto systems [14, 15]. The experimental setup was optimized with the help of a detailed Monte Carlo (MC) simulation using the Geant 4 CERN toolkit, to maximize the signal-to-background ratio during the data taking. More technical details on the experimental setup can be found in [16].
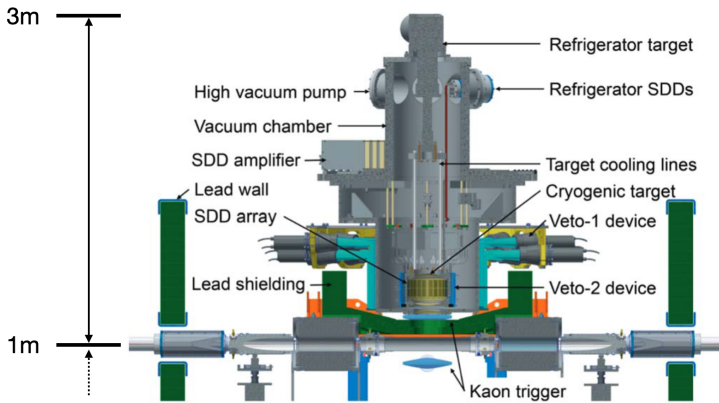

Fig. 1. An overview of the experimental setup [4]. The whole system is installed at the e^+e^- IP in DAΦNE.

3. Kaonic carbon and aluminum lines

The recent measurement of kaonic helium-4 L-series transitions, which was carried out in 2023, confirmed the possibility of measuring other kaonic atoms transition lines at DAΦNE. The analysis of the measured spectrum was performed in the energy range of 4–12 keV, and in this region, several kaonic carbon (K–C) and kaonic oxygen (K–O) lines were observed. These were the result of kaons interacting with the kapton walls ($C_{22}H_{10}N_2O_5$) of the target cell of the experimental setup. Moving to higher energy in the spectrum, other K–C and K–O lines, together with a kaonic aluminum (K–Al) line, are visible and can be measured. With this purpose, a fit to the

spectrum was performed. Each peak is described by a Gaussian function

$$G(E) = \frac{\text{Gain}}{\sqrt{2\pi}\sigma} \, \mathrm{e}^{\frac{-(E-E_0)^2}{2\sigma^2}} \, , \qquad (1)$$

together with a tail component which describes the low-energy contributions due to incomplete charge collection [17]:

$$T(E) = \frac{\text{Gain}}{2\beta\sigma} \, \mathrm{e}^{\frac{(E-E_0)}{\beta\sigma} + \frac{1}{2\beta^2}} \operatorname{erfc} \left(\frac{E-E_0}{\sqrt{2}\sigma} + \frac{1}{\sqrt{2}\beta} \right) \, , \qquad (2)$$

where β is the slope parameter of the tail function. The result of the fit is shown in Fig. 2. The measured values of the energies of the transitions, together with their QED calculated ones, are reported in Table 1. The electromagnetic values have been calculated with vacuum polarization and recoil corrections referring to [18–20], and the results were then compared with the values previously calculated for the KEK-KpX [21], KEK-E570 [22], and DEAR [23] experiments.
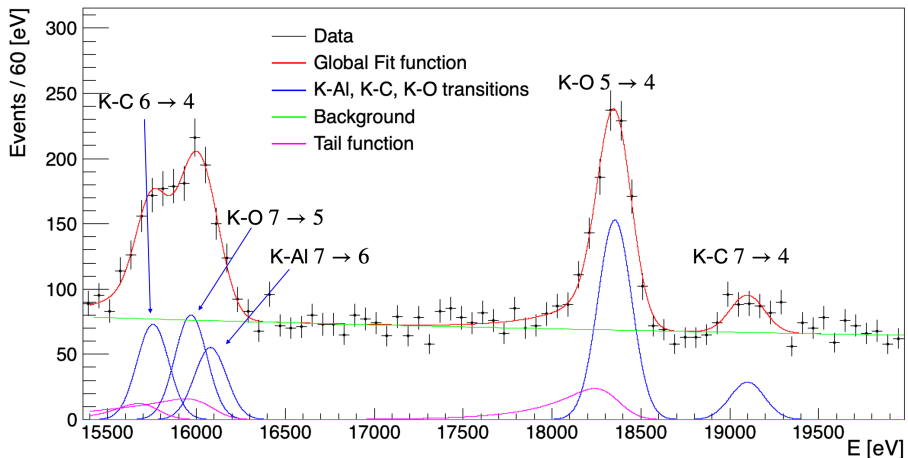

Fig. 2. Fit to the kaonic helium-4 spectrum in the 15–20 keV energy region.

The systematic uncertainties were estimated by measuring the energy residual of the bismuth $L_{\gamma 1}$ line in the raw spectrum, which has a nominal value of 15 248 eV [24] against a measured value of (15239.10 ± 0.68) eV. Therefore, the measured values are in good agreement with the theoretical ones inside the error bars. Nonetheless, the SDDs used by the SIDDHARTA-2 experiment are not optimally designed and calibrated in the 15–20 keV energy range, since the whole experimental setup was conceived to work at its best in the kaonic deuterium region of interest (4–12 keV). This measurement did not highlight any significant shift of these lines induced by the

Table 1. Kaonic carbon, oxygen, and aluminum transition lines with their respective nominal and measured energies.

Transition	E^{QED} [eV]	E^{meas} [eV]
K–C $6 \to 4$	15759.4	15756 ± 23 (stat.) ± 9 (syst.)
K–O $7 \to 5$	15973.3	15970 ± 23 (stat.) ± 9 (syst.)
K–Al $7 \to 6$	16088.3	16080 ± 16 (stat.) ± 9 (syst.)
K–O $5 \to 4$	18370.5	18353 ± 11 (stat.) ± 9 (syst.)
K–C $7 \to 4$	19101.0	19099 ± 32 (stat.) ± 9 (syst.)

strong interaction. This should appear, according to [25], for higher-energy transitions of these kaonic atoms. This study emphasized that, in order to perform such measurements, a dedicated setup with a new detector designed to work in the 40–400 keV energy range is needed.

4. CZT detector for intermediate mass kaonic atoms

In recent times, a considerable improvement in radiation detection technologies was achieved. In the framework of X-ray and γ-ray detectors, compound semiconductors are the most promising, given the possibility to grow crystals with dedicated physical properties for any application. In particular, cadmium–zinc–telluride (CdZnTe, CZT)-based detectors are strong candidates for experiments aiming to measure transitions of intermediate mass kaonic atoms, such as K–Al and K–C. In fact, in the energy region of interest for these transitions (tens to hundreds keV), CZT detectors exhibit good efficiency, room temperature energy resolution, and a fast timing, thus making this novel material excellent to produce new versatile and compact detection systems. Such detectors were already used in the fields of medical imaging [26] and astrophysics [27]. A prototype of CdZnTe-based detector was tested for the first time in a collider by the SIDDHARTA-2 Collaboration [28–30], after accurate studies on the high-rate performances [31]. The first tests in DAΦNE studied the feasibility to perform intermediate-mass kaonic atoms, especially K–Al and K–C, obtaining promising results reported in [30]. A new upgraded CZT detector, built by the SIDDHARTA-2 Collaboration, features two modules with four custom $13 \times 15 \times 5$ mm^3 CdZnTe quasi-hemispherical detectors provided by REDLEN Technologies, connected to analog charge-sensitive preamplifiers (CSPs) and digital pulse processing (DPP) readout electronics, accurately described in [32, 33]. The detectors and the preamplifiers are placed inside a 5 mm thick aluminum box, with an entrance window of 0.2 mm shown in Fig. 3.

Fig. 3. Picture of the CZT detectors installed in DAΦNE.

The apparatus is now installed in the longitudinal plane of the DAΦNE interaction point, in such a way to not interfere with the SIDDHARTA-2 experimental setup and is taking data. The main goal of this run is a preliminary test for the measurement of K–Al and K–C shifts and widths on the $n = 3$ and $n = 2$ levels, respectively, while exploring the possibility of performing new dedicated experiment to measure intermediate-mass kaonic atoms at DAΦNE or at J-PARC in the future.

5. Conclusions

In this paper, the measurement of kaonic atoms transition lines appearing in the high-energy region (15–20 keV) of the spectrum acquired by the SIDDHARTA-2 experiment during the helium-4 run is reported. The analysis of these data delivered new measurements, reported in Table 1, of the kaonic carbon, kaonic aluminum, and kaonic oxygen purely electromagnetic transition lines. This study highlighted the feasibility of measuring transitions where strong interaction is present of intermediate-mass kaonic atoms at DAΦNE. While exploring the possibility to perform new kaonic atoms experiments after the end of the kaonic deuterium SIDDHARTA-2 run [34], the collaboration is now testing a new CdZnTe-based detector which is designed to perform such measurements. The results of these future experiments can provide theoreticians with new valuable input data for phenomenological models of the low-energy QCD with strangeness.

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