Status and perspectives for low energy kaon-nucleon interaction studies at DAΦNE: from SIDDHARTA to SIDDHARTA-2

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The study of the antikaon nucleon system at very low energies plays a key role for the understanding of the strong interaction between hadrons in the strangeness sector. The information provided by the low energy kaon- nucleon interaction is accessible through the study of kaonic atoms. The lightest atomic systems, namely the kaonic hydrogen and the kaonic deuterium, provide the isospin dependent kaon-nucleon scattering lengths by measuring the X-rays emitted during their de-excitation to the 1s level. Until now, the most precise kaonic hydrogen measurement and an exploratory measurement of kaonic deuterium were carried out at the DAΦNE collider by the SIDDHARTA collaboration, combining the excellent quality kaon beam delivered by the collider with new experimental techniques, as fast and very precise X-ray detectors, like the Silicon Drift Detectors. Today, the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions is the experimental determination of the hadronic energy shift and width of kaonic deuterium, and will be measured by the new SIDDHARTA-2 experiment, which is installed in DAΦNE and is ready to start the data taking campaign.

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1. Introduction

The kaonic atom measurements represent a fundamental source of information for understanding the low-energy QCD, i.e. QCD in the non-perturbative regime, moreover in systems with strangeness, which is fundamental also for a better understanding of the chiral symmetry breaking mechanisms since the strange quark has its mass in between the light u and d quarks and the heavy ones, so are an important test ground for all theories and models proposing chiral symmetry breaking mechanisms.

The K^-p interaction is now well understood from recent results of kaonic hydrogen experiments performed by KpX at KEK [1], DEAR [2] and SIDDHARTA [3] at DAΦNE along with theoretical calculations based on these results, while kaonic deuterium transitions to the 1s level are the main aim of the SIDDHARTA-2 experiment. The kaonic deuterium x-ray measurement represents the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions today.

2. The SIDDHARTA-2 experiment: SIDDHARTINO run

The accelerator complex DAΦNE (Double Annular Φ Factory for Nice Experiments) [4, 5] at the National Laboratory Frascati (LNF) in Italy, includes a double ring electron-positron collider, a linear accelerator (LINAC), and a dumping ring (Accumulator). This facility is designed to produce a unique low-momentum kaon beam via the decay of Φ-mesons formed almost at rest. The Φ-mesons decay into $K^+ K^-$ pairs with a probability of 48.9%, delivering charged kaons with a momentum of 127 MeV/c. The kaon beam is ideal for the use in producing and studying kaonic atoms.

The SIDDHARTA-2 experiment at DAΦNE plans to measure the kaonic deuterium x-rays in a gaseous target with improved efficiency and background suppression. The experimental challenge of the measurement is the very small kaonic deuterium X-ray yield (one order of magnitude less than for hydrogen) and the even larger width of the K-lines. During the DAΦNE commissioning phase, preparatory for the kaonic deuterium data taking campaign, the SIDDHARTA-2 experimental apparatus has been installed housing only 8 SDDs arrays, with very good performance in terms of energy and timing resolution, in a reduced configuration called SIDDHARTINO. During this phase, concluded with the K-He4 run in July 2021, the main functionalities have been successfully tested. A schematic drawing of the layout (cross section view) is shown in Figure 1 including all the main components: the cryogenic target cell, the x-ray detector system, the veto, trigger and luminosity systems. A possible insertion of the new HpGe detector, to be used for heavier kaonic atoms, is also shown. The cryogenic target cell was built with less material budget using Kapton as wall material (50 μm kapton cylindrical body with a diameter of 140 mm and a length of 120 mm), and for the reinforcement structure pure aluminium was used. The choice of the Kapton as target cell material was dictated by the need to have a target wall which allows the low-energy (few keV) x-rays coming from inside target (kaonic atoms transitions) to pass through without a significant absorption.

The x-ray detection system of SIDDHARTA-2 consists of newly developed Silicon Drift Detectors arranged close together around the target. Each 450 μm thick silicon array is made by 8 cells arranged in a 2 × 4 matrix for a total active area of 5.12 cm^2. One such silicon wafer is glued on a ceramic carrier which provides the polarization to the units by an external voltage. The charges generated by the x-rays' absorption processes within the bulk are collected to the point-like anode and amplified through the closely bonded CMOS low-noise charge sensitive preamplifier (CUBE) and processed by the a dedicated ASIC circuit (SFERA). Each ASIC elaborates the X-ray events associated to 16 channels, making both the amplitude and the timing information at disposal to the DAQ. The SDD systems' spectroscopic response in terms of linearity, stability, energy and timing resolutions, has been proven to be suitable for high precision kaonic atoms X-ray spectroscopy [6]-[8]. The SIDDHARTA-2 experiment is equipped with a two-stage veto system to actively suppress the synchronous background. The inner layer, called Veto-2, consisting of scintillators read by Silicon Photo-Multipliers (SiPMs) placed behind the SDDs [9], is used to reject the hadronic background coming from border hits of Minimum Ionizing Particles (MIPs), depositing energy in the X-ray range. The outer layer, called Veto-1, made of plastic scintillators read by PMTs which externally surround the SIDDHARTA-2 vacuum chamber [10]. The functioning is based on the kaon moderation time in the gas, which is longer than the corresponding one in solid elements of the setup. Additionally, it allows the rejection of the background, both synchronous and synchronous to the beams.

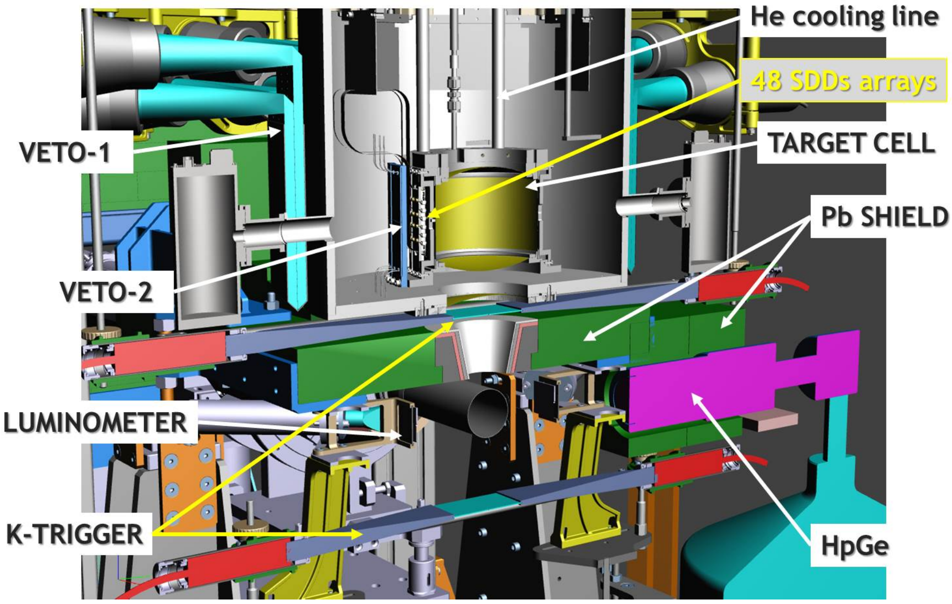

Figure 1: Schematic view of the SIDDHARTA-2 experimental apparatus installed at the Interaction Region of the DAΦNE collider.

The kaon trigger, consisting of two scintillators read by Photo-Multipliers (PMTs), mounted on top and bottom of the IR (Interaction Region), acts as efficient asynchronous (i.e. electromagnetic) background rejection system allowing to apply a timing selection on the detected X-ray events in coincidence with the signals generated by K^+-K^- pairs.

The luminosity monitor, made by two pairs of plastic scintillators read by PMTs placed on the lateral sides of the IR, is used to evaluate the beams' quality in terms of luminosity and background, in particular during the machine optimization phase and further implementation in the trigger system for the HpGe detector [11].

The data acquisition system records the signal amplitudes seen by the 24 SFERA circuits along with the global time information from the kaon trigger. Whenever a kaon trigger occurred, the time difference between the x-ray event and the originating kaon is recorded, as well as the time correlations between the signals on each of the scintillators from the veto system and the DAΦNE bunch frequency. From these data, the time-of-flight information of the kaon detector, the position of the hit on the detector, the rates of the SDDs, and the rate of kaon production could be extracted in the off-line analysis.

3. Future perspectives

The SIDDHARTA-2 kaonic deuterium data taking campaign is scheduled for 2021-2022. Meanwhile, the collaboration is developing a new 1 mm thick SDD technology dedicated to the measurement of light and heavier kaonic atoms to explore higher energy intervals with respect to the SIDDHARTA-2 one, with the aim to obtain additional fundamental information for the non-perturbative QCD in the strangeness sector. The proposed measurements are to be realized using a number of different detectors going from 1mm thick SDDs, to CdZn detectors, HpGe detectors and crystal spectrometers. A possible insertion of the new HpGe detector is also shown in figure 1. We are preparing a feasibility test measurement, in parallel with SIDDHARTA-2 measurements, which aims to determine the charged kaon mass with the requested precision by measuring energies of X-rays from transitions in kaonic atoms of the selected solid targets (e.g. Pb and W) by a HpGe detector[12]. The final configuration of the setup and the real position of the HpGe detector will be determined as a function of the background conditions measured on site. There are, however, a series of measurements of light kaonic atoms transitions which can already be performed with the existent SIDDHARTA-2 setup at the end of kaonic deuterium run, with a limited luminosity. The change is minimal and consists in removing the present gas target and replacing it with a conically shaped patch of solid targets (Li, Be and B), making space for additional rows of detectors in between the SDD one, as in the figure 2. The energy spectra of light kaonic atom transitions for Li,

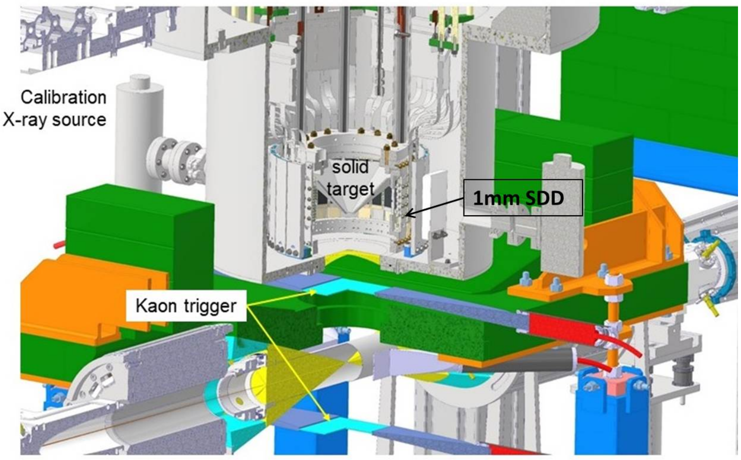

Figure 2: Schematic view of the SIDDHARTA-2 experimental apparatus for solid targets like Li, Be and B.

Be and B targets below 17 keV can achieve a precision below 2 - 3 eV, for an integrated luminosity of about 150 pb^{-1}. Monte Carlo simulations are presently being performed for the optimization of the setup, while an experimental proposal at DAΦNE was submitted. The physics of kaonic atoms is extremely broad and rich. A new set of kaonic atom transitions measurements of solid and gaseous targets, leading for example to a new high precision determination of the charged kaon mass or providing new inputs for cascade model calculations, will provide fundamental information on the antikaon-nuclei interaction, complementing the kaonic-hydrogen and deuterium results [13].

4. Summary

The SIDDHARTA-2 collaboration is prepared to perform the first ambitious kaonic deuterium precision X-ray spectroscopy measurement at the DAΦNE collider of LNF-INFN. In order to achieve this result, a dedicated experimental apparatus has been built and all the integrated systems have been successfully tested during the collider beam optimization phase, concluded with the measurement of the K-He4. The SIDDHARTA-2 kaonic deuterium data taking campaign is planned for 2021 - 2022. In the same time, the collaboration is developing new detector technologies and future proposals dedicated to kaonic atom measurements along the periodic table, for a deeper understanding of the QCD theory, with implications in astrophysics, particle and nuclear physics.

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