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High precision Kaonic Deuterium measurement at the DAΦNE collider: the SIDDHARTA-2 experiment and the SIDDHARTINO run

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The kaonic deuterium 2p → 1s transition X-ray measurement, a fundamental information needed for a deeper understanding of the Quantum ChromoDynamics (QCD) in the strangeness sector, is still missing. The SIDDHARTA-2 collaboration is now ready to achieve this unprecedented result thanks to the dedicated experimental apparatus that will allow to obtain the values of the kaonic deuterium K-transitions with a precision comparable to the most precise kaonic hydrogen measurement to-date performed by SIDDHARTA in 2009. Both the kaonic hydrogen and kaonic deuterium X-ray spectroscopy measurements of the de-excitation towards the fundamental level are a direct probe on KN interaction at threshold, as opposed to the scattering experiments which need an extrapolation to zero energy. Combining these results through the Deser-Truemann like formula, the isospin-dependent kaon-nucleon scattering lengths can be obtained in a model-independent way. The SIDDHARTA-2 setup is presently installed at the DAΦNE (Double Annular Φ Factory for Nice Experiments) collider of Istituto Nazionale di Fisica Nucleare- Laboratori Nazionali di Frascati and it is ready to perform the challenging kaonic deuterium measurement. This paper provides an overview on the SIDDHARTA-2 experimental apparatus and a preliminary result of the kaonic helium run, preparatory for the SIDDHARTA-2 data taking campaign, is also presented.

Keywords: Mesonic; hyperonic and antiprotonic atoms and molecules; X- and Γ-ray spectroscopy; Radiation Detectors; Solid-state Detectors; Kaonic atoms; SIDDHARTA-2.

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1. The SIDDHARTA-2 experiment

Kaonic atoms are formed in highly excited state systems given by the replacement of an electron with a thousand times higher mass negatively charged kaon (K^-). The system then relaxes through different processes (Auger emission, Stark Mixing, Coulomb de-excitation and radiative transitions) with a probability related to their lifetimes. For the low n-states, the strong interaction between the kaon and the nucleus adds up to the electromagnetic one. Thus, since the electromagnetic interaction with the nucleus is very well known in the Quantum ElectroDynamics (QED) framework, even a small deviation from the energy of the level with respect to the QED calculated value allows to get information on the strong interaction between the hadron and the nucleus.

In this context, the kaonic atom X-ray de-excitation transitions towards the fundamental level provide a unique measurement on the KN strong interaction at threshold, without the need to extrapolate to zero like for KN scattering results. Kaonic atom X-ray spectroscopy is a perfect tool to directly investigate the strong interaction in the low-energy limit, for a deeper understanding of the low energy QCD in the non perturbative regime in the strangeness sector (with implications from particle and nuclear physics to astrophysics [1–4]).

In 2009, the SIDDHARTA collaboration performed the most precise measurement to-date of the kaonic hydrogen fundamental level [5]. Nowadays, the SIDDHARTA-2 collaboration is ready to measure the kaonic deuterium K-transitions, aiming to obtain the 1s level shift and the width induced by the KN strong interaction with a precision comparable to the analogous SIDDHARTA results.

By combining the kaonic deuterium and kaonic hydrogen results, it will be finally possible to extract the K^-p and K^-d scattering lengths through the Deser-Truemann-type formulae with isospin-breaking corrections [6, 7], solving a still missing point in the framework of the low energy QCD in the non perturbative regime in the strangeness sector.

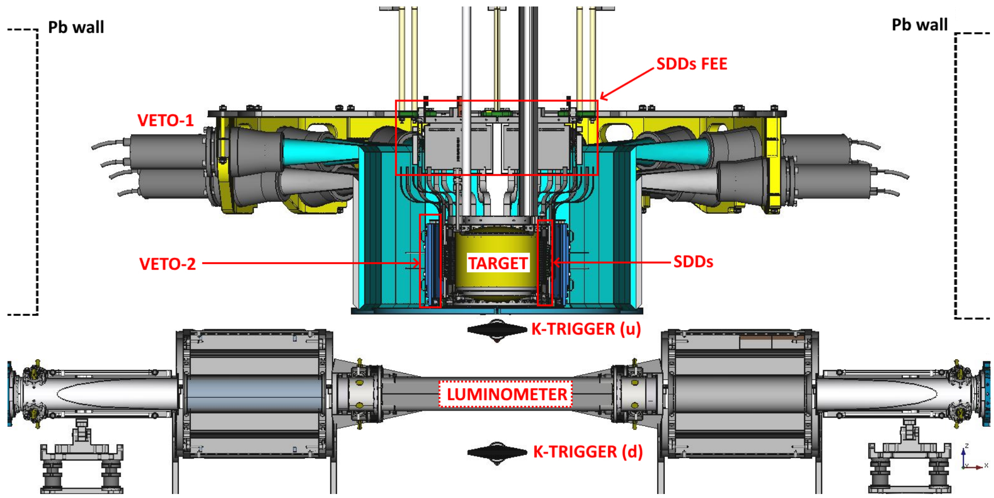

FIGURE 1. Cross-section layout of the SIDDHARTA-2 setup installed above the DAΦNE collider's Interaction Region. The red boxes highlight the SDDs arrays (around the target cell), the Front End Electronic and the veto-2 system behind the solid state detectors. On the side of the setup, Pb walls (black dotted lines) act as passive shielding for the machine electromagnetic background.

The SIDDHARTA-2 setup is presently installed at the DAΦNE collider of Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF), ready to start the unprecedented and challenging kaonic deuterium data taking campaign. The DAΦNE (Double Annular Φ Factory for Nice Experiments) electron-positron collider at INFN-LNF [8, 9] is a world class Φ-factory, which provides a low energy and monochromatic K^+K^- source (16 MeV of kinetic energy, 0.1% energy spread), via the Φ-meson decay (branching ratio ≈ 50%). The properties of the K^- beam provided by the INFN-LNF collider are suitable to perform high precision kaonic atom spectroscopy measurements, as demonstrated by the excellent result obtained by the SIDDHARTA collaboration [5]. During this run, an exploratory measurement of kaonic deuterium has been also performed, obtaining a limit of around 0.1% for the K^-d 2p→1s transition yield [10, 11]. Based on this, the SIDDHARTA-2 collaboration has built an improved setup with respect to SIDDHARTA able to perform the unprecedented kaonic deuterium measurement with a precision comparable to the kaonic hydrogen one.

The major upgrades of the setup are shown in Fig. 1.

On the lateral side of DAΦNE's beam pipe, the luminometer [12] made by two plastic scintillators read by Photo-Multipliers (PMs) monitors the beams' quality (luminosity and background), providing an on-line feedback to the collider, thus playing a fundamental role during the machine beam commissioning phase.

On the vertical side of DAΦNE's beam pipe, a couple of scintillators read by PMs detect the K^+-K^- pairs generated by the Φ meson decay. The K-trigger acts as efficient background suppressor providing a trigger to the SDDs' X-ray signals, allowing to apply a timing window selection for the rejection of asynchronous signals belonging to the electromagnetic background.

The scintillators read by PMs externally sorrounding the SIDDHARTA-2 vacuum chamber form the Veto-1 system [13]. This system is dedicated to the rejection of the hadronic background by separating signals due to the kaon interaction within the gas and the solid. With the kaon stop in a solid being much faster than in gas, a time resolution below 1 ns allows to clearly identify the source of the hadronic background through the signals' timing information.

The cylindrical target cell, made of a high purity aluminium structure and a 150 μm thick Mylar wall, stores the kaonic deuterium gas at a density equivalent to 3% of Liquid Deuterium Density. The density, calculated in order to maximize the kaonic deuterium Kα signals, is obtained operating at around 30 K with a working pressure of 0.4 MPa.

All around the target cell (covering 245.76 cm^2 of active surface), 48 large area and fast SDDs arrays (2 x 4 matrix) are arranged in a head-to-head configuration. The 450 μm thick Silicon bulk units are closely bonded to a C-MOS charge sensitive amplifier (CUBE) and the signals are processed by a dedicated FEE (SFERA, [14, 15]). The SDDs system has been optimized in the laboratory and succesfully tested in the heavy background of the collider [16–18].

Lastly, a series of plastic scintillators read by Silicon Photo-Multipliers (SiPMs) closely behind the SDDs [19] shape the veto-2 system. It is used to reject the hadron bakground associated to signals on the SDDs generated by Minimum Ionizing Particles (MIPs) hitting on the borders of the units.

A dedicated GEANT4 simulation has been done including the previously mentioned SIDDHARTA-2 items, taking the following input parameters for the kaonic deuterium Kα line, both from the theoretical calculations [20, 21] and the SIDDHARTHA results [10, 11], the shift (ϵ) of -800 eV, the width (Γ) of 750 eV and the yield of 0.1%. Consequently, the fit on the Monte Carlo spectrum, assuming 800 pb^{-1} of acquired integrated luminosity, determines that the SIDDHARTA-2 collaboration is expected to be able to

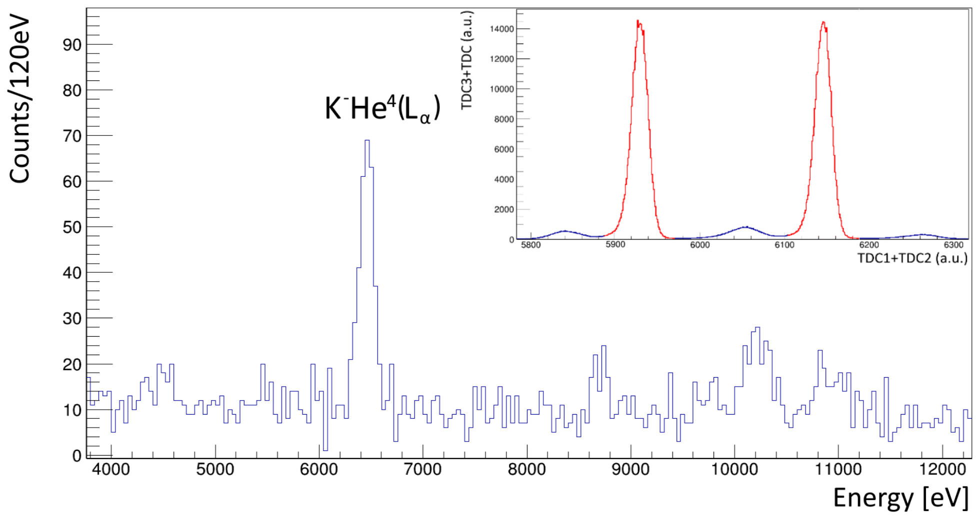

FIGURE 2. Preliminary calibrated spectrum for a sample of 5 pb^{-1} integrated luminosity acquired during the SIDDHARTINO run. The $K^{-}He^{4}$ Lα transition signal is clearly visible, after the Kaon trigger selection. On the top right inset, the MIPs and Kaons (red) distributions on the K-trigger system.

measure the kaonic deuterium observables with a precision comparable to the kaonic hydrogen one [3].

2. The SIDDHARTINO run

The SIDDHARTINO setup, a reduced SIDDHARTA-2 configuration made by 8 SDDs arrays, has been used to evaluate the data taking condition during the collider commissioning phase in preparation for the kaonic deuterium data taking campaign. This phase has been fundamental both to optimize the quality of the beams delivered by the collider and to test the SIDDHARTA-2 main functionalities. Firstly, both the luminosity monitor [12] and the SDDs system [18] have been tested in the heavy background of the collider during the machine beam tuning phase. Then, after having reached satisfactory conditions in terms of luminosity and background, the SIDDHARTINO run concluded in July 2021 with the measurement of the kaonic helium Lα transition. Figure 2 shows as example the preliminary calibrated spectrum obtained for a data sample equivalent to 5 pb^{-1} integrated luminosity, after having applied a sharp cut on the signals associated to the kaons detected by the K-trigger (red distribution on the top-right inset).

The $K^{-}He^{4}$ Lα transition results clearly visible at around 6.4 KeV.

3. Conclusion

The kaonic deuterium 2p $\rightarrow$ 1s transition X-ray measurement, the still missing fundamental information needed for a deeper understanding of QCD in the strangeness sector, is now ready to be performed by the SIDDHARTA-2 collaboration at the DAΦNE Φ-factory of INFN-LNF.

In order to obtain this ambitious and unprecedented result, a dedicated experimental apparatus has been built and its main functionalities have been successfully tested during the collider commissioning phase concluded with the $K^{-}He^{4}$ Lα transition measurement performed by SIDDHARTINO in July 2021.

Now, the SIDDHARTA-2 setup is installed at the Interaction Region of the DAΦNE collider ready to start the kaonic deuterium data taking campaign. Meanwhile, the collaboration is preparing proposals both for extremely precise or heavier kaonic atoms measurements, to deeply investigate the low-energy non-perturbative QCD in the strangeness sector.

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