# KAONIC DEUTERIUM MEASUREMENT
# WITH SIDDHARTA-2 ON DAΦNE*

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The interaction of antikaons with nucleons and nuclei in the low-energy regime represents an active research field in hadron physics with still many important open questions. The investigation of light kaonic atoms is, in this context, a unique tool to obtain precise information on this interaction. The most precise kaonic hydrogen measurement to date, together with an exploratory measurement of kaonic deuterium, were carried out by the SIDDHARTA Collaboration at the DAΦNE electron–positron collider of LNF-INFN, by combining the excellent quality kaon beam delivered by the

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collider with new experimental techniques, as fast and precise Silicon-Drift X-ray detectors. The measurement of kaonic deuterium will be realized in the near future by SIDDHARTA-2, a major upgrade of SIDDHARTA.

## 1. Introduction

The SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) experiment and its successor, SIDDHARTA-2, aim to perform high precision measurements of X-ray transitions in exotic (kaonic) atoms at the DAΦNE collider.

The precise measurement of the shift and width of the $1s$ level, with respect to the purely electromagnetic calculated values, in kaonic hydrogen and kaonic deuterium, induced by the strong interaction, through the measurement of the X-ray transitions to this level, will allow the first experimental determination of the isospin-dependent antikaon–nucleon scattering lengths, fundamental quantities for understanding the low-energy QCD in strangeness sector.

The accurate determination of the scattering lengths will place strong constraint on the low-energy $K^-N$ dynamics, which, in turn, constraints the SU(3) description of chiral symmetry breaking in systems containing the strange quark. The implications go from particle and nuclear physics to astrophysics (the equation of state of neutron stars).

In 2009, SIDDHARTA performed the most precise measurement of kaonic hydrogen [1] and the first exploratory study of kaonic deuterium [2]. Moreover, the kaonic helium-4 and kaonic helium-3 transitions to the $2p$ level were measured for the first time in gas in $^4$He and for the first time ever in $^3$He [3–5].

Presently, from April 2019, a new experiment, SIDDHARTA-2, is under way at the DAΦNE collider, with the aim to perform the first measurement of kaonic deuterium.

## 2. The SIDDHARTA-2 experiment

The case of kaonic deuterium is more challenging than kaonic hydrogen mainly due to the very small kaonic deuterium X-ray yield (one order of magnitude less than for hydrogen), due to even larger width of the $K$-lines and due to the difficulty to perform X-ray spectroscopy in the high-radiation environments of the DAΦNE accelerator.

Experimentally, the case of kaonic deuterium is still open. The SIDDHARTA experiment measured the X-ray spectrum with a pure deuterium target but, due to the limited statistics and high background, the determination of the strong interaction shift and width was impossible. An upper

limit for the X-ray yield of the $K$-lines could be extracted from the data: total yield $< 0.0143$ and $K_\alpha$ yield $< 0.0039$ [2]. Since the kaonic deuterium X-ray measurement represents the most important experimental information missing in the field of the low-energy antikaon–nucleon interactions, a new experiment, SIDDHARTA-2, is under way, making use of an improved apparatus.

The goal of the new apparatus is to increase drastically the signal-to-background ratio, by gaining in solid angle, by taking advantage of a new type of Silicon-Drift Detectors (SDDs) with improved timing resolution and by implementing additional veto systems.

The outcome of the detector developments and dedicated Monte Carlo studies can be summarised in three main updates essential for the successful kaonic deuterium measurement with SIDDHARTA-2:

— An improved X-ray detection system based on newly developed SDDs with excellent timing capability (300 ns) and energy resolution ($\simeq 150$ eV). The SDD array consists of eight square SDD cells, each with an active area of $8 \times 8$ mm$^2$ arranged in a $2 \times 4$ array format. A new advanced production technology allows to set up the cryogenic target and detector systems with an efficient detector packing density, covering a solid angle of almost $2\pi$ sr for stopped kaons in the gaseous target cell.

— A lightweight cryogenic target: the main component of the target cell is the cylindrical wall, which consists of two layers of 50 $\mu$m thick Kapton foils glued together with a two-component epoxy-glue, with an overlap of 10 mm, achieving a total thickness of the order of $(140 \pm 10)$ $\mu$m, with a working temperature of 30 K and a maximum working pressure of 0.3 MPa, allowing an X-ray transmission of 85% at 7 keV.

— A veto system, consisting of an outer veto detector (Veto-1) as active shielding and an inner veto detector (Veto-2) for the suppression of charged particles. Additionally, for both veto systems, an excellent time resolution is required to distinguish between kaons stopped in gas and kaons stopped in the target entrance window or sidewall. MC studies require the time resolution of the veto devices to be better than 500 ps (Full Width Half Maximum, FWHM).

In Fig. 1, the SIDDHARTA-2 apparatus is schematically shown. More details can be found in [6–8].

A detailed Monte Carlo simulation was performed within the Geant4 framework to optimise the critical parameters of the setup, such as target size, gas density, detector configuration and shielding geometry. The Monte Carlo simulation took into account the described improvements with the assumption that the values of shift and width of the 1$s$ ground state of
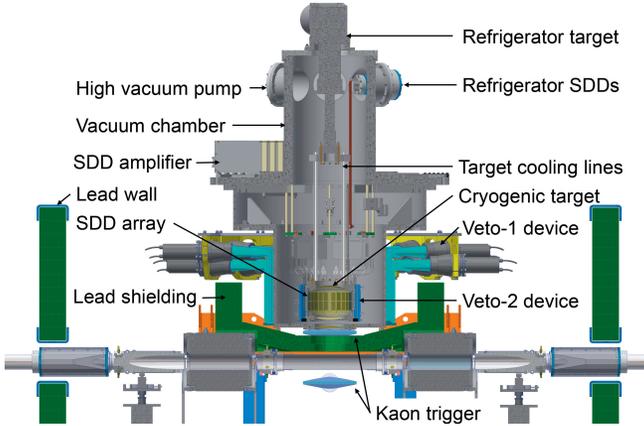
Fig. 1. The SIDDHARTA-2 setup with the cryogenic target cell surrounded by the SDDs and the Veto-2 system within the vacuum chamber, while the Veto-1 device is surrounding the chamber on the outside.

kaonic deuterium were $-800$ eV and 750 eV, respectively, as representative theoretical expected values. Moreover, yields ratios $K_\alpha : K_\beta : K_{\text{total}}$ were those of kaonic hydrogen, with an assumed $K_\alpha$ yield of $10^{-3}$.

Figure 2 shows the expected spectrum for an integrated luminosity of 800 pb$^{-1}$ delivered by DAΦNE in similar machine background conditions as in SIDDHARTA runs. The extracted shift and width can be determined with precisions of about 30 eV and 80 eV, respectively. These values are of the same order as the SIDDHARTA results for kaonic hydrogen.
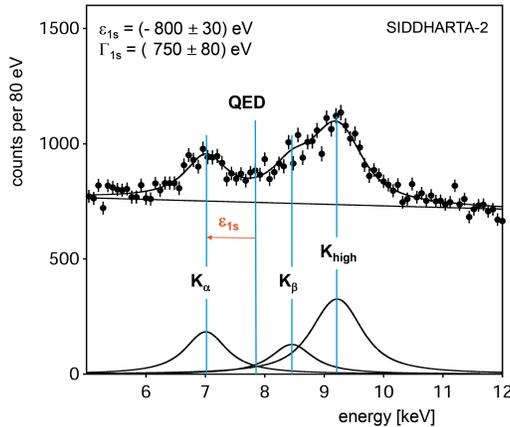


Fig. 2. Simulated SIDDHARTA-2 kaonic deuterium spectrum, assuming a shift $\varepsilon_{1s} = -800$ eV and width $\Gamma_{1s} = 750$ eV of the 1s state, as well as a $K_\alpha$ yield of $10^{-3}$. The spectrum was simulated for an integrated luminosity of 800 pb$^{-1}$.

In spring 2019, the Day-1 setup, SIDDHARTINO, see Fig. 3, containing 8 SDDs units out of the 48 units for the complete SIDDHARTA-2 setup, aiming to measure kaonic helium to quantify the background in the new DAΦNE configuration, previous to the kaonic deuterium measurement, was installed in the DAΦNE accelerator. After the debugging and optimization with the SIDDHARTINO setup, in 2020, the kaonic deuterium measurement will follow with the full SIDDHARTA-2 setup.
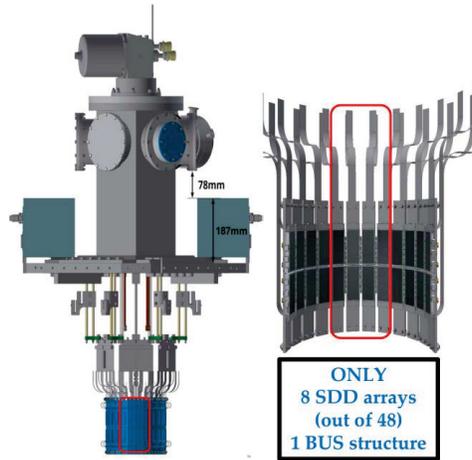


Fig. 3. The SIDDHARTINO setup — detail.

## 3. Summary and perspectives

The kaonic deuterium X-ray measurement represents the most important experimental information missing in the field of the low-energy antikaon nucleon interactions. Experimental results of SIDDHARTA-2 based on newly developed cutting-edge X-ray detectors and lightweight cryogenic target system will lead to essential constraints in theory and will set the physics focus on the low-energy antikaon–neutron interaction, which is up to now an open issue.

Although the importance of kaonic deuterium X-ray spectroscopy has been well recognized, for more than 30 years (R. Dalitz), no experimental results have yet been obtained due to the difficulty of the X-ray measurement. Different theoretical calculations on shift and width of the $1s$ ground state of kaonic deuterium were performed in the last years, as shown in Fig. 4. The expected precision of the experimental measurement at DAΦNE is given as the rectangle coloured in grey/red (shift $\varepsilon_{1s} = \pm 30$ eV, width $\Gamma_{1s} = \pm 75$ eV). The experimental result will set essential constraints for theories and will help to disentangle between different theoretical approaches.
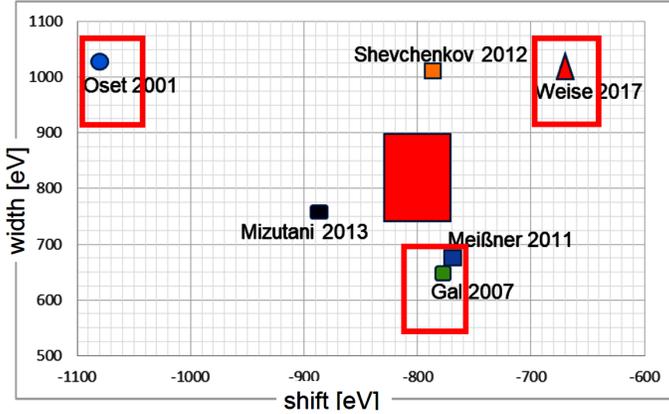
Fig. 4. Different theoretical calculations on shift and width of the $1s$ ground state of kaonic deuterium. The expected precision of the experimental measurement at DAFNE is given as the rectangle coloured in grey/red (shift $\varepsilon_{1s} = \pm 30$ eV, width $\Gamma_{1s} = \pm 75$ eV) [9–14].

The experiments on kaonic atoms at DAΦNE promise to boost even farther our comprehension of the "strangeness physics", with implications extending from particle and nuclear physics to astrophysics (the equation of state of neutron stars).

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