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Studies of kaonic atoms at the DAΦNE collider: from SIDDHARTA to SIDDHARTA-2

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Abstract. The DAΦNE electron-positron collider of the Laboratori Nazionali di Frascati of INFN is a worldwide unique low-energy kaon source and for this reason is suitable for low-energy kaon physics like kaonic atoms and kaon-nucleons/nuclei interaction studies. Kaonic atoms are atomic systems where an electron is replaced by a negatively charged kaon, containing the strange quark, which interacts in the lowest orbits with the nucleus also by the strong interaction. As a result, their study offers the unique opportunity to perform experiments equivalent to scattering at vanishing relative energy. This allows to study the strong interaction between the antikaon and the nucleon or the nucleus "at threshold", without the need of *ad hoc* extrapolation to zero energy, as in scattering experiments. 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 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.

In 2009 SIDDHARTA performed the most precise measurement of kaonic hydrogen [1]. As a result, the $1s$ -level shift ε_{1s} and width Γ_{1s} of kaonic hydrogen were determined to be:

$$\varepsilon_{1s} = -283 \pm 36(stat) \pm 6(syst) \;\; eV \tag{1}$$

$$\Gamma_{1s} = 541 \pm 89(stat) \pm 22(syst) \;\; eV. \tag{2}$$

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 constraints on the low-energy $\mathrm{K^-N}$ 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).

The SIDDHARTA experiment has performed also the kaonic helium-4 and kaonic helium-3 transitions to the 2p level X-ray measurements, for the first time in gas in kaonic helium-4 and for the first time ever in kaonic helium-3 [2, 3, 4] and the first exploratory study of kaonic deuterium [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 [6].

2. The SIDDHARTA-2 experiment

The kaonic deuterium X-ray measurement represents the most important experimental information missing in the low-energy antikaon-nucleon interactions sector, and for this reason a new experiment, SIDDHARTA-2, is under way, making use of an improved apparatus.

The case of kaonic deuterium is more challenging than that of the kaonic hydrogen mainly due to the kaonic deuterium X-ray yield (one order of magnitude less than for hydrogen), the even larger width and the difficulty to perform X-ray spectroscopy in the high radiation environment 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 not possible. An upper limit for the X-ray yield of the K-lines could be extracted from the data: total yield < 0.0143 and K_α yield < 0.0039 [5].

The goal of the new apparatus of the SIDDHARTA-2 experiment is to increase drastically the signal-to-background ratio, by gaining in solid angle, taking advantage of a new type of Silicon-Drift Detectors (SDDs) with improved timing resolution, and by implementing additional veto systems.

The characteristics of the new apparatus can be summarised in three main updates with respect to SIDDHARTA:

- A lightweight cryogenic target: the main component of the target cell is the cylindrical wall, which consists of two layers of 50 μm 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 ± 10) μm, 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.

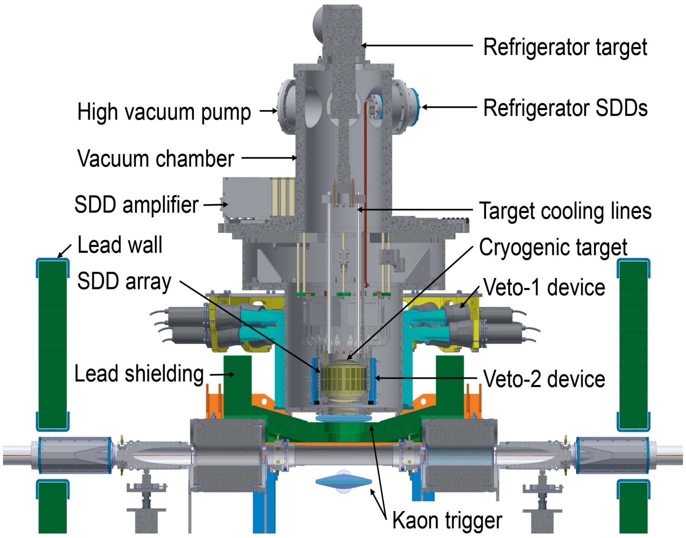

Figure 1. The SIDDHARTA-2 setup with the cryogenic target cell surrounded by the SDDs and the Veto-2 system within the vacuum chamber, while the Veto-1 device is surrounding the chamber on the outside.

- 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 × 8 mm^2 arranged in a 2 × 4 array format. A new advanced production technology allows to setup up the cryogenic target and detector systems with an efficient detector packing density, covering a solid angle of almost 2π sr for stopped kaons in the gaseous target cell.
- Dedicated veto systems, to improve by at least one order of magnitude the signal to background ratio, as compared to the kaonic hydrogen measurement performed by SIDDHARTA (signal/background $\simeq$ 1/3). Two special veto systems are foreseen for SIDDHARTA-2, consisting of an outer barrel of scintillators counters, read by Photomultipliers (PMs), called Veto-1 as active shielding and an inner ring of plastic scintillation tiles (SciTiles), read by Silicon Photomultipliers (SiPMs), placed as close as possible behind the SDDs, for charge particles tracking, called Veto-2.

The SIDDHARTA-2 apparatus [6, 7] is schematically shown in Fig. 1.

A detailed Monte Carlo simulation was performed within the GEANT4 framework to optimise the critical parameters of the setup, like 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 1s ground state of kaonic deuterium were -800 eV and 750 eV, respectively, as representative theoretical expected values. Moreover, yields ratios $K_\alpha : K_\beta : K_{total}$ were those of kaonic hydrogen, with an assumed K_α yield of 10^{-3}.

Fig. 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.

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, was installed in the DAΦNE accelerator. The SIDDHARTINO setup has the aim to measure kaonic helium X-rays in order to quantify the background in the new DAΦNE configuration, previous to the kaonic deuterium measurement.

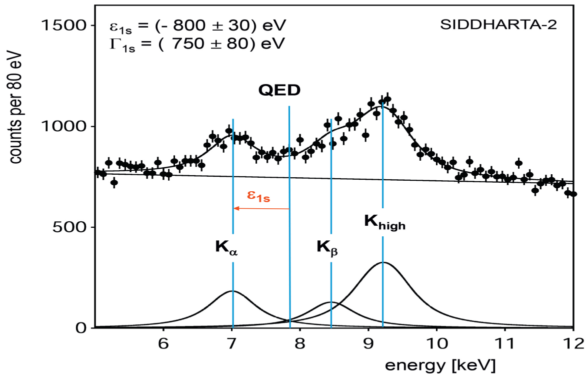

Figure 2. Simulated SIDDHARTA-2 kaonic deuterium spectrum, assuming a shift ε_{1s}= -800 eV and width Γ_{1s} = 750 eV of the 1s state, as well as a K_α yield of 10^{-3}. The spectrum was simulated for an integrated luminosity of 800 pb^{-1}.

After the debug and optimization with the SIDDHARTINO setup, in 2020 the kaonic deuterium measurement will follow with the full SIDDHARTA-2 setup.

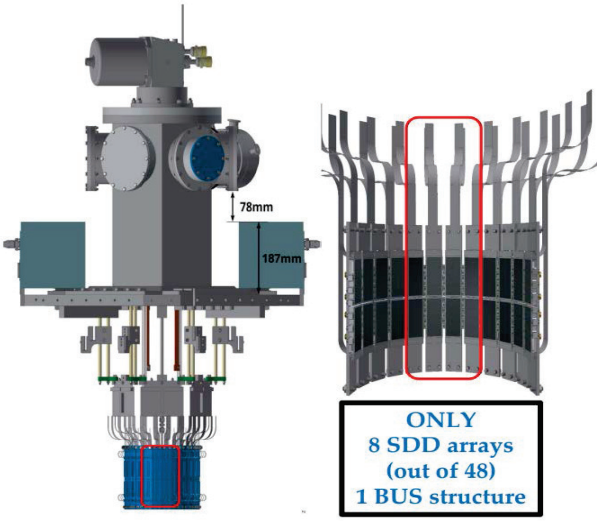

Figure 3. The SIDDHARTINO setup - detail.

3. Conclusions

The DAΦNE collider delivers an excellent quality low-energy charged kaons beam. Such a beam was intensively used by the SIDDHARTA collaboration to perform unique quality measurements of kaonic atoms. In 2020 the kaonic deuterium measurement will be performed by the SIDDHARTA-2 experiment.

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 of the SIDDHARTA-2 experiment is given as the rectangle coloured in red (shift

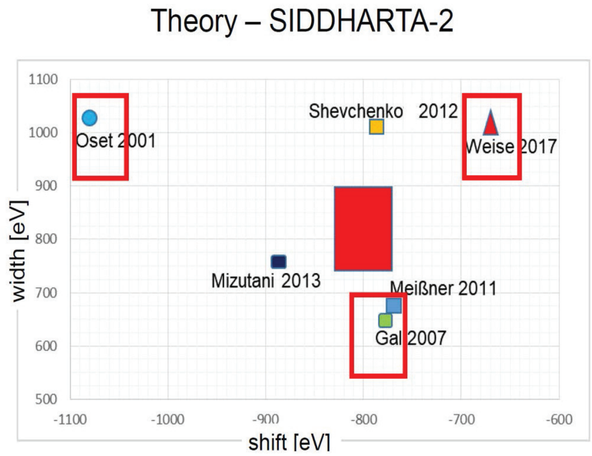

Figure 4. Different theoretical calculations on shift and width of the 1s ground state of kaonic deuterium. The expected precision of the experimental measurement at DAFNE is given as the rectangle coloured in red (shift ε_{1s}= ±30 eV, width Γ_{1s} = ± 75 eV).

ε_{1s}= ± 30 eV, width Γ_{1s} = ± 75 eV). The experimental result will set essential constraints for theories and will help to disentangle between different theoretical approaches.

SIDDHARTA and SIDDHARTA-2 experiments on DAΦNE collider provide unique quality results for the understanding of the low-energy QCD in the strangeness sector, with implications going from particle and nuclear physics to astrophysics.

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