Kaonic atoms experiment at the DAΦNE collider by SIDDHARTA/SIDDHARTA-2

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Abstract

The excellent quality kaon beam provided by the DAΦNE collider of LNF-INFN (Italy) together with SIDDHARTA/SIDDHARTA-2 new experimental techniques, as very precise and fast-response X-ray detectors, allow to perform unprecedented measurements on light kaonic atoms crucial for a deeper understanding of the low-energy quantum chromodynamics (QCD) in the strangeness sector. In this paper an overview of the main results obtained by the SIDDHARTA collaboration, as well as the future plans related to the SIDDHARTA-2 experiment, are discussed.

Contents

1 Introduction

Kaonic atoms are one of the hot issues currently in nuclear and hadronic strangeness physics, both from the experimental and theoretical standpoints [1–23]. The investigation of light kaonic atoms is a unique tool to obtain precise information on the antikaons-nucleons/nuclei interaction in the low-energy regime. The precise measurement of the shift and width of the 1s level, with respect to the purely electromagnetic calculated values, in the lightest kaonic atoms, such as kaonic hydrogen and kaonic deuterium, induced by the strong interaction, will deliver the first experimental isospin-dependent antikaon-nucleon scattering lengths, which are fundamental quantities crucial for understanding the low energy QCD in the strangeness sector, as for example the correlation between spontaneous and explicit chiral symmetry breaking, having also important impact in astrophysics (equation of state of neutron stars).

The most precise measurement for kaonic hydrogen [7], together with an exploratory measurement of kaonic deuterium [24], was performed by the SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) collaboration at the DAΦNE e^+e^- collider of LNF-INFN using the unique quality kaon beam together with new experimental techniques, as fast and precise Silicon-Drift X-ray detectors. A new experiment, SIDDHARTA-2, a major improvement of SIDDHARTA, is in progress, with the goal to perform the first measurement of kaonic deuterium.

2 Kaonic atoms

A kaonic atom is an atomic system where there is a negative charged kaon in the place of the electron. It is formed when the K^- enters in a target, is decelerated to kinetic energy of a few tens of eV due to ionizations and excitations of the molecules and atoms of the medium and then captured into an outer atomic orbit, replacing an electron. The capture occurs in a highly excited state due to the much higher K^- mass with respect to the e^- one. Subsequently, a cascade processes including Auger effect, Coulomb deexcitation and scatterings, bring the kaon to the low angular momentum atomic state. When the kaon reaches the ground level of the kaonic atom, it interacts with the nucleus via the strong interaction and is absorbed by the nucleus. The strong interaction is manifested as a shift of the energy level with respect to the well known electromagnetic value (ε) and a broadening of the level (Γ). The schematic view of cascade processes for kaonic hydrogen is shown in Fig. 1.

The shift and width are determined by the measurement of the X-ray transitions toward

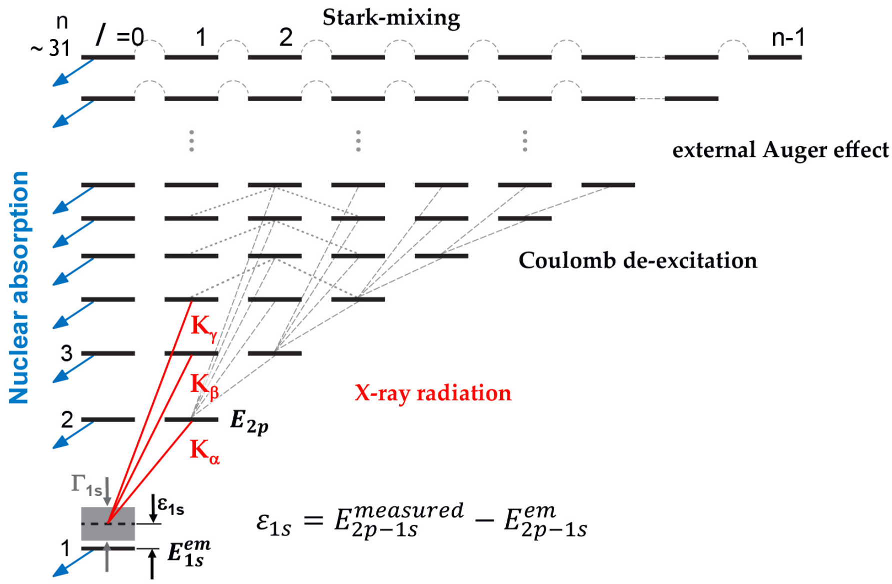

Figure 1: The kaonic hydrogen cascade process, which starts when the kaon is captured in a highly excited state and lead it to the 1s ground level. The fundamental state is shifted and broadened due to strong interaction. Adapted from [1].

the lowest lying states. The ε and Γ quantities measured for the kaonic hydrogen and kaonic deuterium for 1s ground level allow to extract the isospin-dependent $\bar{K}$-nucleon scattering lengths based on Deser-type formulae [1,25].

3 Kaonic atoms measurements by SIDDHARTA and SIDDHARTA-2

3.1 DAΦNE at LNF-INFN

The accelerator complex DAΦNE (Double Annular ϕ Factory for Nice Experiments) [26,27] at the National Laboratory Frascati (LNF) in Italy includes a double ring electron-positron collider and an injection system (linac, accumulator and damping ring) as it is shown in Fig. 2. This facility is designed to produce unique low-momentum kaon beam via the decay of ϕ-mesons formed almost at rest. The ϕ-mesons decay into K^+K^- pairs with probability of 48.9% delivering charged kaons with a momentum of 127 MeV/c (resolution $\Delta p/p < 0.1\%$). The beam is ideal for the purpose of kaonic atoms experiments.

3.2 Silicon Drift Detectors (SDDs) for X-ray detection

The silicon drift detectors (SDDs) proposed by Gatti and Rehak [29,30] were initially developed as position sensitive detectors. Their development during years in terms of energy and time resolution improvement as well as more efficient background rejection make them also applicable for X-ray spectroscopy, including very precise kaonic atoms experiments.

The SSD detector consists of a concentric ring-shaped strip segmentation with a small collecting anode placed in the center of the strips (on one side) and the radiation entrance window (nonstructured junction) allowing for homogeneous sensitivity over the whole detector area (on other side). In this fully depleted device, electric field created in parallel to the surface, leads signal charges into a collecting anode (left panel of Fig. 3). The unique advantage of this detector is the very small value of anode capacitance (allowing to achieve

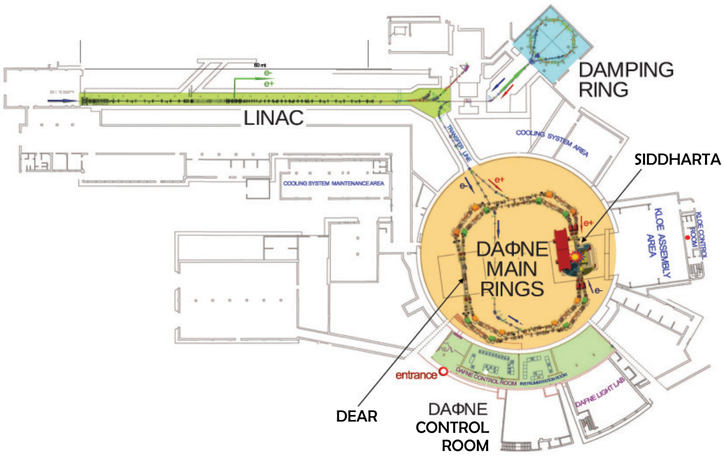

Figure 2: DAΦNE accelerator complex with marked SIDDHARTA experiment installed in the interaction point. Figure adapted from [28].

good time and energy resolution) which is nearly independent of the detector area. It allows to develop detectors with large area and reduced thickness. The thin depletion layer ($\sim$500 μm) leads to less sensitivity to background events (high-energy gamma rays or electrons), but still achieving almost 100% efficiency for 8 keV X-rays. The properties of SDDs used in SIDDHARTA and SIDDHARTA-2 experiments are reported in the next two subsections.

3.2.1 SDD-JFET

For the SIDDHARTA experiment, the front-end n-channel JFET was integrated on the detector chip near the n^+ implanted anode as it is shown in the left panel of Fig. 3. JFET and anode are positioned on the upper side of the system in the center of the p^+ field rings. This configuration allows to achieve a correct matching between detector and front-end electronics capacitance by minimizing the stray capacitances of the various connections.

The SDDs used in the SIDDHARTA experiment were developed within the European research project HadronPhysics3 [31]. 144 SDD cells, each with an area of 1 cm^2 and a thickness of 450 μm have been used. The cells were arranged in 48 subdetector units (each unit of three cells packed monolithically) as shown in the right panel of Fig. 3. The SDDs, operated at a temperature of 170 K, were characterized by drift time of 800 ns and energy resolution of 160 eV (FWHM) at 6 keV.

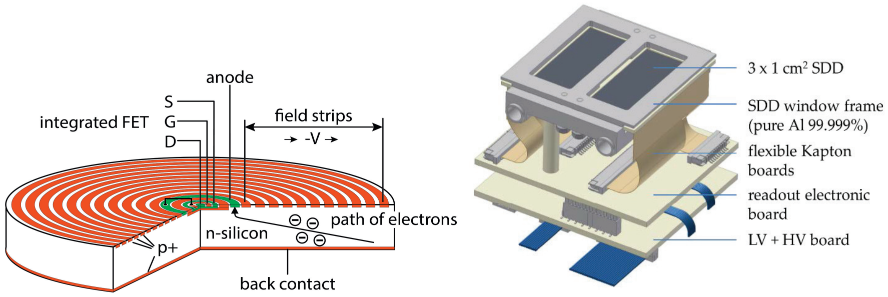

Figure 3: Scheme of SDD structure integrated with JFET (S = source, G = gate, D = drain) and reset mechanism (left). Subdetector unit, used in the SIDDHARTA experiment, including two SDD chips (each with three individual cells). Adapted from [1,32].

3.2.2 SDD-CUBE

For the purpose of kaonic deuterium measurement by SIDDHARTA-2, new monolithic SDD arrays have been developed by Fondazione Bruno Kessler (Italy), in collaboration with Politecnico di Milano, LNF-INFN and SMI (Austria). The new SDD detectors instead of JFET pre-amplifier system are featured in CMOS integrated charge-sensing amplifier (CUBE) [33]. The anode of each SDD is electrically connected with a bonding wire to the CUBE placed on the ceramic carrier (very close to the anode). Thus, the SDDs' performance is almost independent of the applied bias voltages, even for high charged particle rates. Each monolithic array consists of eight square SDD cell (450 μm thick, arranged in a 2×4 array), each with an active area of 8×8 mm^2 (see Fig. 4). With the newly developed SDDs a better time resolution of 300 ns can be achieved with respect to the previous one by reducing the active cell area from 100 mm^2 to 64 mm^2 and by further cooling to 100 K. Moreover, a new SDDs readout (ASIC), named SFERA, has been developed [34,35]. In the experiment 48 SDD arrays will be used covering a solid angle for stopped kaons in the gaseous target of $\sim 2\pi$.

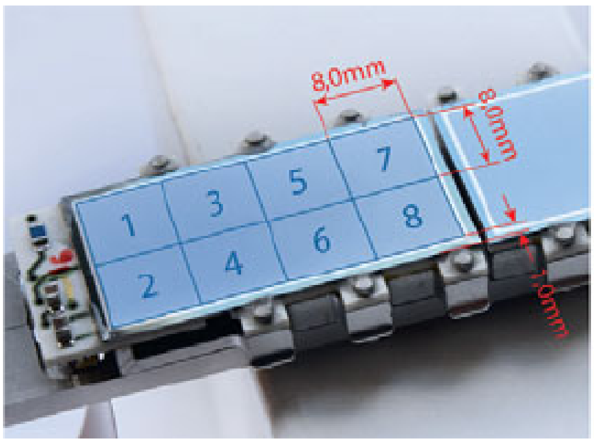

Figure 4: SDD chip consisting of 8 square cells installed on a ceramic carrier and aluminum block provided cooling. Adapted from [1].

3.3 The kaonic hydrogen measurement by SIDDHARTA

The SIDDHARTA experiment has been performed in 2009 [7], using large area SDDs, with the aim to determine the shift and width of kaonic hydrogen 1*s* level with a higher precision than in previously performed measurements by DEAR [5] and KpX [6].

A scheme of the SIDDHARTA setup is presented in Fig. 5. The detection facility consisted of three main components: the kaon detector (trigger), a cryogenic target system and the X-ray detection system.

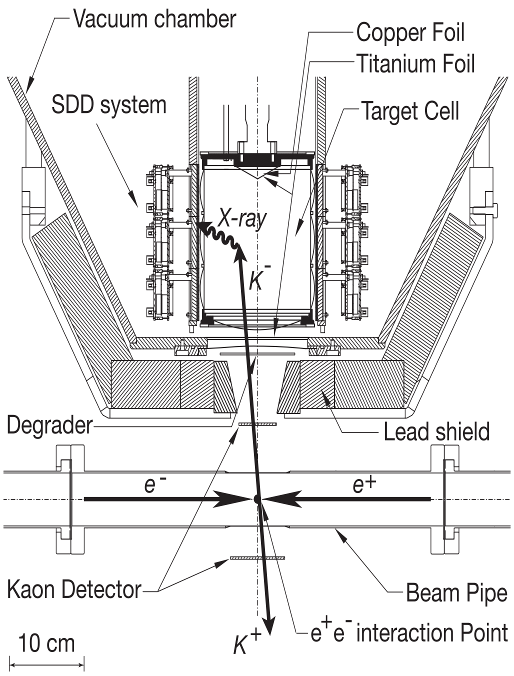

Figure 5: Scheme of the SIDDHARTA setup [36].

In the SIDDHARTA experiment the low-energy charged kaons are degraded and stopped in a high-density cryogenic gaseous target of cylindrical shape (with 13.7 cm diameter and 15.5 cm height), where kaonic atoms are efficiently produced. The gas-target system is crucial for the experiment, since it allows to minimize the Stark mixing phenomena leading to decrease in the yields of kaonic-atom X-rays.

An important part of the detection system is the charged kaon trigger based on the coincidence of two plastic scintillators installed on the top and the bottom of the e^+ and e^- interaction point. The trigger used the back-to-back topology of the charged kaons generated at DAΦNE by the ϕ meson decay. Using the coincidence between the back-to-back correlated K^+ K^- pairs and the X-ray signal from the SDDs, so called tripple coincidence, the asynchronous background (from e^+ and e^- beam losses) was drastically reduced, which allowed to improve significantly the signal-to-background ratio.

The most precise kaonic hydrogen measurement was possible using new triggerable and fast SDDs, characterized by excellent energy and time resolutions, necessary for the background suppression. A detailed description of the X-ray detectors is given in Sec. 3.2.1.

As the first step of SIDDHARTA measurement, calibration and stability checks of SDDs performance were carried out using cryogenic target filled with helium-4 gas [37]. Calibration runs were performed with the X-ray tube producing high intensity titanium (Ti) and copper (Cu) fluorescence X-rays. Based on Ti K_α (4.5 keV) and Cu K_α (8.0 keV) peak positions the energy scale of each SDD was determined. The global in-situ calibration (for summed spectrum of all SDDs) of the gain (energy) and resolution (response shape) was performed using titanium, copper, and gold fluorescence lines (from uncorrelated background in the triggerless mode) and kaonic carbon lines (from wall stops in the triggered mode). The stability checks of SDDs performance were studied using the kaonic helium X-ray lines (high yield L transitions) by installing a thin Ti foil [31].

Additionally, the first-ever exploratory measurement of kaonic deuterium $K-$ series transitions was performed which was essential for quantifying the background lines from kaons captured in setup materials (carbon, nitrogen, and oxygen). The collected data doesn't show peak structures of kaonic deuterium X-rays due to their low yields and broad natural widths (panel (b) in Fig. 6).

To extract the 1s-level shift and width of kaonic hydrogen, the hydrogen and deuterium spectra were fitted simultaneously. Fig. 6a and Fig. 6b show the fit result with the fluorescence lines from the detection setup materials and a continuous background for hydrogen and deuterium, respectively. Fig. 6c shows the kaonic hydrogen X-ray spectrum after the fitted background subtraction. K-series X-rays of kaonic hydrogen are clearly observed [7]. The vertical dot-dashed line in Fig. 6c indicates the X-ray energy of kaonic hydrogen K_α determined based on electromagnetic interaction only.

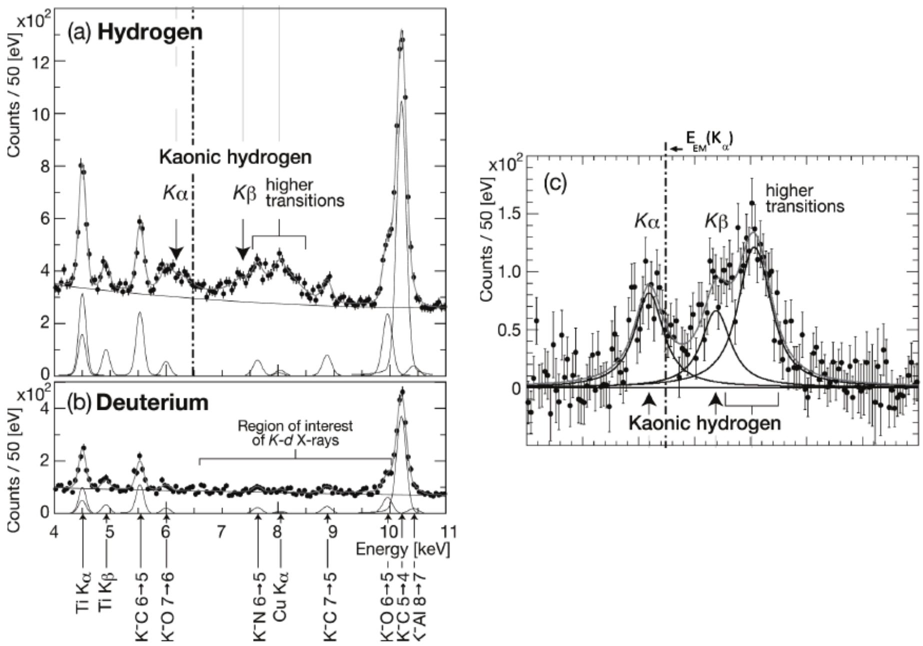

Figure 6: The simultaneous fit of the X-ray energy spectra of hydrogen and deuterium data. (**a**) (**b**) Measured energy spectra with fitted lines. Fit components of the background (X-ray lines and a continuous background) are marked with solid lines. The dot-dashed vertical line indicates the electromagnetic value of the kaonic hydrogen K_α energy. (**c**) The measured kaonic hydrogen X-ray spectrum after background subtraction. The fit components corresponding to the K^-p transitions are shown [7]. Adapted from [1].

The 1s-level shift ε_{1s} and width Γ_{1s} of the kaonic hydrogen were determined to be

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

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

This is the most precise result obtained so far for the kaonic hydrogen atom. The negative sign of 1s level shift (ε_{1s}) implies a repulsive-type strong interaction which is in agreement with the low-energy scattering data [38–40].

3.4 Perspectives for kaonic deuterium measurements by SIDDHARTA-2

SIDDHARTA-2 is a new experiment, which has been installed on DAΦNE in Spring 2019, with the aim to perform the first kaonic deuterium measurement with a precision similar to the SIDDHARTA kaonic-hydrogen one. The kaonic deuterium measurement is a great experimental challenge due to the very small kaonic deuterium X-ray yield (ten times less than for hydrogen) and a very large width of the K-lines.

The exploratory measurement of the X-ray spectrum for kaonic deuterium was performed by the SIDDHARTA collaboration (see Sec. 3.3), however the 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 [24].

The goal of the new apparatus, SIDDHARTA-2, is to increase significantly the signal-to-background ratio, by gaining in solid angle, by taking advantage of a new type of Silicon-Drift Detectors (SDDs) with excellent timing resolution and by using additional designed veto systems. The SIDDHARTA-2 apparatus is schematically shown in Fig. 7. More details can be found in [1, 34, 35].

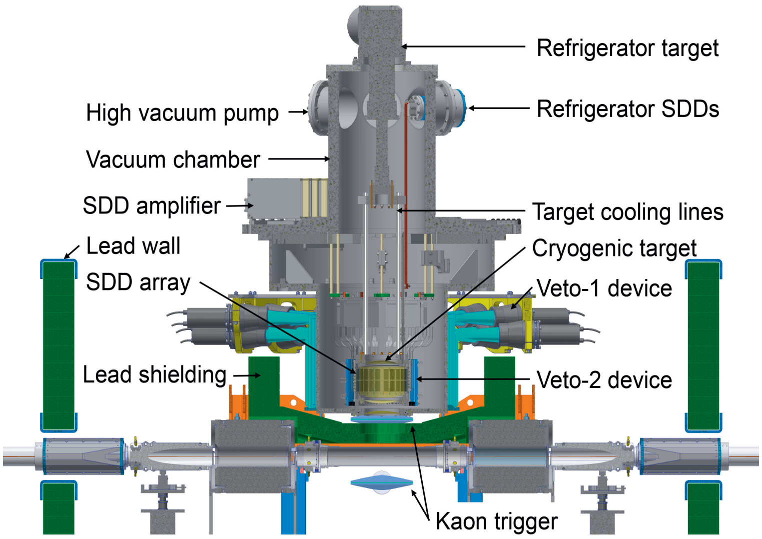

Figure 7: Schematic view of the SIDDHARTA-2 setup consisting mainly of the cryogenic target cell, surrounded by the SDDs arrays, kaon trigger, the Veto-2 system within the vacuum chamber and the Veto-1 device placed outside the chamber.

In order to carry out a successful measurement of kaonic deuterium with SIDDHARTA-2, three main parts of the detection setup have been developed and implemented:

- A new large area X-ray detector, consisting of monolithic silicon drift detectors SDDs, with very good energy and time resolution, described in details in Sec. 3.2.2. An undoubtedly advantage of the new production technology is the possibility of placing the detector systems around cryogenic target with high packing density to cover a solid angle of almost 2π sr for kaons stopped in the target cell.

- Cryogenic lightweight gaseous target of cylindrical shape (14.5 cm diameter and 13 cm high) with (140 ± 10) μm thick walls made of Kapton foils, working at temperature of 30 K and a maximum pressure of 0.3 MPa, allowing to maintain high deuterium gas density (3% of the liquid deuterium density) and an X-ray transmission of 85% at 7 keV.

- A dedicated veto system consisting of Veto-1 and Veto-2, namely a barrel of scintillator counters read by photomultipliers (PMs) mounted around the setup and an inner veto detector of plastic scintillation tiles (SciTiles) read by silicon photomultipliers (SiPMs) installed as close as possible behind the SDDs, respectively. The aim of veto the system is an improvement of a factor at least 40 of the signal-to-background ratio.

A dedicated Monte Carlo simulation was performed (within GEANT4 framework) in order to optimise experimental setup, e.g. parameters of target (size, gas density), detector configuration and shielding geometry. In the Monte Carlo simulation the values of shift and width of the 1s ground level of kaonic deuterium were assumed to -800 eV and 750 eV, respectively, as representative theoretical expected values. Yields ratios $K_\alpha : K_\beta : K_{total}$ are those of kaonic hydrogen, while K_α yield was assumed to 10^{-3}.

Fig. 8 shows the simulated kaonic deuterium spectrum for an integrated luminosity of 800 pb^{-1} for similar machine background conditions as during SIDDHARTA runs. According to the simulation the extracted shift and width can be determined with precisions of the same order as the SIDDHARTA results for kaonic hydrogen, namely 30 eV and 80 eV, respectively.

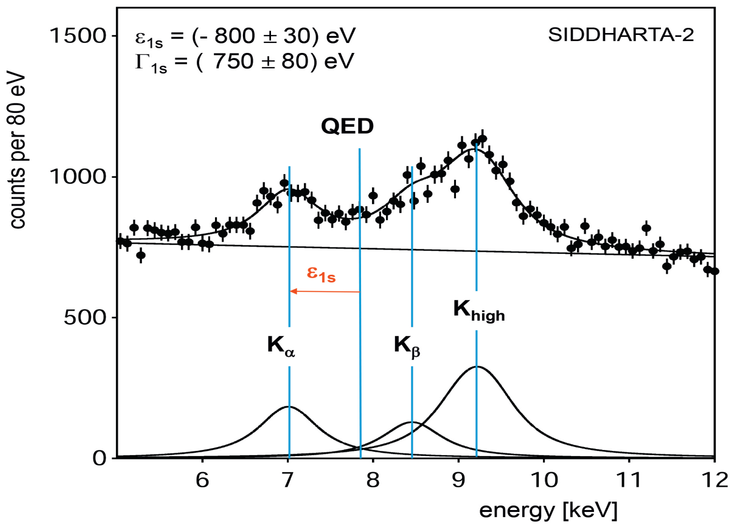

Figure 8: Kaonic deuterium spectrum simulated for SIDDHARTA-2 setup for an integrated luminosity of 800 pb^{-1}. The simulation was carried out assuming a shift $\varepsilon_{1s}= -800$ eV and width $\Gamma_{1s} = 750$ eV of the 1s state, as well as a K_α yield of 10^{-3}.

As step 1, in spring 2019, the SIDDHARTINO setup containing 8 SDDs units out of the 48 units for the complete SIDDHARTA-2 setup, was installed in the DAΦNE accelerator with the aim to measure kaonic helium to quantify the background in the new DAΦNE configuration. After the debug and optimization with the SIDDHARTINO setup, in 2020 the kaonic deuterium measurement will follow with the full SIDDHARTA-2 setup.

4 Conclusion

The measurement of the lightest kaonic atoms, kaonic hydrogen and kaonic deuterium, is crucial for extracting the antikaon-nucleon isospin-dependent scattering lengths, key ingredients for all models and fundamental theories dealing with the low-energy quantum chromodynamics in systems with strangeness. A better understanding of the low-energy QCD in strangeness sector, would allow to unveil one of the most important, yet unsolved, problem in hadron physics: the chiral symmetry breaking giving mass to the surrounding matter. It may also impact on models describing the structure of neutron stars (EOS) taking into account their possible strangeness content.

Experimental investigation of kaonic atoms is, however, very challenging mainly due to the necessity of detection of a weak signal over a large background. The kaonic deuterium X-ray measurement represents the most important experimental information missing in the field of the low-energy antikaon nucleon interactions.The experimental result of SIDDHARTA-2, based on newly developed high-precision X-ray detectors and lightweight cryogenic target system will allow to constraint existing theories and will focus physics on the low-energy antikaon-neutron interaction, which is still an open issue.

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