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The kaonic atoms research program at DAΦNE: overview and perspectives

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Abstract.

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 energy shift and broadening of the lowest-lying states of such atoms, induced by the kaon-nucleus strong interaction, can be determined with high precision from atomic X-ray spectroscopy. This experimental method provides unique information to understand the low energy kaon-nucleus interaction at threshold. The lightest atomic systems, kaonic hydrogen and kaonic deuterium, deliver the isospin-dependent kaon-nucleon scattering lengths. 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 X-ray detectors: Silicon Drift Detectors. The measurement of kaonic deuterium will be realized in the near future by SIDDHARTA-2, a major upgrade of SIDDHARTA. In this paper an overview of the main results obtained by SIDDHARTA together with the future plans, are given.



1. Introduction

The strong interaction, described in the framework of the Standard Model by the QCD, is still not well understood, especially in the low-energy limit, the so called non-perturbative regime. Particularly interesting is the strong interaction involving the strange quarks which, belonging to the light quarks sector, but having a mass of about $100 \text{ MeV}/c^2$, much heavier than the few MeV/c^2 of the up and down quark masses, plays a particular role. Since kaons and antikaons are the lowest mass particles containing strange quarks, for decades their interaction with nucleons and nuclei in the low-energy regime has been subject of intensive studies (for reviews see [1, 2]). Effective field theories contain appropriate degrees of freedom to describe physical phenomena occurring at the nucleon-meson scale, and chiral perturbation theory was extremely successful in describing systems like pionic atoms. However, it is not directly applicable for kaonic systems, where non-perturbative coupled-channel techniques should be used ([3]). These theories are still needing experimental information and confirmation.

There are two experimental approaches to probe the kaon-nucleus strong interaction, both exploited at LNF-INFN. One is by studying the scattering and the reaction channels between kaons and nuclei, and this is the experimental method followed by the AMADEUS collaboration ([4, 5, 6]). The other method consists in precision X-ray measurements of the shift and the broadening of the energy levels of light kaonic atoms caused by the kaon-nucleus strong interaction. This latter method, exploited by the SIDDHARTA and SIDDHARTA-2 collaborations ([7, 8, 9, 10, 11, 12, 13]), is of significant importance, since it is the only method able to provide direct experimental information on the kaon-nucleus interaction at threshold.

1.1. Kaonic atoms

Kaonic atoms are formed when a negatively charged kaon enters, is stopped in a target, is captured and replaces one of the electrons of an atom. Due to the much higher K^- mass with respect to the e^- one, this exotic atom is formed in a highly excited state ($n \simeq 31$ for kaonic hydrogen). The subsequent cascade of the antikaon to the ground level occurs via several different processes; in particular, the last transitions on the $1s$ level are radiative and photons are emitted in the X-ray region.

For light atoms, especially for hydrogen and deuterium, a detectable energy shift from the electromagnetic value of the ground state is expected (ε_{1s}), as well as a broadening (Γ_{1s}) of this state, caused by nuclear absorption (see figure 1).

By measuring ε_{1s} and Γ_{1s} , kaonic atoms offer the unique possibility to determine the s-wave antikaon-nucleon scattering lengths at vanishing energy. With the advance in kaon beam production and in the experimental techniques, we are presently able to perform very high precision measurements, resulting in a deeper and more complete understanding of the many open questions in the QCD. With the advent of the clean kaon beams provided by the DAΦNE collider, and of fast X-ray detectors as the Silicon Drift Detectors, the kaonic atom studies entered the precision era.

2. The SIDDHARTA experiment

With the SIDDHARTA experiment at DAΦNE, the strong interaction induced shift of the ground state of kaonic hydrogen atoms and the absorption width were measured with the highest accuracy up to now [8, 9]. Measurements of the $2p$ shift and width of kaonic helium isotopes [10, 11, 12] were also performed by SIDDHARTA. For the kaonic deuterium measurement an attempt was done, but, due to the very low yield of the transition, only an upper limit on the yield could be extracted [8].

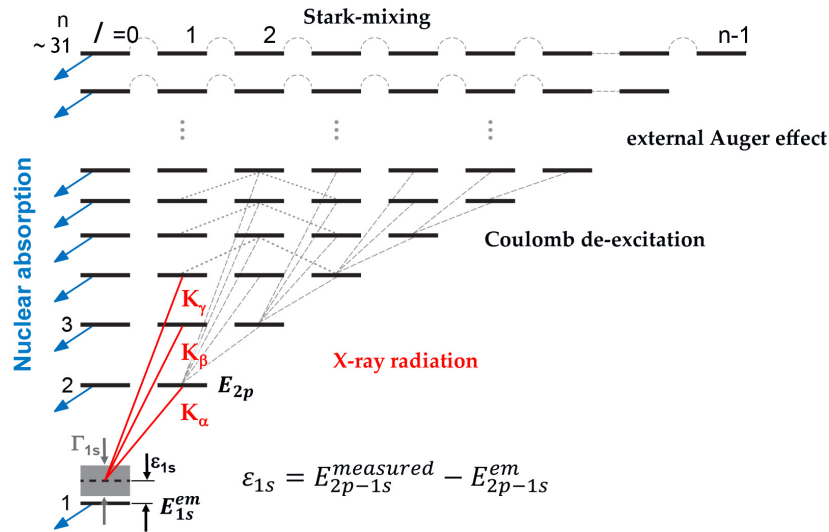


Figure 1. The cascade processes for kaonic hydrogen, starting when the kaon is captured in a highly excited state, down to the $1s$ ground state, which is shifted due to strong interaction and broadened due to nuclear absorption of the kaon by the proton. The shift and width of the $2p$ state due to strong interaction are negligible([14]).

2.1. Experimental setup

The SIDDHARTA setup consisted of two main components, the light-weight cryogenic target cell and a specially developed large area, high resolution X-ray detector system composed of Silicon Drift Detectors (SDDs). The experiment made use of the K^+K^- pairs coming from the Φ decays at DAΦNE, with a 49% branching ratio. The kaons leaving the interaction point through the SIDDHARTA beam pipe were degraded in energy and entered the cryogenic gaseous hydrogen (helium) target placed above the beam pipe (see figure 2), forming a kaonic atom and emitting X-rays.

The K^+K^- pairs were emitted in back-to-back configuration and identified by the kaon detectors, made of two plastic scintillators placed above and below the interaction point as illustrated in figure 2. The kaons were disentangled from the minimum ionizing particles using the time of flight information at the kaon detectors. The coincidence of the two scintillators defined the kaon trigger, which marked the timing of the incident kaons.

A fraction of the negatively charged kaons activating the kaon trigger was successfully stopped inside the volume of the gaseous target placed about 20 cm above the interaction point to form kaonic atoms. A working pressure of 0.3 MPa was achieved, which led to a hydrogen gas density of 2% of liquid hydrogen density, at a working temperature of 25 K.

Special Silicon Drift Detectors were developed with excellent energy resolution (FWHM \simeq 150 eV at 6 keV) and timing capability in the order of $1\mu s$ [15] when operated at 140 K temperature. Using the X-ray signal from the SDDs in coincidence with the K^+K^- pair, the continuous machine background, as well as unwanted fluorescence X-rays, could be efficiently suppressed. The SDDs had a total active area of 144 cm^2 , covering about 10% of the solid angle around the target cell.

The energy calibrations of the SDDs were done every few hours, using the X-ray tube activated K_α lines of Ti (4.5 keV), Mn (5.5 keV) and Cu (8.0 keV). The energy resolution at 6 keV was stable at about 150 eV (FWHM) throughout the measurement. More details about the configuration and the performance of the SIDDHARTA apparatus can be found in

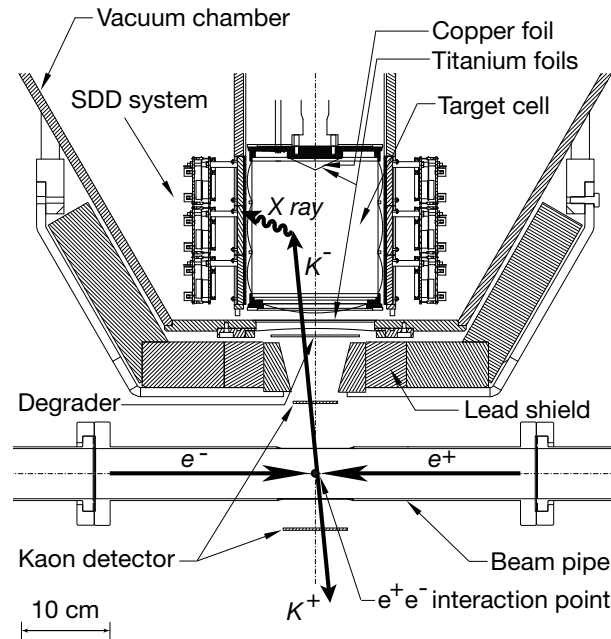


Figure 2. A schematic cutaway view of the SIDDHARTA setup at the DAΦNE interaction point. The charged kaon pairs are identified with two plastic scintillators, and the K^- induced X-rays detected by the SDDs are identified from the time correlation to the kaon pair events.

[8, 9, 10, 11, 12].

Data were taken with gaseous targets of hydrogen (1.3 g/l), deuterium (2.50 g/l), helium-3 (0.96 g/l), and helium-4 (1.65 g/l and 2.15 g/l).

2.2. Kaonic Hydrogen and Kaonic Deuterium measurements

The lightest kaonic atom is K^-p in which the electromagnetic interaction is accompanied by the strong interaction of the kaon with the proton, which is measurable by X-ray spectroscopy of the radiative transitions from the np states ($2p$, $3p$, ...) to the $1s$ ground state (K transitions). The K^-p scattering length a_{K^-p} can be obtained from the equation:

$$\varepsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu_c^2 a_{K^-p} (1 - 2\alpha\mu_c (\ln\alpha - 1) a_{K^-p}) \quad (1)$$

ε_{1s} and Γ_{1s} being the shift and width of the transition to the $1s$ level, (for more details on the various terms see [24]) and it is related to the isospin-dependent scattering lengths by:

$$a_{K^-p} = \frac{1}{2}(a_0 + a_1) \quad (2)$$

Historically, there were several measurements of the strong-interaction shift ε_{1s} and width Γ_{1s} of kaonic hydrogen ([25, 26, 27, 28, 29]). In '70s and '80s three groups ([25, 26, 27]) reported a measured attractive-type shift (positive ε_{1s}), while the information extracted from the analyses of the low energy KN data ([30, 31, 32]) shows a repulsive-type shift (negative ε_{1s}). This contradiction has been known as the “kaonic hydrogen puzzle”. In 1997, the first distinct peaks of the kaonic-hydrogen X-rays were observed by the KEK-PS E228 experiment [28] with a significant improvement in the signal-to-background ratio by the use of a gaseous hydrogen target, where previous experiments had employed liquid hydrogen. It was crucial to use a

low-density target, namely a gaseous target, because the X-ray yields quickly decrease towards higher density due to the Stark mixing effect. The observed repulsive shift was consistent in sign with the analysis of the low energy KN scattering data, resolving the long-standing discrepancy. More recent values reported by the DEAR group in 2005 [29], with substantially reduced errors, firmly established the repulsive shift obtained by the previous E228 experiment. The latest kaonic hydrogen and deuterium X-ray energy spectra, obtained by the SIDDHARTA experiment, are shown in figure 3 [8], together with the fitting functions.

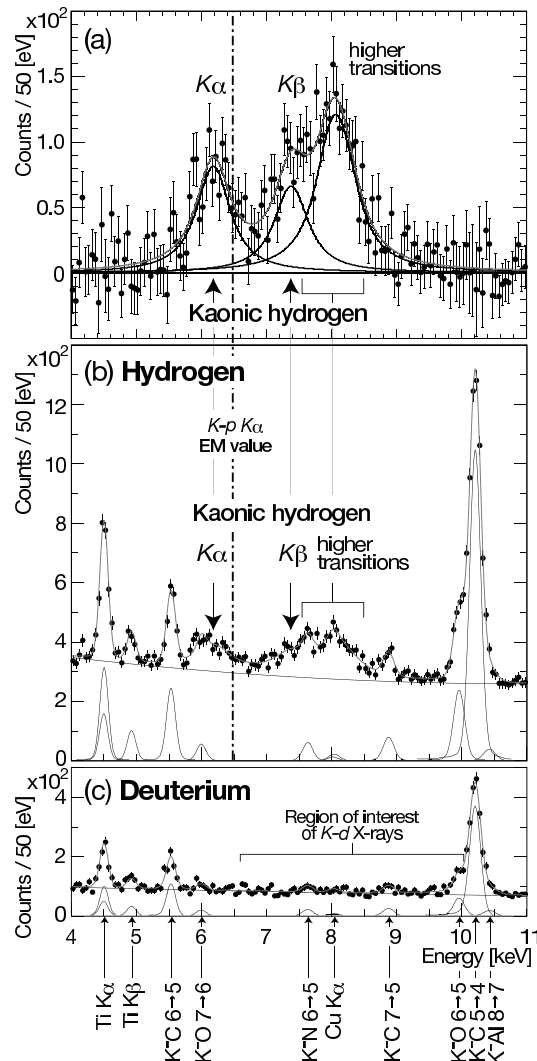


Figure 3. The global simultaneous fit of the X-ray energy spectra of hydrogen and deuterium data. (a) Residuals of the measured kaonic-hydrogen X-ray spectrum after subtraction of the fitted background, clearly displaying the kaonic-hydrogen K -series transitions. The fit components of the K^-p transitions are also shown, where the sum of the functions is drawn for the higher transitions (greater than K_β). (b)(c) Measured energy spectra with the fit lines. Fit components of the background X-rays lines and a continuous background are also shown. The dot-dashed vertical line indicates the e.m. value of the kaonic-hydrogen K_α energy.

The K -series X-rays of kaonic hydrogen were clearly observed, while those for kaonic deuterium were not visible. This appears to be consistent with the theoretical expectation of lower X-ray yield and greater transition width for deuterium ([33]) than for kaonic hydrogen.

The kaonic deuterium spectrum can be used to characterize the background. The vertical dot-dashed line in figure 3 indicates the X-ray energy of kaonic hydrogen K_α calculated using only the electromagnetic interaction (EM). Comparing the kaonic hydrogen K_α measured peak and the EM value, a repulsive-type shift of the kaonic hydrogen $1s$ energy level is easily to be observed. Many other lines from kaonic atom X-rays were detected in both spectra as indicated with arrows in the figure. These kaonic atom lines result from high- n X-ray transitions of kaons stopped in the target cell wall made of kapton ($C_{22}H_{10}O_5N_2$) and its support frames made of aluminium. There are also characteristic X-rays from titanium and copper foils installed for X-ray energy calibration. A global simultaneous fit of the hydrogen and deuterium spectra has been performed, whose results are shown in figure 3 (b) and (c). The kaonic hydrogen lines were represented by Lorentz functions convolved with the detector response function, where the Lorentz width corresponds to the strong interaction broadening of the $1s$ state. The region of interest of Kd X-rays is illustrated in figure 3 (c). The $1s$ level shift ε_{1s} and width Γ_{1s} of kaonic hydrogen were determined to be [8]:

$$\varepsilon_{1s} = -283 \pm 36 \text{ (stat)} \pm 6 \text{ (syst)} \text{ eV} \quad (3)$$

$$\Gamma_{1s} = 541 \pm 89 \text{ (stat)} \pm 22 \text{ (syst)} \text{ eV} \quad (4)$$

This measurement represents the most precise measurement ever performed, and it has been used to set constraints on the calculated real and imaginary part of the K^-p amplitude ([34]).

2.3. Kaonic helium measurements

As a calibration for the kaonic hydrogen measurement, SIDDHARTA used the measurements with kaonic helium that turned out to be very precise and important.

Before the kaonic helium-4 measurement performed by SIDDHARTA, there existed only four other measurements, and the situation was rather ambiguous: the combined results of three compatible measurements [16, 17, 18], performed over 30 years ago, are more than an order of magnitude higher than the theoretical predictions [20, 21] with a 5 standard deviation significance, while a more recent measurement, E570 performed at KEK [19], is not compatible with earlier results, but agrees with theory instead. A conclusive precise measurement on kaonic helium-4 was needed in order to solve this “discrepancy”, together with the first measurement of kaonic helium-3, fundamental to obtain valuable information on the kaon-nuclei interactions at low energies. The kaonic helium spectra obtained by the SIDDHARTA experiment are shown in figure 4 [10, 11, 12].

In the left picture, the peak seen at 6.2 keV is identified as the kaonic helium-3 L_α line (the $3d \rightarrow 2p$ transition). In the right one, the peak seen at 6.4 keV is identified as the kaonic helium-4 L_α line. In addition to these lines, other smaller peaks are clearly visible which are the kaonic atom X-ray lines produced by kaons stopping in the target window made of kapton, and the titanium and manganese lines. The strong-interaction shifts of the kaonic helium $2p$ states were obtained from the difference between the experimentally determined values and the QED calculated ones [22, 23]. The results are:

$$\varepsilon_{2p}(\text{kaonic helium} - 3) = -2 \pm 2 \text{ (stat)} \pm 4 \text{ (syst)} \text{ eV} \quad (5)$$

$$\varepsilon_{2p}(\text{kaonic helium} - 4) = 5 \pm 5 \text{ (stat)} \pm 4 \text{ (syst)} \text{ eV} \quad (6)$$

Thus a shift which is in agreement with the theoretical estimations and, within the errors, with the results reported by the E570 [19] collaboration, was established ([16, 17, 18]).

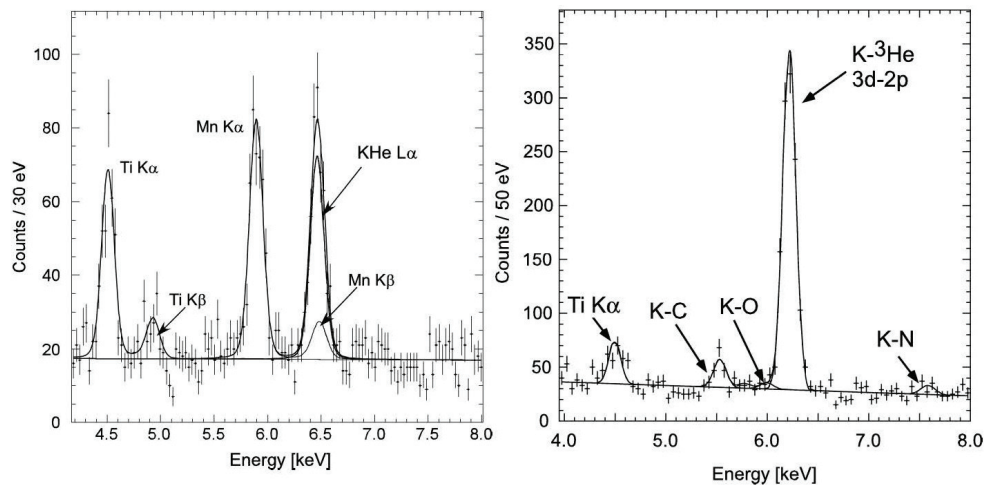


Figure 4. Fitted spectra of the kaonic helium-3 (right) and kaonic helium-4 (left) X-rays. The $3d \rightarrow 2p$ transitions are seen around 6 keV. Together with these peaks, others smaller are seen, the kaonic atom X-ray lines produced by kaons stopping in the target window made of kapton, and the titanium and manganese lines.

3. Future: the SIDDHARTA-2 experiment

The case of kaonic deuterium is more challenging than kaonic hydrogen mainly due to the larger widths of the K -lines and the lower X-ray yield expected. 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 ε_{1s} and Γ_{1s} was impossible. An upper limit for the X-ray yield of the K -lines could be extracted from the data: total yield < 0.0143 , K_{α} yield < 0.0039 [13].

Since the kaonic deuterium X-ray measurement represents the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions today, a new experiment (SIDDHARTA-2) is planned, making use of a much improved apparatus.

3.1. Experimental setup upgrade

A new version of the experimental apparatus, aiming to increase the signal-to-background ratio (S/B) by a factor about 20, allowing the kaonic deuterium measurement, has been developed by the SIDDHARTA-2 collaboration. The major upgrades are shown in figure 5 and listed below ([36]):

- Larger total area and faster SDD detector array; the solution to improve the SDD time resolution consists in the reduction of the single element size (from 10×10 to 8×8 mm²) and the replacement of the integrated J-FET (thermally limited), by a newly-developed amplifier on the ceramics, able to operate at very low temperatures (below 50 K). The shorter path and the higher carrier mobility consent a faster charge packet drift to the anode and therefore, a reduced time window (350 ns instead of 900 ns) for each trigger, with a subsequent suppression of the asynchronous background. The new SDD detectors are produced by Fondazione Bruno Kessler (FBK) in Trento, Italy.
- A veto-1 detector to measure the prompt time of the secondaries from K^- absorption on nuclei. The system consists of scintillators surrounding the vacuum chamber, read at both ends by PMs coupled to mirrors and light-guides (to cope with the narrow space between the setup and the shielding against beam background) [35].

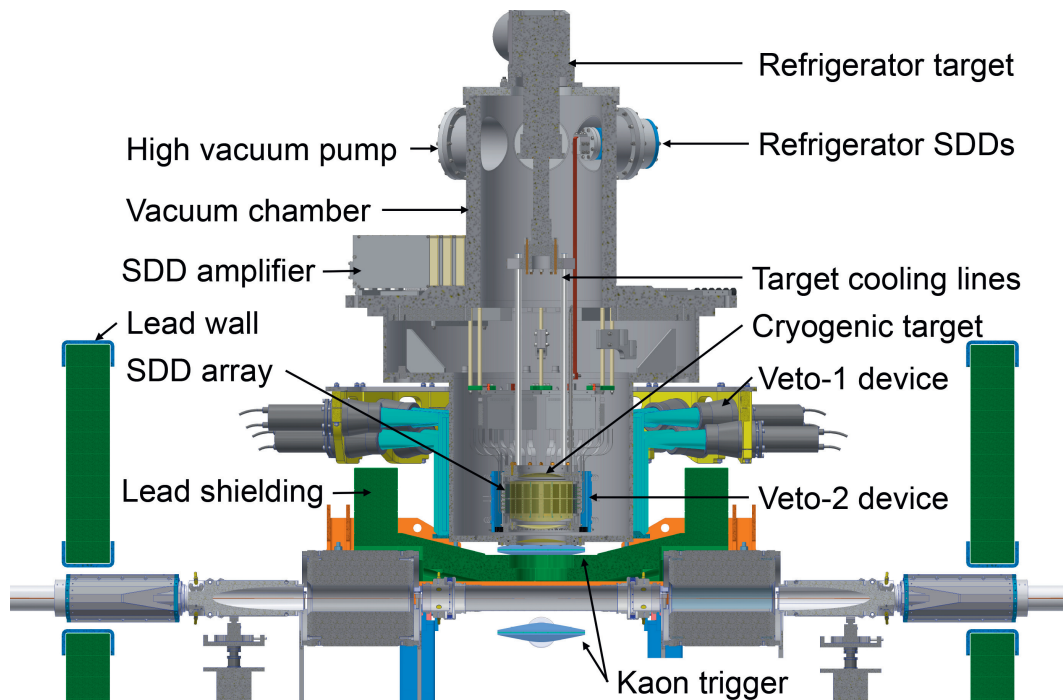


Figure 5. The SIDDHARTA-2 setup with the cryogenic target cell surrounded by the SDDs and the veto-2 system within the vacuum chamber, while the veto-1 device is surrounding the vacuum chamber on the outside.

- A new cryogenic target in reinforced kapton (13 cm diameter, 7 cm height), operating a few hundred mK above the liquid point (25 K) at a pressure of 4 bar (5% LHD), for more efficient kaon stopping.
- A veto-2 system, consisting in scintillators read by SiPMs, placed behind each SDD array, to reject the hadronic background coming from border hits of Minimum Ionizing Particles (MIPs), depositing energy in the X-ray range.
- A kaon trigger with geometric acceptance optimized to match the kaon gas stopping distribution.
- An improved X-ray calibration system, providing low-rate in-situ calibration, as well as high rate calibration between physics runs, to compensate very small fluctuations in each single SDD response.
- Mechanical and cryogenic improvements of the vacuum chamber, necessary to add more cooling power to the SDDs and to the cryogenic target.

3.2. Kaonic deuterium measurement

All the above described items were optimized by GEANT4 simulation, considered reliable after having reproduced, in the same framework, the SIDDHARTA results, both in terms of signal and background. Using theoretically predicted values as inputs to the Monte Carlo simulation, the expected spectrum of the K^-d transitions, for an acquired luminosity of 800 pb^{-1} and assuming a yield of 0.1%, is shown in figure 6.

$K^-d \ 2p \rightarrow 1s$ transition can be measured with a precision of 30 eV for the shift, and 70 eV for the width.

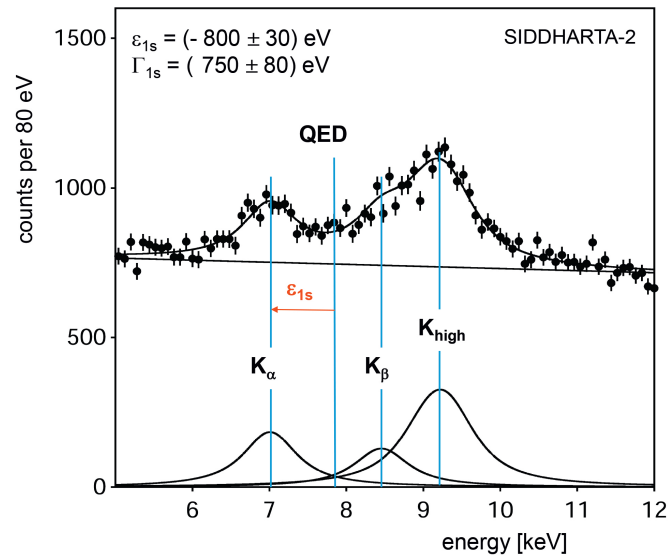


Figure 6. Simulated SIDDHARTA-2 kaonic deuterium spectrum, assuming a shift $\varepsilon_{1s} = -800$ eV and width $\Gamma_{1s} = 750$ eV of the $1s$ state, as well as a K_{α} yield of 10^{-3} . The spectrum was simulated for an integrated luminosity of 800 pb^{-1} .

4. Conclusions

The SIDDHARTA experiment at the DAΦNE electron-positron collider measured the strong-interaction-induced shift and width of kaonic hydrogen and helium transitions with unprecedented accuracy. Important implications for the theory of the strong interaction with strangeness in the low energy regime were provided by the SIDDHARTA constraints.

SIDDHARTA also measured for the first time the kaonic helium-3 transitions to the $2p$ level and the first, measurement, of kaonic helium-4 with a gaseous target. The kaonic deuterium measurement will be performed in 2019 by SIDDHARTA2 experiment, aiming at the determination of $1s$ level shift and width to enable the extraction of the antikaon-nucleon isospin-dependent scattering lengths a_0 and a_1 .

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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