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Unveiling the strangeness secrets: low-energy kaon-nucleon/nuclei interactions studies at DAΦNE

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Abstract. The DAΦNE electron-positron collider at the Laboratori Nazionali di Frascati of INFN, Italy has made available a unique quality low-energy negatively charged kaons "beam", which is used to unveil the secrets of the kaon-nucleon/nuclei interactions at low energies by the SIDDHARTA-2 and AMADEUS experiments. SIDDHARTA has already performed unprecedented precision measurements of kaonic atoms, and is being presently upgraded, as SIDDHARTA-2, to approach new frontiers. The AMADEUS experiment plans to perform in the coming years precision measurements on kaon-nuclei interactions at low-energies, to study the possible formation of kaonic nuclei, of the Λ(1405) and of many other processes involving strangeness.

1 Low energy kaon-nucleon/nuclei studies at DAΦNE

The recently upgraded DAΦNE [1], [2] electron-positron collider at the Frascati National Laboratory of INFN produces the φ-resonance, which decays with a probability of about 50% in K^+K^-, providing an excellent quality low-energy kaon "beam". This beam is intensively used for the study of the low-energy kaon-nucleon/nuclei interactions, a field still lacking experimental data. By making use of this

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negative kaon beam, in 2009 the SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) experiment performed a precision measurement of the strong interaction induced energy shift and width of the *1s* level, via the measurement of the X-ray transitions of kaonic hydrogen and high precision measurements for the kaonic helium3 and 4 X-ray transitions to the *2p* level. The first exploratory measurement of kaonic deuterium was performed too.

SIDDHARTA-2, a major upgrade of SIDDHARTA, presently under preparation, will measure the kaonic deuterium transitions to the 1s level. The final goal is to extract, for the first time, the isospin-dependent antikaon-nucleon scattering lengths, fundamental quantities to understand the chiral symmetry breaking in the strangeness sector.

The AMADEUS (Antikaon Matter at DAΦNE: an Experiment with Unraveling Spectroscopy) experiment will perform the first complete study of the low-energy kaon-nuclei interactions by using a series of cryogenic gaseous targets as d, ^{3}He, ^{4}He, and solid targets. Among the aims of AMADEUS are: the measurement of the $\Lambda(1405)$ decaying to $\Sigma\ \pi$ in all possible combinations and to give a definite answer to the debated question of the existence of the kaonic nuclei. If such states exist we will measure their properties (binding energies, width and decay channels).

2 The SIDDHARTA and SIDDHARTA-2 experiments

In the SIDDHARTA experiment the monochromatic low-energy charged kaon beam which is produced by the decay of the φ-resonance at the DAΦNE collider is degraded and stopped in a cryogenic gaseous target where kaonic atoms are efficiently produced. An important element of the apparatus is the charged kaon trigger, which is based on the coincidence of the signals from two plastic scintillation counters mounted top and bottom of the e^+e^- interaction point. The trigger system takes advantage of the back-to-back topology of the produced low-energy kaons: $\Phi \rightarrow K^+K^-$ and its use drastically increases the signal-to-background ratio, because most of the background is generated by non interacting e^+ and e^- beam particles, uncorrelated in time with the collisions.

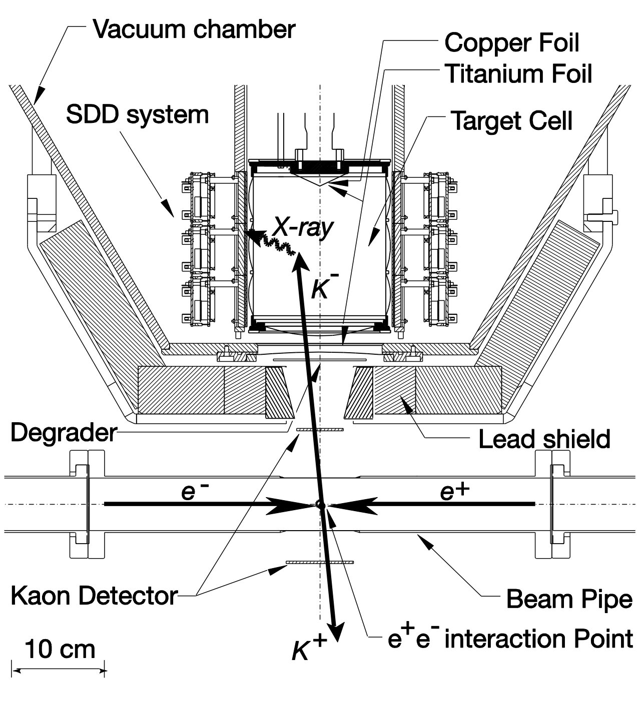

Figure 1. The SIDDHARTA experimental setup installed at the interaction point of DAΦNE.

Kaons are stopped inside the target, producing highly excited kaonic atoms. The kaonic-atom X-rays were detected by 144 Silicon Drift X-ray Detectors (SDDs) mounted around the target. The SDDs, developed within a European research project devoted to this experiment, have a good energy resolution (about 180 eV FWHM at 6 keV) and a timing resolution of about 800 ns (FWHM). A detailed description of the experimental setup is given in Ref.[3].

The setup was installed above the electron-positron interaction point at the DAΦNE collider in 2009, as shown in Fig.1, performing the measurements reported below:

- kaonic hydrogen X-ray transitions to the *1s* level - performing the most precise measurement ever [3].
- kaonic helium4 transitions to the *2p* level, the first measurement using a gaseous target [4], [5].
- kaonic helium3 transitions to the *2p* level, the first measurement ever [5], [6].
- kaonic deuterium X-ray transitions to the *1s* level - as an exploratory measurement [7].

In Figure 2 the kaonic hydrogen spectrum, together with the kaonic deuterium one [3] are shown. The kaonic deuterium measurement was used for the background evaluation, in a common fitting procedure, for the kaonic hydrogen signal from the kaonic hydrogen spectrum.

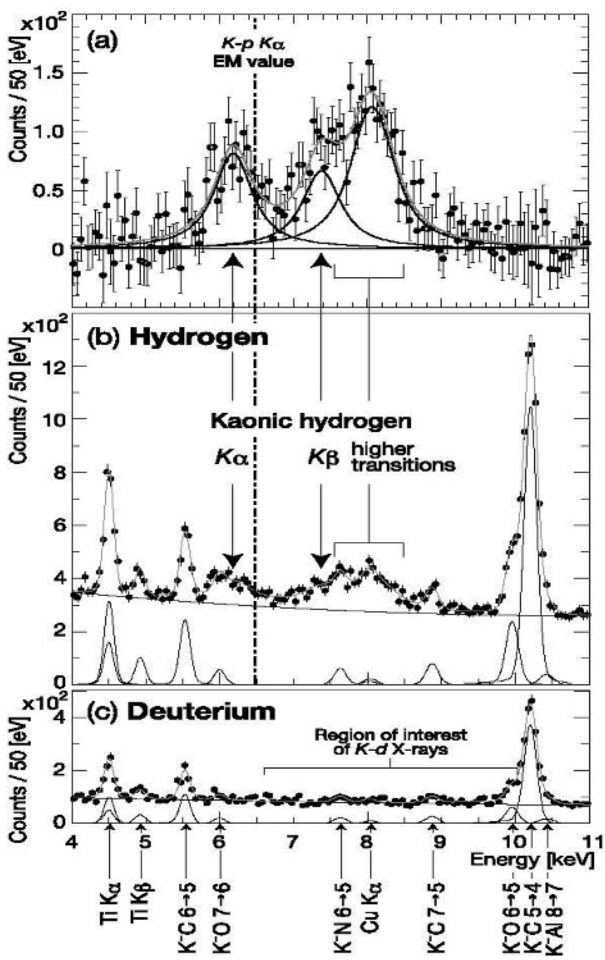

Figure 2. The kaonic-hydrogen X-ray spectrum after subtraction of the fitted background, clearly displaying the kaonic hydrogen K -series transitions.

The *1s*-state strong-interaction shift ε and width Γ of kaonic hydrogen were determined to be:

$$\varepsilon = -283 \pm 36(stat) \pm 6(syst)\ eV, \quad (1)$$
$$\Gamma = 541 \pm 89(stat) \pm 22(syst)\ eV \quad (2)$$

with statistical and systematic errors as reported above. These are the most precise results ever compared to the previous measurements [8, 9]. The values of ε and Γ are consistent with the theoretical predictions [10].

The SIDDHARTA results allow the most precise evaluation of K^- p scattering lengths which yields strong constraints on the theoretical description of the low-energy antikaon-nucleon interactions [11, 12, 13]. For a more complete study of the isospin dependent antikaon-nucleon interaction, the shift and width of kaonic-deuterium 1s state are crucial goals.

The strong-interaction shifts and widths for kaonic-^{3}He and the kaonic-^{4}He were measured by the SIDDHARTA experiment for the 3d → 2p transition.

The resulting shifts [4, 6] agree with the theoretical calculations [14, 15, 16]; the same is valid for the strong-interaction 2p level widths [5] which are in good agreement with the calculated values [14, 17, 18].

The correlations of the shift and width values of the K^{-3}He and K^{-4}He 2p states are plotted in Fig. 3, together with the average values reported in [14, 17] , where the errors bars were calculated by adding the statistical and systematic errors quadratically.

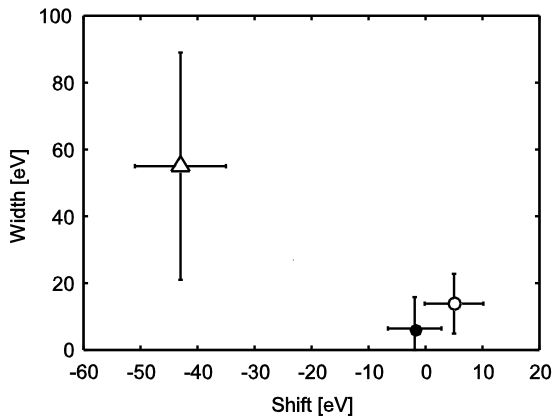

Figure 3. Comparison of the experimental results. Open circle: K-4He 2p state; filled circle: K-3He 2p state. Both are determined by the SIDDHARTA experiment. The average value of the K-4He experiments performed in the 70's and 80's is plotted with the open triangle.

Presently, a major upgrade of the apparatus, SIDDHARTA-2, is undergoing. The upgrade is going to improve the signal/background ratio in order to perform the measurement of kaonic deuterium X-ray transitions to the 1s level and of other types of kaonic atoms transitions [19].

The main improvements to be performed in SIDDHARTA-2 are:

- use of a new vacuum chamber in order to allow adding additional cooling power to SDD detectors and to the target cooling system; the first one gives a faster answer of SDDs, while the second one increases the density of the gas-target, and, consequently, the numbers of stopped kaons.
- a new arrangement of the SDDS around the target cell, which will increase the acceptance;
- a more sophisticated shielding (lead-copper aluminium-plastic) around the setup;

- we are considering the option of an additional a veto (anticoincidence) system to be positioned around the target cell in order to reject those events which pass the lead shielding around the target.

SIDDHARTA-2 will then perform the kaonic deuterium measurement with a similar relative precision as the kaonic hydrogen one, with an integrated luminosity of about 600 pb^{-1}. The SIDDHARTA-2 setup will be ready to take data starting from early 2014.

3 The AMADEUS experiment

The low-energy (< 100 MeV/c) kaon-nuclei interaction studies represent the main aim of the AMADEUS experiment [20, 21]. The complete measurement requires detecting all charged and neutral particles coming from the K^- interactions with various targets with an almost 4π acceptance. The AMADEUS collaboration plans to implement the existent KLOE detector [22, 23] in the internal region remained free between the beam pipe and the Drift Chamber inner wall (having a diameter of 50 cm) with a dedicated setup, see Figure 4. The dedicated setup includes: the target, which can be either solid or a gaseous cryogenic, a trigger (TPC-GEM) and a tracker system (scintillating fibers read by SiPM detectors).

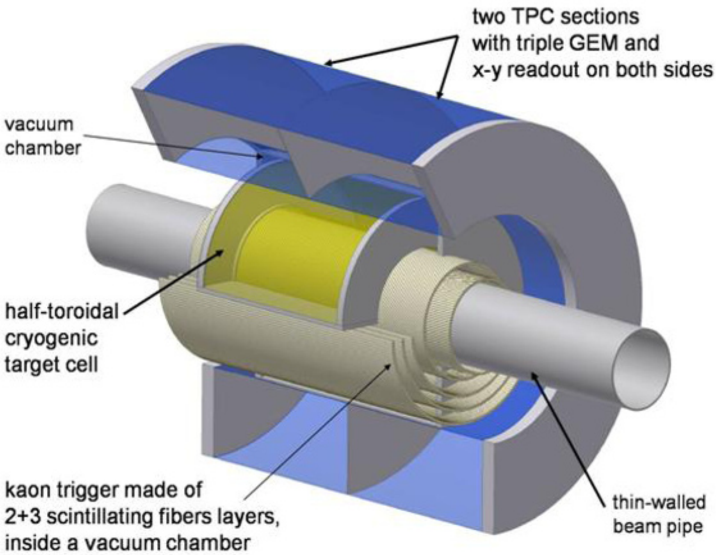

Figure 4. The AMADEUS dedicated setup to be implemented between the beam pipe and inner wall of the Drift Chamber of the KLOE detector. In this situation a cryogenic gaseous target is used.

The negatively charged kaons may stop inside the target or interact at low energies, initiating a series of processes. Among these, a key-role is played by the generation of Λ(1405) which can decay into $\Sigma^0\pi^0$, $\Sigma^+\pi^-$ or $\Sigma^-\pi^+$. We plan to study all these three channels in the same data taking. We plan as well to check the possible existence of “kaonic nuclear clusters” by studying the Λp and Λd channels. Many other kaon-nuclei processes will be investigated, either for the first time, or in order to obtain more accurate results than those actually reported in literature.

Cross sections, branching ratios, rare hyperon decay processes will be investigated, taking advantage of the unique kaon-beam quality delivered by DAΦNE and of the unique characteristics of the KLOE detector. As far as the target is concerned, we plan to use gaseous (such as d, ^{3}He or ^{4}He) and solid (C, Be or Li).

In the summer 2012 a first half cylinder carbon target was built and installed inside the Drift Chamber of KLOE as a first step towards AMADEUS (see Figure 5). The target thickness was optimized to have a maximum of stopped kaons (about 24% of generated) without degrading too much the energy of resulting charged particles inside the target material. The experiment run from October to the end of 2012. The analysis of these data is ongoing; it will provide new insights in the low-energy interactions of charged kaons in the nuclear matter. For the future, other targets are planned to be used compatible with the beam assignment.

Figure 5. The AMADEUS carbon target (half cylinder) installation inside the Drift Chamber of KLOE detector.

4 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 (kaonic hydrogen and kaonic helium).

SIDDHARTA-2 will perform the kaonic deuterium and other types of kaonic atoms transitions measurements in the near future.

The kaonic-nuclei interaction at low-energies is being investigated by the AMADEUS collaboration to search for the possible formation and decay of “kaonic nuclear clusters” and of yet un-measured kaon-nuclei low-energy processes.

SIDDHARTA, SIDDHARTA(-2) and AMADEUS are and will continue to provide unique quality results to unveil the secrets of low-energy QCD in the strangeness sector, with implications going from particle and nuclear physics to astrophysics.

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