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## LOW-ENERGY KAON–NUCLEI INTERACTION STUDIES AT DAΦNE: SIDDHARTA-2 AND AMADEUS\*

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The DAΦNE electron–positron collider of the Laboratori Nazionali di Frascati of INFN has made available a unique quality low-energy negatively charged kaons “beam”, which is being used to study the kaon–nucleon/nuclei interactions by the SIDDHARTA-2 experiment and the AMADEUS Collaboration. The dynamics of the strong interaction processes in the non-perturbative regime is approached by lattice calculations and effective field theories (ChPT) which are still lacking experimental results in the low-energy regime, fundamental for their good understanding. The studies of kaonic atoms and of the kaonic nuclear processes performed by SIDDHARTA-2 and AMADEUS play in this context a key-role.

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## 1. Low-energy kaon–nucleon/nuclei physics studies at DAΦNE

The DAΦNE electron–positron collider [1, 2] at the Frascati National Laboratory of INFN produces the  $\phi$ -resonance, which decays with a probability of about 50% in  $K^+K^-$ , so providing an excellent quality low-energy kaon “beam” (16 MeV of kinetic energy). This beam is intensively used for studies of the low-energy kaon–nucleon/nuclei interactions, a field still largely unexplored. By making use of this beam, the SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) Collaboration performed the highest precision measurement of the strong interaction induced energy shift and width of the  $1s$  level, via the measurement of the X-ray transitions to this level, for kaonic hydrogen [3].

SIDDHARTA realized also high-precision measurements for the kaonic helium3 and 4 X-ray transitions to the  $2p$  level [4–6] and the first exploratory measurement of the kaonic deuterium [7].

SIDDHARTA-2, a major upgrade of SIDDHARTA, is presently under preparation, and will measure in the coming years the kaonic deuterium transitions to the  $1s$  level, which will contribute to extract, for the first time, the isospin-dependent antikaon–nucleon scattering lengths, fundamental quantities for understanding the chiral symmetry breaking in the strangeness sector.

The AMADEUS (Antikaon Matter at DAΦNE: an Experiment with Unraveling Spectroscopy) Collaboration aims to perform the first complete study of the low-energy kaon–nuclei interactions by using a series of gaseous targets as  $d$ ,  $^3\text{He}$ ,  $^4\text{He}$ , and solid targets. These studies will provide unique information about the dynamics of the antikaons interactions with one, two or more nucleons.

## 2. Kaonic atoms studies by SIDDHARTA and SIDDHARTA-2

### 2.1. The SIDDHARTA experiment

The SIDDHARTA technique and results are described in [3, 8], so only a short summary, given to facilitate the understanding of the SIDDHARTA-2 upgrade aiming to perform the first measurement of the kaonic deuterium, is presented here.

The SIDDHARTA experiment was performed at the DAΦNE in 2009, when the most precise measurement of kaonic hydrogen was performed [3]. The monochromatic low-energy charged kaons from DAΦNE are degraded in energy, then stopped in a cryogenic gaseous target, producing kaonic atoms. The target is a critical item, the yields of kaonic atom X-rays decreasing with the gas density, due to the Stark mixing. A too low density, however, does not permit efficient stopping and increases the kaons in-flight decay.

For SIDDHARTA, the yield of the kaonic hydrogen  $K_\alpha$  transitions was  $\sim 1.2\%$  and will presumably drop to  $\sim 0.1\%$  for the kaonic deuterium. The trigger was given by  $K^+K^-$  coincident hits measured by fast scintillators. The X-ray transitions of kaonic atoms were detected with 144 silicon drift detectors (SDDs),  $1\text{ cm}^2$  each, surrounding the target. The SDDs, developed by the Collaboration, had an energy resolution of 150 eV FWHM at 6 keV, while their drift time was below 800 ns FWHM. The fast X-ray detectors pulse, correlated with the trigger signal, conferred a high background rejection ( $10^4$ ) of electromagnetic (EM) showers from the beam losses.

## 2.2. The SIDDHARTA-2 experiment

Presently, an 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 [9]. The main improvements to be performed in SIDDHARTA-2 are:

- a new cryogenic target in reinforced kapton (13 cm diameter, 7 cm height), operating few hundred mK above the liquid point ( $\sim 25\text{ K}$ ) at a pressure of 4 bar (5% LHD), for a more efficient kaon stopping;
- larger total area, faster SDD detector array; the solution to improve the SDD time resolution consists in the reduction of the single element size (from 10 to 8 mm) and the replacement of the integrated J-FET (thermally limited), with a newly-developed amplifier on the ceramics, able to operate at very low temperatures (below 50 K);
- a veto-1 detector [10], which measures 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;
- veto-2 system, consisting in scintillators read by SiPMs, placed behind each SDD array, to reject the hadronic background;
- a kaon trigger with geometric acceptance optimized to match the kaon gas stopping distribution;
- mechanical and cryogenic improvements of the vacuum chamber, necessary to add more cooling power to the SDDs and to the cryogenic target.

A sketch of the SIDDHARTA-2 setup is shown in Fig. 1. For an acquired luminosity of  $800 \text{ pb}^{-1}$  and assuming a yield of 0.1%, a precision of 30 eV for the shift and 70 eV for the width for the kaonic deuterium  $1s$  level could be reached. The estimated values are comparable with the precision obtained for the kaonic hydrogen in SIDDHARTA and will allow to determine the antikaon–nucleon isospin-dependent scattering lengths, at few percent precision level required by the non-perturbative QCD models dealing with strangeness.

The SIDDHARTA-2 setup is presently being built and tested in the laboratory. It will be installed on the DAΦNE collider in summer 2018, and, after tests and optimizations, will perform the kaonic deuterium measurement in 2019.

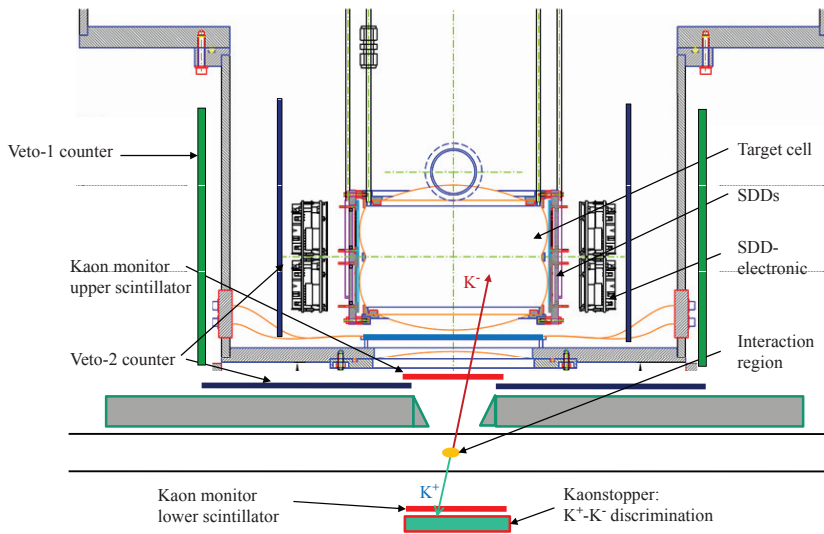


Fig. 1. The SIDDHARTA-2 layout.

### 3. The AMADEUS experiment

The low-energy ( $< 100 \text{ MeV}/c$ ) kaon–nuclei interaction studies represent the main aim of the AMADEUS Collaboration [11, 12]. In order to do these type of measurements in a most complete way, by detecting all charged and neutral particles coming from the  $K^-$  interactions in various targets with an almost  $4\pi$  acceptance, the AMADEUS Collaboration plans to implement the existing KLOE detector [13, 14] with a dedicated setup which contains the target which can be either solid or a gaseous cryogenic one, a trigger (TPC-GEM) and a tracker system (straw tubes or scintillating fibers read by SiPM detectors).

The negatively-charged kaons can be stopped inside the target or interact at low energies, giving birth to a series of processes we plan to study. Cross sections, branching ratios, rare hyperon decay processes will be measured. The  $\Lambda(1405)$  which can decay into  $\Sigma^0\pi^0$ ,  $\Sigma^+\pi^-$  or  $\Sigma^-\pi^+$  will be investigated together with the debated case of the “kaonic nuclear clusters” (for a discussion, see [15]), especially decaying into  $K^-pp$  and  $K^-npp$ . We can study these channels by measuring, for example, their decays to  $\Lambda p$  and to  $\Lambda d$ .

As targets to be employed, we plan to use gaseous ones, like  $d$ ,  $^3\text{He}$  or  $^4\text{He}$  and solid ones as C, Be or Li. A first step towards the AMADEUS realization, an analysis of the KLOE data from 2004–2005 is ongoing. In the summer of 2012, a dedicated target, a half cylinder done in pure carbon was realized and installed inside the Drift Chamber of KLOE as a first setup towards the realization of AMADEUS. The target thickness was optimized such as to have a maximum of stopped kaons (about 24% of the generated ones) without degrading too much the energy of resulting charged particles inside the target material. Data analysis is ongoing. More about the AMADEUS case can be found in [16].

#### 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).

Presently, an enlarged collaboration, SIDDHARTA-2, is upgrading the setup in order to perform the kaonic deuterium and other types of kaonic atoms transitions measurements in the coming years.

The kaon–nuclei interactions at low energies are being investigated by the AMADEUS Collaboration. Preliminary results show how a future dedicated experiment could uncover many of the processes which take place in the antikaon–nuclei interactions.

SIDDHARTA, SIDDHARTA-2 and AMADEUS at DAΦNE 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 (the equation of state for neutron stars).

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