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Unlocking the secrets of the kaon–nucleon/nuclei interactions at low-energies: The SIDDHARTA(-2) and the AMADEUS experiments at the DAΦNE collider

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Abstract

The DAΦNE electron–positron collider at the Laboratori Nazionali di Frascati of INFN has made available a unique quality low-energy negative kaons "beam", which is being used to unlock the secrets of

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the kaon–nucleon/nuclei interactions at low energies by the SIDDHARTA(-2) and the 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 already started a data taking with a dedicated carbon target, plans to perform in the coming years precision measurements on kaon–nuclei interactions at low-energies, in particular to study the possible formation of kaonic nuclei and the $\Lambda(1405)$. The two experiments are briefly presented in this paper.

Keywords: Charged kaons; Low-energy kaon–nuclei interactions; Kaonic atoms; X-rays

1. Low-energy kaon–nucleon/nuclei physics 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" (16 MeV of kinetic energy). This beam is intensively used for the study of the low-energy kaon–nucleon/nuclei interaction, a field still largely unexplored. By making use of this negative kaon beam, in 2009 the SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) experiment performed precision measurements 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. SIDDHARTA achieved as well high precision measurements for the kaonic helium3 and 4 X-ray transitions to the $2p$ level and realized the first exploratory measurement of kaonic deuterium. The SIDDHARTA-2, 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 for understanding important aspects of 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 targets as d, ^{3}He, ^{4}He, and solid targets. Among the aims of AMADEUS are the measurement of $\Lambda(1405)$ decaying to $\Sigma\pi$ in all possible combinations and to give a definite answer to the debated question of the existence of the K^-pp, K^-ppn and K^-pnn kaonic nuclei and, if such states exist, to measure their properties (binding energies, width and decay channels).

2. The SIDDHARTA experiment

In the SIDDHARTA experiment the monochromatic low-energy charged kaons which are produced by the decay of the ϕ-resonance in the DAΦNE collider are degraded and stopped in a cryogenic gaseous target where kaonic atoms are efficiently produced. The gas-target system is a critical feature of the experiment, because the yields of kaonic-atom X-rays decrease sensitively towards higher density due to collisions and Stark mixing with other atoms. An important element of the apparatus is the charged kaon trigger which is based on the coincidence of two plastic scintillation counters mounted top and bottom of the interaction point of e^+e^-. The trigger system takes advantage of the back-to-back topology of the produced low-energy kaons: $\Phi \to K^+K^-$. This system drastically increases the signal-to-background ratio, because most of the background is generated by e^+ and e^- particles lost from the beams, in asynchronous timing with colliding.

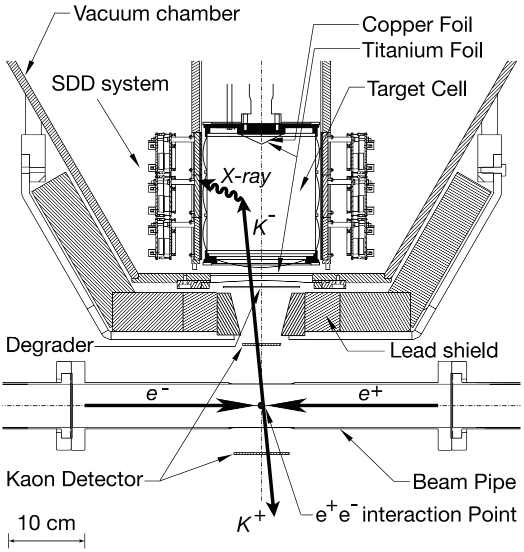

Fig. 1. An overview of the SIDDHARTA experimental setup. The whole system was installed at the interaction point of DAΦNE.

The kaonic-atom X-rays were detected by 144 silicon drift X-ray detectors (SDDs) which were mounted around the target. The SDDs, developed within a European research project devoted to this experiment, have the good energy resolution of 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.

During the data taking campaign the following measurements were performed:

- 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; the results were published in [4,5].
- Kaonic helium3 transitions to the $2p$ level, the first measurement ever; the results were published in Ref. [5,6].
- Kaonic deuterium X-ray transitions to the $1s$ level — as an exploratory measurement.

As an example, Fig. 2 shows the measured kaonic-hydrogen and deuterium X-rays spectra and the global simultaneous fit functions, while in Fig. 3 the kaonic hydrogen spectrum after the background subtraction is shown.

The kaonic-hydrogen X-ray transitions were clearly observed while those for kaonic deuterium were not visible. This is consistent with the theoretical expectation that kaonic-deuterium X-rays have about one order-of-magnitude lower yield [7]. A dot-dashed line in Fig. 2(a) indicates the electro-magnetic (EM) value of the kaonic-hydrogen Kα ($2p \to 1s$) X-ray transition energy. The repulsive-type shift (negative signed ϵ) is clear from the smaller Kα X-ray energy than the EM value, which is consistent with the analysis of $\mathrm{K}^- p$ scattering data. Many other

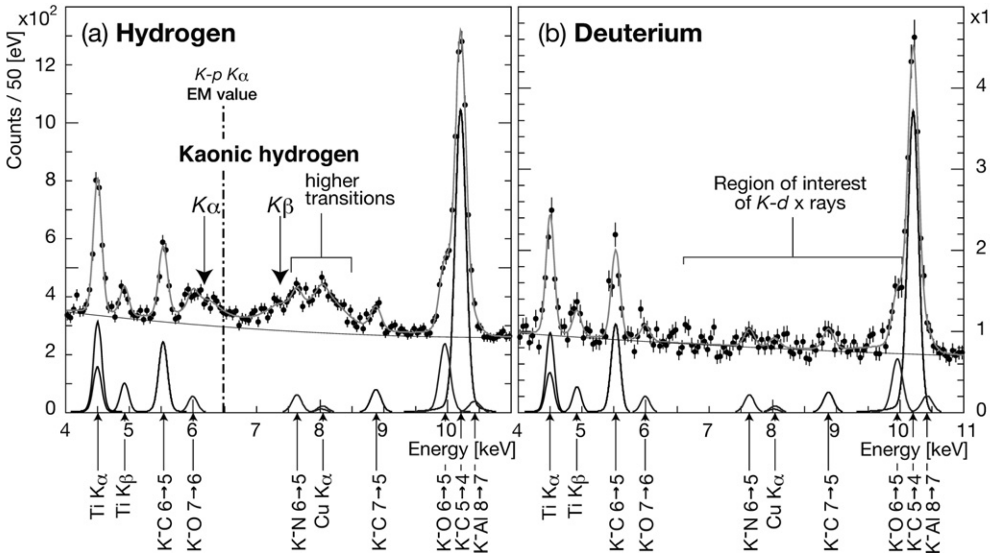

Fig. 2. A global simultaneous fit result of the X-ray energy spectra of kaonic hydrogen (a) and deuterium (b) data. The kaonic-hydrogen X-ray transition are clearly observed. The dot-dashed vertical line indicates the EM energy of the kaonic-hydrogen Kα X-ray. The other kaonic-atom lines are attributable to the target-cell wall made of Kapton polyimide film ($C_{22}H_{10}O_5N_2$) and its aluminum support frames. The characteristic X-rays come from high-purity titanium and copper foils installed for in-situ X-ray energy calibration. A similar-shape continuous background is assumed in the fit.

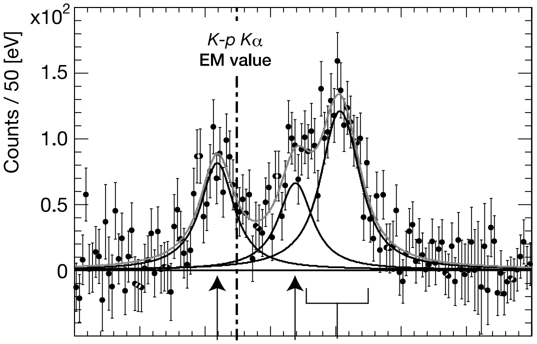

Fig. 3. Residuals of the measured kaonic-hydrogen X-ray spectrum after subtraction of the fitted background, clearly displaying the kaonic-hydrogen K-series transitions.

characteristic X-rays were also detected in both spectra, as indicated in the figures. Other kaonic-atom lines are corresponding to kaons stopped in the target-cell wall made of Kapton polyimide film ($C_{22}H_{10}O_5N_2$) and its aluminum support frames. The characteristic X-rays come from high-purity titanium and copper foils installed for in-situ X-ray energy calibration. Details of analysis is given in Ref. [3].

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

$$\epsilon = -283 \pm 36(\text{stat}) \pm 6(\text{syst})\ \text{eV},$$

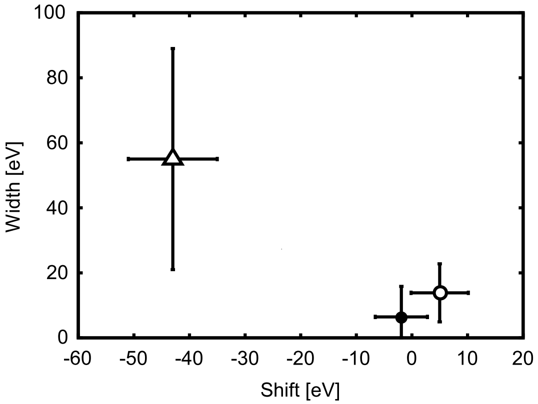

Fig. 4. Comparison of the experimental results. Open circle: K–^{4}He $2p$ state; filled circle: K–^{3}He $2p$ state. Both are determined by the SIDDHARTA experiment.The average value of the K–^{4}He experiments performed in the 70's and 80's is plotted with the open triangle.

$$\Gamma = 541 \pm 89(\text{stat}) \pm 22(\text{syst})\ \text{eV},$$

where the first error is statistical and the second is the systematic one. These are the most precise results compared to the previous measurements [8,9], and the values of ϵ and Γ are consistent with the theories [10].

The SIDDHARTA results allow the most precise evaluation of K^-p scattering lengths which yields vital constraints on the theoretical description of the low-energy $\bar{\mathrm{K}}N$ interactions [11–13]. For further study of the isospin-dependent $\bar{\mathrm{K}}N$ interaction, the shift and width of kaonic-deuterium $1s$ state are crucial objectives.

The strong-interaction shifts and widths both for kaonic-^{3}He and the kaonic-^{4}He were measured by the SIDDHARTA experiment for the $3d \rightarrow 2p$ transition, where kaonic-^{3}He was measured for the first time.

The resultant shifts both for K–^{3}He and K–^{4}He [4,6] agrees with the theoretical calculations [14–16] and the same is valid for the strong-interaction $2p$ level widths [5] which are in good agreement with the estimated values coming from theories [14,17,18]. No abnormally large shifts and widths were found in K–^{3}He and K–^{4}He.

The correlations of the shift and width values of the K–^{3}He and K–^{4}He $2p$ states are plotted in Fig. 4, together with the average values reported in [14,17], where the errors bars were calculated by adding the statistical and systematic errors quadratically. Clearly, the new results gave significantly smaller values both for the shifts and widths.

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 [19]. The main improvements to be performed in SIDDHARTA-2 are:

- 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.
- An improved trigger scheme was studied in order to increase the Signal/Background (S/B) ratio (one has to selectively trigger on kaons entering the target volume). This was realized

Table 1
The gain factors of SIDDHARTA-2, coming from various improvements of SIDDHARTA.

	New geometry and gas density	Timing resolution	$K^{\pm}$ discrimination	del'd anti-coincidence	Prompt anti-coincidence	Total improvement factor
Signal	2.5		0.8			2.0
Kaonic X-rays from wallstops	20					20
Continuous background/ /Signal/KeV at ROI	3.8 ratio of gasstops vs decay + wallstops		2 events due to decay of K^+ removed		2 charged particle veto	15.2
Beam background (asynchron)	4.8 less trigger per signal	1.5 smaller coincidence gate		3 active shielding shielding		21.6

in SIDDHARTA only partially, since the trigger system (scintillators read by PMs) was positioned outside vacuum chamber, about 12 cm away from the target entrance window. Therefore, although the size of the kaon trigger was optimized, a certain number of triggered kaons were not entering the target volume, but were absorbed in the side walls and were producing background events. For this reason, in SIDDHARTA-2 we plan to move the upper scintillator of the kaon trigger close to the entrance window of the vacuum chamber, we will obtain less background and therefore an improvement in the S/B ratio.

- Since the trigger system of SIDDHARTA was not able to differentiate between the different charge states of the incident kaons, the accepted events were a mixture of K^- (including signal) and K^+ (representing background) induced events. For SIDDHARTA-2 we plan to implement a third scintillator below the beam pipe, which will be able to detect positively charges kaons by their decay into muons and thus allows to select exclusively events generated by K^-.
- Thanks to the extra available space at the new interaction region, a more sophisticated shielding (lead-copper-aluminium-plastic) around the setup can be constructed. Moreover, we are considering the option of an additional veto (anticoincidence) system to be positioned around the target cell in order to reject those events which still pass the lead shielding around the target. The new trigger system and the anticoincidence help to suppress the background and to obtain a better Signal/Background ratio.

In order to evaluate the gain factors and the required luminosity to perform the kaonic deuterium measurements, a GEANT4 based Monte Carlo simulations was performed. In the Monte Carlo simulations, it was assumed as input parameter a factor 10 smaller yield of K^-d with respect to the K^-p one and a factor 2 larger width. In Table 1 the final numbers for the gain factors in SIDDHARTA-2 are summarized. Under these conditions, SIDDHARTA-2 can 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 2013.

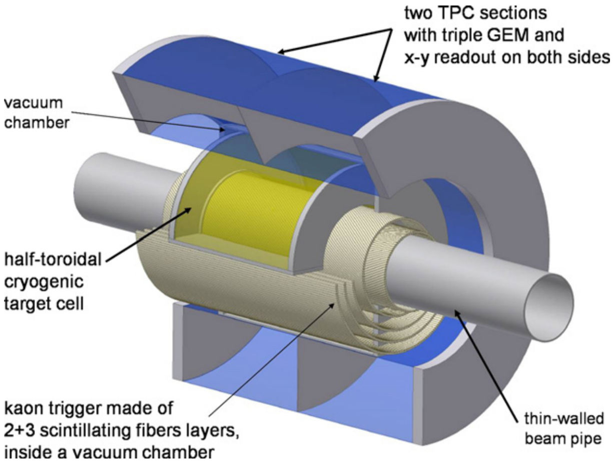

Fig. 5. The AMADEUS dedicated setup implemented in the Drift Chamber of the KLOE detector. In this situation a cryogenic gaseous target is used.

3. The AMADEUS experiment

The low-energy (< 100 MeV$/c$) kaon–nuclei interaction studies represents the main aim of the AMADEUS experiment [20,21]. 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 4π acceptance, the AMADEUS Collaboration plans to implement the existent KLOE detector [22,23] in the internal region of the Drift Chamber with a dedicated setup (see Fig. 5). The dedicated setup contains the target which can be either solid or a gaseous cryogenic one, a trigger (TPC-GEM) and a tracker system (scintillating fibers read by SiPM detectors).

The negatively charged kaons can stop inside the target or interact at low energies, giving birth of a series of processes we plan to study. Among these, a key-role is played by the generation of $\Lambda(1405)$ 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. Another important item is represented by the debated case of the "kaonic nuclear clusters", especially the K^-pp, and K^-–ppn cases. We can study these channels by measuring, for example, their decays to Λp and to Λd. In the same time, 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 targets to be employed, we plan to use gaseous ones, like d, ^{3}He or ^{4}He and solid ones as C, Be or Li. In the summer of 2012 a first dedicated target, 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 (see Fig. 6). 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. By the time of writing this paper (December 2012), the data taking with this target is ongoing, with the objective to integrate by the end of 2012 about 100 pb^{-1} of luminosity. The analysis of these data will provide new insights in the

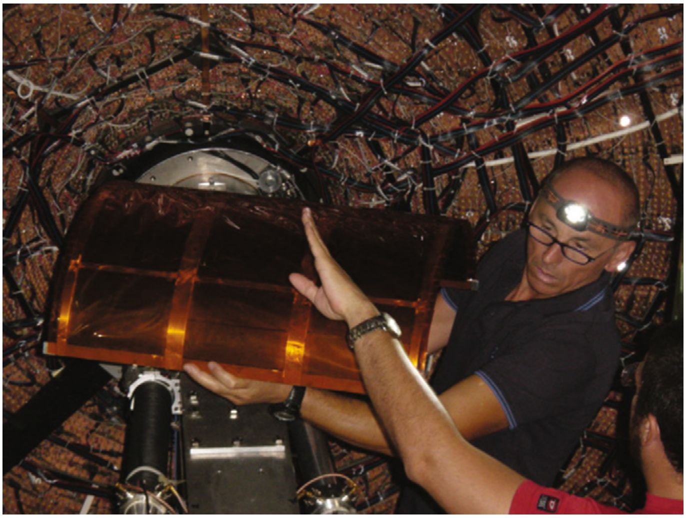

Fig. 6. The AMADEUS carbon target (half cylinder) installed inside the Dift Chamber of KLOE detector.

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.

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 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 unlock the secrets of low-energy QCD in the strangeness sector, with implications going from particle and nuclear physics to astrophysics.

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