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To cite this article: D Sirghi and for the SIDDHARTA, SIDDHARTA-2 and AMADEUS Collaborations
2019 *J. Phys.: Conf. Ser.* **1137** 012037

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Experiments with low-energy kaons at the DAΦNE Collider

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Abstract.

The investigations of light kaonic atoms offer the unique opportunity to perform experiments equivalent to scattering at vanishing relative energies, being their atomic binding energies in the keV range. This allows the determination of the hadron-nucleus interaction at threshold without the need of an extrapolation to zero relative energy. 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. 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. The measurement of kaonic deuterium will be realized in the near future by SIDDHARTA-2, a major upgrade of SIDDHARTA. A correlated study of the kaon-nuclei interaction at momenta below 130 MeV/c is carried out by the AMADEUS collaboration, using the KLOE detector and dedicated targets inserted near the collider interaction point. In this paper an overview of the main results obtained by SIDDHARTA together with the future plans, the SIDDHARTA-2 experiment and with the preliminary results of the study of charged antikaons interacting with nuclei by the AMADEUS collaboration, are shown.



1. Kaonic atoms

A kaonic atom is formed when a negative charged kaon enters in a target, loses its kinetic energy through the ionization and excitation of the atoms and molecules of the medium and is eventually captured into an excited atomic orbit around the nucleus, replacing the electron. Due to the much higher K^- mass with respect to the e^- one, the K^- is captured in the $n \simeq 31$ excited state for kaonic hydrogen (as an example). The kaon then cascades down through a series of atomic states to the lower states, via different cascade process (Auger effect, Coulomb deexcitation, scattering). When a low- n state with a small angular momentum is reached, the strong interaction with the nucleus comes into play and the kaon is absorbed by the proton through the strong interaction with the nucleus.

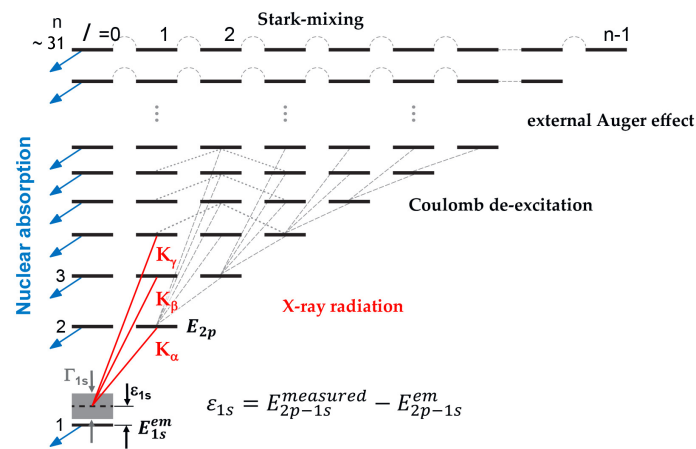


Figure 1. Cascade processes for kaonic hydrogen, starting when the kaon is captured in a highly excited state, down to the 1s ground state, which is shifted due to strong interaction and broadened due to nuclear absorption of the kaon by the proton.

In the study of strong interaction effects, the observables of interest are the shift (ϵ) and the width (Γ) of the atomic levels caused by the strong interaction of the kaon with the nucleus. The electromagnetic interaction with the nucleus is very well known and the energy levels can be calculated at a precision of eV by solving the Klein-Gordon equation. Even a small deviation from the electromagnetic value allows to get information on the strong interaction between the kaon and the nucleus.

2. Kaonic atoms studies by SIDDHARTA and SIDDHARTA-2

2.1. The SIDDHARTA experiment

DAΦNE (Double Annular Φ Factory for Nice Experiments) is a world-class electron-positron collider [1, 2] at the National Laboratory Frascati (LNF) in Italy. DAΦNE is a unique low-energy kaon source via the decay of ϕ -mesons produced almost at rest, which decays with a probability of 48.9% in K^+K^- , producing charged kaons with a momentum of 127 MeV/c, and a momentum spread $\Delta p/p < 0.1\%$. This “kaon beam” is intensively used for studies of the low-energy kaon - nucleon/nuclei interactions, a field still largely unexplored.

The SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) experiment ended its data taking campaign in November 2009, after having performed kaonic atoms transitions measurements on the upgraded DAΦNE collider.

In the SIDDHARTA experiment the monochromatic low-energy charged kaons 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: $\Phi \rightarrow K^+K^-$. 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.

The most precise measurement of kaonic hydrogen existing in literature was possible by the use of new triggerable X-ray detectors, the Silicon Drift Detectors, characterized by good values of energy and time resolutions, which turned out essential for the background suppression. A detailed description of the experimental setup is given in Ref.[3].

During the SIDDHARTA data taking campaign the following measurements were performed:

- kaonic hydrogen X-ray transitions to the $1s$ level, which represents the most precise measurement [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].

As an example, the $1s$ -level shift ε_{1s} and width Γ_{1s} of kaonic hydrogen were determined to be:

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

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

The precise determination of the shift and width of the K -series X-rays of kaonic hydrogen atoms provides new constraints on theories, having reached a quality which demands refined calculations of the low-energy $\bar{K}N$ interaction [8, 9].

2.2. The SIDDHARTA-2 experiment

SIDDHARTA-2 is a new experiment, which will be installed on DAΦNE at the end of 2018, taking advantage of the experience gained in the preceding SIDDHARTA experiment on kaonic hydrogen [3] and kaonic helium [4, 5, 6]. The goal of the new apparatus is to increase drastically the signal-to-background ratio, by gaining in solid angle, taking advantage of the new SDDs with improved timing and implementing additional veto systems. Fig.2 shows the SIDDHARTA-2 apparatus.

A detailed Monte Carlo simulation was performed within the GEANT4 framework to optimise the critical parameters of the setup, like target size, gas density, detector configuration and shielding geometry. The Monte Carlo simulation took into account all the improvements with the following assumptions: the values of shift and width of the $1s$ ground state of kaonic deuterium are -800 eV and 750 eV, respectively; yields ratios $K_\alpha : K_\beta : K_{total}$ are those of kaonic hydrogen, with an assumed K_α yield of 10^{-3} . Fig. 3 shows the expected spectrum for an integrated luminosity of 800 pb^{-1} delivered by DAΦNE in similar machine background condition as in SIDDHARTA runs. The extracted shift and width can be determined with precisions of about 30 eV and 80 eV, respectively. These values are of the same order as the SIDDHARTA results for kaonic hydrogen.

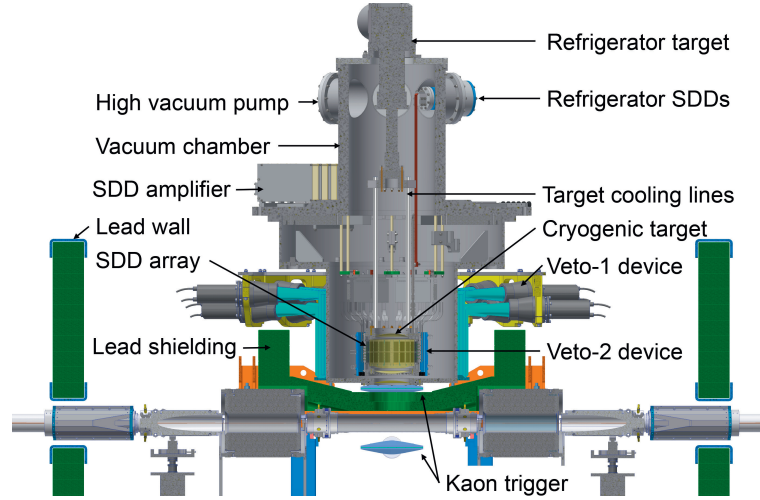


Figure 2. The SIDDHARTA-2 setup with the cryogenic target cell surrounded by the SDDs and the Veto-2 system within the vacuum chamber, while the Veto-1 device is surrounding the vacuum chamber on the outside.

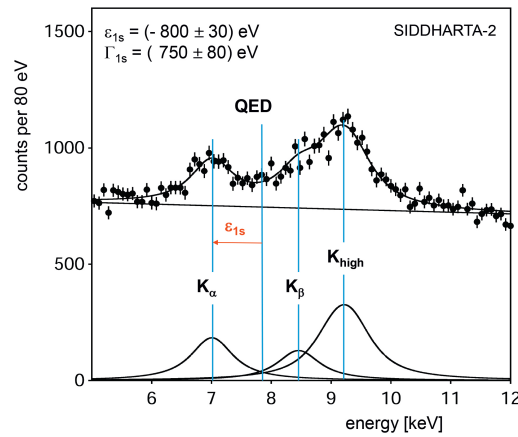


Figure 3. Simulated SIDDHARTA-2 kaonic deuterium spectrum, assuming a shift $\epsilon_{1s} = -800$ eV and width $\Gamma_{1s} = 750$ eV of the $1s$ state, as well as a K_α yield of 10^{-3} . The spectrum was simulated for an integrated luminosity of 800 pb^{-1} .

3. The AMADEUS experiment

The low-energy kaon - nuclei interaction studies represents the main aim of the AMADEUS collaboration [10, 11]. In order to perform these type of measurements coming from the K^- interactions in various targets, the AMADEUS Collaboration plans to propose a dedicated setup which contains the target, which can be either solid or a gaseous cryogenic one, a trigger (TPC-GEM), a tracker system (straw tubes or scintillating fibers read by SiPM detectors) and a calorimeter [12, 13]. 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 [14]), especially decaying into $K^- pp$ and $K^- npp$. We can study these channels by measuring, for example, their decays to Λp and to Λd .

As targets to be employed, we plan to use gaseous ones, like d , ^3He or ^4He and solid ones

as C, Be or Li. A first step towards the AMADEUS realization, an analysis of the KLOE data from 2004-2005 was successfully realized [15], [14]. 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 on 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).

5. Acknowledgments

We thank C. Capocchia and G. Corradi, from LNF-INFN; and H. Schneider, L. Stohwasser, and D. Stueckler from Stefan-Meyer-Institut, for their fundamental contribution in designing and building the SIDDHARTA setup. We thank as well the DAΦNE staff for the excellent working conditions and permanent support. Part of this work was supported by the Austrian Science Fund (FWF): [P24756-N20]; Austrian Federal Ministry of Science and Research BMBWK 650962/0001 VI/2/2009; the Grantin-Aid for Specially Promoted Research (20002003), MEXT, Japan; the Croatian Science Foundation, under project 1680; Ministero degli Affari Esteri e della Cooperazione Internazionale, Direzione Generale per la Promozione del Sistema Paese (MAECI), Strange Matter project; Polish National Science Center through grant No. UMO-2016/21/D/ST2/01155; Ministry of Science and Higher Education of Poland grant no 7150/E-338/M/2018.

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