Kaonic atoms and strangeness in nuclei: SIDDHARTA-2 and AMADEUS experiments

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Abstract. The dynamics of the strong interaction processes in the non-perturbative regime is currently described by lattice calculations and effective field theories (ChPT), still lacking several experimental results, fundamental for reaching a good understanding of the strangeness sector. Among these, the information provided by the low-energy kaon nucleon/nuclei interaction, accessible through the study of kaonic atoms and kaonic nuclear processes, plays a key-role. The lightest atomic systems, the kaonic hydrogen and the kaonic deuterium, provide, in a model-independent way, the isospin-dependent kaon-nucleon scattering lengths, through the timed X-ray spectroscopy of the exotic atoms during their de-excitation to the fundamental level. The most precise kaonic hydrogen measurement to-date, together with an exploratory measurement of kaonic deuterium and of upper-level transitions in kaonic helium 3 and kaonic helium 4 were carried out at the DAΦNE collider by the SIDDHARTA collaboration. The experiment took advantage of the monochromatic charged kaon beam provided by DAΦNE and of the new, fast spectroscopic SDD detectors developed by the collaboration. Presently, a significantly upgraded setup is ready to perform a precise measurement of kaonic deuterium and, afterwards, of heavier exotic atoms. 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 in the central region, near the collider interaction point. Preliminary results of the study of charged antikaons interacting with nuclei are shown, including an analysis of the still controversial Lambda 1405. Therefore, the experiments carried out at the DAΦNE collider represent a unique opportunity to explore the low-energy QCD in the strangeness sector.

1. Low energy QCD in the strange sector

The KN interaction at threshold provides important information on the relationship between spontaneous and explicit chiral symmetry breaking in low-energy QCD. Though the use of kaonic atoms as a perfect tool to extract without extrapolation the scattering lengths was predicted in late 70s, reliable experimental data was available only from the 1990s, after the measurement of the strong-interaction energy shift ε and width Γ of kaonic-hydrogen 1s atomic state, at KEK-PS in Japan [1] and afterwards, at DAΦNE in Italy [2]. From the obtained values, the K^-p scattering length was extracted using a Deser-Trueman-like formula [3], lately improved to account for the isospin-breaking corrections [4]. The measurement permitted a consistent interpretation of the scattering data [5] and the calculation of chiral SU(3) meson-baryon effective Lagrangian. Nevertheless, the amplitudes below the threshold were extrapolated with large uncertainties due to the experimental precision. Successively, the SIDDHARTA collaboration obtained more accurate values for both ε and Γ for kaonic hydrogen, thus providing stronger constraints on the theoretical models. This progress motivated new calculations regarding the structure of Λ(1405) and theoretical investigations on the existence of kaonic nuclear clusters [6], both now under experimental study within the AMADEUS collaboration.

In this context, the importance of kaonic deuterium X-ray spectroscopy has been well recognized, since the isospin-dependent scattering lengths a_0 and a_1, mediated in the K^-p process, cannot be determined without the measurement of a system containing a neutron. As the neutron alone cannot form atoms, the transitions on the lower level of kaonic deuterium will provide the missing information. Up to now, no experimental results have yet been obtained due to the difficulty of the measurement, the k^-D fundamental state being characterized by an extremely low yield (10^{-3}), due to the Stark effect coupled to a larger contribution of the strong interaction, ending up with the k^- nuclear absorption from higher levels.

2. Current experimental status

SIDDHARTA technique and results are fully described in [9], so only a short description will be given, to facilitate the understanding of the upgrade proposed by the SIDDHARTA-2 collaboration for reaching a significant determination of the K^-d transition parameters.

The SIDDHARTA experiment was performed at the DAΦNE e^+e^- collider in Frascati, Italy. The two beams energy is tuned to create φ mesons, which decay in K^+K^- pairs with a BR of 49.1%. The monochromatic, low-energy charged kaons are degraded, then stopped in a cryogenic gaseous target, producing kaonic atoms. The target is a critical item, the yields of kaonic atom X-rays decreasing sensitively with the gas density, due to Stark mixing. On the other hand, a low density does not permit efficient stopping and increases the kaons in-flight decay. For the SIDDHARTA optimized density, the yield was ~1% when filled with hydrogen and will presumably drop to ~ 0.1% for deuterium. The trigger was given by K^-K^+ coincident hits on fast scintillators. The kaonic atom X-rays were detected with 144 silicon drift X-ray detectors (SDDs), 1 cm^2 each, surrounding the target. The SDDs, developed by the collaboration, have an energy resolution of 150 eV FWHM at 6 keV, while their time response is below 800 ns FWHM. The trigger signal, correlated with the fast X-ray detectors pulse, conferred a high background rejection (10^4), most of the background deriving from beam losses, uncorrelated with the Φ production.

3. SIDDHARTA-2 experiment

Starting with a good knowledge of the problems imposed by rare kaonic atom transition measurements (K^-p) and having acquired a perfect understanding of the background sources generating EM and hadronic cascades, the SIDDHARTA group has developed a set methods aiming to increase the S/B ratio by a factor of 14 or better, thus allowing the kaonic Deuterium measurement (for estimated yields one order of magnitude below the KH measured one). The changes and add-ons required for reaching the above objective are briefly described, as follows:

Larger 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 removal of the integrated J-FET transistor (thermally limited), replaced by the newly developed CUBE amplifier mounted directly on the SDD ceramics and able to operate at very low temperatures (below 50 K). Taking advantage of the smaller drift path and higher carrier mobility, the response time was reduced from 900 ns to 350 ns, providing an inverse-proportional asynchronous background reduction.

A gas-moderation detector, measuring the prompt time of the fast secondaries produced by the kaons absorbed on nuclei. The working principle is based on the kaon moderation time in high-density gas, longer than the corresponding one in solid materials. Moreover, a fraction of the stopped k^+ decays slower (~50%) so their contribution to the background is excluded too. The system consists in scintillators surrounding the vacuum chamber, read at two sides by PMs coupled to mirrors and light-guides, necessary to cope with the reduced space between the setup and the shielding.

A new cryogenic target cell operating from 20 to 30 K, with increased pressure (0.4 MPa), for more efficient kaon stopping.

A veto system, consisting in scintillators read by SiPMs, placed behind each SDD array, to reject the hadronic background coming from border hits of MIPs, depositing energy in the X-ray range.

A kaon trigger system with geometric acceptance matching only the kaon gas stopping distribution.

A new K^+ - K^- discrimination detector, to further reduce the background from the K^+ mesons.

An improved X-ray calibration system, providing low-rate in-situ calibration as well as high rate calibration between physics runs, allowing calibrating each single SDD cell.

Mechanical and cryogenic improvements of the vacuum chamber, necessary to add more cooling power to the SDDs and to the cryogenic target.

All described items were carefully optimized by a GEANT4 simulation, which can be considered reliable after having reproduced, in the same framework, the SIDDHARTA measurements, both in terms of signal and background, to 7% accuracy. A plot of the simulated SIDDHARTA-2 setup is shown on the left side of Fig. 1, while the expected result for the kaonic deuterium measurement, for an integrated luminosity of 800 pb^{-1} and assuming a yield of 0.1%, is plot on the right.

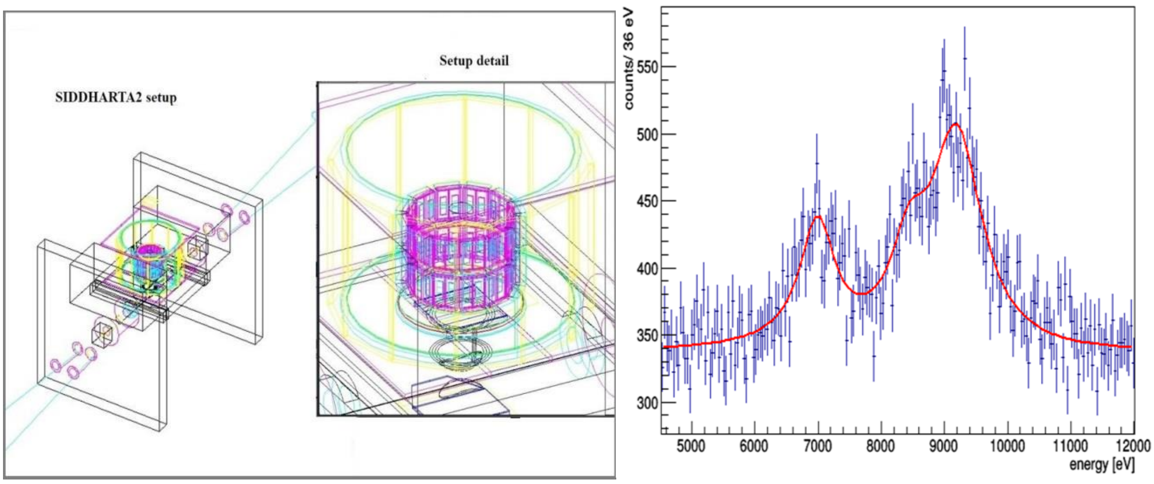

Figure 1: The SIDDHARTA-2 Monte Carlo layout together with the simulated spectrum of K^-d (the Ka line is at 7 keV, while from 8 to 10 keV is the K-complex)

The fit result on the simulated signal indicates the shift and width of the kaonic deuterium 1s level, induced by the presence of the strong interaction, can be extracted with a precision of:

$\delta\varepsilon(1s) = 30$ eV and $\delta\Gamma(1s) = 70$ eV

corresponding to a statistical significance of the $K\alpha$ line of $\sim 20\ \sigma$.

The estimated values are comparable with the precision obtained for kaonic hydrogen in SIDDHARTA and will allow to determine the antikaon-nucleon isospin-dependent scattering lengths, required by the non-perturbative QCD models dealing with strangeness.

4. **AMADEUS**

A research line complementary to that of exotic atoms, the AMADEUS experiment at DAΦNE, deals with the investigation of the low-energy kaon-nucleon/nuclei hadronic interaction. For that purpose, signals from K^- absorption at-rest and in-flight (with momenta below 127 MeV/c), are investigated using a sample corresponding to a total integrated luminosity of 2 fb^{-1} collected by KLOE [12] during the 2004 and 2005 runs. In a first phase the KLOE detector was used as an active target, the nuclear interaction of negatively charged kaons in the gas filling the KLOE Drift Chamber (DC) [13] (mainly 4He) and the DC entrance wall [14] (mainly 12C) was investigated. In the period November/December 2012 a successful data taking was performed with a dedicated pure carbon solid target implemented in the central region of KLOE. A total integrated luminosity of 90 pb^{-1} was collected providing a high statistic sample of purely at-rest K^- nuclear interactions [15]. The ongoing analyses are mainly concerned with the investigation of the K^- multi-nucleon absorption processes (related the possible formation of K^- multi-nucleon bound states [16]) and the Σ^*/Λ^* properties and behavior in nuclear environment.

	yield / $K^-_{stop} \cdot 10^{-2}$	$\sigma_{stat} \cdot 10^{-2}$	$\sigma_{syst} \cdot 10^{-2}$
2NA-QF	0.124	± 0.019	+0.004 -0.008
2NA-FSI	0.265	± 0.027	+0.021 -0.022
Tot 2NA	0.366	± 0.032	+0.022 -0.031
3NA	0.267	± 0.067	+0.043 -0.020
Tot 3body	0.532	± 0.072	+0.047 -0.032
4NA + Uncorr. bkg.	0.753	± 0.052	+0.024 -0.074

Table 1: Production probability of the Σ^0p final state for different intermediate processes normalized to the number of K^- stopped in the DC wall. The statistical and systematic errors are shown as well.

In [17], a clean sample of Σ^0p events, from K^- captures in the KLOE DC wall, was reconstructed. Σ^0p is (together with Λp) an expected decay channel of the ppK$^-$ cluster, free from the Σ conversion processes, which strongly affect the uncorrelated Λp production. A simultaneous fit of several kinematic variables was performed by a simulated cocktail containing K^- absorptions on two or more nucleons (together with an uncorrelated background source). The study allowed isolating, with good precision, the K^- absorption on two nucleons (2NA) free form any final state interaction of the produced Σ^0p pairs (2NA-QF). More difficult is to distinguish between 2NA and 3NA when 2NA is followed by final state interactions of the hyperon or nucleon with the residual nucleus. The obtained results are summarized in Table 1. A second fit of the experimental data has been carried out including a ppK$^-$ component decaying into Σ^0p. A systematic scan of possible binding energies and widths, varying within 15-75 MeV and 30-70 MeV respectively, has been carried. The best fit resulted in a binding energy of 45 MeV and a width of 30 MeV. The corresponding ppK$^-$ yield extracted from the fit is:

Yield K^-_{stop} = $(0.043 \pm 0.009 \text{ stat } ^{+0.004}_{-0.005} \text{ syst}) * 10^{-2}$

In order to test the significance of the bound state with respect to a statistical fluctuation an f-test has been performed. The contribution of the ppK$^-$ component was found to be only significant at the level of 1σ. Although the measured spectra are compatible with the hypothesis of a ppK$^-$ contribution, the significance of the result is not sufficient to claim the discovery of the state. Strongly related to the possible production of kaonic bound states is the fundamental brick of the anti-kaon-nucleon interaction, namely the Λ(1405) state. We are presently investigating the $\Sigma^0\pi^0$ decay of the Λ(1405), produced in K^- absorptions in-flight on 4He and 12C. For kaon momenta of about 100 MeV the Kbar-N sub-threshold region is accessible (despite to the at-rest production) thus allowing to explore the Λ(1405) properties in the region 1415-1432 MeV. In order to extract the Λ(1405) shape it is crucial to disentangle the $\Sigma^0\pi^0$ resonant and non-resonant production. The $\Lambda\pi^-$ momentum spectra, including all the involved processes in K^- capture on 4He and possible final state interactions, were calculated in [18]. The spectra are expressed in terms of two $K^-n \rightarrow \Lambda\pi^-$ transition amplitudes: the isospin I=1 S-wave amplitude (|f^s|) and the resonant I=1 P-wave amplitude, dominated by the Σ(1385). The resonant amplitude is well known from direct experiments, so that measured total momentum distributions can be used to extract the non-resonant |f^s| amplitude below the Kbar-N threshold. The goal is to get information on the corresponding I=0 sub-threshold amplitude in the Σπ channel.

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