

Precision measurements of kaonic atoms at DAΦNE and future perspectives

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1. Precision measurements of kaonic atoms at DAΦNE

1.1 The SIDDHARTA scientific case

The precision measurements of kaonic atoms at the DAΦNE accelerator at the LNF-INFN Laboratories are going to be performed in the framework of the SIDDHARTA international Collaboration [1].

The objective of the SIDDHARTA {Silicon Drift Detector for Hadronic Atom Research by timing Application) experiment is to continue, to deepen and enlarge the successful scientific line, initiated by the DEAR experiment in performing precision measurements of X-ray transitions in exotic (kaonic) atoms at DAΦNE.

The aim of the experiment is a precise determination of the isospin dependent antikaon-nucleon scattering lengths, through an eV measurement of the K_{α} line shift and width in kaonic hydrogen, and a similar, being the first one in the same time, measurement of kaonic deuterium.

SIDDHARTA measures the X-ray transitions occurring in the cascade processes of kaonic atoms. A kaonic atom is formed when a negative kaon (coming from the ϕ -decay, produced at DAΦNE) enters a target, loses its kinetic energy through the ionization and excitation of the atoms and molecules of the medium, and is eventually captured, replacing the electron, in an excited orbit. Via different cascade processes (Auger effect, Coulomb deexcitation, scattering) the kaonic atom deexcites to lower states. When a low- n state with small angular momentum is reached, the **strong interaction** with the nucleus comes into play. This strong interaction is the reason for a **shift** in energy of the lowest-lying level from the purely electromagnetic value and the finite lifetime of the state – corresponding to an increase in the observed level **width**.

For kaonic hydrogen and deuterium the K-series transitions are of main experimental interest since they are the only ones affected by the strong interaction. The K_α lines are clearly separated from the higher K transitions. The shift ε and the width Γ of the 1s state of kaonic hydrogen are related in a fairly model-independent way to the real and imaginary part of the complex s-wave scattering length, a_{K^-p} :

$$\varepsilon + i \Gamma/2 = 412 a_{K^-p} \text{ eV fm}^{-1}$$

This expression is known as the Deser-Trueman formula [2]. A similar relation applies to the case of kaonic deuterium and to its corresponding scattering length, a_{K^-d} :

$$\varepsilon + i \Gamma/2 = 601 a_{K^-d} \text{ eV fm}^{-1}$$

The measured scattering lengths are then related to the isospin-dependent scattering lengths, a_0 and a_1 :

$$\begin{aligned} a_{K^-p} &= (a_0 + a_1)/2 \\ a_{K^-n} &= a_1 \end{aligned}$$

The extraction of a_{K^-n} from a_{K^-d} requires a more complicated analysis than the impulse approximation (K^- scattering from each free nucleon): higher order contributions associated with the K^-d three-body interaction have to be taken into account. This means to solve the three-body Faddeev equations by the use of potentials, taking into account the coupling among the multichannel interactions. An accurate determination of the KN isospin dependent scattering lengths will place strong constraints on the low-energy KN dynamics, which in turn constrains the SU(3) description of chiral symmetry breaking [3]. Crucial information about the nature of chiral symmetry breaking, and to what extent the chiral symmetry must be broken, is provided by the calculation of the meson-nucleon sigma terms.

A meson-nucleon sigma term is defined [4] as the nucleon expectation value of the equal-time double commutator of the chiral symmetry breaking part of the strong-interaction Hamiltonian. The sigma term is then a quantity which directly gives the degree of chiral symmetry breaking. Consequently, its relation to the scattering amplitude represents the corresponding low-energy theorem in the soft meson limit [4].

A phenomenological procedure, which implies dispersion relations and suitable extrapolations allows to extract the sigma terms from the measured amplitudes. Presently only estimates for the KN sigma terms exist; a

measurement of the K^-N scattering lengths at few percent level should allow the determination of these quantities with a precision better than 20%.

The sigma terms are also important inputs for the determination of the strangeness content of the proton. The strangeness fraction depends on both kaon-nucleon and pion-nucleon sigma terms, being more sensitive to the first ones [5].

In 2002, the DEAR experiment has performed the most precise measurement of kaonic hydrogen X-ray transitions to the fundamental $1s$ level, to present [6]:

$$\begin{aligned}\varepsilon &= -193 \pm 37 \text{ (stat.)} \pm 6 \text{ (syst.) eV} \\ \Gamma &= 249 \pm 111 \text{ (stat.)} \pm 30 \text{ (syst.) eV.}\end{aligned}$$

This measurement has triggered new interest and results from the theoretical groups working in the low-energy kaon-nucleon interaction field, as well related to non-perturbative QCD tests.

The new experiment SIDDHARTA, aims to improve the precision obtained by DEAR by an order of magnitude and to perform the first measurement ever of kaonic deuterium.

Other measurements (kaonic helium, sigmonic atoms, precise determination of the charged kaon mass) are as well considered in the scientific program.

1.2 The SIDDHARTA setup

SIDDHARTA represents a new phase in the study of kaonic atoms at DAΦNE.

The DEAR precision was limited by a signal/background ratio of about 1/70. In order to significantly improve this ratio a breakthrough is necessary.

An accurate study of the background sources present at DAΦNE was re-done. The background includes two main sources:

- synchronous background: coming together with the K^- - related to K^- interaction in the setup materials and also to the ϕ -decay process; it can be defined hadronic background;
- asynchronous background: final products of electromagnetic showers in the machine pipe and in the setup materials originated by particles lost from primary circulating beams either due to the interaction of particles in the same bunch (Touschek effect) or due to the interaction with

the residual gas. Accurate studies performed by DEAR showed that the main background source in DAΦNE is of the second type, which shows the way to reduce it. A fast trigger correlated to the negative kaon entrance in the target would cut the main part of the asynchronous background.

While DEAR used for the X rays detection the CCD (Charge Coupled Device) detectors - excellent X-ray detectors, with very good energy resolution (about 140 eV FWHM at 6 keV), but having the drawback of being non-triggerable devices (since the read-out time per device is at the level of 10 s), a recently developed device, which preserves all good features of CCDs (energy resolution, stability and linearity) but additionally is triggerable - i.e. fast (at the level of 1μs) was implemented. This new detector is represented by large area Silicon Drift Detector (SDD), specially designed for spectroscopic application.

The development of the new 1 cm² SDD device is partially performed in the framework of an European Joint Research Activity (JRA10) within the FP6 program, the HadronPhysics I3.

Successful tests of SDD prototypes were performed in 2003 and 2004 at the Beam Test Facility of Frascati (BTF), in realistic (i.e. DEAR-like) conditions. The results of this tests were very encouraging: a trigger rejection factor of 5×10^{-5} was measured.

Extrapolated to SIDDHARTA conditions, this number translates into a S/B ratio in the region of interest about 20/1. By triggering the SDDs, the asynchronous e.m. background (mainly due to Touschek effect) can therefore be eliminated.

The 1 cm² SDD production is finished, in a configuration shown in Figure 1. Presently the SDDs are under test. The first results show a very good experimental resolution, Figure 2, and a stability of the order of 2-3 eV at 6 keV energy (by using a 1 mV stabilized power supply developed in the framework of SIDDHARTA).

In parallel, the general layout is proceeding, Figure 3, such as to be ready to install at DAΦNE and start taking data in early 2007, with the goal to perform eV precision measurement on kaonic hydrogen and deuterium during 2007-2008.

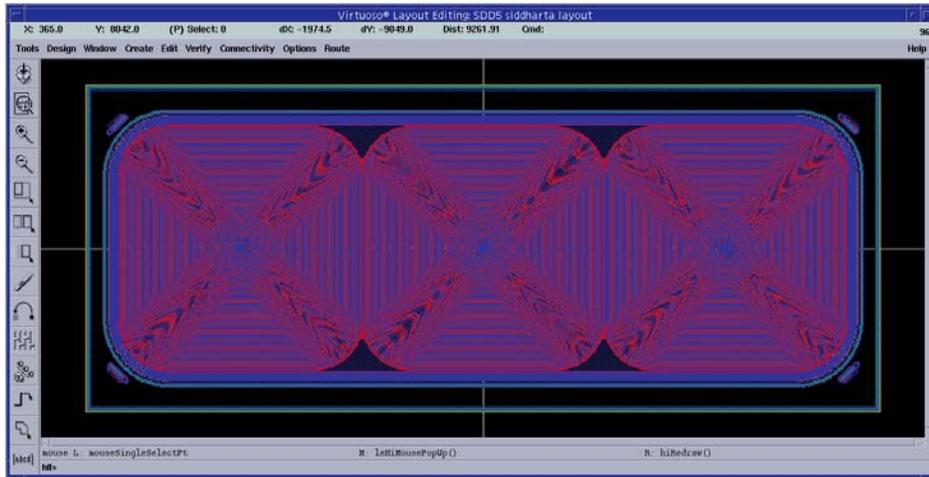


Figure 1: The SIDDHARTA SDD layout with 3 1cm^2 SDD chips (for a total of 192 cm^2 SDDs)

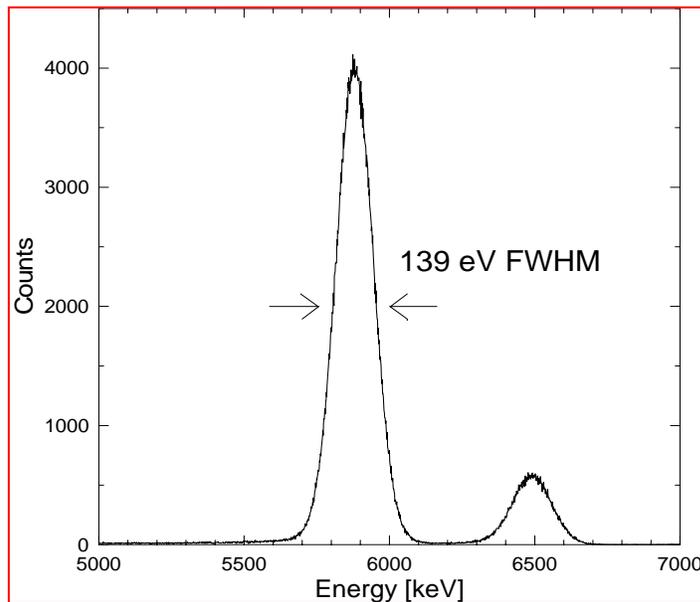


Figure 2: The energy resolution obtained with SDD prototype

1.3 The SIDDHARTA Monte Carlo simulations

Intensive SIDDHARTA monte Carlo simulations were performed in the framework of GEANT 3,21. [7]. The simulated kaonic hydrogen spectrum is shown in Figure 4. The result of the simulations show that for a total integrated luminosity of about 1 fb^{-1} , SIDDHARTA can accomplish the kaonic hydrogen and kaonic deuterium measurements at eV precision level.

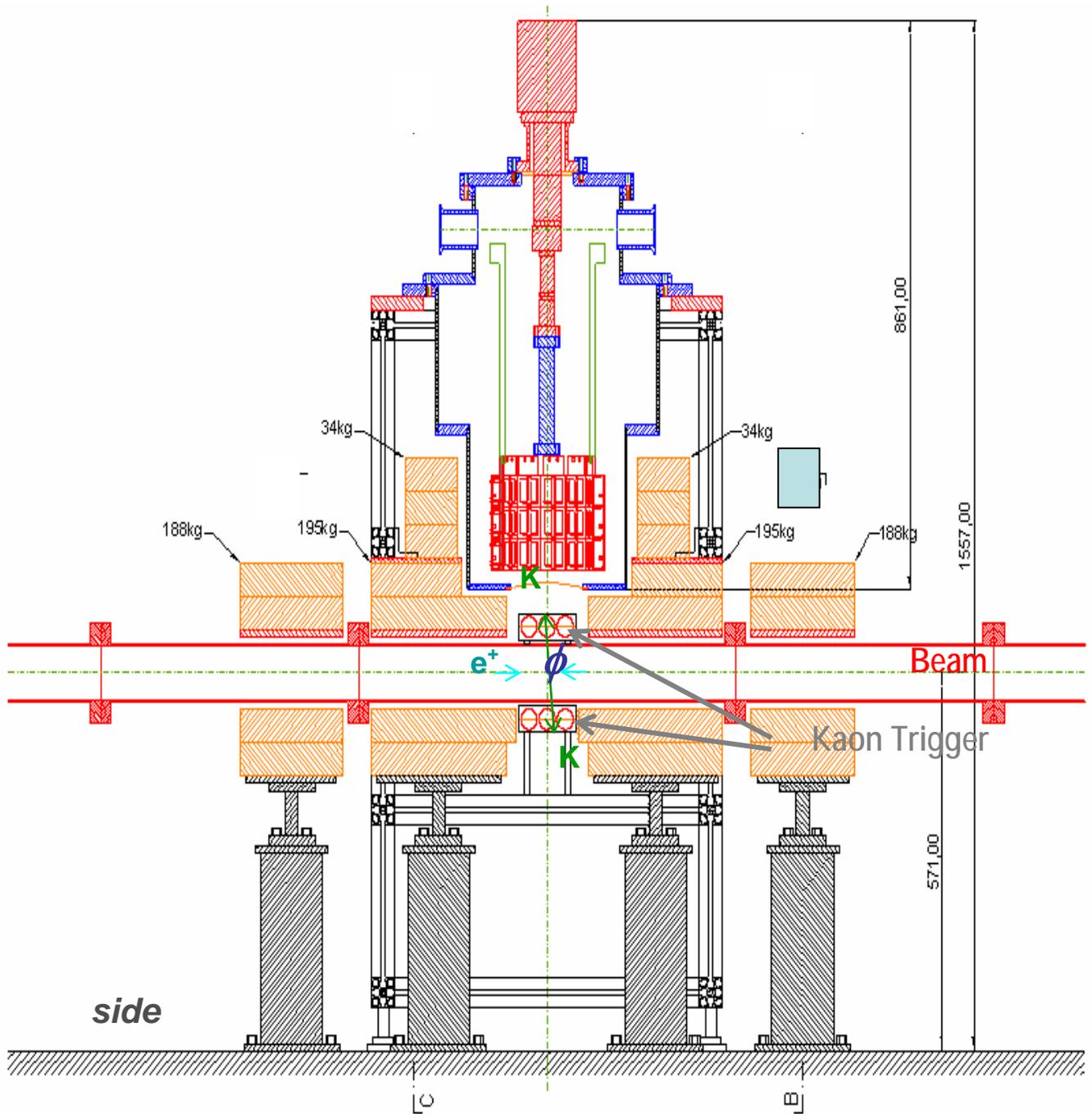


Figure 3: The SIDDHARTA layout at DAΦNE

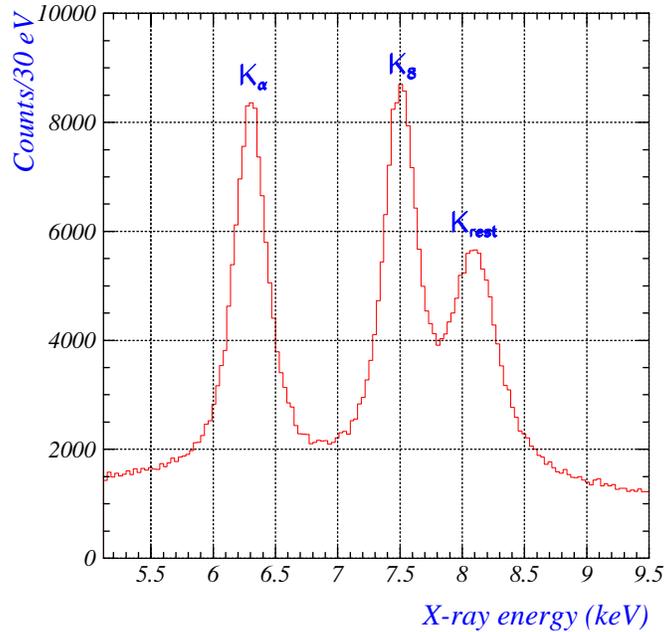


Figure 4: Kaonic Hydrogen Monte Carlo simulated spectrum for SIDDHARTA for an integrated luminosity of about 200 pb^{-1} .

2. Future perspectives – the AMADEUS experiment

After the SIDDHARTA and FINUDA experiments at the actual DAFNE will be accomplished, a plan for an upgrading of DAΦNE in luminosity or luminosity and energy is considered (after 2009). At this new upgraded facility, DAΦNE2, the SIDDHARTA group intends to continue the physics of kaon-nucleon/nuclei interaction in the framework of a new, enlarged collaboration: AMADEUS. In what follows, a brief presentation of AMADEUS is done.

2.1 The deeply bound kaonic nuclei scientific case

A new paradigm in strangeness nuclear physics is represented by the recently studied “Nuclear \bar{K} bound states in light nuclei” by Y. Akaishi and T. Yamazaki [8], whose first experimental indications have been produced at KEK [9,10,11], LNF [12], GSI [13] and BNL [14].

In a few-body nuclear system, in fact, the isospin $I=0$ $\bar{K}N$ interaction plays an important role: it favours discrete nuclear bound states of \bar{K} , while contracting the nucleus thus producing a cold dense nuclear system.

Many important impacts then follow:

- such compact exotic nuclear systems are formed with binding energies so large (100-200 MeV) that their widths turn out very narrow, less than (20-30 MeV), since the $\Sigma\pi$ decay channel is closed energetically and, additionally, the $\Lambda\pi$ channel is forbidden by isospin selection rule;

- high-density cold nuclear matter would be formed around K^- , which could provide information concerning a modification of the kaon mass and of the $\bar{K}N$ interaction in the nuclear medium. How hadrons behave and how their properties change in nuclear medium is interesting and important from the viewpoint of spontaneous and explicit symmetry breaking of QCD [15]. The masses of light hadrons are largely of dynamical origin and reflect the symmetry pattern of QCD.

- kaonic nuclear clusters could provide information on a transition from the hadronic phase to a quark-gluon phase [16]. At low baryon densities matter exists in aggregates of quarks and gluons with their colour charges combined to form neutral (colour-singlet) objects. This is a domain of low-energy QCD, the physics of the hadronic phase in which mesons, baryons and nuclei reside. In this phase, the QCD vacuum has undergone a qualitative change to a ground state characterized by strong condensates of quark-antiquark pairs and gluons. At large quark densities and Fermi momenta, another sector of the phase diagram, it is expected that Cooper pairing of quarks sets in and induces transitions to a complex pattern of superconducting and superfluid phases. Information on changes of vacuum properties of QCD and quark condensate could therefore also be obtained.

- empirical information could be obtained on whether kaon condensation can occur in nuclear matter, with implications in astrophysics: neutron stars, strange stars.

- nuclear dynamics under extreme conditions (nuclear compressibility, etc) could be investigated.

The new proposal, AMADEUS, at DAΦNE2, has the goal of performing systematic spectroscopic measurements of deeply bound kaonic nuclei.

2.2 The AMADEUS proposal

In September 2005, a (pre)Letter of Intent was written [17] in which it was shown that DAΦNE2 is an ideal facility to perform spectroscopic measurements of deeply bound kaonic nuclei – both in the production and in the decay phases. Consequently, the AMADEUS (Antikaonic Matter at DAFNE: an Experiment Unraveling Spectroscopy) collaboration was born, with the aim to perform these measurements for light and heavier nuclei (going from helium to lithium, boron and so on). The AMADEUS is planned to be done using KLOE detector [18] as a facility. A first preliminary drawing of the AMADEUS setup is shown in Figure 5.

The LOI will be delivered shortly (Spring 2006) and will contain more technical and physics details.

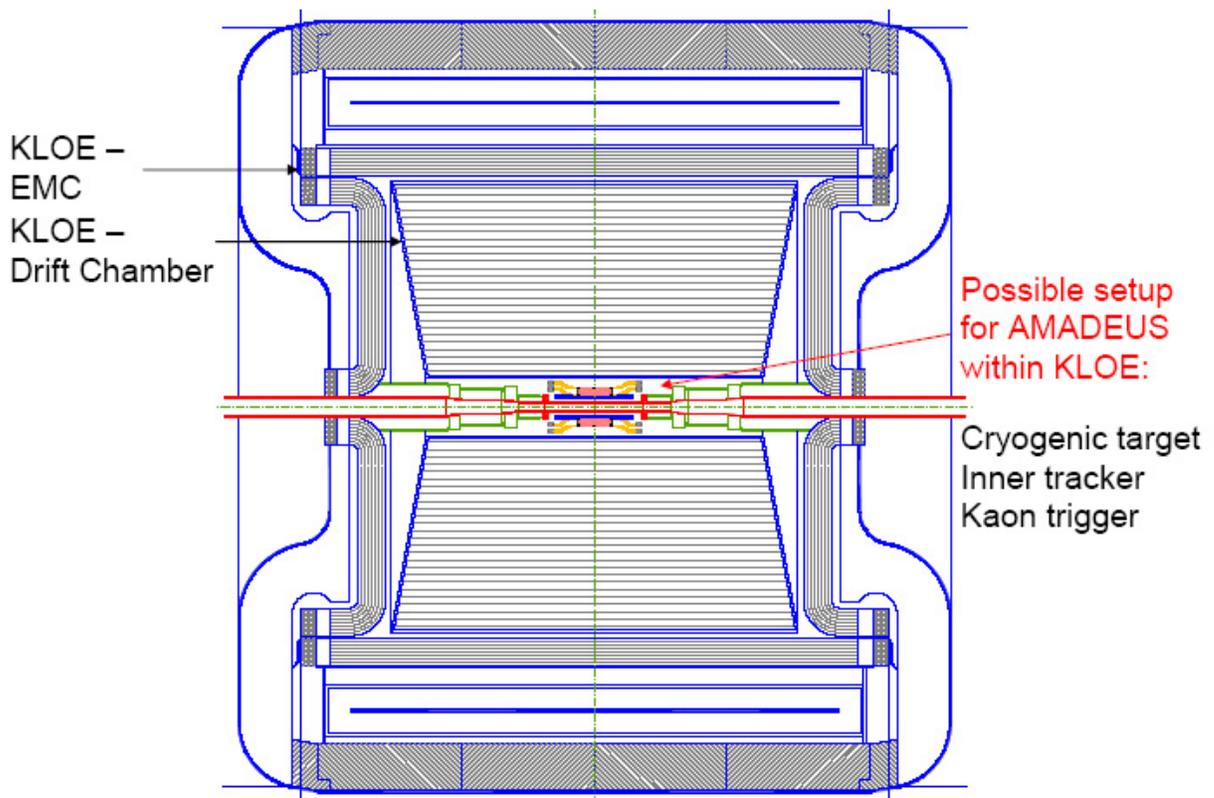


Figure 5: Preliminary AMADEUS setup within KLOE.

Acknowledgements

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