

Precision measurements of kaonic atoms at DAΦNE and future perspectives

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Abstract. The DAΦNE electron-positron collider at the Frascati National Laboratories has made available a unique “beam” of negative kaons providing unprecedented conditions for the study of the low-energy kaon-nucleon interaction, a field still largely unexplored. The DEAR (DAΦNE Exotic Atom Research) experiment at DAΦNE and its successor SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by Timing Application) aim at a precision measurement of the strong interaction shift and width of the fundamental $1s$ level, via the measurement of the x-ray transitions to this level, for kaonic hydrogen and kaonic deuterium. The aim is to extract the isospin dependent antikaon-nucleon scattering lengths and to contribute to the understanding of aspects of chiral symmetry breaking in the strangeness sector.

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1 The SIDDHARTA scientific case

The precision measurements of kaonic atoms at the DAΦNE accelerator [1] of the LNF-INFN Laboratories are going to be performed in the framework of the SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research by timing Application) international collaboration [2]. The SIDDHARTA experiment will continue, deepen and enlarge the successful scientific line, initiated by the DEAR experiment [3], 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, first 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 (from the decays of ϕ s, 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 ex-

cited orbit. Via different cascade processes (Auger effect, Coulomb deexcitation, scattering, electromagnetic transitions) 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 for a finite lifetime of the state, due to nuclear absorption of the kaon.

For kaonic hydrogen and deuterium the K-series transitions are of primary 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} :

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

This expression is known as the Deser-Trueman formula [4]. A similar relation applies to the case of kaonic deuterium and to its corresponding scattering length, a_{K-d} .

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

$$a_{K-p} = 1/2(a_0 + a_1); \quad a_{K-n} = a_1 \quad (2)$$

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 requires solving the three-body Faddeev equations by the use of potentials, taking into account the coupling among the multichannel interactions.

An accurate determination of the K^-N isospin dependent scattering lengths will place strong constraints on the low-energy K-N dynamics, which in turn constrains the SU(3) description of chiral symmetry breaking [5].

In 2002, the DEAR experiment performed the most precise measurement to date of kaonic hydrogen X-ray transitions to the 1s level [9]:

$$\epsilon = -193 \pm 37(stat.) \pm 6(syst.) eV \quad (3)$$

$$\Gamma = 249 \pm 111(stat.) \pm 30(syst.) eV \quad (4)$$

This measurement has triggered new interest from the theoretical groups working in the low-energy kaon-nucleon interaction field, and as well it is related to non-perturbative QCD tests [6–8].

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 also considered in the scientific program.

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. To significantly improve this ratio, a breakthrough is necessary. An accurate study of the background sources present at DAΦNE was redone. The background includes two main sources:

- synchronous background: coming together with the kaons – related to K^- interactions in the setup materials and also to the ϕ -decay processes; it can be defined as hadronic background;

- asynchronous background: final products of electromagnetic showers in the machine pipe and in the setup materials originating from 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 a kaon entering into the target would cut the main part of the asynchronous background.

X rays were detected by DEAR using CCDs (Charge-Coupled Devices) [10], which are 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 $1\mu s$), was implemented. This new detector is a large area Silicon Drift Detector (SDD), specially designed for spectroscopic application. The development of the new 1 cm² SDD device is partially performed under the Joint Research Activity JRA10 of the I3 project "Study of strongly interacting matter (HadronPhysics)" within FP6 of the EU.

The trigger in SIDDHARTA will be given by a system of scintillators which will recognize a kaon entering the target making use of the back-to-back production mechanism of the charged kaons at DAΦNE from ϕ decay.

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 these tests were very encouraging: a trigger rejection factor of 5×10^{-5} was measured. Extrapolated to SIDDHARTA conditions, this number translates for the kaonic hydrogen measurement into a S/B ratio in the region of interest of about 20/1. By triggering the SDDs, the asynchronous e.m. background (mainly due to the Touschek effect) can therefore be eliminated. Taking into account the synchronous background contribution, we can estimate a total S/B ratio of about 4/1.

The SDD production, with 3 SDD cells, each of 1 cm² area, monolithically integrated on one chip, is finished, in the 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 (by using a 1 mV stabilized power supply developed in the framework of SIDDHARTA).

The SIDDHARTA setup will contain about 200 SDD chips of 1 cm² each, placed around a cylindrical target, containing high density gaseous hydrogen (deuterium). The setup will be installed above the beam pipe. The various elements of the SIDDHARTA setup are under production and testing, such as to be ready to install at DAΦNE to start taking data in autumn 2007.

The kaonic hydrogen simulated spectrum obtainable from about 300 pb⁻¹ of integrated luminosity in SIDDHARTA, with a signal/background ratio of about 4/1 is shown in Fig. 3.

With such a spectrum, a precision at the level of an eV for kaonic hydrogen is reachable.

3 Conclusions

DAΦNE has unique features as a kaon source which is intrinsically clean and of low momentum – a situation unattainable with fixed target machines – especially suitable for kaonic atom research.

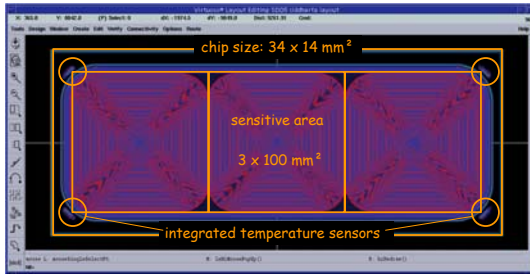


Fig. 1. SDD layout on the readout side: 3 SDD cells, read independently, each of 1 cm^2 area, monolithically integrated on one chip.

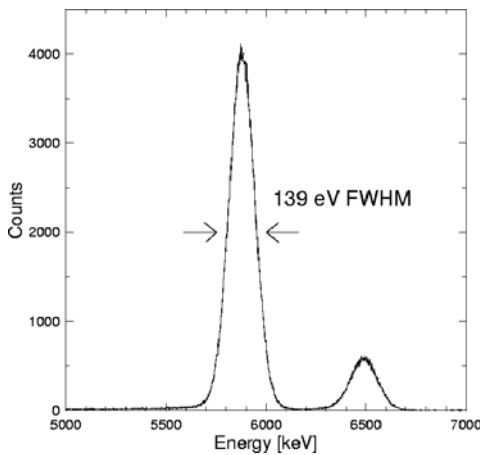


Fig. 2. The X-ray spectrum from an Iron source as measured in the laboratory with an SDD chip prototype.

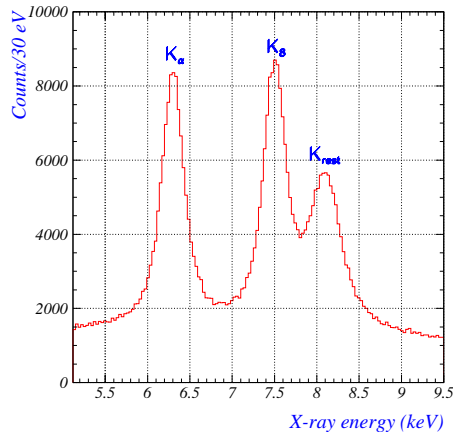


Fig. 3. The kaonic hydrogen Monte Carlo simulated spectrum for about 300 pb^{-1} of integrated luminosity in SIDDHARTA and a signal/background ratio equal to 4:1.

The DEAR/SIDDHARTA experiments combine the newly available techniques with the good kaon beam quality to initiate a renaissance in the investigation of the low-energy kaon-nucleon interaction.

DEAR has performed the most precise measurement of kaonic hydrogen; the eV precision measurement of the strong interaction shift and width of the fundamental level in kaonic hydrogen will be performed by SIDDHARTA. The first measurement of kaonic deuterium is also planned. These results will open new windows in the study of the kaon-nucleon interaction, in particular chiral symmetry breaking in the strangeness sector, via the determination of the kaon nucleon sigma terms.

The measurement of kaonic helium, feasible in SIDDHARTA, allows study of the behaviour of the subthreshold resonance $\Lambda(1405)$ in nuclear matter. Other light kaonic atoms can be studied in SIDDHARTA as well.

DAΦNE proves to be a real and ideal “kaonic atom” factory.

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