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Kaonic atoms measurements at the DAΦNE accelerator

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Abstract The DAΦNE electron-positron collider at the Frascati National Laboratories has made available a unique "beam" of negative kaons. The SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) experiment, successor of DEAR (DAΦNE Exotic Atom Research), aims at a precision

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measurement of the strong interaction shift and width of the fundamental 1*s* level, via the measurement of the x-ray transitions to this level, for kaonic hydrogen and kaonic deuterium. The final goal is to extract the isospin dependent antikaon-nucleon scattering lengths which contribute to the understanding of aspects of non-perturbative QCD in the strangeness sector. Other possible hadronic atoms measurements at DAΦNE are under study.

Keywords Kaonic atoms · X-ray transitions · Antikaon-nucleon physics

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1 The scientific case

The precision measurements of kaonic atoms at the upgraded DAΦNE accelerator [1, 2] of the LNF-INFN Laboratories are going to be performed by the SIDDHARTA international collaboration [3]. This will continue, deepen and enlarge the scientific program initiated by the DEAR experiment [4], by performing precision measurements of X-ray transitions in exotic (kaonic) atoms at DAΦNE.

The aim is a precise determination of the isospin dependent antikaon-nucleon scattering lengths, through a few-eV-precision measurement of the K_α line shift and width in kaonic hydrogen, and a first-time measurement of kaonic deuterium. The SIDDHARTA group will measure the X-ray transitions occurring in the cascade processes of kaonic atoms. A kaonic atom is formed when a negative kaon (from the decay of ϕs, 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, 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 causes 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 in a measurable way. 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 (neglecting isospin breaking corrections) to the real and imaginary part of the complex s-wave scattering length, a_{K^-p}:

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

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This expression in known as the Deser-Trueman formula [5–7]. A similar relation applies to the case of kaonic deuterium and to its corresponding scattering length, a_{K^-d}.

The observable scattering lengths a_{K^-p} and a_{K^-d} can be expressed in terms of the $\bar{K}N$ isospin dependent scattering lengths a_0 $(I = 0)$ and a_1 $(I = 1)$. The kaonic hydrogen scattering length is simply the average of the two:

$$a_{K^-p} = 1/2(a_0 + a_1) \tag{2}$$

while the kaonic deuterium scattering length a_{K^-d} is related to a_0 and a_1 in the following way:

$$a_{K^-d} = 2(\frac{m_N + m_K}{m_N + m_K/2})a^{(0)} + C \tag{3}$$

where

$$a^{(0)} = \frac{1}{2}(a_{K^-p} + a_{K^-n}) = \frac{1}{4}(3a_1 + a_0) \tag{4}$$

corresponds to the isoscalar $\bar{K}N$ scattering length. The first term in (3) represents the lowest-order impulse approximation, i.e., K^- scattering from each (free) nucleon. The second term, C, includes all higher contributions related to the physics associated to the K^-d three-body interaction.

The determination of the $\bar{K}N$ scattering lengths requires the calculation of C. This is a well-known three-body problem, solvable by the use of Faddeev equations, when the two-body interactions are specified. The K^-d three-body problem includes the complication that the K^-p and K^-n interactions involve significant inelastic channels. The K^-p and K^-n scattering lengths are thus complex and so is the K^-d scattering length. Incorporating $\bar{K}N$ scattering data and its sub-threshold behavior, the two-body potentials are determined in a coupled-channel formalism including both elastic and inelastic channels. Three-body Faddeev equations are then solved by the use of the potentials, taking into account the coupling among the multi-channel 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 [8].

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

$$\varepsilon = -193 \pm 37(stat.) \pm 6(syst.)\ eV; \quad \Gamma = 249 \pm 111(stat.) \pm 30(syst.)\ eV \tag{5}$$

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 [10–17].

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.

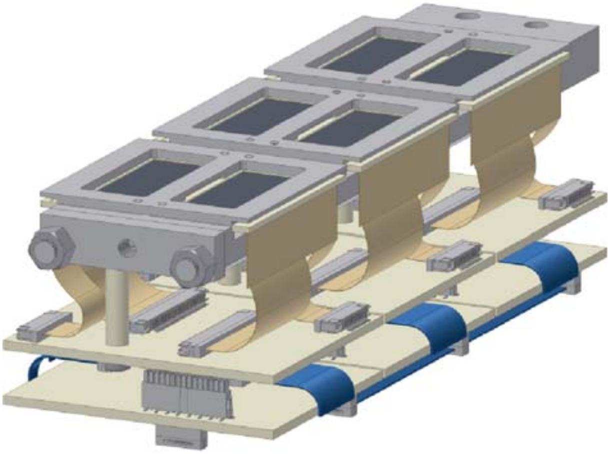

Fig. 1 An 18 cm^2 SDD unit, containing 18 SDD individual chips

2 The SIDDHARTA setup and plans

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 in DEAR using CCDs (Charge-Coupled Devices) [18], 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 the order of 10 s). Recently developed Silicon Drift Detectors (SDD), which preserve the good energy resolution, stability and linearity of CCDs, but which can be triggered with 1 μs timing, were implemented. This new detector is a large area Silicon Drift Detector (SDD), specially designed for spectroscopic application. The development of the new 1 cm^2 SDD device, with excellent spectroscopic characteristics (140 eV FWHM of resolution at 6 keV) was 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 is given by a system of scintillators which recognize a kaon entering the target by making use of the back-to-back production mechanism of the charged kaons at DAΦNE from ϕ decay of the type $\phi \rightarrow K^+K^-$.

By triggering the SDDs, the asynchronous e.m. background (mainly due to the Touschek effect) can be much reduced (orders of magnitude) with respect to DEAR.

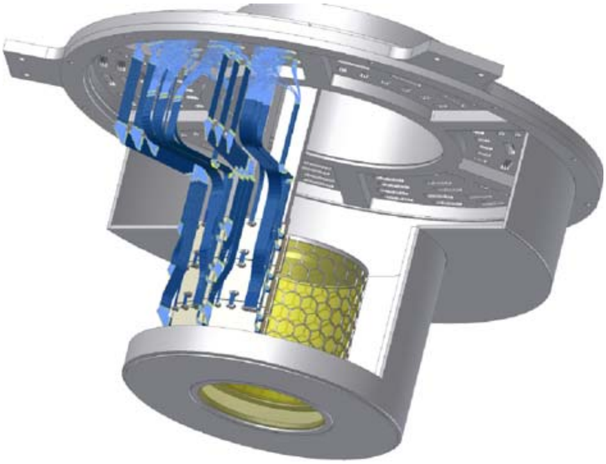

Fig. 2 The SIDDHARTA target cell surrounded by SDD units (detail)

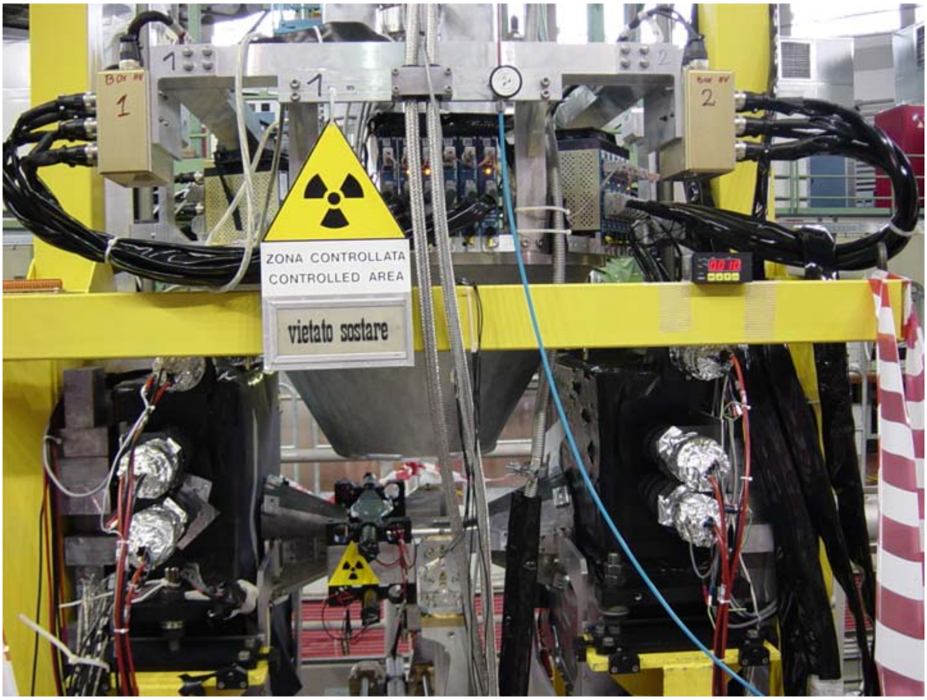

Fig. 3 The SIDDHARTA setup installed in the dedicated interaction region of DAΦNE

The SIDDHARTA setup contains about 150 SDDs. 3 single SDD detectors are integrated on one chip, which are organized in bigger units, containing 18 single SDDS, Fig. 1. These ones are positioned around a target made of kapton, 75μm thick, reinforced with an aluminium grid, filled with the cryogenic gas under study, as in

Fig. 2. The target and SDDs, together with part of readout electronics, are contained in a vacuum chamber.

The SIDDHARTA setup was built, assembled and tested in the period 2003–2007. It was installed on DAΦNE in early September 2008, - just above the Interaction Point - as shown in Fig. 3.

Presently, the SIDDHARTA setup is in debug phase, being ready to start the dedicated data taking in early 2009, with the plan to collect 400 pb^{-1} of integrated luminosity for the kaonic hydrogen, in order to perform a < 10 eV precision measurement on the position of the $1s$ level and about 600 pb^{-1} for the first measurement of kaonic deuterium.

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.

The SIDDHARTA experiment combines recent techniques in the use of large area triggerable SDD detectors with the good kaon beam quality of DAΦNE to initiate a renaissance in the investigation of the low-energy kaon-nucleon interaction.

The DEAR group performed the most precise measurement of kaonic hydrogen to date and the SIDDHARTA group plans to reach eV precision in the measurement of both the strong interaction shift and the width of the $1s$ level to be followed by the first attempted kaonic deuterium measurement. These results will open new windows in the study of the kaon-nucleon interaction.

The measurement of kaonic ^{3}He and ^{4}He, feasible in SIDDHARTA, allows study of the behaviour of the subthreshold resonance $\Lambda(1405)$ in nuclei. Other light kaonic atoms can also be studied in SIDDHARTA.

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

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