The SIDDHARTA experiment 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-rays transitions to this level, for kaonic hydrogen and kaonic deuterium. The final aim is to extract the isospin dependent antikaon-nucleon scattering lengths which contribute to the understanding of aspects of chiral symmetry breaking in the strangeness sector. Other kaonic atoms transition measurements possible at DAΦNE are under study.

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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 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 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 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, see Figure 1.

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}:

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

This expression in known as the Deser-Trueman formula [4]. A similar relation applies to the case of kaonic deu-

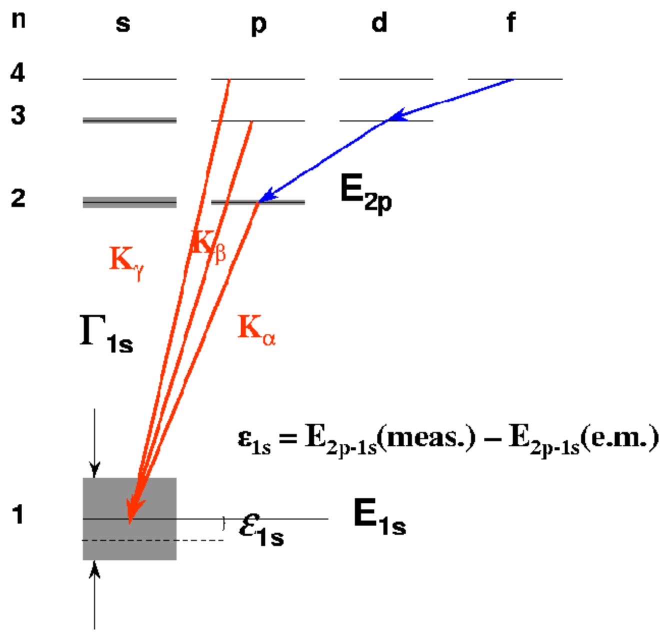

Fig. 1. The cascade process in kaonic atoms with the shift and the broadening of the 1s level, with respect to the purely electromagnetic calculated value, due to the presence of the strong interaction.

terium and to its corresponding scattering length, a_{K^-d}:

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

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:

$$a_{K^-p} = 1/2(a_0 + a_1) \tag{3}$$

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

$$a_{K^-d} = 2\left(\frac{m_N + m_K}{m_N + m_K/2}\right)a^{(0)} + C \tag{4}$$

where

$$a^{(0)} = \frac{1}{2}(a_{K^-p} + a_{K^-n}) = \frac{1}{4}(3a_1 + a_0) \tag{5}$$

corresponds to the isoscalar $\bar{K}N$ scattering length. The first term in eq. (4) 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 [5].

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

$$\epsilon = -193 \pm 37(stat.) \pm 6(syst.)\ eV \tag{6}$$

$$\Gamma = 249 \pm 111(stat.) \pm 30(syst.)\ eV \tag{7}$$

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 [7–9].

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 DA*Φ*NE. 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 DA*Φ*NE 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 DA*Φ*NE 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 (≈ 140 eV

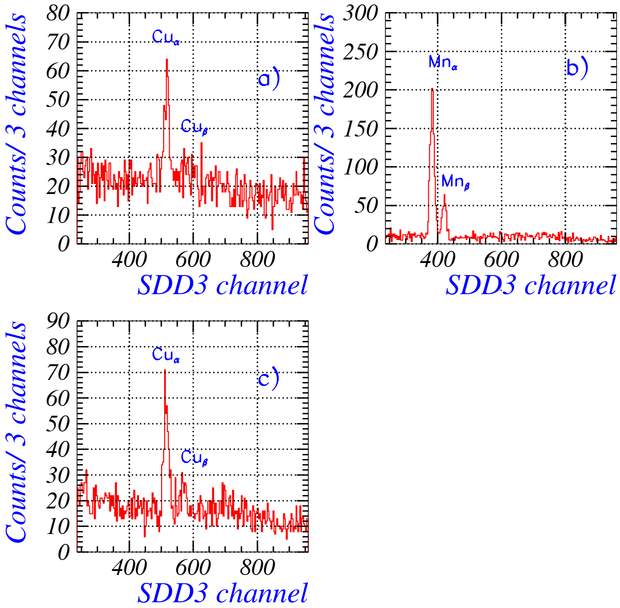

Fig. 2. a) No trigger, only BTF signal which excites the Cu-line, 5 Hz rate - 16 hours of DAQ; b) No trigger, 60 Hz, BTF signal (Cu) covered by Sr plus Fe radioactive sources as asynchronous background - 20 minutes DAQ; c) same as b) but trigger on, 5Hz as in a) - 16 hours of DAQ.

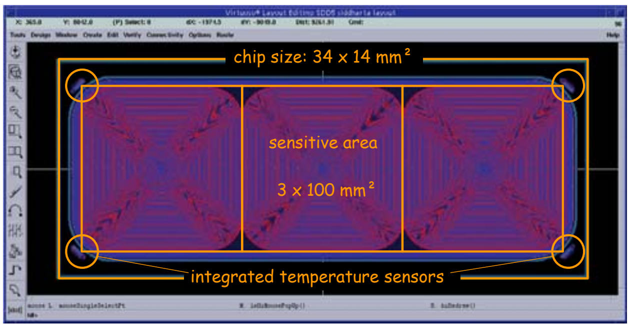

Fig. 3. SDD layout on the readout side: 3 SDD cells, read independently, each of 1 cm^2 area, monolithically integrated on one chip.

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 a large area Silicon Drift Detector (SDD), specially designed for spectroscopic application. The development of the new 1 cm^2 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: of the type:

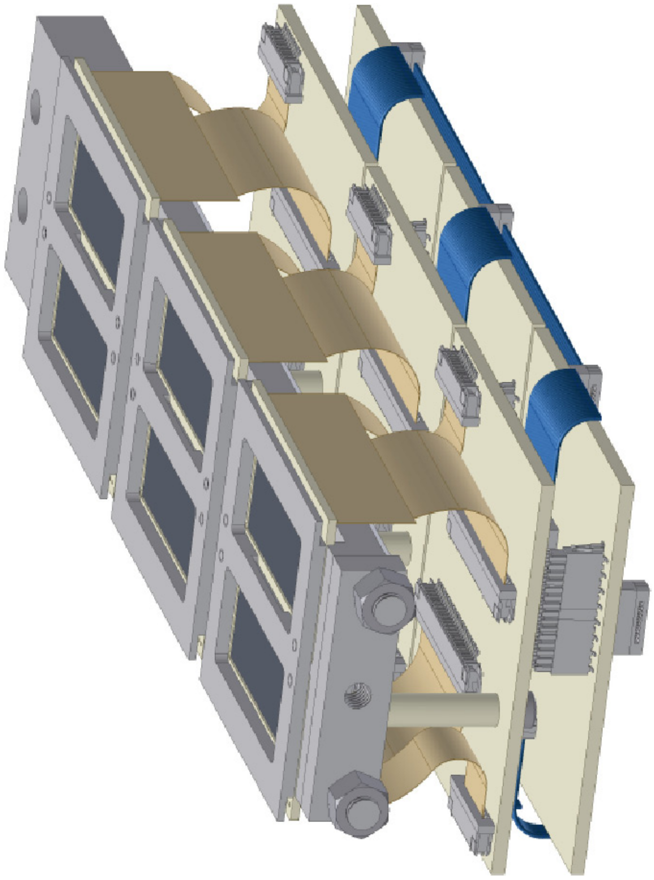

Fig. 4. An 18 cm^2 SDD unit, containing 18 SDD individual chips.

$$\phi \rightarrow K^+K^-. \qquad (8)$$

Successful tests of SDD prototypes were performed in 2003 and 2004 at the Beam Test Facility of Frascati (BTF), with a prototype SDDs array: 7 chips of 5mm^2 each. A trigger was implemented and tested with a time window of 1μs. A synchronous (with BTF beam) as well as an asynchronous background (Fe and Sr sources) were implemented and it was checked that the rejection factor is in agreement with what is expected in realistic (i.e. DEAR-like) conditions. The results of these tests were very encouraging: a trigger rejection factor of 5 x 10^{-5} was measured, see Figure 2.

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.

Presently the SDDs are under test. The first results show a very good experimental resolution, Figure 5, and a stability of the order of 2-3 eV at 6 keV (by using a

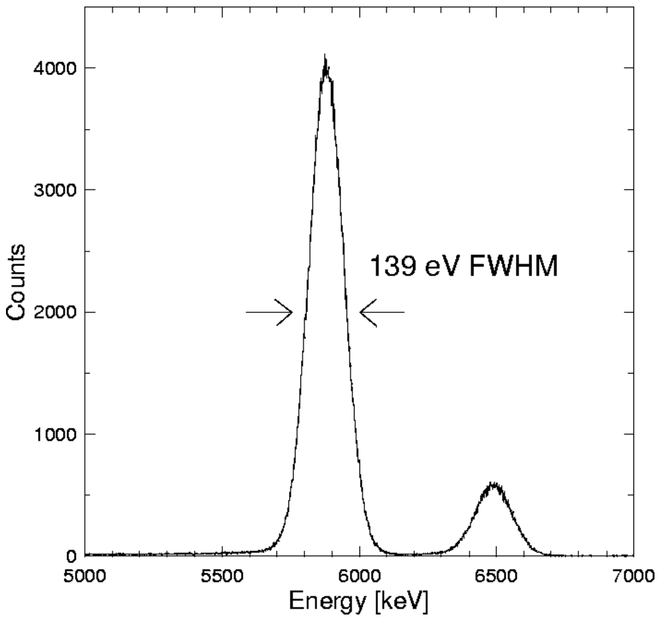

Fig. 5. The X-ray spectrum from an Iron source as measured in the laboratory with an SDD chip prototype. Te experimental resolution, FWHM (Full Width Half Maximum) at 5.9 keV is 139 eV.

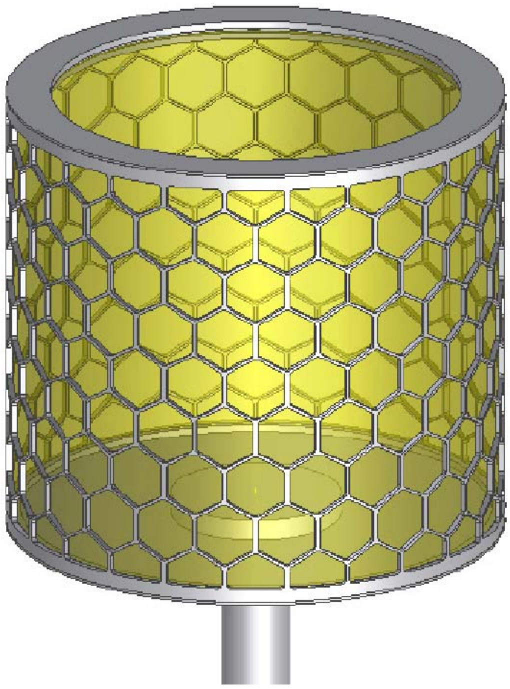

Fig. 6. The SIDDHARTA target cell, done in kapton, reinforced with an aluminium grid. It will contain about 3 liters of cryogenic and high density hydrogen (deuterium) gas.

1 mV stabilized power supply developed in the framework of SIDDHARTA).

The SIDDHARTA setup will contain about 200 SDD chips of 1 cm^2 each, placed around a cylindrical target, containing high density cryogrenic gaseous hydrogen (deuterium). The target is going to be made of kapton, 75μm thick, reinforced with aluminium grid, see Figure 6.

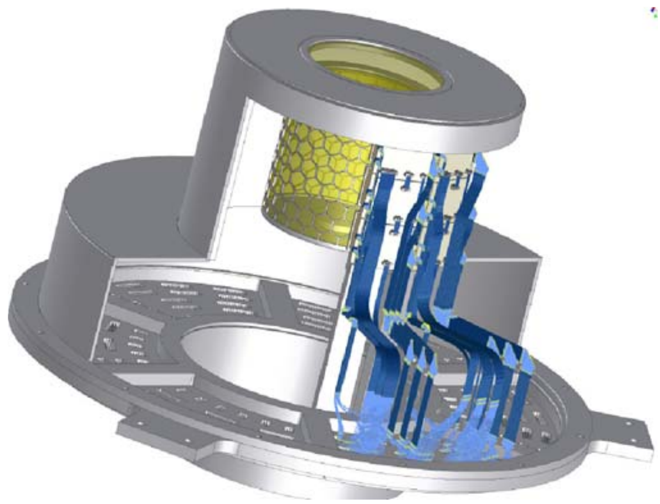

Fig. 7. The SIDDHARTA target cell surrounded by SDD units (detail).

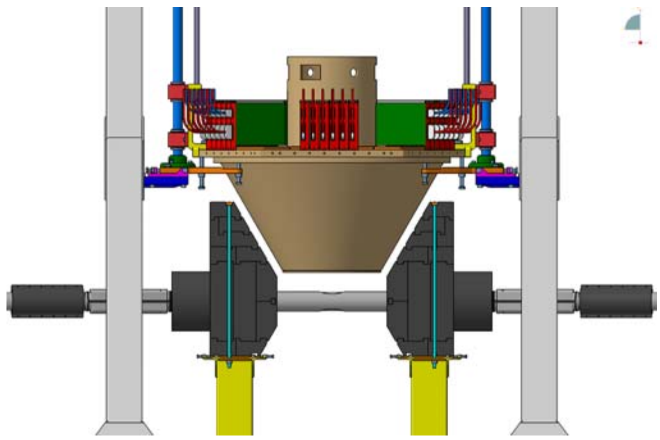

Fig. 8. The schematic drawing of the SIDDHARTA setup in the Interaction Region of DA*Φ*NE.

12 SDD 18 cm^2 units will be placed all around the target cell, as shown in Figure 7.

The setup will be installed above the beam pipe; in Figure 8 there is a drawing of the final setup in the DA*Φ*NE interaction region.

Lead shielding, proved to be efficient in the background reduction in DEAR, will be installed in the Interaction Region as well.

The various elements of the SIDDHARTA setup are under production and testing, such as to be ready to install at DA*Φ*NE to start taking data in autumn 2007.

3 Monte Carlo simultions

A Monte Carlo simulation of the SIDDHARYTA setup was developed in the framework of the GEANT simulation package (version 3.21).

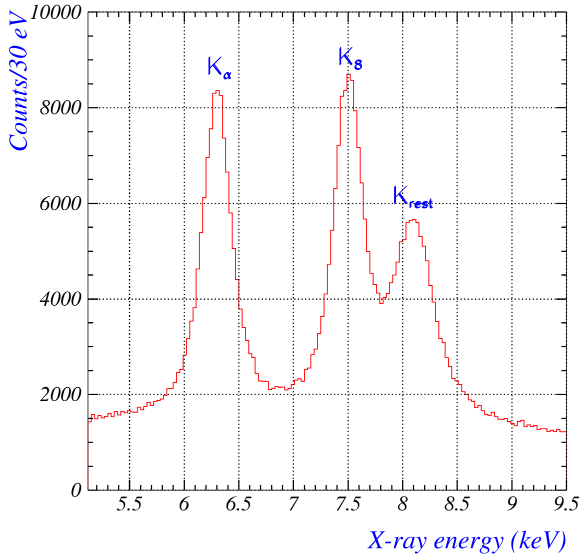

Fig. 9. The kaonic hydrogen Monte Carlo simulated spectrum for about 300 pb^{-1} of integrated luminosity in SIDDHARTA and a signal/background ratio equal to 4:1.

The 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. 9.

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

Further Monte Carlo studies, especially oriented to the machine background simulation, are undergoing.

4 Conclusions

DA*Φ*NE 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 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 nuclei. Other light kaonic atoms can be studied in SIDDHARTA as well.

The precision measurement of the charged kaon mass by using kaonic nitrogen transitions, proved to be possible by DEAR [11] is as well under study.

DA*Φ*NE proves to be a real and ideal “kaonic atom” factory.

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