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MEASUREMENT OF KAONIC ATOMS AT DAΦNE

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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 1*s* level, via the measurement of the x-ray 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.

Key words: kaonic atoms, X-ray transitions, scattering lengths, low-energy QCD.

1. INTRODUCTION

The DAΦNE [1] electron-positron collider at the Frascati National Laboratories has made available a unique "beam" of negative kaons providing so unprecedented conditions for the study of the low-energy kaon-nucleon interaction, a field still largely unexplored.

The DEAR (DAΦNE Exotic Atom Research) experiment [2] at DAΦNE and its successor SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) [3] aim at a precision measurement of the strong interaction shifts and widths 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 and to contribute to the understanding of aspects of chiral symmetry breaking in the strangeness sector.

In practice, in studying kaonic hydrogen (deuterium) in order to measure the strong interaction component of the kaon-nucleon force, one measures the shift ε

of the position of the K_α line ($2p \to 1s$ transition) from the one calculated from a purely electromagnetic interaction:

$$\epsilon = | E_{2p\to 1s}^{measured} | - | E_{2p\to 1s}^{e.m.} | \quad (1)$$

and the width (broadening) Γ of the $1s$ level given by the strong interaction, see Fig. 1.

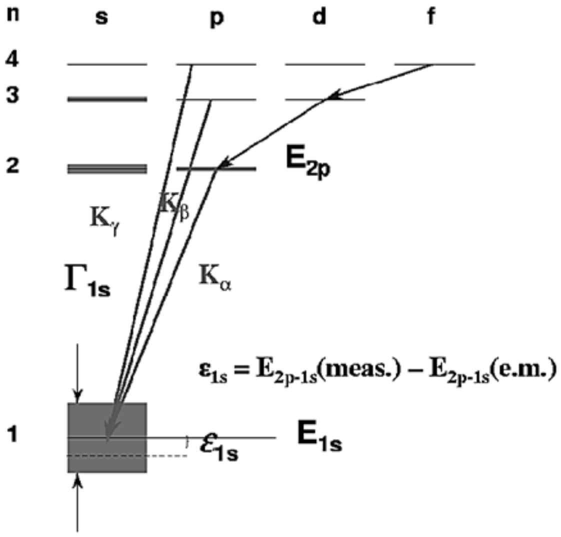

Fig. 1 – The cascade process in kaonic atoms with the shift and the broadening of the $1s$ level, with respect to the purely electromagnetic calculated value, due to the presence of the strong interaction.

The electromagnetic transition energy in kaonic hydrogen is calculated with 1 eV precision by solving the corresponding Klein-Gordon equation and applying the corrections for finite size and vacuum polarization. The resulting value is:

$$E_{2p\to 1s}^{e.m.} = (6480 \pm 1)\ \text{eV} \quad (2)$$

where the 1 eV error is dominated by the uncertainty of the kaon mass.

Until the advent of DAΦNE, the kaonic hydrogen parameters were measured at KEK [4], where the following results were found:

$$\epsilon = -323 \pm 63 \pm 11\ \text{eV} \quad (3)$$

$$\Gamma = 407 \pm 208 \pm 100\ \text{eV} \quad (4)$$

This measurement showed clearly that the antikaon-nucleon interaction is of repulsive type, but cannot be considered a precision measurement. The challenging aim of the DEAR/SIDDHARTA experiment is, therefore, to measure the kaonic hydrogen transition with a precision at the eV level. The kaonic deuterium will be measured for the first time. These results will represent a breakthrough in the study of the low-energy antikaon-nucleon interaction.

In Section 2, the physics of kaonic atoms is dealt with. The DEAR experimental setup installed at DAΦNE is presented in Section 3, while DEAR experimental results on kaonic atoms are reported in Section 4. The paper ends with the presentation of the coming experiment, SIDDHARTA, in Section 5, followed by Section 6 – Conclusions.

2. THE PHYSICS OF KAONIC ATOMS

A kaonic atom is formed whenever a negative kaon enters an atomic target, for instance hydrogen (deuterium), looses its kinetic energy through ionization and excitations of the medium atoms and molecules and is eventually captured in an excited orbit, replacing an electron. Various collisional cascade processes and radiative transitions deexcite the kaonic atom.

When the kaon reaches low-n states with small angular momentum, it is absorbed through the strong interaction with the nucleus. This strong interaction causes a shift in the energies of the low-lying levels (essentially the $1s$ level) from their purely electromagnetic values, while the finite lifetime of the state is seen in an increase in the observed level width.

The shift ϵ and the width Γ of the $1s$ state of kaonic hydrogen are related to the real and imaginary part of the complex s-wave scattering length, a_{K^-p}. To the lowest order, neglecting isospin-breaking corrections, in the case of kaonic hydrogen these relations are given by the so-called Deser-Trueman formula [5]:

$$\epsilon + i\Gamma/2 = 2\alpha^3\mu^2 a_{K^-p} = (412\ eV\ fm^{-1}) \cdot a_{K^-p} \tag{5}$$

where α is the fine structure constant and μ the reduced mass of the K^-p system.

A similar relation applies to the case of kaonic deuterium and to the corresponding scattering length a_{K^-d}:

$$\epsilon + i\Gamma/2 = 2\alpha^3\mu^2 a_{K^-d} = (601\ eV\ fm^{-1}) \cdot a_{K^-d} \tag{6}$$

Recent results by using the non-relativistic effective Lagrangian approach to bound states have shown that the isospin-breaking corrections to the Deser relations might be important [6]. The main source is represented by the unitary cusp in the K^-p elastic amplitude. As far as Coulomb corrections are concerned, they are much smaller, remaining within a few percent.

Further investigations using effective field theories or lattice calculations to predict QCD amplitudes and compare with data from atomic spectra are needed [6, 7].

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:

$$a_{K^-p} = 1/2(a_0 + a_1) \tag{7}$$

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

$$a_{K^-d} = 2\left(\frac{m_N + m_K}{m_N + m_K/2}\right)a^{(0)} + C \tag{8}$$

where

$$a^{(0)} = \frac{1}{2}(a_{K^-p} + a_{K^-n}) = \frac{1}{4}(3a_1 + a_0) \tag{9}$$

corresponds to the isoscalar $\bar{K}N$ scattering length. The first term in eq. (8) 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].

3. THE DEAR SETUP ON DAΦNE

The principle of the DEAR experiment is straightforward: low momentum negative kaons produced in the decay of the ϕ-mesons at DAΦNE leave the thin-wall beam pipe, are degraded in energy to a few MeV, enter a gaseous target through a thin window and are finally stopped in the gas. The stopped kaons are captured in an outer orbit of the gaseous atoms, thus forming the exotic kaonic atoms. The kaons cascade down and some of them will reach the ground state emitting X rays. The energy of the X rays emitted in these transitions is measured with a CCD (Charge-Coupled Device) detector system [9].

Fig. 2 shows a schematic of the DEAR experimental setup. The cylindrical cryogenic target cell had a diameter of 12.5 cm and a height of 14 cm. Special care was taken to avoid materials with fluorescence X rays in the region of the kaonic atoms transitions. Therefore, a light target was chosen, made only of aluminium (top-plate and entrance ring), kapton (side wall and entrance window) and a support structure in fiberglass.

Two measurements were performed: tha kaonic nitrogen and kaonic hydrogen ones – results of which will be presented in next Section. The target was operated:

- for kaonic nitrogen at 1.5 bar and 120 K, corresponding to a density of $\rho = 3.4\rho_{NTP}$;
- for kaonic hydrogen at 2 bar and 25 K, corresponding to a density of 2.1 g/l.

16 CCD detector chips (Marconi Applied Technologies, CCD55-30) with a total area of 116 cm^2 were placed around the cryogenic target cell. Each chip has 1242 × 1152 pixels with a pixel size of 22.5 μm × 22.5 μm and a depletion depth of about 30 μm. The working temperature was stabilized at 165 K to achieve the energy resolution of 150 eV at 6 keV with a readout every 90 seconds. The CCD front-end electronics and controls, and the data acquisition system, were specially made for this experiment [10].

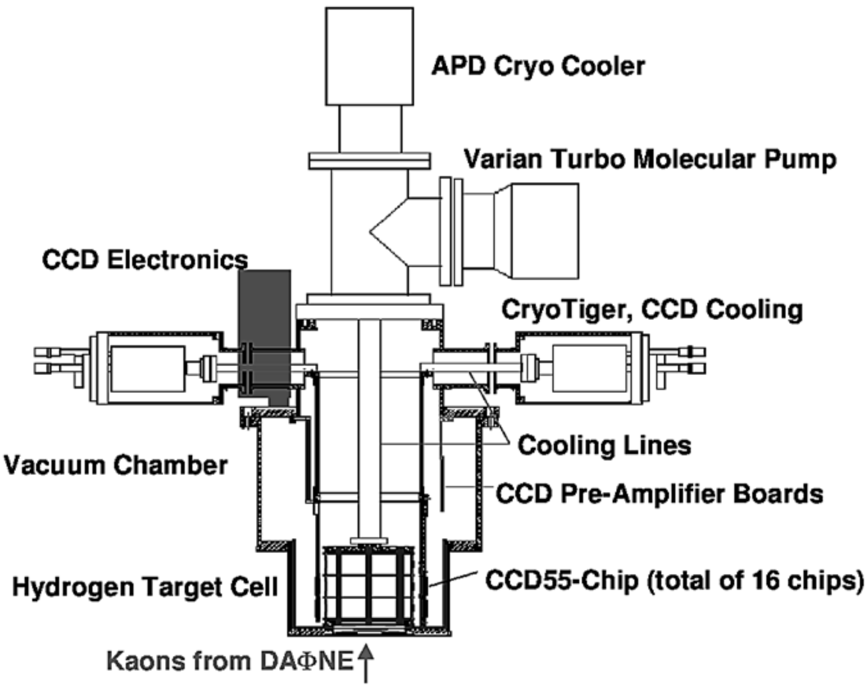

Fig. 2 – Schematic representation of the DEAR setup.

4. EXPERIMENTAL RESULTS ON KAONIC ATOMS

The DEAR experiment was installed at DAΦNE at the beginning of 1999. It took data for periods of 2–3 months/year, sharing the DAΦNE beam with the KLOE experiment [11].

After a period of machine and setup optimization, with a continuous increase of luminosity and decrease of background (optics and shielding), in 2002 DEAR performed two kind of kaonic atoms measurements: the kaonic nitrogen and the kaonic hydrogen one.

In what follows, the results of these measurements are presented.

4.1. KAONIC NITROGEN RESULTS

The measurement of kaonic nitrogen had multiple tasks and deliverables:

- a feasibility study of the DEAR technique to produce and detect kaonic atoms at DAΦNE;
- study of the machine background and of the setup performance and the optimization of the signal to background ratio;
- the first measurement of kaonic nitrogen transition yields.

Understanding the atomic cascade processes in kaonic nitrogen is especially important due to the possible role of this exotic atom for a precise determination of the charged kaon mass – still an open problem [12]. Even if X-ray transitions were measured for many kaonic atoms [13] no results have been published for nitrogen, apart the preliminary DEAR ones [12].

For the kaonic nitrogen transition yields measurement, DEAR used a cryogenic and pressurized gaseous target, because the yield of kaonic nitrogen transitions in these conditions is high enough to allow a fast feedback. Data using the nitrogen target were taken for about one month (October 2002), leading to the optimization of the setup performance in terms of signal/background ratio. A total of 17.4 pb^{-1} of integrated luminosity was collected, from which 10.8 pb^{-1} taken in stable conditions were selected for the analysis of the energy spectrum.

In Fig. 3 the kaonic nitrogen spectrum after subtraction of the continuous background is shown.

Three kaonic nitrogen X-ray lines are well indentified. The $n = 6 \rightarrow 5$ kaonic nitrogen transition peak at 7.6 keV is clearly seen. The transition lines $n = 7 \rightarrow 6$ and $n = 5 \rightarrow 4$ at 4.6 and 14.0 keV are overlapped with the Ti-K_α and Sr-K_α lines, respectively.

In order to estimate the transition yields, Monte Carlo calculations which took into account the kaon stopping efficiency in the target gas, the X-ray absorption in gas and target windows and the CCD quantum efficiency, were performed.

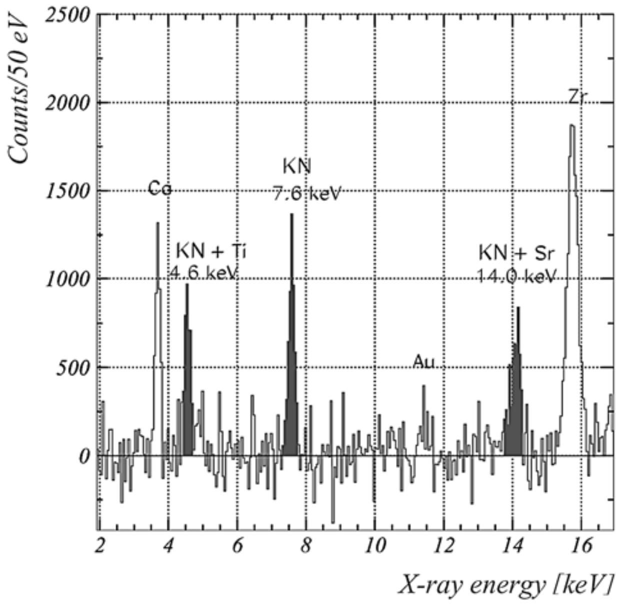

Fig. 3 – The kaonic nitrogen continuous background subtracted spectrum.

The determined yields are [14]:

1. for the $n = 7 \rightarrow 6$ transition:

$$41.5 \pm 8.7(stat.) \pm 4.1(syst.)\%; \tag{10}$$

2. for the $n = 6 \rightarrow 5$ transition:

$$55.0 \pm 3.9(stat.) \pm 5.5(syst.)\%; \tag{11}$$

3. for the $n = 5 \rightarrow 4$ transition:

$$57.4 \pm 15.2(stat.) \pm 5.7(syst.)\%. \tag{12}$$

The precision in the position of the $n = 6 \rightarrow 5$ energy transition value: 7.558 ± 0.005 keV, could be used to evaluate the charged kaon mass from the first order of the Klein-Gordon equation using a point-like nucleus, which resulted in:

$$M_{K^-} = 493.884 \pm 0.314 \text{ MeV} \tag{13}$$

which represents an improvement by one order of magnitude in precision with respect to the DEAR preliminary results [12].

4.2. KAONIC HYDROGEN RESULTS

In the period November-December 2002 the kaonic hydrogen measurement was performed – just after the kaonic nitrogen one. Data for 58.4 pb^{-1} were collected in this period. At the end of the period, a background measurement with separated electron and positron beams and intentionally high X-ray background was performed (no-collision spectrum).

Two independent analyses were performed in order to obtain the kaonic hydrogen lines from which to extract the strong interaction shift and width. In both analyses Voigt functions with Gaussians for the detector resolution were used for the kaonic hydrogen lines. Fit parameters were the intensities of K_α, K_β and K_γ, the energy of K_α and the Lorentzian width for K_α, equal for all the K-transitions, obviously.

In one of the analyses a simultaneous fit of the kaonic hydrogen and no-collision spectra was performed. The same function fitted the continuous background and the electronic peaks, apart a normalization factor. The energy region corresponding to K_{high} (higher than K_γ) was excluded from the fit, since the lines in this region could not be distinguished by the fit and no precise information exists for the relative yields. It was estimated by Monte Carlo that the systematic error introduced by this cut is at the level of the eV and was included in the final result.

Apart from kaonic hydrogen transitions, there are lines coming from the excitation of materials (electronic X-ray transitions) present in the setup. A thin Titanium foil was placed on the upper wall of the target cell for calibration purpose. Other materials – Iron, Zinc, etc. – are present in very small quantities (ppm) in the materials of the setup.

In the second analysis the kaonic hydrogen spectrum was analyzed together with a spectrum built as a sum of the kaonic nitrogen one and a subset (low CCD occupancy) of the no-collision one. A constrained fit based on the ratios of the electronic transitions in the two spectra, was then performed. The K_{high} region was dealt with analogously the first analysis. Some tests of the stability of the results and of the systematic errors were done by considering various cascade models of kaonic hydrogen transitions giving the transition yields [6].

The "pure" kaonic hydrogen spectrum with the background (continuous and structured) subtracted is shown in Fig. 4.

The weighted averages of the two analyses for the shift and width of the 1s ground state of kaonic hydrogen are [15]:

$$\epsilon = -193 \pm 37(stat.) \pm 6(syst.)\ \text{eV} \tag{14}$$

$$\Gamma = 249 \pm 111(stat.) \pm 39(syst.)\ \text{eV} \tag{15}$$

These results confirm the KEK values and the repulsive character of the K^-p interaction at threshold. They differ however significantly from the KEK results (eq. (3) and (4)) in two aspects: the errors are a factor 2–3 smaller; moreover, DEAR was able, for the first time, to obtain a full pattern of the K-series lines of kaonic hydrogen: K_α, K_β and K_γ were clearly identified with an overall statistics significance of 6.2σ.

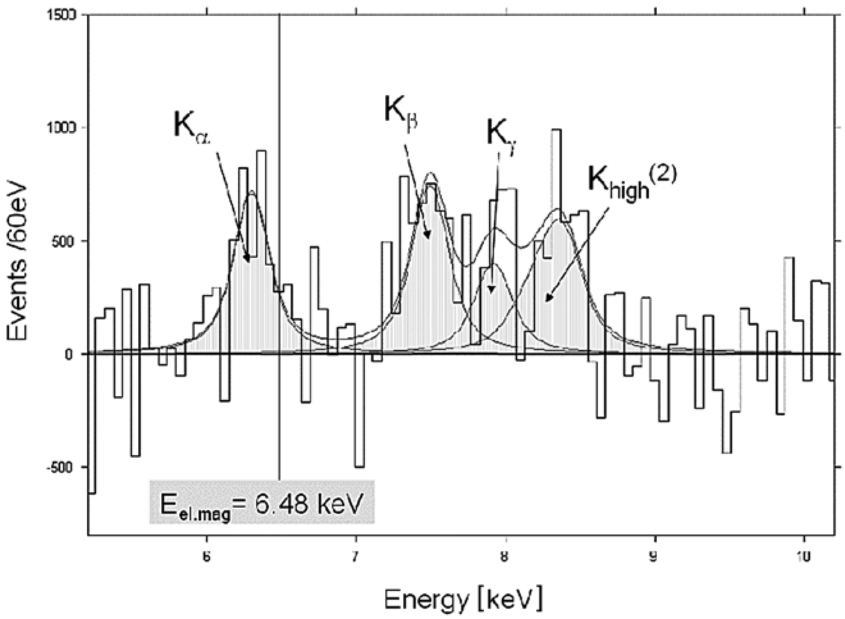

Fig. 4 – The kaonic hydrogen background (continuous and structured) subtracted spectrum.

The future experiment, SIDDHARTA, plans to improve by one order of magnitude the precision in kaonic hydrogen and to perform the first measurement of kaonic deuterium transitions.

5. THE SIDDHARTA EXPERIMENT

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), 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 μs), 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:

$$\phi \rightarrow K^+ K^- . \tag{16}$$

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 1 μs. 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 5×10^{-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 SIDDHARTA setup will contain 216 SDD chips of 1 cm^2 each, grouped in chips containing 3 SDDs (Fig. 5), organized in units containing 18 cm^2 SDDs (Fig. 6). The SDDs are placed around a cylindrical target, containing high density cryogrenic gaseous hydrogen (deuterium). The target is going to be made of kapton, 75 μm thick, reinforced with aluminium grid.

SDDs together with the readout electronics were intensively tested. The tests shown a very good experimental resolution, Fig. 7, 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).

12 SDD 18 cm^2 units will be placed all around the target cell, as shown in Fig. 8.

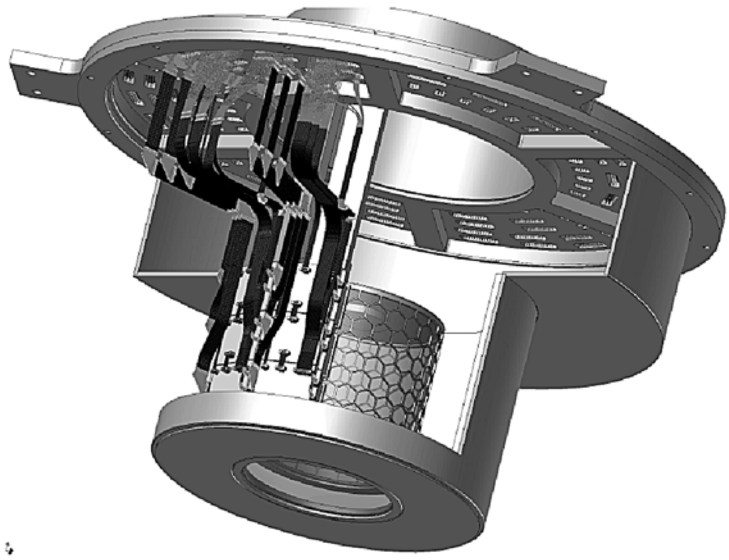

Fig. 8 – The SIDDHARTA target cell surrounded by SDD units (detail).

The setup will be installed above the beam pipe; in Fig. 9 there is a drawing of the final setup in the DAΦNE interaction region.

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

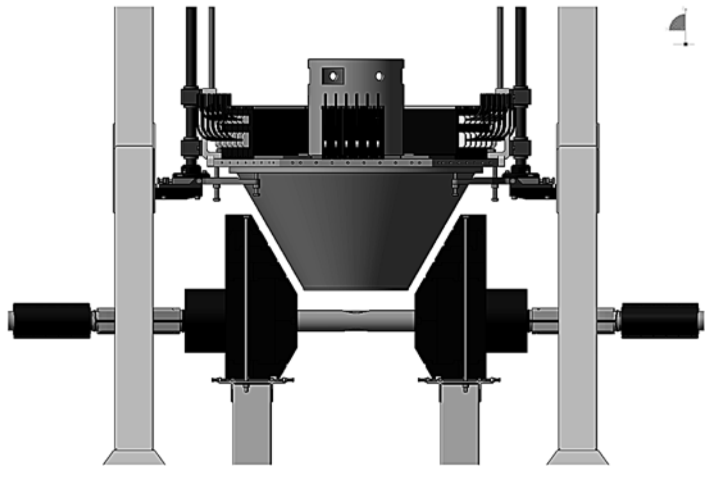

Fig. 9 – The schematic drawing of the SIDDHARTA setup in the Interaction Region of DAΦNE.

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.

6. 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 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 Λ(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, is as well under study.

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

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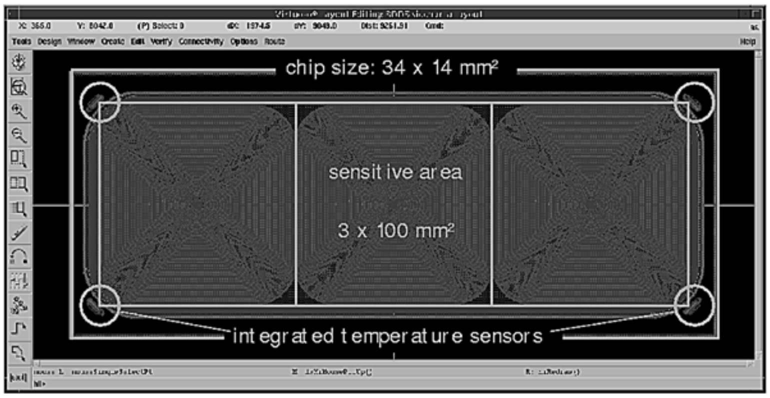

Fig. 5 – SDD layout on the readout side: 3 SDD cells, read independently, each of 1 cm² area, monolithically integrated on one chip.

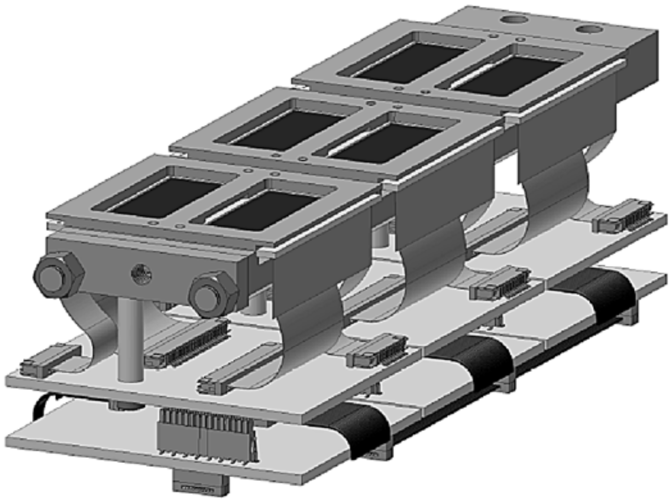

Fig. 6 – An 18 cm² SDD unit, containing 18 SDD individual chips.

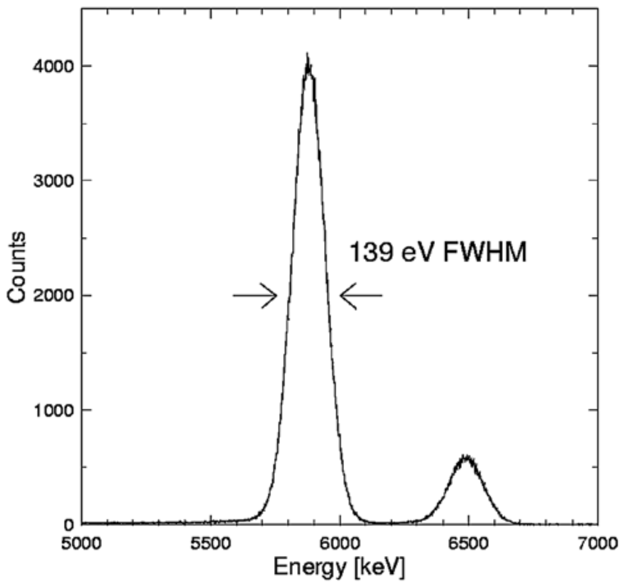

Fig. 7 – The X-ray spectrum from an Iron source as measured in the laboratory with an SDD chip prototype. Te experimental resolution, FWHM (Full Width Half Maximum) at 5.9 keV is 139 eV.