DEAR and SIDDHARTA: present and future precision measurements on kaonic hydrogen and kaonic deuterium

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On behalf on the DEAR/SIDDHARTA Collaborations

1. DEAR / SIDDHARTA scientific program

DEAR (DAΦNE Exotic Atom Research) is one of the first experiments which was installed at the DAΦNE ϕ-factory at the Laboratori Nazionali di Frascati dell'INFN [1]. After the optimization of the setup and of the machine optics, in 2002 DEAR performed the kaonic hydrogen measurement. The results of the analysis of this data set are reported in the present paper, together with the future plans, namely the SIDDHARTA (Silicon Drift Detector for Hadronic Atoms Research by Timing Application) experiment. The objective of DEAR/SIDDHARTA is a precise determination of the isospin dependent antikaon-nucleon scattering lengths, through a percent level 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.

DEAR/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 as 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} :

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

This expression in 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} :

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

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

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

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 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 [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].

2. The DEAR setup at DAΦNE

DEAR uses a pressurized cryogenic target (23 K and 1.82 bar) built in kapton, with fiber glass reinforcement, for the kaonic hydrogen measurement, in order to optimize the number of kaons stopped in the target, and, in the same time, not to have a reduction of the signal due to the Stark effect. The X-ray detector system consists of 16 CCDs.

The setup was installed in one of the two interaction regions of DAΦNE, and had periods of data taking starting from December 1999, when first collisions were achieved.

The first periods of data taking were dedicated to background understanding and reduction, by the use of appropriate shielding and machine optics solutions. This period was followed by a measurement of the first exotic atom at DAΦNE, namely the kaonic nitrogen, in May 2001 [6].In October 2002 the kaonic nitrogen was remeasured, just before the kaonic hydrogen measurement which was performed in the November – December 2002.

The results of these measurements are reported below.

3. Kaonic nitrogen results

The measurement of kaonic nitrogen had the following objectives:

- to prove the feasibility of the DEAR method to produce and detect exotic atoms using the K^- beam from ϕ-decay in DAΦNE. The choice of nitrogen is dictated by the high yields of the transitions, so allowing a fast feedback;
- to optimize the kaon stopping point distribution, by learning how to finely tune the degrader, in the view of the delicate kaonic hydrogen measurement.

These objectives were achieved; the first kaonic nitrogen spectrum was measured in May 2001, the results being published in [6]. In October 2002 the kaonic nitrogen spectrum was re-measured, with the new target built completely in kapton and the degrader was optimized such as to have the signal uniformly distributed on all the 16 CCDs. The results, as a background subtracted spectrum, are shown in Fig. 2.

The spectrum shown in Fig. 2 corresponds to a statistics of about 10.5 pb^{-1} of integrated luminosity. There are 3 kaonic nitrogen lines clearly visible: the 4.6 keV (7 -> 6), the 7.6 keV (6 -> 5) and the 14.0 keV (5 -> 4) transitions. The calcium peak is coming from the fiber glass reinforcement of the target; titanium and zirconium lines are coming from calibration foils placed inside the target in the view of the calibration of the energy scale to be performed during the kaonic hydrogen measurement. The yields of the 3 previous transitions were deduced: (41.5 +/- 7.4 (stat.) +/- 4.1(sys.))% , (55.0 +/- 3.9 (stat.) +/- 5.5 (sys.))%, and (57.4 +/- 15.2 (stat.) +/- 5.7(sys.))% respectively and compared with cascade calculations.

The results have been sent to Phys. Lett. **B** and accepted for publication [7].

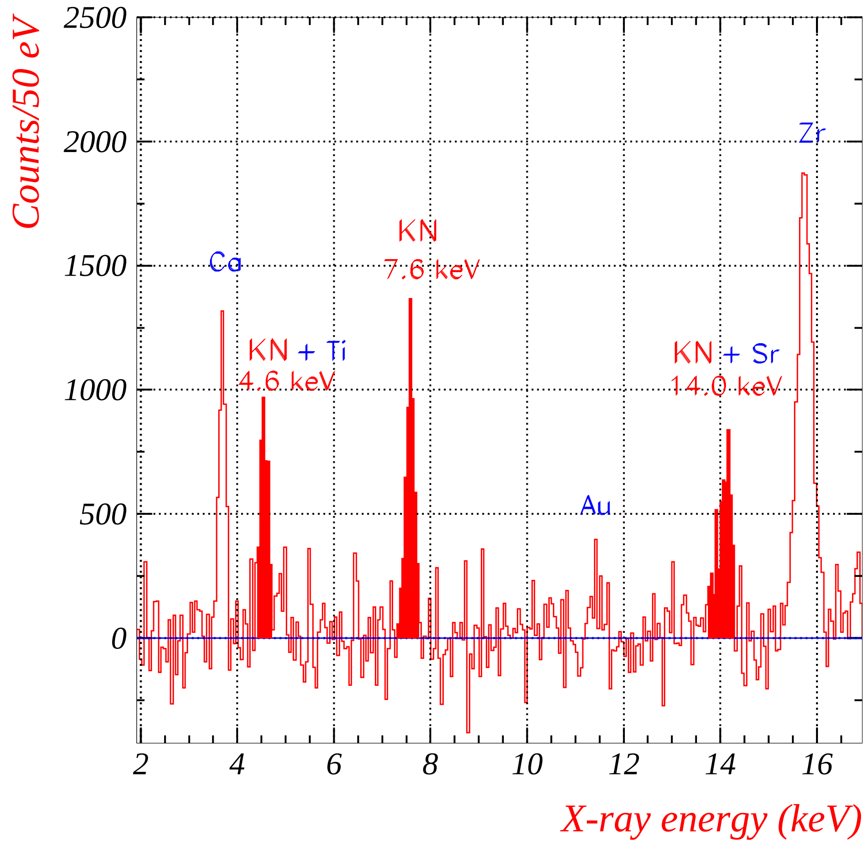

Figure2: The kaonic nitrogen (October 2002) background subtracted spectrum

4. Kaonic hydrogen results

The kaonic hydrogen data acquisition lasted from 31 October 2002 until 16 December 2002, for a total integrated luminosity of about 58 pb^{-1}. This measurement was followed, until 23 December 2002, by a pure background (no-collisions) measurement, necessary for the background subtraction. Two independent analyses were performed: a simultaneous fit of kaonic hydrogen and of background data and a constrained fit of kaonic hydrogen and the bulk of all 2002 data. The two results are in agreement and are giving a significance of kaonic hydrogen transition of about 6 σ. The preliminary shift and width values are:

$$\varepsilon = -(200 +/- 45)\ \mathrm{eV}$$

$$\Gamma = (250 +/- 137)\ \mathrm{eV}$$

where only the statistical error is reported, the systematic one being under study (much smaller, however, than the statistical one). This measurement confirms, with higher precision, the KEK results [8], so representing the most precise measurement of kaonic hydrogen performed up to now. It is as well a strong motivation for the community working on the low-energy kaon-nucleon interactions.

The kaonic hydrogen background subtracted spectrum is shown in Figure 2. The titanium line is coming from foil placed inside the target in the view of the calibration of the energy scale; the cromium, iron, zinc and gold lines are coming from materials of the setup, while the kaonic carbon transition at 5.6 keV is generated by the kaons which stop in the target wall, made of kapton.

Starting from the success of this measurement, a continuation of the scientific program on exotic atoms is foreseen, based on a happy marriage between the good-quality ``kaon-beam” delivered by DAΦNE and a setup with a cryogenic target optimizing the kaons stopping inside, equipped with good-quality X-ray detectors: the new experiment SIDDHARTA (Silicon Drift Detector for Hadronic Atoms Research by Timing Application), which represents a new step in the study of kaonic atoms at DAΦNE.

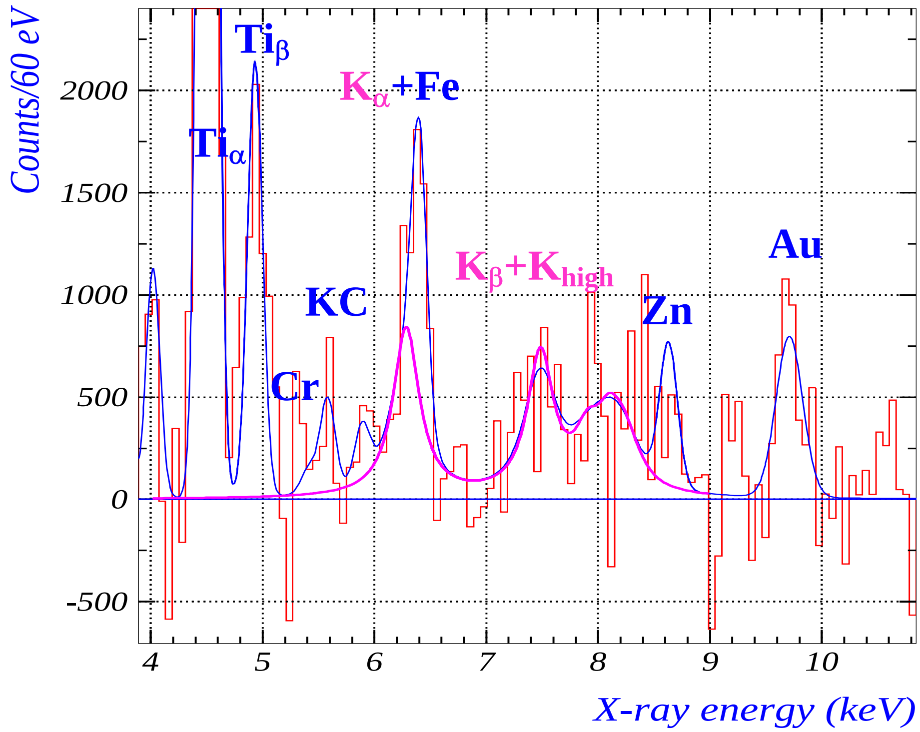

Figure2: The kaonic hydrogen background subtracted spectrum

5. Future plans or from DEAR to SIDDHARTA

As stated in the previous Section, DEAR has performed the most precise kaonic hydrogen measurement presently available. This was possible due to a continuous work, in collaboration with the DAΦNE team, of background reduction (a factor about 100).

However, the Signal/Background ratio (1/80) is not sufficient to perform an ~ eV precision measurement and there is no room left for additional shielding on one side and machine improvements on the other one.

In these conditions only a careful re-consideration of the whole setup, especially the detector, can allow to achieve important steps forward. DEAR used for the X rays detection the CCD (Charge Coupled Device) detectors, excellent X-ray detectors with good energy resolution (FWHM of ~140 eV at 6 keV), but having the drawback of being non-triggerable devices (read-out time about 10 s). A new device was then identified as X-ray detector, which preserves all good features of the CCD (energy resolution, linearity and stability) and is triggerable (at the level if about 1 μs). This new detector is the Silicon Drift Detector (SDD), specially designed for spectroscopical use.

A first test of an array of 7 SDD detectors, 5 mm^2 each, was successfully performed at the Beam Test Facility of Frascati (BTF) in July 2003, in DEAR-like conditions as far as background level is concerned, showing that a trigger rejection factor of 5×10^{-5} is achievable. Extrapolated to SIDDHARTA conditions, this number translates into a S/B ratio of about 8/1 for kaonic hydrogen, and 1/1 for kaonic deuterium.

A preliminary SIDDHARTA setup, based on a toroidal geometry, is shown in Fig. 3.

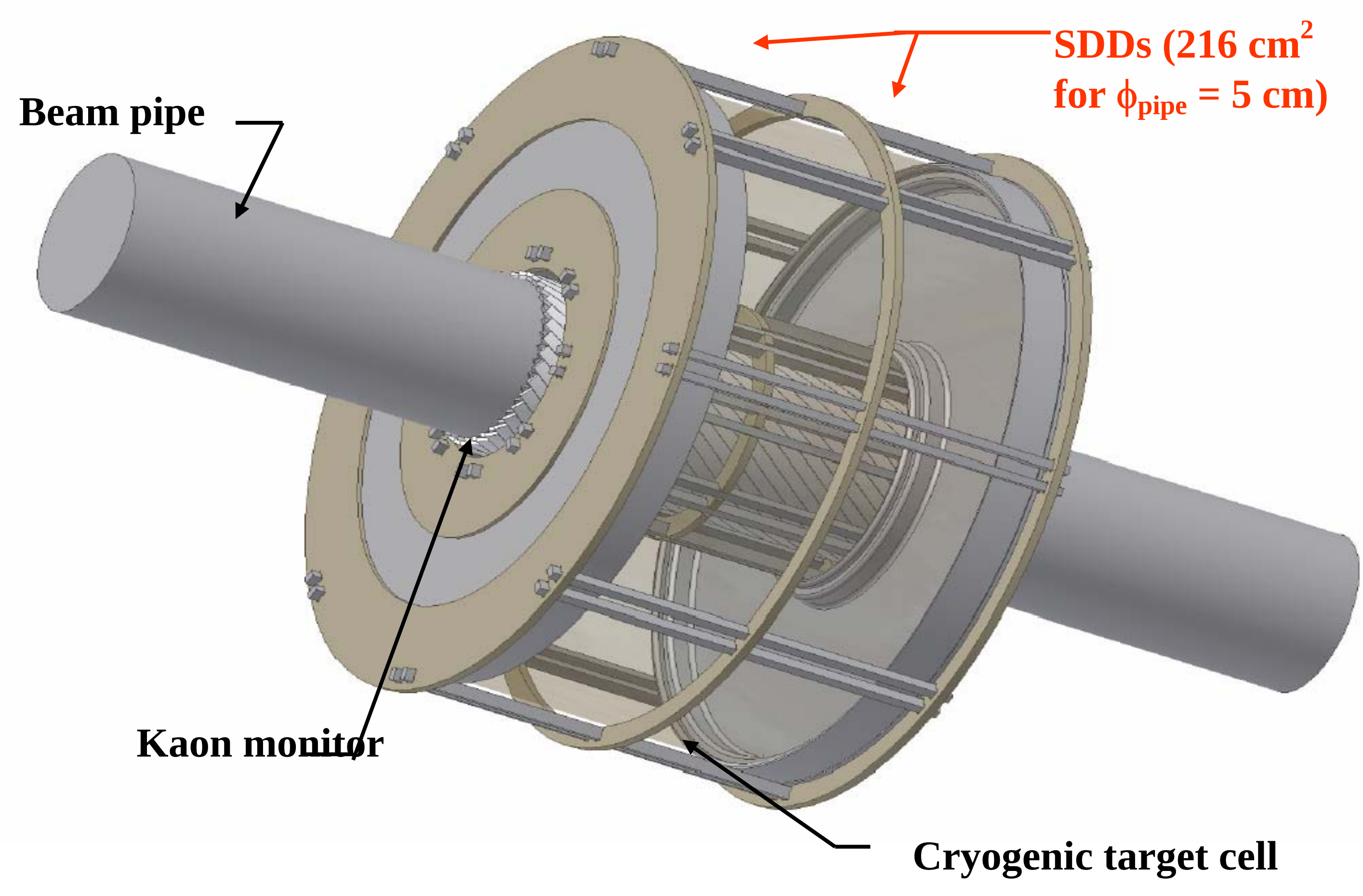

Figure3: The SIDDHARTA preliminary setup

Apart from an eV precision measurement of kaonic hydrogen and the first measurement of kaonic deuterium, due to the triggering capabilities of SDDs and to their efficiency extended of to tens of keV, SIDDHARTA is performing studies of feasibility for the following measurements:

- kaonic helium;
- other light kaonic atoms;
- measurement of other types of hadronic exotic atoms (sigmonium hydrogen);
- precision measurement of the charged kaon mass.

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