THE PHYSICS OF KAONIC ATOMS AT DAΦNE

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on behalf on the DEAR/SIDDHARTA Collaborations

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Abstract. The DEAR experiment is the biggest effort yet launched to study low-energy kaon physics. The objective of the DEAR(DAΦNE Exotic Atom Research) and the coming SIDDHARTA (Silicon Drift Detector for Hadronic Atoms Research by Timing Application) experiment is an eV precision measurement of the K_α line shift and width, due to the strong interaction, in kaonic hydrogen and a similar measurement - the first one – in kaonic deuterium. The final aim is a precision determination of the antikaon-nucleon isospin dependent scattering lengths, which allows a better understating of the chiral symmetry breaking scenario in the strangeness sector. DEAR has performed the most precise measurement up to now on gaseous kaonic nitrogen and kaonic hydrogen in 2002. It is for the first time that the K-complex could be clearly identified. An eV precision measurement of kaonic hydrogen and kaonic deuterium is foreseen in the framework of the newly started SIDDHARTA project, which continues the DEAR scientific line.

Key words: kaonic atom, charged kaon mass

1. DEAR/SIDDHARTA SCIENTIFIC PROGRAM

The study of kaonic atoms represents one of the main activities at the DAΦNE accelerator at Frascati. This kind of physics was pursued in the framework of the DEAR (DAΦNE Exotic Atom Research) experiment and will be continued by the SIDDHARTA (Silicon Drift Detector for Hadronic Atoms Research by Timing Application) experiment. DEAR is one of the first experiments which were 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 nitrogen and the kaonic hydrogen measurements. The results of the analysis of this data set are reported in the present paper, together with the future plans - the SIDDHARTA experiment.

The objective of DEAR/SIDDHARTA is a precise determination of the isospin dependent antikaon-nucleon scattering lengths, through a an eV precision 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 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} :

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

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}:

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

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

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

$$a_{K^-n} = a_1 \qquad (4)$$

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 [4].

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.

2. THE DEAR SETUP AT DAΦNE

A schematic view of the DEAR experimental setup is shown in fig.1 [5]. A light-weight cell with a glass-fiber reinforced epoxy grid was constructed to avoid the fluorescence X-rays in the region of interest and to minimize the bremsstrahlung background. The cylindrical cryogenic target cell had a diameter of 12.5 cm and a height of 14 cm, and was operated with hydrogen at 25 K and 2 bar, resulting in a density of 2.1 g/l (3% of liquid hydrogen density). The X-ray detector system consists of 16 CCD (Charge Coupled Device) detector chips (CCD55-30).

Target and cryogenic setup layout

- Target cooling head
- Turbomolecular pump
- CCD cooling heads
- Amplifiers
- Target cold finger
- Vacuum chamber
- External shielding (Pb,Cu,Al)
- Internal shielding (polycarbonate)
- CCD boards
- CCD cooling line
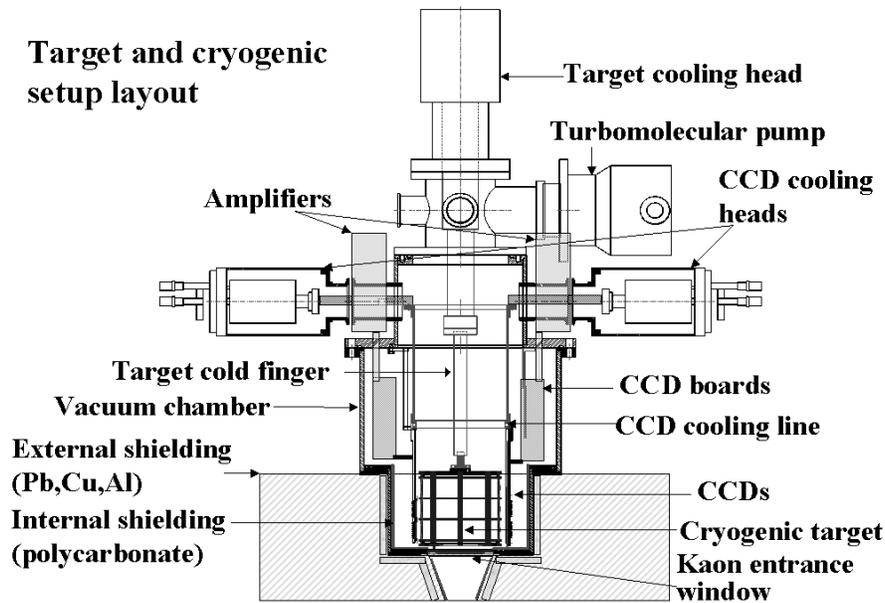- CCDs
- Cryogenic target
- Kaon entrance window

Fig. 1 – Schematic representation of the DEAR setup

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. After a period of machine and setup optimization, with a continuous increase of luminosity and decrease of background, DEAR performed two kinds of kaonic atoms measurements: the kaonic nitrogen and the kaonic hydrogen one. The results of these measurements are reported below.

3. KAONIC NITROGEN RESULTS

The measurement of kaonic nitrogen represented the first step in the DEAR scientific program and had the following objectives:

- to prove the feasibility of the DEAR method to produce and detect exotic atoms using the K⁻ beam from the φ-decay in DAΦNE. The choice of nitrogen is dictated by the high yields of the transitions, so allowing a fast feedback. (the yield of the kaonic nitrogen x rays is 20 times higher than kaonic hydrogen x rays). The kaonic nitrogen was the first exotic atom measurement at DAΦNE, the measurement being done in May 2001 [6].

- to optimize the kaon stopping point distribution inside the gaseous target, by learning how to finely tune the degrader, in the view of the delicate kaonic hydrogen measurement;

- to study the ways to reduce the background.

- to obtain information concerning the yields of kaonic nitrogen transitions.

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.

In October 2002, we re-measured the kaonic nitrogen spectrum, just before the start of the kaonic hydrogen data taking. For the measurement ok kaonic nitrogen done in October 2002 we used the same setup like for kaonic hydrogen, but the target was filled with nitrogen gas at 1.5 bar and 120 K – corresponding to a density of 3.4 ρ_{NTP}. Data using the nitrogen target were taken for about one month, the total collected luminosity was 17.4 pb^{-1}, from which 10.8 pb^{-1} taken in stable conditions, were selected for the analysis of the energy spectrum.

The results, as a background subtracted spectrum, are shown in Fig. 2. Three kaonic nitrogen X-ray lines are well identified. The n=6→5 kaonic transition peak at 7.6 keV is clearly seen. The transition lines n=7→6 and n=5→4 at 4.6 keV and 14.0 keV are overlapped with the Ti-K$_\alpha$ and Sr-K$_\alpha$ lines, respectively. 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.

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

The determined yields are [5]:

1.   for the n=7→6 transition: (41.5 ± 8.7 (stat.) + 4.1(sys.))%
2.   for the n=6→5 transition: (55.0 ± 3.9 (stat.) ± 5.5 (sys.))%
3.   for the n=5→4 transition: (57.4 ± 15.2 (stat.) ± 5.7(sys.))%

The precision in the position of the n=6→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:
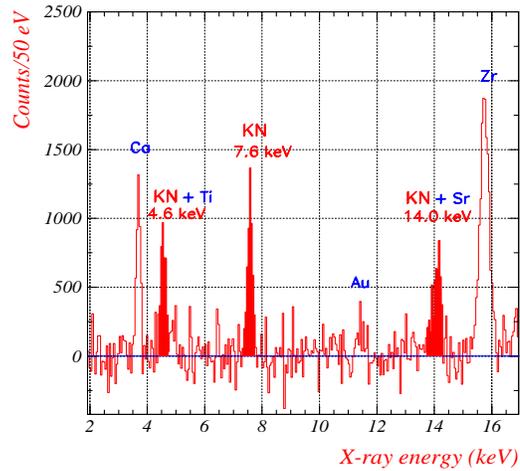
$$M_{K^-} = 493.884 \pm 0.314 \text{ MeV} \qquad (5)$$

Fig. 2 – The kaonic nitrogen (October 2002) background subtracted spectrum

4. KAONIC HYDROGEN RESULTS

The kaonic hydrogen measurement lasted from 30 October to 23 December 2002. It was divided in two periods:

- the kaonic hydrogen data, from 30 October until 16 December 2002 for a total of about 58 pb^{-1} integrated luminosity;

- no-collision background data, taken from 16 to 23 December 2002, for which the beams were slightly separated in the DEAR interaction point, with the same setup, with the same conditions as the signal data and with the scrapers configurations such to obtain an overall statistics for background comparable (factor 1.4 less) with that for the signal spectrum.

The analysis of the kaonic hydrogen K-lines meets 3 crucial challenges:

- determination of the continuous background shape, to which the width of the kaonic hydrogen lines is very sensitive;

- disentanglement of the residual iron K_α fluorescence line (coming from the setup components) which partially overlaps the kaonic K_α signal;

- dealing with the high kaonic hydrogen K-series transitions $5 \rightarrow 1$ and higher (K_{high}), which cannot be resolved and have poorly known yields. In order to deal at best with these challenges, two independent analyses were performed. Both used Voigt functions with fixed Gaussian width for the detector resolution to fit the kaonic hydrogen lines with the following parameters: intensities of K_α, K_β and K_γ, energy of K_α, one Lorentzian width for all K-lines, as the hadronic broadening comes from the ground state width only. The energy differences between K_α and K_β, K_γ, K_{high} were fixed to their electromagnetic values. The two analysis methods differ essentially in the background spectrum which was used.

Analysis I [7] used the bulk of no-collision data as background spectrum. A simultaneous fit of the two spectra, kaonic hydrogen and no-collision, was performed, by constructing a χ^2 function as sum of the two individual ones. The

same shape (a quadratic polynomial) of the continuous background component, apart a normalization factor, was used to fit both spectra. All the fluorescence lines were normalized with the same factor. The fit range was selected to be from 2.9 keV to 10.4 keV, excluding the K_{high} energy range (7.74 - 8.82 keV), in order to avoid model-dependency as far as the intensities were concerned. The systematic errors introduced by these cuts were studied by Monte Carlo simulations and included in the global systematic error.

Analysis II used as a background spectrum the sum of kaonic nitrogen data [5] and a subset (low CCD-occupancy) of no-collision data. By means of activation analyses performed in the laboratory it was checked that the silicon and iron fluorescence peaks do have the same origin (CCD itself and its support) in both signal and background spectra. Consequently, the intensity ratio of the silicon fluorescence peaks with respect to the integrated continuous background in the two spectra, described by two independent cubic polynomials, was used to normalize the iron fluorescence peak in the kaonic hydrogen spectrum. Concerning the influence of the K_{high} transitions, the fit range was restricted to a region where this contribution is marginal, given only by their low-energy tails. In order to study this contribution, different values for the K_{high}/K_γ yields ratios, obtained from cascade calculations [8], were imposed in the fit. The effect of varying the yields ratios as well as the fit energy range was studied and included in the systematic error. The two analyses gave consistent results.

In Fig. 3, the fitted kaonic hydrogen x-ray spectrum is shown (spectra look the same in both Analyses). A zoom of the $(K^-p)K_\alpha$ region shows the disentangling of the Fe K_α and $(K^-p)K_\alpha$ lines.

Fig. 4 shows the kaonic hydrogen x-ray spectrum after continuous and structured background subtraction, for both analyses. The fitting curves of the various kaonic hydrogen lines are as well shown. Shifts and widths obtained in the two analyses are reported.

The weighted average of the two independent analyses for the K_α transition energy gave 6287 ± 3 (stat.) ± 6 (syst.) eV, where the statistical error is the smaller of the two individual ones.

The pure electromagnetic value of the K_α kaonic hydrogen x ray is 6480 ± 1 eV. Hence, the resulting ground-state shift ε_{1s} is:

$$\varepsilon_{1s}= -193 \pm 37(\text{stat}) \pm 6(\text{syst.}) \text{ eV} \qquad (6)$$

The weighted 1s strong interaction width (FWHM) Γ_{1s} is:

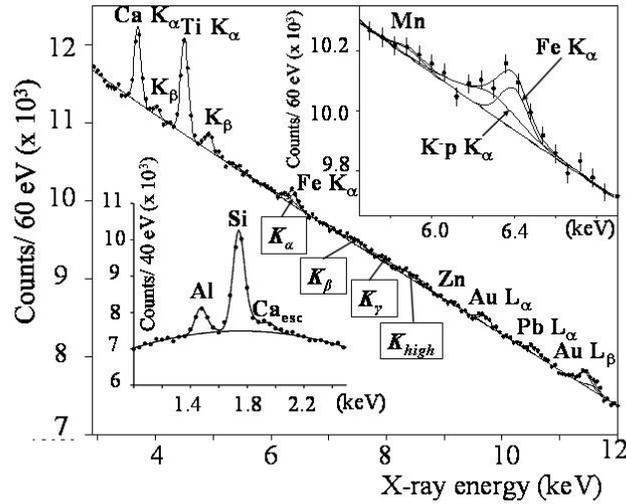$$\Gamma_{1s}=249 \pm 111(\text{stat.}) \pm 3 0 \text{ (syst.) eV} \qquad (7)$$

Fig. 3 – The measured kaonic hydrogen x-ray spectrum

The kaonic hydrogen transitions (indicated by boxes) and the electronic excitations coming from the setup material are visible. The fit curves (total and components) are shown. Upper-right insert: zoom of the kaonic hydrogen K_α line region with the continuous background; the iron K_α and the kaonic hydrogen K_α lines disentangled. Lower-left insert: zoom of the silicon peak region with the aluminum, silicon and calcium escape peaks.

The recently performed *KpX* experiment at KEK [9] succeeded in observing unambiguously, for the first time, a distinct K_α x-ray peak in kaonic hydrogen, but the overall statistics of the KEK experiment was insufficient to obtain a precise determination of the s-wave K⁻p scattering length.

Our result is consistent with the KEK measurement, within 1σ of their respective errors and confirms the repulsive character of the K⁻p interaction at threshold. They differ, however, significantly in three important aspects:

- the uncertainty of the DEAR result is about 2 times smaller than that of the KEK values;

- the absolute values of ε_{1s} and Γ_{1s} are 40% lower, which points towards a less repulsive strong interaction.

DEAR observed the pattern of kaonic hydrogen K-lines, clearly identifying K_α, K_β, K_γ transitions, with an intensity ratio 1.1 ± 0.5 for K_α/K_β (compatible with [8] within 2σ), and limiting the intensity of K_γ/K_α to 0.2 ± 0.5. The K_α, K_β, K_γ overall statistical significance is $6.2\ \sigma$.
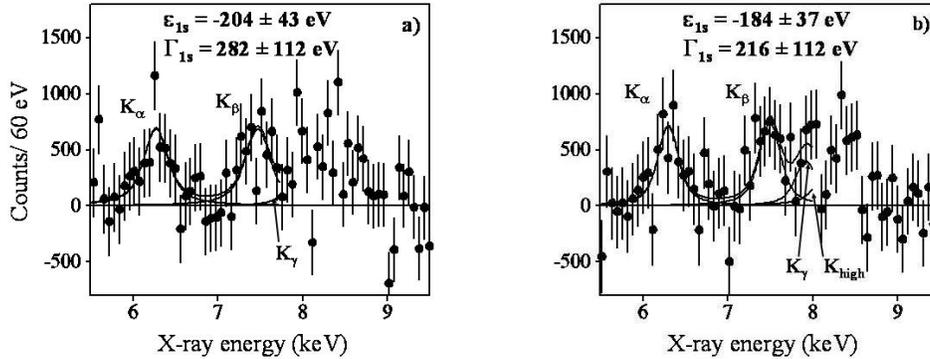
Fig. 4 – The kaonic hydrogen x-ray spectrum after continuous and structured background subtraction: a) results of Analysis I; b) results of Analysis II. The fitting curves of the various kaonic hydrogen lines are shown.

5. FUTURE: THE SIDDHARTA EXPERIMENT

DEAR has performed the most precise kaonic hydrogen measurement presently available; the precision which was achieved, however, is at the level of tens of eV, whilst the goal of a precision measurement should push this precision in the eV range. The DEAR precision was limited by as signal/background ration of about 1/70.

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 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 1μs). This new detector is the Silicon Drift Detector (SDD), based on which a new experiment, which continues the DEAR scientific line, was born.

The new experiment is SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application). Presently, construction and testing of the SDD detectors and of the electronics and mechanical structures are in progress. A preliminary version of the SIDDHARTA setup is shown in Fig. 5. With this setup, it was estimated that a measurement at a eV for kaonic hydrogen becomes feasible with an integrated luminosity of about 100 pb^{-1}. The setup will be installed at DAΦNE in 2007 and start data taking for kaonic hydrogen followed by kaonic deuterium.

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 (sigmonic hydrogen), precision measurement of the charged kaon mass.
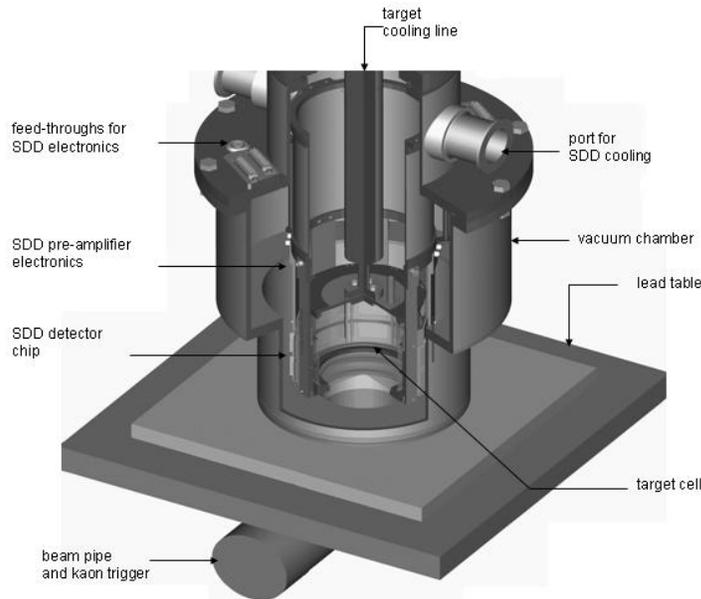

Fig. 5 – SIDDHARTA preliminary setup

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