Eur Phys J A (2004) **19**, s01, 185–188
Digital Object Identifier (DOI) 10.1140/epjad/s2004-03-031-y

EPJ A direct
electronic only

First results on kaonic hydrogen from the DEAR experiment

C. Guaraldo[1], G. Beer[9], A.M. Bragadireanu[1,5], M. Cargnelli[4], C. Curceanu (Petrascu)[1,5], J.-P. Egger[2,3], H. Fuhrman[4], M. Iliescu[1,5], T. Ishiwatari[4], K. Itahashi[7], M. Iwasaki[6], B. Lauss[8], V. Lucherini[1], L. Ludhova[2], J. Marton[4], F. Mulhauser[2], T. Ponta[1,5], L.A. Schaller[2], R. Seki[10,11], D. Sirghi[1,5], F. Sirghi[1], P. Strasser[6], and J. Zmeskal[4]

[1] INFN-Laboratori Nazionali di Frascati, C.P. 13, Via E. Fermi 40, I-00044 Frascati, Italy;
[2] Universite de Fribourg, Institut de Physique, Bd. de Perolles, CH-1700 Fribourg, Switzerland;
[3] Universite de Neuchatel, Institut de Physique, 1 rue A.-L. Breguet, CH-2000 Neuchatel, Switzerland;
[4] Institute for Medium Energy Physics, Boltzmanngasse 3, A-1090 Vienna, Austria;
[5] Institute of Physics and Nuclear Engineering "Horia Hulubei", P.O. Box MG - 6, R-76900, Bucharest, Romania;
[6] Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-01, Japan;
[7] Tokyo Institute of Technology, 2-12-1 Ookoyana Meguro, Tokyo 152, Japan;
[8] Physics Department, University of California and Berkeley, Berkeley CA 94720, USA;
[9] University of Victoria, Department of Physics and Astronomy, P.O. Box 3055 Victoria, BC, Canada V8W3P6;
[10] W.E. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA;
[11] Department of Physics and Astrophysics, California State University, Northridge, CA 91330, USA

Received: 29 Jul 2003 / Accepted: 14 Nov 2003 /
Published Online: 6 Feb 2004 –

Abstract. The objective of DEAR (DAΦNE Exotic Atom Research) is the 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 aim is a precision determination of the antikaon-nucleon isospin dependent scattering lengths in order to obtain the kaon nucleon sigma terms. In a first phase, dedicated to the calibration and optimization of the setup, the experiment collected data on kaonic nitrogen: for the first time a complex of three transitions ($7 \rightarrow 6$ at 4.6 keV, $6 \rightarrow 5$ at 7.6 keV and $5 \rightarrow 4$ at 14 keV) was measured, and the corresponding yields obtained. The kaonic hydrogen measurement was performed for a total integrated luminosity of about 60 pb^{-1} in the last months of the 2002 year. Data analyses are in progress, preliminary results being hereby presented, together with those on kaonic nitrogen.

PACS. 36.10.-K – 36.10.Gv

1 DEAR scientific program

The objective of DEAR (DAΦNE Exotic Atom Research) [1] is the precise determination of the isospin dependent antikaon-nucleon scattering lengths, through a percent level measurement of the K_α line shift and broadening, due to strong interaction, in kaonic hydrogen, and a similar (the first one) measurement in kaonic deuterium.

A kaonic atom is formed when a negative kaon (coming from the ϕ-decay, produced at DAΦNE) enters the target, loses its kinetic energy through ionization and excitation processes, and is eventually captured, replacing the electron, in an excited orbit ($n \simeq 25$). Via different cascade processes (Auger effect, molecular dissociation, radiative 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 the shift in energy of the lowest-lying level from the purely electromagnetic value and for the finite lifetime of the state corresponding to an increase in the observed level width.

For kaonic hydrogen and kaonic 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 are clearly separated from the kigher K transitions. The shift ϵ and the width Γ of the 1s state of kaonic hydrogen are related in a fairly model-independent way (Deser-Trueman formula [2]) to the real and imaginary part of the complex s-wave scattering length, a_{K^-p}:

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

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

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

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

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

The extraction of a_{K^-n} from a_{K^-d} requires a more complicated analysis than the simple 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 multichanneled 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 constraints 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, whose definition is given below.

By considering the scattering process:

$$M_a(q) + N(p) \to M_b(q') + N(p') \quad (4)$$

with the four momentum of the particles indicated in parenthesis and a, b denoting the SU(3) indices of the mesons, the meson nucleon sigma-term is defined [4] as the expectation value in the nucleon state of the equal-time double commutator of the chiral symmetry breaking part of the strong-interaction Hamiltonian:

$$\sigma_{MN}^{ba} = i < p|[Q_b^5, [Q_a^5, H_{SB}]]|p >, \quad (5)$$

where $Q_{a,b}^5$ is the axial-vector charge and H_{SB} is the symmetry breaking part operator of the total Hamiltonian. The sigma term is then a quantity which directly gives the degree of chiral symmetry breaking. Its relation to the scattering amplitude $T_{ba}(\nu, t, q^2, q'^2$, kinematic invariants of the process) is given by the so-called low-energy theorem. Precisely, one has, in the soft-meson limit ($q^2, q'^2 \to 0$, $\nu = t = 0$):

$$\sigma_{MN}^{ba} = -f_a f_b T_{ba}(0, 0, 0, 0) \quad (6)$$

where the f's are the meson decay constant.

A phenomenological procedure, which requires an extrapolation of the measured amplitude, via dispersion relations, to a favored point of the (t, ν) plane, the so-called Cheng-Dashen point and then to zero, where, according to (6), sigma terms are defined, allows to extract the latter. Presently only estimates, with 70% uncertainties, exist; a measurement of the K^-N scattering lengths at few percent level should allow the determination of sigma terms 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 of both kaon-nucleon and pion-nucleon sigma terms, being more sensitive to the first ones [5].

2 The DEAR setup

The schematic drawing of the DEAR setup is shown in Fig. 1. The main elements of the setup are indicated in the figure. A pressurized cryogenic target (23 K and 1.82 bar) was used for the kaonic hydrogen measurement, in order to optimize the distribution of the kaons stopped in the target, and to avoid an important loss of the signal due to the Stark effect.

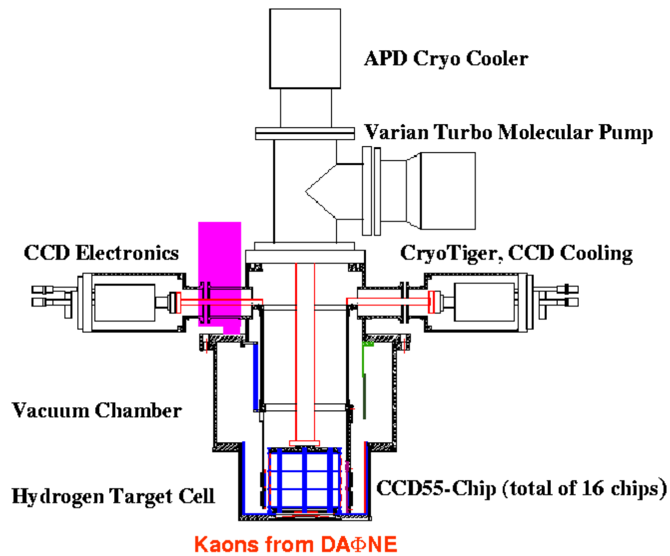

Fig. 1. The DEAR experimental setup

The target cell was done in kapton 75μm thick, cylindrical shaped, with a diameter of 11 cm, reinforced with epoxy-fiberglass bars, in order to have as less material as possible in front of the CCDs, to avoid electronic transitions which could interfere with the line to be measured.

The cryogenic setup was equipped with 16 CCD-55. The following performances were obtained:

- thermal noise: about 15 eV FWHM;
- energy resolution at 5.9 keV: 136 eV;
- linearity of the scale from 1 to 16 keV: 10^{-4};
- stability: fluctuations below 4 eV/month;
- charge transport inefficiency: 10^{-4}.

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. The first measurement of an exotic atom at DAΦNE, namely kaonic nitrogen, followed in May 2001; this measurement was redone in October 2002, when, for the first time, three transitions of kaonic nitrogen were clearly seen ($7 \to 6$ at 4.6 keV, $6 \to 5$ at 7.6 keV and $5 \to 4$ at 14 keV) and the corresponding yields extracted. Results of this measurement are presented Sect. 3.

The first measurement by DEAR of kaonic hydrogen was performed in the period November - December 2002. Preliminary results of this measurement are presented in Sect. 4.

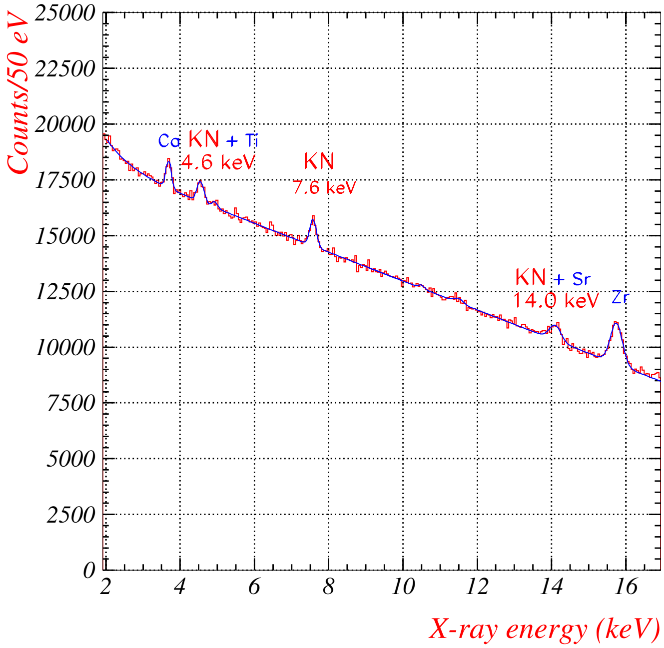

Fig. 2. Kaonic nitrogen spectrum obtained in the October 2002 measurement

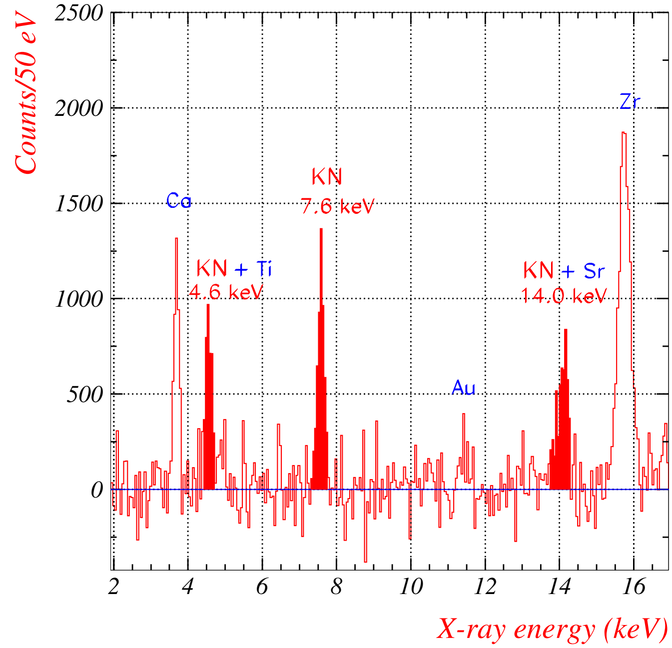

Fig. 3. Energy spectrum obtained for the run of October 2002 with kaonic nitrogen. Kaonic nitrogen transitions are clearly seen, as indicated in the figure

3 Kaonic nitrogen results

The measurement of kaonic nitrogen (whose transitions have yields 20 times higher than kaonic hydrogen and therefore a fast feedback can be obtained) performed by DEAR had the following primary objectives:

– to prove the feasibility of the DEAR technique to produce and detect exotic atoms using the K^- beam from the ϕ-decay at DAΦNE;
– to optimize the kaon stopping distribution inside the gaseous target.

These objectives were achieved in May 2001, when the first measurement of kaonic nitrogen $7 \to 6$ and $6 \to 5$ transitions, at 4.6 and 7.6 keV respectively, was performed. The results were published [6], suggesting a new method for a future precision measurement of the charged kaon mass.

In October 2002 the kaonic nitrogen spectrum was remeasured, just before the start of the kaonic hydrogen data taking.

The scientific aim of this run was the study of different degrader configurations to take into accout the effect of the boost in the ϕ-production.

A statistics corresponding to about 10.5 pb^{-1} integrated luminosity was collected. The overall X-ray energy spectrum, as measured by the 16-CCD 55, is shown in Fig. 2.

A refined analysis of the spectrum was performed [7]. This analysis allowed, for the first time,to disentangle a complex of three kaonic nitrogen transition:

1. the $7 \to 6$ transition, at 4.57 keV;
2. the $6 \to 5$ transition, at 7.59 keV;
3. the $5 \to 4$ transition, at 13.96 keV.

Table 1. Kaonic nitrogen results

Transition	Number of events	Yield of transition (%)
$7 \to 6$	2690 ± 650	33.7 ± 8.1
$6 \to 5$	5320 ± 395	55.5 ± 4.2
$5 \to 4$	1360 ± 330	66.4 ± 15.6

The continuous background subtracted spectrum is shown in Fig. 3.

The number of events for each transition is reported in Table 1.

Apart of the kaonic nitrogen transitions, in the spectrum are present:

– calcium line, at about 3.7 keV, due to the presence of calcium in the fiberglass reinforcement of the kapton target;
– silicon line - silicon being the material of the CCDs;
– aluminium line - from the top cover of the target;
– strontium line - from the ceramics-support of the CCDs;
– zirconium line - from the zirconium foil placed inside the setup with the purpose of energy scale calibration.

The transition yields, for the first time measured, were extracted by using Monte Carlo simulation of the setup and of the contributing physical processes. The preliminary results on the yields are reported in Table 1 and constitute important checks for cascade calculations in the field of exotic (kaonic) atom transitions.

The yields reported in Table 1 contain only the statistical errors; an accurate study on systematic errors is undergoing.

4 Kaonic hydrogen preliminary results

In order to perform the first kaonic hydrogen measurement at DEAR the target was filled with hydrogen in cryogenic and pressurized conditions: 23 K and 1.82 bar. The kaonic hydrogen measurement lasted from 30 October to 22 December 2002. It was divided into two periods:

- from 30 October to 16 December a continuous run with kaonic hydrogen; the total integrated luminosity, measured by the DEAR kaon monitor, was 58 pb^{-1};
- from 16 December to 22 December a background run with no collisions in the DEAR Interaction Region - with a statistics equivalent to about half of the kaonic hydrogen one.

Two types of analyses are undergoing:

- a global fit of the kaonic hydrogen spectrum;
- a measured background subtracted spectrum analysis.

The two analyses give compatible preliminary results. In Fig. 4, the normalized measured background subtracted spectrum is shown. The resulting spectrum was then fit with Voigtian functions (convolution between pure Breit-Wigner, for signal, and Gaussian, to take into account the experimental resolution). The K_α line of kaonic hydrogen, together with a bump corresponding to the $K-$complex are clearly evident. A peak corresponding to the $6 \rightarrow 5$ transition of kaonic carbon is as well present, with a statistical evidence of 2σ. The statistical evidence of the K-complex transition is (sum of individual contribution) more than 6σ. The very preliminary results on the shift and width for the kaonic hydrogen transitions are:

$$\epsilon = 6(150 \pm 45)\ eV \quad (7)$$

$$\Gamma = 6(250 \pm 90)\ eV \quad (8)$$

Further analyses and checks are undergoing.

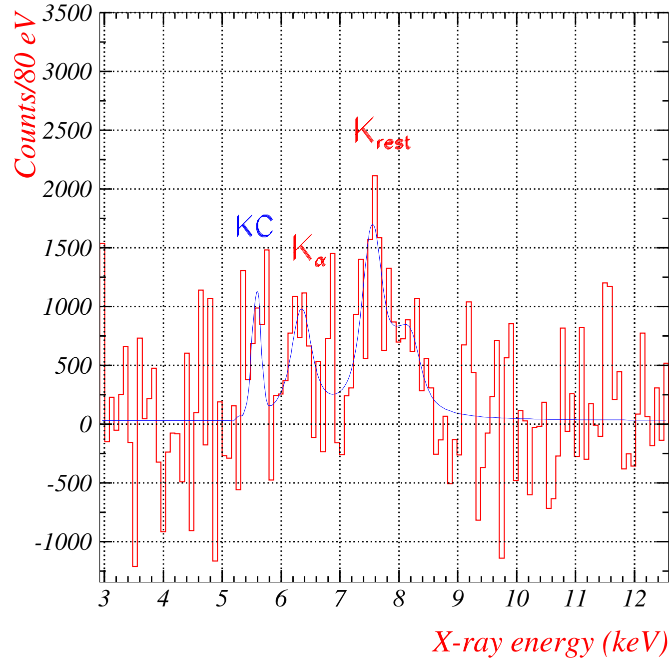

Fig. 4. Kaonic hydrogen measured background subtracted spectrum

5 Future plans

For the future, in order to achieve a percent level measurement of the shift and width for kaonic hydrogen and kaonic deuterium K_α lines an upgrade of the DEAR setup is in progress. One of the problems to cope with during the kaonic hydrogen measurement performed in 2002 was still the presence of a high background. The measurement was performed with a signal/background ratio of about 1/70. In order to further reduce the background, the use of a trigger system is a must. The CCD devices are non-triggerable, due to the fact that data read-out is slow (seconds). Consequently, the collaboration is planning to use new fast triggerable devices, namely large area Silicon Drift Detectors (SDD). The trigger is given by the entrance of the charged kaon in the target volume. The event can be identified and measured with high accuracy and low contamination by the use of a three-scintillator telescope, synchronized with the bunch frequency. The timing window (1 μs) to be used in trigger, together with the excellent energy resolution (140 eV at iron position) of the SDD will allow a dramatic decrease of the background so to obtain a signal/background ratio of about 1/1 for kaonic hydrogen and 1/5 for kaonic deuterium.

Other exotic atoms (kaonic helium and other light atoms, as well as sigmonium atoms) and a high-precision measurement of the charged kaon mass will eventually become feasible.

Acknowledgements. The DAΦNE group in warmly acknowledged for the very good cooperation and team-work. Part of the work was supported by a "Transnational access to Research Infrastructure" (TARI) Contract No. HPRI-CT-1999-00088.

References

1. S. Bianco et al.: Rivista del Nuovo Cimento **22**, No. 11 (1999) 1
2. S. Deser et al.: Phys. Rev. **96**, 774 (1954); T.L. Truemann: Nucl. Phys. **26**, 57 (1961); A. Deloff: Phys. Rev. C **13**, 730 (1976)
3. C. Guaraldo: Proceedings of III International Workshop on Physics and Detectors for DAΦNE, November 16-19, Frascati, Italy, Frascati Physics Series Volume XVI (1999) 642
4. E. Reya: Rev. Mod Phys. **46**, 545 (1974); H. Pagels: Phys. Rep. **16**, 219 (1975)
5. R.L. Jaffe and C.L. Korpa: Comments Nucl. Part. Phys. **17**, 163 (1987)
6. G. Beer et al: Phys. Lett B **535**, 52 (2002)
7. T. Ishiwatari and P.D. Thesis: RIKEN (2003)