Precision measurements on kaonic hydrogen and kaonic deuterium: DEAR and SIDDHARTA

M. Iliescu[a] *

[a]INFN, Lab. Nazionali di Frascati, C.P. 13,Via E. Fermi 40, I-00044, Frascati, Italy

The SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) experiment [1] represents the scientific and technical development of DEAR (DAΦNE Exotic Atom Research) [2], as part of the program dedicated to exotic atoms at DAΦNE [3]. The objective consists in an eV precision measurement of the kaonic hydrogen K_α line shift and width induced by the strong interaction, and the first measurement of kaonic deuterium. These values will allow a precise determination of antikaon-nucleon scattering lengths and a better understanding of the chiral symmetry breaking scenario in the strangeness sector. DEAR performed the most precise measurement up to now on kaonic hydrogen, at the end of 2002. The SIDDHARTA collaboration is developing a new set of large area, triggerable X-ray Silicon Drift Detectors (SDD), which will improve by 2 orders of magnitude the background rejection, allowing to reach the proposed objectives. The results of DEAR, as well as the state of the art of the new setup are presented.

1. INTRODUCTION

In order to measure the strong interaction component of the kaon-nucleon force in kaonic hydrogen (deuterium), one measures the shift ϵ of the position of the K_α line ($2p \rightarrow 1s$ transition) from the one calculated from a purely electromagnetic interaction:

$$\epsilon = |E^{measured}_{2p\rightarrow 1s}| - |E^{e.m.}_{2p\rightarrow 1s}| \tag{1}$$

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

The electromagnetic transition energy in kaonic hydrogen is given with a precision of 1 eV by the Klein-Gordon equation, after applying the corrections for finite size and vacuum polarization. The resulting value is $E^{e.m.}_{2p\rightarrow 1s} = (6480 \pm 1)\ eV$, where the 1 eV error is dominated by the uncertainty of the kaon mass.

Before DAΦNE operation, the kaonic hydrogen parameters were measured at KEK [4], where the following results were found:

$$\epsilon = -323 \pm 63 \pm 11\ eV;\ \Gamma = 407 \pm 208 \pm 100\ eV. \tag{2}$$

This measurement showed that the antikaon-nucleon interaction is of repulsive type, but cannot be considered a precision one. The kaonic deuterium has yet to be measured, the two transitions allowing the determination of the antikaon-nucleon scattering lengths.

*On behalf of DEAR and SIDDHARTA collaborations

2. THE DAΦNE COLLIDER

The DAΦNE electron-positron collider at the Frascati National Laboratories has made available a negative kaon "beam", providing the conditions for the study of the low-energy kaon-nucleon interaction. The monochromatic kaon beam from Φ decay at rest, mostly emitted in the plane transverse to the beam pipe due to the Φ polarization, facilitates stopping the kaons in a small volume and therefore detecting with high efficiency the rare events associated with exotic atom transitions. The minimal beam-related hadronic background (Φ decays in 49% back-to-back charged and 31% neutral kaons), as well as the high luminosity delivered ($\sim 2\times10^{31}$), are other important characteristics. The integrated luminosity delivered to DEAR in 2002 was 70 pb^{-1}.

3. 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 and is eventually captured in an excited orbit. Collisional cascade processes and radiative transitions deexcite the atom. When the kaon reaches low-n states with small angular momentum, it is absorbed through the strong interaction with the nucleus. This 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 by 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 parts 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]:

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

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}. 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 the average of the two,

$$a_{K^-p} = 1/2(a_0 + a_1), \tag{4}$$

while the kaonic deuterium scattering length a_{K^-d} is related to a_0 and a_1 by

$$a_{K^-d} = 2(\frac{m_N + m_K}{m_N + m_K/2})a^{(0)} + C, \tag{5}$$

where

$$a^{(0)} = \frac{1}{2}(a_{K^-p} + a_{K^-n}) = \frac{1}{4}(3a_1 + a_0) \tag{6}$$

corresponds (in the t-channel) to the isoscalar $\bar{K}N$ scattering length. The first term in eq. (5) represents the lowest-order impulse approximation, i.e. K^- scattering from each (free) nucleon, while the second term, C, includes all higher contributions related to the K^-d three-body interaction. In this framework, the DEAR/SIDDHARTA results will contribute to a precise extraction of the scattering amplitude at threshold and will place a strong constraint on the extrapolations to zero energy [6].

4. KAONIC HYDROGEN MEASUREMENTS PERFORMED BY DEAR AT DAΦNE

The low momentum negative kaons produced in the decay of the ϕ-mesons, after passing through a thin-walled beam pipe, are degraded in energy to a few MeV, then enter a gaseous target through a thin window, where they are finally stopped, forming the exotic kaonic atoms. The kaons cascade down emitting X rays. The energy of the X rays emitted in these transitions is measured with a CCD (Charge-Coupled Device) detector system [7]. The initial run time was dedicated to machine and setup optimization, in order to increase the luminosity and to reduce the background. After that, in 2002, DEAR performed two kind of kaonic atom measurements: the kaonic nitrogen and the kaonic hydrogen one. 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, a 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. In the period November-December 2002 the kaonic hydrogen measurement was performed. The target was operated at 2 bar and 25 K ($\rho = 2.1$ g/l) which represents the result of a Monte Carlo optimization. Data for 58.4 pb^{-1} were collected in this period. At the end of the period, a background measurement with separated beams and high X-ray background was performed (no-collision spectrum for background subtraction). The obtained kaonic hydrogen spectrum is presented in Fig. 1.

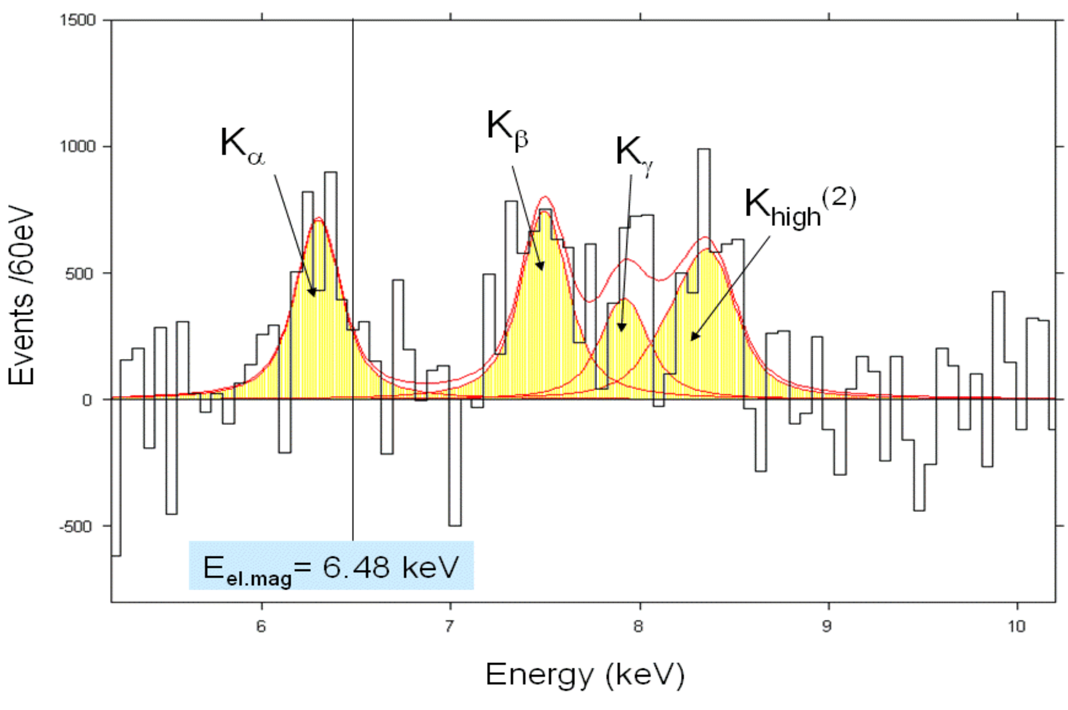

Figure 1. The kaonic hydrogen (background subtracted) spectrum.

The results coming from two independent analyses are in good agreement and the weighted averages for the shift and width of the 1s ground state of kaonic hydrogen are:

$$\epsilon = -193 \pm 37(stat.) \pm 6(syst.)\ eV;\ \Gamma = 249 \pm 111(stat.) \pm 39(syst.)\ eV. \quad (7)$$

5. THE SIDDHARTA EXPERIMENT

The DEAR precision was limited by a signal/background ratio of about 1/70. Consequently, an accurate study of the background sources in the present DAΦNE configuration was done. Two main sources were identified: a synchronous background, related to the interaction of K^- on the nuclei of the setup and to the ϕ-decay processes, and an asynchronous background, consisting in final products of electromagnetic showers in the collider pipe and setup materials, originated by particles lost from the beams, either due to the Touschek effect or to the interaction with the residual gas. The asynchronous background represents the major problem of the experiment (about 2 orders of magnitude higher than the synchronous one). Consequently, a fast trigger, correlated to the negative kaon entrance in the target allows to cut off the dominant contribution. The detectors used by DEAR (X-ray spectroscopic CCDs) were not appropriate for triggered setup, due to the long readout time. A newly developed detector was identified, which preserves the good features of the CCDs (resolution, linearity and stability) but is fast enough to be synchronized with a trigger of one μs width. The estimated background reduction, corresponding to this time window, is 2-3 orders of magnitude higher than the one obtained by DEAR. The detector is the large area Silicon Drift Detector (SDD)[8] and constitutes the key element of the SIDDHARTA experiment, which continues the DEAR scientific line.

Presently, construction and testing of the SDD detectors, electronics and mechanics are in progress. An eV level measurement for kaonic hydrogen, with the new setup, becomes feasible, for an integrated luminosity of about 100 pb^{-1}. The first measurement of kaonic deuterium becomes feasible, as well. The setup will be installed at DAΦNE in the end of 2006.

REFERENCES

1. J. Zmeskal, SIDDHARTA Technical Note IR-2 (2003); C. Curceanu (Petrascu), SIDDHARTA Technical Note IR-3 (2003).
2. S. Bianco *et al.*, Rivista del Nuovo Cimento 22, No. 11 (1999) 1.
3. G. Vignola, Proc. of the "5th European Particle Accelerator Conference", Sitges, Eds. S. Myres *et al.*, Institute of Physics Publishing, Bristol and Philadelphia (1996) 22.
4. M. Iwasaki *et al.*, Phys. Rev. Lett 78 (1997) 3067; T.M. Ito *et al.*, Phys. Rev. A 58 (1998) 2366.
5. S. Deser *et al.*, Phys. Rev. 96 (1954) 774; T.L. Truemann, Nucl. Phys. 26 (1961) 57; A. Deloff, Phys. Rev. C 13 (1976) 730.
6. E. Reya, Rev. Mod. Phys. 46 (1974) 545; H. Pagels, Phys. Rep. 16 (1975) 219.
7. J.-P. Egger, D. Chatellard, E. Jeannet, Part. World. 3 (1993) 139.
8. E. Gatti, P.Rehak, Nucl. Instr. and Meth. 225 (1984) 608; E. Gatti, P.Rehak, Nucl. Instr. and Meth. A 235 (1985) 224.