MEASUREMENT OF KAONIC HYDROGEN WITH DEAR AT DAΦNE AND FUTURE PERSPECTIVES

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The objective of the DEAR (DAΦNE Exotic Atom Research) and the coming SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) experiments 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 to better understand the chiral symmetry breaking scenario in the strangeness sector. DEAR has performed the most precise measurement up to now on kaonic hydrogen at the end of 2002. It is for the first time that the K-complex could be clearly identified. The obtained result is presented in this paper. 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.

1. Introduction

The DAΦNE [1] electron-positron collider at the Frascati National Laboratories has made available a unique negative kaons "beam", providing so unprecedented conditions for the study of the low-energy (anti)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 generated shifts and widths of the fundamental $1s$ level of kaonic hydrogen and kaonic deuterium, via the measurement of the x-ray transitions to this level. The aim is to extract the isospin dependent antikaon-nucleon scattering lengths and, so, 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:

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

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

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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 $E^{e.m.}_{2p\rightarrow 1s} = (6480 \pm 1)\ eV$ 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:

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

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 experiments 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 briefly discussed. The DEAR experimental setup installed at DAΦNE is presented in Section 3, while 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. 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]:

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

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}.

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 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 [6,7,8].

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 in the following way:

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

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. 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. 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.

In this framework, the DEAR/SIDDHARTA results will not only contribute to a precise extraction of the scattering amplitude at threshold, but , hopefully, will place strong constraint on the extrapolations to zero energy which are required in any analysis of scattering data. In fact, the s-wave K^-N amplitudes will be determined more accurately, below and above threshold. This will provide a tighter constraint on the p-wave parameters from experimental data and, eventually, reduce the uncertainty in the phenomenological procedure used to calculate the so-called kaon-nucleon sigma terms, fundamental quantities in understanding the chiral symmetry breaking in strangeness sector [9].

3. The DEAR setup on DAΦNE

The principle of the DEAR experiment is the following: low momentum negative kaons produced in the decay of the ϕ-mesons at DAΦNE leave the thin-walled 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 [10].

Fig. 1 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. The target was operated with hydrogen at 2 bar and 25 K (ρ = 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 x 1152 pixels with a pixel size of 22.5 μm x 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 [11].

4. Kaonic hydrogen measurement

The DEAR experiment was installed at DAΦNE at the beginning of 1999. After a period of machine and setup optimization, with a continuous in-

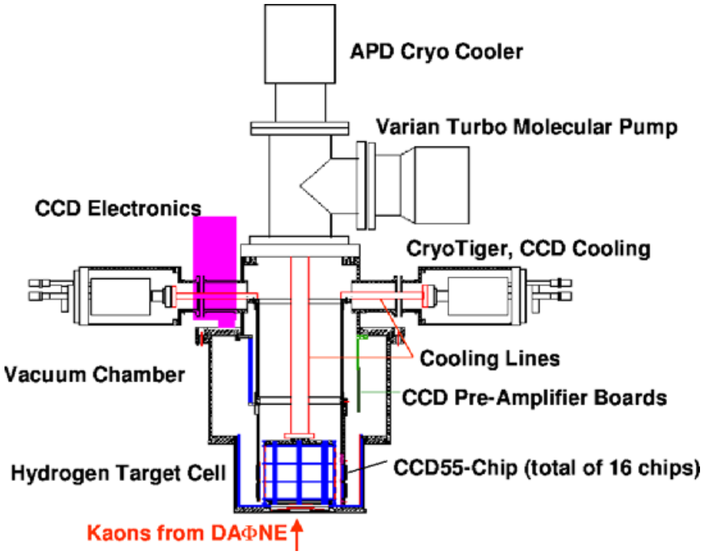

Figure 1. *Schematic representation of the DEAR setup*

crease of luminosity and decrease of background, in 2002 DEAR performed two kind of kaonic atoms measurements: the kaonic nitrogen and the kaonic hydrogen one. The measurement of kaonic nitrogen [12] 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.

In the period November-December 2002 the kaonic hydrogen measurement was performed. 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.

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.

In the second analysis the kaonic hydrogen spectrum was analyzed together with a spectrum built as a sum of the kaonic nitrogen [12] 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 to 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 [13].

The "pure" kaonic hydrogen spectrum with the background (continuous and structured) subtracted is shown in Fig. 2.

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

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

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. (2)) 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 statistical significance of 6.2 σ.

5. Future perspectives: the SIDDHARTA experiment

DEAR has performed the most precise measurement of kaonic hydrogen; 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 a signal/background ratio of about 1/70. In order to go beyond this ratio a jump of quality is necessary. Consequently, an accurate study of the background sources present at DAΦNE was re-done. The background includes two main sources: synchronous background: coming together with the K^- - related to the interaction of K^- on the nuclei of the setup and also to the ϕ-decay processes;

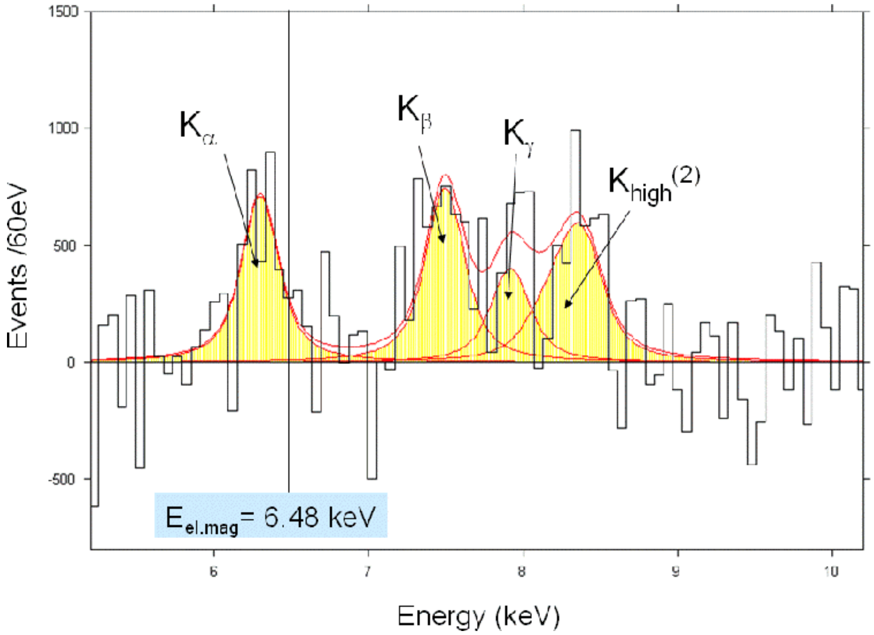

Figure 2. *The kaonic hydrogen background (continuous and structured) subtracted spectrum*

it can be defined hadronic background; asynchronous background: final products of electromagnetic showers in the machine pipe and in the setup materials originated by 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 the negative kaon entrance in the target would cut the main part of the asynchronous background. This was not possible in DEAR, which used as X-ray detector the CCDs - which are slow devices.

A new detector was then identified, which preserves all the good features of the CCDs (resolution, linearity and stability) but is fast enough to supply a trigger at the level of one μs. It was estimated to cut in such way the background present in DEAR by 2-3 orders of magnitude. The detector is the newly developed large area Silicon Drift Detector (SDD) [14], 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) [3].

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. 3. With this setup, it was estimated that a measurement at eV level for kaonic hydrogen becomes feasible with an integrated luminosity of about 100 pb^{-1}. The setup will be installed at DAΦNE in the end of 2006 and start taking data for kaonic hydrogen, followed by kaonic deuterium.

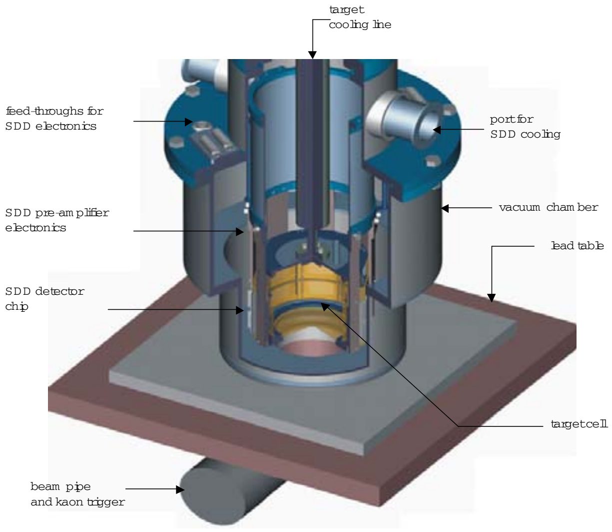

Figure 3. *SIDDHARTA preliminary setup.*

6. Conclusions

DAΦNE collider has unique features as kaons source: intrinsically clean and 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 low-energy kaon-nucleon interaction.

DEAR has performed the most precise measurement of kaonic hydrogen; the eV precision measurement of the strong interaction parameters of the fundamental level in kaonic hydrogen will be performed by SIDDHARTA. The first measurement of kaonic deuterium is as well planned. These results will open new windows in the study of the kaon-nucleon interaction, in particular the chiral symmetry breaking in the strangeness sector.

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