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FIRST MEASUREMENT OF KAONIC HYDROGEN AND NITROGEN X-RAYS AT DAΦNE

J. Zmeskal *
Institute for Medium Energy Physics, Austrian Academy of Sciences
Vienna, Austria

ABSTRACT

The DEAR experiment (DAΦNE Exotic Atom Research) is a powerful effort to study low-energy kaon physics. DEAR uses the unique beam of almost monochromatic negative kaons produced by the Frascati Φ-Factory complex at LNF (Laboratori Nazionali di Frascati), to perform a precise measurement of the energies emitted in the transitions to the ground state of kaonic hydrogen. The shift and the width of the 1s state are sensitive quantities to test the current understanding of low-energy antikaon-nucleon interaction.

1 Introduction

The objective of DEAR is the precise determination of the isospin dependent antikaon-nucleon scattering lengths, through an eV-level measurement of the

* On behalf of the DEAR Collaboration

1s shift and width in kaonic hydrogen and kaonic deuterium [1]. DEAR investigates the characteristic properties of the strong interaction of antikaons with nucleons at almost zero energy, whereby the light quarks (u, d, s) are involved. The masses of the nucleons are considerable larger than the sum of their constituent quark masses. This phenomenon is proposed to originate from spontaneous breaking of chiral symmetry of massless quarks due to strong interaction [2]. In the world in which we live, quarks are massive and their masses are different: m(s)$\gg$m(d)$\sim$m(u). Therefore, chiral symmetry must be broken and the SU(3) symmetry is not exact to the extent required to obtain the experimentally observed mass spectrum.

We do not know, at least on a fundamental level, the origin of the symmetry breaking, its nature, to what extent it is broken, which are the breaking mechanisms and therefore, which model must be used to describe it. In this work a measurement of energies and widths of the X-ray transitions to the ground state in kaonic hydrogen atoms, which will allow to extract the K^-p s-wave interaction at low-energy, is presented. Further on, this information will give an important contribution to the understanding of the chiral symmetry breaking scenario in the strangeness sector.

In contradiction to the analysis of the low-energy scattering experiments (extrapolated down to threshold, a negative energy shift was extracted) three out of four kaonic hydrogen X-ray experiments performed in the last twenty-five years claimed to observe a positive energy shift and therefore an attractive strong interaction between the kaon and the proton (only the KpX measurement gives also a negative shift) [3]. Our analysis of the kaonic hydrogen data gives a negative shift and therefore a repulsive contribution of the strong interaction, which confirms the result of the KpX experiment [4], but with a much better precision.

A repulsive contribution of the strong interaction can be traced back to the presence of the $\Lambda(1405)$ resonance, which leads to the possible existence of strongly bound kaonic states in light nuclei [5].

2 The DEAR experimental setup

DEAR makes use of low momentum negative kaons, produced by the decay of Φ-mesons at DAΦNE. The kaons are degraded in energy to a few MeV, enter a gaseous hydrogen target through a thin window and are finally stopped in the gas. The kaon entrance window has a diameter of 100 mm and is made of Kapton with a thickness of 125 μm. The distance from the entrance window to the center of the beam pipe is approximately 110 mm.

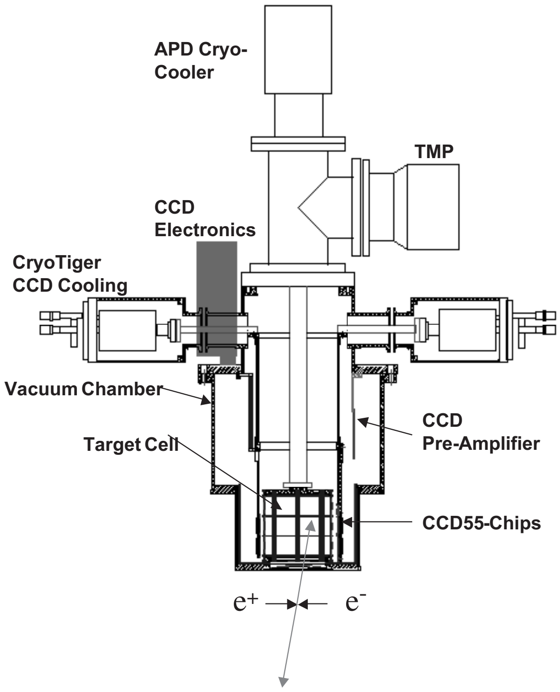

Figure 1: *The DEAR setup: A cryogenic lightweight target cell surrounded by a CCD-detector inside a common vacuum housing.*

The target cell, surrounded by the CCD mounting devices, is placed in the center of the vacuum chamber and is connected to the two-stage closed cycle helium refrigerator via a copper cylinder. The refrigerator system (APD Cryo-Cooler) provides a cooling power of about 10 W at 25 K. The insulation vacuum is maintained to better than 10^{-6} mbar using a wide-range turbo molecular pump (TMP), see also figure 1.

A light-weight target cell with a glass-fiber reinforced epoxy grid was constructed to avoid fluorescence X-rays in the region of interest and to minimize the bremsstrahlung background. The cell has a diameter of 125 mm and a height of 140 mm. The hydrogen gas target cell (ultra pure hydrogen gas is used, which is cleaned through a palladium diffusion device) typically works at a gas pressure of 2 bar and has a temperature of 23 K, stabilized to better than 0.1 K. With these settings a gas density of 2.2 mg/cm^3 (3.1 % of liquid hydrogen density) is achieved, corresponding to a gas pressure at room temperature of about 30 bar.

16 CCD detector chips (CCD55-30) with a total area of 116 cm^2 were used. Each chip has 1242 x 1152 pixels with a pixel size of 22.5 μm x 22.5 μm and a depletion depth of 30 μm. To minimize thermal noise, and thus reduce the overall noise, the CCDs are operated at a temperature around 150 K, cooled by two one-stage closed-cycle refrigerators (APD CryoTiger), each with a refrigeration capacity of 20 W at 120 K. Thus, an energy resolution of 150 eV at 6 keV could be achieved.

A sophisticated shielding of the DEAR target and detector was developed through different test runs at DAΦNE. Finally, a graded shielding structure was used, starting with lead, followed by a copper and aluminum layer, with an inner layer of polycarbonate. With this setup the bremsstrahlung background could be reduced drastically, which was demonstrated using nitrogen as target gas.

3 Kaonic nitrogen results

The series of kaonic nitrogen measurements performed at DAΦNE had multiple tasks and deliverables: a first measurement of kaonic nitrogen transitions; the study of the machine background and the DEAR setup performance.

A refined analysis of the kaonic nitrogen spectrum taken in October 2002 was performed [6]. For the first time three lines of kaonic nitrogen transitions were clearly identified (fig. 2) and the corresponding X-ray yields could be determined (see table 1).

Using these experimental yields as input for a cascade calculation [7], in particular, the residual K-shell electron population could be extracted. A K-shell electron fraction of approximately 1-3% is found, using the present cascade approach [6]. Understanding the atomic cascade processes in kaonic nitrogen is especially important to prove the feasibility for a precision measurement to determine the charged kaon mass – still an open problem [8].

Table 1: *Kaonic nitrogen transition energies, measured events, and extracted yields*

transition	energy [keV]	events	yield [%]
$7 \to 6$	4.5773	3310 ± 690	$41.5 \pm 8.7 \pm 4.1$
$6 \to 5$	7.5957	5280 ± 380	$55.0 \pm 3.9 \pm 5.5$
$5 \to 4$	13.996	1210 ± 320	$57.4 \pm 15.2 \pm 5.7$

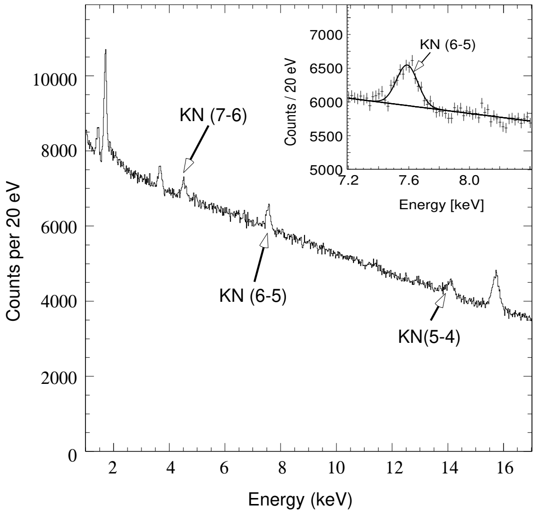

Figure 2: *Energy spectrum of kaonic nitrogen. The arrows indicate the position of the kaonic nitrogen X-ray lines. The peaks at 1.4, 1.7, 3.6 and 15.7 keV are the Al-Kα, Si-Kα, Ca-Kα, and Zr-Kα lines, respectively. The insert shows the fit of the 6→5 kaonic nitrogen transition.*

On the other hand the kaonic nitrogen measurement is essential to tune the machine and to optimize the apparatus for the kaonic hydrogen experiment. Improvements of the detector shielding (signal to background) as well as an optimization of the kaon stopping distribution in the gaseous target cell could be measured directly with kaonic nitrogen X-rays within a few days.

4 Kaonic hydrogen first (preliminary) results

The experimental challenge of DEAR is the extraction of a small signal in the presence of a large low-energy X-ray background mainly from electron gamma showers resulting from lost electrons and positrons due to either Touschek scattering or interaction with residual gas. The careful optimization of the shielding of our experimental setup and the improvements in the beam optics achieved by the machine crew made the goal of DEAR possible, namely, to perform a first measurement of kaonic hydrogen X-rays at DAΦNE in the last two months of 2002.

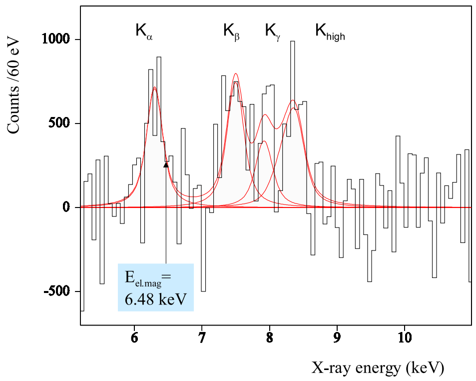

Figure 3: *Background subtracted kaonic hydrogen spectrum for an integrated luminosity of 60 pb^{-1}. Kaonic hydrogen lines $K\alpha$, $K\beta$ and $K\gamma$ are fitted.*

Although, all materials used for the target cell and the mounting devices for the CCDs were carefully checked, still it was not possible to avoid iron impurities completely. The iron fluorescence line coming from iron impurities overlaps partly with the kaonic hydrogen Kα-line. Due to background measurements with nitrogen gas in the target cell and with hydrogen, but without collisions in the DAΦNE interaction zone (no kaons), the iron fluorescence line could be determined and therefore subtracted.

The linearity as well as the energy stability of the CCD detector were measured in-situ using titanium and zirconium lines (the foils were placed on top of the target cell). The CCD detector system was extremely stable (better than 0.1%) during beam time. Stability was checked by fixing the energy position of the Ti- and Zr-lines and then the position of the Ca-line (originating from the glass-fiber epoxy grid of the target cell) was fitted with an accuracy better than 1 eV. In addition the Ti Kα-line width for the sum of all CCDs was better than 150 eV for the whole beam time.

Two completely independent analyses starting from the set of raw-data were performed. The main differences were the treatment of the subtraction of the continuous background and the determination of the fluorescence X-ray lines. Figure 3 shows the resulting kaonic hydrogen spectrum with the continuous background as well as the fluorescence X-ray lines subtracted. The K_α-line together with the X-ray lines of the K-complex are clearly visible. Both analysis methods gave a compatible (preliminary) result:

$$\begin{aligned} \varepsilon &= -193 \pm 37 \text{ (stat.)} \pm 6 \text{ (syst.) eV}, \\ \Gamma &= 249 \pm 111 \text{ (stat.)} \pm 30 \text{ (syst.) eV}. \end{aligned}$$

In summary, the analysis of the first measurement of kaonic hydrogen at DAΦNE already leads to an improved accuracy in the determination of the shift and width of the ground state of kaonic hydrogen and confirms the repulsive contribution of the strong interaction found in the KpX experiment at KEK, Japan. For the first time the Kβ and Kγ lines could be disentangled.

Theoretical predictions based on chiral perturbation theory and quantum field theoretical approach are confronted with our new result [9] [10].

5 Future program

DEAR has performed the most precise measurement on the kaonic hydrogen at present, disentangling the line of the K-complex for the first time. Essential for a future eV level measurement of the shift and width for kaonic hydrogen and for a first measurement of kaonic deuterium is an upgrade of the setup, which is in progress [11]. A large area Silicon-Drift-Detector is under construction. A drastic improvement in the signal-to-background ratio is expected.

Studies of other light exotic atoms (mainly ^{4}He and ^{3}He) are in discussion. A high-precision experiment to determine the charged kaon mass [12] seems to be feasible in the future.

Acknowledgments

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