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DEAR: RESULTS ON KAONIC HYDROGEN

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An experimental program is conducted by the international collaboration DEAR at Laboratori Nazionali di Frascati (LNF) to measure the strong interaction induced shift and width of the kaonic hydrogen 1s atomic state via X-ray spectroscopy with unprecedented precision. The features of this experiment as well as the performance are described. Preliminary results of the analysis of the kaonic hydrogen X-ray data and a comparison with other experimental and theoretical results are presented. An outlook to the future and perspectives of the ongoing experimental program on kaonic atoms at LNF is given.

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1 Introduction

It is well known that exotic atoms serve as valuable tools for a wide range of basic research. Especially the lightest hadronic atoms (i.e. pionic, kaonic and antiprotonic hydrogen, deuterium and helium) are well suited for precision studies of the strong interaction at low energies.

The DEAR project [1] at LNFrascati is using exotic atoms to study fascinating topics of current research in hadron physics, especially in low energy quantum chromodyamics (QCD) describing the strong interaction of mesons and baryons. The main goal of the experimental program is a determination of the isospin-dependent antikaon-nucleon ($\overline{K}N$) scattering lengths at the percent level using kaonic hydrogen and kaonic deuterium atoms - it will be the first measurement of the X-ray spectrum of kaonic deuterium atoms. A comprehensive description of the physics program can be found in [2]. The measurements in the DEAR project started with the study of kaonic nitrogen atoms and proceeded then with the simplest kaonic atom - the kaonic hydrogen. Due to the strong interaction between antikaon and nucleon the ground state of the kaonic hydrogen atom is shifted and broadened, whereas the higher states are essentially unaffected. The strong interaction ground-state shift is determined from the difference between the measured X-ray transition energies (from the atomic p states to the 1s state) and the transition energies calculated on the basis of a purely electromagnetic interaction which are obtained by solving the corresponding Klein-Gordon equation and corrections (e.g. vacuum polarization). There was a

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confusing situation about character (attractive or repulsive) of the kaon-proton interaction in the past. In contrast to kaon scattering experiments the kaonic hydrogen experiments indicated an attractive shift. This puzzling situation was clarified only a few years ago in the KpX experiment [3], where the sign of the strong interaction shift was settled to be negative and thus the interaction to be repulsive.
The strong interaction shift ϵ_{1s} and width Γ_{1s} of kaonic hydrogen are related to the complex K^-p scattering length, by the Deser-Goldberger-Baumann-Thirring formula [4].

$$\epsilon_{1s} + i\,\frac{\Gamma_{1s}}{2} = 412\ [\mathrm{eV\ fm}^{-1}]\ a_{K^-p}\ [\mathrm{fm}]. \tag{1}$$

The scattering length a_{K^-p} is connected to the scattering lengths a_0 for isospin 0 and a_1 for isospin 1

$$a_{K^-p} = \frac{1}{2}(a_0 + a_1). \tag{2}$$

For the determination of isospin-dependent scattering lengths a_0 and a_1 one have to measure the strong interaction shift and width of the kaonic hydrogen and the kaonic deuterium ground state. The advantage of the kaonic atom method which allows the extraction of the scattering lengths in the zero energy limit directly compared with the kaon scattering measurements (which require an extrapolation to zero energy) has to be stressed. Furthermore, these measurements will contribute significantly to the understanding of low-energy QCD, i.e. insight to chiral symmetry breaking in a system with strangeness can be gained. According to the recent theory [5] deeply bound kaonic states can exist where $\Lambda(1405)$ may act as a ”doorway state”. Information about the $\Lambda(1405)$ sub-threshold resonance can be extracted which is also responsible for the repulsive character of the antikaon-nucleon interaction.

2 Experimental setup

At the DAΦNE facility Φ mesons are produced by electron-positron collisions at the resonance energy of 1.02 GeV c.m. which decay (with about 50 percent branching ratio) in K^+K^- pairs. In our experiments an average of 3×10^6 K^- per day was produced.

The kaons are penetrating a degrader and are stopped inside a cryogenic gas target (Fig. 1). All the materials of the setup were carefully selected to suppress fluorescence lines in the region of interest of the kaonic hydrogen spectrum. The target cell consists of thin Kapton foils for the kaon entrance window (125 μm) and for walls in front of the X-ray detectors (75 μm) supported by a grid structure made of glass-fiber reinforced epoxy. For the hydrogen measurement the target cell was filled with pure hydrogen gas at 25K with a density of 2 g/l, corresponding to 3% of liquid hydrogen density. The chosen density ensures sufficient kaon stopping probability as well as suppression of Stark mixing leading to kaon absorption from higher states. The X-ray detection system [6] surrounding the target cell consists of an array of 16 CCD-55 chips with a pixel matrix 1242 $\times$ 1152 (pixel size 22.5 $\times$ 22.5 μm) and 30 μm depletion depth. The cooled and temperature stabilized CCDs (T $\sim$ 165 K) exhibit an excellent energy resolution of about 150 eV at 5.9 keV. The X-ray detection efficiency of the CCD array with a total area of about 115 cm^2 is 5.8 %, estimated by Monte Carlo simulations.

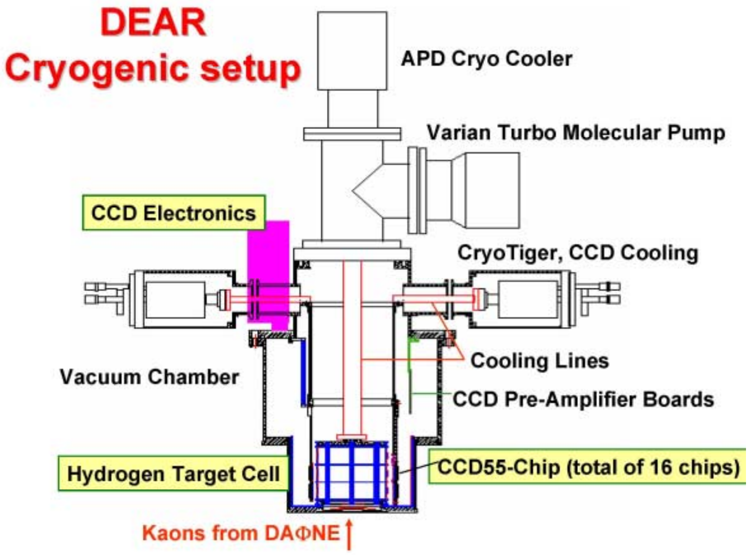

Fig. 1. This drawing shows the DEAR setup used for the kaonic nitrogen and kaonic hydrogen measurements.

As a first step measurements with pure nitrogen gas were performed in order to investigate the kaonic nitrogen atom which might serve for a precision measurement of the charged kaon mass in the future. The experiment succeeded in measuring three X-ray transitions for the first time (KN(7-6), KN(6-5) and KN(5-4)) and to obtain the corresponding yields [7]. Beside the impact on new cascade calculations [8] it was found that kaonic nitrogen atoms are almost completely stripped of electrons and a high precision measurement of the charged kaon mass is not hindered by electron screening. Furthermore, the measurements with the nitrogen target delivered background data for the analysis of the hydrogen measurement (see below) and allowed to optimize the degrader configurations and to minimize the background by proper shielding which resulted in a suppression by a factor ~ 100. Finally the measurements with cryogenic hydrogen filling were performed. An integrated luminosity of about 58 pb^{-1} was collected, corresponding to 2.5×10^{6} kaonic hydrogen atoms (see Tab. 1). Detecting the back-to-back emitted charged kaons with scintillation counters the kaon flux was measured [9]. The no-collision measurement with separated electron and positron beams served for background determination.

3 Data analysis

The efficient extraction of the kaonic X-ray spectrum requires careful data treatment. After setting the noise threshold a selection of single and double pixel events is performed, thus discriminating pixel clusters due to charged particle or high energetic gamma-ray interaction. Data taken in stable conditions are selected and the charge transfer efficiency is corrected. For the energy

Tab. 1. Calculated numbers of kaons and kaonic atoms produced in the measurements in pure nitrogen and hydrogen gas. The gas stopping efficiency leading to the number of produced kaonic atoms was obtained by Monte Carlo simulations.

measurement	gas	kaons [10^6]	kaonic atoms [10^6]
N1	N_2	20.6	0.60
N2	N_2	25.1	0.75
H	H_2	84.1	2.50
H	H_2	no coll.	—

calibration and the determination of the detector response function the background fluorescence lines are used. The analysis uses the data measured with kaons stopped in the hydrogen target and also the background data for which we use 2 data sets: no collision data - data measured with the hydrogen target and separated beams (no collision data) and the no collision data plus data measured with the target filled with nitrogen. The kaonic hydrogen data versus the background data are normalized with the X-ray intensities of the silicon fluorescence line. The components of the X-ray spectrum consist of a continuous background due to bremsstrahlung, fluorescence X-ray lines from structure materials and kaonic X-ray lines. The applied procedure to extract the spectrum of the kaonic hydrogen K transitions is as follows: the continuous background is fitted with a cubic function, the kaonic K_α line is disentangled from the partially overlapping fluorescence K_α line from iron (any iron contamination in the setup was avoided but still a small background of iron X-rays was present) and the sensitivity of different assumptions on the higher K lines (n≥4) yields is tested. The intensity of the iron K_α is obtained from the fit of the background data. For the fit of the kaonic hydrogen data this intensity is varied within the error bars. As fit parameters are used the intensities of the kaonic K_α, K_β, and K_γ lines, the strong interaction width of the 1s ground state (which is reflected in the X-ray line width) and the energy position of the kaonic K_α line. The fit range for the kaonic hydrogen data leaves out the region of the kaonic hydrogen n≥4 lines because of the uncertainty of their yields. The stability of the fit result is tested by varying the fit range.

4 Preliminary results

After subtraction of all the background components the resulting energy spectrum of kaonic K lines is obtained, as shown in Fig. 2. We find a repulsive interaction kaon-proton shown by the shift to lower energy, verifying the result obtained by the KpX experiment. The K_β and K_γ lines are disentangled for the first time. We find that the strong interaction shift ϵ_{1s} and the width Γ_{1s} in the ground state are

$$\epsilon_{1s} = -193 \pm 37(stat.) \pm 6(syst.)\ \mathrm{eV}, \tag{3}$$

$$\Gamma_{1s} = 249 \pm 111(stat.) \pm 30(syst.)\ \mathrm{eV}. \tag{4}$$

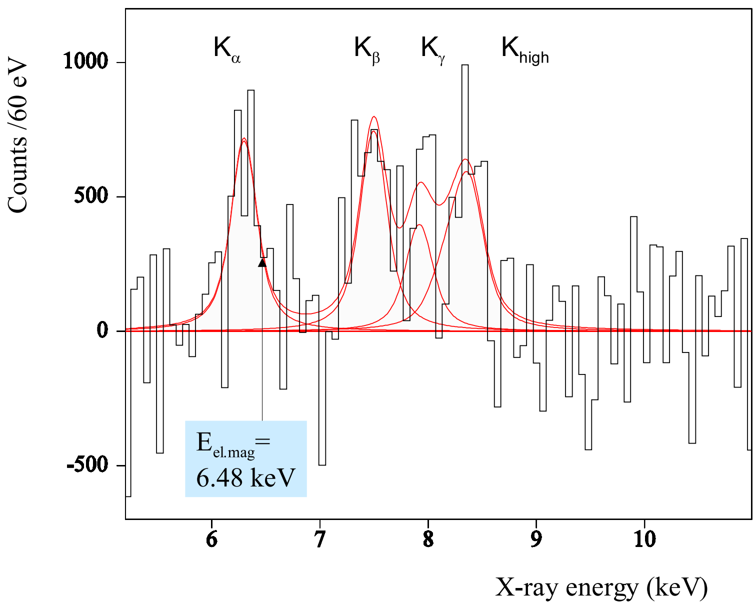

Fig. 2. The energy spectrum of kaonic hydrogen X rays after subtracting all the background components is displayed showing the separated lines of the K_α,K_β and K_γ transitions. Indicated is also the pure electromagnetic value for the K_α transition of 6.48 keV.

Applying the Deser-Goldberger-Baumann-Thirring formula(1) we find for the complex K^-p scattering length:

$$a_{K^-p} = -0.468(\pm 0.089 \pm 0.015) + i\ 0.303(\pm 0.135 \pm 0.036)\ \text{fm}. \tag{5}$$

Presently new theoretical studies on kaonic hydrogen are coming up [10–15].

A recent theory [10] with a quantum field theoretic and relativistic covariant model of low-energy kaon-nucleon interaction near threshold of K^-p gives the following values:

$$\epsilon_{1s} = -203 \pm 15\ \text{eV}, \tag{6}$$

$$\Gamma_{1s} = 226 \pm 28\ \text{eV}, \tag{7}$$

which are in good agreement with our preliminary experimental results. Recently a systematic study of corrections due to electromagnetic and QCD isospin-breaking interactions on the basis of chiral perturbation theory was published [13]. Further theoretical works are in progress and succeeded already in new results e.g. the study of the energy level displacements of excited np states of kaonic hydrogen. For the shift and width of the 2p state ϵ_{2p}=0.6 meV and Γ_{2p}=2 meV are obtained [12].

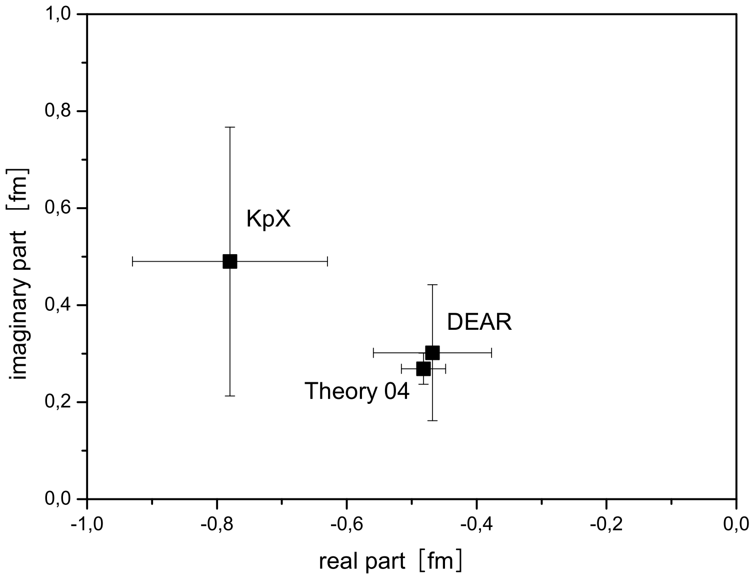

Fig. 3. The real part versus the imaginary part of the complex K^-p scattering length is plotted for the result of KpX experiment [3] and our preliminary DEAR result together with the theoretical result of ref [10]

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5 Summary and Outlook

The DEAR experiment is one of the first experiments at the DAΦNE facility. Exotic atoms like kaonic nitrogen and kaonic hydrogen were produced and studied at DAΦNE for the first time. We verified the repulsive character of the kaon-proton interaction. Our experiment gained smaller values and significantly higher precision for the strong interaction shift and width of the kaonic hydrogen ground state. Beside the kaonic hydrogen K_α line the distinct lines of K_β and K_γ were measured. The experimental approach was shown to have the potential for further experiments on kaonic hydrogen and deuterium with substantially higher precision - a precision at the percent level is anticipated. For this purpose new X-ray detectors (large area silicon drift detectors) providing timing capability are in development now (see contribution of M. Cargnelli to this conference [16]). The usage of the time correlation between kaons and X-rays will improve the signal-to-background ratio by more than 2 orders of magnitude. Together with a new target cell these X-ray detection system will open the way to the first measurement of kaonic deuterium which is challenging because the yield of kaonic deuterium is expected to be 10 times smaller than that of kaonic hydrogen.

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