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Nuclear Physics B Proceedings Supplement 00 (2012) 1–6

Nuclear Physics B Proceedings Supplement

X-ray spectroscopy of light kaonic atoms - new results and perspectives

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Abstract

The antikaon interaction on nucleons and nuclei in the low-energy regime is neither simple nor well understood. Rather direct access to this field is provided by x-ray spectroscopy of light kaonic atoms like kaonic hydrogen, deuterium and helium isotopes. A series of precision measurements on kaonic atoms was performed very successfully by the SIDDHARTA Collaboration at the DAΦNE electron-positron collider at LNF-INFN (Frascati, Italy). Consequently, new precision data on the strong interaction observables (i.e. energy shift and broadening of low-lying atomic states) were delivered having an important impact on the theory of low-energy QCD with strangeness. Presently, the follow-up experiment, SIDDHARTA-2, is in preparation, aiming at a determination of the strong interaction observables in kaonic deuterium as the highest priority; other type of measurements (light and heavier kaonic atoms) are as well foreseen. With the kaonic deuterium data the antikaon-nucleon isospin-resolved scattering lengths can be extracted for the first time. An overview of the progress and present status of experimental studies and an outlook to future perspectives in this fascinating research field is given.

Keywords:
strong interaction, exotic atoms, x-ray spectroscopy

1. Introduction

A special type of exotic atoms are the hadronic ones in which an electron is substituted by a negatively charged hadron like a π^- or an antikaon $\overline{K}$ (K^-) as orbiting particle. The principal interaction in such systems is electromagnetic. However, the strong interaction leads to an energy shift and broadening of low-lying atomic states due to the hadron-nucleus strong interaction.Among the hadronic atoms an interesting case is the one represented by the mesonic ones. The most simple mesonic atoms are hydrogen-like meson-meson systems (e.g. $\pi^+\pi^-$, $K^\pm\pi^\mp$ and pionic hydrogen (π^-p). These systems can be well described in the framework of chiral perturbation theory [1]. Very interesting is the low energy interaction with nucleons and nuclei with participation of strange quarks. Here the prototype system is kaonic hydrogen (K^-p). Due to resonances below the $\overline{K}$N threshold like the elusive Λ(1405) resonance in the s-wave just 27 MeV below the K$^-$p threshold or the Σ(1385) in the p-wave. The theoretical situation is by far more complicated. Nowadays a very successful theoretical description in this regime is presented by SU(3) effective field theory with coupled channels [2]. In the last 15 years a tremendous progress was achieved in the x-ray experiments on the lightest kaonic atoms like kaonic hydrogen and kaonic helium isotopes [3] because of new x-ray detectors like silicon-drift-detectors (SDDs) [4]. There are several sources of experimental information on the $\overline{K}$p interaction: K$^-$p forward scattering data [5], $\Sigma\pi$ mass spectrum, threshold branching ratios [6] and last-but-not data from the least x-ray experiments. A big advantage of x-ray studies of hadronic atoms is the rather direct access to the strong interaction observables - the shift ϵ and width Γ of atomic states [7].

- Kaonic hydrogen: shift and width of the 1 s state of K$^-$p (ϵ^p_{1s}, Γ^p_{1s})
- Kaonic deuterium: shift and width of the 1 s state of K$^-$d (ϵ^d_{1s}, Γ^d_{1s})
- Kaonic helium isotopes: shift and width of the 2p state of K-^{3,4}He ($\epsilon^{^{3,4}He}_{2p}$, $\Gamma^{^{3,4}He}_{2p}$)

The history of x-ray studies of kaonic hydrogen is already an old one. In former experiments the sign of the energy shift was found to be positive and thus contradicting the negative sign from the scattering data. This puzzling situation was clarified by an experiment at KEK [8, 9] which obtained a negative shift. Afterwards this finding was verified in the DEAR experiment [10] at DAΦNE collider of LNF/INFN. The most recent SIDDHARTA experiment at DAΦNE on kaonic hydrogen achieved the most precise values of the strong interaction observables, i.e. shift ϵ^p_{1s} and width Γ^p_{1s} of the 1s ground state [11].These data are extremely important constraints for the theory of the antikaon-nucleon interaction and triggered new studies [12]. It has to be pointed out that the understanding of the $\overline{K}$N interaction is extremely important for the question of deeply bound kaonic systems like the prototype system K$^-$pp. This topic was studied experimentally [13] and theoretically [14] for many years. There are indications for the existence from FINUDA [15], DISTO [16] and other experiments. However, this issue is still controversial.

2. Experimental results on the $\overline{K}N$ interaction

The strong interaction in light kaonic atoms is studied by precision x-ray spectroscopy of the Lyman (kaonic hydrogen) or Balmer (kaonic helium) x-ray transitions respectively. The shift is given by the deviation from the pure electromagnetic transition energy which can be calculated with sufficient precision (~ 1eV) using the Klein-Gordon equation and taking the QED corrections like vacuum ploarization into account. It has to be noted that only the lowest quantum states are measurably affected by the strong interaction (e.g. ground state 1s in the case of kaonic hydrogen). The up-to-now most precise data on the strong interaction in kaonic hydrogen were obtained in the x-ray spectroscopy by the SIDDHARTA experiment [11] at the DAΦNE electron-positron collider at Laboratori Nazionali di Frascati of INFN. Furthermore, new data on the antikaon-helium-4 [17] interaction and for the first time x-ray data of kaonic helium-3 [18] were measured. The x-ray spectroscopy of kaonic deuterium is challenging because of the anticipated low x-ray yield of the Lyman transitions and the larger broadening of the x-ray lines. A first exploratory study was done within the SIDDHARTA experiment [19]. The requirements of a kaonic deuterium measurement will be fulfilled in the future SIDDHARTA-2 experiment which will provide stringent contraints for the antikaon-nucleon interaction at low energy.

2.1. Status of K$^-$ - proton interaction

The SIDDHARTA experiment used the unique kaon source of DAΦNE where the K$^-$ mesons are emitted in the decay of the Φ vector meson $\Phi \rightarrow K^- + K^+$ which has a branching ratio of ~ 49%. The big advantages are the nearly mono-energetic K$^-$ with a low momentum of 127 MeV/c emitted in a back-to back correlation with the K$^+$. Furthermore the initial hadronic background is much smaller than in an extracted beam. Because of the low momentum of the K$^-$ the kaons can be stopped in low-density gas targets thus avoiding kaon loss due to the Stark effect. In the SIDDHARTA experiment the x-ray transitions in kaonic hydrogen atoms were measured with a ring-shaped array of Silicon Drift Detectors (SDDs) [20] exhibiting a large solid angle, high intrinsic efficiency in the region of interest, very good energy resolution (ΔE ~ 150 eV at 5.9 keV) and timing information. Especially important is the timing capability to overcome a limitation of the former DEAR experiment which suffered from the high asynchronous background. With the time correlation between the incoming

K^- and the emitted x-ray the asynchronous background can be suppressed by orders of magnitude.

The SIDDHARTA experimental setup is shown in fig.1. The cryogenic gas target is surrounded by the SDD array consisting of 144 SDDs each with 1 cm^2 active area. The negatively charged kaons are stopped in the cryogenic hydrogen gas kept at 23 K.

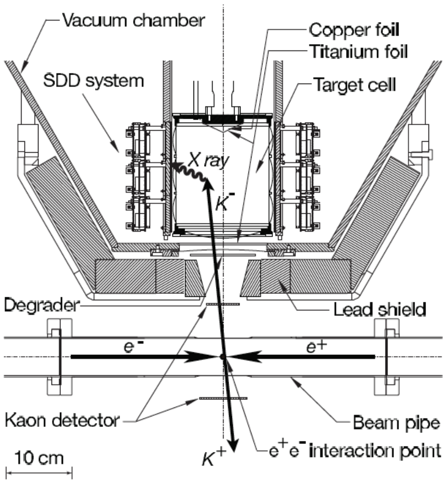

Figure 1: Sketch of the SIDDHARTA experimental setup.

The measured x-ray spectrum shows in the region of interest the K_α, K_β and higher K transitions (see fig.2) of the kaonic hydrogen. One can see the deviation of the K_α peak from the calculated position without the contribution of the strong interaction.

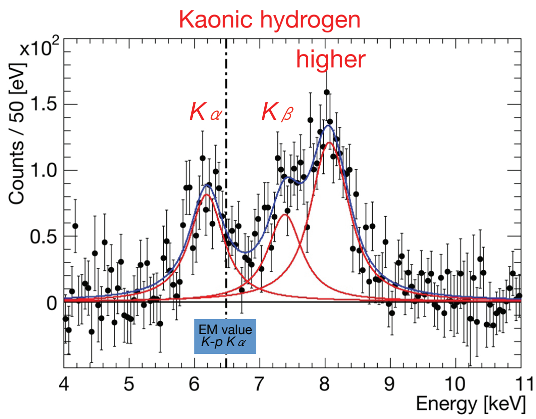

Figure 2: X-ray enery spectrum of kaonic hydrogen in the range from 4 to 11 keV. All background components are removed. The calculated electromagnetic value for the K_α line is indicated.

The deviation from the pure electromagnetic transition energies of the Lyman lines and the line broadening due to strong interaction was determined using the following convention.

shift[eV]	width[eV]	ref.
+40±60	0^{+230}_{-0}	[21]
+370±80	560±260	[22]
+193±60	80^{+220}_{-80}	[23]
-323±63(stat.)±11(syst.)	407±208(stat.)±100(syst.)	[8]
-193±208(stat.)±100(syst.)	249±111(stat.)±30(syst.)	[10]
-283±36(stat.)±6(syst.)	541±89(stat.)±22(syst.)	[11]

Table 1: Results of x-ray experiments on kaonic hydrogen. The old experiments performed at NIMROD/Rutherford Lab. and CERN in the 70's and 80's obtained a positive shift value in contradiction to scattering data. The newer experiments KpX, DEAR and finally SIDDHARTA obtained consistent negative values for the shift.

$$\epsilon^p_{1s} = E^{meas.}_{np\to 1s} - E^{calc.}_{np\to 1s} \quad (1)$$

Here $E^{meas.}_{np\to 1s}$ stands for the measured transition energies and $E^{calc.}_{np\to 1s}$ for the calculated pure electromagnetic energies. Finally we got the following values for the strong interaction parameters:

$$\epsilon^p_{1s} = -283 \pm 36(stat) \pm 6(syst)eV \quad (2)$$

$$\Gamma^p_{1s} = 541 \pm 89(stat) \pm 22(syst)eV. \quad (3)$$

A comparison of the results of recent experiments on kaonic hydrogen is given in the fig.3.

From the observables ϵ^p_{1s} and Γ^p_{1s} one is able to determine the K^--p scattering length a_p. For the extraction of a_p the Deser-Trueman formula [24, 25] was used in the past:

$$\epsilon^p_{1s} + \frac{i}{2}\Gamma^p_{1s} = 2\alpha^3\mu_c^2 a_{K^-p} \quad (4)$$

α is the fine structure constant and μ_c the reduced mass.
This simple formula (4) had to be refined in order to take into account Coulomb corrections. An improved Deser-type formula was accordingly developed [26].

$$\epsilon^p_{1s} + \frac{i}{2}\Gamma^p_{1s} = 2\alpha^3\mu_c^2 a_{K^-p}(1 - 2\alpha\mu_c(ln\alpha - 1)a_{K^-p}) (5)$$

Applying the equation 5 to the SIDDHARTA ϵ^p_{1s} and Γ^p_{1s} data [27] the K^-p scattering length can be deduced

$$a_{K^-p} = -0.65(\pm 0.10) + i0.81(\pm 0.15)fm \quad (6)$$

There is intense activity in theoretical studies using our SIDDHARTA result with significant progress. As an example a recent theoretical result (NLO calculation)

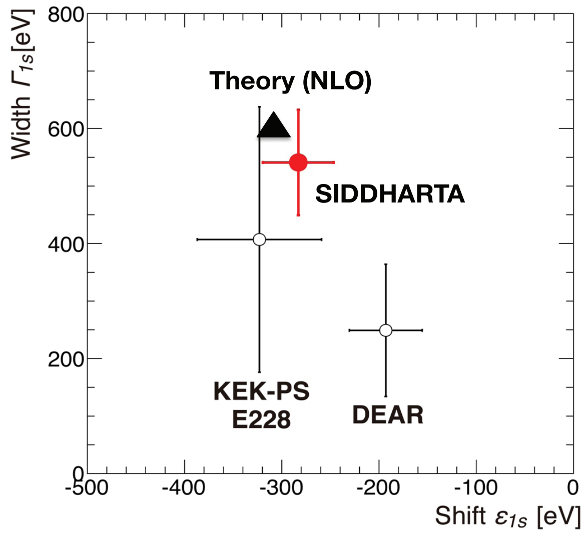

Figure 3: Comparison of recent experimental results on shift and width of kaonic hydrogen (KEK-PS E228 [8], DEAR [10] and SIDDHARTA [11]). For a comparison as an example of recent theoretical studies the result (triangle) of a next-to-leading-order calculation [12] is shown.

[12] obtained a_{K^-p}=-0.70 + i 0.89 fm which is consistent with the experimental result 6.

An equivalent equation can be applied to give the K$^-$d scattering length a_{K^-d}.

The relation between a_{K^-p} and the isospin (F=0,1) resolved scattering lengths a_0 and a_1 is given by

$$a_{K^-p} = (a_0 + a_1)/2 \qquad (7)$$

In order to extract a_0 and a_1 one needs the information about the K$^-$n scattering length since K$^-$n $=a_1$.

2.2. *Status of K$^-$d interaction*

In spite of the big success of SIDDHARTA some goals are still to be reached with new sophisticated experiments. In SIDDHARTA we performed an exploratory study with a deuterium target filling. Due to low statistics and high background the shift and width of the kaonic deuterium K lines is still an open issue. Therefore, top priority for the follow-up experiment SIDDHARTA-2 is the measurement of the shift and width of the ground state of kaonic deuterium providing the most stringent constraint on the isospin-dependent antikaon-nucleon interaction.

The anticipated shift and width from theoretical studies are an important input for the planning of SIDDHARTA-2. There are some theoretical studies on ϵ_{1s} and Γ_{1s} values in kaonic deuterium [28, 29]. Recently values with estimated uncertainties for the shift 779±170 eV and for the width 650±280 eV were obtained [30].

The main challenges of the kaonic deuterium experiment are the low X-ray yield of the Lyman np→1s transitions depending on the hadronic width of the 2p state and the challenging signal-to-background ratio. Numerous improvements of the experimental techniques are foreseen for the kaonic deuterium X-ray study.

- Trigger geometry and target density: By placing the upper kaon-trigger detector closely in front of the target entrance window, the probability that a triggered kaon really enters the gas and is stopped there is much enlarged. Making the detector smaller than the entry area gives away some signal, but suppresses efficiently the kaonic lines from ”wall stops” (kaons entering the gas volume, but passing from inside to the cylindrical target walls). The ”signal per trigger” number goes up, which also reduces the accidental background coming along with every trigger. We intend to double the gas density which enhances the gas stops and further reduces the wall stops.

- K$^+$ discrimination by 2 complementary methods: A ”kaon stopper” scintillator is placed directly below the lower kaon trigger. When a K$^-$ stops there, only one (large) signal from pileup of stopping and kaon-absorption secondaries is seen, however in the case of a K$^+$, the kaon-decay particles are seen after the signal from the stopping (mean lifetime 12.8 ns), with a flash-ADC we will be able to distinguish the 2 cases with high efficiency. In addition we will use scintillators surrounding the target to measure K$^-$ absorption secondaries (pions). The time-window for gas stops is about 4 ns wide. By this condition we also suppress stops in the entry window.

- Active shielding: The scintillators surrounding the target will also be used as a prompt anticoincidence if the spatial correlation of SDDs hit and scintillator indicates that the hit has originated from a pion (”charged particle veto”). An anticoincidence covering the SDD time window of about 600 ns (with an exception of the 4ns of the stopping time in the gas) will reduce the accidental background. Although the scintillators have only low efficiency for gamma rays, the high rate of secondaries from the electromagnetic showers allows a relevant reduction of accidental ("beam") background. Remarkably, the upper trigger scintillator has 2 functions, it is also used as an anticoincidence counter: after the passing of the kaon and eventual prompt kaon-absorption secondaries, it vetos beam-background.

- Operation of SDDs at lower temperature using liquid argon: tests indicate that an improvement of the timing resolution by a factor of 1.5 is feasible by more cooling, i.e. going down to ∼185K. The energy resolution decreases somewhat, but will still be sufficient for the broad kaonic deuterium x-ray transitions.

- The signal enhancement is due to moving the target cell closer to the IP, by changing its shape, by better solid angle of the SDDs and by the higher gas-density.

According to our preliminary studies the signal can be improved by a factor 2 and the signal-to-noise ratio by about twenty.

In Fig. 4 we show a Monte Carlo simulation of the SIDDHARTA-2 expected kaonic deuterium spectrum, obtained for an integrated luminosity of about 800 pb^{-1}. It allows the determination of the strong interaction induced parameters (shift and width) with a relative precision of ∼10% and ∼20% respectively.

3. X-ray experiments on light kaonic atoms

The study of kaonic helium isotopes open the access to the interaction of antikaons with simple nuclei. In kaonic helium the Balmer x-ray transtions (e.g. 3d → 2p) are in a similar energy range like the kaonic hydrogen Lyman lines. The big advantage of kaonic helium is the much higher x-ray yield compared to kaonic hydrogen. Therefore, in SIDDHARTA the measurement of kaonic helium-4 was also used as check of the experiment but has also high importance for the understanding of the physics involved. The large shift found in old experiments can be ruled out. However, theoretical studies yielded a possible 2p state shift of up to ∼10eV and a isotopic difference between K^-He-3 and K^-He-4 [32] under the assumption of the existence of kaonic nuclear bound states. A possible isotopic difference between haonic He-3 and He-4 cannot be ruled out by the SIDDHARTA data. New experiments on kaonic He-3 are planned at J-PARC with enhanced sensitivity [33, 34].

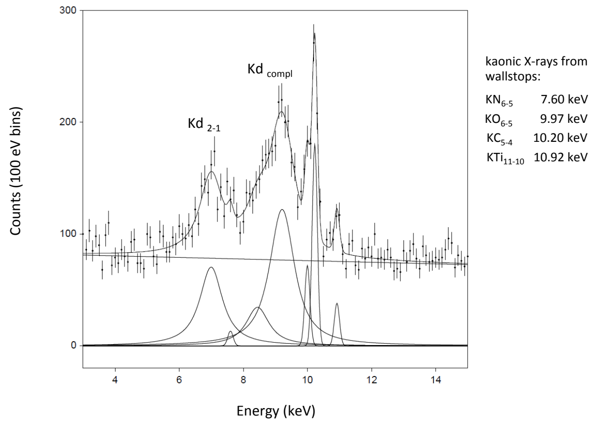

Figure 4: A Monte Carlo simulation of the kaonic deuterium x-ray spectrum with the K_α and hight K lines indicated [31]. Here as input parameters ϵ_{1s}=-800 eV and Γ_{1s}=800 eV and an integrated luminosity of 800 pb^{-1} were used. Additional background kaonic x-ray lines (e.g. transitions in kaonic nitrogen, oxygen and carbon - see insert right) are due to wallstops in the structure materials

4. Conclusions

The SIDDHARTA collaboration finalized the kaonic hydrogen data analysis recently and obtained values of the low-energy strong interaction parameters of kaonic hydrogen with unprecedented accuracy. Therefore, crucially improved constraints for the theory are presently available. The impact of SIDDHARTA on the theoretical work on the K^--nucleon interaction at threshold is remarkable. Subsequently a consistent picture was achieved using effective field theory with coupled channels and putting together various sources of information on the antikaon-nucleon interaction [12]. Motivated by the big success of SIDDHARTA an extremely important information for understanding better the low-energy QCD in the strangeness sector is still missing - the case of kaonic deuterium has the highest priority for the SIDDHARTA follow-up experiment SIDDHARTA-2.

Acknowledgment

We thank C. Capoccia, G. Corradi, B. Dulach, and D. Tagnani from LNF-INFN; and H. Schneider, L. Stohwasser, and D. Stückler from Stefan-Meyer-Institut, for their fundamental contribution in designing and building the SIDDHARTA setup. We thank as well the DAΦNE staff for the excellent working conditions and permanent support. Part of this work was supported by

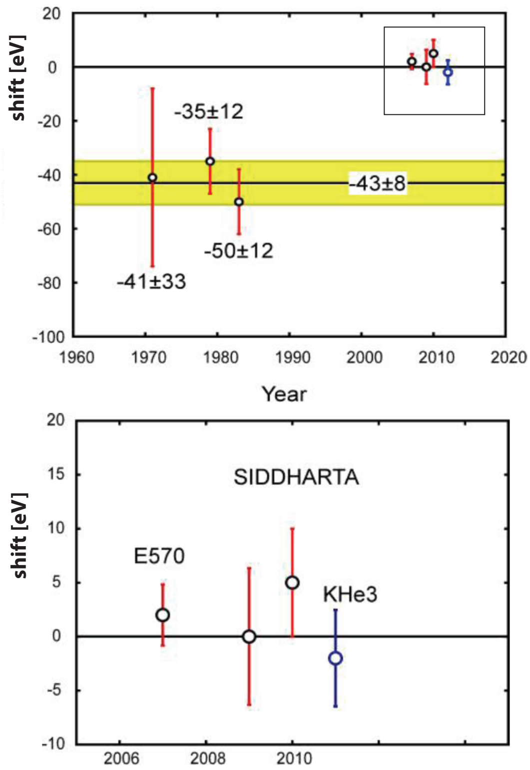

Figure 5: Results on the 2p level shift obtained in x-ray experiments. The old experiments [35, 36, 37] revealed an average of ϵ_{2p}=43±8 eV for kaonic ^{4}He whereas the results of the recent experiments [38, 17] give a very small shift. The SIDDHARTA experiment measured ϵ_{2p} for ^{3}He for the first time [18] and obtained a small value also in this case.

the European Community-Research Infrastructure Integrating Activity "Study of Strongly Interacting Matter" (acronym HadronPhysics2, Grant Agreement no. 227431) under the Seventh Framework Programme of EU; HadronPhysics I3 FP6 European Community program, Contract No. RII3-CT-2004-506078; Austrian Federal Ministry of Science and Research BMBWK 650962/0001 VI/2/2009; Romanian National Authority for Scientific Research, Contract No. 2-CeX 06-11-11/2006; and the Grant-in-Aid for Specially Promoted Research (20002003), MEXT, Japan.

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