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Spectroscopy of kaonic atoms at DAFNE and J-PARC

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Abstract. The interaction of antikaons (K^-) with nucleons and nuclei in the low-energy regime represents a very active research field in hadron physics. A unique and rather direct experimental access to the antikaon-nucleon scattering lengths is provided by precision X-ray spectroscopy of transitions in low-lying states in the lightest kaonic atoms (i.e. kaonic hydrogen and deuterium). In the SIDDHARTA experiment at the electron-positron collider DAFNE of LNF-INFN we measured the most precise values of the strong interaction observables in conic hydrogen. The strong interaction on the 1s ground state of the electromagnetically bound K-p atom causes an energy shift and broadening of the 1s state. SIDDHARTA will extend the spectroscopy to kaonic deuterium to get access to the antikaon-neutron interaction and thus the isospin dependent scattering lengths. At J-PARC a kaon beam is used in a complementary experiment with a different setup for spectroscopy of kaonic deuterium atoms. The talk will give an overview of the of the upcoming experiments SIDDHARTA and the complementary experiment at J-PARC.Furthermore, the implications of the experiments for the theory of low-energy strong interaction with strangeness will be discussed.

1 Introduction

In the low-energy domain the interaction of antikaons (K^-) with nucleons and nuclei numerous studies in experiment and theory were performed (for reviews see [1]). From the

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spectroscopy of higher Z kaonic atoms the potential of the $\overline{K}N$ interaction could be determined but it turns out that one has to take corrections in these multi-nucleon systems into account. The experiments with kaonic hydrogen and deuterium are of special interest these systems give a rather straightforward access to the K^- interaction on the two isospin channels of the nucleon. In the $\overline{K}N$ interaction in the kaonic atoms the sub-threshold resonance $\Lambda(1405)$ has a strong impact. It influences strongly the hadronic shift and width of the 1s groundstate at threshold. On the other hand it is still in discussion whether the $\Lambda(1405)$ is a one-pole or two-pole resonance [2]. The elementary case of the antikaon interaction with the nucleons give information about $\Lambda(1405)$ and it can be studied with kaonic hydrogen X-ray spectroscopy. In the past the results were puzzling, but could solved by an experiment at KEK [3]. The interaction of K^- ($\overline{K}$) with nucleons in the two isospin states can be precisely determined by X-ray spectroscopy of the simplest kaonic atoms, i.e. kaonic hydrogen and kaonic deuterium. In these exotic atoms the strong interaction leads to an energy shift ϵ_{1s} from the calculated electromagnetic value (i.e. without strong interaction) and a broadened width Γ_{1s} of the 1s ground state. By measuring the X-ray transitions to the 1 s state ϵ_{1s} and Γ_{1s} can be determined. Recently advances in the theoretical description of the $\overline{K}N$ interaction on the basis of field theory were made. The measured hadronic shift and width of kaonic hydrogen are used as anchor points for these calculations. In order to determine the isospin-separated scattering length for the isospin I=0 scattering length a_0 scattering length and the I=1 scattering length a_1, respectively.

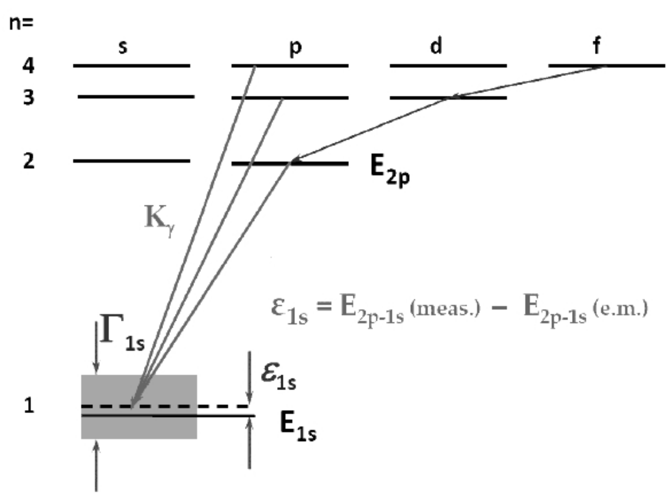

Figure 1. Transitions to the 1s ground state in kaonic hydrogen. Only the 1s state is measurably influenced by the strong antikaon-nucleon interaction. The calculated electromagnetic transition energy is about 6.5 keV which can be precisely measured with SDDs.

The lightest kaonic atom is the K^-p atom in which the principal interaction is the electromagnetic interaction accompanied by the strong interaction of the kaon with the proton which is measurable by X-ray spectroscopy of the radiative transitions from the p states (2p, 3p, ... for n=2,3,....) to the 1s ground state (K transitions). The energy shift ϵ_{1s} is calculated by Equ.1, ϵ_{1s} is given by the difference between the measured $E^{meas.}_{np\rightarrow 1s}$ and the calculated electromagnetic transition energy $E^{em}_{np\rightarrow 1s}$.

$$\epsilon_{1s} = E^{meas.}_{np\to 1s} - E^{em}_{np\to 1s}. \tag{1}$$

With the following improved Equ.2 [4] the scattering K^--p length a_p can be calculated taking corrections ito account

$$\epsilon_{1s} + \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu_c^2 a_p(1 - 2\alpha\mu_c(ln\alpha - 1)a_p). \tag{2}$$

Equ.3 gives the relation of this scattering length a_p to the isospin-dependent scattering lengths a_0 (isospin 0) and a_1 (isospin 1).

$$a_p = \frac{1}{2}(a_0 + a_1). \tag{3}$$

The measurement of X-ray spectrum of kaonic hydrogen imposes a challenge due to the small amount of kaons to be stopped in a low-density hydrogen gas and X-ray yield. In the framework of SIDDHARTA the experimental studies on kaonic atoms at DAΦNE were focused on the X-ray spectroscopy of kaonic hydrogen and helium isotopes taking advantage of the ideal conditions of this Φ-factory: Low-momentum (127 MeV/c) K^- emitted back-to-back in the Φ two-body decay (branching ratio of about 50 %. The SIDDHARTA experiment employed silicon drift detectors (SDDs) for X-ray spectroscopy. A triple coincidence of X-ray and the back-to back emitted kaons from the Φ meson decay are possible due to the timing capability of SDDs. These successful experiments will be complemented by a first measurement of the even more challenging study of the X-ray spectrum of kaonic deuterium.

2 SIDDHARTA results on light kaonic atoms

SIDDHARTA succeeded in essential experimental results using the low-energy kaons from DAΦNE and an array of SDD X-ray detectors.

2.1 Kaonic helium isotopes

SIDDARTA had many successes like the first measurement of the strong interaction in kaonic helium-3 [5] and the first measurement of kaonic helium-4 in a gas target [6].

2.2 Kaonic hydrogen

Certainly the highlight of SIDDHARTA was the up-tonow most precise measurement of the strong interaction in kaonic hydrogen. Out of these data ϵ_{1s} and Γ_{1s} could be determined at unprecedented precision [7].

$$\varepsilon_{1s} = -283 \pm 36(stat) \pm 6(syst)eV. \tag{4}$$

$$\Gamma_{1s} = 541 \pm 89(stat) \pm 22(syst)eV. \tag{5}$$

Furthermore, the X-ray yields of the K transitions in kaonic hydogen were determined which is important for the understanding of the electromagnetic cascade processe in hadronic atoms [8].

SIDDHARTA also performed an exploratory X-ray study with a pure deuterium filling. An upper limit for the X-ray yield of the K lines could be extracted from the data: total yield <0.0143, Kα yield <0.0039 [9]. However, ϵ_{1s} and Γ_{1s} could not be determined due to the limited statistics and the background condition. Nevertheless, this study is important for the planning of the SIDDHARTA 2 experiment on kaonic deuterium.

To determined a_0 and a_1 it is necessary to measure strong interaction shift and width of kaonic deuterium. This is a far more challenging experimental issue. The kaonic deuterium case is still open and will be studied by SIDDHARTA-2 applying a significantly improved setup.

3 Kaonic deuterium with SIDDHARTA2

Experimentally the case of kaonic deuterium is still open and challenging due to the anticipated low X-ray yield (~ 10 % of the kaonic hydrogen yield) which demands highly efficient X-ray detection and the expected larger hadronic width [10–14] which requests largely improved background suppression. For the Monte Carlo simulation of the kaonic deuterium X-ray spectrum a value of 800 eV for shift and width were used according to theory.

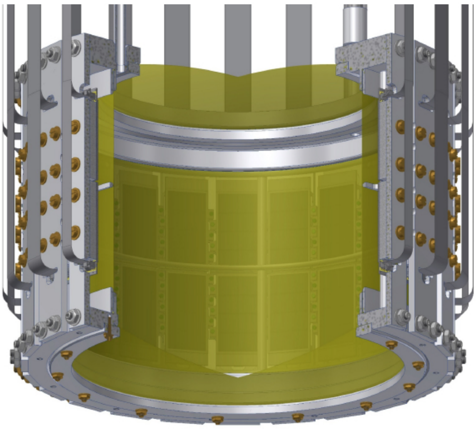

Figure 2. Design of the gas volume of SIDDHARTA 2 which provides the mandatory stabilty and the transmission for X-rays. The volume will be surrounded by arrays of X-ray detectors and shielding devices.

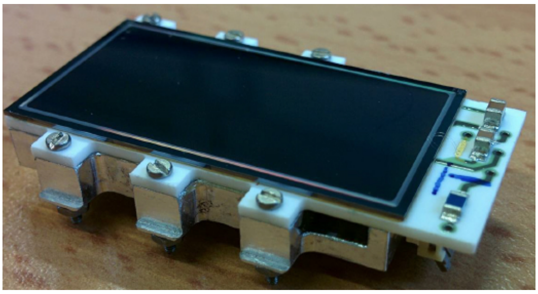

Figure 3. New SDD X-ray detectors for SIDDHARTA2 with a cell area of 64 mm^2, total area of 512mm^2. The detectors will be cooled to about 170K and have a drift time of smaller than 500ns.

A new experiment SIDDHARTA-2 [15–17] is planned which is based on a strongly improved apparatus. The improvements include an optimized geometry, deuterium gas density, discrimination of K^+, active shielding and better SDD timing performance by cooling. According to Monte Carlo studies one expects an X-ray energy spectrum for an integrated luminosity of 800 pb^{-1} shown in Fig. 4. For the hadronic shift and width one expects 30eV and 80 eV, respectively [18]. This experiment is planned for DAΦNE and in a complementary experiment at J-PARC.

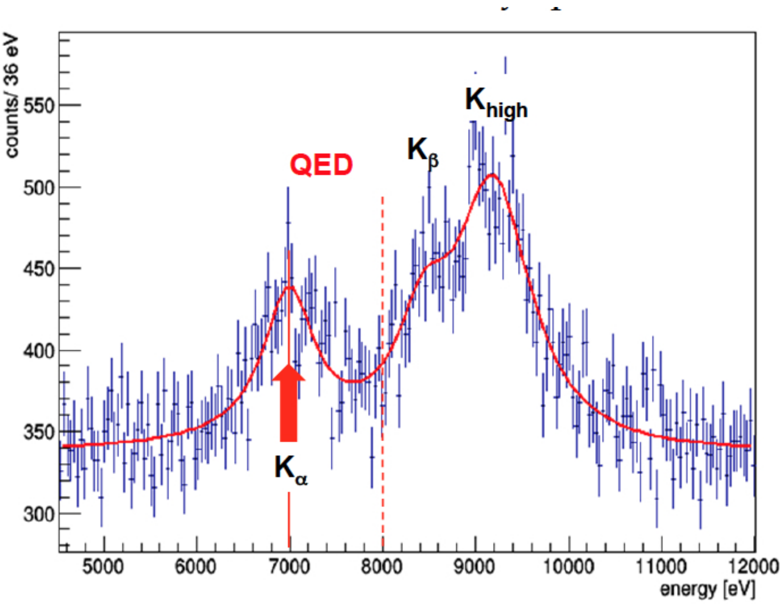

Figure 4. GEANT4 simulated kaonic deuterium X-ray spectrum (the pure electromagnetic 2p-1s transition is indicated by an arrow) with a detector active area of 246 cm^2 and assuming $\epsilon_1 s$=-800 eV and $\Gamma_1 s$=800eV [19]. Withe a K_{alpha} yield of 0.1 percent the signal-to-background ratio is 1:4.

4 Kaonic deuterium at J-PARC

An experiment on kaonic deuterium [20, 21] - complimentary to SIDDHARTA2 at LNF - will be performed at J-PARC (E57) using the K1.8BR kaon beam line and particle tracking by the central drift chamber (CDC) of the J-PARC-E15 experiment. The pure cryogenic deuterium target will be installed In the centre of the spectrometer and for the X-ry spectroscopy SDD derectors will surrounfd the target cell. The light-weight target cell is designed for a density of 5 % of liquid hydrogen density for sufficienty kaon stopping. Since the momentum of the kaon beam is higher than in the case of SIDDHARTA 2 a massive degrader has to be installed in front of the deuterium target. The particle tracking with the large acceptence CDC will allow for an efficient background reduction. According to Monte Carlo simulations the hadronic shift and width of the K transitions in kaonic deuterium can be measured with a comparable precision like in SIDDHARTA2 - but with different systematics.

5 Summary

After the successful experiments of SIDDHARTA new experiments at LNF and J-PARC are in preparation for measuring the hadronic shift and width of kaonic deuterium using X-ray spectroscopy. For the first time the interaction in both isospin channels will be quantitatively studied and the scattering lengths a_0 and a_1 will be extracted. These data will have tremendous impact on the theory of antikaon-nucleon interaction [22, 23], which might also have implications in the question about strangeness in the universe.

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