Precision X-ray spectroscopy of kaonic atoms as a probe of low-energy kaon-nucleus interaction

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Abstract. In the exotic atoms where one atomic $1s$ electron is replaced by a K^-, the strong interaction between the K^- and the nucleus introduces an energy shift and broadening of the low-lying kaonic atomic levels which are determined by only the electromagnetic interaction. By performing X-ray spectroscopy for Z=1,2 kaonic atoms, the SIDDHARTA experiment determined with high precision the shift and width for the $1s$ state of $K^- p$ and the $2p$ state of kaonic helium-3 and kaonic helium-4. These results provided unique information of the kaon-nucleus interaction in the low energy limit.

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1 Introduction

Precision X-ray spectroscopy of the Z=1,2 kaonic atoms holds the key to understand the low-energy interaction between the kaon and the nucleus. In kaonic hydrogen which is the simplest kaonic atom, the strong interaction induced shift and width of the $1s$ state can be deduced from the K-series X-rays, and they are related to the s-wave $K^- p$ scattering length $a_{K^- p}$ through the Deser-Trueman formula [1]. This scattering length consists of two isospin dependent components of a_0 (I=0) and a_1 (I=1), which are among the most fundamental parameters for the low-energy $\bar{K}N$ interaction, and which can only be derived experimentally from X-ray spectroscopy. To disentangle these two components, precise measurement of the kaonic deuterium $1s$ shift and width is necessary, further taking into account higher order contributions from the three-body interaction [2]. Experimentally this measurement is extremely difficult mainly due to the small X-ray yield and the broad width of the $1s$ level. Until now an unambiguous detection of the kaonic deuterium X-rays has not been achieved and the measurement remains to be the major challenge of upcoming experiments.

For the Z=2 kaonic atoms, there had been a long-standing discrepancy between the theoretical and the measured strong-interaction induced shift of the $2p$ level of kaonic helium-4. This "kaonic helium puzzle" was solved by the KEK E570 experiment which showed the $2p$ level shift was 2 ± 2(stat) ± 2(syst) eV [3], refuting the previous average shift of about - 40 eV from three early experiments [4–6]. More essentially, the precise measurement of the kaonic helium $2p$ level shift is a test ground for possible deeply-bound kaonic nuclear states predicted by Akaishi and Yamazaki [7, 8]. A series of electronvolt precision measurement of the shift and the width of the $2p$ level for both kaonic helium-3 and kaonic helium-4 atoms can effectively narrow down the allowed range of the nuclear potential of kaon in the search of deeply-bound states.

The measurements we have performed in the SIDDHARTA experiment will be introduced in detail next.

2 The SIDDHARTA experiment

2.1 Experimental method

The experiment was performed at the DAΦNE $e^- e^+$ collider in Frascati, Italy. The beam energies are tuned to produce ϕ (1020) resonance at rest in the lab frame, and then with a 49% branching ratio the ϕ decays into a pair of $K^+ K^-$. As the kaon detectors, we used two plastic scintillators placed above and below the interaction point as illustrated in Fig. 1. The kaons are distinguished from the minimum ionizing particles using the time of flight information at the kaon detectors. And then from the coincidence of the two scinillators we defined the kaon trigger, which marks the timing of the incident kaons.

A fraction of the negatively charged kaons that made the kaon trigger will stop inside the volume of the gaseous target placed about 20 cm above the interaction point to form kaonic atoms. With the time correlation between the subsequent X-rays detected by the SDDs and the kaon trigger, one can distinguish the kaon origin X-rays from the background coming from the processes that are asynchronous to the kaon pair production.

With a total active area of 144 cm^2, the SDDs cover about 10% of the solid angle around the target cell. The energy calibration of the SDDs were done every few hours by shining Ti and Cu foils with an X-ray tube. Using the K_α lines of Ti (4.5 keV) and Cu (8.0 keV), we determined the scale of the energy spectra, and the energy resolution at 6 keV was stable at about 150 eV (FWHM) throughout our measurement. At the operating temperature of 140 K, the SDDs showed a timing resolution of 700 FWHM, effectively rejected the asynchronous background by four orders of magnitude. The

configuration and the performance of the detectors are discussed in detail in previous publications of the SIDDHARTA experiment [9, 10].

During the data taking in 2009, we accumulated data with gaseous targets of hydrogen (1.3 g/l), deuterium (2.50 g/l), helium-3 (0.96 g/l), and helium-4 (1.65 g/l and 2.15 g/l).
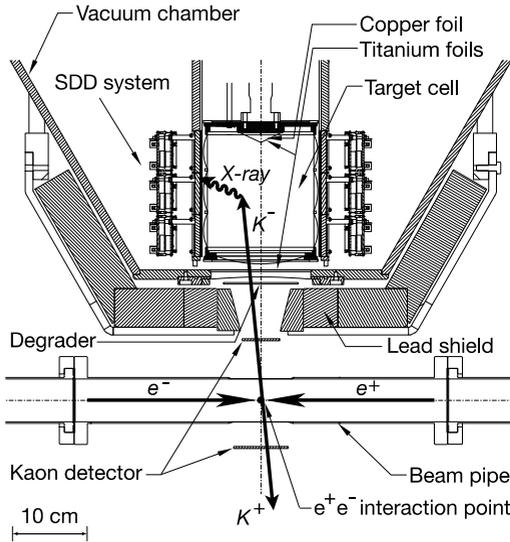
Figure 1. A schematic cutaway view of the SIDDHARTA setup at the DAΦNE interaction point. The charged kaon pairs are identified with two plastic scintillators, and the K^- induced X-rays detected by the SDDs are identified from the time correlation to the kaon pair events.

2.2 Kaonic hydrogen and deuterium

The main objective of the SIDDHARTA experiment is the precise measurement of the kaonic hydrogen K-series X-rays, thus most of the beam time was dedicated to the hydrogen target measurement to a total intergrated luminosity of 340 pb^{-1}. A total amount of 100 pb^{-1} integrated luminosity was dedicated to the first exploratory kaonic deuterium measurement.

In the final analysis to derive the $1s$ shift ϵ_{1s} and width Γ_{1s} of kaonic hydrogen, the kaonic X-ray spectra from the two data sets were fitted simultaneously. As the yield of the kaonic deuterium K-series X-rays is more than one order of magnitude smaller than that of the kaonic hydrogen, the spectrum from the deuterium target measurement helped determining the background X-rays from other kaonic atoms when the K^- stopped inside the target cell made of Kapton. This combined analysis contributed to reduce the systematic errors in the kaonic hydrogen results, which achieved the best precision up to date for the $1s$ shift ϵ_{1s} = -283 ± 36 (stat.) ± 6 (syst.) eV and for the width Γ_{1s} = 541 ± 89 (stat.) ± 22 (syst.) eV [10]. The results solved the discrepancy between two recent kaonic hydrogen X-ray experiments KpX in KEK [11] and DEAR at DAΦNE [12], in that the two results do not overlap with each other within error bars. The improved precision presents more stringent constrains to the theoretical study of the low-energy QCD near the K^-p threshold.

From the deuterium target spectrum which showed no significant amount of signal of kaonic deuterium X-rays, we evaluated an upper limit for the yield of the kaonic deuterium K_α X-ray as

$Y(K_\alpha) < 0.0039$ (C.L. 90%) [13]. It presents an important reference to plan for the future precision measurement of kaonic deuterium X-rays.

2.3 Kaonic helium-3 and helium-4

The strong interaction induced $2p$ level shift and width are measured for both kaonic helium-3 and helium-4 atoms, and it is the first time that kaonic helium-3 X-rays are measured. The results of the shift as listed in 1 are consistent with the results of E570 [3], thus a zero-compatible shift of the $2p$ level from experiment is established, which is in agreement with the theoretical estimations in [6, 15]. We have not found abnormally large widths which can directly support the estimations made in conjunction with the prediction of a deeply-bound kaon states[7, 8].

Table 1. Results on the energy shifts (ΔE_{2p}) and widths (Γ_{2p}) of the kaonic helium-3 and kaonic helium-4 $2p$ states [9, 14].

Target	ΔE_{2p} [eV]	Γ_{2p} [eV]
helium-4	+5 ± 3 (stat.) ± 4 (syst.)	14 ± 8 (stat.) ± 5 (syst.)
helium-3	-2 ± 2 (stat.) ± 4 (syst.)	6 ± 6 (stat.) ± 7 (syst.)

3 Future perspectives

Following the method successfully developed in the SIDDHARTA experiment, the extended SIDDHARTA-2 collaboration is in preparation of a series of upgrades and modifications of the apparaturs, aiming at the first precision measurement of kaonic deuterium X-rays [16].

Acknowledgements

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