PROCEEDINGS OF SCIENCE

Kaonic atoms at DAΦNE

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The SIDDHARTA collaboration has measured the K-series x rays of kaonic hydrogen and kaonic deuterium atoms, and the L-series x rays of kaonic helium-3 and kaonic helium-4 atoms to determine the strong-interaction energy-level shift and width of the lowest lying atomic states. These measurements offer a unique possibility to precisely determine the isospin-dependent $\overline{K}$-nucleon scattering lengths and fruitful knowledge concerning kaon-nucleus low energy interaction. Especially for kaonic hydrogen, the system composed of a K^- and a proton is a simple and sensitive testing ground for low energy QCD in the strangeness sector. In this paper, we present an overview of this experiment and preliminary spectra of those kaonic x rays.

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1. INTRODUCTION

Kaonic atom is a Coulomb bound system formed by a negatively-charged kaon and a nucleus. The atom can be produced by stopping a K^- in matter, resulting in a highly excited state in the initial stage of the production. A typical principal quantum number of the state is of $n \sim \sqrt{m_K/m_e} \sim 30$, where m_K and m_e are the reduced masses of kaon and electron, respectively. Emitting Auger electrons and x rays, the deexcitation of the atom proceeds until the kaon in a state of low angular momentum is absorbed by the nucleus due to the kaon-nucleus strong interaction. The strong interaction causes a shifting of the lowest atomic energy level from its pure electromagnetic (EM) value [1], and a broadening due to reducing the lifetime of the state by the absorption. By the spectroscopy of the x rays feeding the lowest level, the strong-interaction shift and width can be deduced.

With the simplest kaonic atom, *i.e.*, kaonic hydrogen, the measured strong-interaction shift and width of the $1s$ atomic state provide direct information on the $\overline{K}N$ s-wave interaction at K^-p threshold. The relation is known as Deser-Truman formula [1] (where recently a correction of isospin breaking effects turns out to be important [2]). The K-series kaonic-hydrogen x-ray data are therefore crucial for theories of the $\overline{K}N$ system together with the low-energy $\overline{K}N$ data. These studies allow the investigation of chiral SU(3) dynamics in low-energy QCD and the role of explicit chiral symmetry-breaking due to the relatively large strange quark mass. The data are also strongly related to recent hot topics – the structure of the $\Lambda(1405)$ resonance and the deeply bound kaonic systems. Recent progress of this field is summarized in [3].

The first distinct peaks of the kaonic-hydrogen x rays have been observed by the KEK-PS E228 collaboration [4] using a gaseous hydrogen target and Si(Li) x-ray detectors. Recently, DEAR collaboration [5] has again measured the x rays at the DAΦNE positron-electron collider at the Laboratori Nazionali di Frascati of INFN using CCD as x-ray detectors. Both experiments firmly established a repulsive-type shift (*i.e.*, negative value of ΔE_{1s}) of the kaonic-hydrogen $1s$-energy level. Using the most recent values obtained by DEAR, theoretical studies had been intensively performed. However most of them had difficulties in explaining all the experimental results in a consistent way with DEAR result (*e.g.*, [6]).

In the present SIDDHARTA experiment we have measured the K-series kaonic-hydrogen x rays and will provide the most precise values to settle this unsatisfactory situation.

In addition we have exploratory performed the first-ever measurement of K-series kaonic-deuterium x rays, and measured L-series kaonic-^{3}He and kaonic-^{4}He x rays as well. Concerning kaonic helium, the present kaonic-^{3}He measurement was for the first time, while, until recently, for kaonic ^{4}He there was a discrepancy between experimental results [7, 8, 9] and theoretical predictions (*e.g.*, [10, 11]). This discrepancy was eventually solved in recent years by the KEK-PS E570 collaboration [12] and the present experiments [13].

[1] The strong-interaction shift $\Delta E_{(n,l)}$ of the level with principal quantum number n and the orbital angular momentum l, is defined as $\Delta E_{(n,l)} \equiv -(E_{(n,l)} - E^{EM}_{(n,l)})$, where $E_{(n,l)}$ is the measured energy, and $E^{EM}_{(n,l)}$ is the energy calculated using only the EM interaction.

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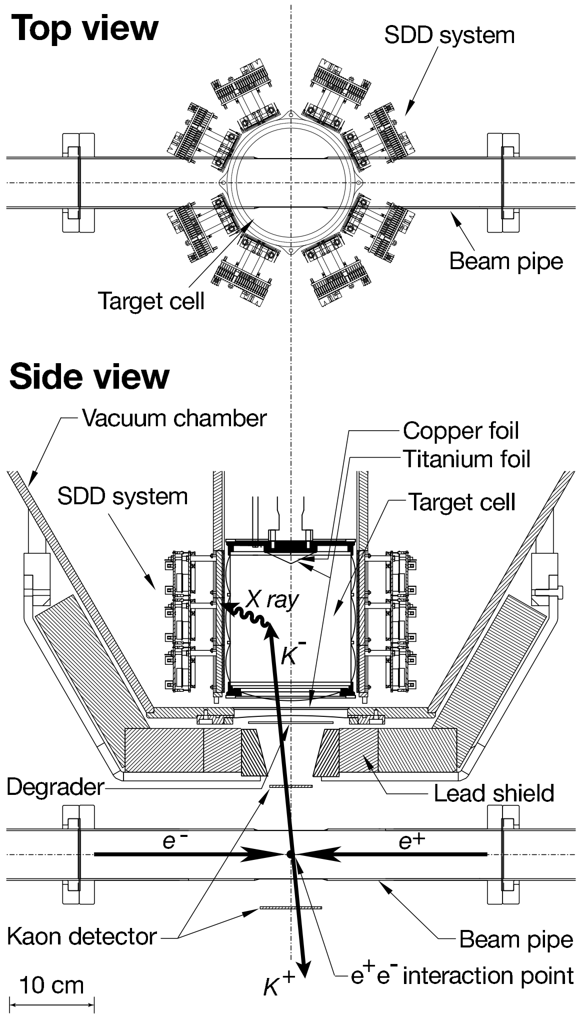

Figure 1: A schematic view of the SIDDHARTA setup installed at the e^+e^- interaction point of DAΦNE.

2. EXPERIMENT

The SIDDHARTA experiment was performed at the DAΦNE positron-electron collider, the same facility as that of DEAR experiment. The collider produces the ϕ-resonances which decay into back-to-back K^+K^- pairs emitted with a branching ratio of ~ 49 %. Resulting monochromatic low-energy kaons [2] (~ 16 MeV in kinetic energy) are degraded and stopped in a cryogenic gaseous target. Figure 1 shows a schematic view of the SIDDHARTA setup. To detect the back-to-back K^+K^- pairs, two plastic scintillation counters were mounted above and below the e^+e^- interaction point. A kaon trigger was defined by the coincidence of the two counters. X rays emitted from the kaonic atoms were detected by 144 silicon drift detectors (SDDs) each having an effective area of 1 cm^2 and a thickness of 450 μm. The SDD has an excellent energy resolution of ~ 150 eV (FWHM) at 6 keV (a factor of two better than Si(Li) detectors used in E228 [4]), and a good timing

[2] In fact, kaons from the ϕ resonance have a small energy spread due to a slight momentum boost of the ϕ resulting from the 55 mrad e^+e^- crossing angle.

resolution of sub-micro seconds in contrast to the CCD detectors used in DEAR [5] which had no timing capability. A detailed description of our experimental setup is given in a separate paper [14].

3. RESULTS

A correlation plot of the x-ray energy measured by SDDs vs the time difference between kaon arrival and x-ray detection for hydrogen data is shown in Fig. 2. The horizontal band is due to the kaon-induced events. Its projected time and energy spectra are also displayed in the figure. A typical width of the time-correlation, after a time-walk correction, was about 800 ns (FWHM) which reflected the drift-time distribution of the electrons in the SDD. The kaon and background time gates, each having a width of 1 μsec, are indicated therein with arrows. Comparing the energy spectra of data with SDD timing gates set to “kaon” and “background”, the synchronous background related to the charged kaon secondaries and the asynchronous background originating from lost beam particles were found to be comparable.

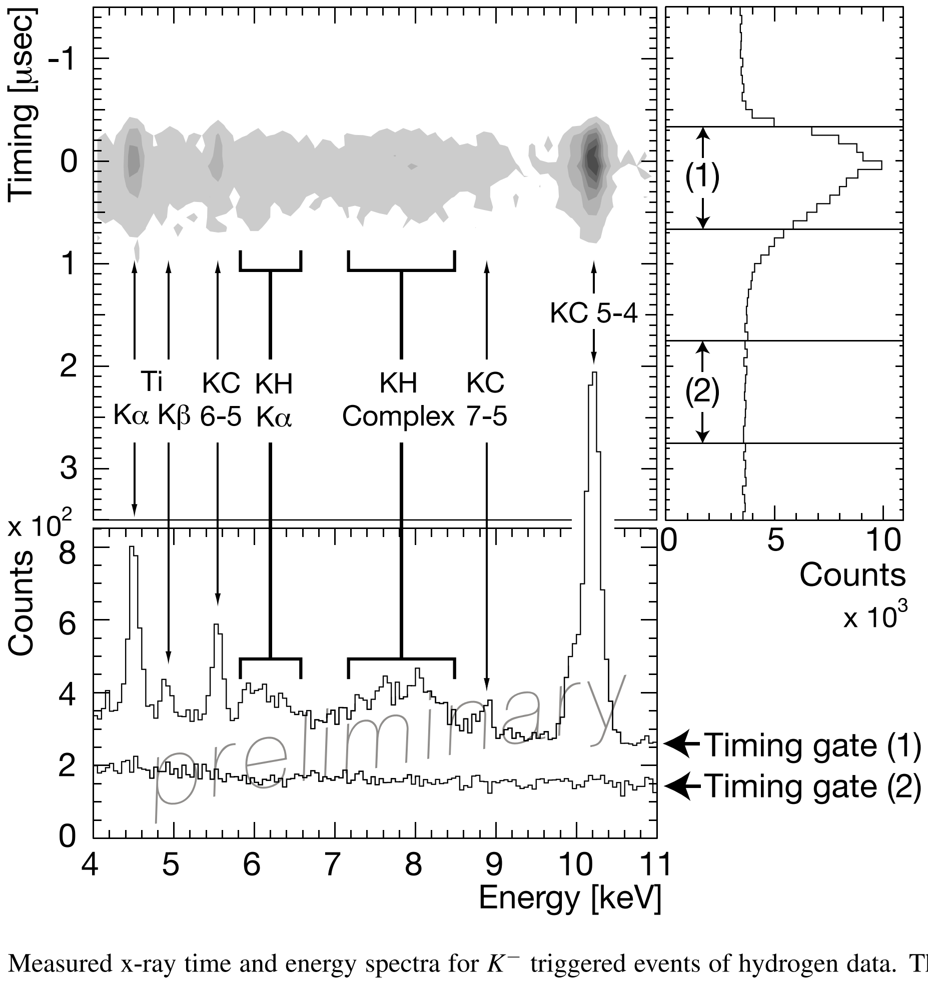

Figure 2: Measured x-ray time and energy spectra for K^- triggered events of hydrogen data. The top-left panel shows a correlation plot of the x-ray energy measured by SDDs vs the time difference between kaon arrival and x-ray detection, where a time-walk correction was applied. The projections on the time and energy axes are also shown at the right and bottom. The solid and dashed energy spectra, respectively, are obtained by selecting kaon and background time gates indicated with (1) and (2) in the timing spectrum.

3.1 HYDROGEN AND DEUTERIUM

The top panel of Fig. 3 shows a preliminary x-ray spectrum taken with hydrogen target overlaying that taken with deuterium target, using a part of statistics of SIDDHARTA. Both spectra are normalized by integral luminosities. K-series x-ray transitions of kaonic hydrogen were clearly observed while those for kaonic deuterium were not visible. This appears to be consistent with the theoretical expectation of lower x-ray yield and greater width for the case of deuterium (*e.g.*, [15]). Many other kaonic-atom x rays and characteristic x rays were detected in both spectra as indicated with arrows in the figure. Those kaonic-atom lines are attributable to the target-cell wall made of Kapton polyimide film ($C_{22}H_{10}O_5N_2$) and its support frames made of aluminum. The characteristic x rays come from high-purity titanium and copper foils installed for *in-situ* x-ray energy calibration.

The bottom panel of Fig. 3 shows a kaonic-hydrogen x-ray spectrum after background subtraction assuming the x-ray spectrum with deuterium target to be background. In the spectrum, a very preliminary fit result with each fit components are also shown. There are three background x-ray lines overlapping with the kaonic-hydrogen signals : kaonic oxygen 7-6 (6.0 keV), kaonic nitrogen 6-5 (7.6 keV) and fluorescence x ray of copper K_α (8.0 keV). These intensities can be estimated from the fit of kaonic-deuterium spectrum with an assumption that the relative intensities of those peaks are the same as in the kaonic-hydrogen spectrum.

Dot-dashed lines in the figure indicate the EM values of K-series x-ray energy of kaonic hydrogen and kaonic deuterium. Comparing the kaonic-hydrogen K_α peak and the EM value $E^{EM}_{K^-pK_\alpha}$, there is no room for doubt about a repulsive-type shift (negative ΔE_{1s}) of the kaonic-hydrogen 1s-energy level. The preliminary analysis shows that we have obtained much lower background in comparison with the DEAR experiment, and can determine the most precise values of the strong-interaction energy-level shift and width of the 1s atomic state. The analysis is now being finalized towards publication.

3.2 HELIUM-3 AND HELIUM-4

Figure 4 shows the measured x-ray spectrum taken with ^{3}He and ^{4}He targets. Both spectra are normalized by integral luminosities as well as the hydrogen and deuterium case. L-series x-ray transitions of both kaonic atoms were distinctly observed. Actually we used the x rays of kaonic ^{4}He also for testing our experimental technique and optimize the degrader thickness by repeatedly changing the target filling to helium gas. Because the kaonic-helium x rays were yielded one order of magnitude faster than the kaonic-hydrogen x ray (higher yield), as shown in the comparison of the two figures, Fig. 3 and Fig. 4, both which are normalized by the integral luminosities.

Dot-dashed lines in the figure indicate the EM values of L-series x-ray energies for kaonic ^{3}He and kaonic ^{4}He. Comparing the kaonic-helium K_α peak and the EM value $E^{EM}_{K^-\mathrm{He}K_\alpha}$ for both spectra, those peak centers are close to the EM values; and we finally derived the 2p-level shift for kaonic-^{3}He and ^{4}He atoms as $\Delta E_{2p} = -2 \pm 2$ (stat) ± 4 (syst) eV (K-^{3}He) [14] and $\Delta E_{2p} = 0 \pm 6$ (stat) ± 2 (syst) eV (K-^{4}He) [13] respectively, while the old kaonic-^{4}He measurements in the 70's and 80's show a large strong-interaction shift of the 2p level : $\Delta E_{2p} = -43 \pm 8$ eV [7, 8, 9, 10]. Together with the recent result of E570 [12], our results certainly exclude the earlier claim of a large shift of about -40 eV, and are in agreement with theoretical calculations [10, 11, 16].

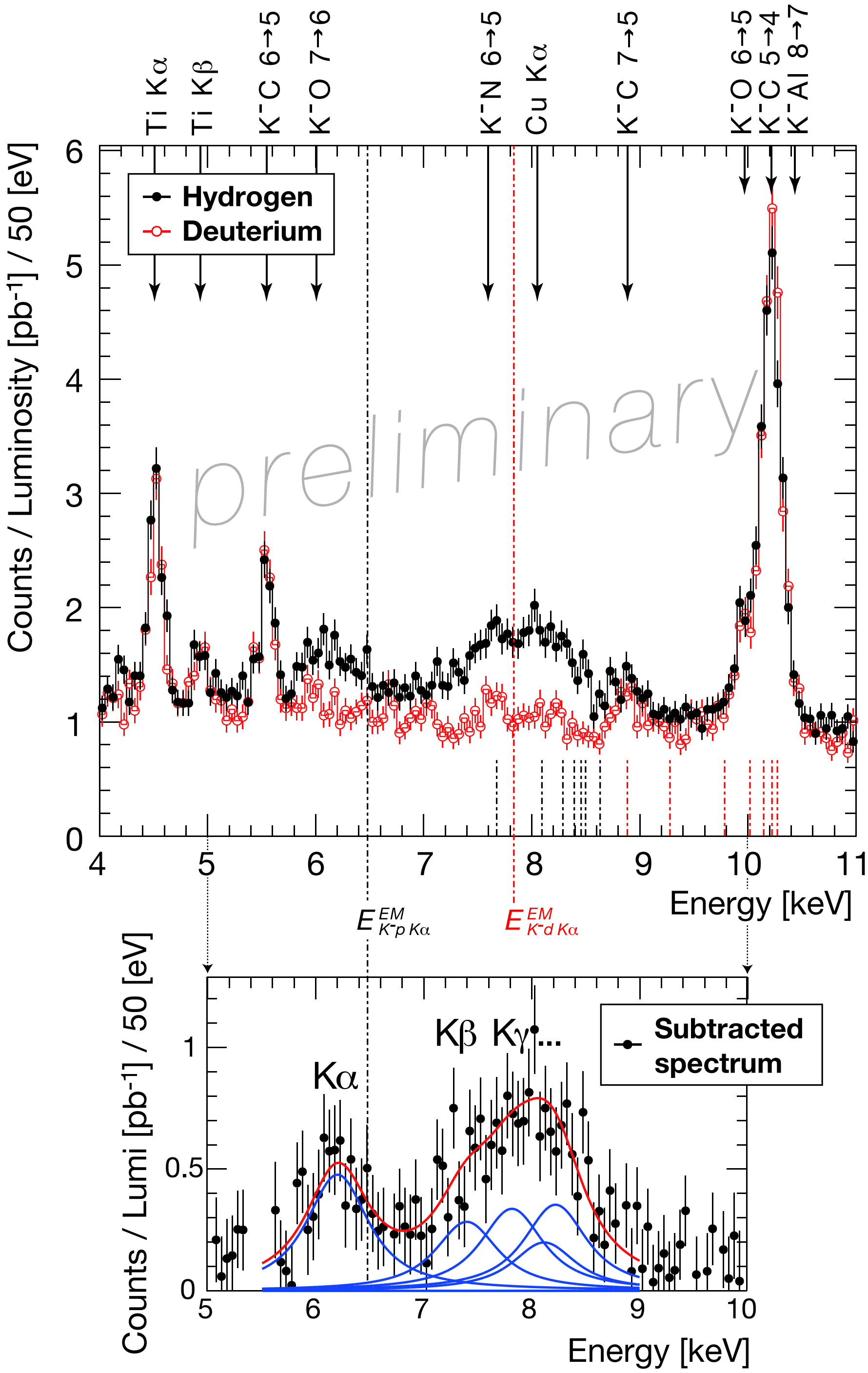

Figure 3: The measured x-ray spectrum taken with hydrogen target (black) overlaying that taken with deuterium target (red), both which are normalized by the integral luminosities. The bottom panel shows the kaonic-hydrogen x-ray spectrum after background subtraction assuming the x-ray spectrum with deuterium target to be background, together with a preliminary fit result with each fit components. The dot-dashed vertical lines indicate the EM values of the *K*-series x-ray energies for kaonic-hydrogen and kaonic-deuterium atoms.

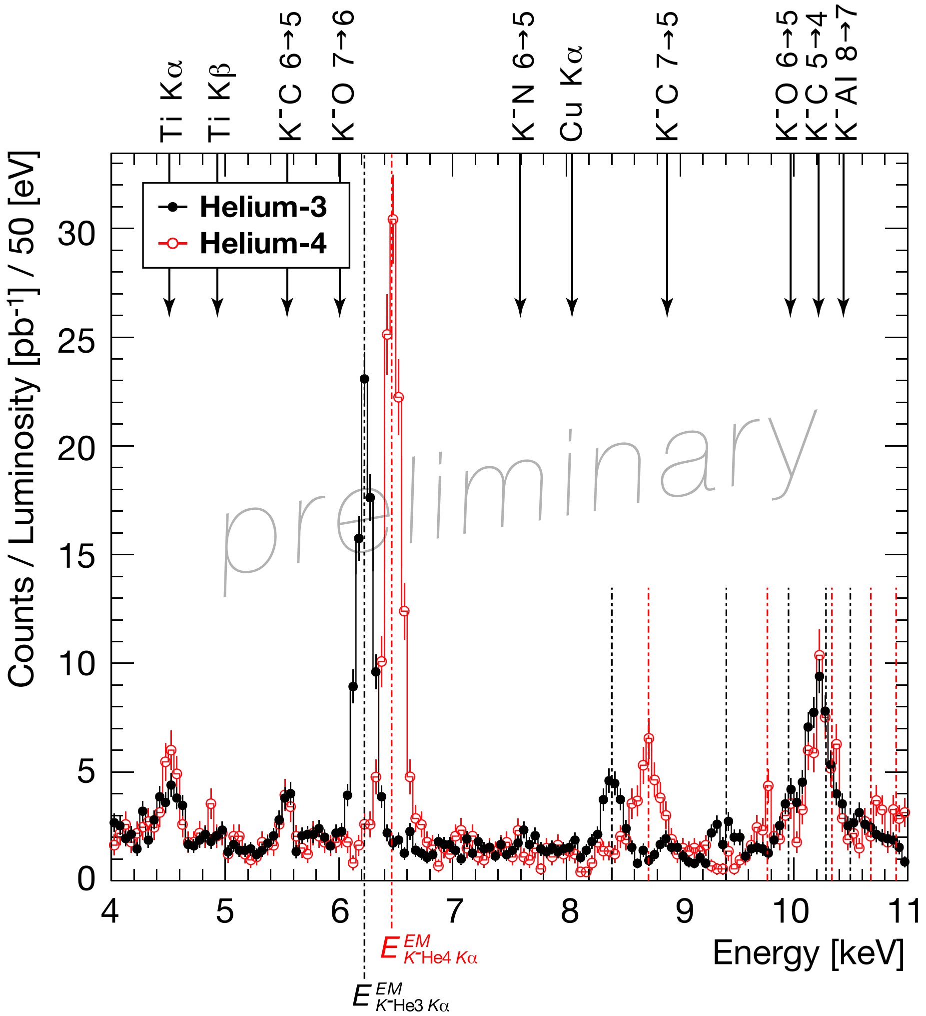

Figure 4: The measured x-ray spectrum taken with ^{3}He target (black) overlaying that taken with ^{4}He target (red), both which are normalized by the integral luminosities. The dot-dashed lines indicate the EM values of *L*-series x-ray energies for kaonic-^{3}He and kaonic-^{4}He atoms.

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