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Precise measurement of kaonic helium atoms x-rays

M. Iio[a], G. Beer[b], H. Bhang[c], P. Buehler[d], M. Cargnelli[d], J. Chiba[e], S. Choi[c]
C. Curceanu[f], Y. Fukuda[g], C. Guaraldo[f], T. Hanaki[e], R. S. Hayano[h],
A. Hirtl[d], M. Iliescu[f], T. Ishikawa[h], S. Ishimoto[i], T. Ishiwatari[d], M. Iwai[i],
K. Itahashi[a], M. Iwasaki[a], B. Juhasz[d], P. Kienle[d,j], J. Marton[d], Y. Matsuda[a]
H. Ohnishi[a], S. Okada[a], H. Outa[a], D. Pietreanu[f], F. Sakuma[a], M. Sato[a]
P. Schmid[d], D. Sirghi[f], F. Sirghi[f], S. Suzuki[i], T. Suzuki[a], H. Tatsuno[h],
D. Tomono[a], E. Widmann[d], T. Yamazaki[a,h], H. Yim[c] and J. Zmeskal[d]

[a] *RIKEN Nishina Center, RIKEN, Wako-shi, Saitama 351-0198, Japan*
[b] *University of Victoria, Box 3055, Victoria, British Columbia, Canada*
[c] *Seoul National University, Kwanak-gu, Seoul 151-742, South Korea*
[d] *Stefan Meyer Institut für subatomare Physik, 1090 Vienna, Austria*
[e] *Tokyo University of Science, Noda-shi, Chiba 278-8510, Japan*
[f] *Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy*
[g] *Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan*
[h] *The university of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[i] *KEK(High Energy Accelerator Research Organization), Ibaraki, Japan*
[j] *Technische Universiät at München, 85748, Garching, Germany*

Abstract

We performed an accurate and clean measurement of the kaonic-^{4}He Balmer-series x-rays at KEK-PS [E570]. The $2p$-level strong-interaction shift was estimated to be $2 \pm 2(stat) \pm 2(syst)$ eV in agreement with most theories, thus solving the long-standing kaonic helium puzzle. For the near future, we are planning an experiment to measure the x-rays of kaonic-^{3}He at J-PARC [E17]. Crucial information for the isospin dependent $\bar{K}$-nucleus strong interaction at the low energy limit will be provided by the E17 experiment.

1 Introduction

The strong-interaction energy-level shift and width of kaonic atoms were measured for understanding of the $\bar{K}$-nucleus interaction in the low energy limit. The experimental data of most kaonic atoms except helium and oxygen were in good agreement with the fitting by the optical-potential models [1]. The $2p$-level shift and width of kaonic-^{4}He have been measured in the past by three experiments. The average of the shift, determined by the past three kaonic-^{4}He x-rays measurements, was $\sim$40 eV large shift [2] [3] [4], while a majority of theoretical calculations suggested very small shift below 1 eV [5] [6] [7]. As to this discrepancy, there has been a long debate, the so-called "kaonic helium puzzle". On the other hand, Akaishi and Yamazaki predicted a large $2p$-level shift ($\mid \Delta E_{2p} \mid \sim$10 eV) of kaonic-^{4}He and kaonic-^{3}He atoms [8] by their theoretical framework of a "deeply-bound kaonic nuclear system" [9]. Therefore precise measurement of the $2p$ energy level shift of kaonic helium atoms has been long awaited.

In the present experiment at KEK [E570], we have performed a measurement of the Balmer-series x-rays of kaonic-^{4}He with a precision of $\sim$2 eV (statistical), thus a definitive answer has been provided to this long-standing puzzle. It is extremely important to measure the $2p$ shifts of both kaonic-^{4}He and kaonic-^{3}He in order to confirm of not the isospin dependence of Akaishi's prediction [8]. We therefore plan to measure the x-rays of kaonic-^{3}He at J-PARC [E17] using a similar technique to that of E570.

2 E570 experiment

The E570 experiment was performed at the K5 beamline of the KEK 12 GeV proton synchrotron in October, 2005 (cycle 1) and December, 2005 (cycle 2). The E570 experimental apparatus was essentially no different from the KEK-PS E549 experiment performed on the same beamline for one month from the end of May, 2005 [10], except for the inclusion of silicon drift x-ray detectors (SDD) and energy calibration foils in the superfluid liquid ^{4}He target system. Figure 1 shows a schematic view of the experimental setup around the target. The kaonic-^{4}He atom was generated by negatively-charged kaons stopped inside the superfluid ^{4}He target cell (cylindrical shape 15 cm long and 20 cm in diameter at a density of 0.145 g/cm^3). Incident kaons with momentum $\sim$650 MeV/c were degraded in carbon degraders, counted with beamline counters, and tracked by a beamline drift chamber. The energy losses of the incident particles were measured by a scintillation counter named T0.

In E570, a significant improvement over the past experiments was achieved by incorporating the following:

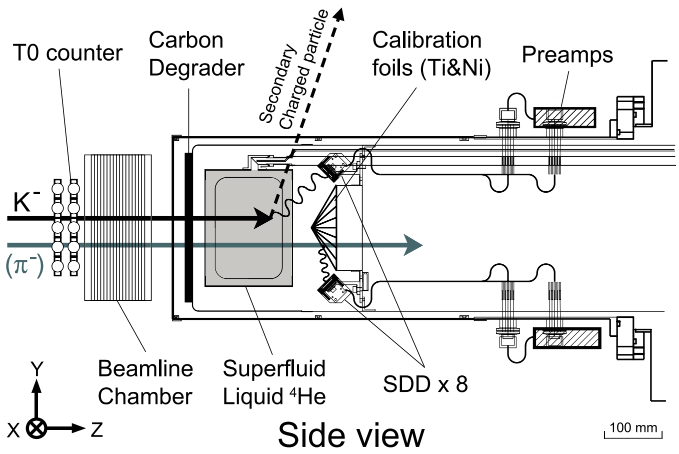

Figure 1: *A schematic side view of the E570 setup around the cylindrical target with the x-ray detection system. Eight SDDs are mounted on holders tilted at a 45 degree angle to the beam center in an annular-shaped pattern. Fan-shaped high-purity titanium and nickel foils are put alternately on a cone-shaped support located on the beam axis.*

2.1 Silicon drift x-ray detector

For this experiment, Silicon Drift Detectors (SDDs) produced by KETEK [11)] were adopted for energy resolution improvement of x-ray detection. Each SDD has an effective area of 100 mm^2 and a 260 μm-thick active layer. The temperature of the SDDs was kept at $\sim$85 K during the experimental period by a connection to the thermal-radiation shield for the helium target cooled by liquid nitrogen. Typical energy resolution is 190 eV (FWHM) at 6.4 keV, which is about twice as good as that of the Si(Li) x-ray detectors used in the previous three experiments. The time resolution is about 160 nsec (rms).

In the SDD, the electrons produced by an x-ray hit drift radially toward the central anode where they are collected. The small anode size (and hence small capacitance) is essential to realize the good energy resolution despite the large effective area. The small anode area also makes it possible to reduce the active layer thickness, while the capacitance is still kept small. The thin active layer helps to reduce continuum background caused by the Compton scattering occurring inside the detector.

2.2 Cuts for reducing background events

The X-ray events coming from the kaonic-^{4}He transitions were selected by the reaction vertices reconstructed from an incident kaon track and a second charged particle track which come from the liquid ^{4}He target, which is called the “fiducial volume cut”. Moreover, in-flight kaon decay/reaction events were rejected by applying a correlation cut between the z-coordinate of the reaction vertex and the energy loss in T0. As a result, a good signal-to-noise ratio of $\sim$4 was achieved, which is about 5 times better than that of the past experiments.

2.3 In-beam energy calibration

The energy calibration was done by using characteristic x-rays induced by beam particles on high-purity titanium and nickel foils placed just behind the target cell. The energy of the kaonic-^{4}He $3d \rightarrow 2p$ x-ray, $\sim$6.4 keV, lies between these characteristic x-ray energies of 4.5 keV(Ti) and 7.5 keV(Ni). To obtain high-statistics energy calibration spectra, we accumulated SDD self-triggered events together with the stopped-K^- triggered events, which provide high-accuracy in-situ calibration spectra. To avoid detecting the background characteristic x-rays from other than the titanium and nickel, high-purity aluminum foils were placed on all objects in the view of the SDDs.

3 Analysis and result of E570

A typical x-ray spectrum for SDD self-triggered events is shown in Figure 2(a). Characteristic x-ray peaks of titanium and nickel were obtained with high statistics. Time-dependent gain drift was corrected about every 20 hours. The energy scale was calibrated by K_α lines of titanium and nickel with well-known energies. Figure 3 (a), (b) respectively show the stopped-K^- triggered-event x-ray spectra taken in October, 2005 (cycle 1) and December, 2005(cycle 2). These spectra had cats applied to reduce background events, kaonic-^{4}He $3d \rightarrow 2p$, $4d \rightarrow 2p$ and $5d \rightarrow 2p$ transitions are clearly observed, while the titanium and nickel x-ray peaks are greatly suppressed.

To fit the spectra containing kaonic-^{4}He x-ray peaks, a convolution of a Gaussian (representing the detector response) and a Lorentz function (representing the natural width), a “Voigt function”, was adopted as the main-peak function, where as a Gaussian response was employed as a main-peak func-

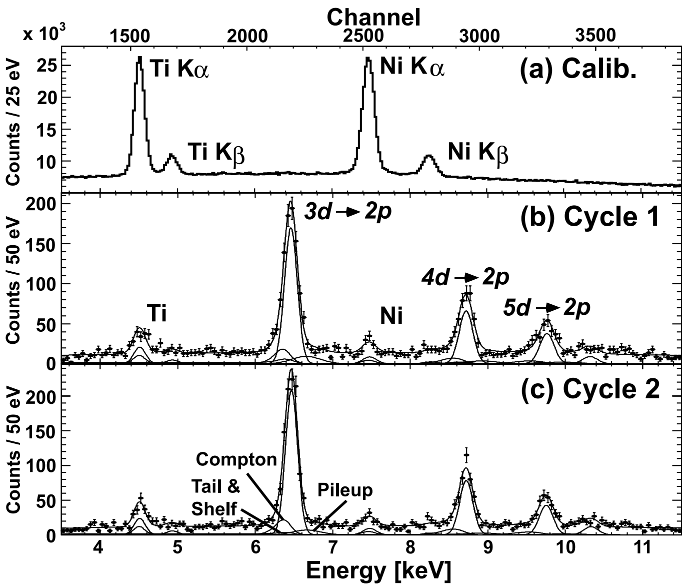

Figure 2: *(a) A typical x-ray spectrum for self-triggered events which provides high-statistics energy-calibration information. (b), (c) Measured x-ray spectra for stopped-K^- events obtained from the runs in October, 2005 (cycle 1) and December, 2005 (cycle 2) respectively. A fit line is also shown for each spectrum, along with individual functions of the fit.*

tion for fitting the characteristic x-ray peaks since their natural width is much less than the energy resolution of the SDDs. A low-energy tail structure due to Compton scattering must be taken into account to obtain an x-ray peak position with a precision of a few eV. The effects were studied by simulating the x-ray data with GEANT4 including an extension package for Low-Energy Compton Scattering (LECS). Using spectrum analysis, we established that pileup effects due to the high-rate beam conditions were non-negligible. The spectral function due to the pileup events could be estimated by waveform analysis using Flash ADC data. As a result, the measured values of the kaonic-^{4}He x-ray transition energy are given in Table 1 with only statistical errors. In this table, we also tabulate the EM values updated from Refs. [2)] [3)] [4)] by Koike [12)] using the latest kaon mass given by the particle data group (PDG) [13)].

Table 1: *Measured and EM calculated* [12] *kaonic-^{4}He x-ray energies of* $3d \rightarrow 2p$, $4d \rightarrow 2p$ *and* $5d \rightarrow 2p$ *transitions. The quoted error is purely statistical.*

Transition	$3d \rightarrow 2p$	$4d \rightarrow 2p$	$5d \rightarrow 2p$
Measured energy (eV)	6466.7 ± 2.5	8723.3 ± 4.6	9760.1 ± 7.7
EM calc. energy (eV)	6463.5	8721.7	9766.8

Since the strong-interaction shifts are negligibly small for the levels with a principal quantum number n larger than two, the $2p$-level shift ΔE_{2p} can be derived from the Balmer-series x-ray energies using the equation:

$$\Delta E_{2p} = (E_{(n,d)} - E_{(2,d)}) - (E^{EM}_{(n,d)} - E^{EM}_{(2,d)}) \qquad (1)$$

where $E_{(n,d)} - E_{(2,d)}$ and $E^{EM}_{(n,d)} - E^{EM}_{(2,d)}$ correspond to the measured and calculated EM x-ray energies, respectively. Taking the average of the $2p$-level shifts of the three lines, we obtained the shift as:

$$\Delta E_{2p} = 2 \pm 2(stat) \pm 2(syst)eV. \qquad (2)$$

This value is consistent with 0 in agreement with most theories [5] [6] [7]. To conclude, $2p$-level shift was determined by using silicon drift detectors which lead to a much improved energy resolution and signal-to-noise ratio compared to the Si(Li) x-ray detectors used in the past experiments. Our careful and precise result excludes the earlier claim of a large shift of about ∼40 eV. Therefore, "long-standing kaonic helium puzzle" has been solved. We have already published these results in Physics Letters B [14].

4 J-PARC E17 experiment

The measurement of the $2p$-level shifts of both kaonic-^{4}He and kaonic-^{3}He not only provide the crucial information on the isospin-dependent $\bar{K}$-nucleus strong-interaction at the low energy limit, but also are extremely important in order to understand the basis of the Akaishi-Yamazaki prediction of "deeply-bound kaonic nuclei". Unlike the case of kaonic-^{4}He, no data exist yet on the kaonic-^{3}He x-rays. Therefore, we are planning an experiment to measure the x-rays of the kaonic-^{3}He at J-PARC [E17] [15].

The E17 experiment will be performed at the K1.8BR beamline of the J-PARC 50 GeV proton synchrotron. The principle of the E17 experiment is the same as that of E570. We stop negatively-charged kaons in a liquid helium target, and observe x-rays with silicon drift detectors. Incoming kaons and charged particles emitted from the K^--reaction vertices are tracked. This experiment is closely related to another experiment "A search for deeply-bound kaonic nuclear states by in-flight $^3He(K^-, n)$ reaction"[E15] [16]. Both of these experiments address the question of deeply-bound kaonic states, and there is a large overlap of the collaboration members. Both experiments will use the same beamline, Cylindrical Detector System (CDS) and liquid ^{3}He target. At the present stage of the preparation, the CDS and target used by both experiments have been conceptually developed. To start an experiment in winter, 2009, we are also advancing the development of the beamline detectors for stopped-K^- experiments and the preamps of the SDDs.

5 Summary

Kaonic-^{4}He Balmer-series x-rays were measured with a precision of $\sim$2 eV (statistical) at the KEK-PS K5 beamline. The kaonic-^{4}He atom x-ray energy of the $3d \rightarrow 2p$ transition was determined to be $6467 \pm 3(stat) \pm 2(syst)$ eV. The $2p$-level strong interaction shift was deduced as $\Delta E_{2p} = 2 \pm 2(stat) \pm 2(syst)$ eV. A precise measurement of kaonic-^{3}He x-rays is planned for the J-PARC K1.8BR beamline. At present, some devices for the experiment have been developed. E17 experiment will start in January, 2009 at the earliest.

6 Acknowledgements

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