Precise measurement of kaonic helium $3d \to 2p$ x-rays

S. Okada*, G. Beer†, H. Bhang**, M. Cargnelli‡, J. Chiba§, S. Choi**, C. Curceanu¶, Y. Fukuda‖, T. Hanaki§, R. S. Hayano††, M. Iio*, T. Ishikawa††, S. Ishimoto‡‡, T. Ishiwatari‡, K. Itahashi*, M. Iwasaki*, B. Juhasz‡, P. Kienle‡, J. Marton‡, Y. Matsuda*, H. Ohnishi*, H. Outa*, M. Sato‖, P. Schmid‡, S. Suzuki‡‡, T. Suzuki*, H. Tatsuno††, D. Tomono*, E. Widmann‡, T. Yamazaki*,††, H. Yim** and J. Zmeskal‡

*Nishina Center for Accelerator-based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
†Department of Physics and Astronomy, University of Victoria, Box 3055, Victoria, British Columbia, Canada V8W 3P6
**Department of Physics, Seoul National University, Son 56-1, Sillim-dong, Gwanak-gu, Seoul 151-742, South Korea
‡Stefan Meyer Institut für subatomare Physik, Boltzmanngasse 3, 1090 Vienna, Austria
§Department of Physics, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan
¶Laboratori Nazionali di Frascati dell' INFN, C.P. 13-1-00044 Frascati, Italy
‖Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo 152-8551, Japan
††Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
‡‡High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tskuba, Ibaraki 305-0801, Japan

Abstract.
We have performed an experiment to measure the strong-interaction shift of $2p$ states of kaonic helium-4 atom with a precision better than $\sim$2 eV. The measurement will give an answer to the longstanding "kaonic helium puzzle" and provide crucial information to understand the basis of the Akaishi-Yamazaki prediction of deeply-bound kaonic nuclei, which is one of the interpretations of the strange multibaryon candidates recently reported at KEK, DAΦNE and BNL.

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The kaonic atom is an exotic atom which contains a negatively-charged kaon bound to a nucleus by the Coulomb force. The system can be produced by stopping kaons in a target medium resulting a highly excited state[1] in the initial stage of the production. Then the atom looses its energy by emitting Auger electrons and x-rays, until the kaon-nucleus strong-interaction width Γ_{abs} becomes larger than the radiative-transition width Γ_X. Such an orbit is called the "last orbit", since x-rays are not emitted below this level.

[1] A typical principal quantum number is $n \sim \sqrt{M_K^*/m_e} \sim 30$, where M_K^* and m_e respectively are reduced masses of the kaon and the electron.

From the spectroscopy of x-rays feeding the last orbit, the strong-interaction shift[2] and width of the last orbit can be deduced. This information offers the unique possibility to precisely determine the $\bar{K}$-nucleus strong interaction at the low energy limit, hence many experiments have been done to collect data on various targets, from helium to uranium inclusively [1]. It has been known that most of the available kaonic-atom data can be fitted fairly well by optical-potential models [1, 2], except for kaonic helium. The average $2p$ shift[3] of the three existent kaonic-^{4}He measurements up to the present one is $\Delta E_{2p}^{exp} = -43 \pm 8$ eV [3–5], while a majority of theoretical calculations predict $\Delta E_{2p}^{calc} \sim 0$ eV (*e.g.,* one of the recent calculations indicates $\Delta E_{2p}^{calc} \sim -0.2$ eV [2]). This discrepancy is known as the "kaonic helium puzzle".

The kaonic helium puzzle has recently attracted a renewed interest in connection with the Akaishi-Yamazaki (AY) prediction of "deeply-bound kaonic nuclei" [6]. Treating $\Lambda(1405)$ as a $\bar{K}$-N bound state, the AY model predicts unconventionally deep $\bar{K}$-nucleus potentials, which accommodate the deeply-bound $\bar{K}$-nucleus states. When the AY model with their coupled-channel model calculation is applied to the kaonic-^{4}He atom, the $2p$ level shift could be as large as $|\Delta E_{2p}| \sim 10$ eV at maximum [7]. If the measured $2p$ energy shift is $|\Delta E_{2p}^{exp}| <\sim 10$ eV and not consistent with 0 eV, a strongly attractive potential which accommodates deeply-bound kaonic nuclear systems propounded by Y. Akaishi and T. Yamazaki [6] will be justified. This will therefore help to clarify the nature of the strange multibaryon candidates reported by E471 at KEK [8], FINUDA at LNF[9], and by Kishimoto *et al.* at BNL [10].

This situation motivated us to measure the energy of $3d \rightarrow 2p$ x-rays of the kaonic-^{4}He atom with much improved precision. The present experiment was performed at the K5 beamline of the KEK 12 GeV proton synchrotron from October to December 2005 (KEK-PS E570). Figure 1 shows a schematic view of the experimental setup. In E570, a significant improvement over the past experiments was achieved by incorporating the following:

- **SDDs** : Instead of a conventional Si(Li) x-ray detector, we used eight silicon drift detectors (SDDs). In the SDD, the electrons produced by an x-ray hit are radially drifted toward the anode at the center and are collected there, so that the anode size (and hence its capacitance) can be kept small, independent of the detector area. This results in a good energy resolution despite a large effective area of some 100 mm^2. In addition, the small anode area makes it possible to reduce the active layer thickness, while the capacitance is still kept small. The thin active layer (260 μm in the case of E570 SDDs, compared with 4 mm for Si(Li) counters used in the past experiments) helps to reduce continuum background caused by the soft-Compton process. The typical energy resolution is $\sim$185 eV (FWHM) at 6.4 keV which corresponds to the energy of $3d \rightarrow 2p$ x-rays of kaonic helium atoms.
- **Fiducial volume cut** : Continuum background events could be drastically reduced by applying a "fiducial volume cut", which requires that the reaction vertex ob-

[2] The shift ε is defined as the difference between the (fictitious) binding energy calculated assuming a pure-Coulomb potential and the strong-interaction-affected (*i.e.,* actual) binding energy.
[3] The last orbit of kaonic helium is $2p$.

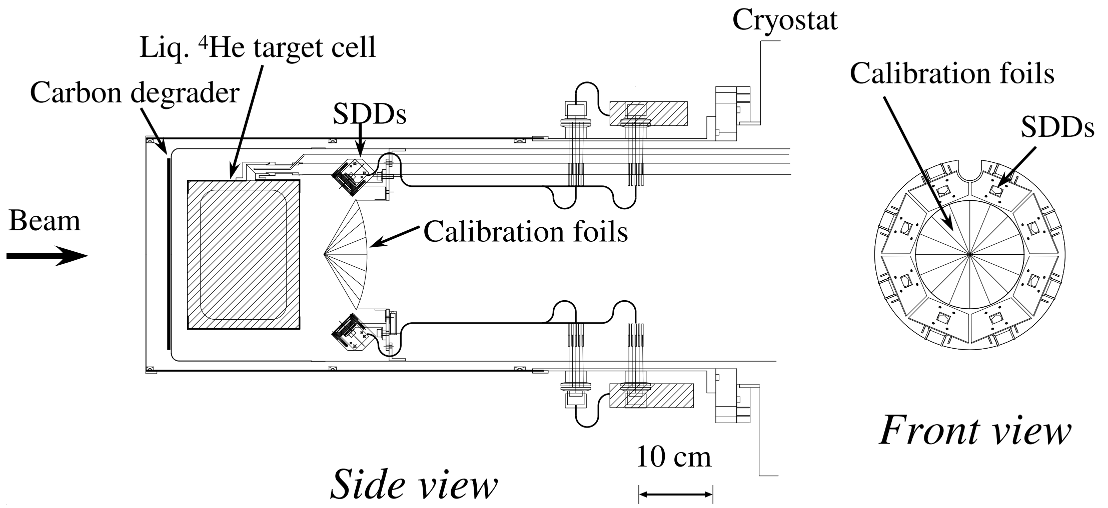

FIGURE 1. Schematic view of the liquid ^{4}He target assembly with the x-ray detector system.

tained by tracing an incident kaon and a secondary charged particle is within the liquid helium-4 volume. With the fiducial cut, a good S/N ratio of $\sim$4 was achieved, which is about 5 times better than that of the past experiments.

- **In-beam energy calibration** : The energy calibration was done by characteristic x-rays induced by the incident beam (mainly contaminating pions in the kaon beam) on pure titanium and nickel foils, and simultaneously measuring the kaonic helium atom x-rays. Since the energy of the $3d \rightarrow 2p$ kaonic helium atom x-ray, $\sim$6.4 keV, lies between the characteristic x-ray energies, 4.5 keV(Ti) and 7.5 keV(Ni), this will provide an accurate in-situ calibration.

In total, $\sim 1.5\times 10^3$ events of nearly background-free $3d \rightarrow 2p$ x-rays could be accumulated, which implies, with a 185 eV (FWHM at 6.4 keV) resolution, we will achieve a statistical error of $\sigma \sim 2$ eV (=185/2.35/$\sqrt{1.5\times 10^3}$ eV). The offline analysis including the systematic error estimation is now in progress.

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