Precision spectroscopy of Kaonic Helium $3d \rightarrow 2p$ X-rays

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

[a]Nishina Center for Accelerator-based Science, RIKEN, Wako, 351-0198, Japan
[b]Department of Physics and Astronomy, University of Victoria, Victoria, Canada
[c]Department of Physics, Seoul National University, Seoul, 151-742, South Korea
[d]Stefan Meyer Institut für subatomare Physik, Vienna, Austria
[e]Department of Physics, Tokyo University of Science, Noda, 278-8510, Japan
[f]Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy
[g]Department of Physics, Tokyo Institute of Technology, Meguro, 152-8551, Japan
[h]Department of Physics, University of Tokyo, Bunkyo, 113-0033, Japan
[i]High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan

We have measured the strong-interaction shift of $2p$ states of kaonic helium-4 atoms with a precision of $\sim$2 eV using Silicon Drift Detectors (SDDs) which lead to much improved energy resolution and signal-to-noise ratio compared to the conventional Si(Li) x-ray detector used in the past experiments. 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.

1. INTRODUCTION

The kaonic atom is an exotic atom which contains a negatively-charged kaon (K^-) bound to a nucleus by the Coulomb force. The system is formed when a K^- stops in a target medium and is captured by the target atom into an outer atomic orbit, which results in 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 becomes larger than the radiative-transition width. Such an orbit is called the "last orbit", since x-rays are not emitted below this level. From the spectroscopy of x-rays feeding the last orbit, the strong-interaction shift[2] and width of the last orbit can

[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 K^-−He and e^-−He.
[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.

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 hydrogen 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 before the present experiment 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 acceptable. 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.

2. EXPERIMENT

The present experiment (KEK-PS E570) was carried out at the K5 beamline of the 12-GeV proton synchrotron (PS) in the High Energy Accelerator Research Organization (KEK). Figure 1 shows a schematic view of the experimental setup. In the present experiment, a significant improvement over the past experiments was achieved by incorporating the following:

2.1. Silicon Drift Detector

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 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 ∼185 eV (FWHM) at 6.4 keV which corresponds to the energy of $3d \rightarrow 2p$ x-rays of kaonic helium atoms.

[3] The last orbit of kaonic helium is $2p$.

2.2. Fiducial volume cut

Continuum background events was drastically reduced by applying a "fiducial volume cut", which requires that the reaction vertex obtained by tracing an incident kaon and a secondary charged particle is within the liquid ^{4}He volume. Figure 2 shows a projection of reaction vertices along the beam axis around the liquid ^{4}He target. All components of the target assembly are clearly seen. With the fiducial cut, a good signal to noise ratio of $\sim$8 was achieved, which is about 10 times better than those of the past experiments.

2.3. 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, while 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.

3. RESULT AND SUMMARY

A preliminary energy spectrum of kaonic helium-4 atom x-rays for about half of the total E570 statistics is shown in the top figure of Fig. 3. The $3d \rightarrow 2p$ peak at $\sim$6.4 keV has been clearly observed, together with other transitions feeding the $2p$ state, $4d \rightarrow 2p$ and $5d \rightarrow 2p$. The bottom figure of Fig. 3 shows a high-statistics characteristic x-ray spectrum obtained by independently triggered events without requiring a stopped K^- and a secondary particle (self triggered events), which is used for the energy calibration. The number of events of titanium $K_{\alpha 1}$ was about 1.5 $\times 10^4$ per 8 hours for each SDD.

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).

At the present stage of the analysis, it appears that the energy shift of $2p$ states of kaonic helium-4 atoms is significantly less than $\sim$40 eV of the earlier claims. The detailed analysis concerning the shift value for full statistics including systematic error estimation is now in progress.

REFERENCES

1. C.J. Batty, E. Friedman and A. Gal, Phys. Reports **287**, 385 (1997).
2. S. Hirenzaki, Y. Okumura, H. Toki, E. Oset, and A. Ramos, Phys. Rev. **C 61**, 055205 (2000).
3. C.E. Wiegand and R. Pehl, Phys. Rev. Lett. **27**, 1410 (1971).
4. C.J. Batty *et al.*, Nucl. Phys. **A 326**, 455 (1979).
5. S. Baird *et al.*, Nucl. Phys. **A 392**, 297 (1983).
6. Y. Akaishi and T. Yamazaki, Phys. Rev. **C 65**, 044005 (2002).
7. Y. Akaishi, proceedings for *International Conference on Exotic Atoms (EXA05)*, Austrian Academy of Sciences Press, Vienna, 2005, p. 45.
8. T. Suzuki *et al.*, Phys. Lett. **B 597**, 263 (2004).
9. M. Agnello *et al.*, Phys. Rev. Lett. **94**, 212303 (2005).
10. T. Kishimoto *et al.*, Nucl. Phys. **A 754**, 383c (2005).

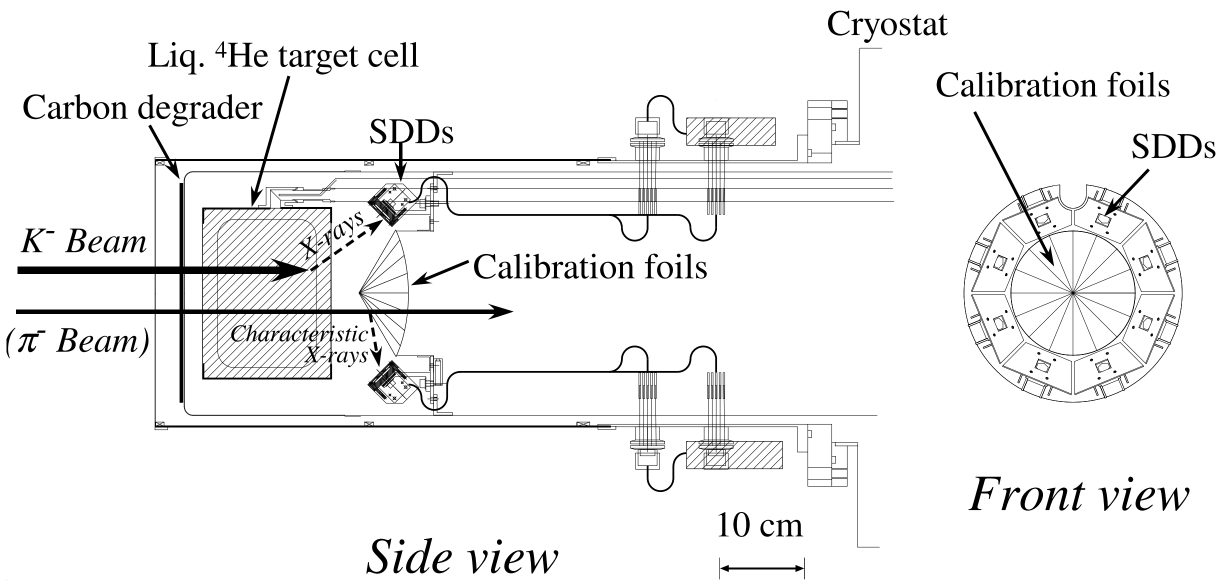

Figure 1. Schematic view of the liquid ^{4}He target assembly with the x-ray detector system.

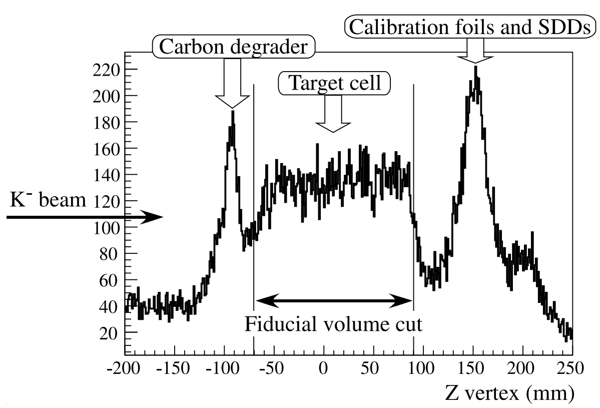

Figure 2. The projection of reaction vertices along the beam axis around the liquid ^{4}He target assembly.

.

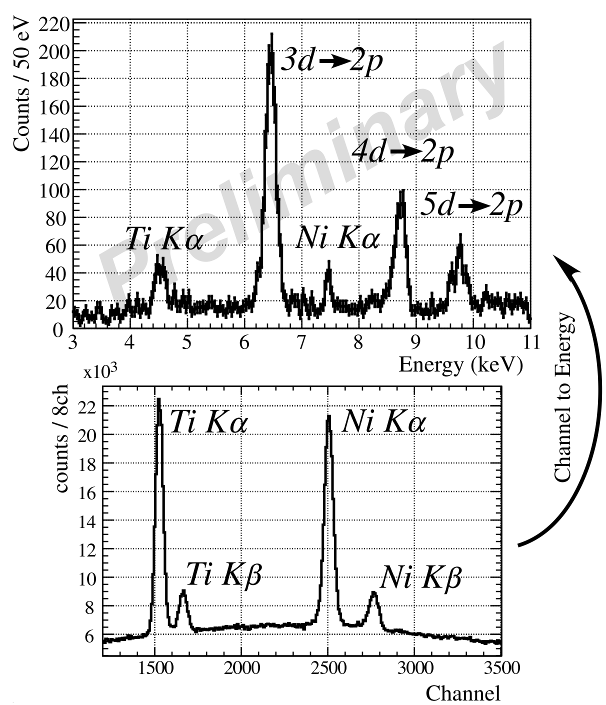

Figure 3. A preliminary kaonic helium atom x-ray energy spectrum for half of all statistics (top) and a typical characteristic x-ray spectrum with calibration self trigger (bottom).