Kaonic helium X-ray measurement in the SIDDHARTA experiment

H. Shi, M. Bazzi, G. Beer, L. Bombelli, A.M. Bragadireanu, E. M. Cargnelli, G. Corradi, C. Guaraldo, R. S. Hayano, M. Iliescu, T. Ishiwatari, M. Iwasaki, P. Kienle, P. Levi Sandri, A. Longoni, V. Lucherini, J. Marton, S. Okada, D. Pietreanu, A. Rizzo, A. Romero Vidal, A. Scordo, D. L. Sirghi, F. Sirghi, H. Tatsuno, A. Tudorache, V. Tudorache, O. Vazquez Doce, E. Widmann, J. Zmeskal

A. School of Science, Univ. of Tokyo, Tokyo, Japan
B. INFN, Laboratori Nazionali di Frascati (Roma), Italy
C. Dep. of Phys. and Astro., Univ. of Victoria, Victoria B.C., Canada
D. Politecnico di Milano, Sez. di Elettronica, Milano, Italy
E. IFIN-HEI, Magurele, Bucharest, Romania
F. Stefan Meyer Institut für subatomare Physik, Vienna, Austria
G. INFN Sez. di Roma I and Inst. Superiore di Sanita, Roma, Italy
H. RIKEN, The Inst. of Phys. and Chem. Research, Saitama, Japan
I. Tech. Univ. München, Physik Dep., Garching, Germany

E-mail: shx@nucl.phys.s.u-tokyo.ac.jp

Abstract. The SIDDHARTA (Silicon Drift Detector for Hadronic Atom Research with Timing Application) collaboration performed X-ray spectroscopy measurement of kaonic atoms at the DAΦNE e+e− collider. Low energy negative kaons from DAΦNE φ-factory were stopped in gaseous targets to produce kaonic atoms. We employed specially designed Silicon Drift Detectors (SDDs) to detect the kaonic X-rays. Based on the energy of kaonic-^4^He 3d → 2p transition, we determined a new value of the 2p level strong-interaction shift of kaonic-^4^He: 0 ± 6 (stat.) ± 2 (syst.) eV[1]. Together with the result of recent E570 experiment[2] at the KEK-PS, a small shift (if any) of kaonic-^4^He 2p level has become well established.

1. Introduction

In the SIDDHARTA experiment, we determined a new value on the 2p level strong shift of kaonic-^4^He atom[1] based on the helium-4 target data taken in early 2009. This shift value is the first physics result of the experiment, and the objective of this paper as well.

The precision spectroscopy of kaonic atom X-ray is an established method to study the low energy kaon-nucleus strong interaction. In kaonic atoms, strong interaction causes atomic level with low n to shift and broaden relative to the electromagnetic case. The shifts and widths can be calculated by adding an optical potential to the Coulomb interaction[6]. For kaonic-^4^He atom,
the last observable shift $\Delta E$ and width $\Gamma$ appear at the $2p$ level, at which the nuclear absorption terminates the atomic cascade. Here the $2p$ level shift is defined as: $\Delta E \equiv -(E_{2p} - E_{2p}^{EM})$, where $E_{2p}$ is the energy of $2p$ level and $E_{2p}^{EM}$ is the energy calculated only with the electromagnetic interaction (EM). One can determine $\Delta E$ directly from the X-ray energy of $3d \rightarrow 2p$ transition obtained from spectroscopy measurement, since the $3d$ level shift is negligible.

The average of three early experiments[5-7] shown in Fig.1 concluded that $\Delta E$ is centered at -43 eV, indicating a “repulsive” shift. However, optical potential calculation using the kaonic atom data with $Z \geq 3$ predicts that $\Delta E$ is close to zero. Recent coupled-channel model calculation done by Akaishi[4] further poses a limit of $\pm 10$ eV to the shift. Nonetheless the large shift obtained from the early experiments cannot be explained.

This discrepancy between theory and experiment lasted for more than two decades before being resolved in 2007 by the E570 group at the KEK-PS. Based on an unambiguous $3d \rightarrow 2p$ transition line of kaonic-$^4$He, the group determined a new value of the $2p$ shift as: $\Delta E = + 2 \pm 2$ (stat.) $\pm 2$ (syst.) eV[2], which is consistent with all theoretical calculations.

The SIDDHARTA experiment aims primarily at a precise measurement of $K$-series kaonic hydrogen X-rays and first-ever measurement of the kaonic deuterium X-rays to determine the strong-interaction energy-level shift and width of the lowest-lying atomic states. The measurement with helium-4 target was performed to tune the setup and performance of SDDs. Helium-4 is an ideal choice for the purpose for two reasons: the X-ray yield per incident kaon for the kaonic-$^4$He $3d$-$2p$ transition is ten times higher than that of the kaonic hydrogen $2p$-$1s$ transition, and the energies of both are close to 6 keV. As a result of helium-4 target measurement, we achieved comparable statistics, signal-to-noise (S/N) ratio and energy resolution with respect to the KEK experiment. Thus the consistent results from the two recent experiments establish unambiguously that the $2p$ strong shift (if any) of kaonic-$^4$He atom is small.

![Figure 1. Results on kaonic helium-4 2p shift of all the experiments. Range of Akaishi prediction is marked with a red band on the right side of y-axis.](image)

2. Setup of SIDDHARTA experiment

The SIDDHARTA setup was mounted above one collision point of the DAΦNE electron-positron collider, as illustrated in the schematic view in Fig. 2. We shielded the vacuum chamber with lead walls to reduce the continuous background from the DAΦNE beam line. The target cell
and the SDDs were mounted inside the vacuum chamber which was cooled to 170 K for SDD operation.

![Diagram of SIDDHARTA setup](image)

**Figure 2.** A schematic cutaway view of SIDDHARTA setup mounted above DAΦNE collision point.

The energy of DAΦNE electron/positron beam is tuned to produce $\phi$ mesons at rest in the lab frame. With a branching ratio of 49%, the $\phi$ meson decays into back-to-back $K^+K^-$ pairs. The charged kaons have a small energy spread and a low kinetic energy centered at 16 MeV. Such features are essential for our stopped kaon experiment with a gaseous target.

As the kaon detector (see Fig. 2), we installed two plastic scintillation counters above and below the collision point. Both were 1.5 mm thick. Identification of kaons from other minimum ionizing particles (MIPs) was done using time of flight information. From the timing spectrum of top-bottom kaon detectors shown in Fig. 3, kaon events were well distinguished from MIPs with the former being more abundant by a factor of 10. A simultaneous detection of a $K^+K^-$ pair would generate a signal to be employed as a “kaon trigger”. If an X-ray event at one of the SDDs was detected within 6 $\mu$s after the kaon trigger, the X-ray event would be tagged with a kaon coincidence flag for analysis. An intrinsic efficiency of 50% for the kaon trigger exists due to the fact that only half of the triggers have a $K^-$ going upward to produce kaonic atom.

The incident $K^-$ going upward was further decelerated by a mylar degrader whose thickness was optimized to stop the kaon inside the target. The degrader had a step-like shape to compensate the $\phi$ boost effect caused by a crossing angle of 50 mrad of the beams. After the degrader the kaon went through a Kapton entrance window of the vacuum chamber, and the bottom of the target cell, before finally being stopped inside the gas target. A cylindrical target cell made of Kapton held the target gas inside, which was cooled to 27 K and kept at a pressure of 0.95 bar. Such condition corresponds to about 10 bar at normal temperature and pressure. Negatively charged kaons stopped inside the target cell would produce kaonic atoms and emit X-rays uniformly.

For X-ray detection, we employed 144 silicon drift detectors (SDDs) developed specially for the experiment. Each SDD has an effective area of 1 cm$^2$, and all the SDDs mounted outside the target cell cover 10% of the solid angle. In addition to a good energy resolution of FWHM $\sim$ 150
The in-situ energy calibration of SDDs was carried out using an $^{55}$Fe source and titanium foils placed close to the target cell, as illustrated in Fig. 2. Two characteristic peaks of $K_\alpha$ X-ray from Ti at 4.5 keV and Mn at 5.9 keV were the reference lines.

During the beam time, we recorded all detected X-rays from the calibration source and those induced by kaon-correlated charged particles. For analysis, we categorized the X-ray data into two types: the first type has no correlation to “kaon trigger” mentioned before, called as “self-trigger” data; the second type has a coincidence with the kaon trigger, thus called “kaon coincidence” data.

Energy calibration for each SDD was done using the self-trigger data with high statistics for $K$-series lines of calibration sources. The $K_\alpha$ lines of Ti and Mn have well-known energies and intensity ratio between $K_{\alpha 1}$ and $K_{\alpha 2}$. Such in-situ calibration reduced the variation in energy scale due to fluctuation in the long term stability of the SDDs. Data of 60 SDDs were selected out of 144 SDDs installed based on energy resolution, peak shape and stability of the Ti and Mn lines. The summed up spectrum without kaon coincidence of the selected data is shown in Fig. 4, in which a resolution of $151 \pm 2$ eV at 6.5 keV was confirmed.

3. Result of kaonic-$^4$He X-ray measurement

From September 2008 to November 2009, we collected data with helium-4, hydrogen, helium-3 and deuterium targets. The kaonic-$^4$He data of this paper were taken in January 2009 for two weeks. During this period, we accumulated an integrated luminosity of $20 \text{ pb}^{-1}$, corresponding to a number of $4.7 \times 10^6$ kaons detected by the kaon detector.

Applying the kaon coincidence condition to the same SDD data set of Fig. 4, we obtained the correlation between the X-ray energy and the timing information shown in Fig. 5. The Mn
Figure 5. Correlation between energy and timing information, with triple coincidence. One channel at y-axis corresponds to 3.5 ps.

Kα line close to 6 keV comes continuously from the 55Fe source, forming a band regardless of kaon timing. Another lighter band of Ti Kα line excited by Mn X-rays can also be identified.

Moreover, within the 1.2 µs time region denoted as kaon timing in Fig. 5, we see clearly the Ti Kα events from titanium foil excited by charged particles correlated with kaons, and most essentially, the kaonic-4He Lα event close to 6.5 keV.

The kaonic X-ray energy spectrum with kaon timing selection is shown in Fig. 6, where the background events were rejected with a factor of 10⁴ comparing to Fig. 4. Accidental Mn and Ti X-ray events still yield distinguishable peaks. Close to 6.5 keV, the kaonic-4He Lα line overlaps with the Mn Kβ line. Therefore we have to extract the Mn Kβ component from the overlap part to obtain the kaonic-4He Lα peak.

To determine the energy of kaonic-4He Lα line, we took the following procedure. First fit the self-trigger X-ray spectrum to obtain the parameters including: the mean value of Ti and Mn Kα and Kβ lines, the ratio of Mn Kβ/Kα peak intensity. Then fix these parameters and use the response functions of characteristic X-ray lines determined in the first step to fit the kaon coincident spectrum. A Voigt function was added to fit the kaonic-4He Lα line, with the energy resolution of 151±2 eV (FWHM) obtained from calibration data. Finally the X-ray energy of the kaonic-4He Lα line was determined to be

$$E_{2p}^{\text{exp}} = 6463.6 \pm 5.8 \text{ eV},$$

where the second term is the statistical error.

We considered the following contributions to systematic error to the kaonic-4He X-ray energy. Energy linearity, gain drift and SDD hit rate dependence were all found to be ±0.5 eV. The influence from the contamination of the Mn Kβ line was found to be negligible. Taken into account the uncertainty of the parameter determination in the fit functions, the total systematic error is estimated to be ±2 eV.

4. Conclusion
From the $E_{2p}^{\text{exp}}$ in previous section, using the value of 3d-2p energy $E_{2p}^{EM} = 6463.5 \pm 0.2 \text{ eV}$ [2], calculated by QED only, we determined a new value for the 2p level shift of kaonic-4He atom as:

$$\Delta E = 0 \pm 6(\text{stat}) \pm 2(\text{syst})\text{eV},$$
Figure 6. X-ray spectrum after applying kaon coincidence[1]. The $L_\alpha$ line of kaonic helium-4 overlaps with the Mn $K_\beta$ line. Intensity ratio between the Mn $K_\beta$ to $K_\alpha$ and the mean value of $K_\beta$ is fixed from the self-trigger data spectrum.

where the second term and third term on the right hand side denote statistical error and systematic error respectively.

The measurement of helium-4 target successfully achieved its goal of tuning the SDD system. More significantly, it is the first time that kaonic-$^4$He atom is produced with a gaseous target, and the result on the $2p$ level shift firmly established the resolution provided by the E570 group to the long-standing puzzle.

Acknowledgements
We thank C. Capoccia, B. Dulach and D. Tagnani, from LNF-INFN; H. Schneider, L. Stohwasser and D. Stücker from Stefan-Meyer-Institut, for their fundamental contributions in designing and building the SIDDHARTA setup. We thank as well the DAΦNE staff for the excellent working conditions and permanent support. We acknowledge the support of the European Community-Research Infrastructure Integrating Activity Study of Strongly Interacting Matter (acronym HadronPhysics2, Grant Agreement n. 227431) under the Seventh Framework Programme of EU. We also acknowledge the support of the Global COE Program ”the Physical Sciences Frontier” and Grant-in-Aid for Specially promoted Research (20002003), MEXT, Japan. The correspondent author is personally supported by the DC1 Research Fellowship for Young Scientists of JSPS, Japan.

References
[1] Bazzi M et. al. 2009 Physics Letters B 681 310
[2] Okada S et. al. 2007 Physics Letters B 653 387
[3] Batty C J, Friedman E and Gal A 1997 Phys. Rep. 287 385
[4] Akaishi Y 2005 Proc. Inter. Conf. on Exotic Atoms (EXA05) p.45
[5] Wiegand C E and Pehl R 1971 Phys. Rev. Lett. 27 1410
[6] Batty C J et. al. 1979 Nucl. Phys. A 326 455
[7] Baird S et. al. 1983 Nucl. Phys. A 392 297