

E570: Precision spectroscopy of kaonic helium $3d - 2p$ X rays

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Executive Summary

The goal of E570 as stated in the original proposal was to measure the energy of the $3d \rightarrow 2p$ x-ray of kaonic ${}^4\text{He}$ atom to a precision better than a few electron volts, in order to study the low-energy \bar{K} -nucleus strong interaction. The experiment was conducted in October – December of 2005 at the K5 beam channel by integrating novel large-area silicon drift x-ray detectors into the liquid-helium target of the E549 setup, and the final result has recently been published in Ref. [1].

The energy of the $3d \rightarrow 2p$ transition was determined to be 6467 ± 3 (stat) ± 2 (syst) eV, thereby fulfilling the initial goal of the experiment. The resulting strong-interaction energy-level shift is in agreement with theoretical calculations, thus eliminating a long-standing discrepancy between theory and experiment.

Based on the success of E570, the collaboration proposed an experiment to measure the $3d \rightarrow 2p$ X-rays of kaonic helium-3 at the K1.8BR beamline of J-PARC (E17), which has been approved as one of the “Day-1” experiments.

1 Introduction

Prior to E570, the strong-interaction shift of the $2p$ level ΔE_{2p} for kaonic ${}^4\text{He}$ has been measured in three experiments. The average of the three previous results gives $\Delta E_{2p} = -43 \pm 8$ eV [2, 3, 4], while most of the theoretical calculations give $\Delta E_{2p} \sim 0$ eV [5, 6, 7] (*e.g.* $\Delta E_{2p} = -0.13 \pm 0.02$ eV [5]). They disagree by more than five standard deviations, and this discrepancy is known as the “kaonic helium puzzle”.

E570 was therefore performed to measure the Balmer-series x-rays of kaonic ${}^4\text{He}$ atoms, setting as our experimental objective a precision of ~ 2 eV, thus shedding new light on the kaonic helium puzzle.

2 Experiment

E570 was carried out at the K5 beamline. We accumulated data in two periods – 520 hours in October 2005 (cycle 1) and 260 hours in December 2005 (cycle 2). The experimental apparatus was essentially the same as that of E549, except for the inclusion of x-ray detectors and energy calibration foils in the helium-target cryostat. A schematic view of the E570 setup around the target is shown in Fig. 1.

The kaonic ${}^4\text{He}$ atoms were produced by means of the stopped- K^- reaction using a superfluid ${}^4\text{He}$ target. Incident negatively-charged kaons with momentum ~ 650 MeV/ c were degraded in carbon degraders, counted with beamline counters, tracked by a high-rate beamline drift chamber and stopped inside the ${}^4\text{He}$ target. The energy losses before stopping were measured in a set of scintillation counters, T0. X-rays emitted from the kaonic ${}^4\text{He}$ atoms were detected by eight x-ray detectors which viewed the target from downstream through the 75 μm -thick Mylar window of the target vessel. Secondary charged particles produced in the kaon-absorption process following emission of kaonic x-rays were detected by charged-particle trigger/tracking systems placed on the left, right, top and bottom of the target.

E570 achieved a significant improvement over the past experiments by incorporating the following features:

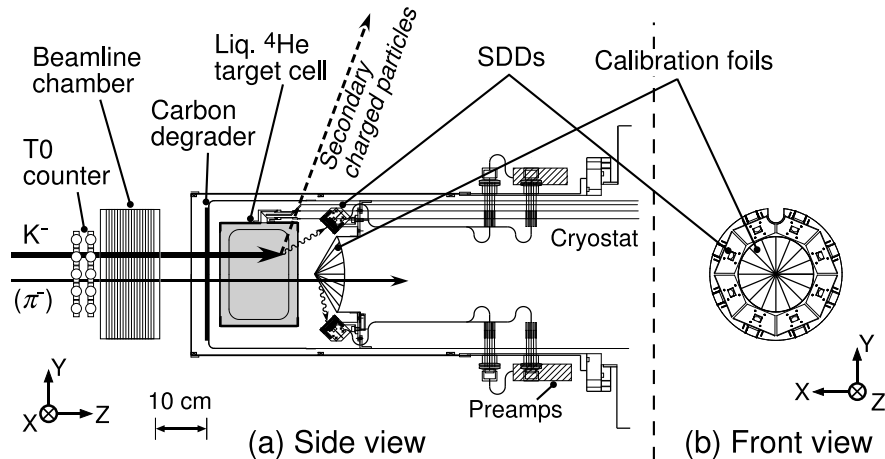


Figure 1: (a) A schematic side view of the E570 setup around the cylindrical target with the x-ray detection system. (b) A front view of the silicon drift detector (SDD) assembly. Eight SDDs are mounted on holders tilted at a 45 degree angle to the beam center in an annular-shaped pattern. Fan-shaped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

Silicon drift detectors As x-ray detectors, we employed eight silicon drift detectors (SDDs), each having an effective area of 100 mm^2 and a $260 \text{ }\mu\text{m}$ -thick active layer with an energy resolution of $\sim 190 \text{ eV}$ (FWHM) at the kaonic-helium $3d \rightarrow 2p$ x-ray energy, 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 comparable with that of a Si(Li) detector.

Cuts applied to reduce background We required that the reaction vertices reconstructed from an incident kaon track and an outgoing secondary charged particle track should be within the target, which is called the “fiducial volume cut”. See Fig. 2. 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, continuum background events were drastically reduced.

In-beam energy calibration The energy calibration was done by using characteristic x-rays induced by beam pions on high-purity titanium and nickel foils placed just behind the target cell. 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.

3 Results

Figure 3 (a) shows a typical x-ray spectrum for SDD self-triggered events, which is used for the energy calibration. Characteristic x-ray peaks of titanium and nickel were obtained with high statistics. The energy scale was calibrated by K_α lines of titanium and nickel with the well-known energies [8] and intensity ratios [9] of $K_{\alpha 1}$ and $K_{\alpha 2}$.

After applying the event selections and calibrating the energy scale, we obtained x-ray energy spectra for stopped- K^- triggered events: Figure 3 (b) and (c) respectively show the x-ray spectra taken in the runs in October 2005 (cycle 1) and December 2005 (cycle 2). In total, $\sim 7 \times 10^2$ (cycle 1) and $\sim 8 \times 10^2$ (cycle 2) events of $3d \rightarrow 2p$ x-rays were accumulated for each cycle. In comparison to the most recent measurement of the kaonic ^4He spectrum [4], we achieved ~ 2 times better energy resolution, ~ 3 times higher statistics, and ~ 6 times better signal-to-noise ratio.

Many fine details of the signal and calibration pulses were found necessary to attain eV accuracy and will be discussed extensively in a paper to follow. Here, we briefly summarize the spectral fitting method with a SDD-response function studied in detail, and show the fit results.

1. An energy-dependent experimental energy resolution was employed as is usually the case for silicon detectors: $\Delta E(\text{FWHM}) = 2.35\omega\sqrt{W_N^2 + FE/\omega}$, where W_N denotes the contribution of noise to the resolution (independent of the x-ray energy), E is the x-ray energy, F is the Fano factor (≈ 0.12 for silicon), and ω is the average energy for electron-hole creation in silicon.

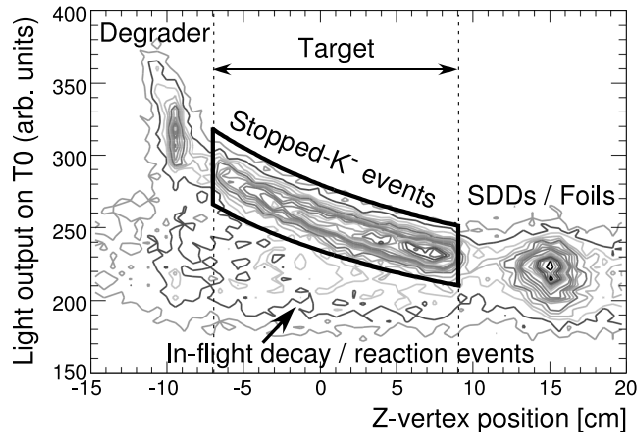


Figure 2: A typical density plot between the z -coordinate of the reaction vertex and the light output on T0, used to reject in-flight kaon decay/reaction events.

2. Because of the large incoherent (Compton) total scattering cross section of liquid ${}^4\text{He}$ (~ 1 barn/atom at photon energies of ~ 10 keV), a low-energy tail structure due to the Compton scattering must be taken into account. The x-ray spectra were simulated with the GEANT code using the Low Energy Compton Scattering (LECS) package [10] with a realistic setup of E570 and the measured stopped- K^- distribution.
3. We also have waveform data available from flash ADCs (FADCs), which were accumulated as well as ordinary comparator-type pulse-height ADC data. Using the waveform analysis, it is shown that there is a non-negligible pileup effect due to the high-rate beam condition of E570. The spectral function attributed to the pileup events could be estimated as a Gaussian on the right flank of the main-peak function.
4. There are many empirical investigations of the response function of silicon detectors using monoenergetic x-rays (*e.g.* [11, 12]), and it is known that there is an exponential-like feature decreasing steeply in intensity towards lower energy on the left flank of the main-peak function (called the “tail function”) and a flat shelf-like feature which extends to near zero energy (called the “shelf function”) [12], due to electron transport processes and imperfections in the fabrication processes. These effects were also taken into account in the spectral fitting separately from the Compton tailing effect in the liquid ${}^4\text{He}$ target mentioned above.

The intensity ratios of these components (pileup Gaussian, tail and shelf functions) to the main-peak component (Voigtian) were estimated by fitting the high-statistics x-ray spectra for self-triggered events. The estimated intensity ratios were then fixed in the fits of the x-ray spectra for stopped- K^- triggered events.

Resulting fit-lines are overlaid on the x-ray spectra shown in Fig. 3 (b) and (c) with each contribution, and the fit residuals are also shown under each spectrum, with thin lines denoting the $\pm 2\sigma$ values of the data. As a result, the kaonic ${}^4\text{He}$ x-ray energy of the $3d \rightarrow 2p$ transition was determined to be

$$E_{(3,d)} - E_{(2,p)} = 6467 \pm 3 \text{ (stat)} \pm 2 \text{ (syst)} \text{ eV} \quad (1)$$

where the first error is statistical and the second is systematic. The quoted systematic error is a linear summation of the contributions from the intensity ambiguities of the Compton tail, pileup, shelf and tail functions for kaonic-helium x-rays. The other transition energies ($4d \rightarrow 2p$ and $5d \rightarrow 2p$) obtained in this fit are listed in table 1 with only statistical errors. In this table, we also tabulate the EM values updated from Refs. [2, 3, 4] by Koike [13] using the latest kaon mass given by the particle data group (PDG) [14]. These values are consistent with another recent calculation [15] and differ slightly from the ones used in previous experiments [2, 3, 4]. The intrinsic width obtained in the fits seems to be very small and it needs more study to disentangle it from instrumental effects.

Since the strong-interaction shifts are negligibly small for the levels with the 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

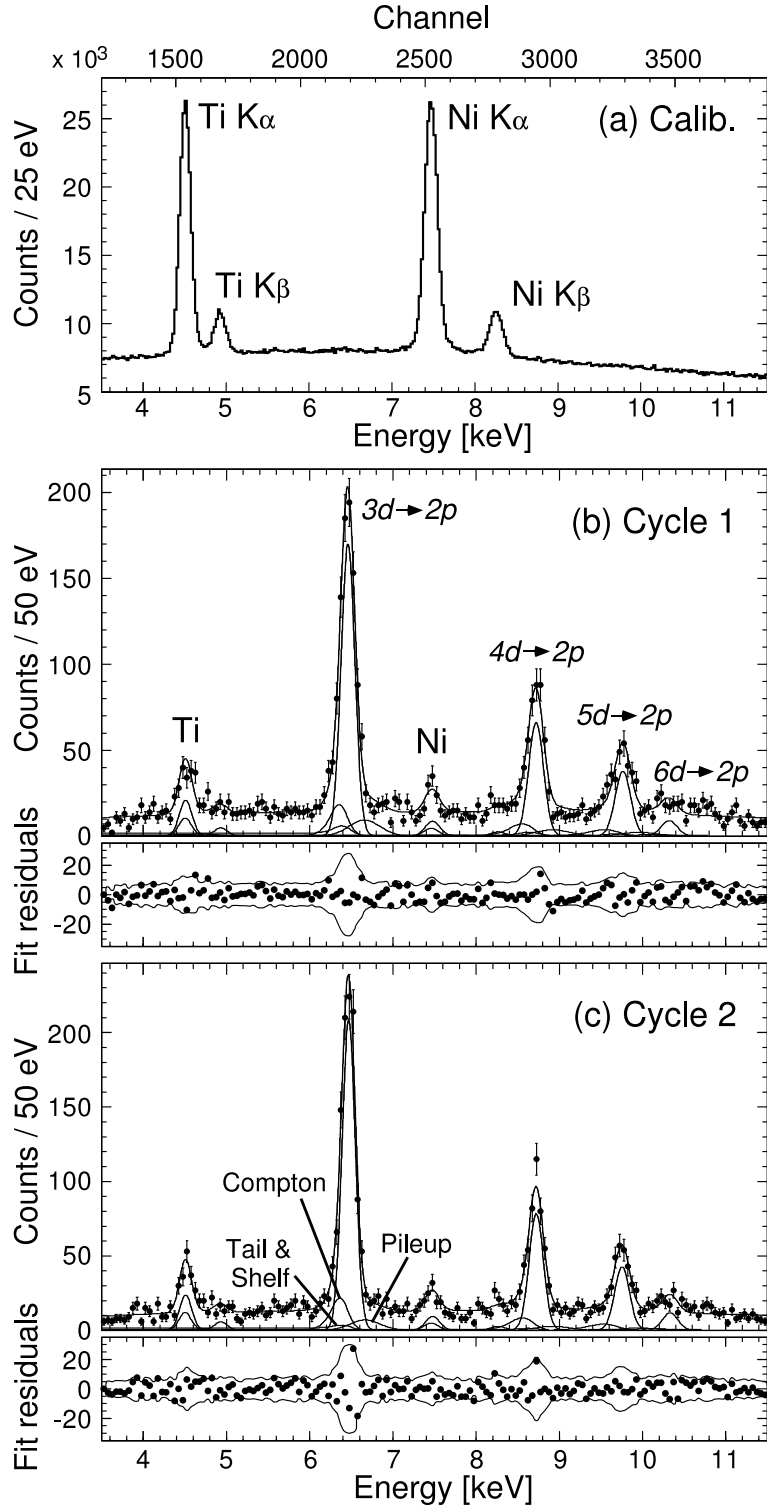


Figure 3: (a) A typical x-ray spectrum for self-triggered events which provides high-statistics energy-calibration information. (b)(c) Measured x-ray spectra for stopped- K^- events obtained from the runs in October 2005 (cycle 1) and December 2005 (cycle 2) respectively. A fit line is also shown for each spectrum, along with individual functions of the fit. The fit residuals are shown under each spectrum, with thin lines denoting the $\pm 2\sigma$ values of the data, where σ is the standard deviation due to the counting statistics.

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) [13]	6463.5	8721.7	9766.8

Table 1: Measured and EM calculated [13] kaonic ${}^4\text{He}$ x-ray energies of $3d \rightarrow 2p$, $4d \rightarrow 2p$ and $5d \rightarrow 2p$ transitions. The quoted error is purely statistical.

equation:

$$\Delta E_{2p} = (E_{(n,d)} - E_{(2,p)}) - (E_{(n,d)}^{EM} - E_{(2,p)}^{EM}), \quad (2)$$

where $E_{(n,d)} - E_{(2,p)}$ and $E_{(n,d)}^{EM} - E_{(2,p)}^{EM}$ correspond to the measured and calculated EM x-ray energies, respectively. To combine all statistics of the observed Balmer-series lines, we calculated ΔE_{2p} for each line using Eq. 2 and took their statistical averages; the $2p$ -level shift was then derived as

$$\Delta E_{2p} = 2 \pm 2 \text{ (stat)} \pm 2 \text{ (syst) eV}, \quad (3)$$

where EM values listed in table 1 [13] were adopted, and the systematic error was estimated in the way mentioned above. Note that the EM energy and thus the energy shift are sensitive to the value of the kaon mass, for which two slightly disagreeing measurements exist [14] leading to a large error in the PDG value. If the kaon mass changes by one standard deviation from the current value of $493.677(16)$ MeV/ c^2 [14], ΔE_{2p} changes by about 0.2 eV [13].

4 Conclusion

In conclusion, we have measured the Balmer-series x-rays of kaonic ${}^4\text{He}$ atoms 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. The kaonic ${}^4\text{He}$ x-ray energy of the $3d \rightarrow 2p$ transition was determined to be 6467 ± 3 (stat) ± 2 (syst) eV.

Using three observed transition lines ($3d \rightarrow 2p$, $4d \rightarrow 2p$ and $5d \rightarrow 2p$) with the corresponding EM values [13], the $2p$ -level shift was deduced as $\Delta E_{2p} = 2 \pm 2$ (stat) ± 2 (syst) eV. Figure 4 shows a comparison of the $2p$ -level shifts between this work and the previous experiments [2, 3, 4]. Our result excludes the earlier claim of a large shift of about -40 eV.

The theoretical calculations of the shift are very close to zero (~ -0.1) eV by an analysis with global fits to existing kaonic-atom x-ray data on various nuclei using an optical potential [16, 5], and also by a calculation using an SU(3) chiral unitary model [6]. A recent calculation by Friedman gives a value of -0.4 eV as the lowest possible one [7], when the non-linear density dependence is included [17]. On the other hand, Akaishi calculated the shift as a function of the real part (U_0) of the $\bar{K}N$ potential depth at a certain coupled potential depth ($U_{coupl} = 120$ MeV) [18]. The calculation was based on the coupled-channel approach between the $\bar{K}N$ channel and the $\Sigma \pi$ decay channel. A large shift ($|\Delta E_{2p}| \sim 10$ eV) is predicted near the resonance between atomic and nuclear poles, when the potential depth is at around ~ 200 MeV. The presently observed small shift disfavors the values of $(U_0, U_{coupl}) = (\sim 200 \text{ MeV}, 120 \text{ MeV})$ within his framework.

Our careful and precise determination of the $2p$ -level shift resolved the long-standing kaonic helium puzzle. The present data alone are not sufficient to deduce the \bar{K} -nucleus potential strength at the center of the nucleus. A unified study with the $2p$ width to be determined in further analysis and with data to be collected in kaonic ${}^3\text{He}$ x-ray spectroscopy [19] will indubitably yield invaluable constraints for the theories.

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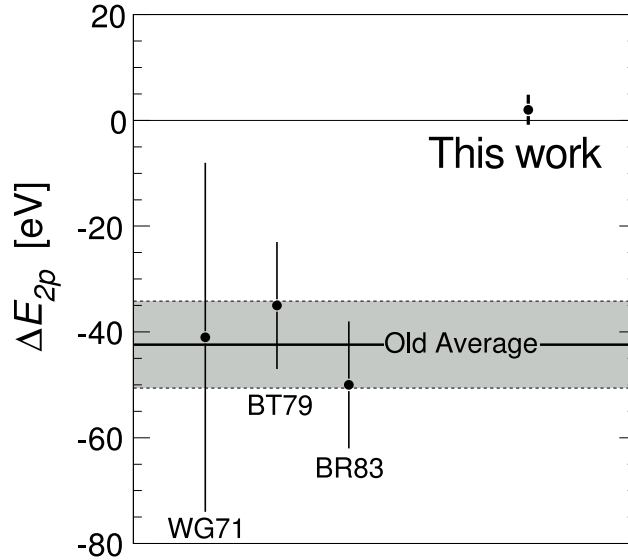


Figure 4: The $2p$ -level shift of kaonic ${}^4\text{He}$, ΔE_{2p} , obtained from this work and the past three experiments (WG71 [2], BT79 [3], BR83 [4]). Error bars show quadratically added statistical and systematic errors. The average of these past experiments is indicated by the horizontal gray band.

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