K- He atom 3d-2p X-ray Energy

Strong-interaction shift (and width)

3d-2p X-ray (~ 6.4 keV)

Width : $\Gamma_{2p}$
Shift : $\Delta E_{2p}$

(Coulomb-only)

Strong interaction

Nuclear Absorption
2 experiments
<p>| ① | E570 | K⁻⁴He | KEK | Published |</p>
<table>
<thead>
<tr>
<th></th>
<th>E570</th>
<th>K(^{-4})He</th>
<th>KEK</th>
<th>Published</th>
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<tr>
<td>2</td>
<td>E17</td>
<td>K(^{-3})He</td>
<td>J-PARC</td>
<td>“Day-1” (2009)</td>
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</table>
Long-standing kaonic-helium puzzle
3 past experiments

C.Wiegand and R. Pehl,
3 past experiments


C. Batty et al., Nucl. Phys. A326, 455 (1979)
3 past experiments

1971

C. Wiegand and R. Pehl,

1979

C. Batty et al.,
Nucl. Phys. A326, 455 (1979)

1983

S. Baird et al.,
Si(Li) 360 eV FWHM

Retractable calibration source (\(^{55}\text{Fe}\))

Target

Kaonic Helium X-ray Spectroscopy

$\Delta E_{2p}$ (eV)

$\langle$ repulsive $\rangle$

Publication Year
Kaonic Helium X-ray Spectroscopy

$\Delta E_{2p} (\text{eV})$

$\leftarrow$ repulsive

$\text{World average}$

$-43 \pm 8 \text{ eV}$
but theory...
The diagram shows the shift in the $2p$ level for various atomic numbers $Z$. The graph includes data points for $Z=2$ and $Z=16$, with $^4\text{He}$ and $^{16}\text{O}$ highlighted. The $2p$, $3d$, and $4f$ levels are indicated on the graph.
(chiral unitary+ optical model): \( \sim 0.2 \text{eV} \)

Very small shift @ \( Z=2 \)

Puzzle: $5\sigma$ discrepancy

Kaonic Helium X-ray Spectroscopy

Exp: $-43 \pm 8$ eV

World average

Theory $\sim 0$ eV
Take-home message
Take-home message

The shift is small
Take-home message

The shift is small

No more puzzle
Precision measurement of the $3d \rightarrow 2p$ x-ray energy in kaonic $^4\text{He}$

S. Okada$^{a,*}$, G. Beer$^b$, H. Bhang$^c$, M. Cargnelli$^d$, J. Chiba$^e$, Seonho 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. Iwai$^i$, M. Iwasaki$^{a,g}$, B. Juhász$^d$, P. Kienle$^{d,j}$, J. Marton$^d$, Y. Matsuda$^a$, H. Ohnishi$^a$, H. Outa$^a$, M. Sato$^{g,l}$, 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$^d$

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Accepted 13 August 2007
Precision measurement of the $3d \rightarrow 2p$ x-ray energy in kaonic $^4$He

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Abstract

We have measured the Balmer-series x-rays of kaonic $^4$He atoms using novel large-area silicon drift x-ray detectors in order to study the $\bar{K}$–nucleus strong interaction. The energy of the $3p \rightarrow 2p$ transition was determined to be 6467 ± 8 eV, which is the energy of the level with principal quantum number $2p$. This result is in agreement with theoretical calculations, thus eliminating a long-standing discrepancy between theoretical calculations and the average of three previous measurements.

Keywords:

Kaonic atom; X-ray spectroscopy; Silicon drift detector
$\Delta E_{2p} = 2 \pm 2\,^{\text{stat}} \pm 2\,^{\text{sys}}\,\text{eV}$
how E570 did it

Poster: H. Tatsuno
Four important points
1 resolution
1 resolution
2 S/N (and statistics)
1 resolution
2 S/N (and statistics)
3 calibration
1. resolution
2. S/N (and statistics)
3. calibration
4. line shape
1 x2 better resolution
SDD (silicon drift detector)

Electrons drift to a small anode (small capacitance)

High resolution (185 eV FWHM @ 6.4 keV), despite large area (100 mm$^2$)

8 such SDDs used in E570
2 x6 better S/N
**FIG. 1:** The partially cutaway drawing of the E570 experimental setup. LC: Lucite Čerenkov counter, T0 and T1: timing counters, TC: trigger counters.

B. Trigger and signal readout

We made two types of triggers, one was the kaon trigger for tagging the stopped-\( K^- \) events, and the other was the SDD self trigger which was used for calibrating individual SDDs. The kaon trigger required that the incoming charged particle to be a kaon and that at least one secondary-charged particle hit the TC or both the Pstart and the Pstop. Typical trigger rate was 500 Hz (450 kaon triggers and 50 SDD-self triggers), and about 76% of triggers were accepted by the data acquisition system.

The charge-pulse signal from an SDD was taken out through a hermetic port and was integrated by a charge-sensitive preamplifier. A transistor reset method was used to eliminate a feedback resistance, resulting in suppressing the contribution of thermal noise. On the other hand, a reset pulse invoked an overshoot peak just after the reset timing, which was rejected at the hardware level (450 \( \mu \text{s} \)-width veto). Signal crosstalk of a neighboring detector which shared a hermetic port was also rejected (16 \( \mu \text{s} \)-width veto) not to trigger. In addition, we rejected the overshoot events due to huge energy deposits of charged particles penetrated the SDDs (1 \( \mu \text{s} \)-width veto).

The output signal of the preamplifier was fed to a CAEN 16-channel spectroscopy amplifier model N568B (3 \( \mu \text{s} \) shaping time). The pulse height of each SDD was recorded by a peak-sensing analog-to-digital converter (ADC) with a 7-\( \mu \text{s} \) gate width and also by a flash ADC. The timing information was recorded by a 5-\( \mu \text{s} \) range time-to-digital converter (TDC). The data were taken in two periods – 520 hours in October 2005 (cycle 1) and 260 hours in December 2005 (cycle 2). In the cycle 1, only 3 out of 8 SDDs yielded useful data; the faulty detectors were then replaced, and 7 SDDs were functional in the cycle 2.

III. ANALYSIS

A. Event selection

1. Fiducial volume

Fig. 3 shows a density plot of \( x-y \) vertices reconstructed as described in the previous section, and Fig. 4 shows a correlation plot between the \( z \) coordinate of the vertex and the light output of kaons on the T0. The light output was calibrated in MeV\(_{\text{ee}}\) unit by using incident minimum-ionizing particles in the beam (mostly \( \pi^- \), etc.).

\( K^- \ 650 \text{ MeV/c} \)
FIG. 2: (a) The schematic drawing of side view of the E570 setup around the cylindrical target with the x-ray detection system. (b) The front view of the silicon drift detector (SDD) assembly. Eight x-ray detectors 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.

FIG. 3: A typical density plot between the \(x\) and \(y\) coordinate of the reaction vertex. We adopted \(\sqrt{x^2 + y^2} < 10.0\) cm as an \(x\)-\(y\) vertex cut.

with considering the saturation of the photomultipliers and the Birks effect [15] of the plastic scintillators. Here, we applied fiducial volume cuts of \(\sqrt{x^2 + y^2} < 10.0\) cm on the radius from the target center, and of \(-6.5 < z < 8.5\) cm on the \(z\) coordinate.

FIG. 4: A typical density plot between the \(z\)-coordinate of the reaction vertex and the light output on the T0. For this plot, \(x\)-\(y\) vertex cut of \(\sqrt{x^2 + y^2} < 10.0\) cm had already been applied.

2. Rejecting in-flight decays and reactions

The in-flight decayed or reacted kaons were contaminating the selected vertices even after applying the fiducial volume cuts. To reject them, we used a relation between the energy deposits of kaons on the T0 and the reconstructed vertices in the target as shown in Fig. 4. The in-flight contamination located in the region of lower light output than that of correlation.

Fiducial selection
Fiducial selection

FIG. 2: (a) The schematic drawing of side view of the E570 setup around the cylindrical target with the x-ray detection system. (b) The front view of the silicon drift detector (SDD) assembly. Eight x-ray detectors 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.

FIG. 3: A typical density plot between the x-ray detectors and the target.

Light output (MeVee)

FIG. 4: A typical density plot between the x-ray detector's light output and the reaction vertex. The in-flight contamination located in the region of lower light output than that of correlation. The in-flight decayed or reacted kaons were contaminated by fiducial volume cuts. To reject them, we used a relation of the selected vertices even after applying the fiducial volume cut of the plastic scintillators. Here, vertex cut.

X coordinate (cm)

Y coordinate (cm)

Z coordinate (cm)
FIG. 5: A typical density plot between the $z$-coordinate of the reconstructed vertex and the ID $\text{stopK}$ defined in Eq. (1). The right figure shows the projection of ID $\text{stopK}$ with the fiducial volume cuts. We defined here the “stopped kaons” as $\text{ID}_{\text{stopK}} > -1.0$, and the selected histogram of the $z$ vertex is shown in the bottom figure.

We defined an index to cut the in-flight events, $\text{ID}_{\text{stopK}} = L - L_{\text{sim}}(z)$,

$$\text{(1)}$$

where $L$ is the measured light output on the T0 and $L_{\text{sim}}(z)$ is the Birks-corrected simulated value. Fig. 5 shows a density plot between the ID $\text{stopK}$ and $z$-vertex position. The projected histogram of ID $\text{stopK}$ with the fiducial volume cuts is shown in the right figure. We adopted here the “stopped kaons” as $\text{ID}_{\text{stopK}} > -1.0$, and the selected histogram of the $z$ vertex is shown in the bottom figure.

3. Timing selection

The timing of stopped kaons was selected by the TDC data of SDDs to reduce the accidental background. Fig. 6 (a) shows the typical correlation plot between the SDD timing (the time difference between kaons arriving and x-rays detection) and the SDD pulse height, which exhibits a vertical band due to x rays induced by kaons. The events of kaonic-helium $^3\text{He}$ $→ 2\text{p}$ x rays are pointed by an arrow. The accidental hits of titanium and nickel characteristic x rays were observed, which were shown as thin horizontal lines.

Figure 6 (b) shows the timing spectrum. The time walk due to leading-edge-type discriminators was already corrected. Time resolution of the SDD was $\sim 130$ ns ($\sigma$) at $\sim 83$ K, which reflected the drift-time distribution of the electrons in the SDD. We selected the data within $0 \text{ to } 500$ accepted with time-walk correction, fiducial volume cut and ID$\text{stopK}$ selection.

B. Energy calibration

The parameters of energy calibration for individual x-ray detectors were determined using the characteristic x rays of titanium and nickel, which were recorded in the self-tigger data. Single run lasted about 2 hours. The yield of titanium $K\alpha$ x ray is $5 \times 10^2$ events per hour per SDD. To obtain accurate calibration parameters and to trace the gain drifts of x-ray detectors, we needed at least $10^4$ events (20-hour data), thus about ten 2-hour runs were grouped into a “meta-run.”

Figure 7 shows a typical ADC spectrum of the SDD. Titanium and nickel $K\alpha$ lines were clearly observed. A calibration line converting ADC channel into energy was determined from the positions of these $K\alpha$ lines with the well-known energies [16] and intensity ratios [17] of $K\alpha_1$ and $K\alpha_2$. The information of x rays used for calibration is listed in Table I.
3 in-situ calibration
Ti & Ni foils

4He

Carbon degrader

SDDs

Cryostat

SDDs

Calibration foils

Beam

20 cm

15 cm

6.2 cm

9.43 cm

10 cm

Side view

Front view
E570 target & X-ray detectors

Target cell

SDD

foils
existed in the incident beam) on high-purity titanium and nickel foils placed just behind the target cell. The energy of the kaonic-helium $^{3}\text{d} \rightarrow ^{2}\text{p}$ x-ray, $\sim 6.4$ keV, lies between the characteristic x-ray energies, 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- $^{\text{K}^-}$ trigger 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

Fig. 2 shows the correlation between the $z$-coordinate of the reaction vertex and the light output of T0. Each component of the target assembly (a carbon degrader, a target cell and SDDs/foils) is clearly seen. We applied a fiducial volume cut of $-7.0 < z < 9.0$ cm on the $z$-coordinate as shown in Fig. 2, and $\sqrt{x^2 + y^2} < 11.0$ cm on the radius from the target center. Slower incident kaons, which give larger light output on T0, stop upstream in the target, while faster kaons (hence smaller pulse height) stop downstream. Events which follow this trend were selected as stopped- $^{\text{K}^-}$-timing events when lying within the solid-lined box in Fig. 2.

Stopped- $^{\text{K}^-}$-timing events were selected using SDD timing information to reduce the accidental background. Time resolution of the SDD after time-walk correction was $\sim 160$ ns ($\sigma$) at $\sim 83$ K, which reflected the drift-time distribution of the electrons in the SDD. Data within $\pm 2$ standard deviations from the average SDD hit timing were selected.

Fig. 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. Typical yields of titanium $^{\text{K}^\alpha}$ peaks are $5 \times 10^2$ events per hour for each SDD. Time-dependent gain drift was corrected about every 20 hours. The energy scale was calibrated by $^{\text{K}^\alpha}$ lines of titanium and nickel with the well-known energies \cite{10} and intensity ratios \cite{11} of $^{\text{K}^\alpha_1}$ and $^{\text{K}^\alpha_2}$.

After applying the event selections described above and calibrating the energy scale, we obtained x-ray energy spectra for stopped- $^{\text{K}^-}$-triggered events shown in Fig. 3. Kaonic-helium $^{3}\text{d} \rightarrow ^{2}\text{p}$, $^{4}\text{d} \rightarrow ^{2}\text{p}$ and $^{5}\text{d} \rightarrow ^{2}\text{p}$ transitions are clearly observed, while the Ti and Ni x-ray peaks are greatly suppressed. Fig. 3 (b) and (c) respectively show the x-ray spectra taken in 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 $\sigma$ is the standard deviation due to the counting statistics.
istic x-ray energies, 4.5 keV (Ti) and 7.5 keV (Ni). To obtain SDDs/foils is clearly seen. We applied a fiducial volume cut of 3.

Analysis of the SDD after time-walk correction was high statistics. Typical yields of titanium and nickel were obtained with characteristic x-ray peaks of titanium and nickel were obtained with average SDD hit timing were selected.

Fig. 2 shows the correlation between the energy of the kaonic-helium lines of titanium and nickel with the well-known energy calibration spectra. Data within ±6.4 keV, lies between the characteristic x-ray, and intensity ratios.

Kaonic-helium lines of titanium and nickel with the well-known energy calibration spectra, we accumulated SDD high-statistics energy calibration information. (b), (c) Measured x-ray spectra for stopped- kaon trigger, fiducial & timing cut.

SDD Self trigger
4 line shape
existed in the incident beam) on high-purity titanium and nickel foils placed just behind the target cell. The energy of the kaonic-helium $^3d \rightarrow ^2p$ x-ray, $\sim 6.4$ keV, lies between the characteristic x-ray energies, 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.

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![Fit](Okada et al., PLB 653 (2007) 387)
- Gaussian --> Voigtian
- “Escape” & “Shelf” are neglected.
- added “Compton Tail”
Gaussian --> Voigtian
“Escape” & “Shelf” are neglected.
added “Compton Tail”
Gaussian $\rightarrow$ Voigtian

"Escape" & "Shelf" are neglected.

added "Compton Tail"
- Gaussian --> Voigtian
- “Escape” & “Shelf” are neglected.
- added “Compton Tail”
結果

Results
Same-scale comparison

C. Batty et al., Nucl. Phys. A 326, 455 (1979)
Same-scale comparison

1971

1979

1983

2007

-5

-4

-3

-2

-1

0

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

Counts / 50 eV

Fit residuals

Energy (keV)

Energy (keV)

Energy (keV)
Same-scale comparison

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shift = $E^{\text{exp}} - E^{\text{EM}}$

$E_{\text{EM}}(\text{eV})$ 6463.46 ± 0.15 (Koike)

due to the K mass error
shift = $E^{\text{exp}} - E^{\text{EM}}$

$E_{\text{EM}}(\text{eV}) = 6463.46 \pm 0.15$ (Koike)

due to the K mass error

corresponds to ±1 eV in X-ray energy
Akaishi calculated the shift as a function of the real part (value of unitary model zero (to the value of the kaon mass, for which two slightly disagreeing systematic error was estimated in the way mentioned above. The current value of 493.677(16) MeV the earlier claim of a large shift of about 0.2 eV compares to the Si(Li) x-ray detectors used in the past experiments. The average of these past experiments is indicated by the horizontal gray band. In conclusion, we have measured the Balmer-series x-rays by about 0.2 eV

References

\[ \Delta E_{2p} = 2 \pm 2(\text{stat}) \pm 2(\text{sys}) \text{ eV} \]
what about the width?
Old average

Shift (eV) vs. $\Gamma$ (eV)

Old average
$\Gamma_{2p} < 17 \text{ eV (95\%)}$

Tatsuno et al., soon to be published
$K^- {^3He}$

E17: the “day-1” experiment @ J-PARC

Next talk: M. Iio
Fig. 1
Hadron Hall Layout Plan
Hadron hall

Fig. 1
Hadron Hall Layout Plan

K1.8-DR

K1.8

High-P

K1.1/K0.8 (S-type)

K0.8/K1.1 (C-type)

KL
E17(15) setup
E17(15) setup

E15 components

Magnet Q8

Beam

Cryostat

120 cm

30 cm

Magnet

CDH

CDC

Adjustable degrader

LC

T1

T0

BLC

SDD

Main degrader

Liq. $^3$He

Kaon Decay Veto

CDH

Magnet
E17(15) setup

E17 specific

Cryostat

Magnet Q8

Adjustable degrader

Main degrader

LC T1 T0 B1 C

SDD

Liq. $^3$He

Kaon Decay Veto

CDH

Beam veto
Getting ready

beamline chamber

88 mm
Getting ready

beamline chamber

K- beamline chamber

88 mm

target ($^3$He ~500 cm$^3$, liquified in the heat exchanger)
Getting ready

beamline chamber

K$^-$

target ($^3$He $\sim$500 cm$^3$, liquified in the heat exchanger)
Getting ready

**Target** ($^3$He $\sim$500 cm$^3$, liquified in the heat exchanger)

*Diagram showing the beamline chamber and 8 SDDs.*
Getting ready

- Target ($^3$He ~500 cm$^3$, liquefied in the heat exchanger)
- Beamline chamber
- Preamps in vacuum
- 8 SDDs

K$^-$ beam
Summary

結論

Summary
Now the $K^{-4}\text{He}$ $2p$ shift is consistent with all theory calculations
✓ Now the $K^{-4}\text{He}$ $2p$ shift is consistent with all theory calculations

✓ No more Kaonic Helium puzzle
✓ Now the K^-4He 2p shift is consistent with all theory calculations

✓ No more Kaonic Helium puzzle

✓ Width also appears to be small
✓ Now the $K^{-4}\text{He}$ 2$p$ shift is consistent with all theory calculations

✓ No more Kaonic Helium puzzle

✓ Width also appears to be small

✓ E17 J-PARC Day-1 experiment will measure $K^{-3}\text{He}$
The E570 collaboration

G. Beer¹, H. Bhang², M. Cargnelli³, J. Chiba⁴, S. Choi²,
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S. Suzuki⁹, T. Suzuki⁸, H. Tatsuno⁷, D. Tomono⁸,
E. Widmann³, T. Yamazaki⁸, H. Yim², J. Zmeskal³

Victoria Univ.¹, SNU², SMI³, TUS⁴, INFN(LNF)⁵,
Tokyo Tech⁶, Univ. of Tokyo⁷, RIKEN⁸, KEK⁹
The E15/E17 collaboration


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