Kaonic 3He and 4He X-ray measurement in SIDDHARTA

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On behalf of
SIDDHARTA collaboration

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## Experimental results before SIDDHARTA

| Z | A | Target | Last orbit | Level shift | Old experiments | New experiments |
|---|---|--------|------------|-------------|-----------------|-----------------|
| 1 | 1 | $^1$H   | 1s         | Attractive  | Davies (79), Izycki (80), Bird (83) | Repulsive       |
|   |   |        |            |             | KpX(97), DEAR (05) |                 |
| 1 | 2 | $^2$D   | 1s         | No data     | No data         |                 |
| 2 | 3 | $^3$He  | 2p         | No data     | No data         |                 |
| 2 | 4 | $^4$He  | 2p         | Large       | Wiegand (71), Batty (79), Baird (83) | Small           |
|   |   |        |            |             | KEK E570 (07)   |                 |

Recently performed experimental results: different from old data

**SIDDHARTA experiment:**
- All light targets (from hydrogen to helium-4)
- Confirmation of “New experimental results” and improvement of precession
- First data of kaonic deuterium and kaonic helium-3
Introduction
-- History --
Kaonic atom data (Z ≥ 3) Used for studies of K^barN interaction

Optical model

\[ 2\mu V_{\text{opt}}^{(2)}(r) = -4\pi \left(1 + \frac{\mu}{m}\right) b_0 \rho(r). \]

Experimental X-ray data of shift & width: Well fitted with optical potentials

Expected shift of K-4He 2p state: \( \Delta E \sim 0 \text{ eV} \)

| Shift [eV]   | Ref                          |
|--------------|------------------------------|
| -0.13±0.02   | Batty, NPA508(1990) 89c      |
| -0.14±0.02   | Batty, NPA508(1990) 89c      |
| -0.4         | Bianco, Nuo. Cim.22 (1999) 1 |
| -1.5         | Akaishi, Proc. EXA05         |
Kaonic helium atom data ($Z=2$)

$$\Delta E_{2p} = E_{\text{exp}} - E_{\text{e.m.}}$$

| $\Delta E_{2p}$ (eV) | $\Gamma_{2p}$ (eV) |
|-----------------------|---------------------|
| $-41 \pm 33$          | -                   |
| $-35 \pm 12$          | $30 \pm 30$        |
| $-50 \pm 12$          | $100 \pm 40$       |
| **Average**           | **$-43 \pm 8$**     |

**1971**

C. Wiegand and R. Pehl,
Phys. Rev. Lett. 27, 1410 (1971)

**1979**

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

**1983**

S. Baird et al.,
Nucl. Phys. A392, 297 (1983)

$$\Delta E_{2p} = -43 \pm 8 \text{ eV}$$

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**World average**
Possible shift of Kaonic helium ($Z=2$)

Y. Akaishi, EXA05 proceedings

Q: K-4He experimental results (~40 eV shift) correct? 
Q: non-zero shift (~5 eV) on K-4He? 
Q: How about K-3He? 
Large, small, tiny???

Need: New experiments both on He-3 and He4

Prediction of "deeply bound kaonic nuclei" → "hot topics"

Large shift (-40 eV) cannot be explained by any models.

K-nucl model
Small (<±10 eV)

Optical model
Tiny (~ 0 eV)

K-He4 exp
Large (~40 eV)
Akaishi Prediction -10~ +10 eV

Optical model ~0 eV

\[ \Delta E_{2p} = 2 \pm 2 \text{ (stat)} \pm 2 \text{ (syst) eV} \]

\[ \Delta E_{2p} = -43 \pm 8 \text{ eV} \]

Disagree!

E570 results (’07)

K-\(^4\)He 2p level shift

1983

S. Baird et al., Nucl. Phys. A392, 297 (1983)

2007

S. Okada et al., PLB653(07)387

3d-2p

4d-2p

5d-2p
Solving the kaonic helium puzzle

Old Experiments

Large shift
(- 43±8 eV)

E570

Small shift
(+2±2±2 eV)

More than 3 σ difference

Experimental confirmation need!
→ SIDDHARTA experiment
SIDDHARTA Experiment
**SIDDHARTA Experimental Setup**

**DAFNE e⁺e⁻ collider**
510 MeV (e⁻, e⁺)
Production of φ at rest

\[ e^+ + e^- \rightarrow \phi \rightarrow K^+ + K^- \]

**K⁻ beam at DAFNE**
1. Monochromatic
2. Low-energy
3. No hadronic background

**Efficient stops in Gas target**

**Triple coincidence:**
\[ SDD_x \ast \text{Scint}_K \ast \text{Scint}_K \]

**Rejected:**
Background events uncorrelated to K⁺K⁻ pair productions
### Comparison of X-ray detectors

| experiment | KpX | DEAR | E570 |
|------------|-----|------|------|
| Detector   | Si(Li) | CCD | SDD |
| Area       | [mm²] | 200 | 724 | 100 |
| Thickness  | [mm]  | 5   | 0.03 | 0.26 |
| ΔE (FWHM)  | [eV]  | 410 | 170 | 185 |
| Δt (FWHM)  | [ns]  | 290 | -  | 430 |

T. Ishiwatari, Hyp. Int. 194(09)165
Comparison of X-ray detectors

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T. Ishiwatari, Hyp. Int. 194(09)165
Kaonic He-4 X-rays at SIDDHARTA

2009

Target size: r=6cm, h=12 cm
Target density: 27 K, 0.95 bar = 10 bar at NTP

First measurement with gas target

Installed SDD: 144 cm², Used in Analysis: 60 cm²
SDD operation temp. : 170 K,
SDD Energy resolution: ~150 eV (at 6 keV)

For precise determination:
Fe source + Ti foil Installed
(4.5 keV & 5.9 keV X-rays as in-beam calibration lines)
KHe-4 energy spectrum at SIDDHARTA

PLB681(2009)310; NIM A 628(2011)264

No-coincidence

Counts / 10 eV

Energy [keV]

Counts / 30 eV

K-He data taking

Target

Fe55

Degrader

Ti foil

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

$\Delta E = E_{\text{exp}} - E_{e.m.}$

$= 0 \pm 6\text{(stat)} \pm 2\text{(syst)}$ eV
Summary of KHe-4 shifts (up to 2007)

- **SIDDHARTA**
  - $+0 \pm 6 \text{(sta)} \pm 2 \text{(sys)}$

- **E570**
  - $+2 \pm 2 \text{(sta)} \pm 2 \text{(sys)}$

- **Akaishi Prediction**
  - $-10 \sim +10 \text{ eV}$

- **Optical model**
  - $\sim 0 \text{ eV}$

- **K-He4 exp**
  - Large ($-40 \text{ eV}$)

- **K-nucl model**
  - Small ($< \pm 10 \text{ eV}$)

- **Optical model**
  - Tiny ($\sim 0 \text{ eV}$)
Data taking periods of SIDDHARTA in 2009

K-He4 data with Fe source

55Fe source:
Good for reduce sys. error on K-4He
Bad for “background” events on K-H,K-D

Removed 55Fe source in other data

Use of Mn Ka (5.9 keV) from 55Fe

Systematic error = +/-2 eV

PLB681(2009)310
Data taking periods of SIDDHARTA in 2009

DAFNE shutdown in Summer

New alignment of setup → Improve S/N ratio

K-He3 data (~4 days)

He-4
He-3
D
H

55Fe source:
Good for reduce sys. error on K-4He
Bad for “background” events on K-H, K-D

Removed $^{55}\text{Fe}$ source in other data
Data taking scheme at DAFNE

Instead of Fe source, “X-ray tube” data taken

Estimated systematic error ~ 5 eV

Production data

- Ti/Cu foil
- SDDs
- degrader
- Scintillators

Calibration data

- Ti/Cu foil
- SDDs
- X-ray tube

Production data:

- $K^-$

Calibration data:

- $K^+$

$e^-$

$\phi$

$e^+$

Estimated systematic error ~ 5 eV

Instead of Fe source, “X-ray tube” data taken
SDD X-ray energy spectra

Calibration data with X-ray tube

(a)

Ti Kα

Cu Kα

count / 30 eV

x 10^6

x 10^5

x 10^4

x 10^3

x 10^2

x 10^1

x 10^0

Ti/Cu foil

SDDs

calibration data

X-ray tube

Ti/Cu foil

e^-

e^+

Calibration Ti&Cu
SDD X-ray energy spectra

Calibration data with X-ray tube

Not correlated to Kaon signals

Production data

Energy scale determined by X-ray tube data

Energy spectrum with uncorrected to kaon timing [Fig. (b)]
SDD X-ray energy spectra

Calibration data with X-ray tube

Not correlated to Kaon signals

Production data

Selected with K+K- & SDD timing

Time difference between SDD & Kaon detector
Rate dependency
Peak position shifts due to hit rate of SDDs:
Hit rate in (a) is ~10 times higher than in (b)

~10 eV peak shift compared to (a)

Calibration in (a): not reliable!
SDD X-ray energy spectra

Calibration data with X-ray tube

Not correlated to Kaon signals

Production data (a) (b)

Rate dependency

Peak position shifts due to hit rate of SDDs: Hit rate in (a) is ~10 times higher than in (b)

~10 eV peak shift compared to (a)

Significant for K-He measurement

After beam time, (X-ray tube only)

X-ray tube current [mA]

SDD hit rate

Peak shift [eV]

High rate

Low rate

High rate

Significant for K-He measurement
SDD X-ray energy spectra

Calibration data with X-ray tube

Not correlated to Kaon signals

Production data

1. Good SDD selection
2. Gain adjustment,
3. correction of time-dependent fluctuation

Precise energy calibration

High rate

Low rate
SDD X-ray energy spectra

Not correlated to Kaon signals

Production data

Low rate

Ti Ka

Cu Ka

Au La

Ti/Cu/Au lines: compared to the reference values

Average: shifted to lower
Systematic fluctuation??

Data analysis of other target

(K fit value) - (Ref.)
Evaluation of systematic error

Sum of data of K-D, K-3He, K-4He After shut down (=same geometry)

- Peak shift: -6.5 eV
- Accuracy of energy determination: +/- 3.5 eV
Evaluation of systematic error

Time (or target) dependency

K-D (=Red)
K-3He (=Blue)
K-4He (=Black)
After shut down (=same geometry)

Summer shutdown

- Peak shift: - 6.5 eV
- Accuracy of energy determination: +/- 3.5 eV
SDD X-ray energy spectra

Calibration data with X-ray tube

Not correlated to Kaon signals

Production data

Peak shift due to rate dependency: 6.5 eV
Precision of energy calibration: ±3.5 eV

Evaluated from known X-ray energy peaks (Ti, Mn, Cu, Au lines and kaonic C, O lines)

Correction term:

\[ \varepsilon = +6.5 \pm 3.5 \text{ eV} \]
Kaonic Helium-3 energy spectrum

X-ray energy of K-3He 3d-2p

\[ E_{\text{exp}} = 6223.0 \pm 2.4(\text{sta}) \pm 3.5(\text{sys}) \text{ eV} \]

QED value: \[ E_{\text{e.m.}} = 6224.6 \text{ eV} \]

\[ \Delta E_{2p} = E_{\text{exp}} - E_{\text{e.m.}} \]

\[ \Delta E_{2p} = -2 \pm 2(\text{sta}) \pm 4(\text{sys}) \text{ eV} \]

World First!
Observation of K-3He X-rays
Determination of strong-interaction shift

arXiv:1010.4631v1 [nucl-ex], PLB697(2011)199
DAFNE shutdown in Summer

\[ \Delta E_{2p} = -2 \pm 2(\text{sta}) \pm 4(\text{sys}) \text{ eV} \]
**K-4He (3d-2p)**

\[ \Delta E_{2p} = +5 \pm 3(\text{sta}) \pm 4(\text{sys}) \text{ eV} \]

**K-3He (3d-2p)**

\[ \Delta E_{2p} = -2 \pm 2(\text{sta}) \pm 4(\text{sys}) \text{ eV} \]

**DAFNE shutdown in Summer**

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Referenced: PLB697(2011)199
### Comparison of results

#### Kaonic 4He 2p level shift

| Target                  | Shift [eV]     |
|-------------------------|----------------|
| KEK E570                | +2±2±2 eV      |
| SIDDHARTA (w/ 55Fe)     | +0±6±2 eV      |
| SIDDHARTA (New)         | +5±3±4 eV      |

#### Kaonic 3He 2p level shift

| Target          | Shift [eV]     |
|-----------------|----------------|
| SIDDHARTA       | -2±2±4 eV      |
| J-PARC E17      | ??±?±? eV      |

**Shift** \( \Delta E_{2p} = E_{\text{exp}} - E_{\text{e.m.}} \)

- \( \Delta E_{2p} > 0 \) ("attractive" shift),
- \( \Delta E_{2p} < 0 \) ("repulsive" shift),
Comparison of results

PLB653(2007)387  Kaonic $^4$He 2p level shift

| Target        | Shift [eV] |
|---------------|------------|
| KEK E570      | $+2\pm2\pm2$ eV |

1. Calibration/ and peak shape from Ti (4.5 keV) and Cu (8.0 keV). Apply for K-$^4$He (6.4 keV).
2. Simulation of Compton tail using measured kaon stopping distribution. Sys err = uncertainty of above

Sato, ECT* Workshop 2009

In-beam calibration

Channel

(a) Calib. E570 data

Ti Kα  Ti Kβ

(c) Cycle 2 E570 data

Compton Tail & Shell

K-target

K-beam

15 cm

for K-$^4$He 3d-2p

Due to Compton scattering

Energy eV
Comparison of results

PLB681(2009)310  Kaonic $^4$He 2p level shift

| Target        | Shift [eV] |
|---------------|------------|
| SIDDHARTA (Test) | +0±6±2 eV |

1. Calibration and peak shape from Mn (5.9 keV)
Sys err = energy non-linearity, uncertainty of corrections of temporal fluctuation & rate dependency

Ishiwatari, ECT* Workshop 2009

Graph showing no-coincidence and coincidence spectra with Mn Kα, Ti Kα, Ti Kβ, Mn Kβ, and KHe Lα peaks.

NIM A 628(2011)264

Graph showing peak shift vs. time with and without correction.
Comparison of results

| Target                | Shift [eV] |
|-----------------------|------------|
| SIDDHARTA (He-4) Gas  | +5±3±4 eV  |
| SIDDHARTA (He-3) Gas  | -2±2±4 eV  |

Compared to several X-ray peaks with known energy
Sys err = uncertainty of energy determination obtained from them

Correction term:
\[ \varepsilon = +6.5 \pm 3.5 \text{ eV} \]
## Comparison of results

| Shift [eV] | Reference |
|------------|-----------|
| +2 ± 2 ± 2 | PLB653(2007)387 |
| +0 ± 6 ± 2 | PLB681(2009)310 |
| +5 ± 3 ± 4 | arXiv:1010.4631, |
| -2 ± 2 ± 4 | PLB697(2011)199 |

*error bar* = ±√((stat)^2 + (syst)^2)
Comparison of results

| Shift [eV] | Reference               |
|------------|-------------------------|
| KEK E570   | +2±2±2 PLB653(2007)387 |
| SIDDHARTA (He4 with 55Fe) | +0±6±2 PLB681(2009)310 |
| SIDDHARTA (He4) | +5±3±4 arXiv:1010.4631, |
| SIDDHARTA (He3) | -2±2±4 PLB697(2011)199 |

Question: both 0-eV shift?

Within error, consistent with 0 eV,
But
Within error, cannot exclude 0-eV shift

Possible isotope shift!? → Gold of J-PARC E17

*error bar* $= \pm \sqrt{(stat)^2 + (syst)^2}$
Summary

- To check whether abnormal shift on K-3He and 4He 2p state, kaonic He 3d-2p transition was measured in SIDDHATRA
- First measurement in gas targets
- First observation of kaonic 3He, prior to J-PARC
- Shift both of 3He and 4He was found to be small

|                | Shift [eV] | Reference               |
|----------------|------------|-------------------------|
| K-He4 (with 55Fe) | +0±6±2     | PLB681(2009)310         |
| K-He4           | +5±3±4     | arXiv:1010.4631, PLB697(2011)199 |
Outlook

• Isotope shift between He3 & He4??
• Determination of width
• Determination of X-ray yields between gas & liquid
• Further kaonic atom measurements with $Z \geq 3$

|                  | Shift [eV]     | Reference                  |
|------------------|---------------|----------------------------|
| K-He4 (with 55Fe)| $+0 \pm 6 \pm 2$ | PLB681(2009)310           |
| K-He4            | $+5 \pm 3 \pm 4$ | arXiv:1010.4631, PLB697(2011)199 |
| K-He3            | $-2 \pm 2 \pm 4$ |                            |
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Austrian Science Fund (FWF): [P20651-N20]
Evaluation of systematic error

Production data

KHe-3 data with Fe source

Mn Ka

-5.6+/−3.3 eV

Mn Kb+Fe Ka

-6.5+/−3.5 eV

With correction, Mn position

\[ \Delta E_{Mn} = +0.9 \pm 3.3 (\text{stat}) \pm 3.5 (\text{syst}) \text{ eV} \]
Evaluation of systematic error

"kaon-coincidence" with K-d data

Fit of kaonic (C/O/Al) atom X-ray lines with known energy

Kapton window (C22H10N2O5)

Low-energy side

Ti Ka
K-C (6-5)
Ti Kb
K-O (7-6)
shift: -8.6+/−4.2 eV (excl. Ti Kb)

High-energy side

shift: -9.0+/−3.2 eV

K-C(5-4)
K-N (6-5)
KO (6-5)
K-C (7-5)
K-Al (8-7)
Evaluation of systematic error

confirmation of the accuracy of energy determination & peak shift

Mn Ka (K3He)

Ave: -7.4 eV

High-E (KD)

Low-E (KD)

Average of three points: consistent with the systematic error band

To obtain absolute energy from a fit value,

\[ E_{\text{exp}} = E_{\text{fit}} + \varepsilon \]

\[ \varepsilon = +6.5 \pm 3.5 \text{ eV} \]
In helium, cross section of Compton effect is significant even in low-energy photons (~6.5 keV). 1/3 = Compton effect

Liquid He (E570)

for K-^4^He 3d-2p

Due to Compton scattering

10% of X-rays in Liq. He (E570) → 10 eV peak shift (if Compton neglected)

0.1 % of X-rays in 10 bar He (SIDDHARTA) → 0.1 eV peak shift (if Compton neglected) → We can neglect this shift!
Expected X-ray yields in helium gas

~2 times of X-ray yields in gas, compared in liquid

Need to check!
Kaonic atom data with $Z>3$

1. Errors on shift & width are large.
2. Isotope difference on shift & width were not measured in almost all the targets (Except Boron).
3. X-ray yield vs. target density
4. Metal or solid targets were used
   (Except: hydrogen, deuterium, He-3&He-4, nitrogen)

Text book: Fundamentals in hadronic atom theory (A. Deloff)
Table 1
Compilation of $K^-$ atomic data

| Nucleus | Transition | $\epsilon$ (keV) | $\Gamma$ (keV) | $Y$     | $\Gamma_u$ (eV) | Ref. |
|---------|------------|------------------|----------------|---------|----------------|------|
| He      | $3 \rightarrow 2$ | $-0.04 \pm 0.03$ | $-0.035 \pm 0.012$ | $0.03 \pm 0.03$ | $0.002 \pm 0.026$ | $0.055 \pm 0.029$ | $0.95 \pm 0.30$ | $0.25 \pm 0.09$ | $0.04 \pm 0.02$ | [15] |
| Li      | $3 \rightarrow 2$ | $0.002 \pm 0.026$ | $0.079 \pm 0.021$ | $0.172 \pm 0.58$ | $0.25 \pm 0.09$ | $0.04 \pm 0.02$ | [17] |
| Be      | $3 \rightarrow 2$ | $-0.208 \pm 0.035$ | $0.810 \pm 0.100$ | $-0.167 \pm 0.035$ | $0.700 \pm 0.080$ | $-0.076 \pm 0.014$ | $0.442 \pm 0.022$ | $0.55 \pm 0.03$ | $0.30 \pm 0.04$ | [18] |
| C       | $3 \rightarrow 2$ | $-0.590 \pm 0.080$ | $1.730 \pm 0.150$ | $0.07 \pm 0.013$ | $0.99 \pm 0.20$ | [18] |
| O       | $4 \rightarrow 3$ | $-0.025 \pm 0.018$ | $0.017 \pm 0.014$ | $-0.076 \pm 0.014$ | $0.442 \pm 0.022$ | $0.55 \pm 0.03$ | $0.30 \pm 0.04$ | [19] |
| Mg      | $4 \rightarrow 3$ | $0.27 \pm 0.015$ | $0.14 \pm 0.015$ | $0.78 \pm 0.06$ | $0.08 \pm 0.03$ | [19] |
| Al      | $4 \rightarrow 3$ | $0.130 \pm 0.050$ | $0.490 \pm 0.160$ | $-0.076 \pm 0.014$ | $0.442 \pm 0.022$ | $0.55 \pm 0.03$ | $0.30 \pm 0.04$ | [19] |
| Si      | $4 \rightarrow 3$ | $0.240 \pm 0.050$ | $0.810 \pm 0.120$ | $-0.130 \pm 0.015$ | $0.800 \pm 0.033$ | $0.49 \pm 0.03$ | $0.53 \pm 0.06$ | [19] |
| P       | $4 \rightarrow 3$ | $-0.330 \pm 0.08$ | $1.440 \pm 0.120$ | $0.26 \pm 0.03$ | $1.89 \pm 0.30$ | [18] |
| S       | $4 \rightarrow 3$ | $-0.550 \pm 0.06$ | $2.330 \pm 0.200$ | $0.22 \pm 0.02$ | $3.10 \pm 0.36$ | [18] |
| Cl      | $4 \rightarrow 3$ | $-0.770 \pm 0.40$ | $3.80 \pm 1.0$ | $0.16 \pm 0.04$ | $5.8 \pm 1.7$ | [18] |

Determined shift and width using natural abundance, assuming the same shift & width & yield
Nitrogen data missing!
Isotope difference between 10B and 11B(??)