June 2, 2007
(Nuclear physics at J-PARC)

Precision spectroscopy of Kaonic Helium X-rays

KEK-PS E570 :

Cycle 1 : October 2005

Cycle 2 : December 2005

RIKEN
Shinji Okada
for KEK-PS E570 collaboration

KEK-PS E570 collaboration list

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M. Iwasaki[8], B. Juhasz[3], P. Kienle[3], J. Marton[3], Y. Matsuda[8],
H. Ohnishi[8], S. Okada[8], H. Outa[8], M. Sato[6], P. Schmid[3],
S. Suzuki[9], T. Suzuki[8], H. Tatsuno[7], D. Tomono[8],
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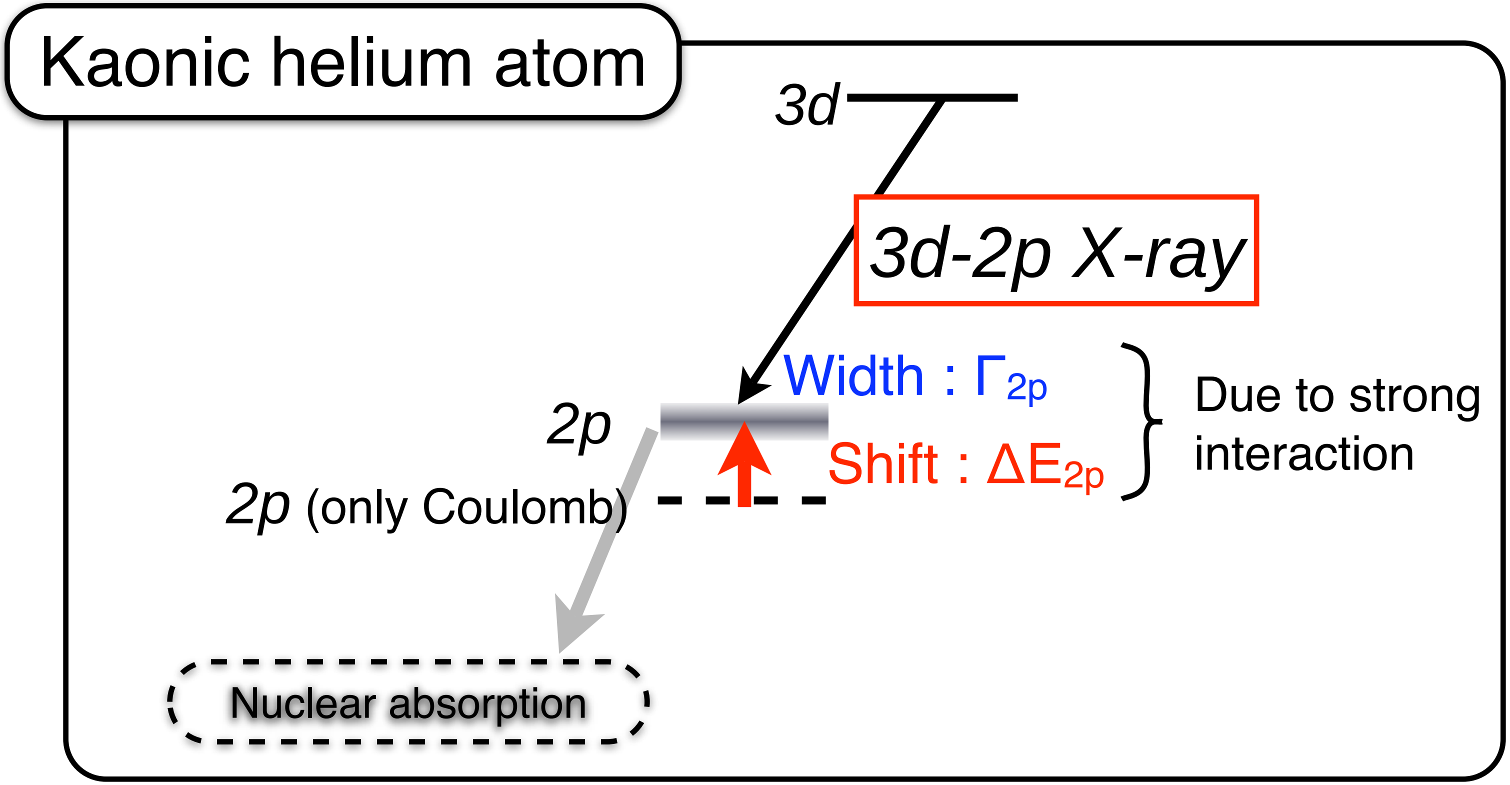
Tokyo Tech[6], Univ. of Tokyo[7], RIKEN[8], KEK[9]

Introduction

What do we measure ?

Last orbit level shift of Kaonic atom is sensitive to
$\bar{K}$-nucleus strong interaction.

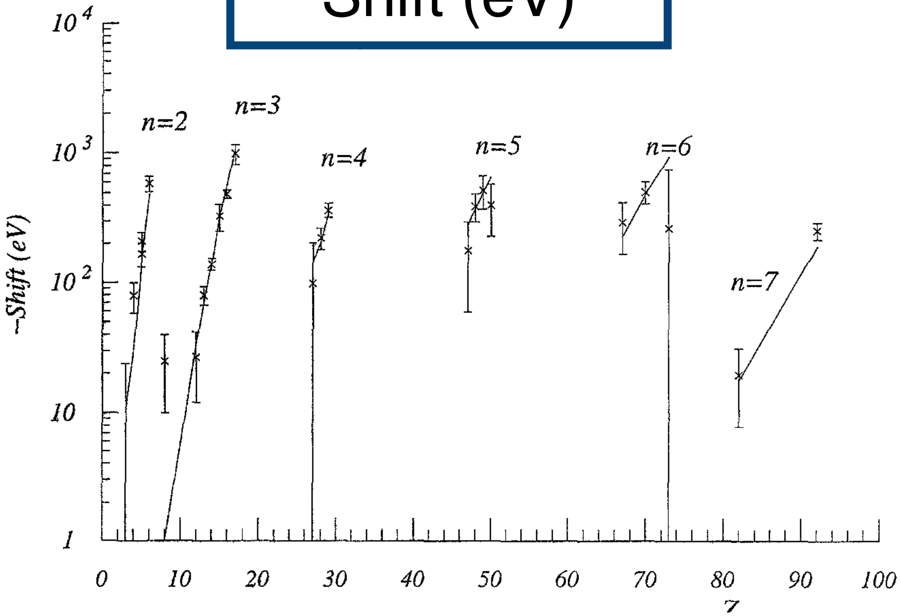


Precisely determine the $\bar{K}$-nucleus strong interaction at vanishing relative energy
-> many experiments have been done (from Helium to Uranium)

Kaonic atoms

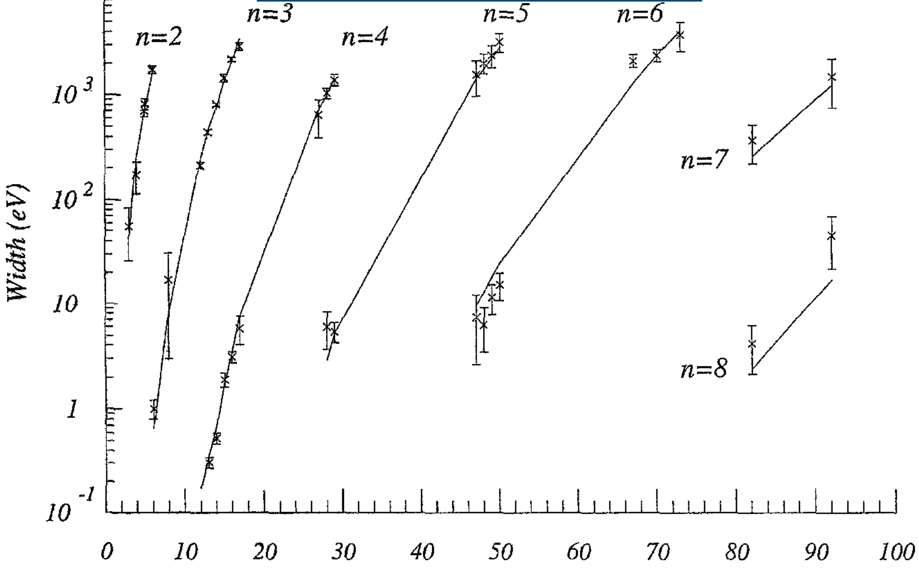
Last-orbit energy-level shift and width of kaonic atoms

Shift (eV)



Z (nucleus atomic number)

Width (eV)



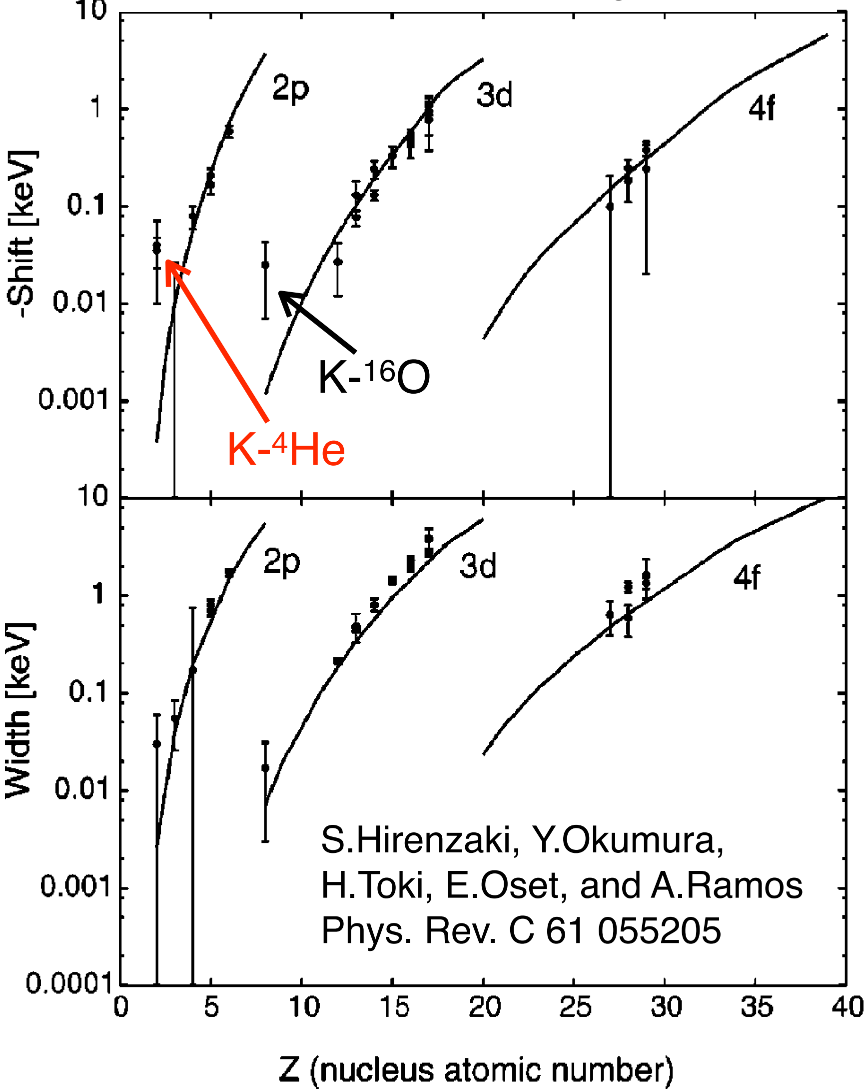
Z (nucleus atomic number)

fitted fairly well by optical-potential model

Batty, Friedman and Gal, Phys. Rep. 287 (1997) 385

The Kaonic Helium Puzzle

SU(3) chiral-unitary model



K-^{16}O

K-^{4}He

S.Hirenzaki, Y.Okumura,
H.Toki, E.Oset, and A.Ramos
Phys. Rev. C 61 055205

The Kaonic Helium Puzzle

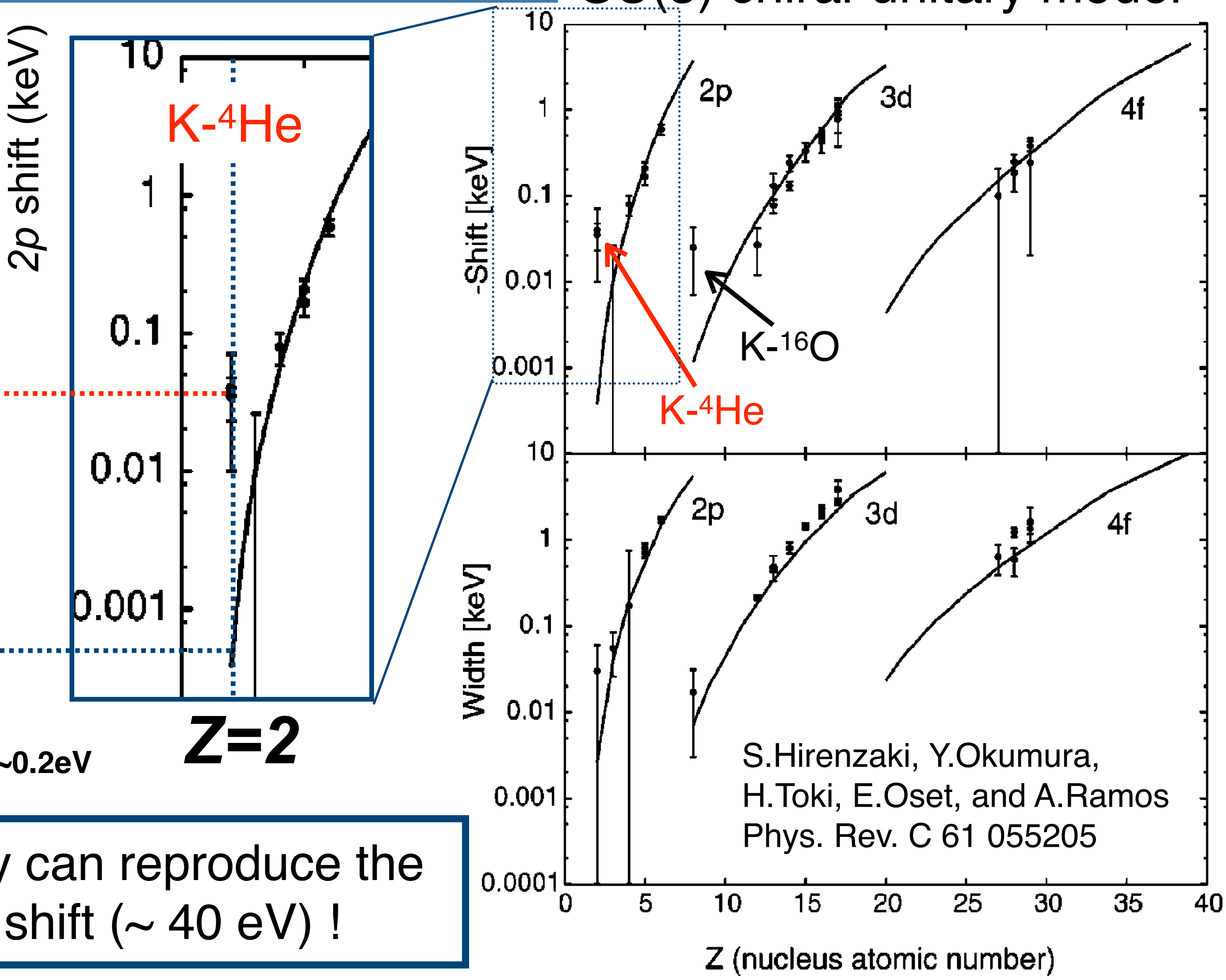
past 3 exp.

Exp.
~ -40 eV

Theo.
~ 0 eV

SU(3) chiral unitary : **~0.2eV**

SU(3) chiral-unitary model



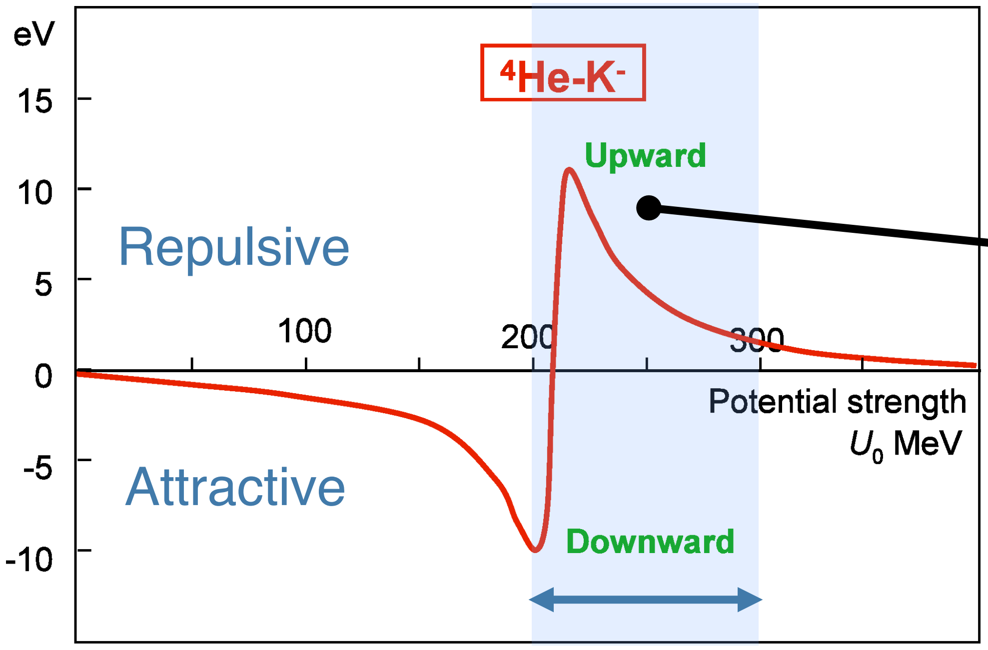
S.Hirenzaki, Y.Okumura,
H.Toki, E.Oset, and A.Ramos
Phys. Rev. C 61 055205

No theory can reproduce the large shift (~ 40 eV) !

A possible **large shift**

Coupled-channel calculation by Y. Akaishi
($\bar{K}N$ channel - $\Sigma\pi$ decay channel)

***2p*-level shifts of the K^--^{4}He atom**



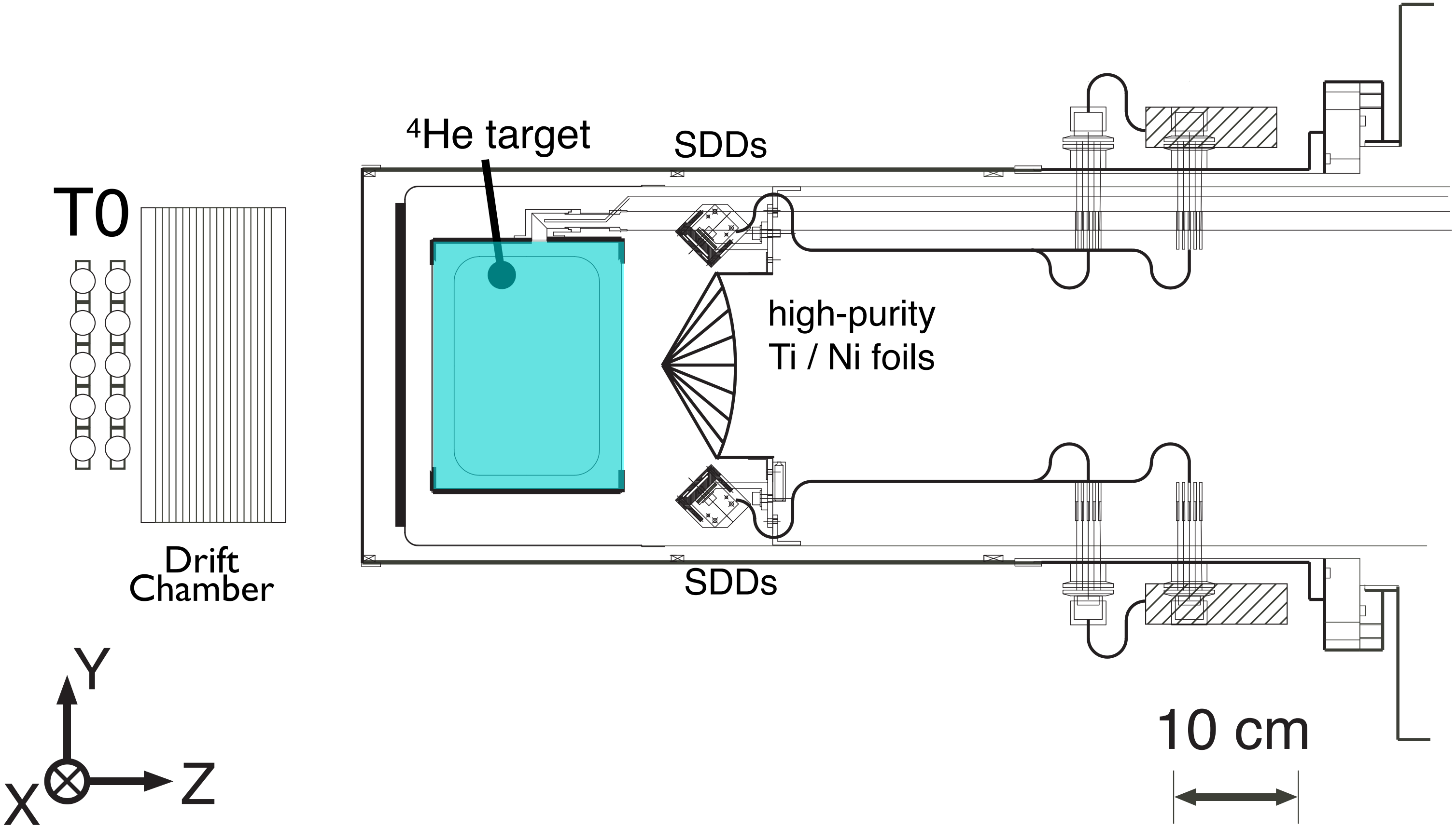
Large shift is acceptable
$|\Delta E_{2p}|$ ~ 10 eV (at max.)

200~300MeV
Predicted region

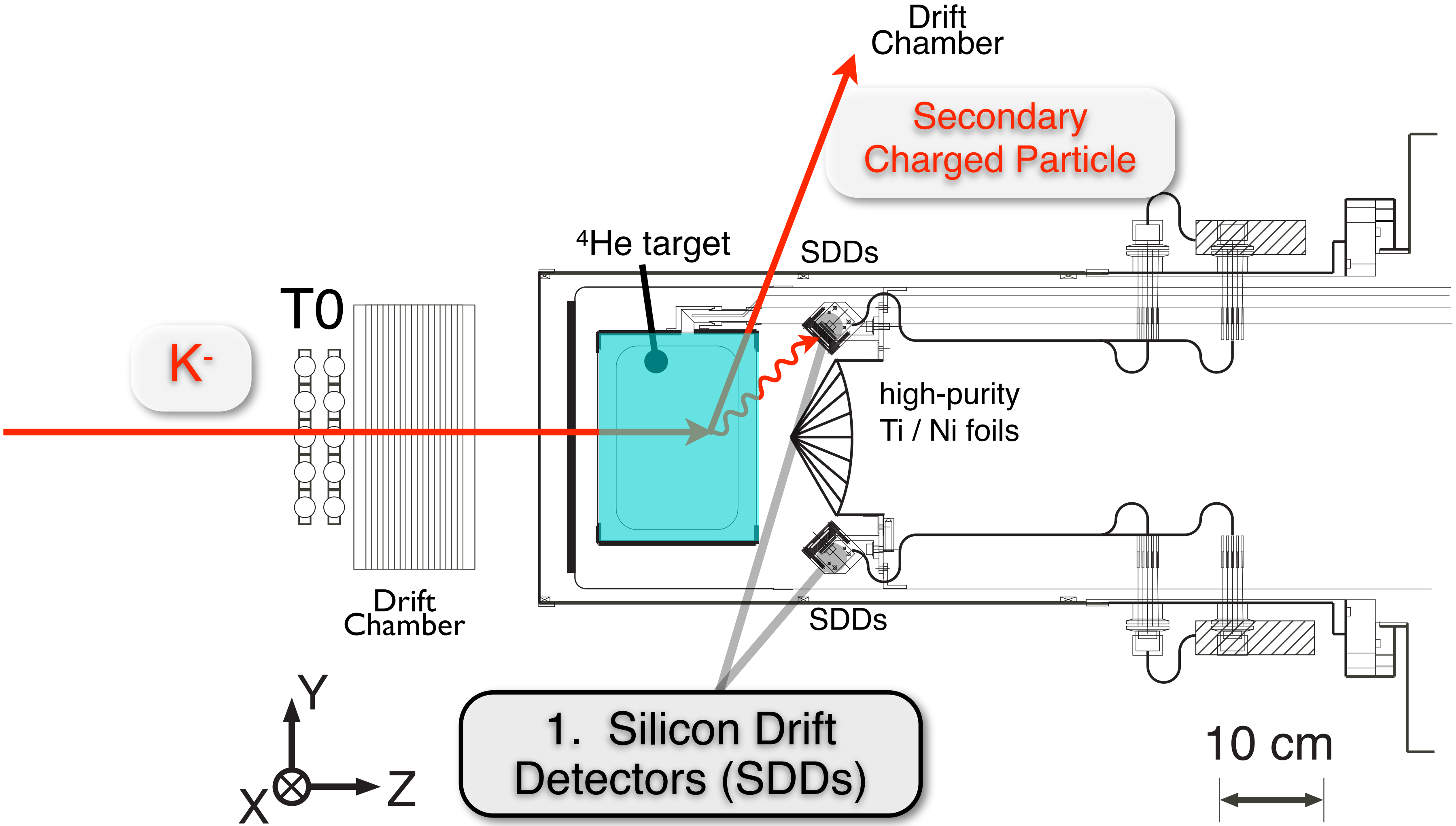
Y.Akaishi, EXA05
proceedings (2005)

Experiment

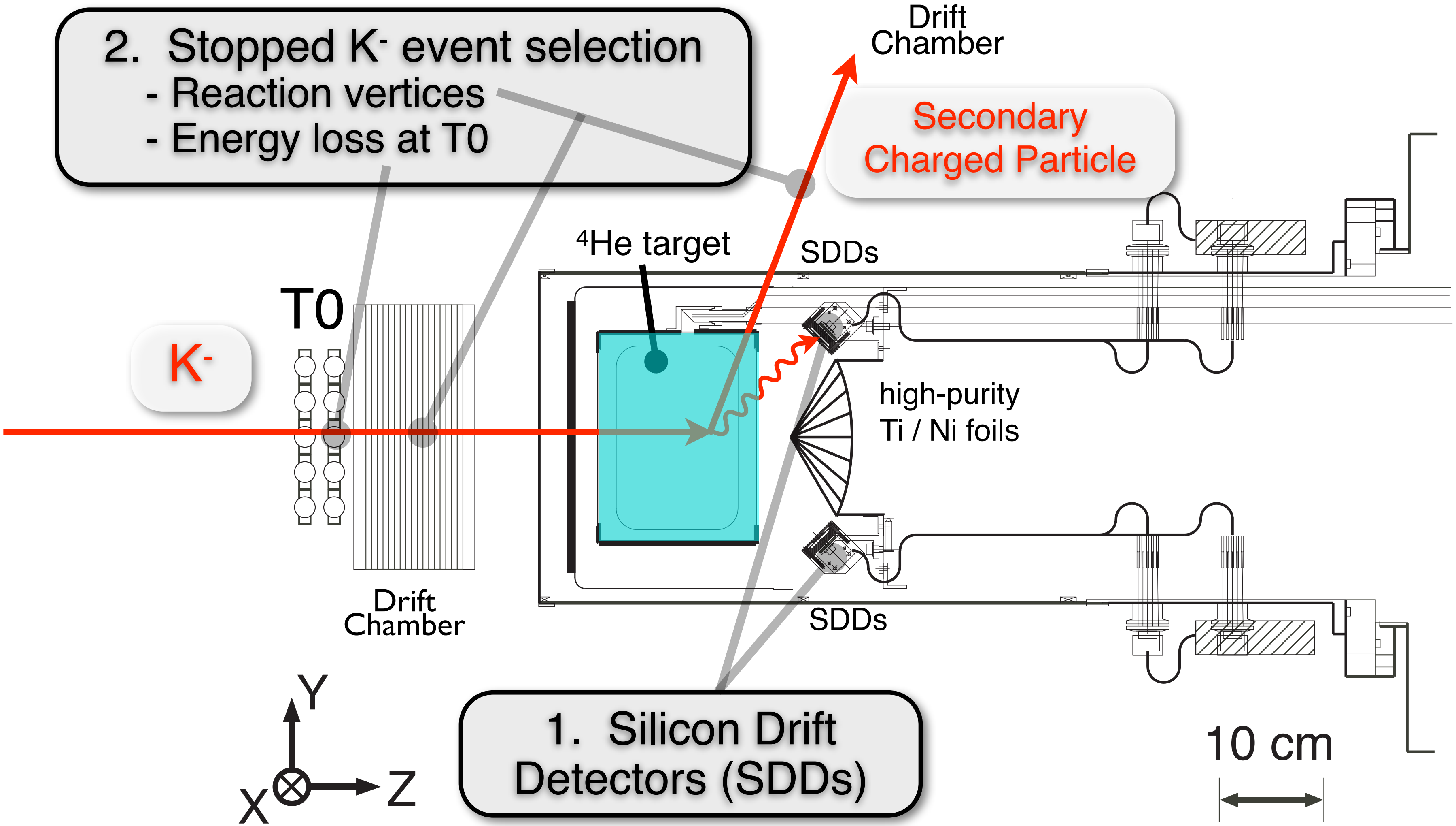
Experimental setup



Experimental setup



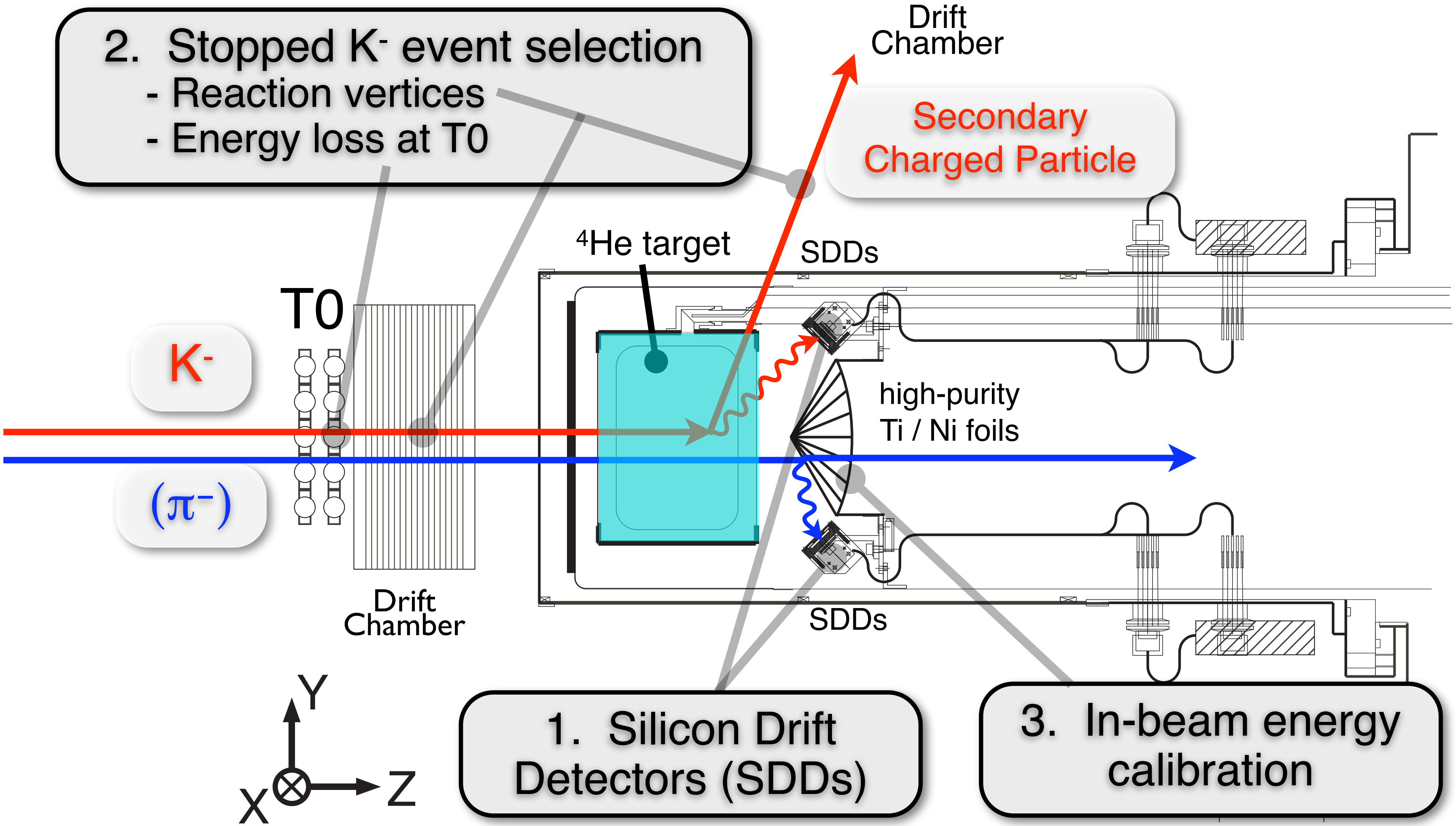
Experimental setup



2. Stopped K⁻ event selection
    - Reaction vertices
    - Energy loss at T0

1. Silicon Drift Detectors (SDDs)

Experimental setup



2. Stopped K⁻ event selection
   - Reaction vertices
   - Energy loss at T0

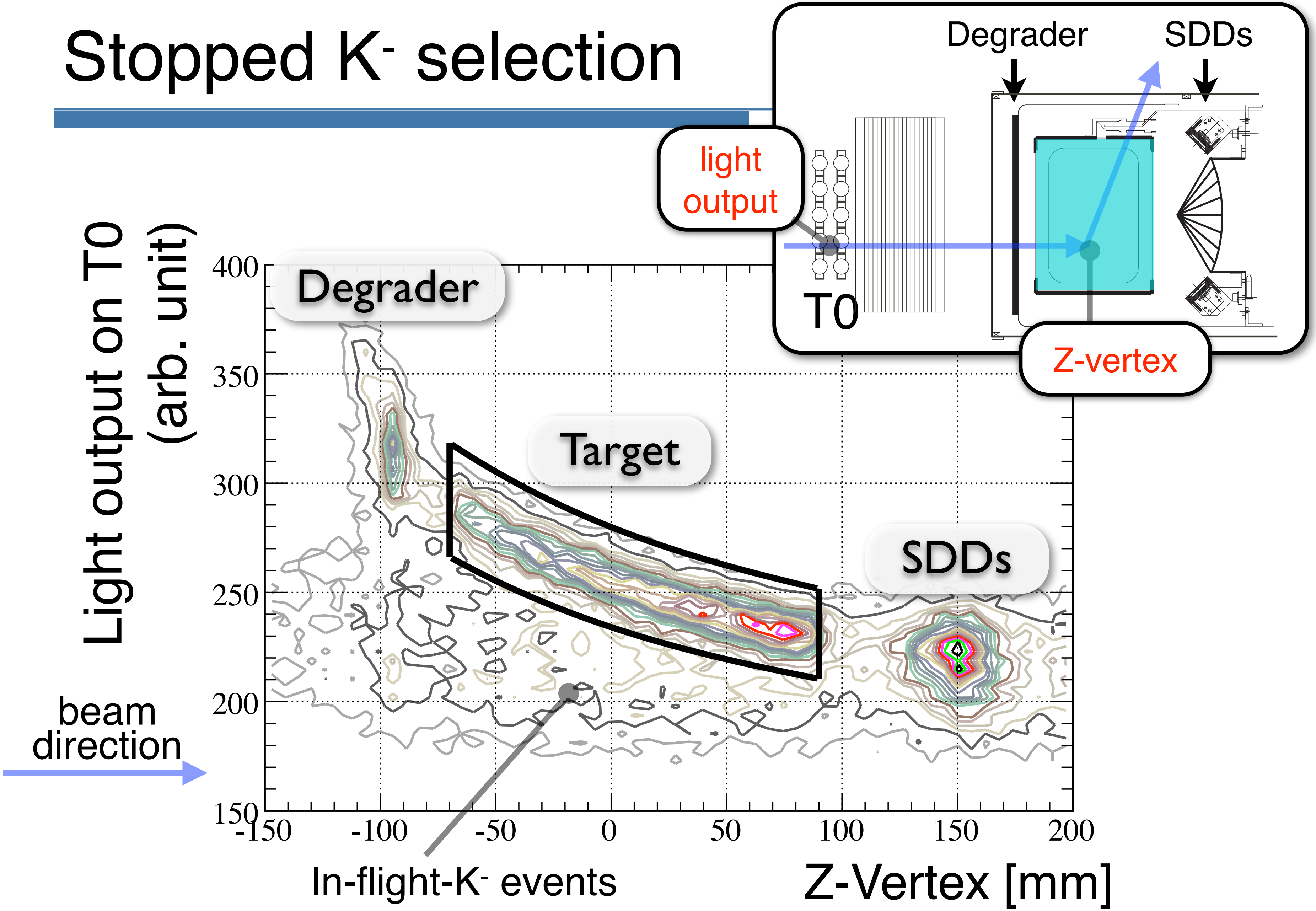
Secondary Charged Particle

1. Silicon Drift Detectors (SDDs)

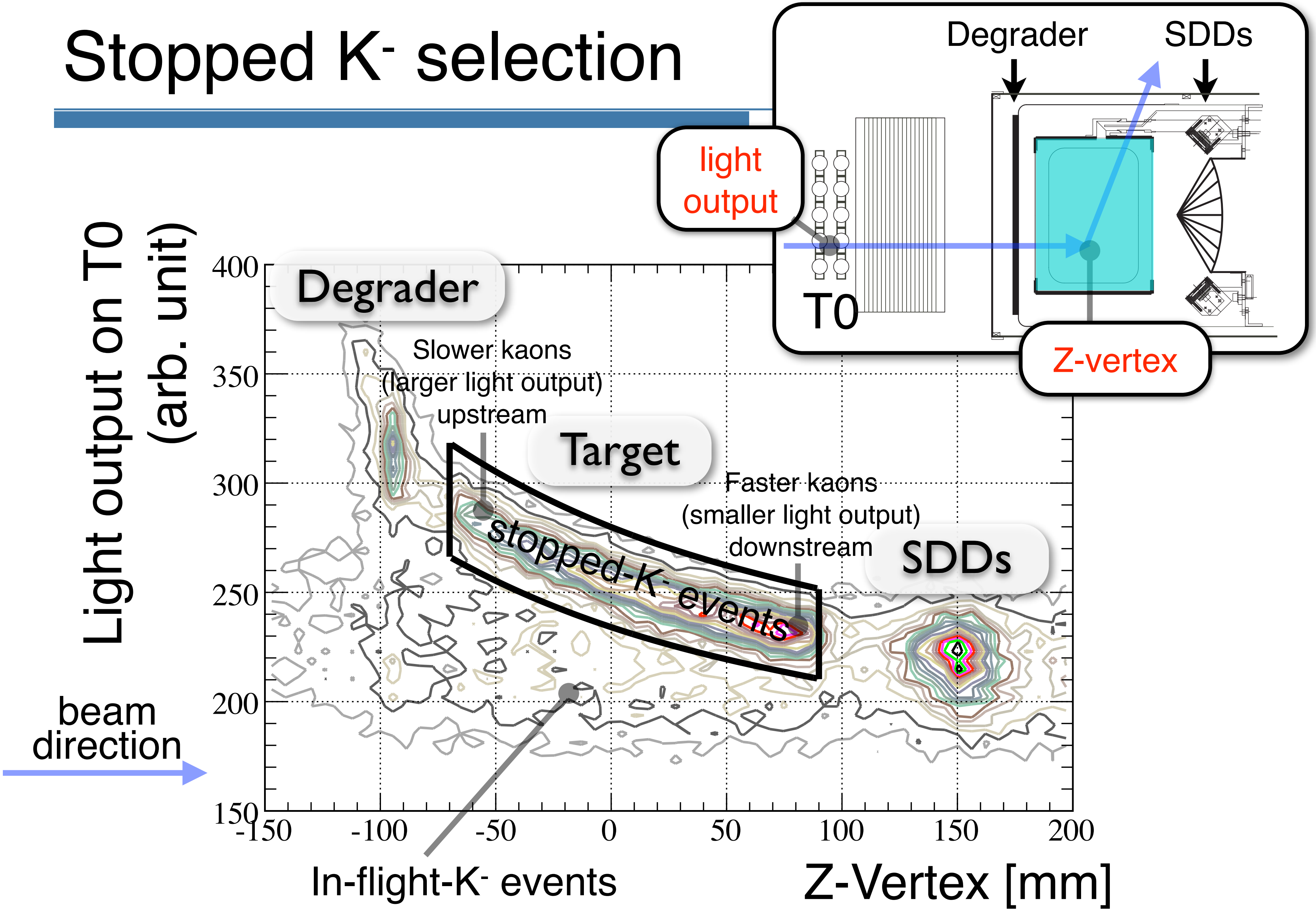
3. In-beam energy calibration

Analysis

Stopped K$^-$ selection



Stopped K$^-$ selection



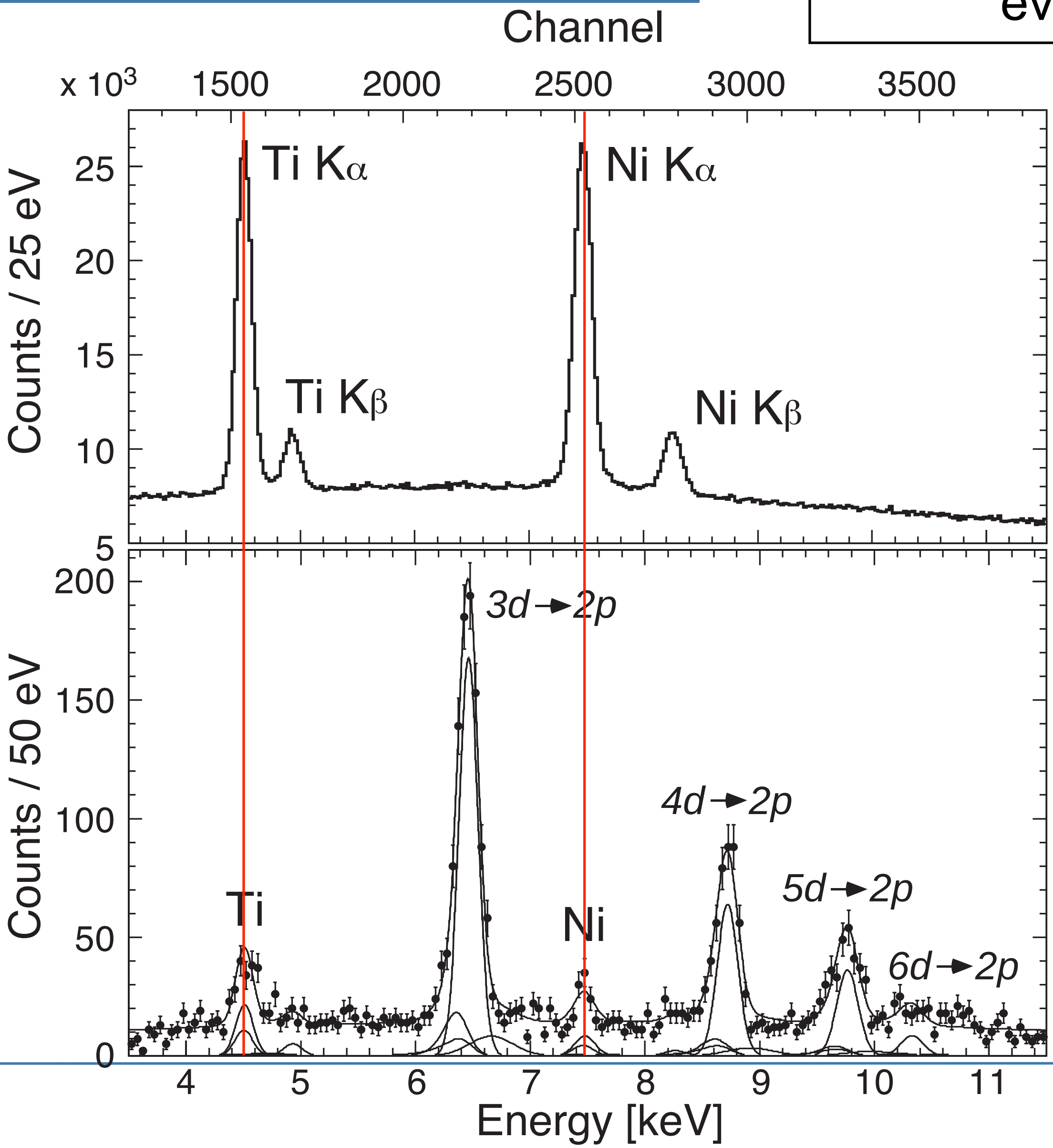
Energy calibration

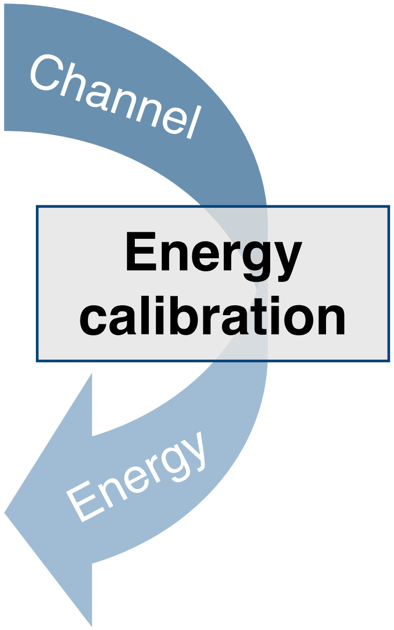
Ti Kα : 5 ×10^2 / hour / SDD

Gain drift adjustment :
every ~20 hours

SDD self
triggered
events

Stopped-K^-
triggered
events





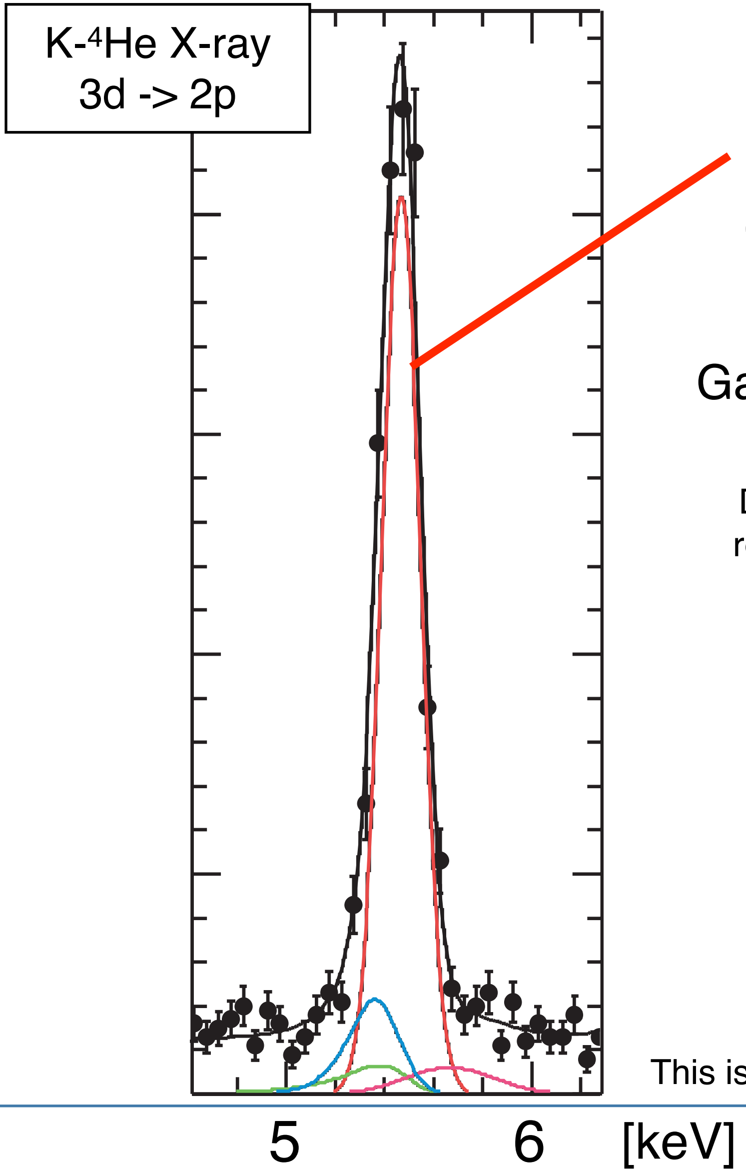
Energy calibration

Spectral fitting

Fitting functions

Cycle 1 : 520 hours in Oct. 2005

Cycle 2 : 260 hours in Dec. 2005



Main peak

(Voigt function)

Convolution of
Gaussian & Lorentzian

Detector response

for Natural width

This is spectrum for cycle 2

Fitting functions

Cycle 1 : 520 hours in Oct. 2005

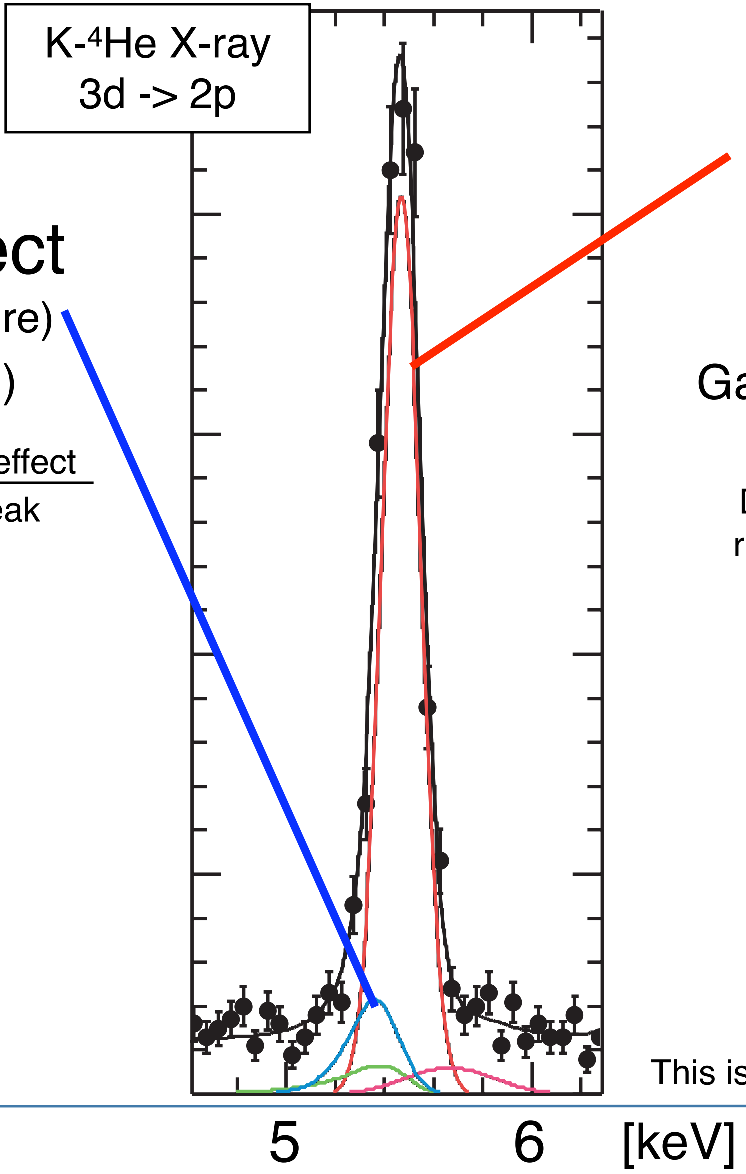
Cycle 2 : 260 hours in Dec. 2005

1) Compton scattering effect

(low-energy tail structure)

~ 14 % (cycle 1 & 2)

Intensity ratio = $\frac{\text{Compton effect}}{\text{Main peak}}$



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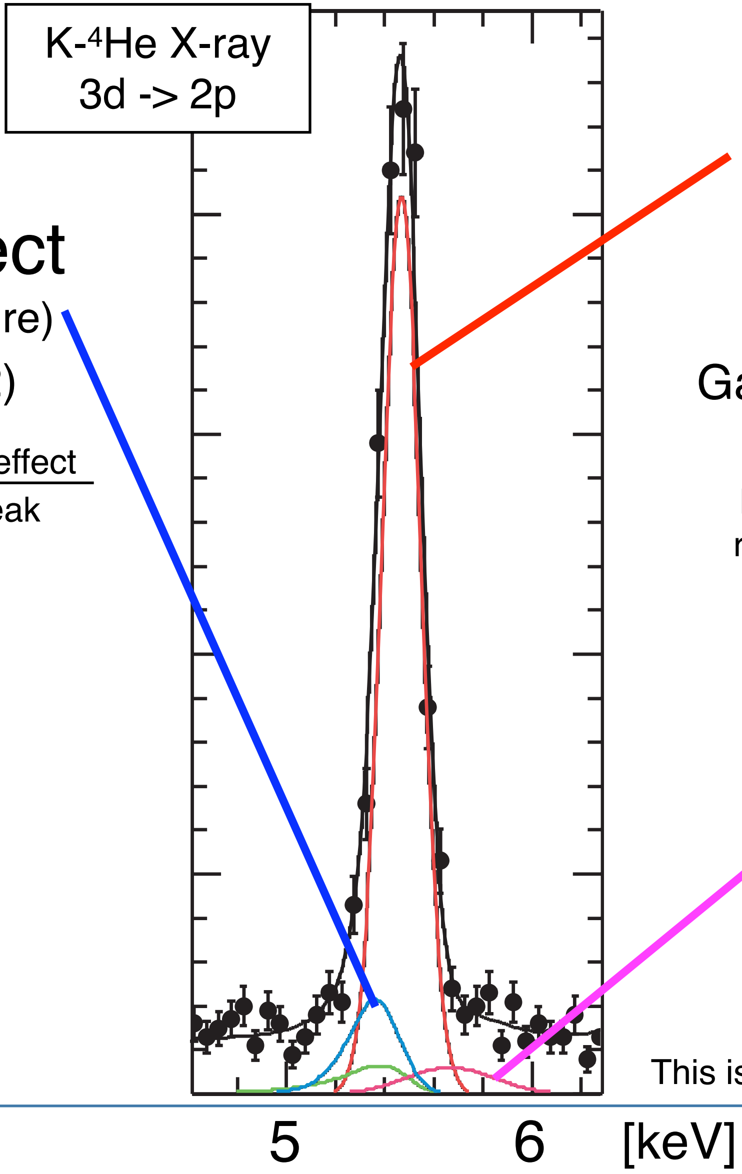

This is spectrum for cycle 2

1) Compton scattering effect

(low-energy tail structure)

~ 14 % (cycle 1 & 2)

↑

$$\text{Intensity ratio} = \frac{\text{Compton effect}}{\text{Main peak}}$$

Main peak

(Voigt function)

Convolution of
Gaussian & Lorentzian

↑ Detector response

↑ for Natural width

2) Pileup effect

~ 11 % (cycle 1)
~ 6 % (cycle 2)

Fitting functions

Cycle 1 : 520 hours in Oct. 2005

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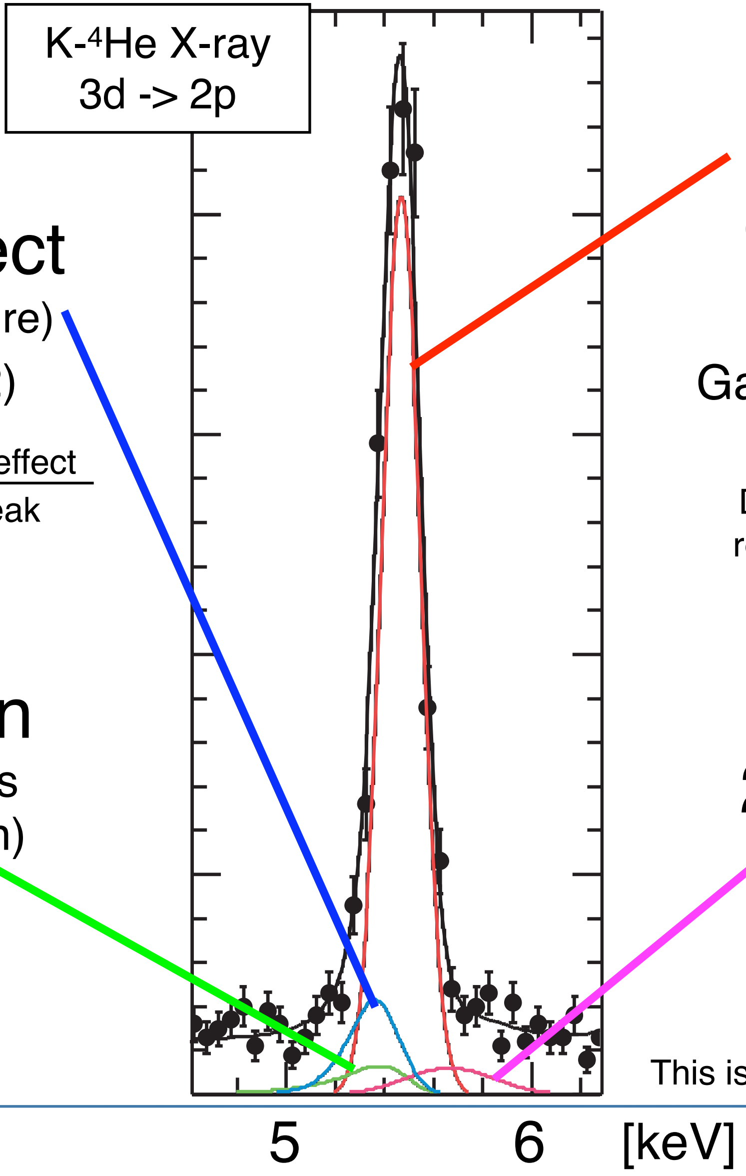


1) Compton scattering effect

(low-energy tail structure)

~ 14 % (cycle 1 & 2)

Intensity ratio = $\frac{\text{Compton effect}}{\text{Main peak}}$

Main peak

(Voigt function)

Convolution of Gaussian & Lorentzian

Gaussian: Detector response

Lorentzian: for Natural width

3) Tail function

(empirically known as the response function)

~ 4 % (cycle 1)

~ 3 % (cycle 2)

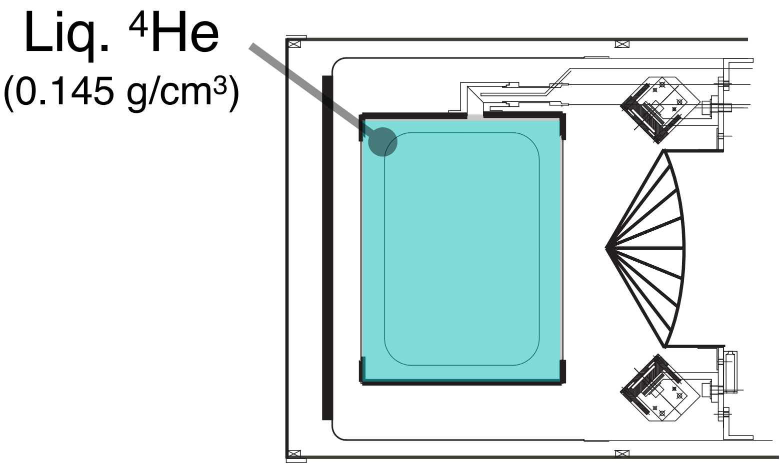
2) Pileup effect

~ 11 % (cycle 1)

~ 6 % (cycle 2)

This is spectrum for cycle 2

1) Compton scattering effect

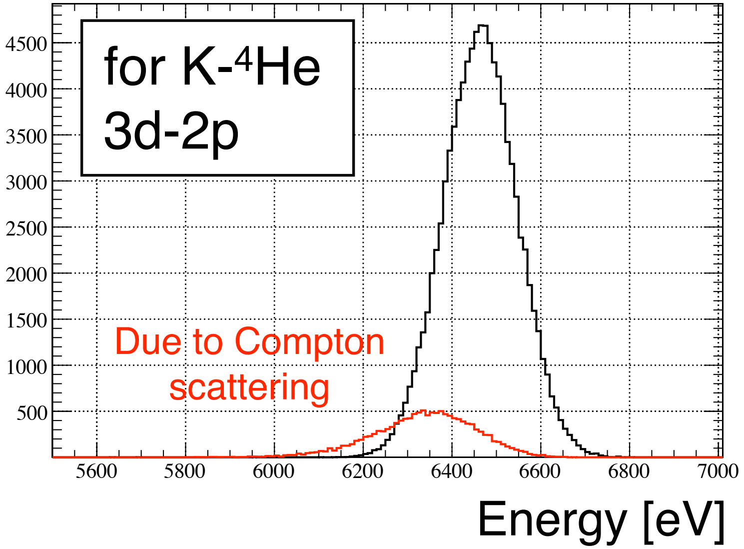


Liq. ^{4}He
(0.145 g/cm^3)

Incoherent
(Compton) scattering

The cross section for liq. ^{4}He :
~ 1 barn/Atom @10keV

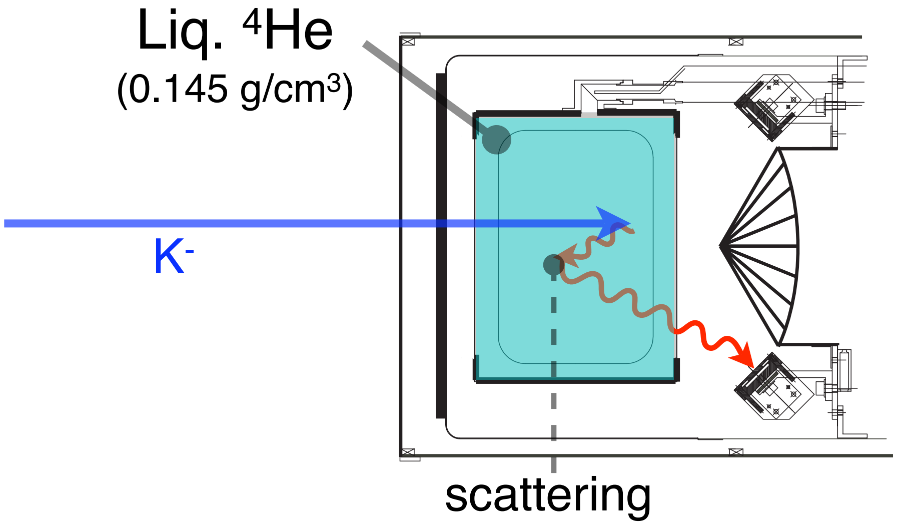
This cause the low energy tail structure.



Estimated by Monte carlo simulation (Geant4 : LECS package)

- Spectral shape
- Intensity ratio

1) Compton scattering effect



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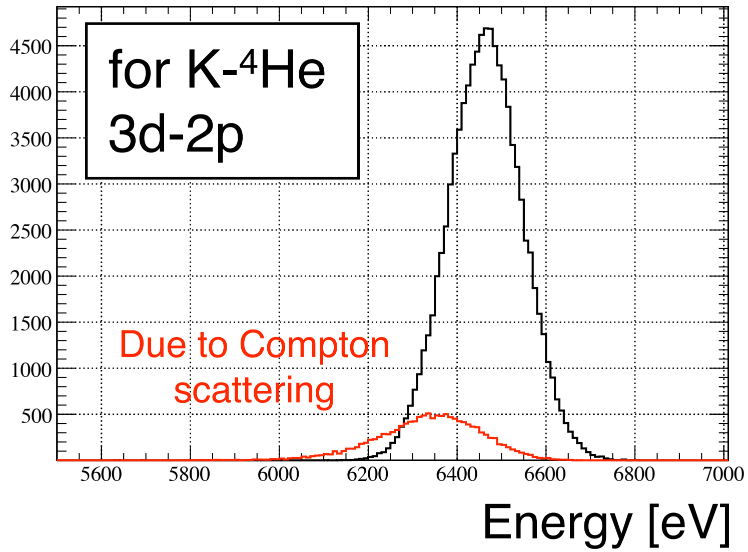


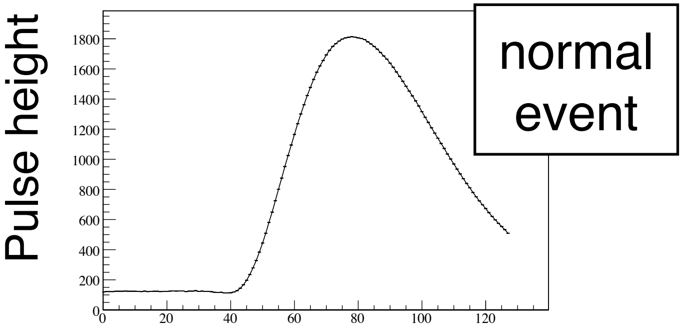
Estimated by Monte carlo simulation (Geant4 : LECS package)

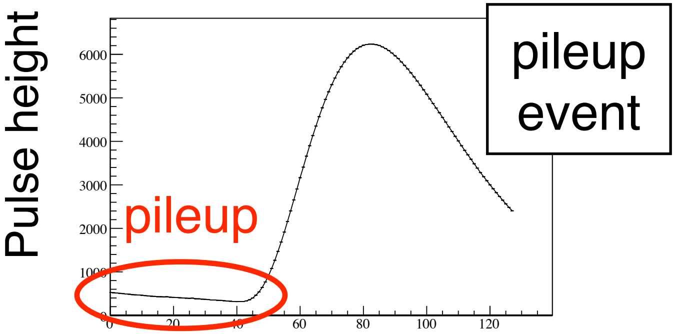
- Spectral shape
- Intensity ratio

2) Pileup effect

Waveform data of flash ADC

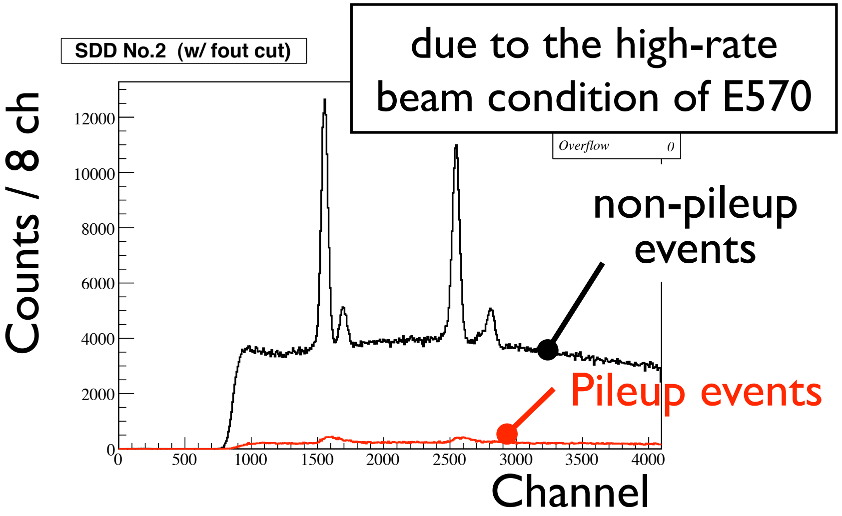
typical signal shape





80 nsec / data point (12.5 MHz) shaping time 3 μs

available FADC data : only for about half of cycle 1

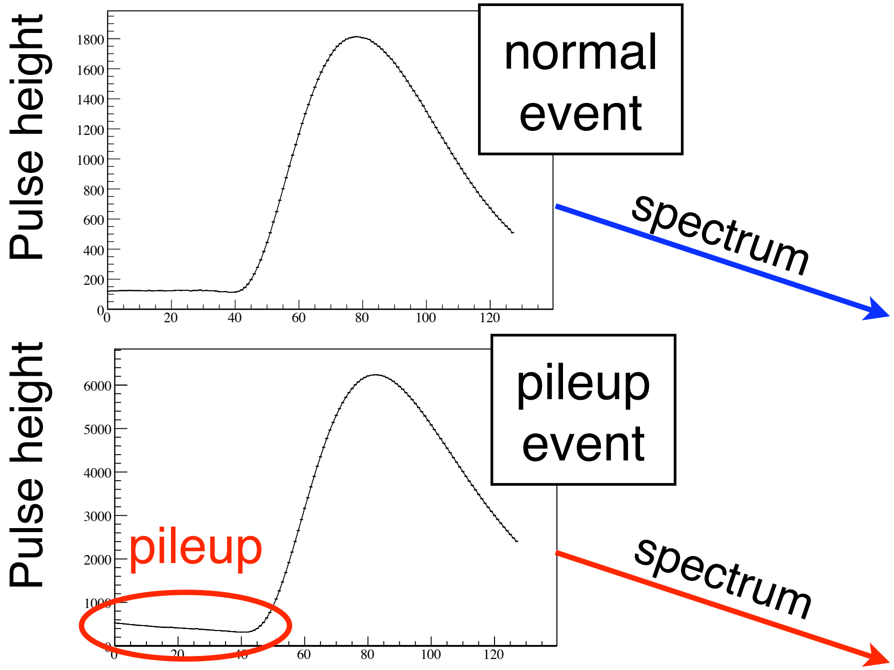


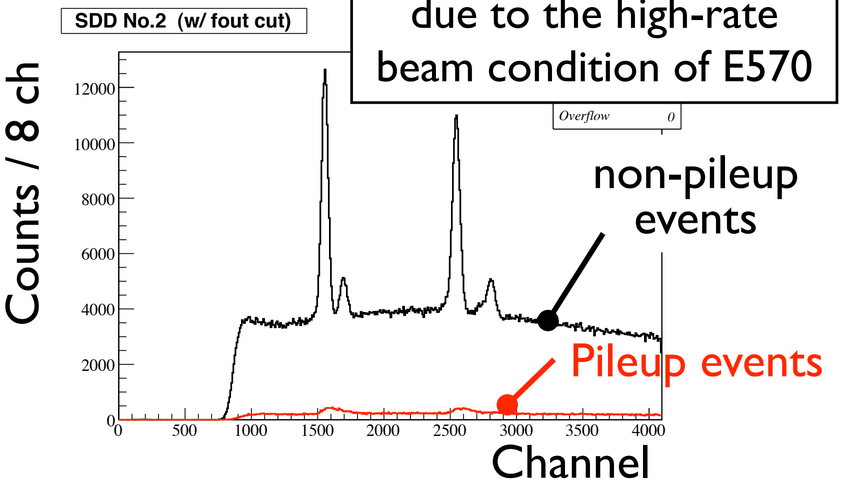
due to the high-rate beam condition of E570

2) Pileup effect

Waveform data of flash ADC

typical signal shape





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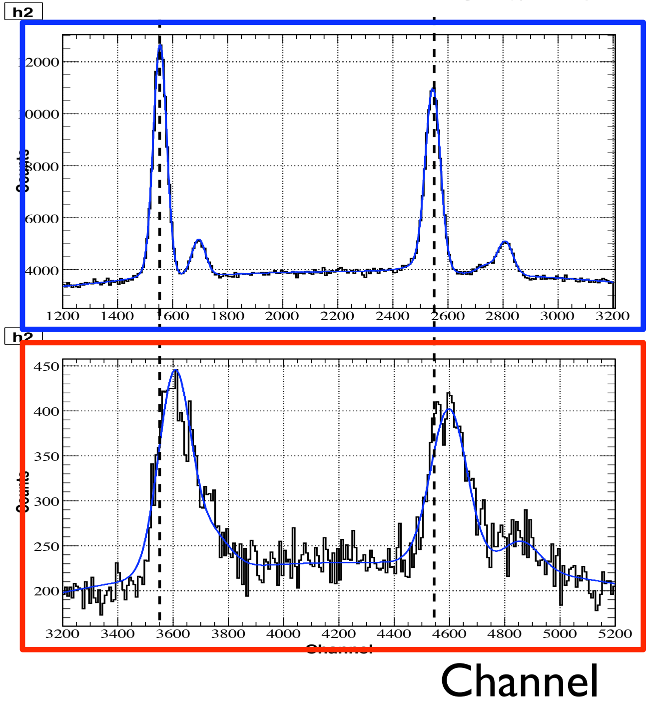

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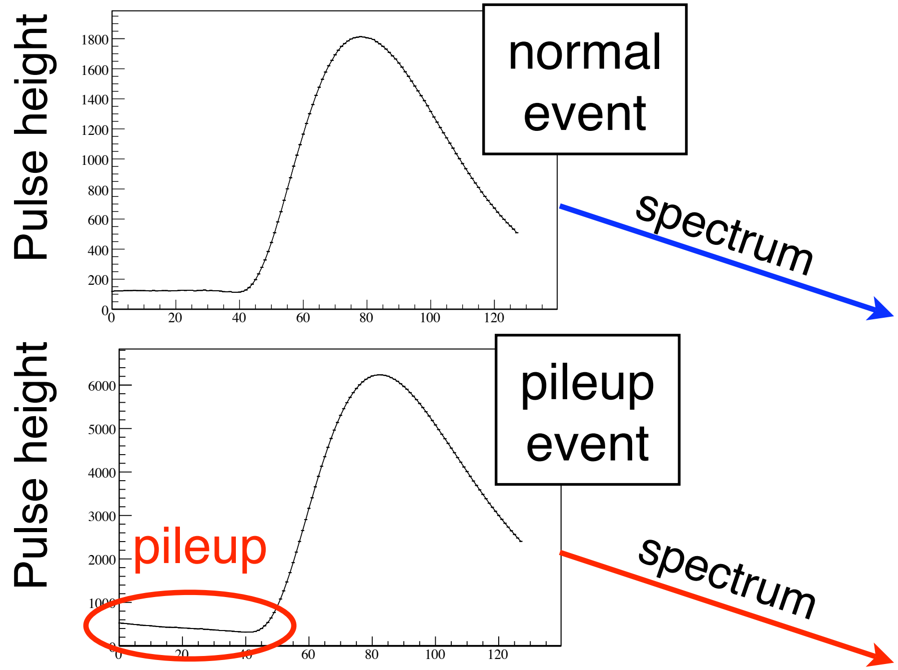
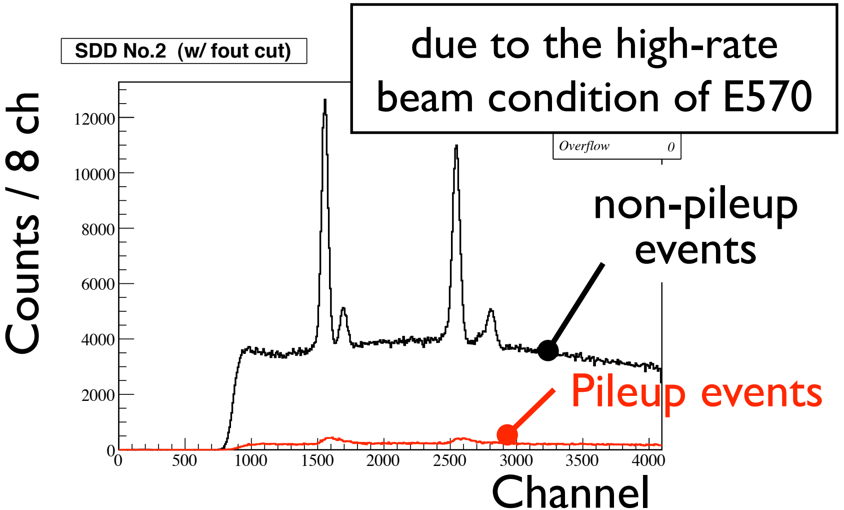
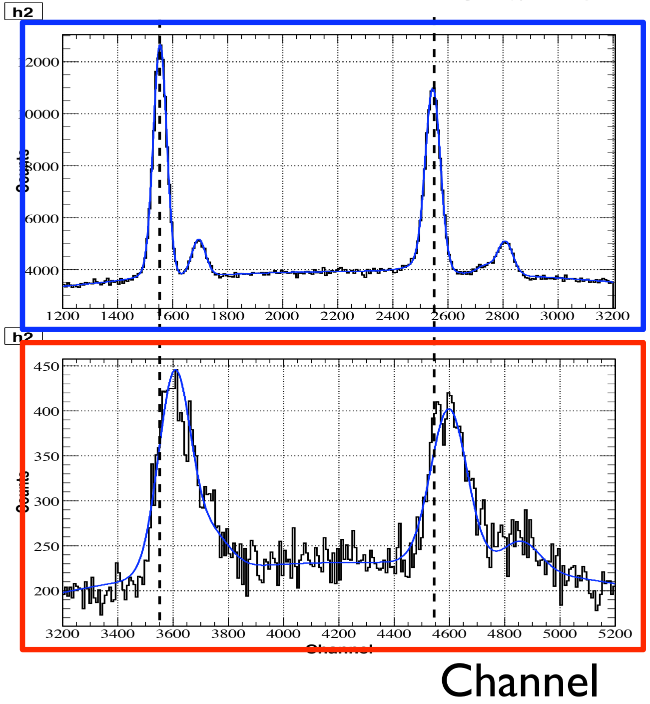




due to the high-rate beam condition of E570



80 nsec / data point (12.5 MHz) shaping time 3 μs

available FADC data : only for about half of cycle 1

Estimation of the pileup function

The spectra obtained by event selection using FADC data is used for the estimation of the relative mean value and width by fitting those spectra.
... Intensity ratio : by fitting calib. spectra fixing these parameters (mean & width)

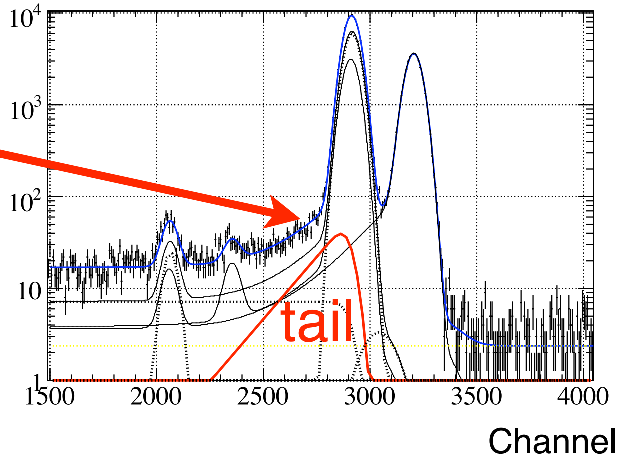
3) Tail function

--> Due to detector response

--> The tail function is empirically known for silicon detector as :

$$Tail(E) = \frac{F^{G}_{tail}(E)\cdot Gain}{2\beta\sigma}\exp\left(\frac{E-E_0}{\beta\sigma}+\frac{1}{2\beta^2}\right)\cdot \mathrm{erfc}\left(\frac{E-E_0}{\sqrt{2}\sigma}+\frac{1}{\sqrt{2}\beta}\right)$$

Typical x-ray spectrum from ^{55}Fe source



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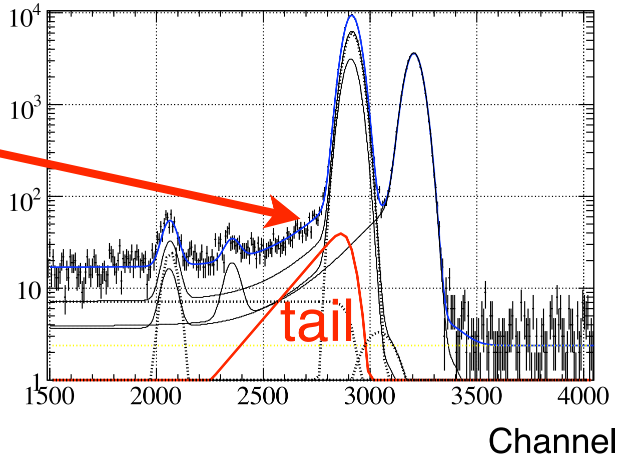
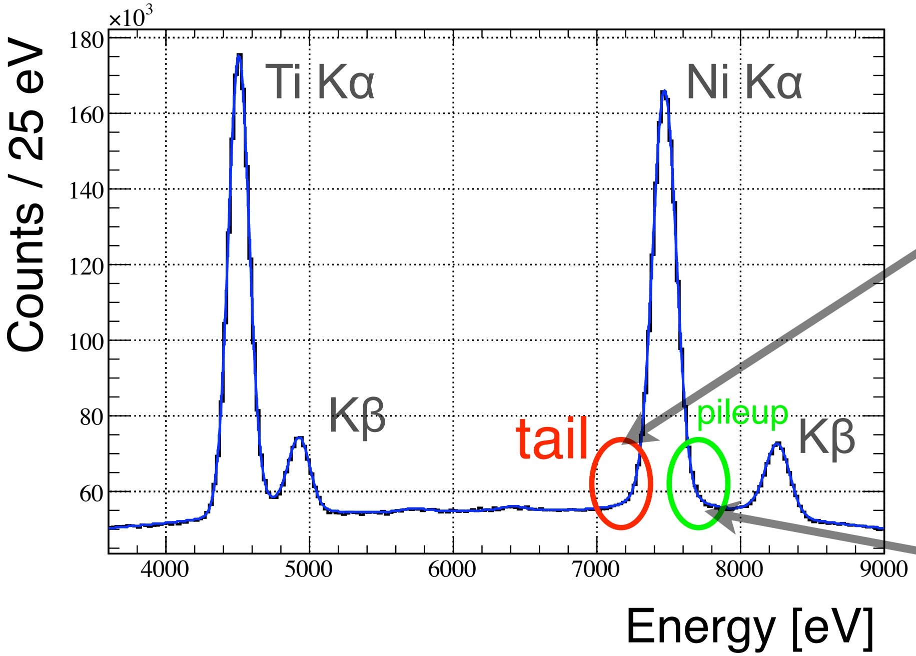


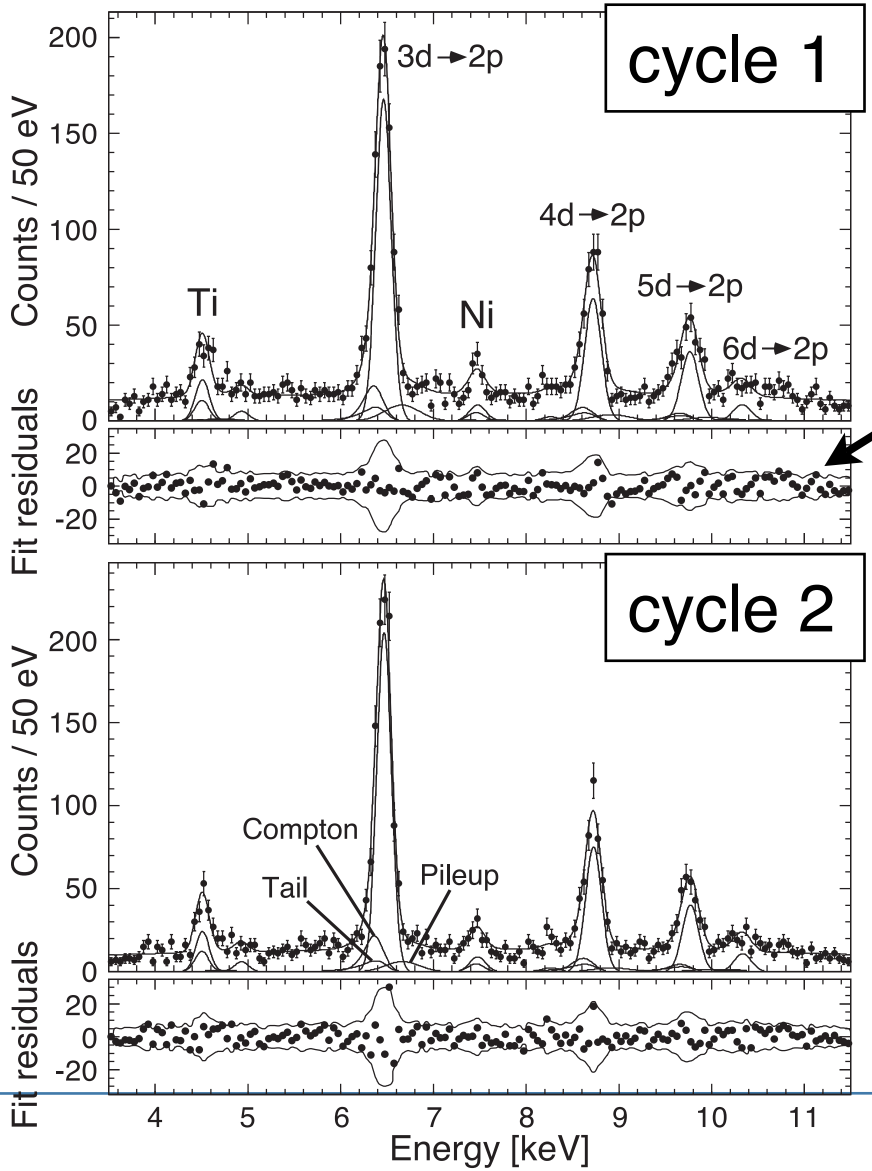


estimated by fitting the high-statistics calibration spectra. (self-triggered events)

Intensity ratio of pileup effect is also estimated by this fitting

Result

Fitting results



Cycle 1 : October 2005

Cycle 2 : December 2005

Thin lines denote the ±2σ values of the data.

The fit residuals are within these lines.

In comparison to the previous exp :

- ✓ 2 times better resolution (185eV@6.4keV)
- ✓ 2.5 times higher statistics
- ✓ 10 times better S/N ratio

2p-level shift (preliminary)

Transition energies (with only statistical errors)

	energy [eV]	EM value
3d->2p	6467.0 ± 2.5	6463.5
4d->2p	8723.5 ± 4.6	8721.7
5d->2p	9761.4 ± 7.6	9766.8

-- EM calculation --

* T.Koike : private communication

* J.P.Santos et al., Phys. Rev. A 71, 032501 (2005)

using 3d-2p energy

$$\Delta E_{2p} = E_{3d\text{-}2p} - E^{EM}_{3d\text{-}2p} = 3 \pm 3\ \text{(stat) eV}$$

using all transition energies

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

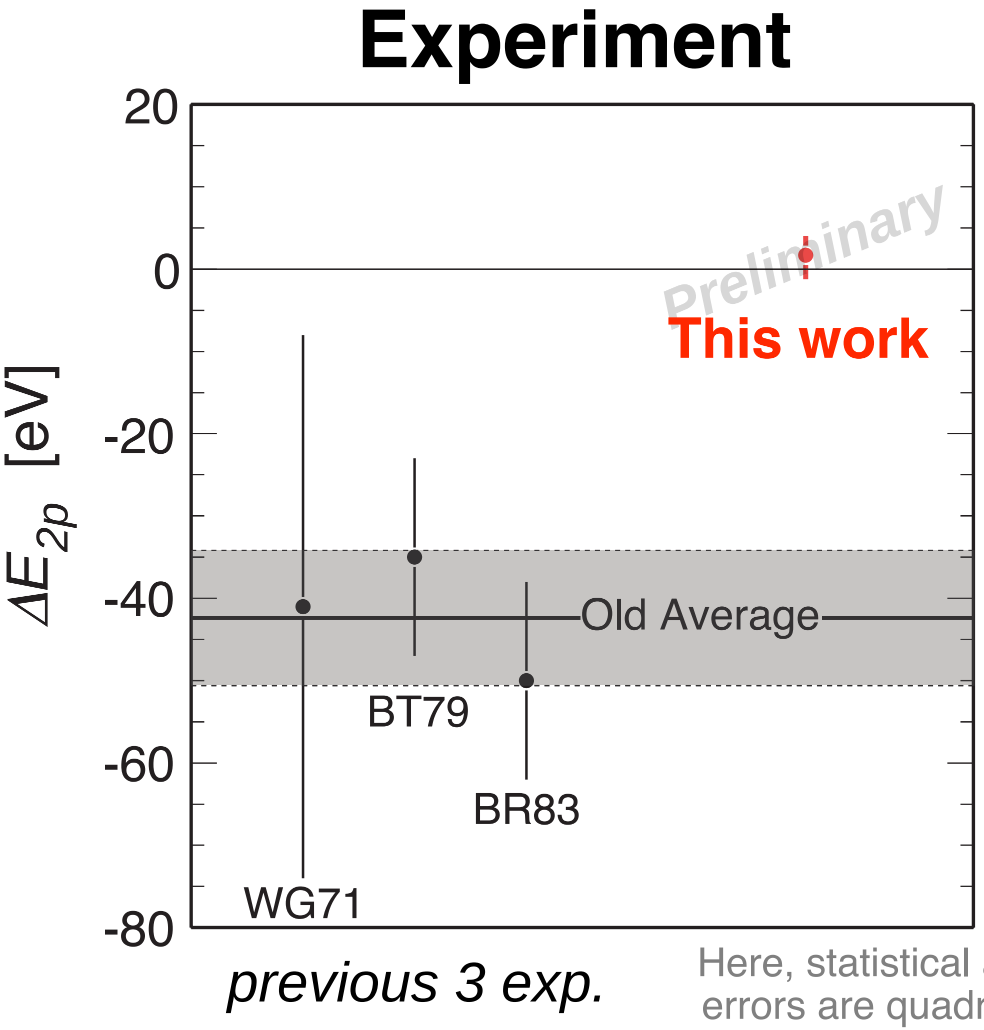
Systematic error is comparable to the statistical error.

Preliminary

Preliminary

WG71 : C.E. Wiegand and R. Pehl, PRL27,1410 (1971).
BT79 : C.J. Batty et al., NPA326, 455 (1979).
BR83 : S. Baird et al., NPA392, 297 (1983).
BT90 : C.J. Batty, NPA 508, 89c (1990).
HZ00 : S. Hirenzaki et al., PRC 61, 055205 (2000).
FR06 : E. Friedman, private communication (2006).
AK05 : Y.Akaishi, EXA05 proceedings (2005)

Comparison



Here, statistical and systematic errors are quadratically added.

Comparison

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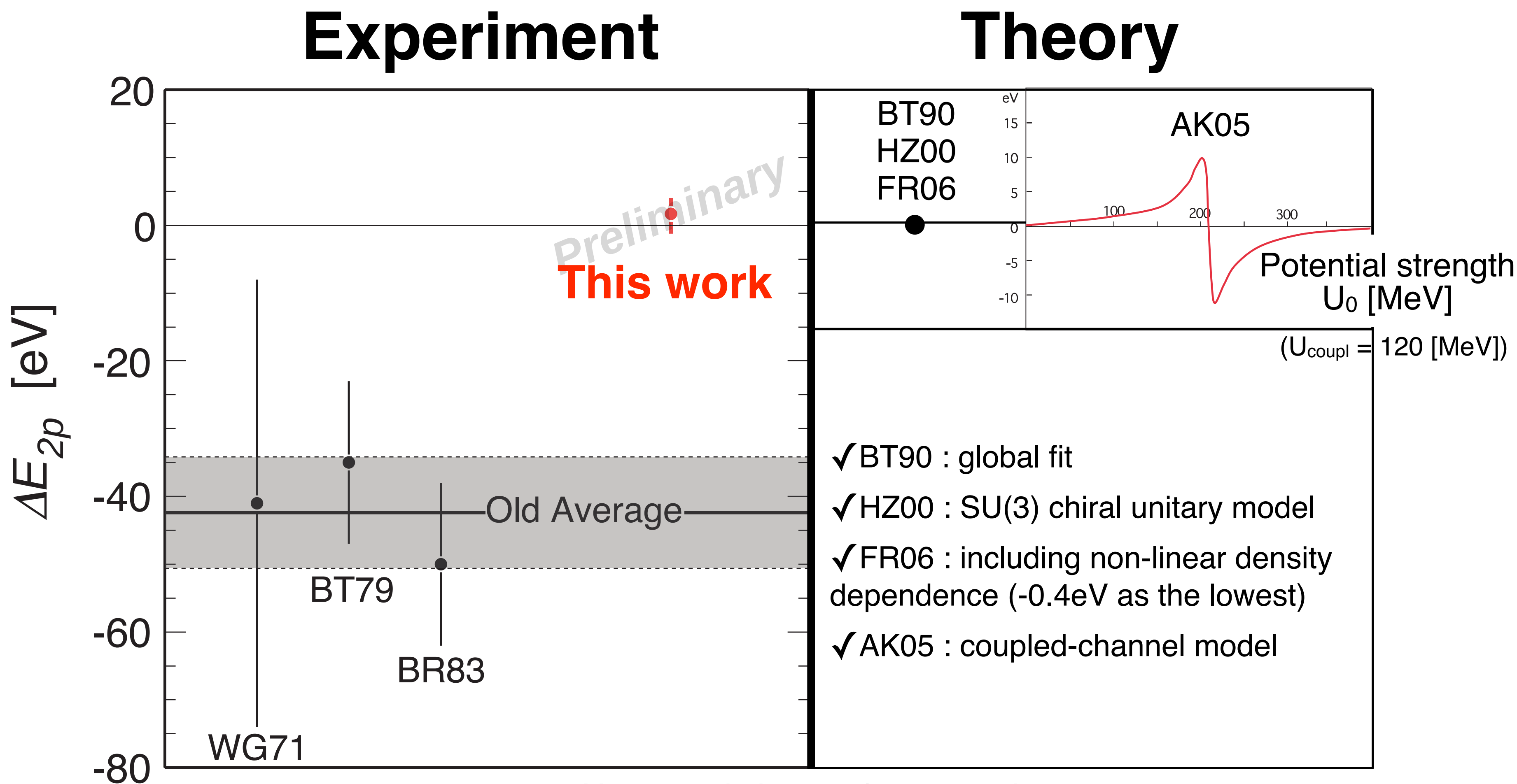


- ✓BT90 : global fit
- ✓HZ00 : SU(3) chiral unitary model
- ✓FR06 : including non-linear density dependence (-0.4eV as the lowest)
- ✓AK05 : coupled-channel model

previous 3 exp.

Here, statistical and systematic errors are quadratically added.

Summary

- Precisely measured K^{-}-^{4}He x-ray spectrum
  - High energy resolution : 185 eV @6.5keV
  - Good S/N ratio : applying stopped-K- event selection
  - Energy calibration was successfully done by using characteristic X-rays from Ti and Ni foils
- 3d->2p energy : $E_{3d\text{-}2p}$ = 6467.5 ± 2.5 (stat) eV
- Using all transition energies : ΔE_{2p} = 2 ± 2 (stat) eV
- Our precise determination of ΔE_{2p} resolved the long-standing kaonic helium puzzle.

Preliminary

Preliminary

Now, we are preparing to publish the result.

Backup slides

Systematic error estimation

1) Compton scattering effect

Error from the cross section of bound Compton scattering and Rayleigh scattering in 4He is only several %.

(according to EGS4 developers)

--> For ± 5 % change of the intensity,
the energy moves ± ~0.4 eV.

2) Pileup effect

Ambiguity of the intensity-ratio estimation could be less than ± 10 %according to the FADC analysis.

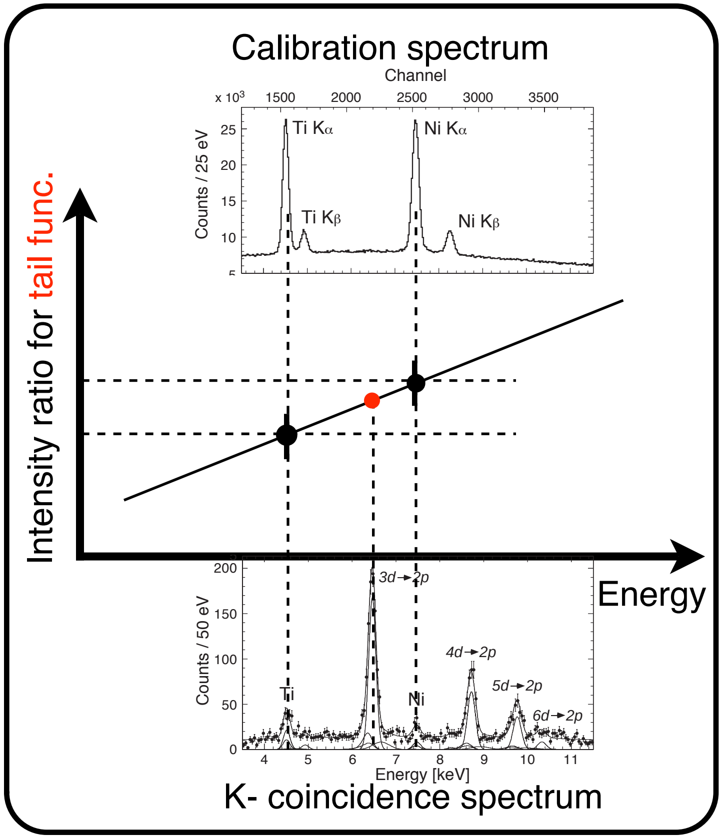
--> For ± 10 % change of the intensity,
the energy moves ± ~0.4 eV.

3) Tail function (SDD response function)

Tail-intensity ratio for KHeX Lα was estimated by interpolation of ratios for Ti and Ni characteristic x-rays.

--> When we use intensity ratios for Ti and Ni to those for kaonic x-ray lines,
the energy moves +0.1 / -1.1 eV.

For tail function



Energy dependent resolution

$$\Delta E(\mathrm{FWHM}) = 2.35\omega\sqrt{W_N^2 + FE/\omega}$$

E : X-ray energy [eV]

ω : average energy for electron-hole creation in silicon (3.81eV)

W_N : contribution of noise to the resolution
(independent of the x-ray energy)

F : Fano factor (~0.12 for silicon)