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

T. Ishiwatari / SMI, Vienna

On behalf of

SIDDHARTA collaboration

PLB681(09)310
PLB697(11)199

6. Sep. 2011, EXA2011, Vienna, Austria

SIDDHARTA Collaboration

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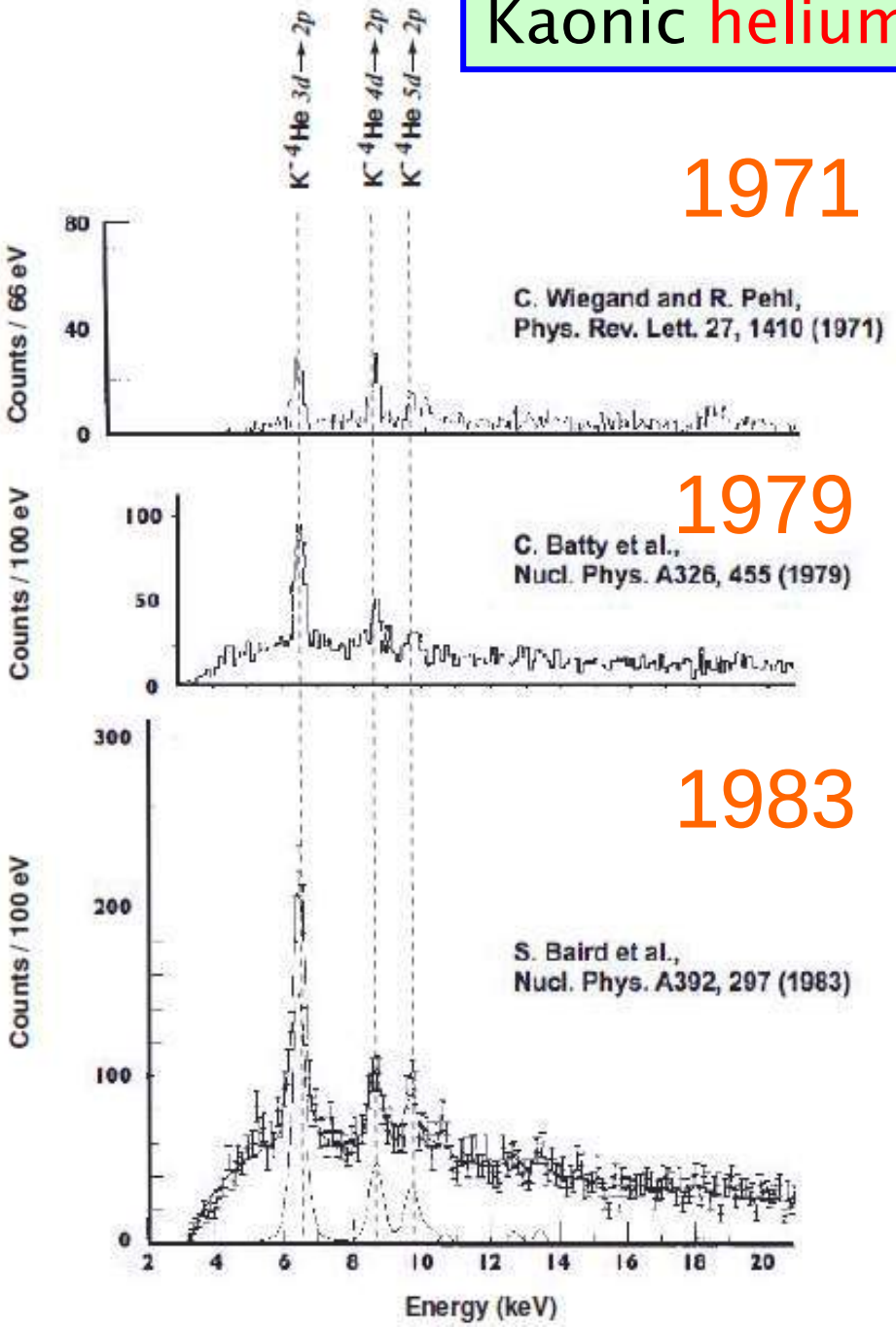
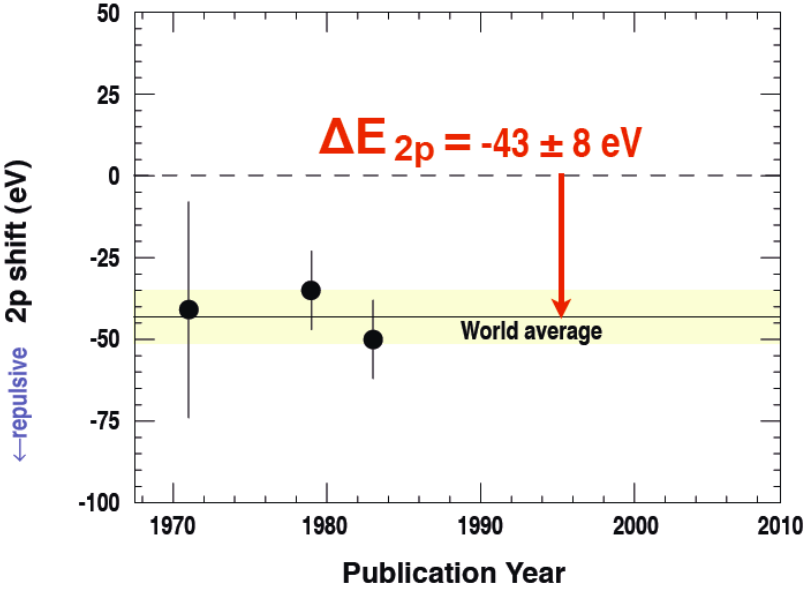
Introduction
-- History --

Kaonic helium atom data (Z=2)

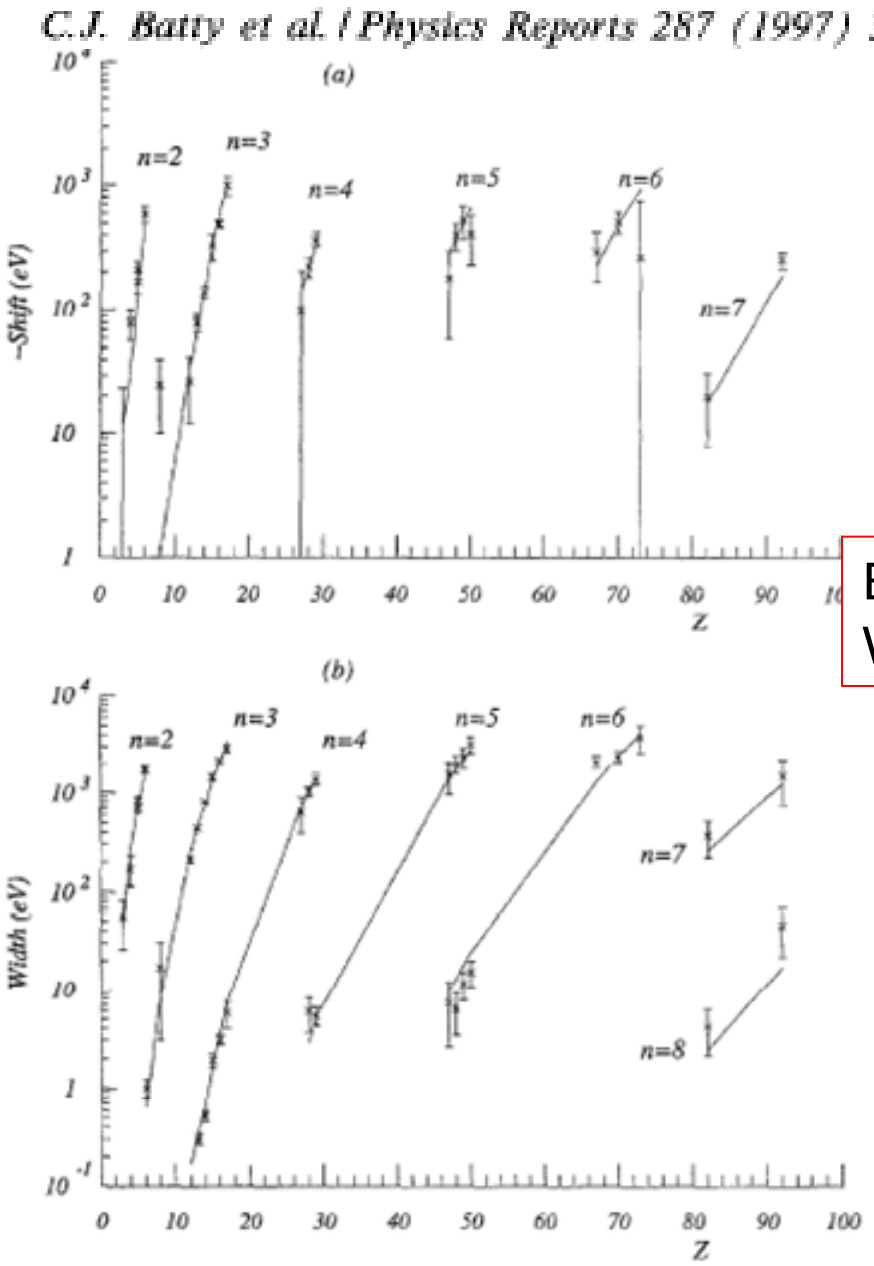


$$\Delta E_{2p} = E_{\exp} - E_{e.m.}$$

ΔE_{2p} (eV)	Γ_{2p} (eV)
-41 ± 33	–
-35 ± 12	30 ± 30
-50 ± 12	100 ± 40
Average -43 ± 8	55 ± 34
Shift	Width



Kaonic atom data (Z≥3)



Kaonic atom data (Z≥3)
Used for studies of $K^{bar}N$ interaction

Optical model

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

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

Expected shift of K-4He 2p state:
$\Delta E \sim 0$ 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

Future directions in kaonic atom physics

E. Friedman

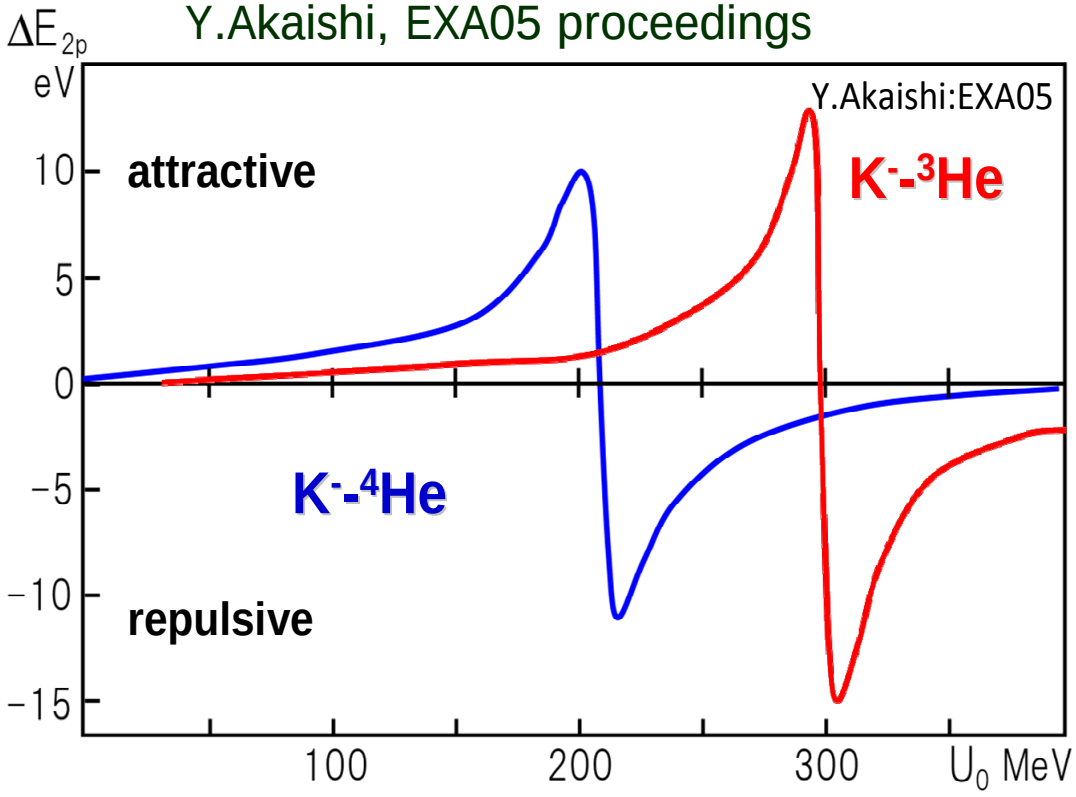
Predictions for the 2p level in kaonic He isotopes (in eV).

		^{3}He		^{4}He	
added phen.	1385 res.	shift	width	shift	width
no	no	0.2	1.9	0.4	2.1
no	yes	-0.1	1.9	-0.1	2.3
yes	no	0.3	2.1	-0.2	1.6
yes	yes	0.0	1.9	-0.3	1.9

EXA2011, Vienna, September 2011

Possible shift of Kaonic helium (Z=2)

Y.Akaishi, EXA05 proceedings



K-He4 exp

Large (-40 eV)

disagree

K-nucl model

Small (<±10 eV)

Optical model

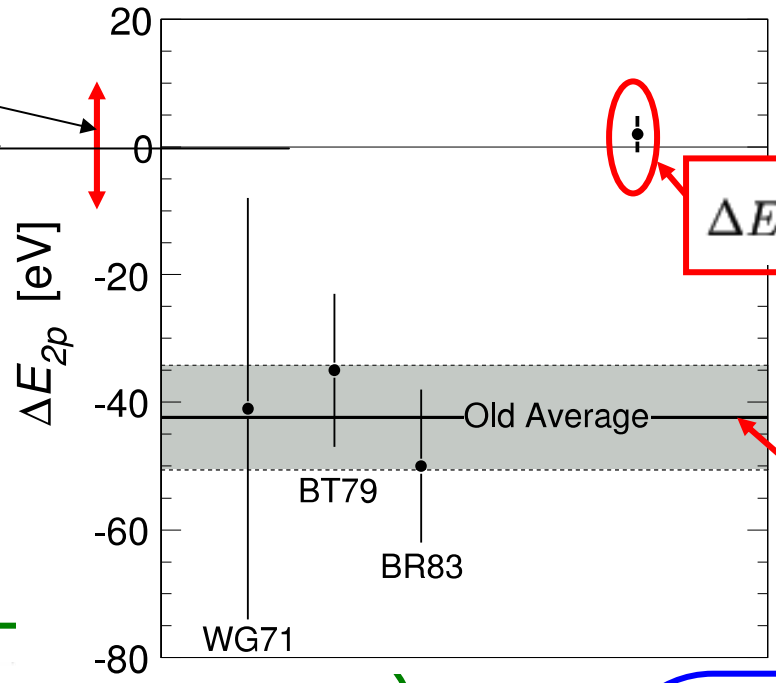
Tiny (~ 0eV)

K-^{4}He 2p level shift

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

Akaishi Prediction
-10~ +10 eV

Optical model
~0eV

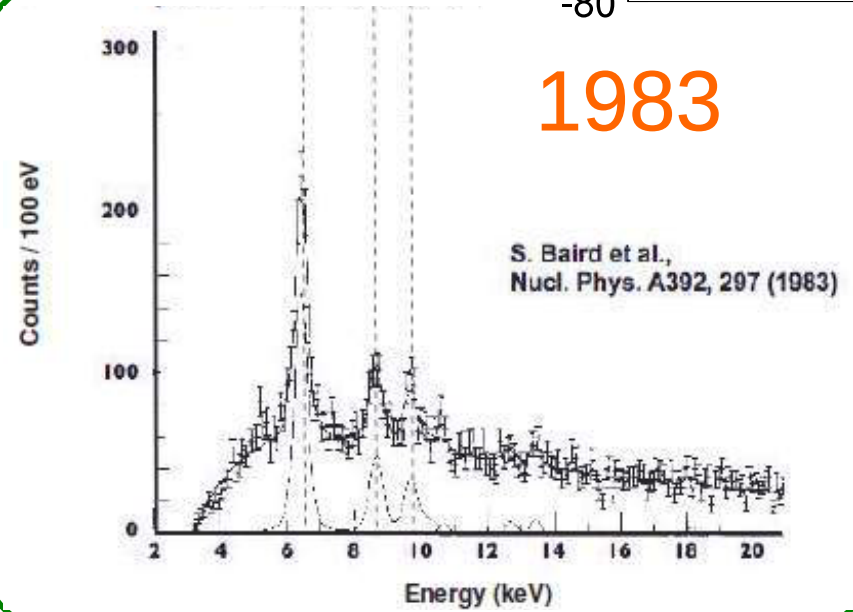


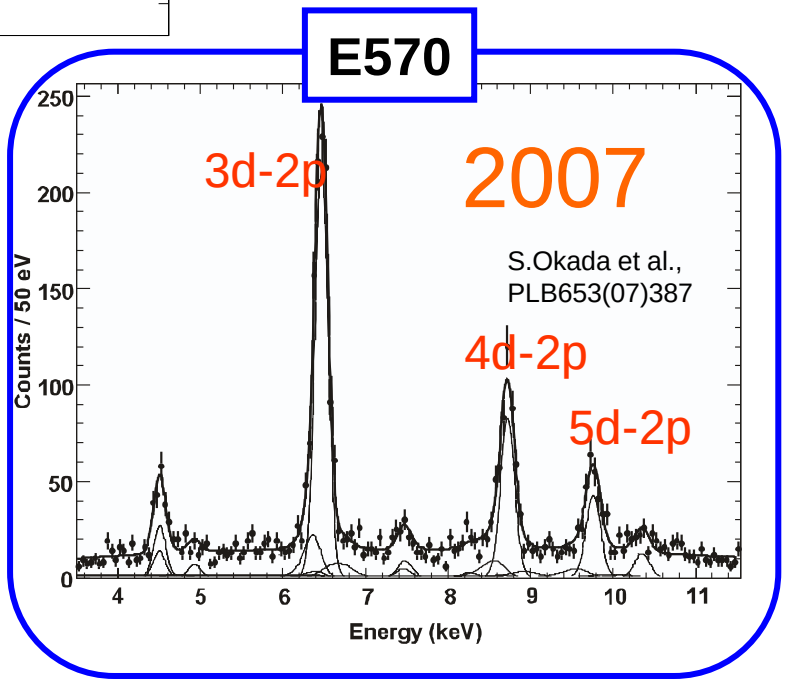
E570 results ('07)

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

Disagree!

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

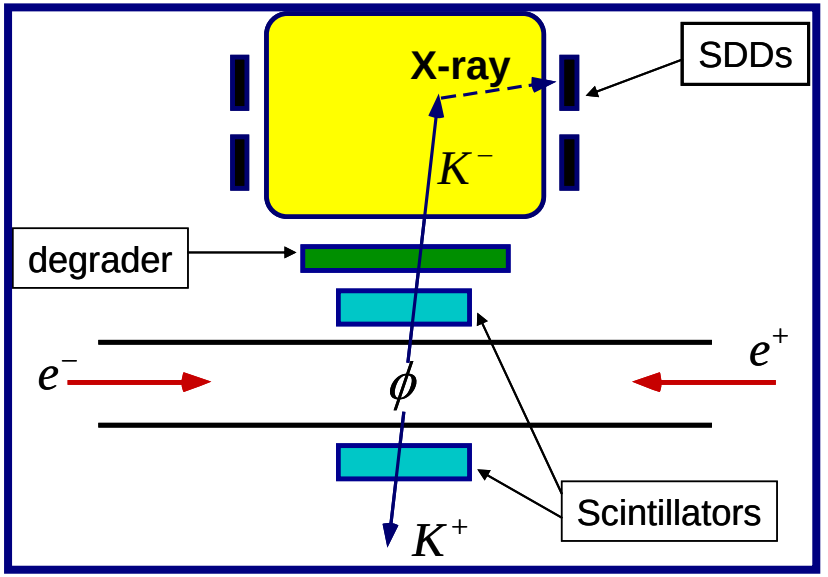




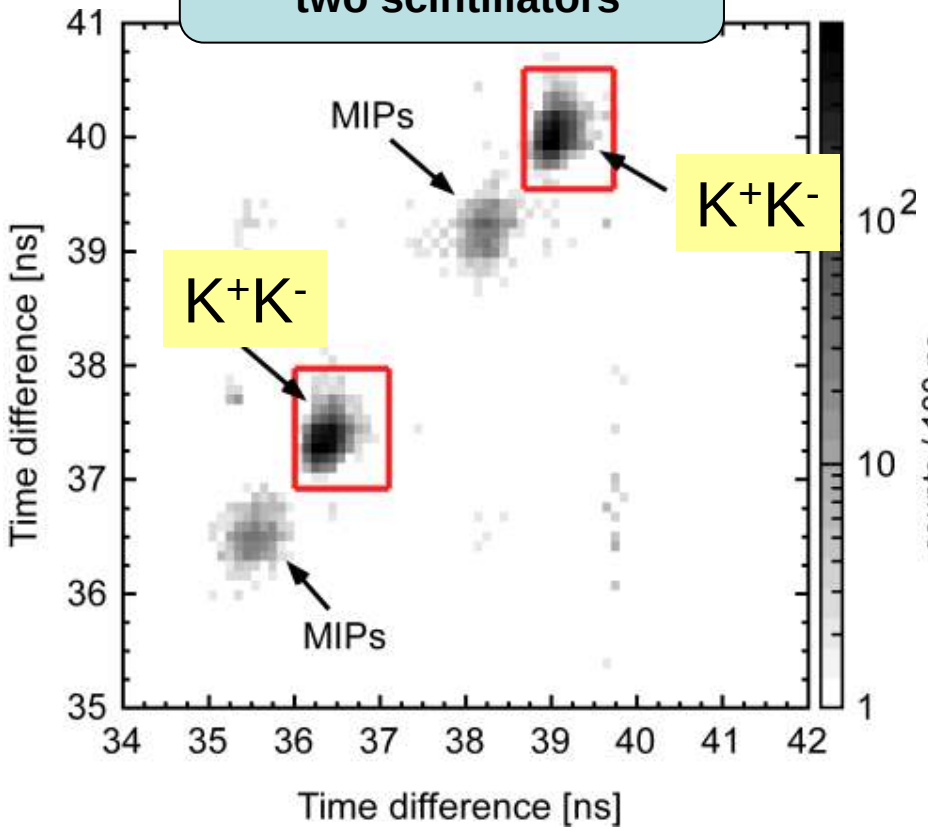
SIDDHARTA Experiment

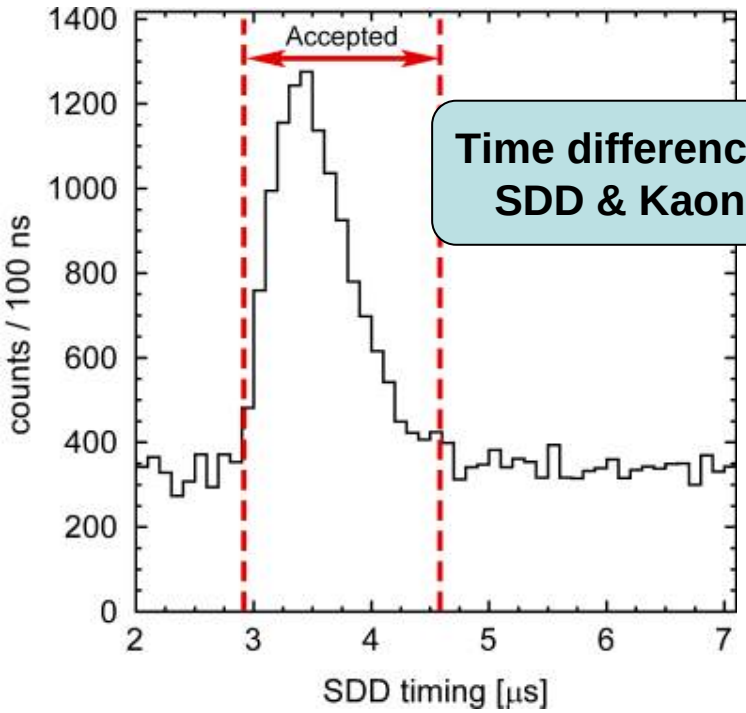
SIDDHARTA Experimental Setup

Triple timing coincidence:
SDD (X-ray)***Scin*** (K^+)***Scin*** (K^-)



Time difference between two scintillators

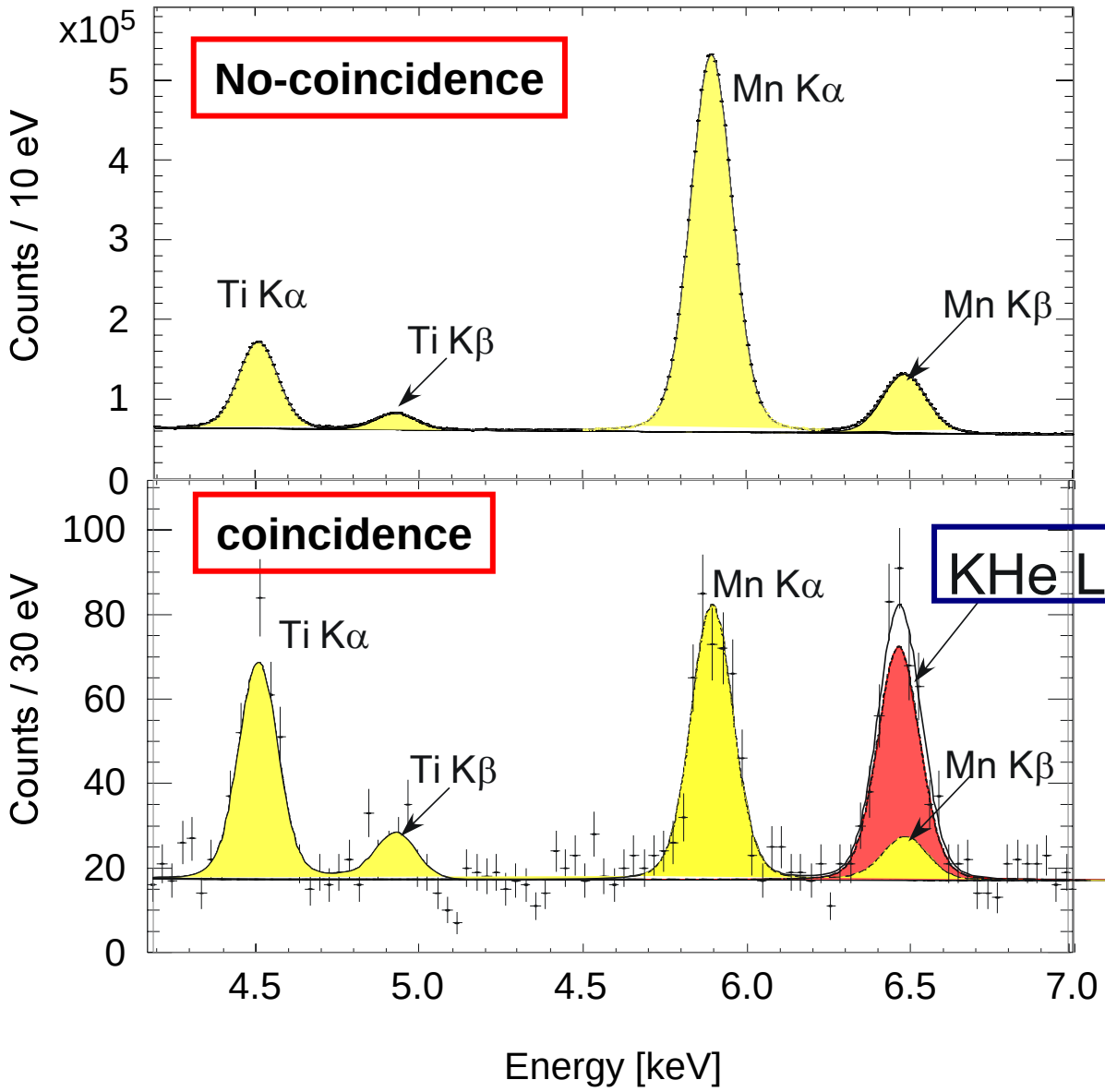


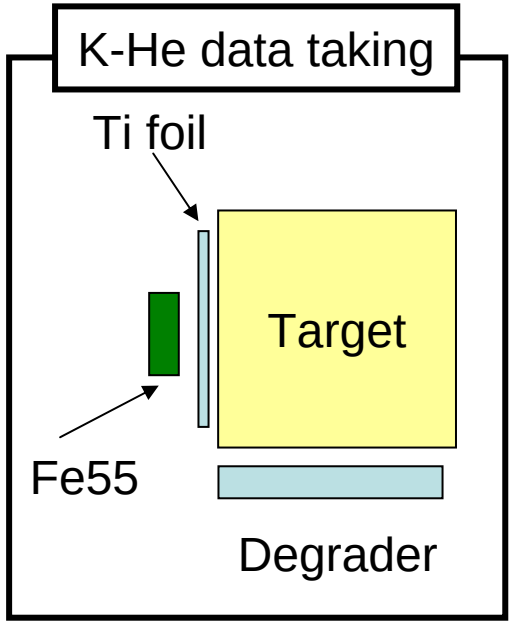


Time difference between SDD & Kaon detector

KHe-4 energy spectrum at SIDDHARTA

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

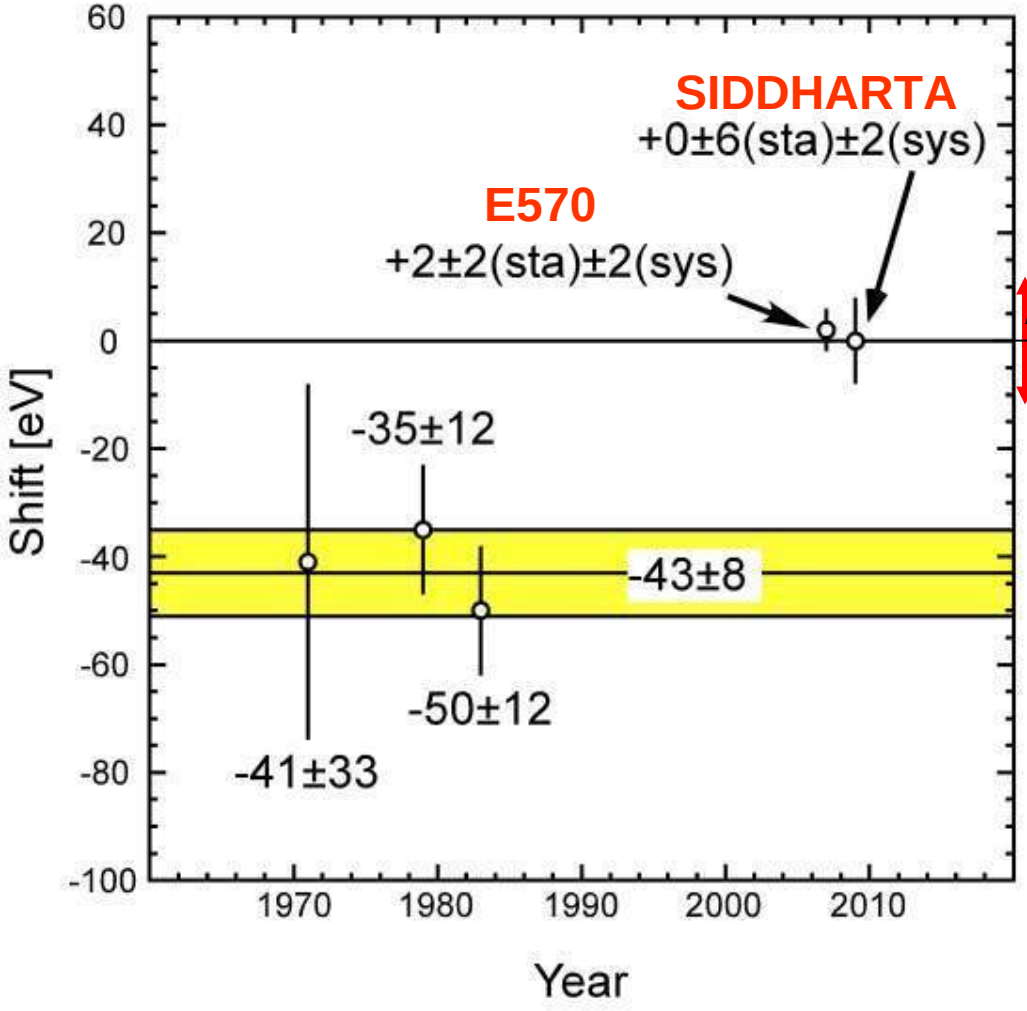




$$E_{\text{exp}} = 6463.6 \pm 5.8 \text{ eV},$$

$$\Delta E = E_{\text{exp}} - E_{e.m.}$$
$$= 0 \pm 6(\text{stat}) \pm 2(\text{syst}) \text{ eV}$$

Summary of KHe-4 shifts (up to 2007)



Akaishi Prediction
-10~ +10 eV

Optical model
~0eV

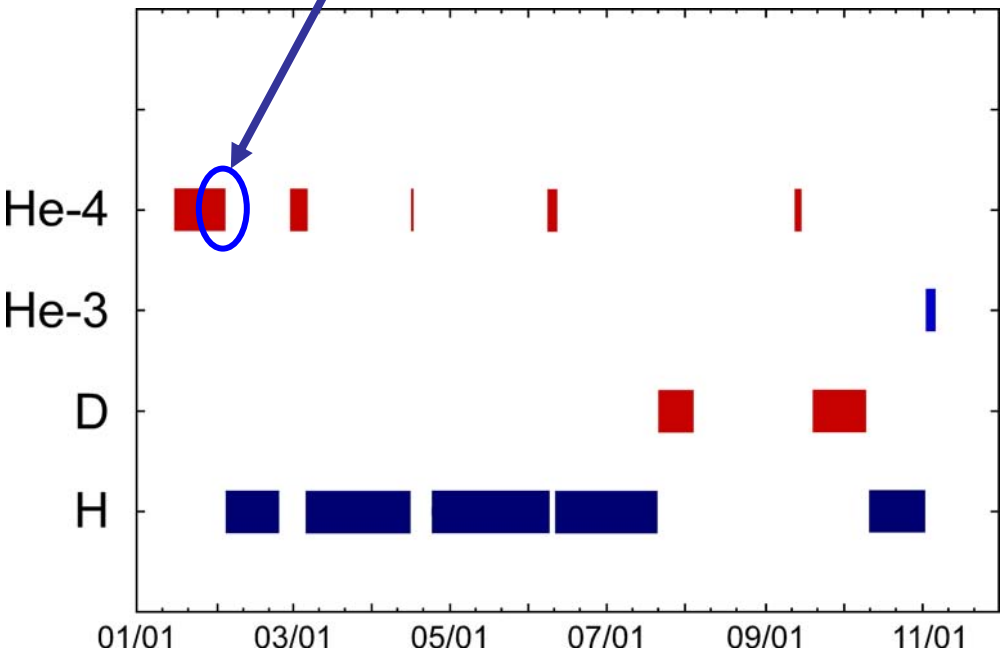
Optical model
Tiny (~ 0eV)

K-nucl model
Small (<±10 eV)

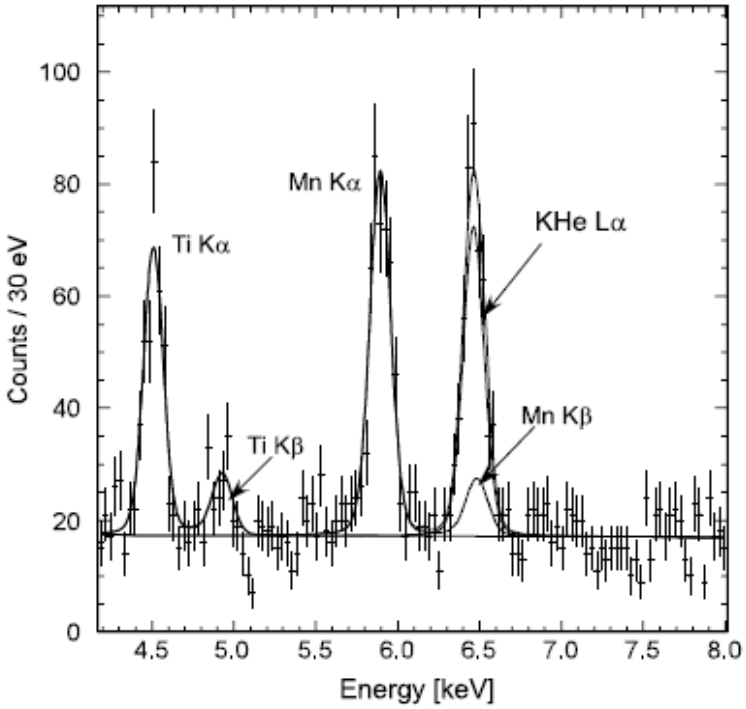
K-He4 exp
Large (-40 eV)

Data taking periods of SIDDHARTA in 2009

K-He4 data with Fe source



PLB681(2009)310



55Fe source:
Good for reduce sys. error on K-^{4}He
Bad for "background" events on K-H,K-D

Use of
Mn Ka (5.9 keV) from ^{55}Fe

Systematic error = +/-2 eV

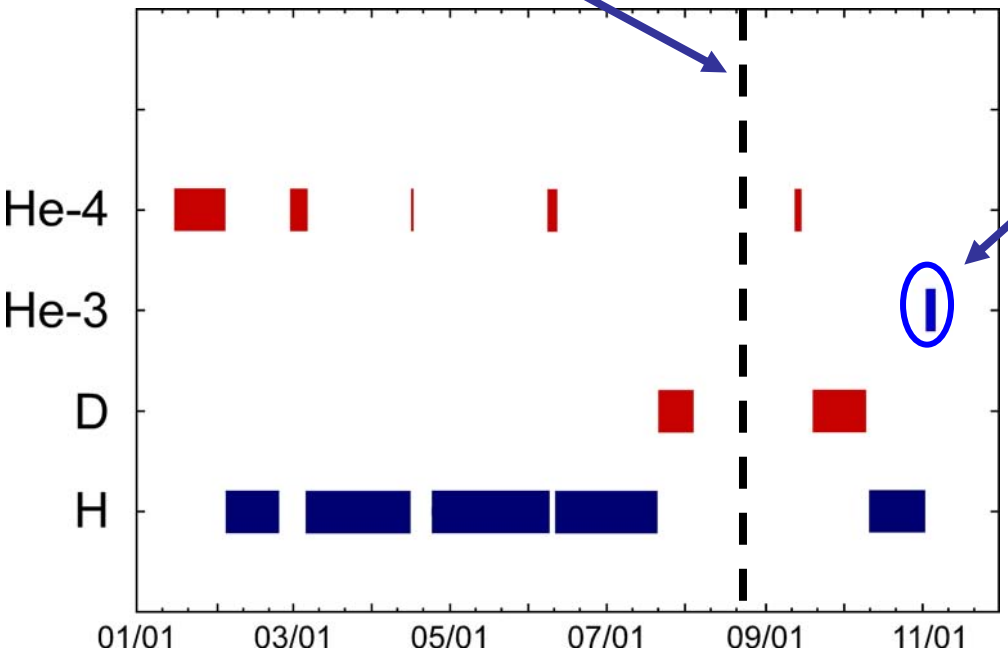
Removed ^{55}Fe source in other data

Data taking periods of SIDDHARTA in 2009

DAFNE shutdown in Summer

New alignment of setup
→Improve S/N ratio

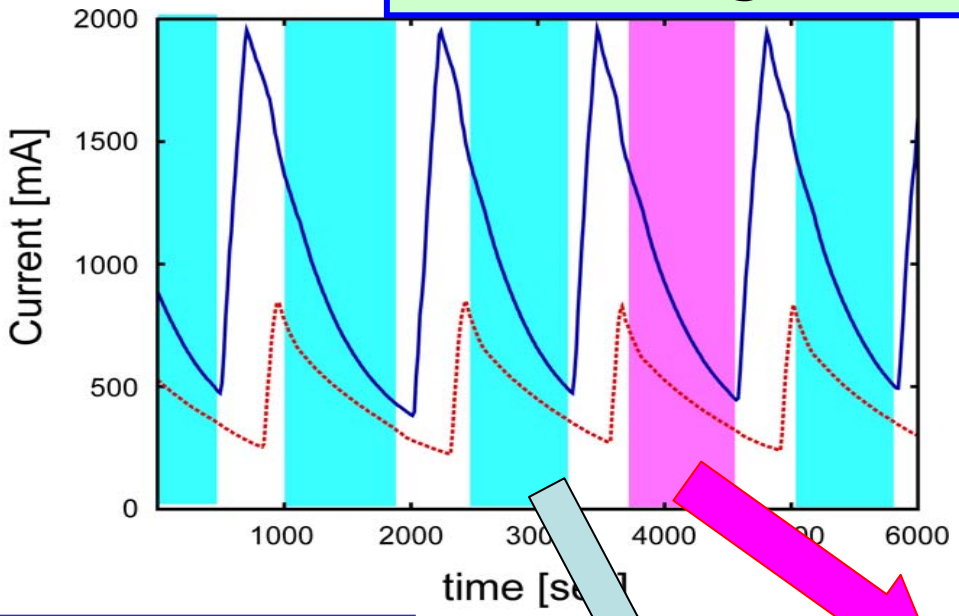
K-He3 data (~4days)



55Fe source:
Good for reduce sys. error on K-^{4}He
Bad for "background" events on K-H,K-D

Removed ^{55}Fe source in other data

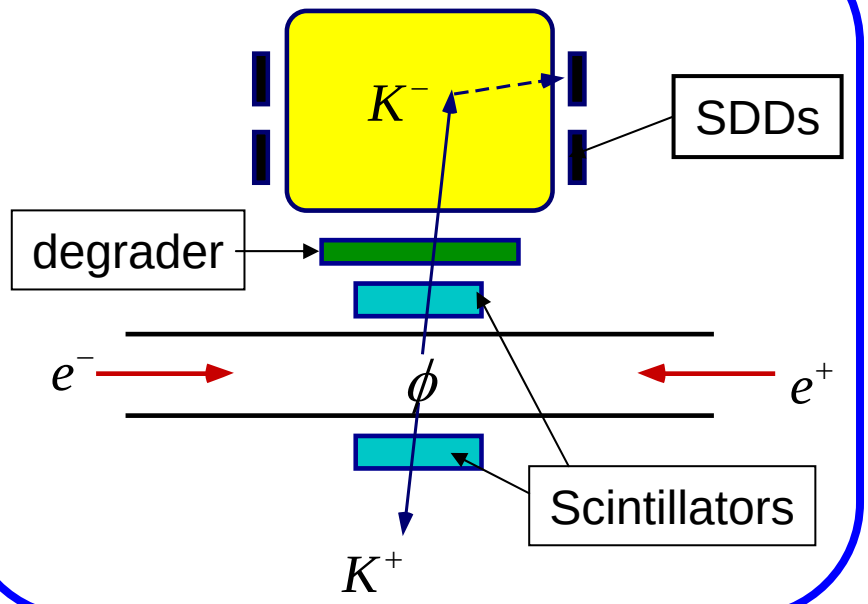
Data taking scheme at DAFNE



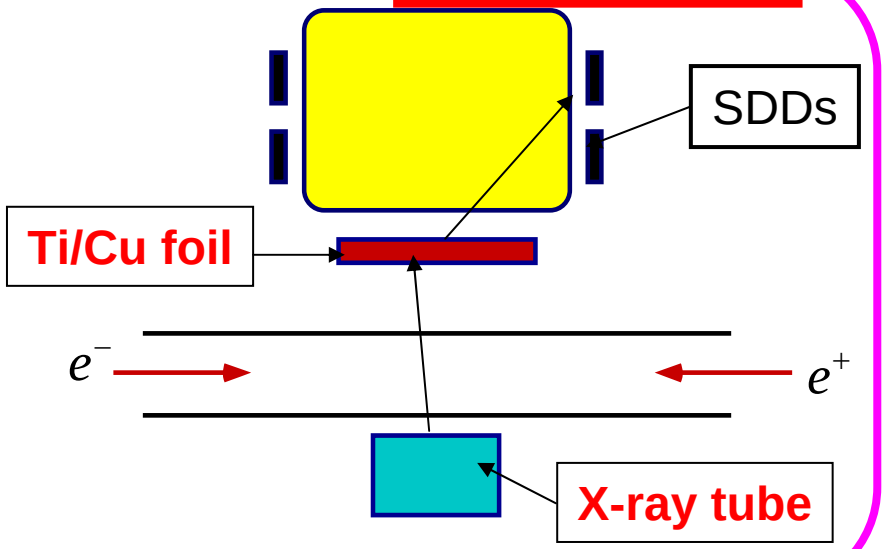
Instead of Fe source,
"X-ray tube" data taken

Estimated
systematic error ~ 5 eV

Production data

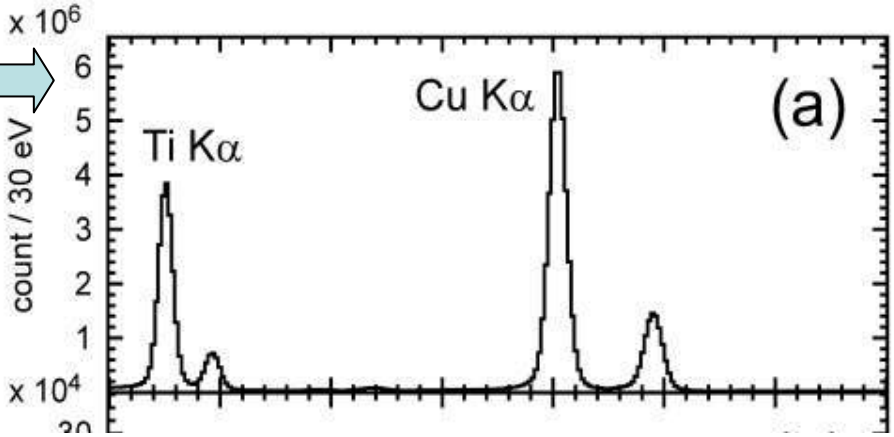


calibration data

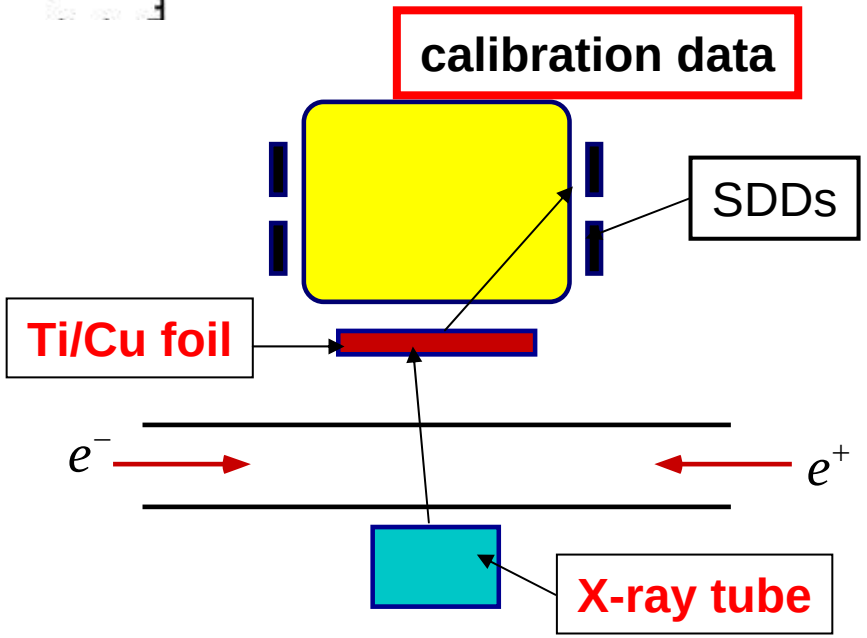


SDD X-ray energy spectra

Calibration data with **X-ray tube**



Calibration Ti&Cu

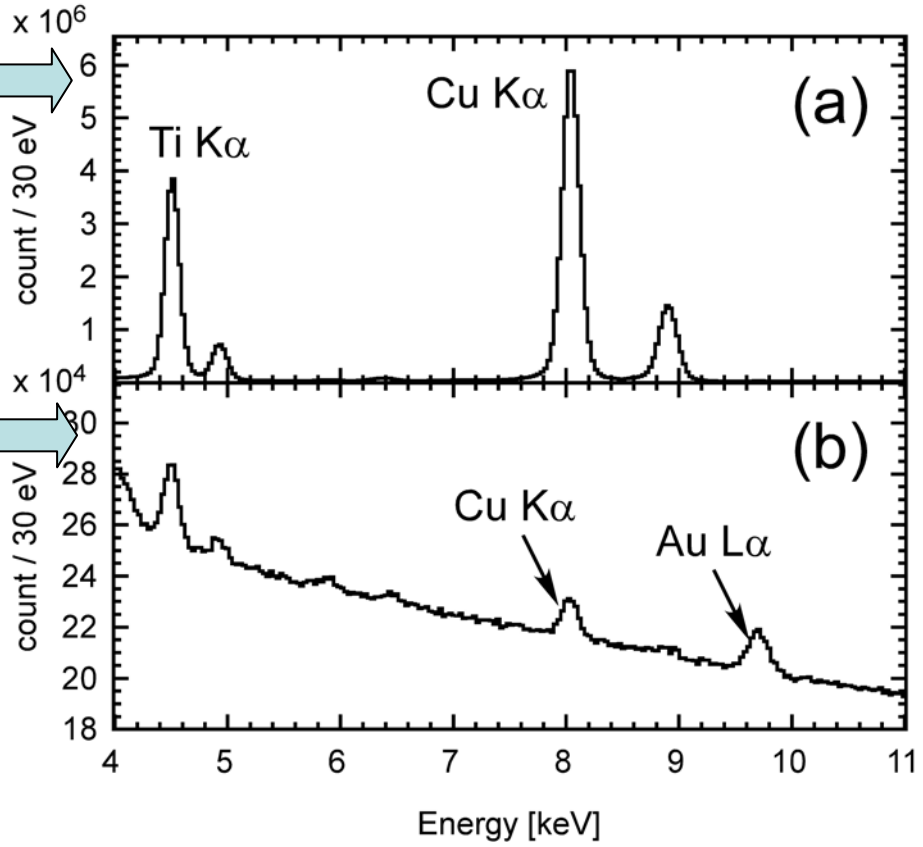


SDD X-ray energy spectra

Calibration data with **X-ray tube**

Not correlated to Kaon signals

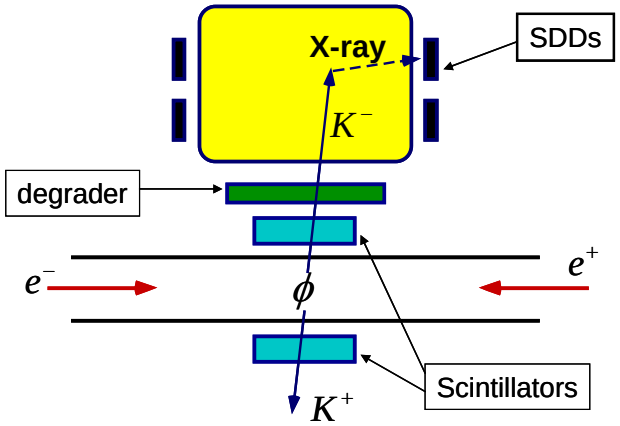
Production data



Calibration Ti&Cu

Energy scale determined by X-ray tube data

Energy spectrum with uncorrected to kaon timing [Fig. (b)]



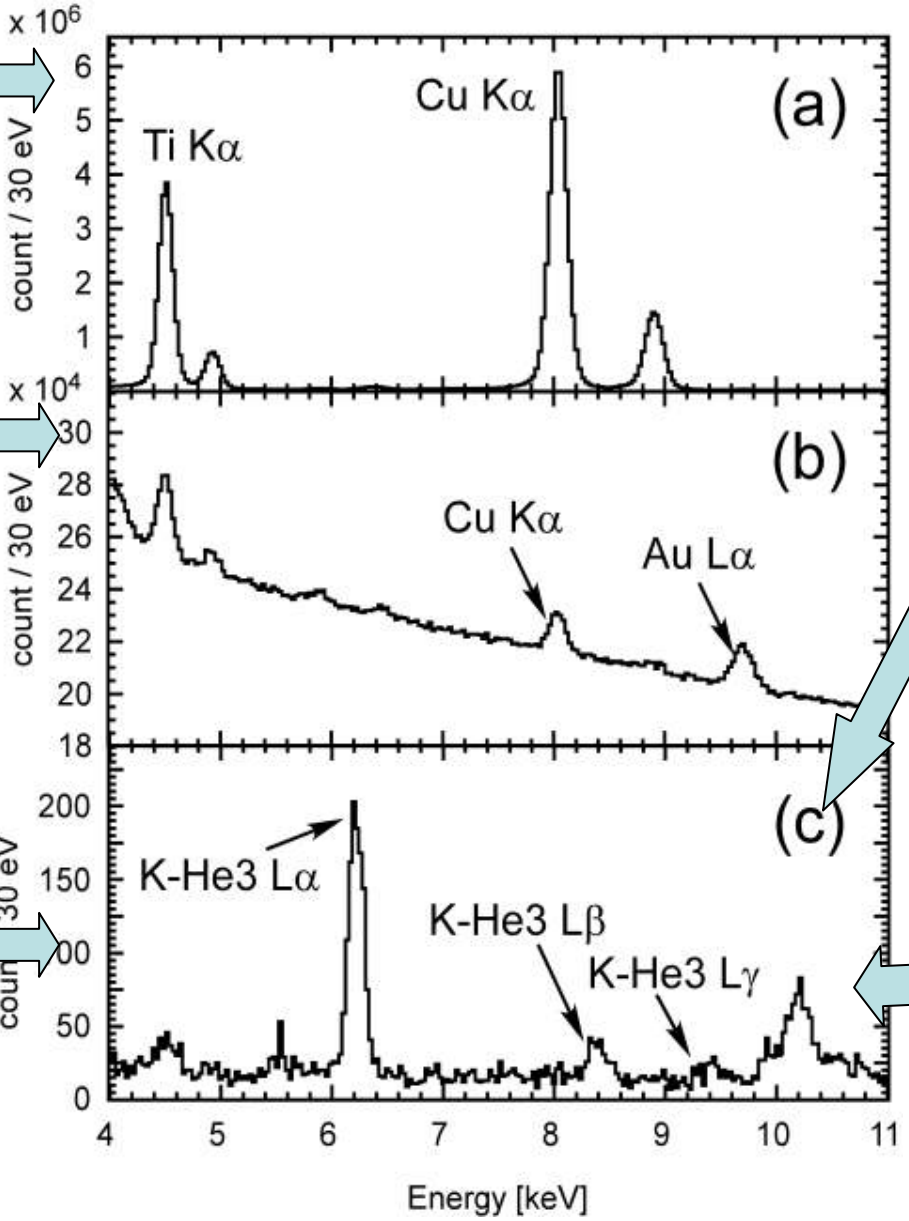
SDD X-ray energy spectra

Calibration data with **X-ray tube**

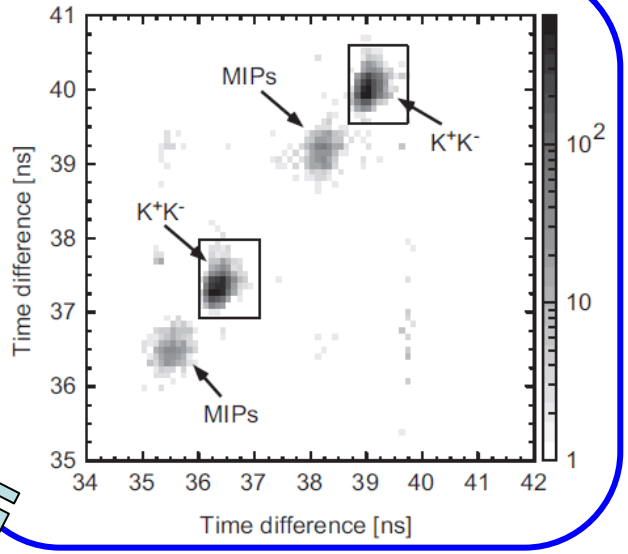
Production data

Not correlated to Kaon signals

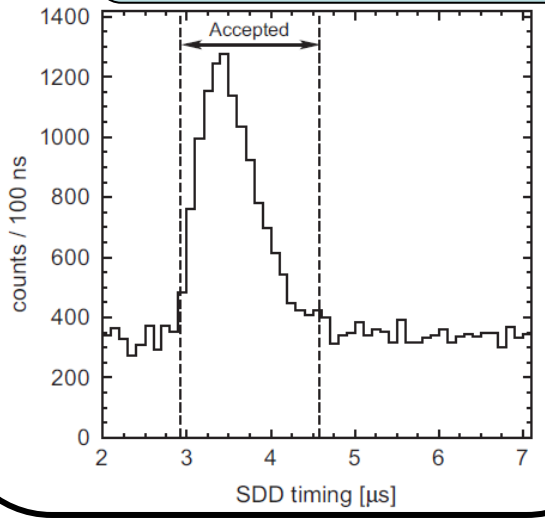
Selected with K+K- & SDD timing



Kaon detector



Time difference between SDD & Kaon detector

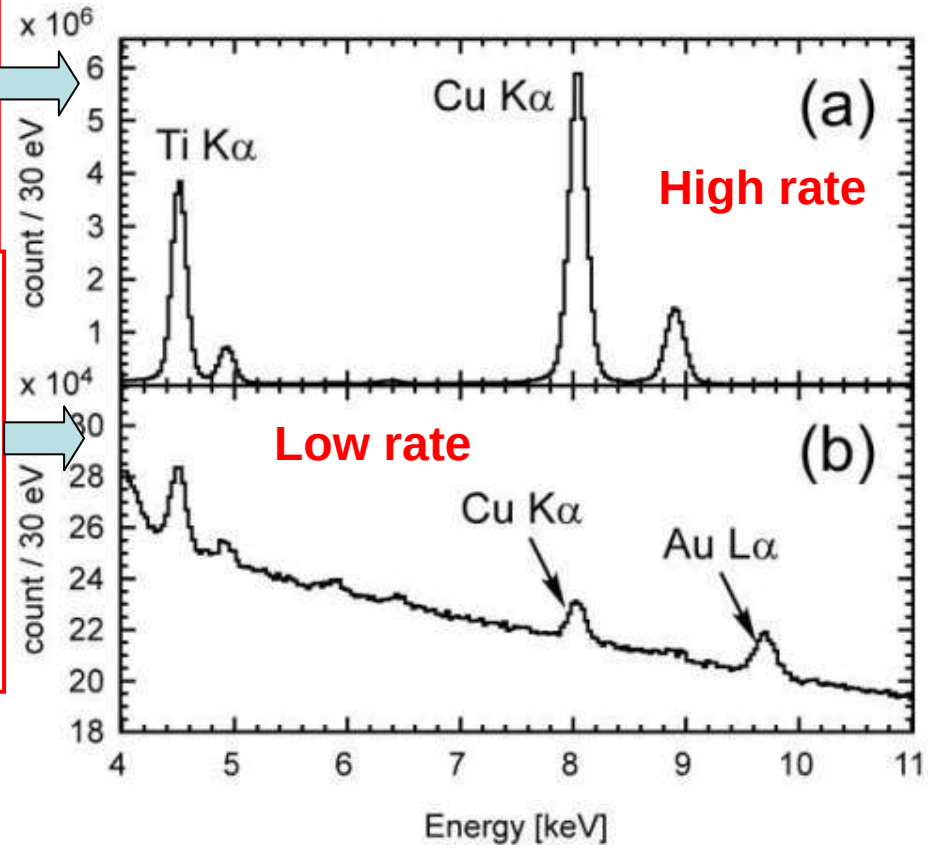


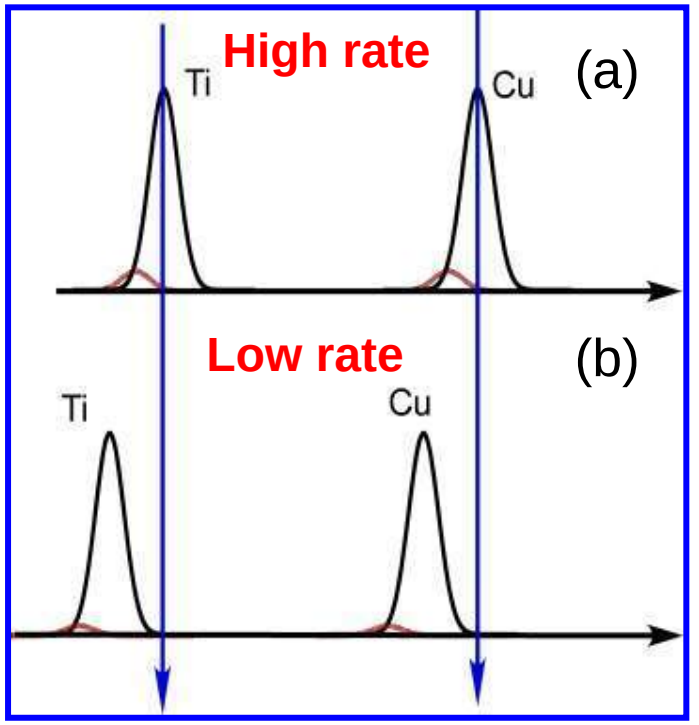
SDD X-ray energy spectra

Calibration data with **X-ray tube**

Not correlated to Kaon signals

Production data





Rate dependency

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

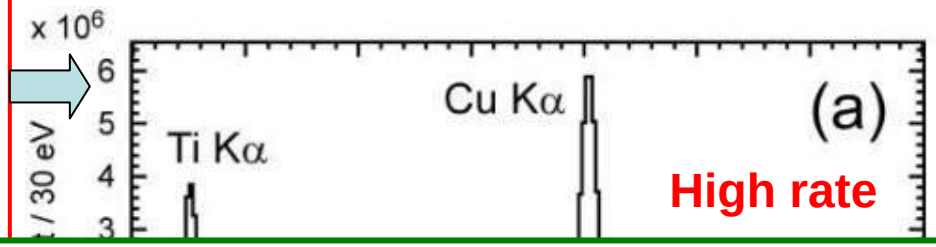
~10 eV peak shift compared to (a)

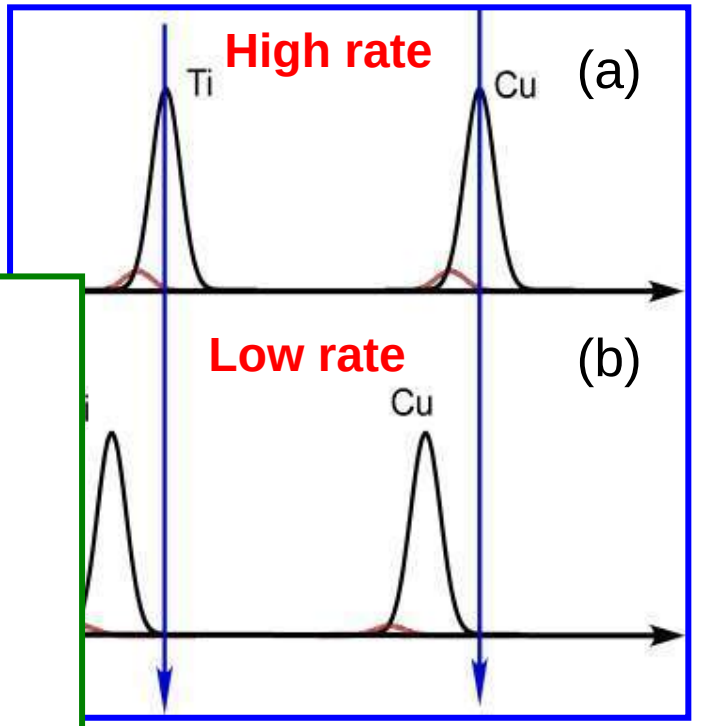
Calibration in (a): not reliable!

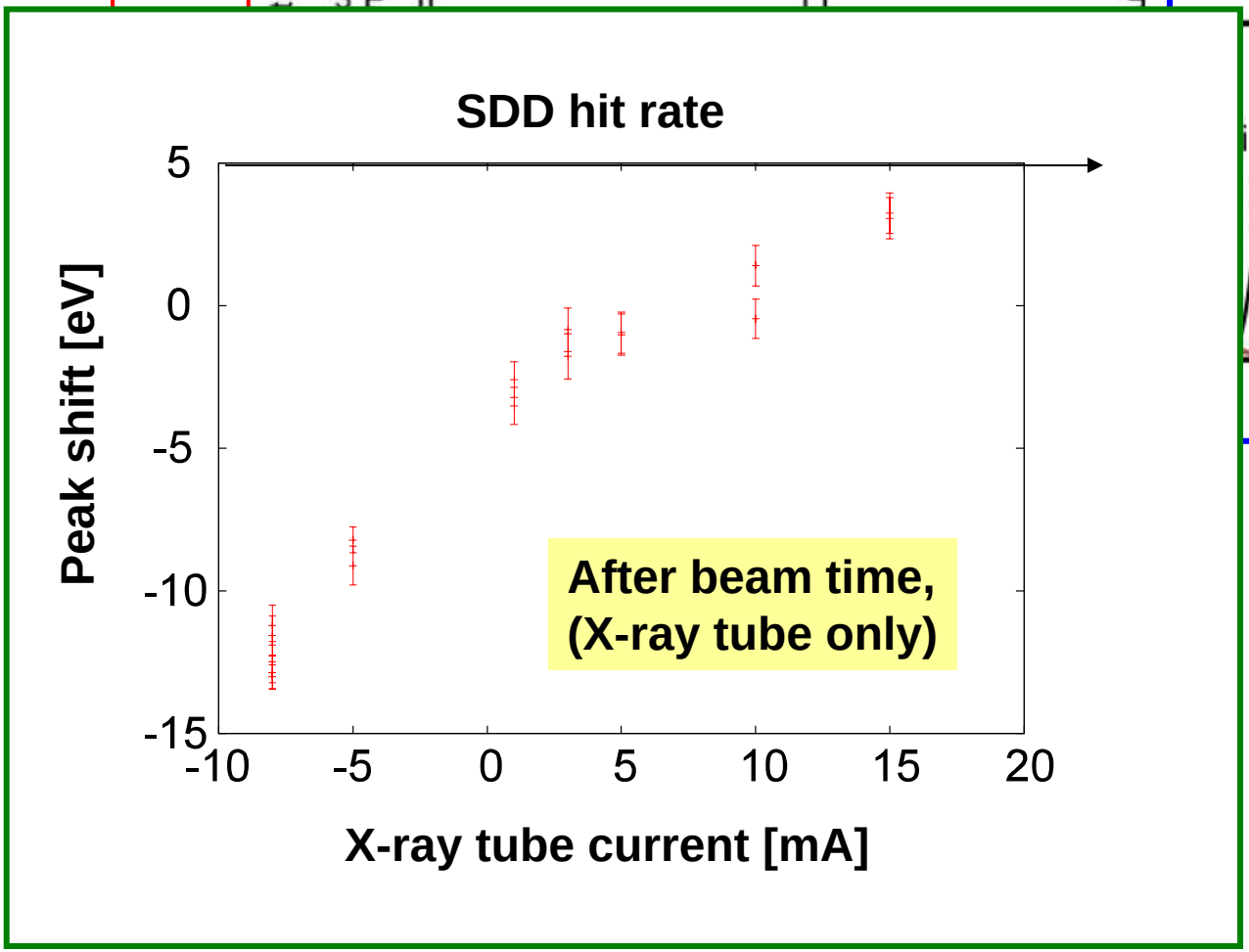
Significant for K-He measurement

SDD X-ray energy spectra

Calibration data with **X-ray tube**







~10 eV peak shift compared to (a)

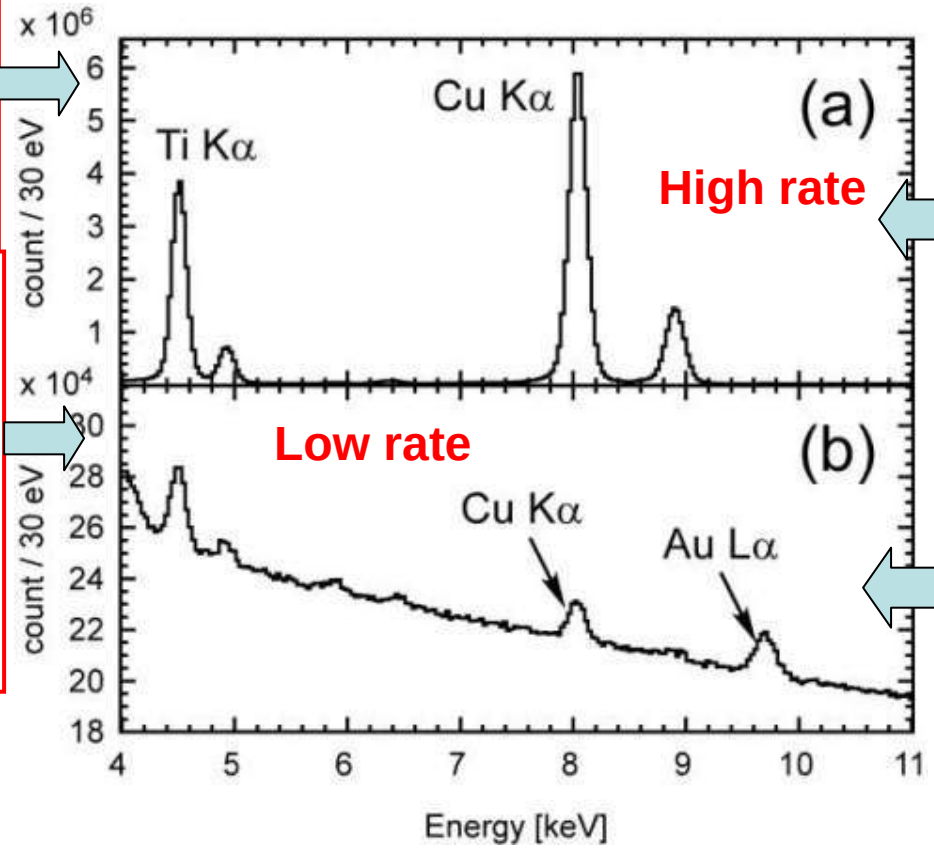
Significant for K-He measurement

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

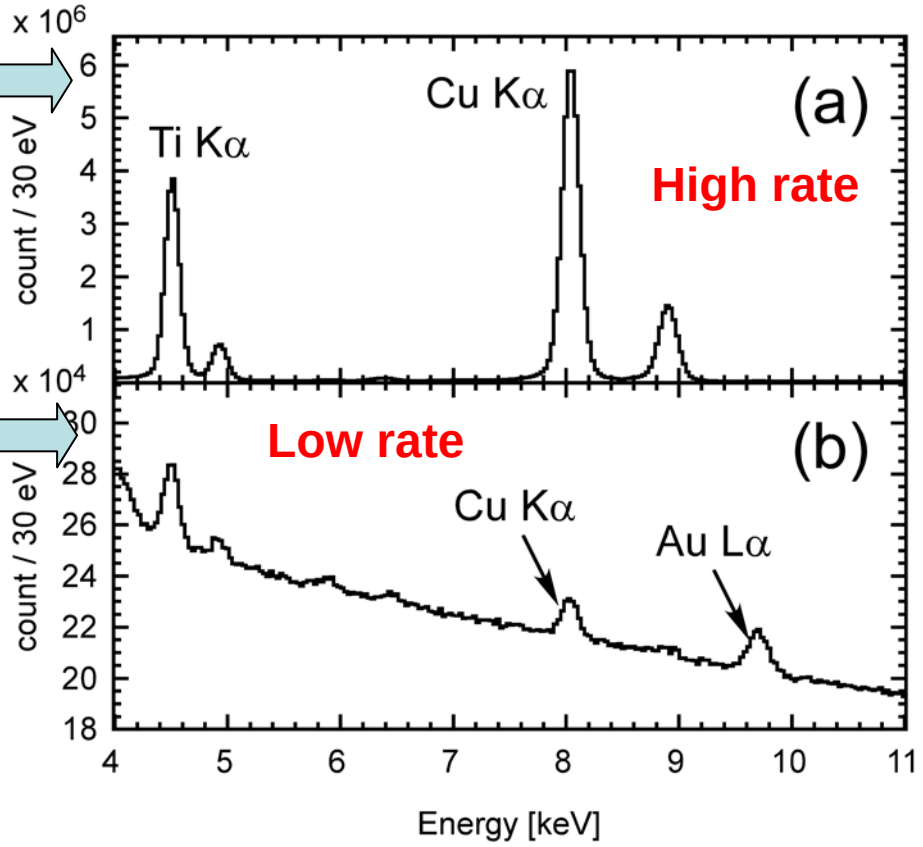
Precise energy calibration

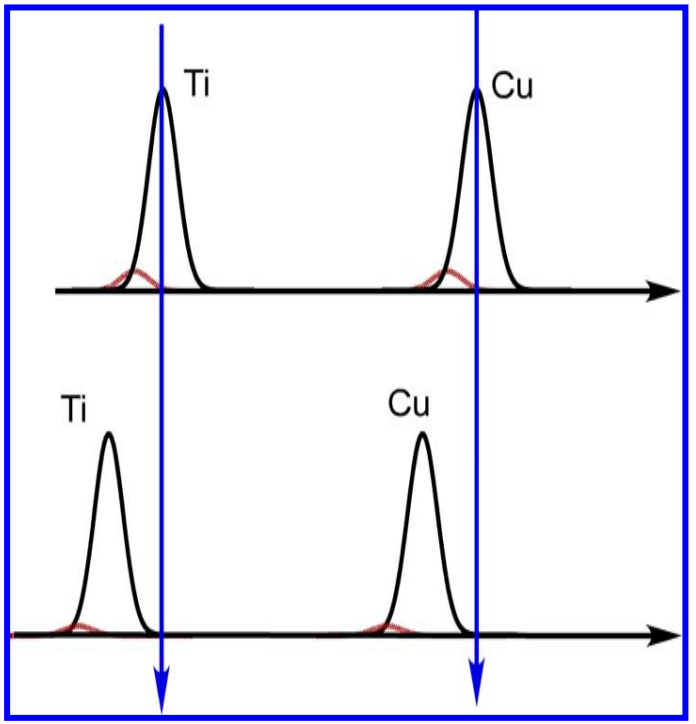
SDD X-ray energy spectra

Calibration data with **X-ray tube**

Not correlated to Kaon signals

Production data



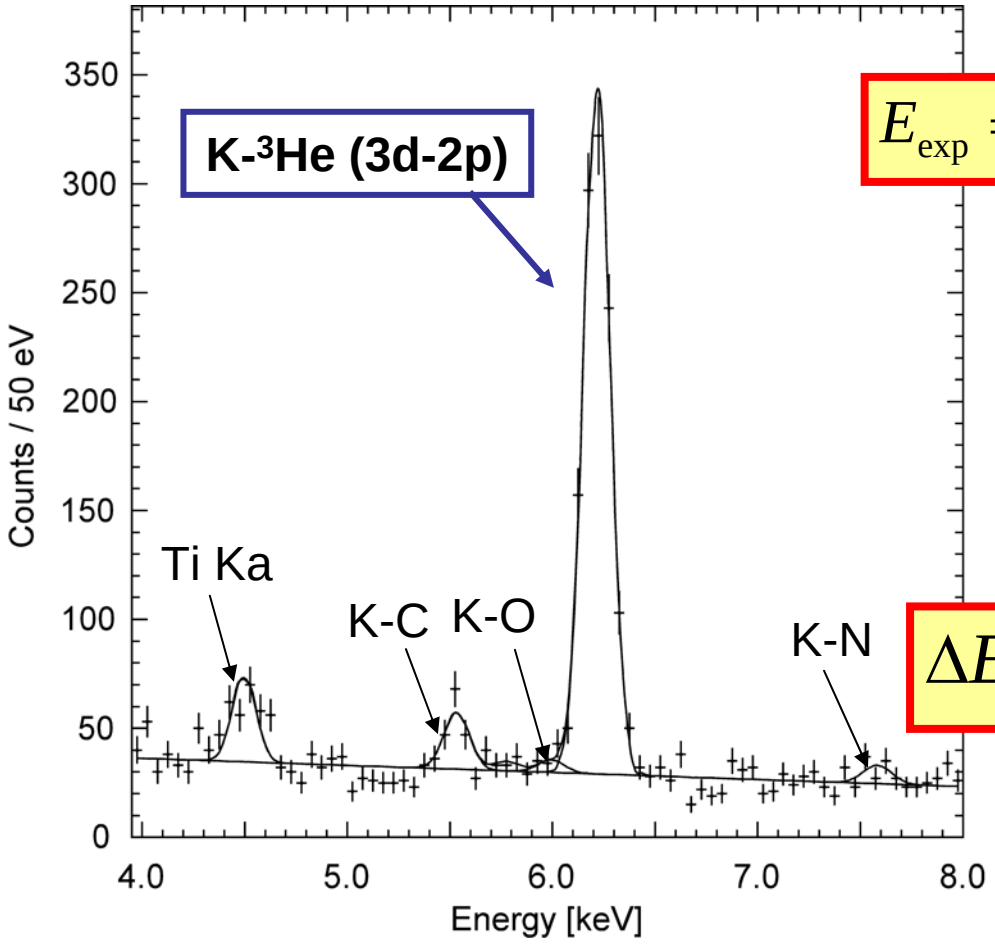


peak shift : 6.5 eV
Precision : +-3.5 eV

Correction term:

$$\varepsilon = +6.5 \pm 3.5 \text{ eV}$$

Kaonic Helium-3 energy spectrum



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

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

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

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

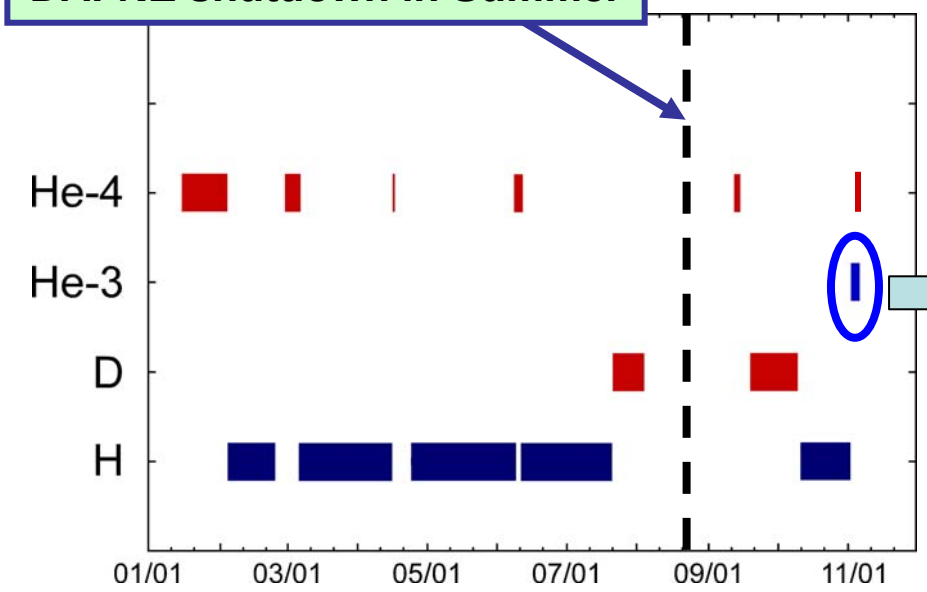
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

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

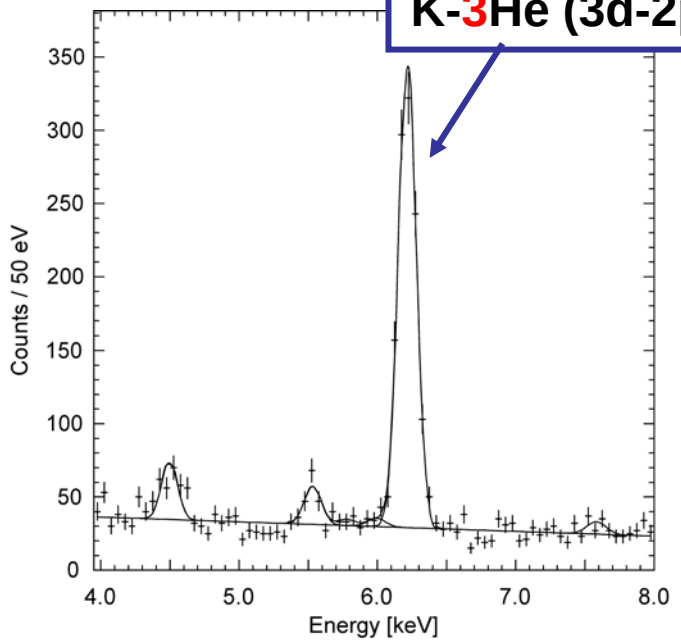
arXiv:1010.4631v1 [nucl-ex], PLB697(2011)199

PLB697(2011)199

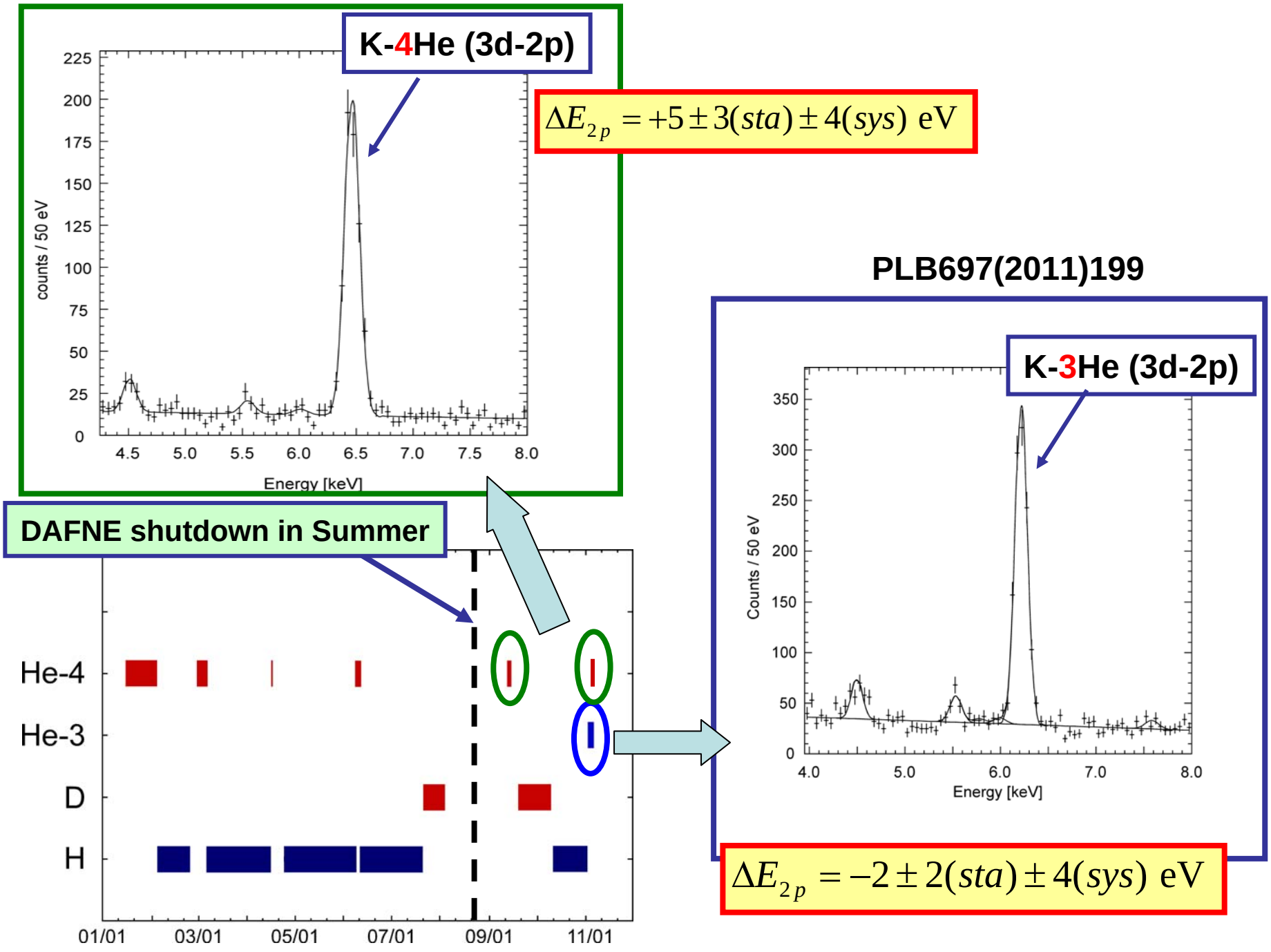
DAFNE shutdown in Summer



K-3He (3d-2p)



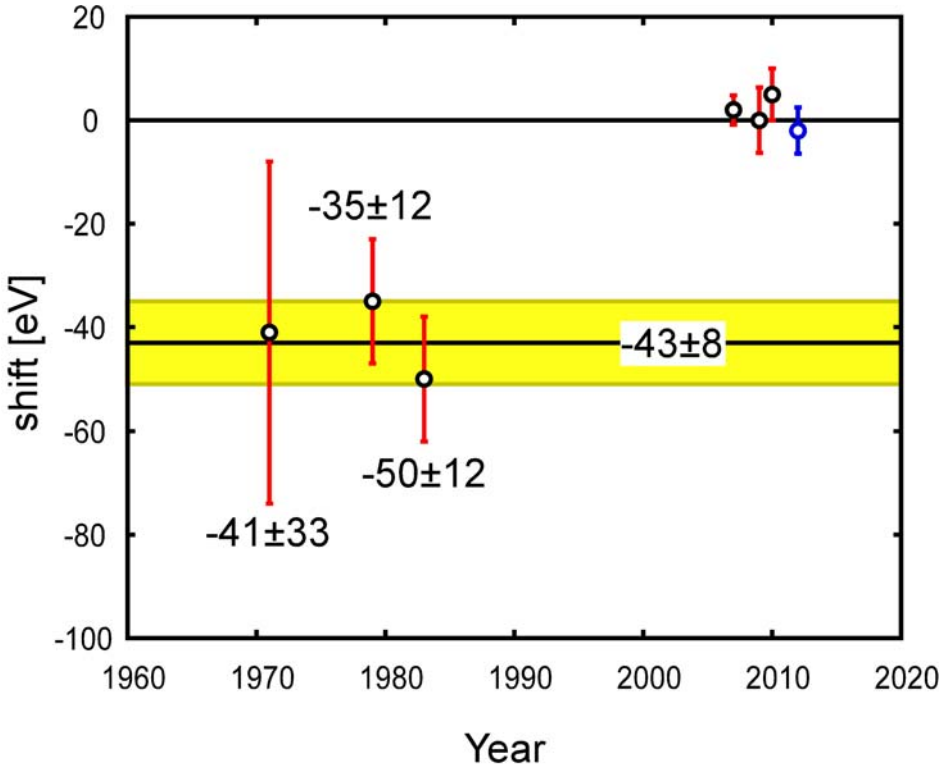
$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

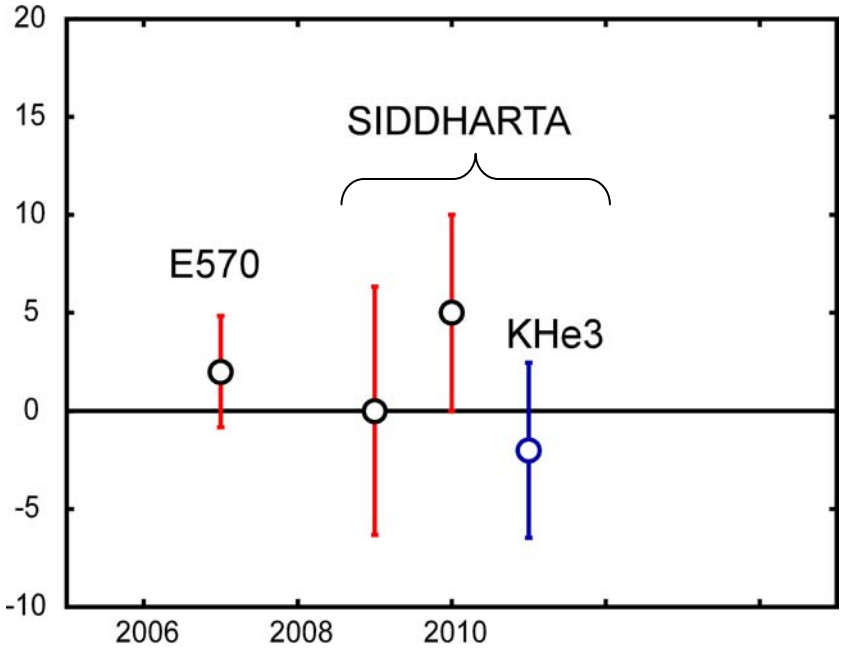

K-4He (3d-2p)
$\Delta E_{2p} = +5 \pm 3(sta) \pm 4(sys)$ eV
counts / 50 eV
Energy [keV]
PLB697(2011)199
K-3He (3d-2p)
Counts / 50 eV
Energy [keV]
$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)$ eV
DAFNE shutdown in Summer
He-4
He-3
D
H
01/01
03/01
05/01
07/01
09/01
11/01

Discussion

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, PLB697(2011)199
SIDDHARTA (He3)	-2±2±4	





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

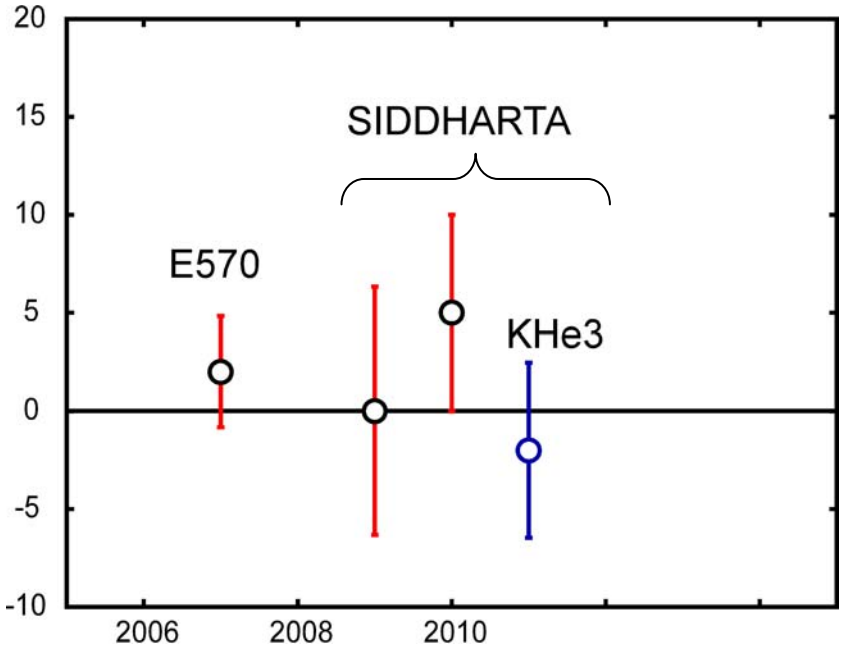
Comparison of results

	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, PLB697(2011)199
SIDDHARTA (He3)	-2±2±4	

Question: both 0-eV shift?

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

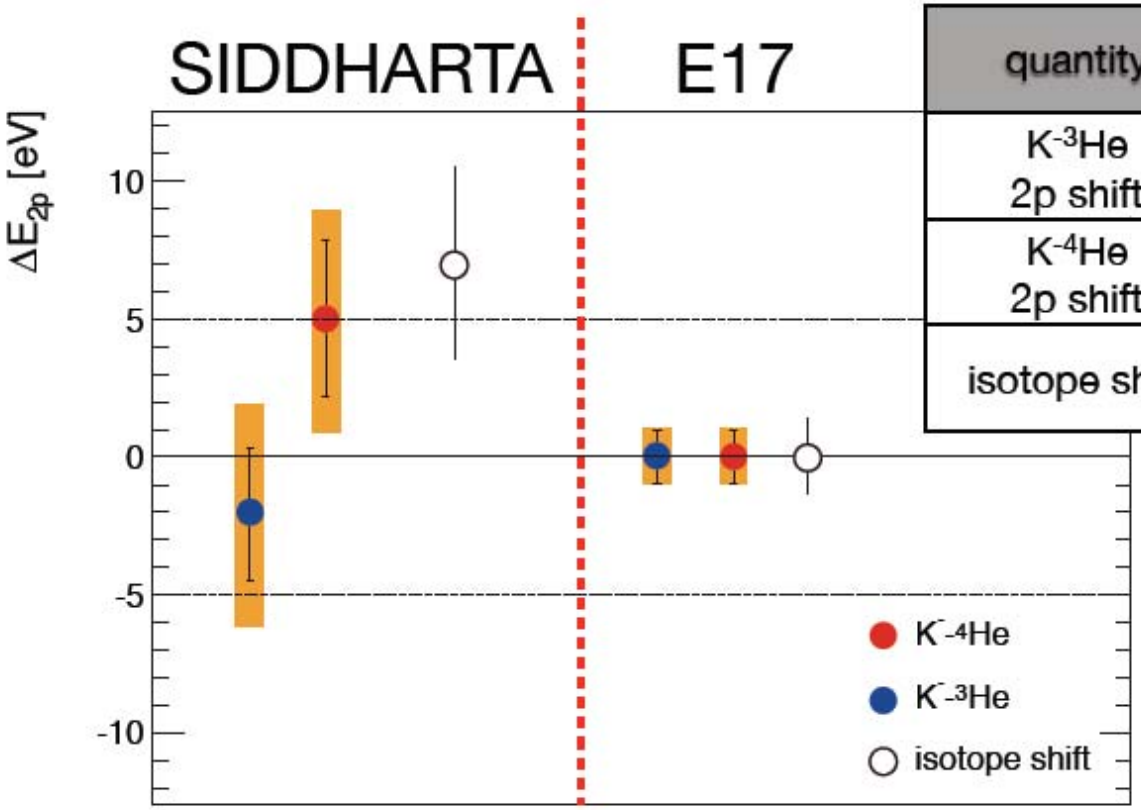
A shift of more than 1 eV??
Possible isotope shift!?
→ Gold of J-PARC E17



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

Outlook

The (slightly) modified E17 goals



quantity	Uncertainty (eV)
$K^-{}^3He$ 2p shift	± 1 (stat.)
$K^-{}^4He$ 2p shift	± 1 (stat.)
isotope shift	± 1.5 (stat.)

PAC, J-PARC, by Hayano

Strong-interaction width

"Old experiments"

	Γ_{2p} (eV)
Wiegand (71)	–
Batty (79)	30 ± 30
Baird (83)	100 ± 40
Average	55 ± 34

E570 preliminary results

The fitted width was

$$\Gamma_{2p} = 6 \pm 5 \text{ (stat)} \; {}^{+4}_{-5} \text{ (syst) eV.}$$

An upper limit of the width was determined to be

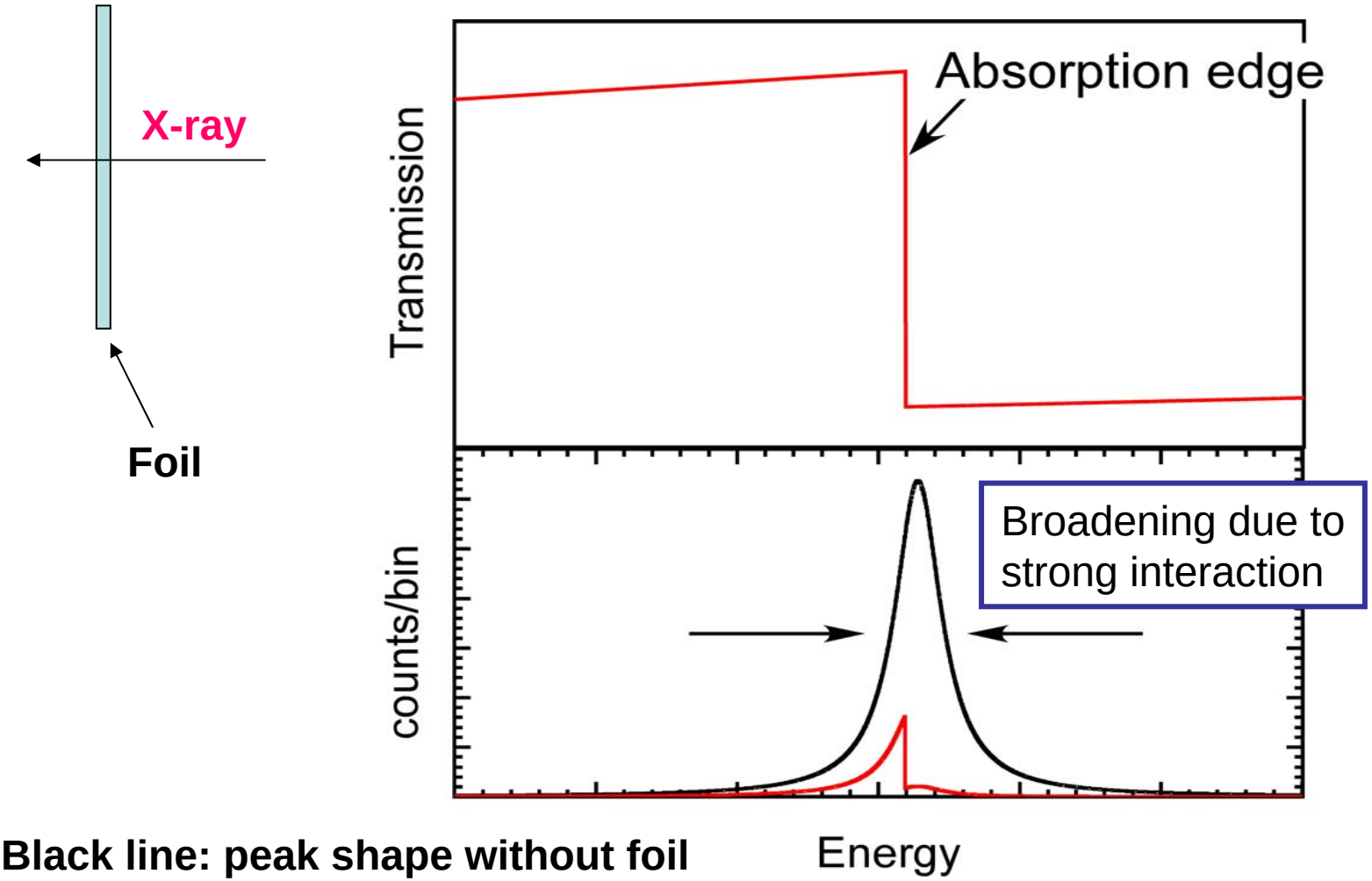
$$\Gamma_{2p} \leq 17 \text{ eV } 95\% \text{ confidence level}$$

SIDDHARTA results:

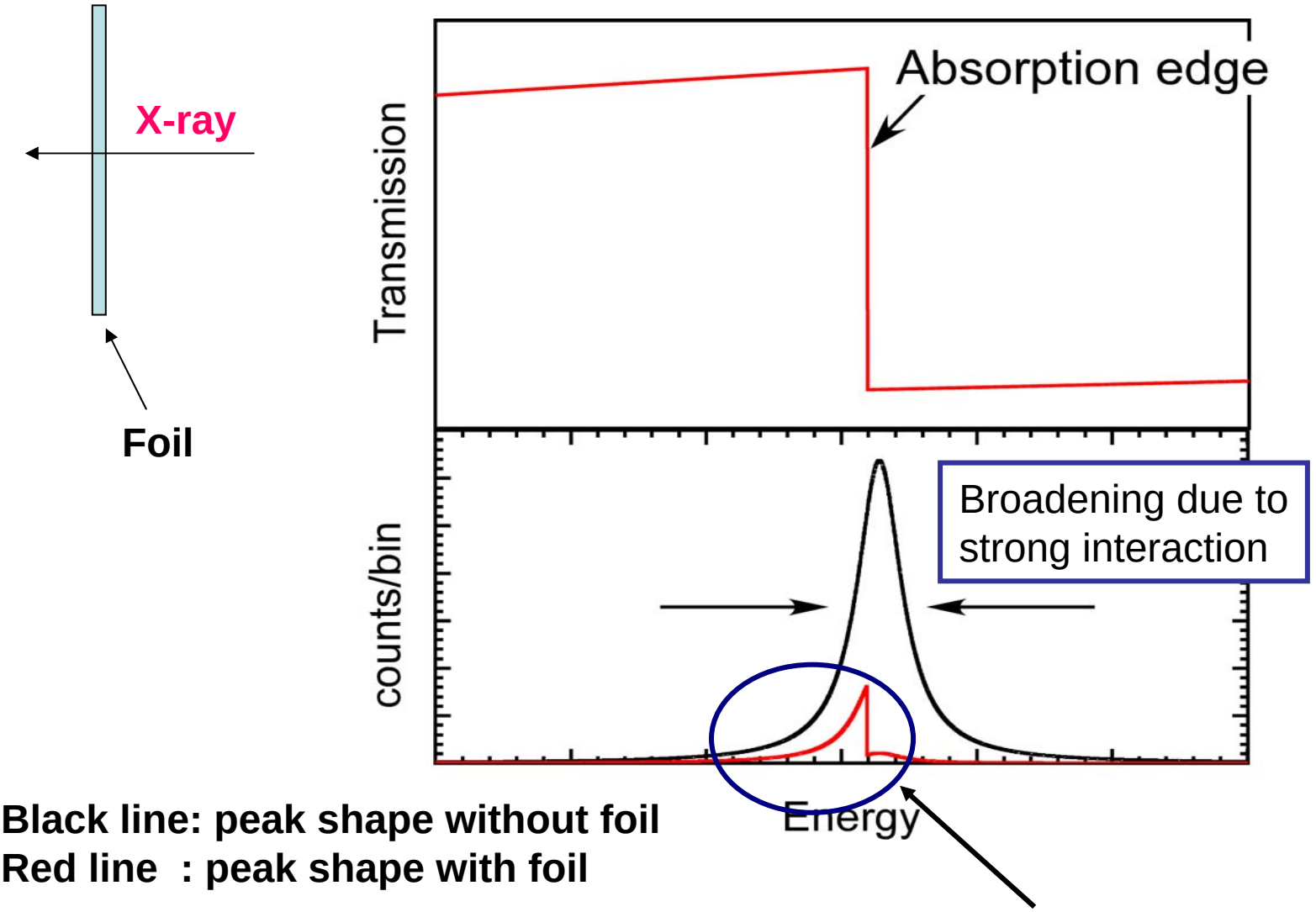
Under detection limits
Precise values under study

Width is much smaller than the detector resolutions
→Need much better X-ray detector
→Or other technique !?

c.f.
SDD resolution
~ 150 eV at 6 keV

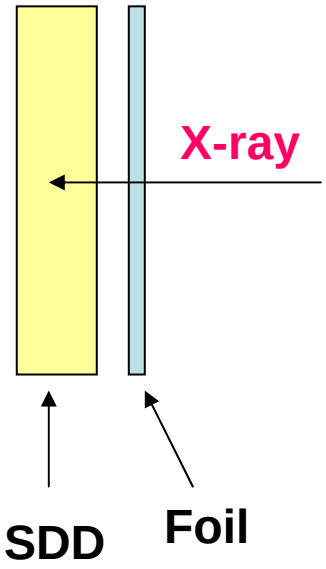


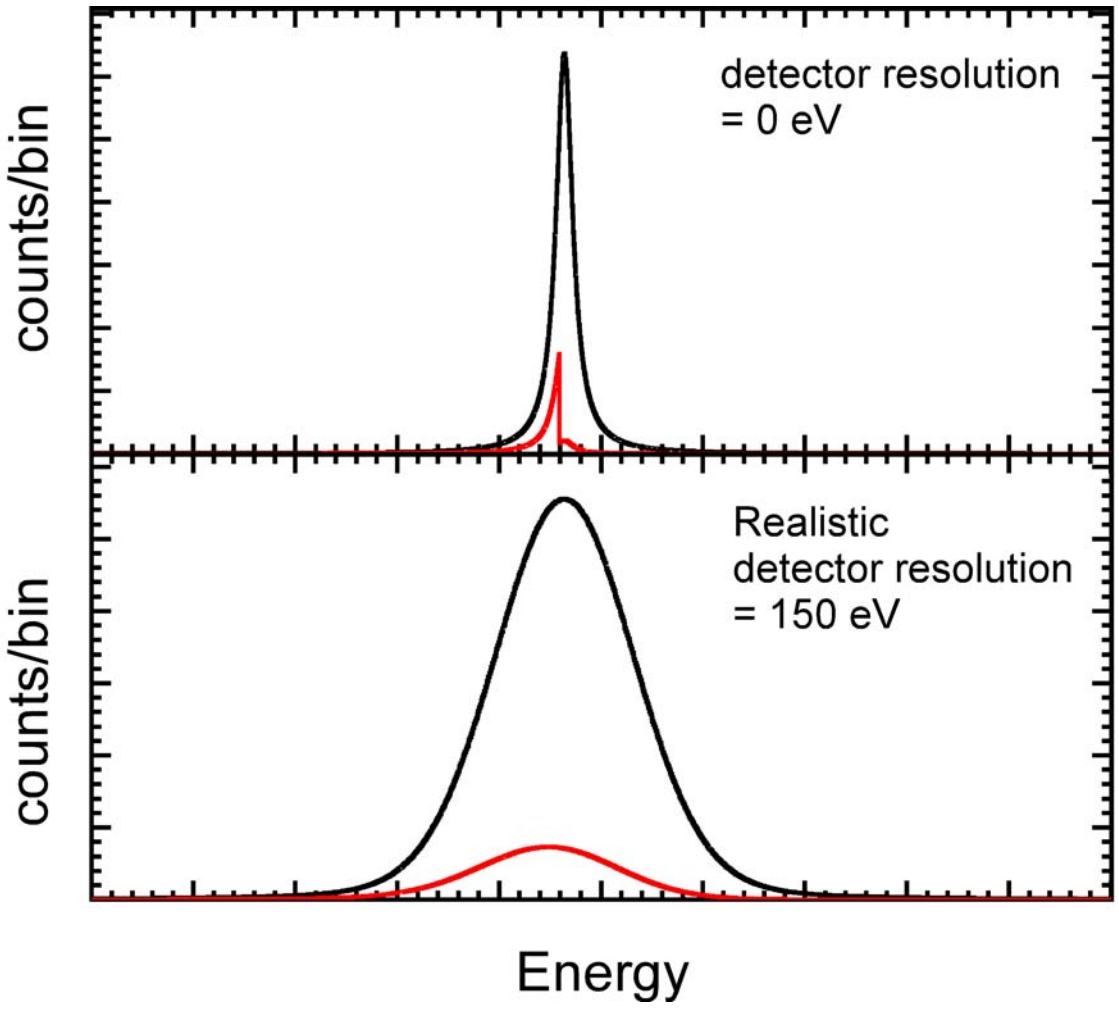
Black line: peak shape without foil
Red line : peak shape with foil



Black line: peak shape without foil
Red line : peak shape with foil

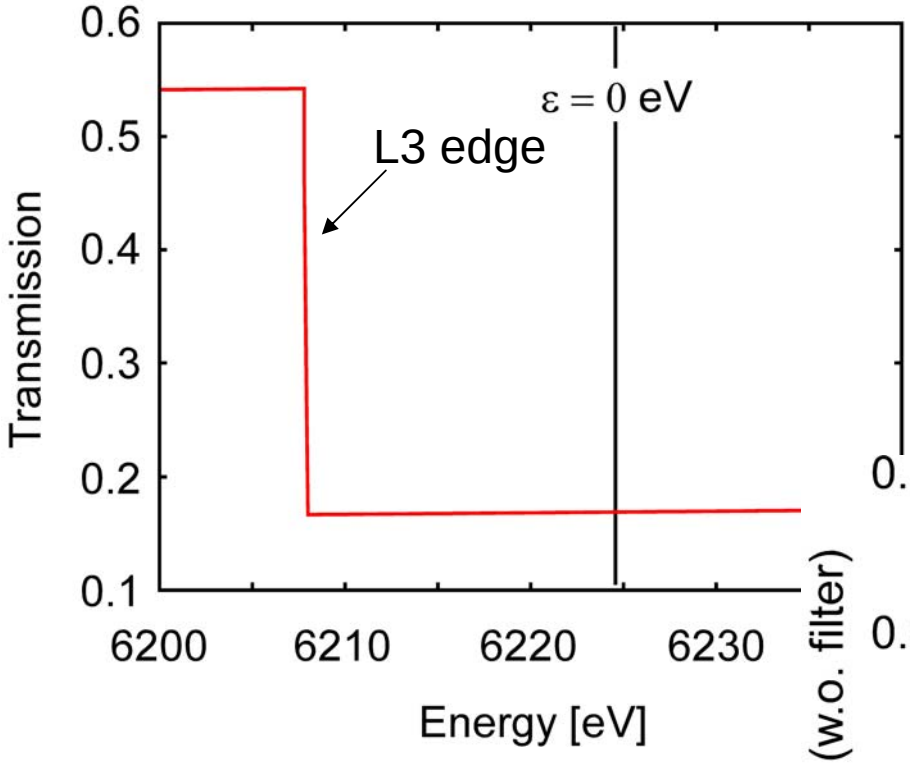
No. of events is related to shift & width





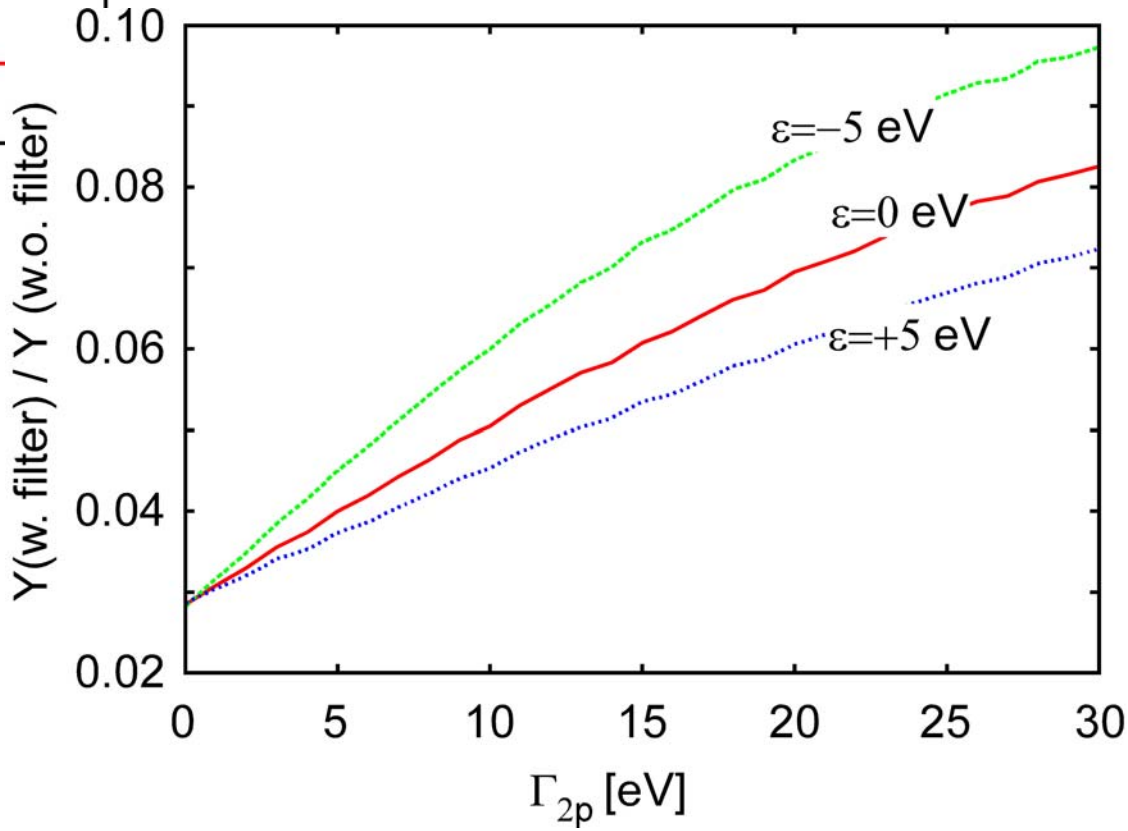
X-ray attenuation → Strong interaction width

X-ray transmission vs Width



K-He3 case,
Neodymium foil

Filter: 10-micron Nd



Summary

- K-3He and 4He X-rays were measured in SIDDHATRA
- First measurement in gas targets
- First observation of kaonic 3He,

  prior to J-PARC E17
- Both shifts: as small as a few eV

	Shift [eV]	Reference
K-He4 (with 55Fe)	+0±6±2	PLB681(2009)310
K-He4	+5±3±4	arXiv:1010.4631, PLB697(2011)199
K-He3	-2±2±4	

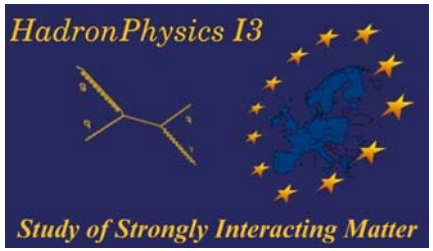
Outlook

- Isotope shift between He3& He4??
- Determination of width
- Determination of X-ray yields between gas &liquid
- Measurements of kaonic He 1s shifts?

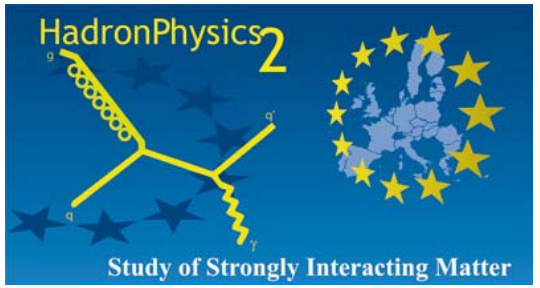
(Estimated shift: ~ 6 keV, width: ~5 keV, yield~0.05%)

	Shift [eV]	**Reference**
K-He4 (with 55Fe)	**+0±6±2**	**PLB681(2009)310**
K-He4	**+5±3±4**	**arXiv:1010.4631, PLB697(2011)199**
K-He3	**-2±2±4**	

Supported by



HadronPhysics I3 FP6 European Community program: Contract No. RII3-CT-2004-506078



European Community Research Infrastructure Integrating Activity "Study of Strongly Interacting Matter" (HadronPhysics2, Grant Agreement No. 227431) under the Seventh Framework Programme of EU

BMWF

Austrian Federal Ministry of Science and Research BMBWK [650962/0001 VI/2/2009]

ANCS
Autoritatea Nationala pentru Cercetare Stiintifica

Romanian National Authority for Scientific Research [2-CeX 06-11-11/2006]

JSPS
Grants-in-Aid for Scientific Research
< KAKENHI >

Grant-in-Aid for Specially Promoted Research (20002003), MEXT, Japan

FWF

Austrian Science Fund (FWF): [P20651-N20]

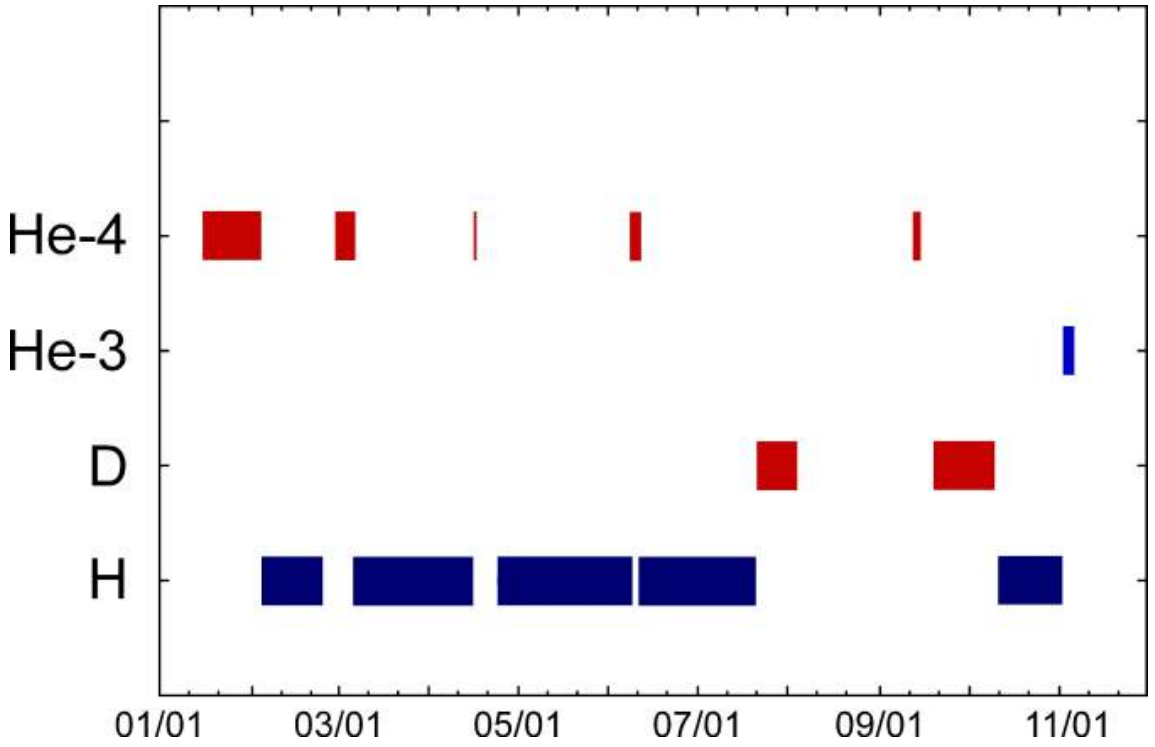
Experimental results before SIDDHARTA

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

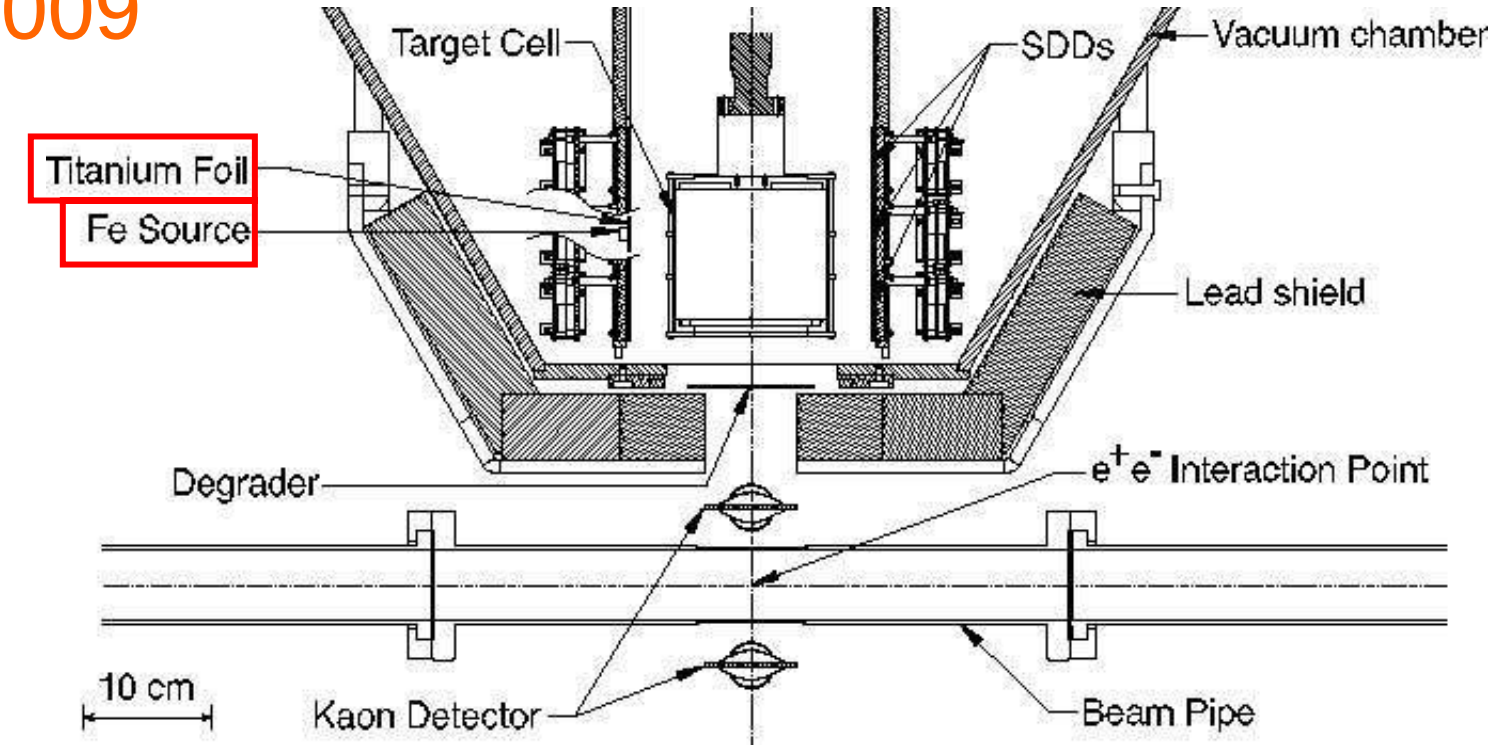
Data taking periods of SIDDHARTA in 2009



	Reference
He4 with 55Fe	**PLB681(2009)310**
He4	**arXiv:1010.4631, PLB697(2011)199**
He3	
H	**arXiv:1105.3090**

Kaonic He-4 X-rays at SIDDHARTA

2009

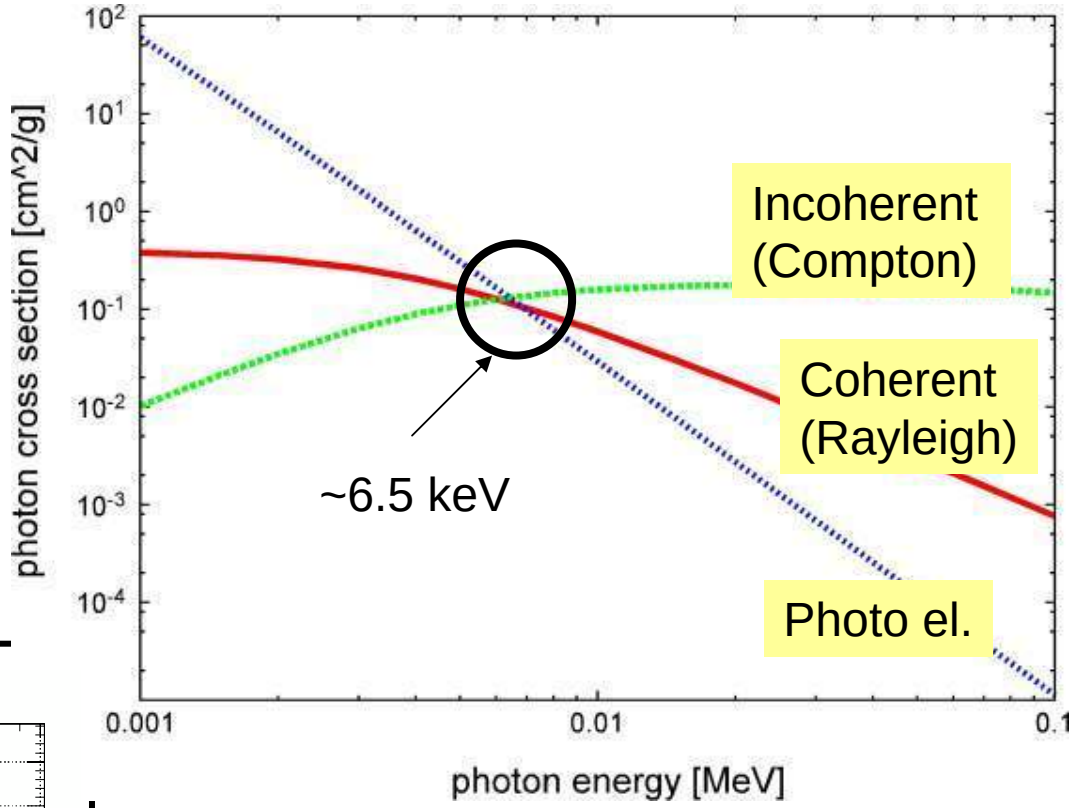


10 bar at NTP

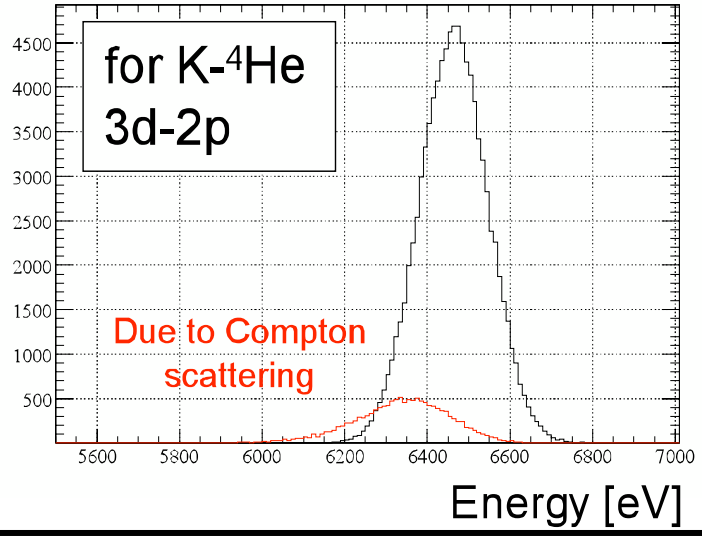
First measurement with gas target

precise calibration:
4.5 keV & 5.9 keV X-rays
as in-beam calibration lines

Photon cross section in helium



Liquid He (E570)



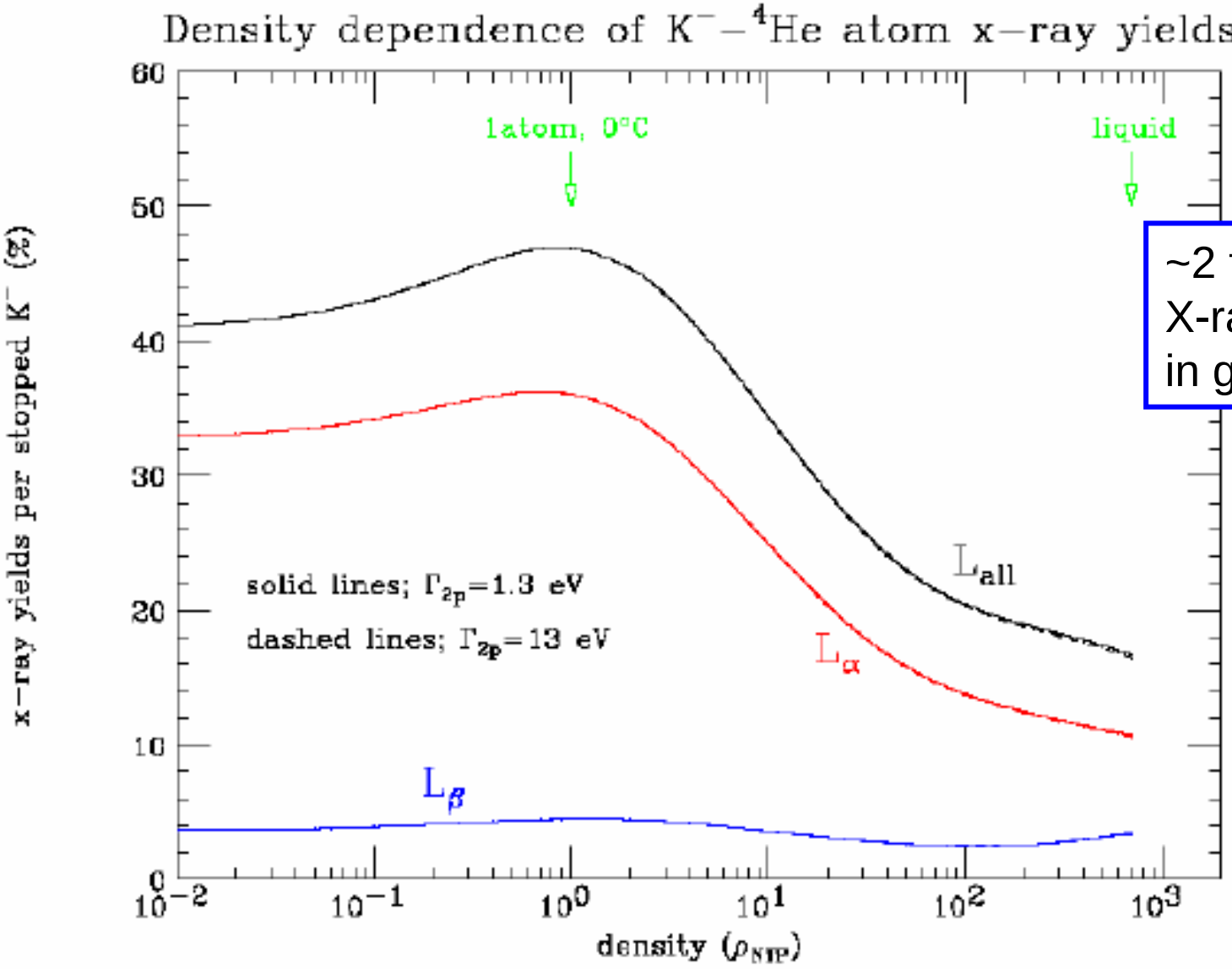
10% of X-rays in Liq. He (E570)
→ 10 eV peak shift (if Compton neglected)

0.1 % of X-rays in 10 bar He (SIDDHARTA)
→0.1 eV peak shift (if Compton neglected)

Expected X-ray yields in helium gas

Y. Akaishi (EXA05 Presentation)

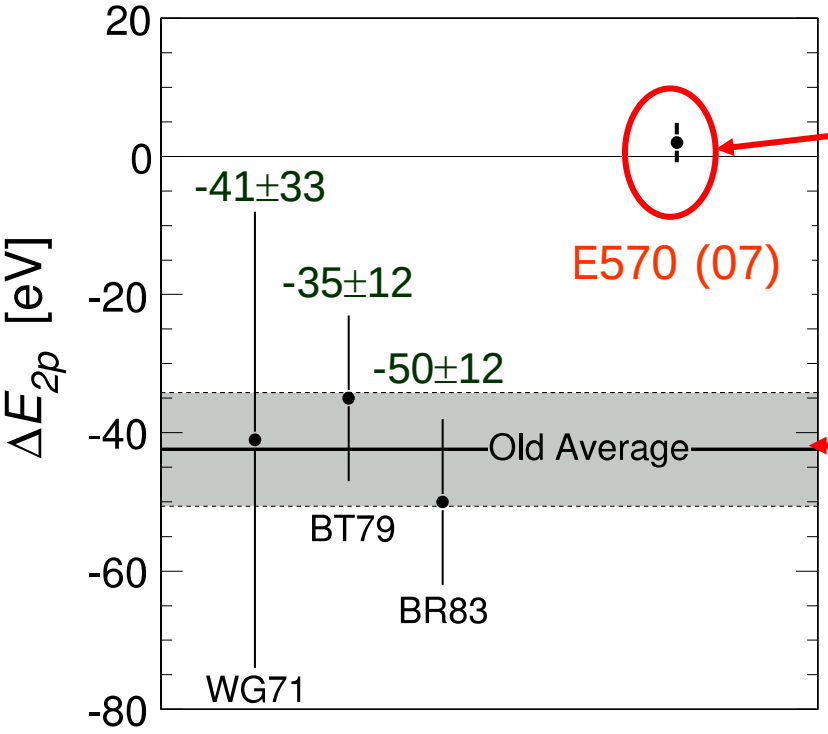
Calculated by T. Koike



~2 times larger
X-ray yields
in gas than in liquid

Need to check!

Experimental results since 1971



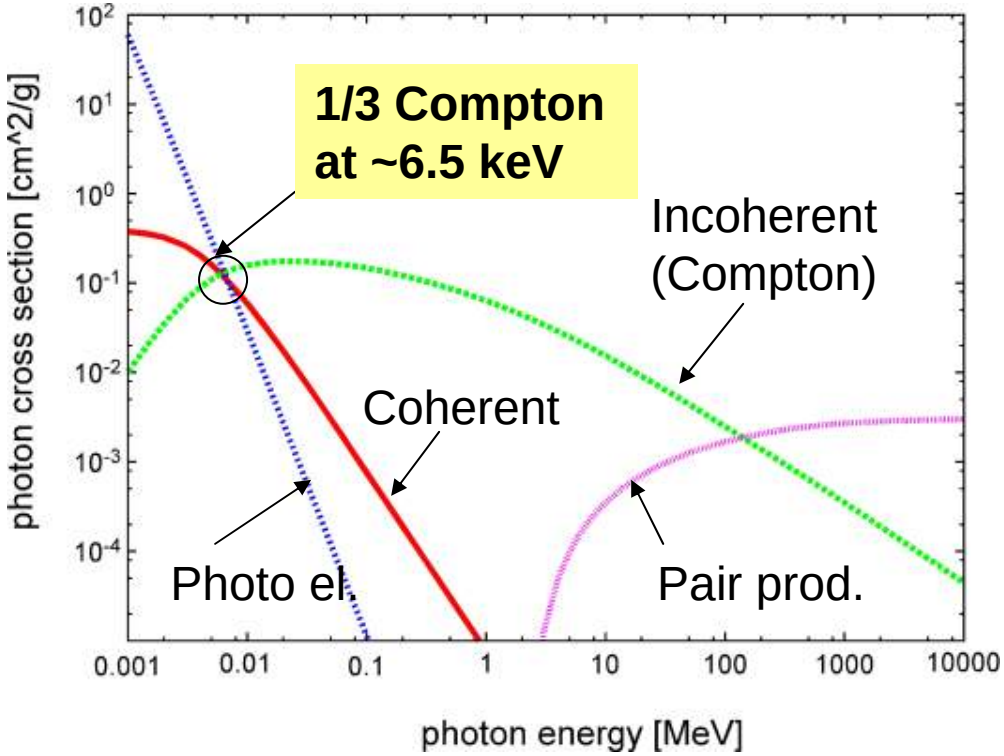
E570 results ('07)

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

Disagree!

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

All the experiments used liquid helium targets.
→ Compton scattering in He

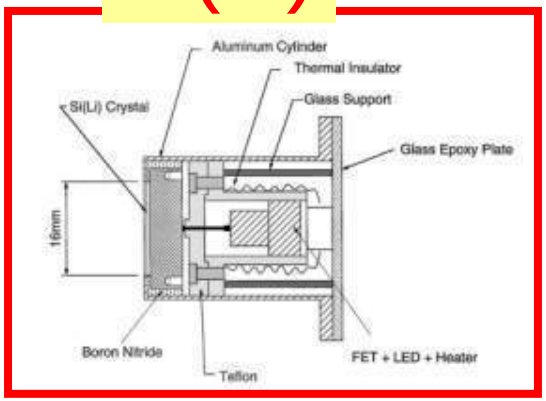


Comparison of X-ray detectors

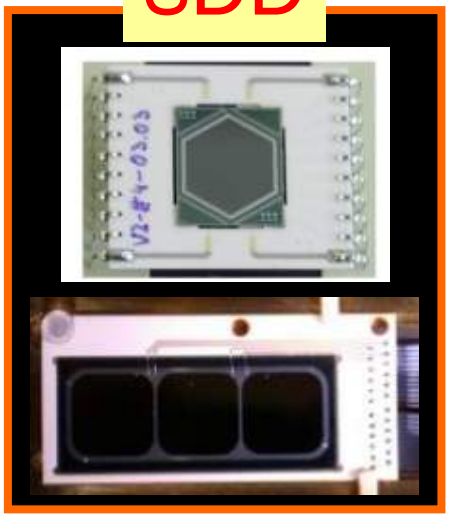
Good time resolution

Good energy resolution

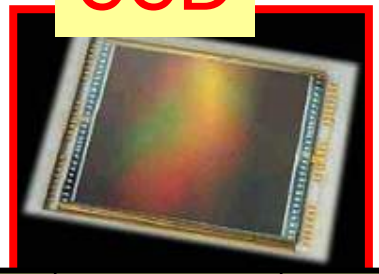
Si(Li)



SDD

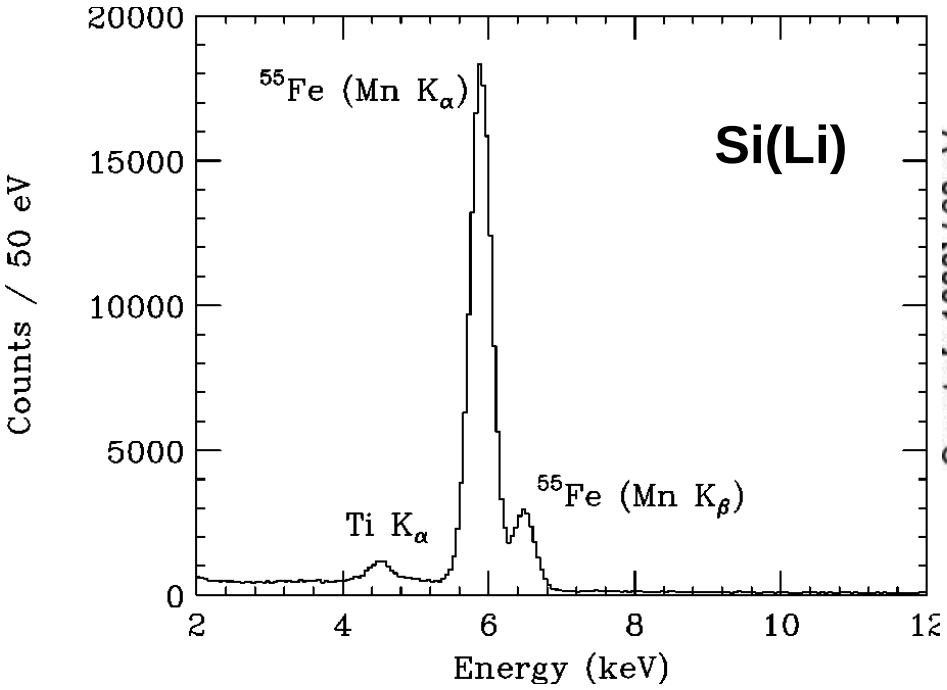


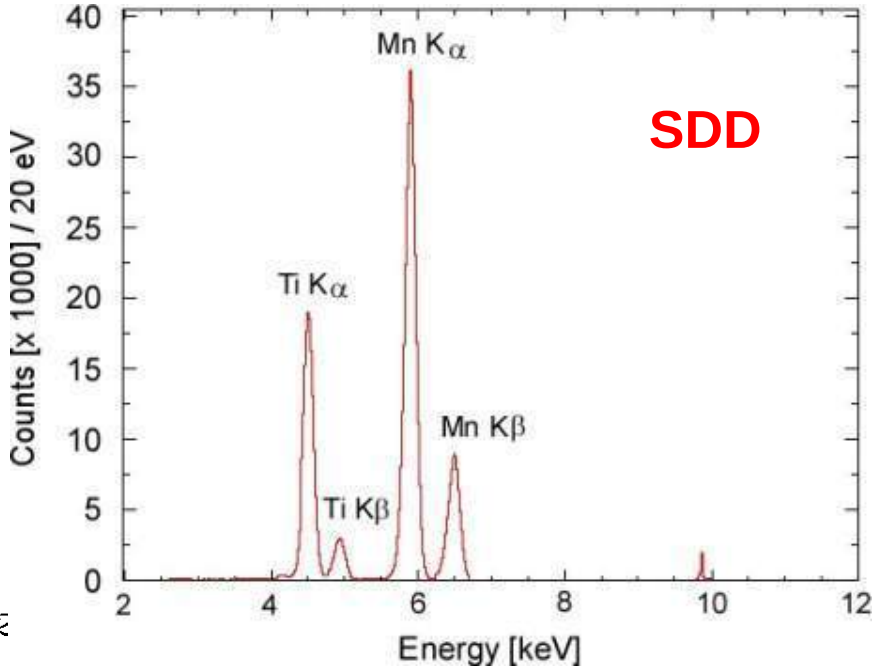
CCD

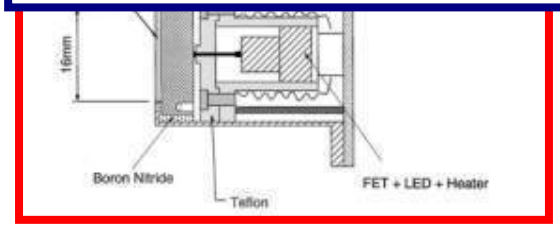


experiment		KpX	DEAR	E570
Detector		Si(Li)	CCD	SDD
Area	[mm2]	200	724	100
Thickness	[mm]	5	0.03	0.26
Δ E (FWHM)	[eV]	410	170	185
Δ t (FWHM)	[ns]	290	-	430

T.Ishiwatari,
Hyp. Int. 194(09)165







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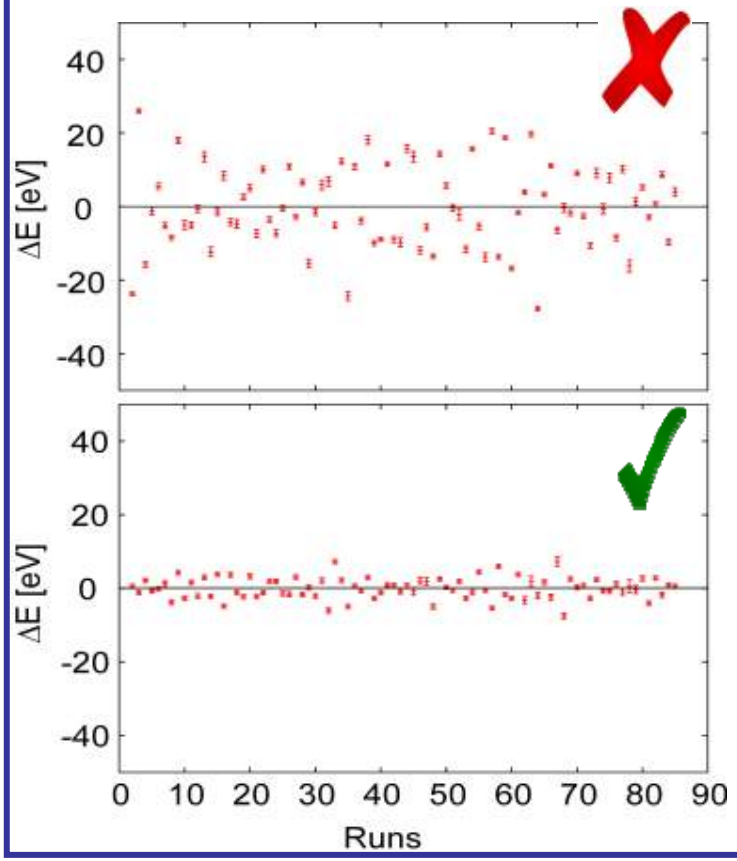
T.Ishiwatari,
Hyp. Int. 194(09)165

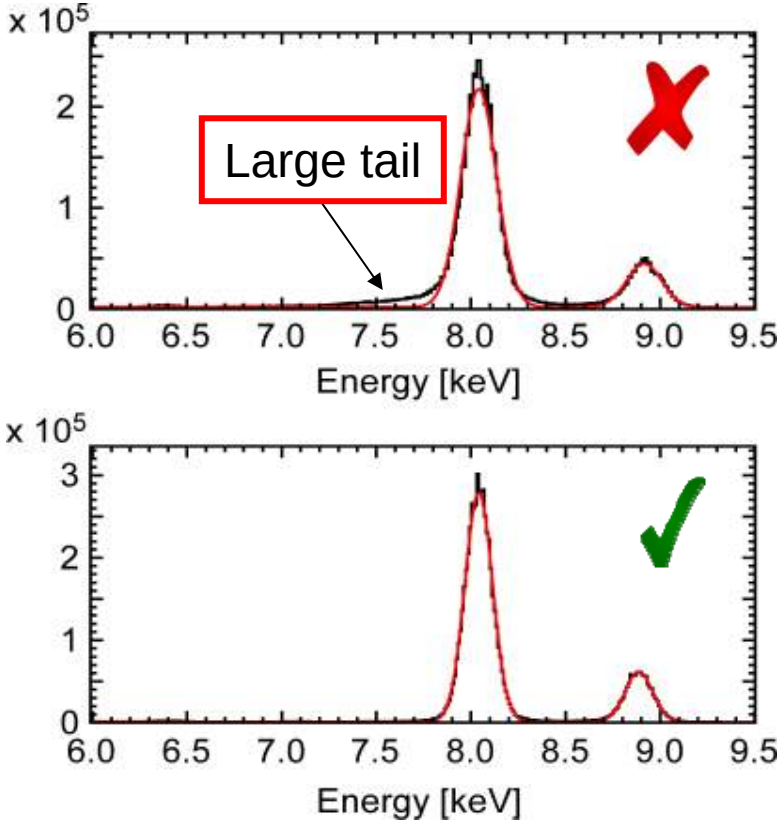
SDD selection

Analysis of "calibration" (X-ray tube) data

Stability of peak position



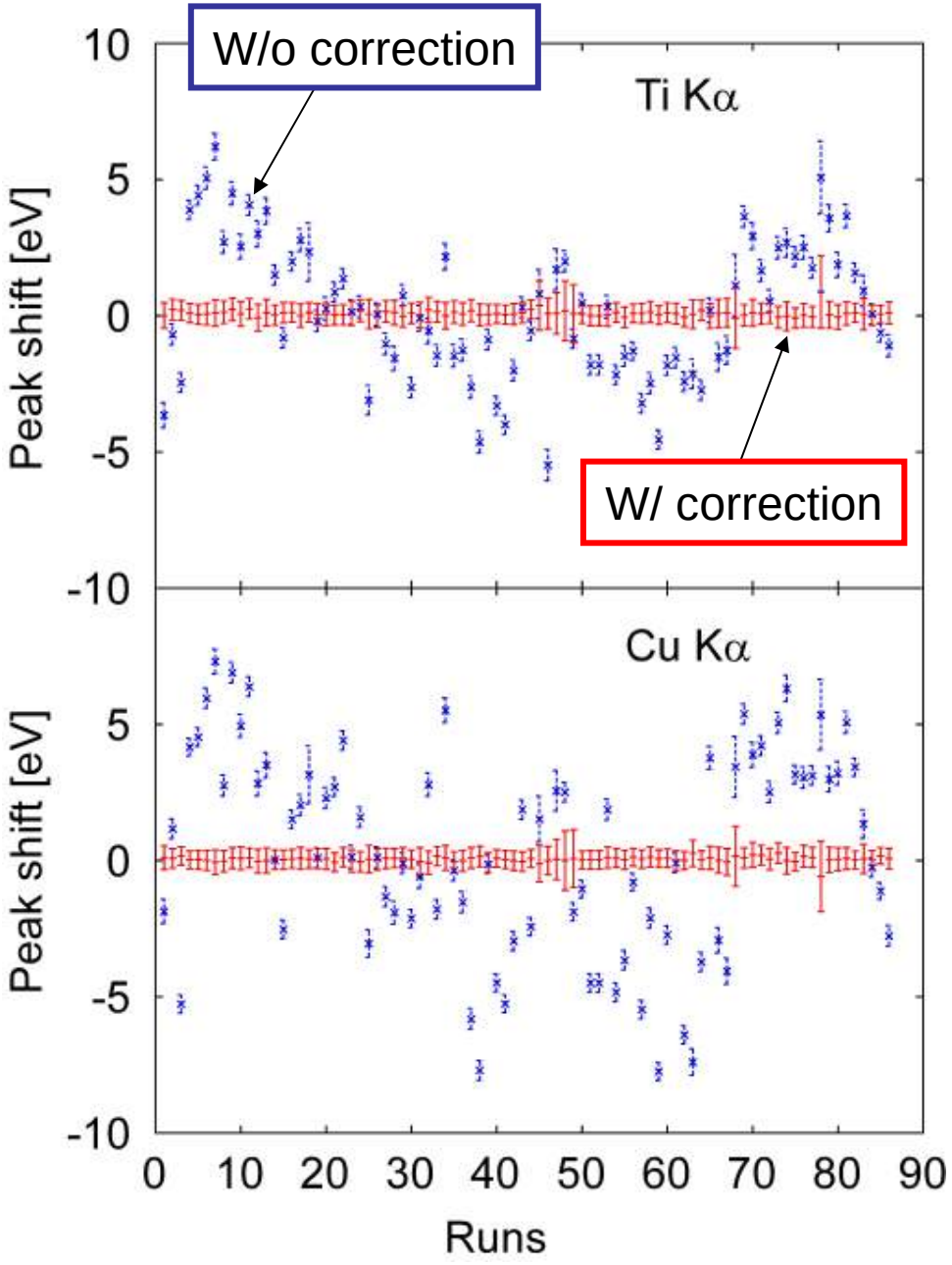
X-ray peak shape



Selection of Good SDDs,
in terms of energy resolution, peak shape, stability

92 SDDs out of 144 SDDs installed

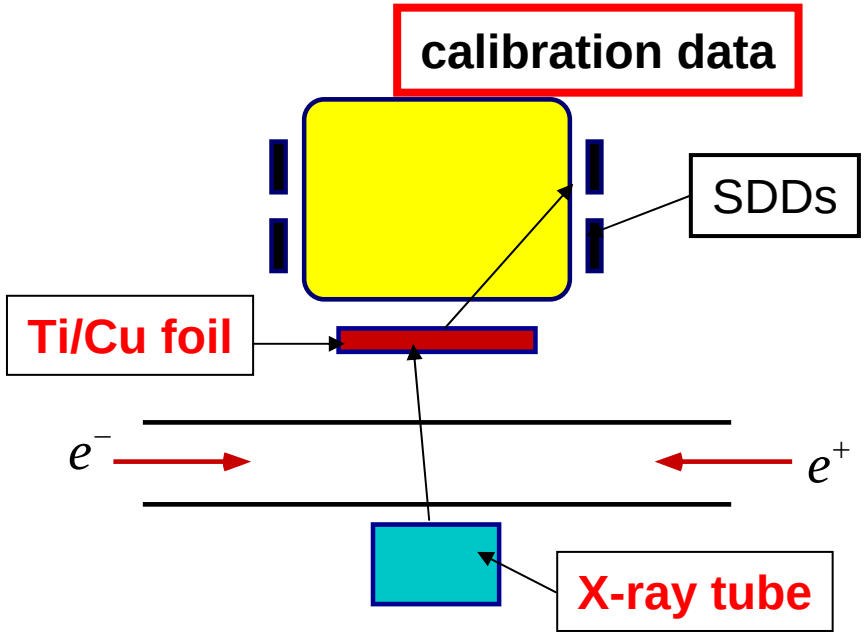
Correction of temporal fluctuations



Ti/Cu peak pos. vs time in a typical SDD

Fluctuation: Typically ~ +/- 5 eV

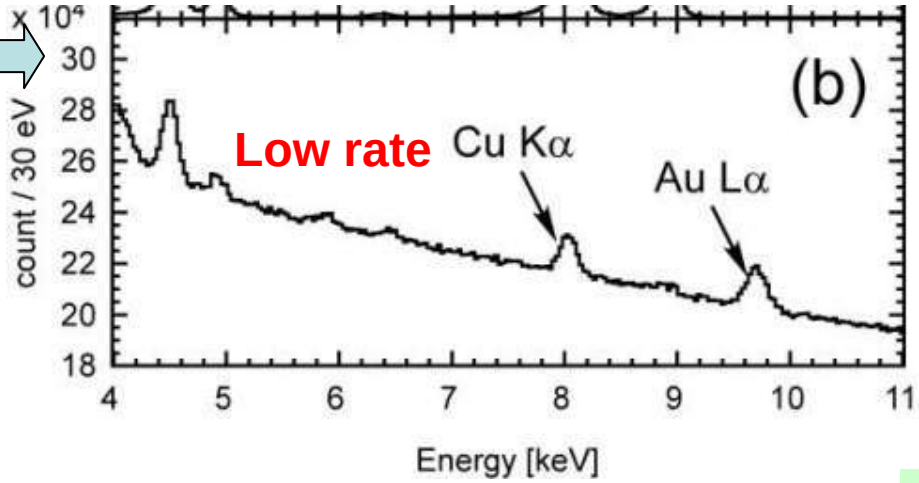
Fluctuation Corrected



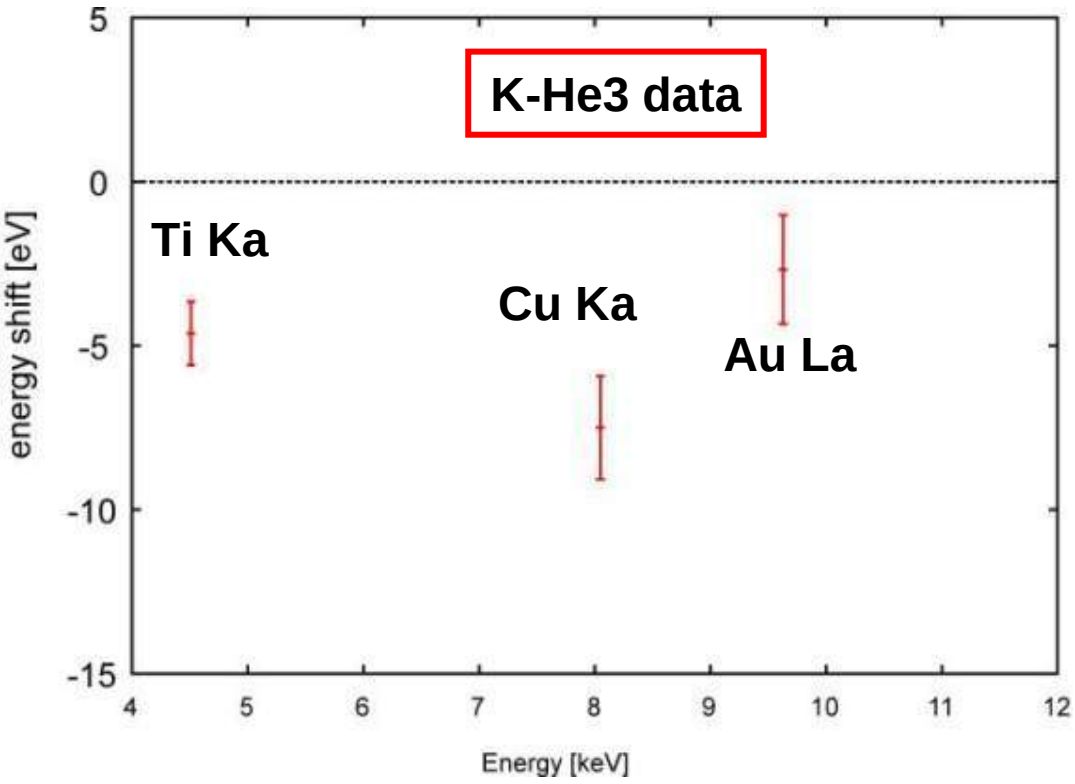
Production data

Not correlated to Kaon signals

SDD X-ray energy spectra



(Fit value) – (Ref.)



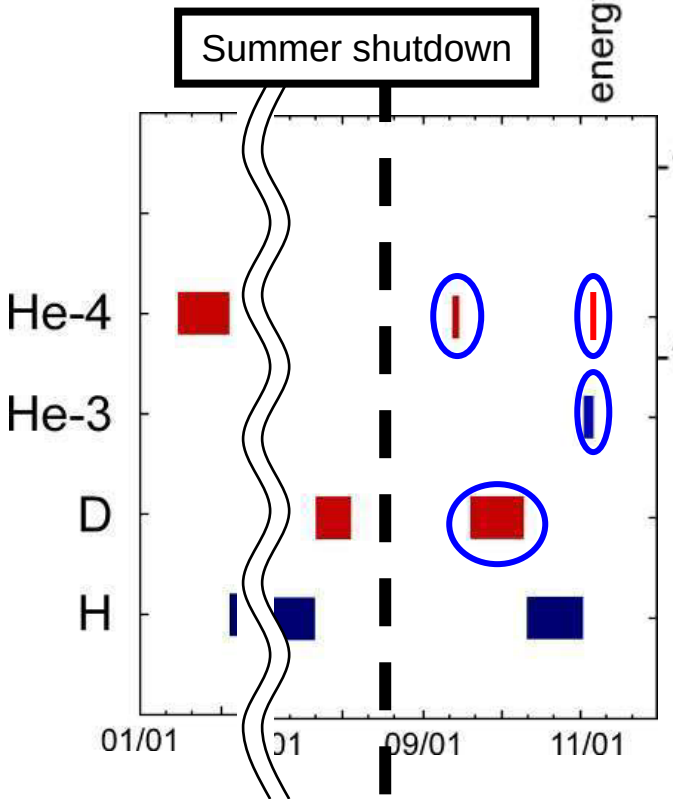
Ti/Cu/Au lines: compared to the reference values

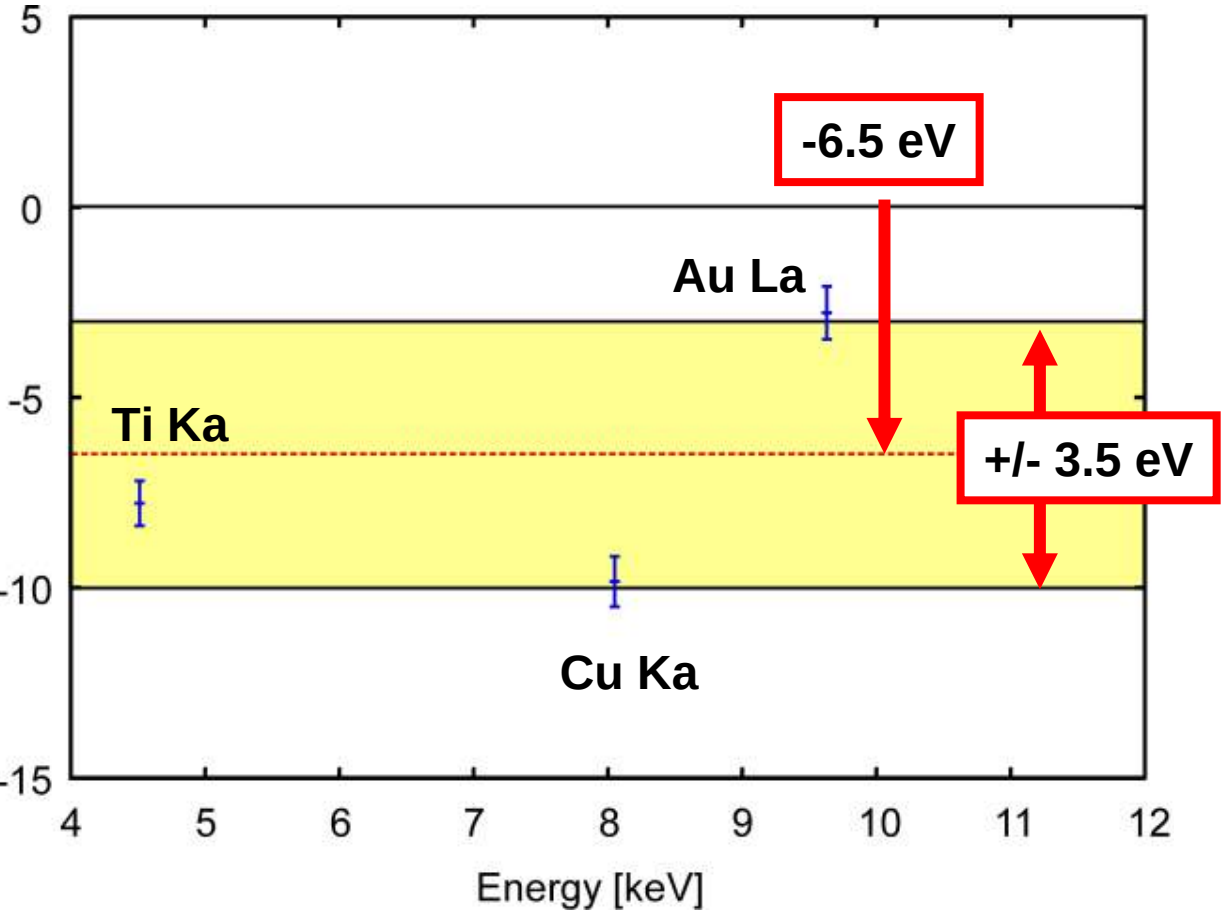
Average: shifted to lower
Systematic fluctuation??

Data analysis of other target

Evaluation of systematic error

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



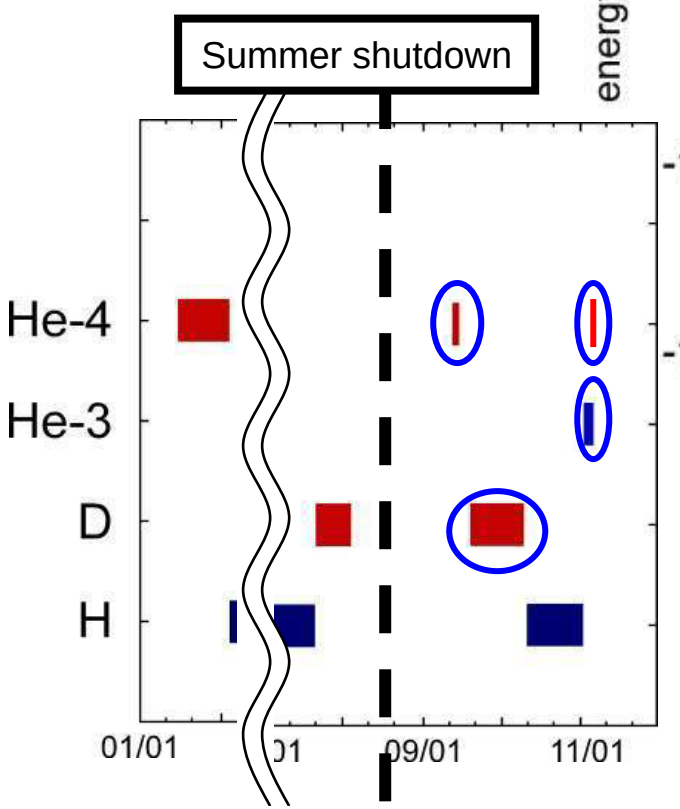


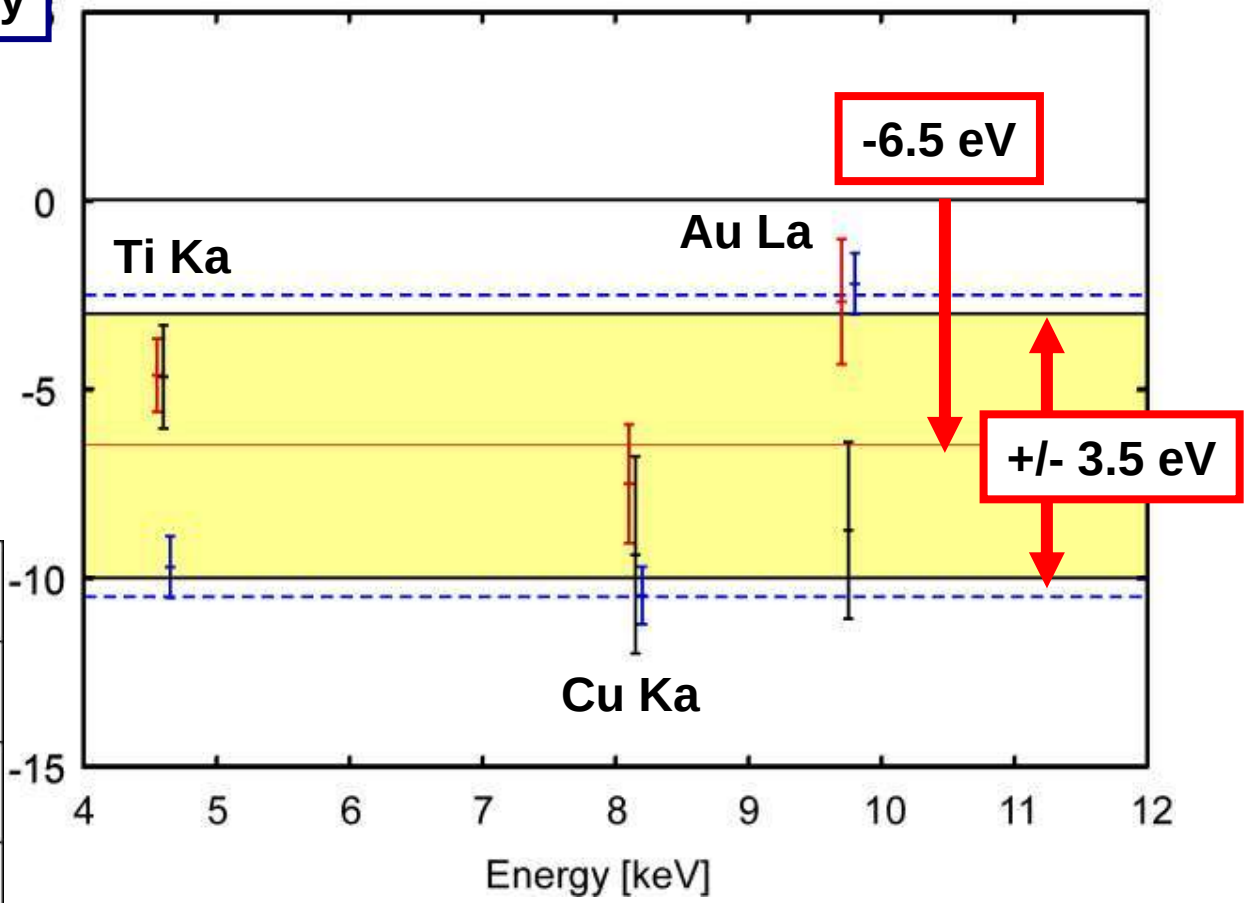
- **Peak shift: - 6.5 eV**
- **Accuracy of energy determination: +/- 3.5 eV**

Evaluation of systematic error

Time (or target) dependency

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

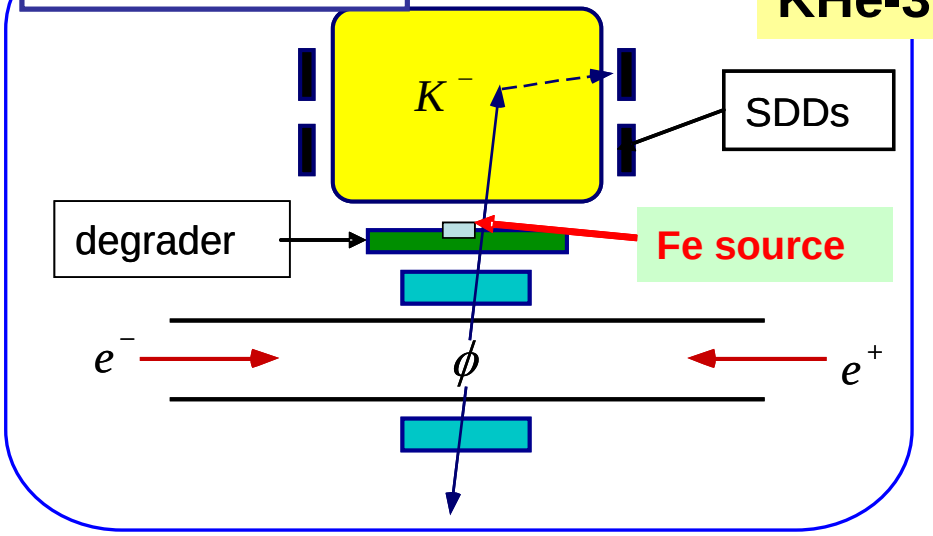




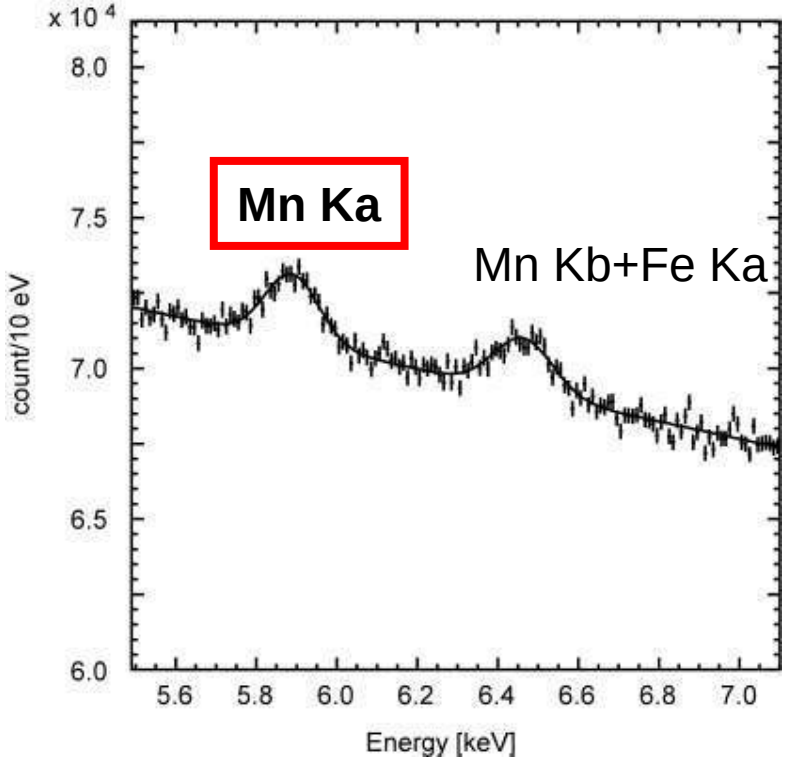
- **Peak shift: - 6.5 eV**
- **Accuracy of energy determination: +/- 3.5 eV**

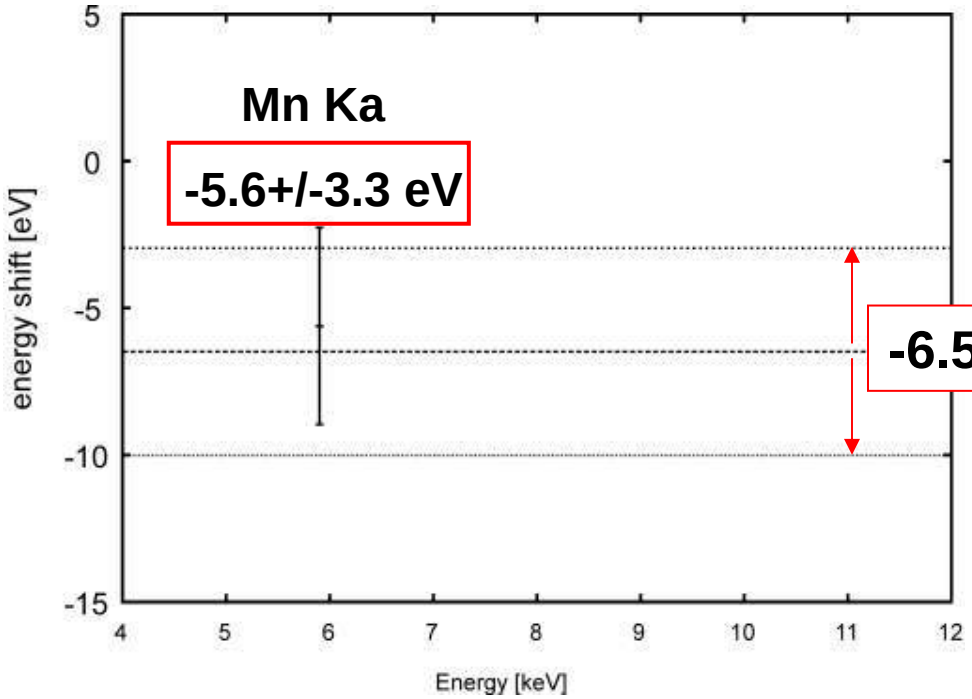
Evaluation of systematic error

Production data



KHe-3 data with Fe source





With correction, Mn position

$$\Delta E_{Mn} = +0.9 \pm 3.3(stat) \pm 3.5(syst)\,\mathrm{eV}$$

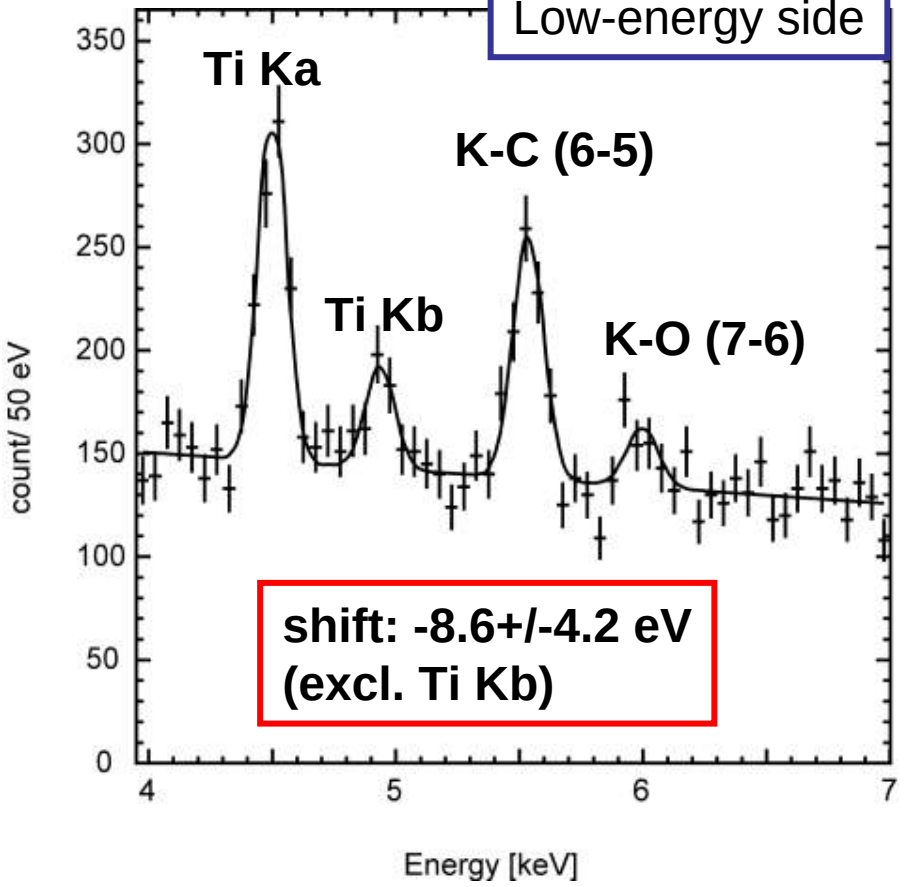
Evaluation of systematic error

“kaon-coincidence” with K-d data

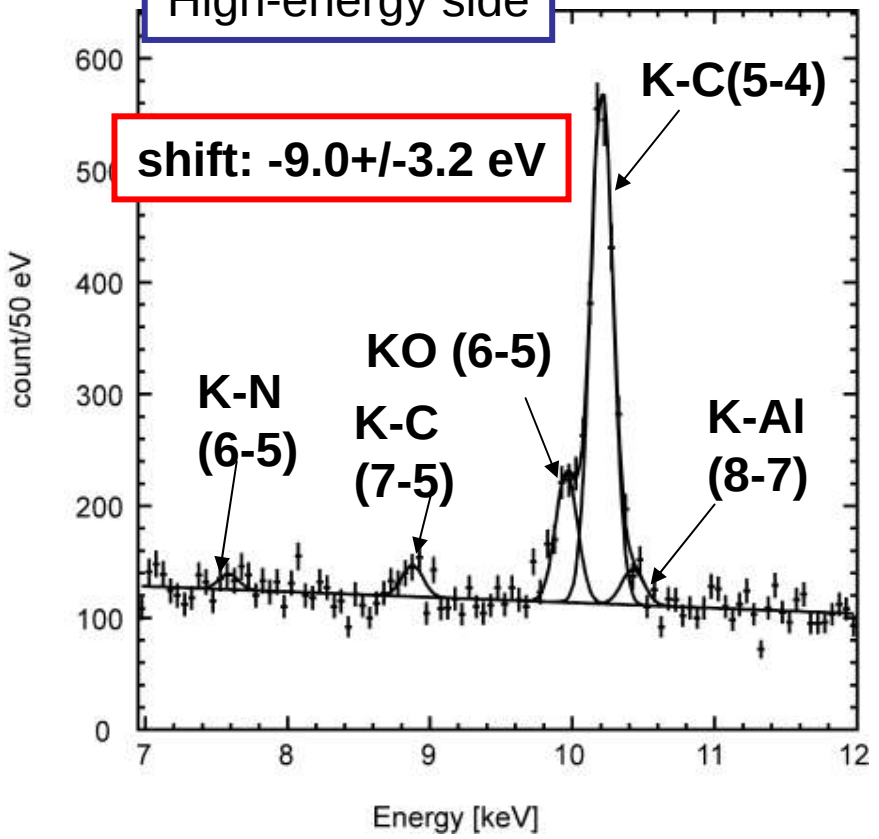
Kapton window (C22H10N2O5)

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

Low-energy side

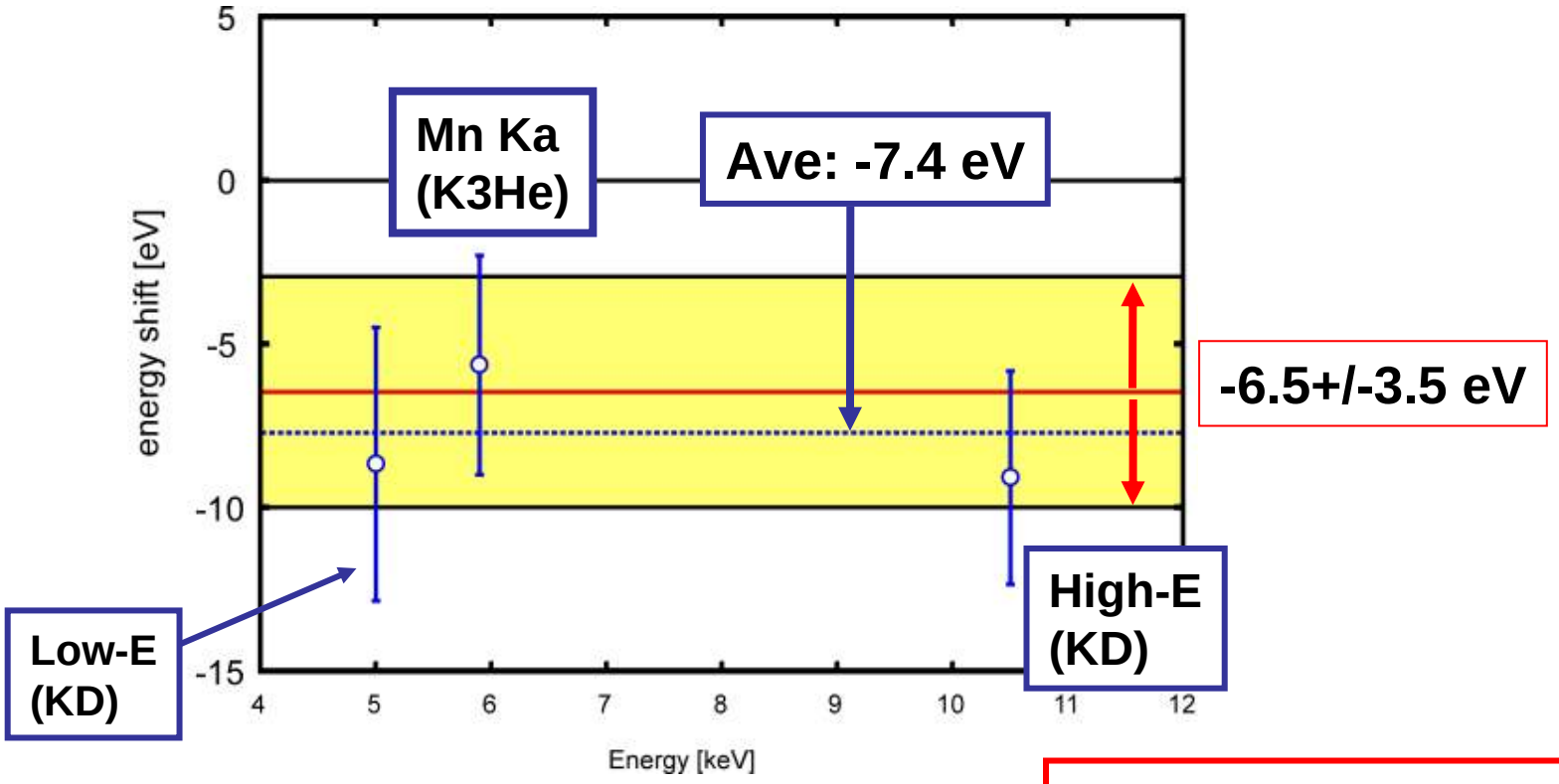


High-energy side



Evaluation of systematic error

confirmation of the accuracy of energy determination & peak shift



Average of three points: consistent with the systematic error band

To obtain absolute energy from a fit value,

$$E_{\mathrm{exp}} = E_{\mathrm{fit}} + \varepsilon$$

$$\varepsilon = +6.5 \pm 3.5\ \mathrm{eV}$$

Comparison of results

PLB653(2007)387

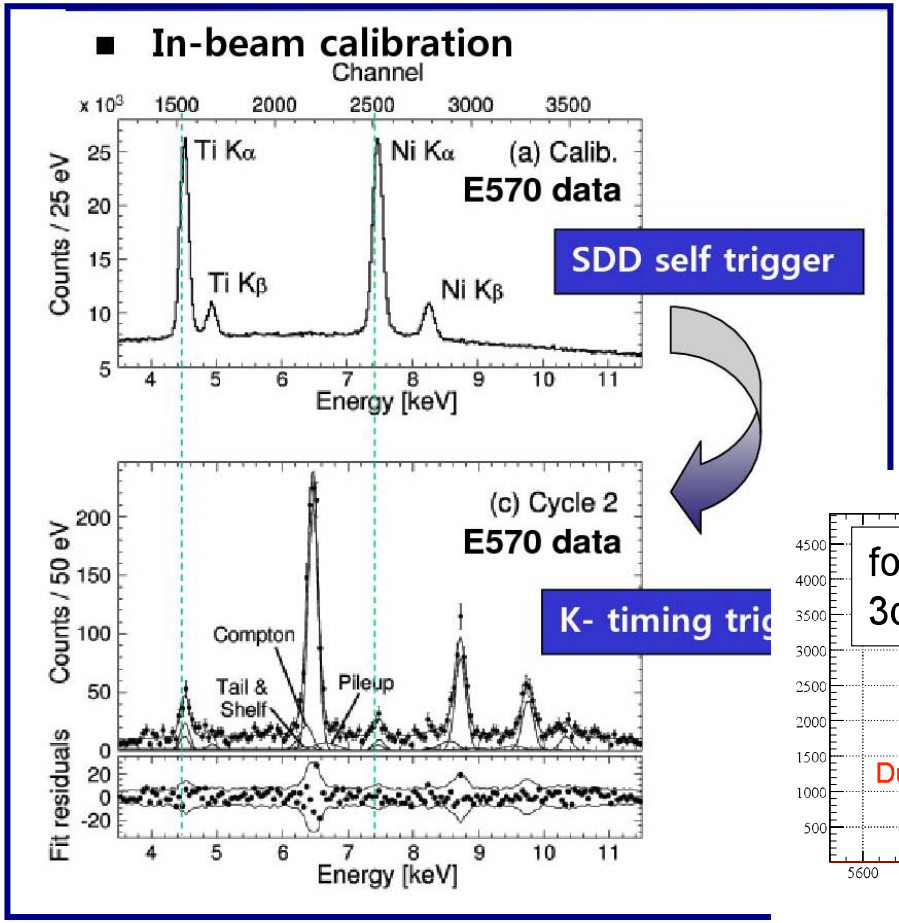
Kaonic 4He 2p level shift

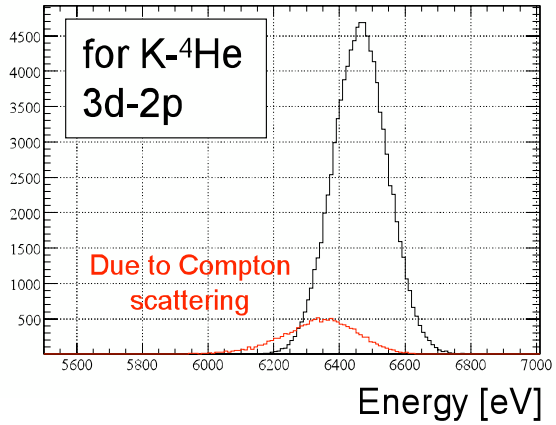
	Target	Shift [eV]
KEK E570	Liquid	+2±2±2 eV

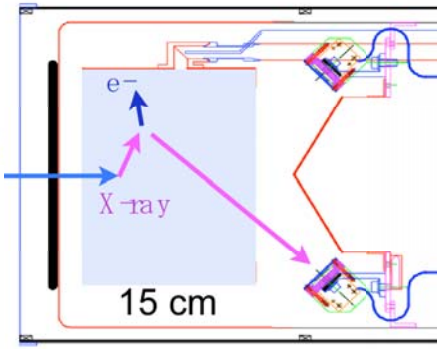
1. calibration/ and peak shape from Ti (4.5 keV) and Cu (8.0 keV). Apply for K-4He (6.4 keV)
2. Simulation of Compton tail using measured kaon stopping distribution.

Sys err = uncertainty of above

Sato, ECT* Workshop 2009







Comparison of results

PLB681(2009)310

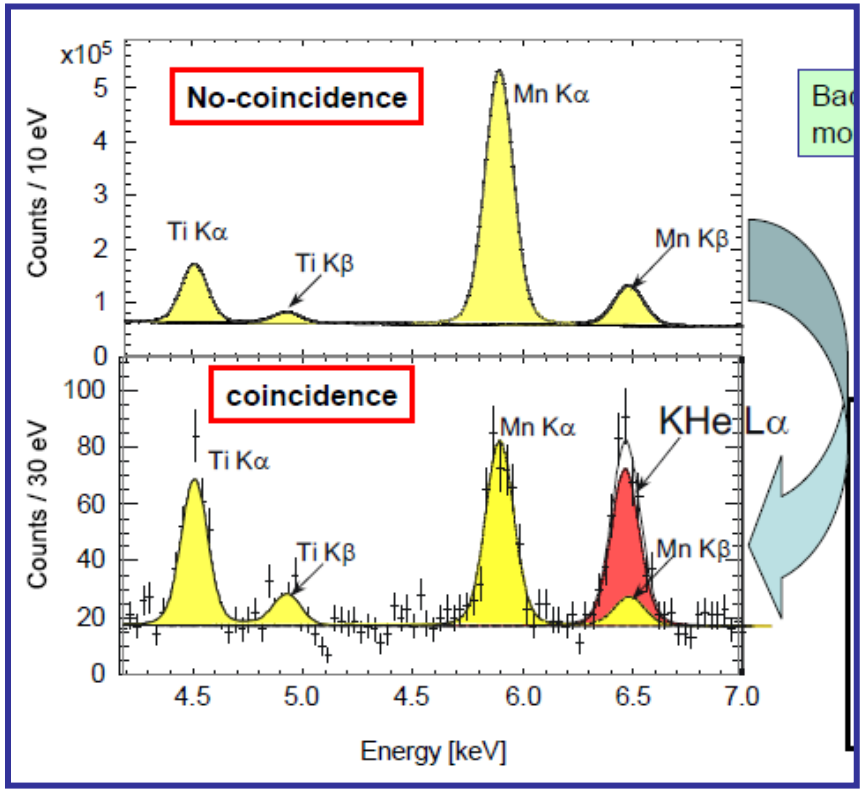
Kaonic 4He 2p level shift

	Target	Shift [eV]
SIDDHARTA (Test)	**Gas**	**+0±6±2 eV**

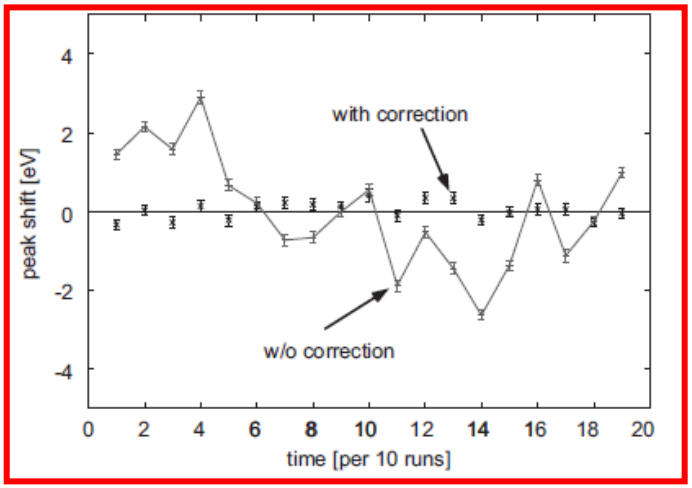
1. Calibration and peak shape from Mn (5.9 keV)

Sys err = energy non-linearity, uncertainty of corrections of temporal fluctuation & rate dependency

Ishiwatari, ECT* Workshop 2009



NIM A 628(2011)264



Comparison of results

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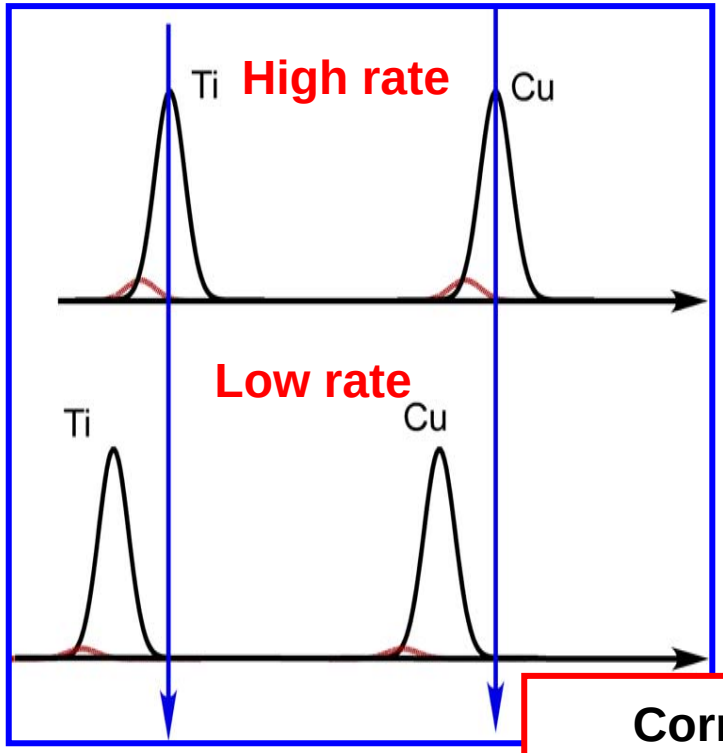
	Target	Shift [eV]
SIDDHARTA (He-4)	Gas	+5±3±4 eV
SIDDHARTA (He-3)	Gas	-2±2±4 eV



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

Kaonic 4He 2p level shift

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

Kaonic 3He 2p level shift

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

shift $\Delta E_{2p} = E_{\exp} - E_{e.m.}$ $\quad \Delta E_{2p} > 0\,(\text{"attractive" } shift),$

$\Delta E_{2p} < 0\,(\text{"repulsive" } shift),$