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

T. Ishiwatari / SMI, Vienna

On behalf of

SIDDHARTA collaboration

PLB681(09)310

PLB697(11)199

13. 6, 2011, Hadron2011, Munich, Germany

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)

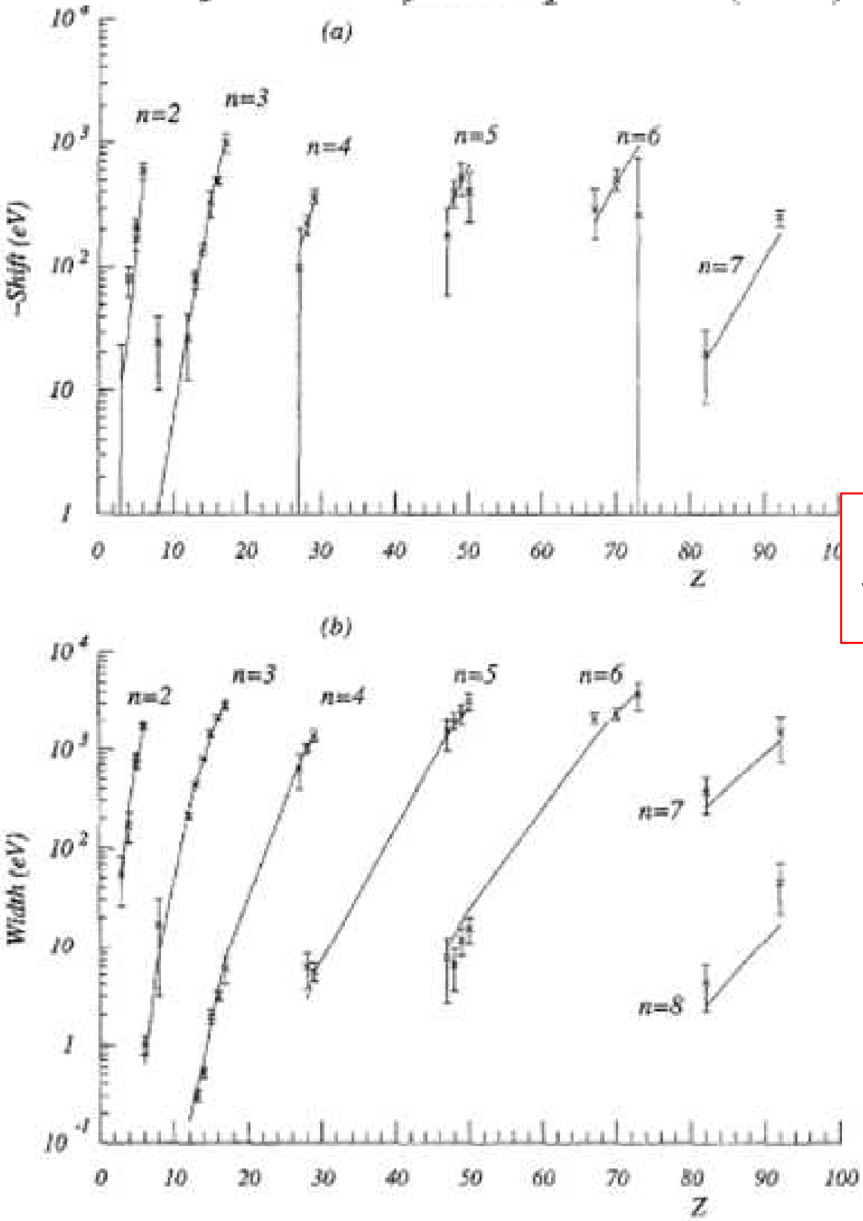
Recently performed experimental results: different from old data

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)

C.J. Batty et al. / Physics Reports 287 (1997) 385–445



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

Optical model

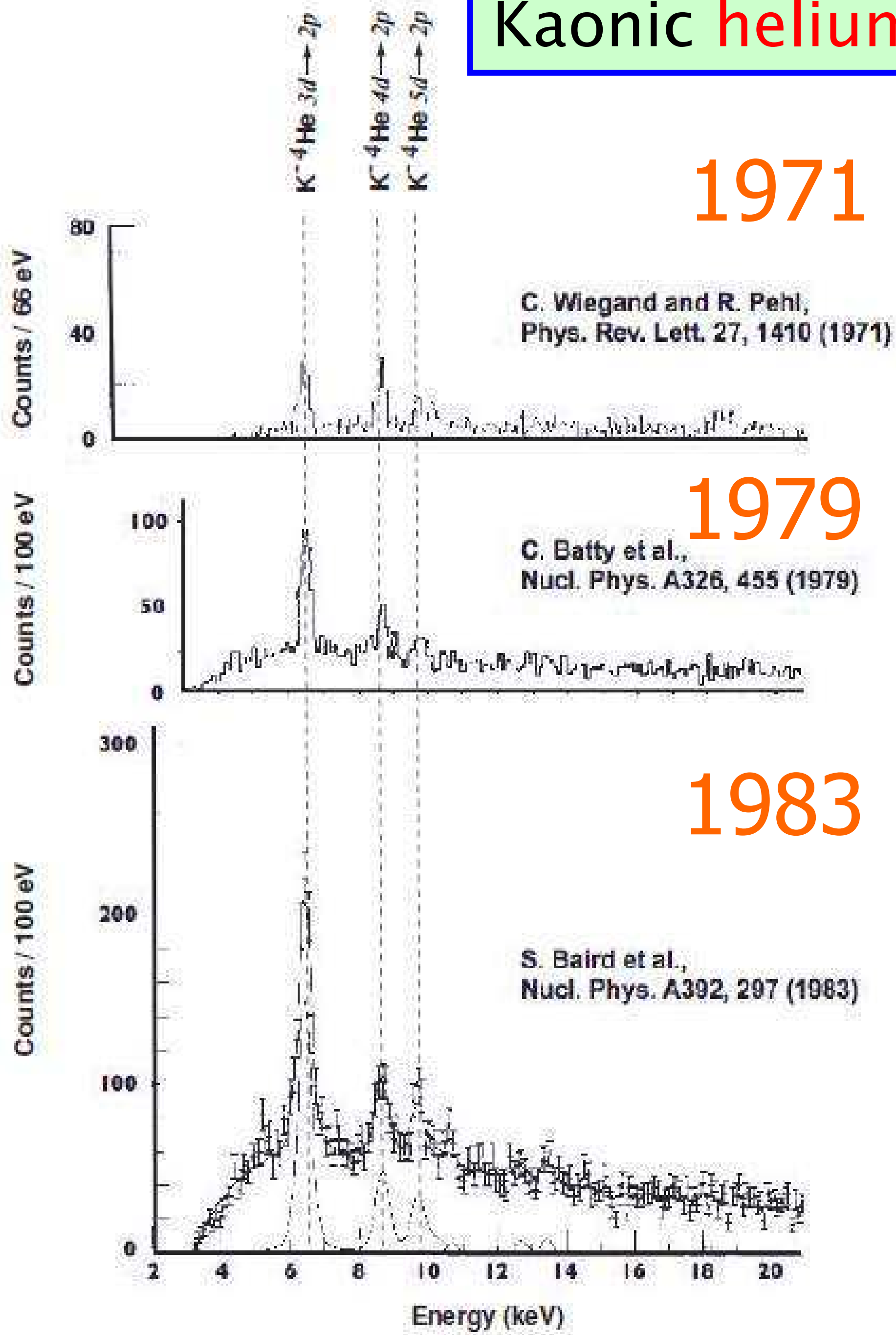
$$2\mu V^{(2)}_{\rm opt}(r) = -4\pi\left(1+\frac{\mu}{m}\right)b_0\rho(r).$$

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

Expected shift of K-4He 2p state:
ΔE ~ 0 eV

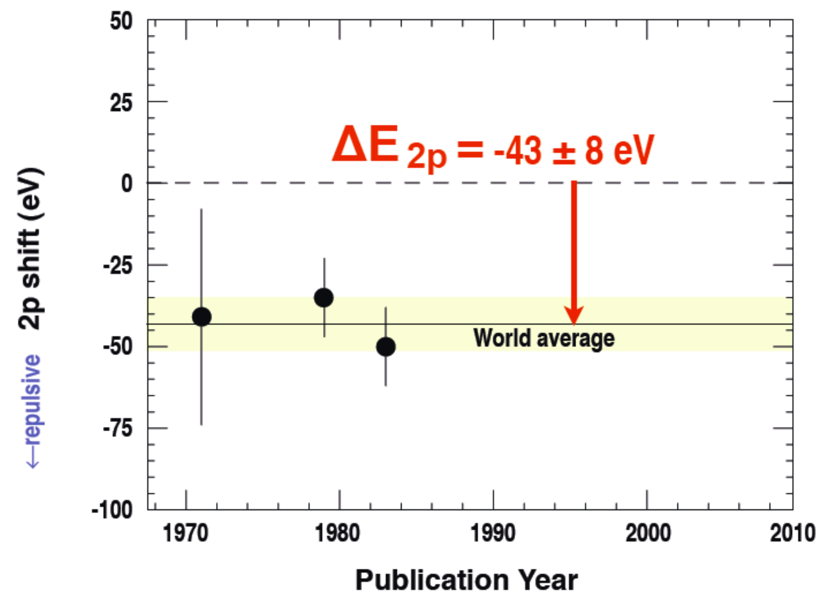
Shift [eV]	Ref
-0.13±0.02	Batty, NPA508(1990) 89c
-0.14±0.02	Batty, NPA508(1990) 89c
-0.4	Bianco, Nuo. Cim.22 (1999) 1
-1.5	Akaishi, Proc. EXA05

Kaonic helium atom data (Z=2)



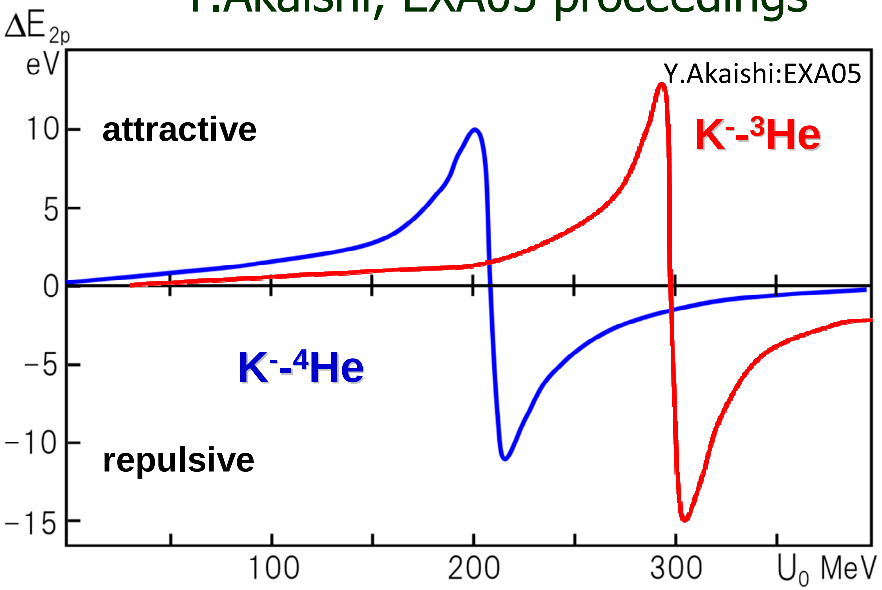
$$\Delta E_{2p} = E_{\exp} - E_{e.m.}$$

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



Possible shift of Kaonic helium (Z=2)

Y.Akaishi, EXA05 proceedings



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

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

K-nucl model
Small (<±10 eV)

Optical model
Tiny (~ 0eV)

disagree

K-He4 exp
Large (-40 eV)

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???

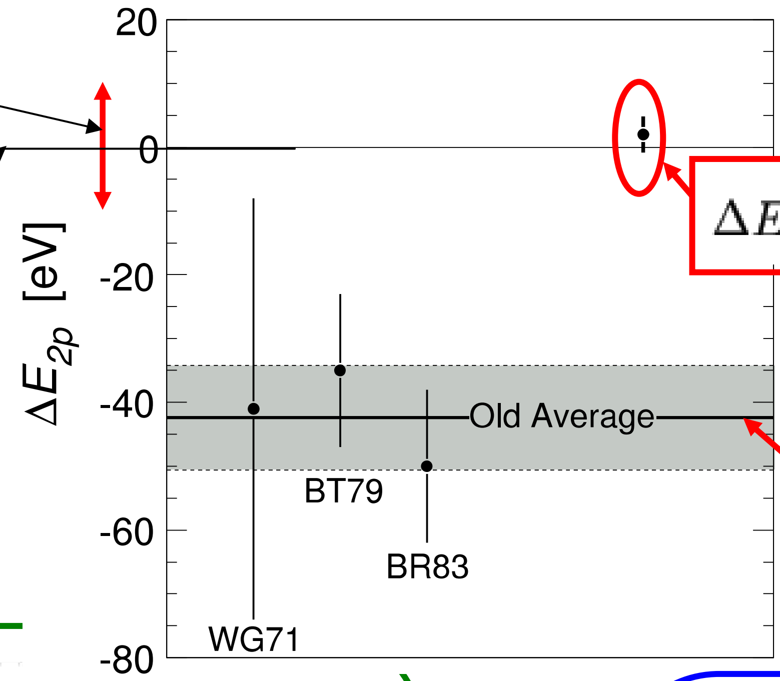
Need: New experiments both on He-3 and He4

K-^{4}He 2p level shift

PLB653(07)387

Akaishi Prediction
-10~ +10 eV

Optical model
~0eV

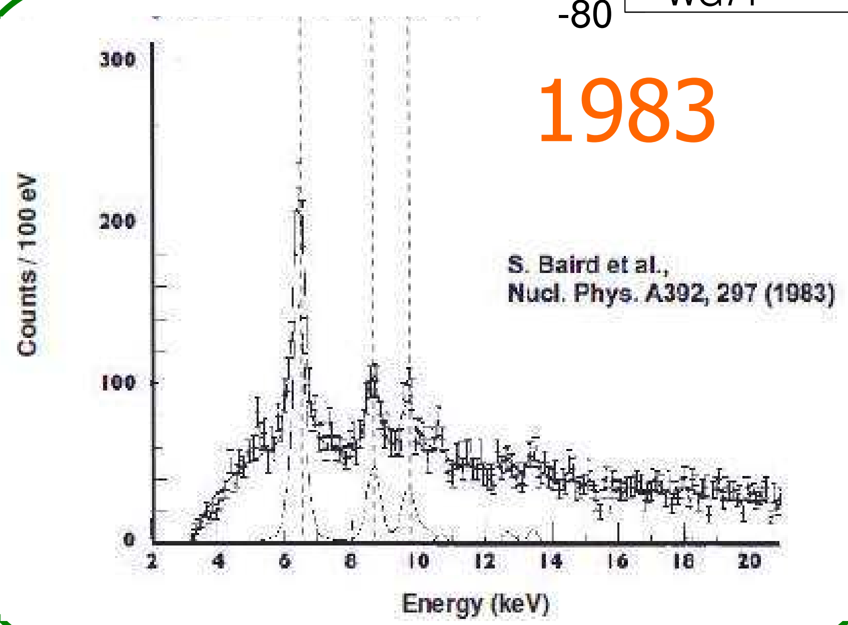


E570 results ('07)

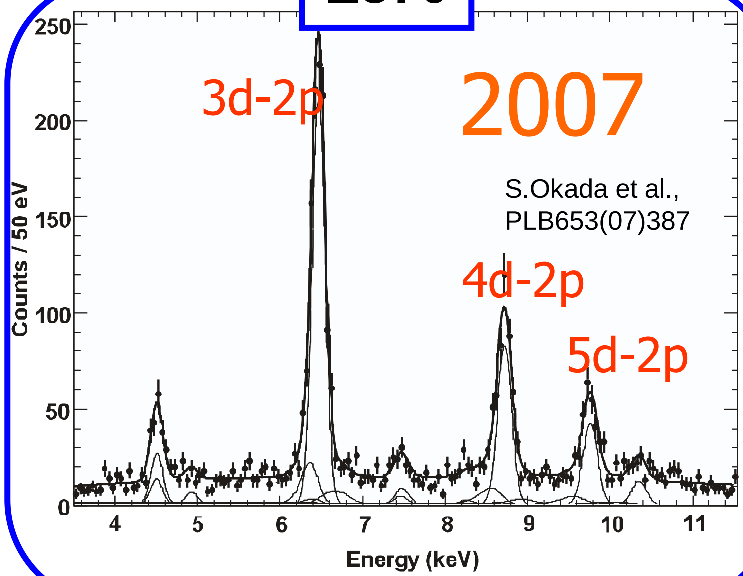
$$\Delta E_{2p} = 2 \pm 2 \text{ (stat) } \pm 2 \text{ (syst) eV}$$

Disagree!

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



E570



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

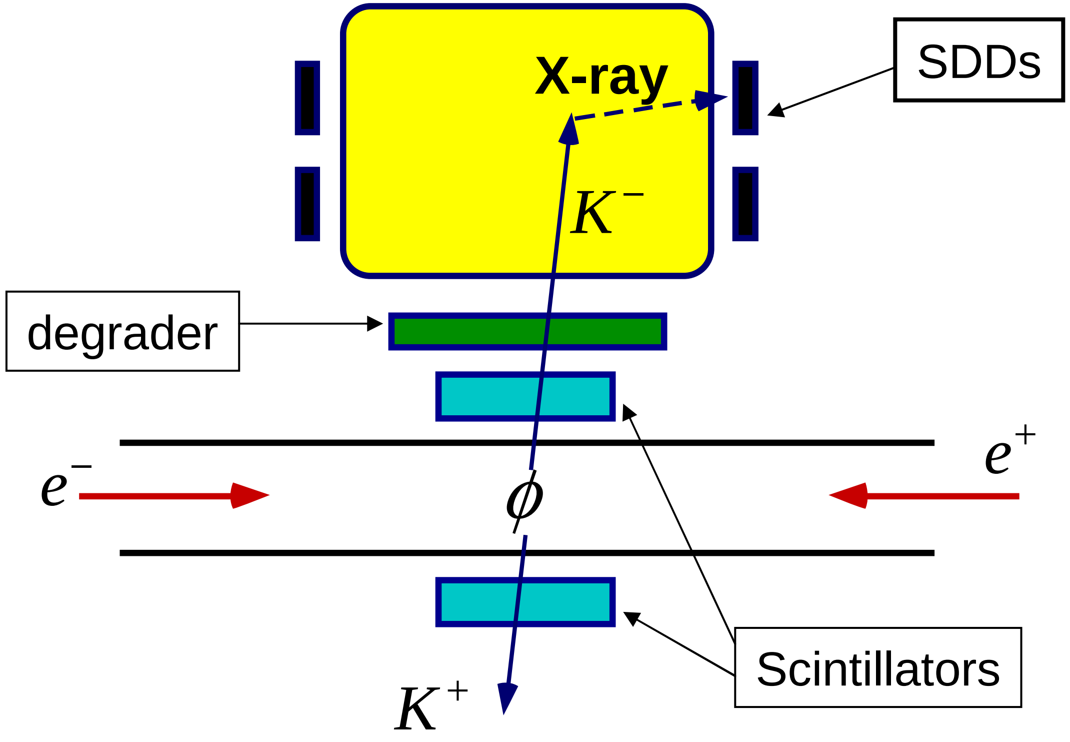
SIDDHARTA Experimental Setup

DAFNE e^+e^- collider
510 MeV (e^-, e^+)
Production of ϕ at rest

$$e^+ + e^- \to \phi \to K^+ + K^-$$

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

Efficient stops in Gas target



Triple coincidence:
SDD_X * $Scint_K$ * $Scint_K$

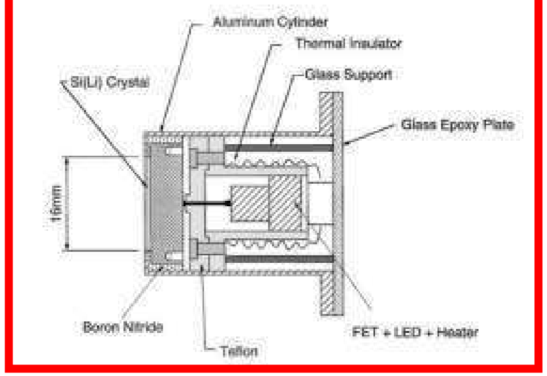
Rejected:
Background events uncorrelated to K+K- pair productions

Comparison of X-ray detectors

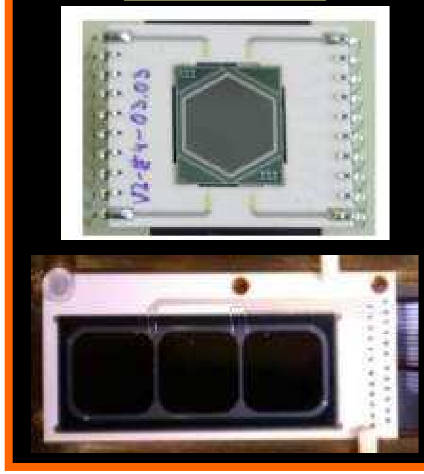
Good time resolution

Good energy resolution

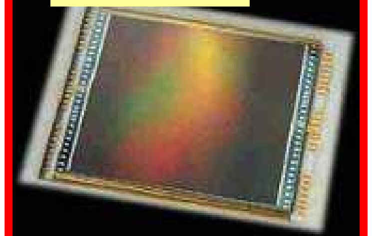
Si(Li)



SDD

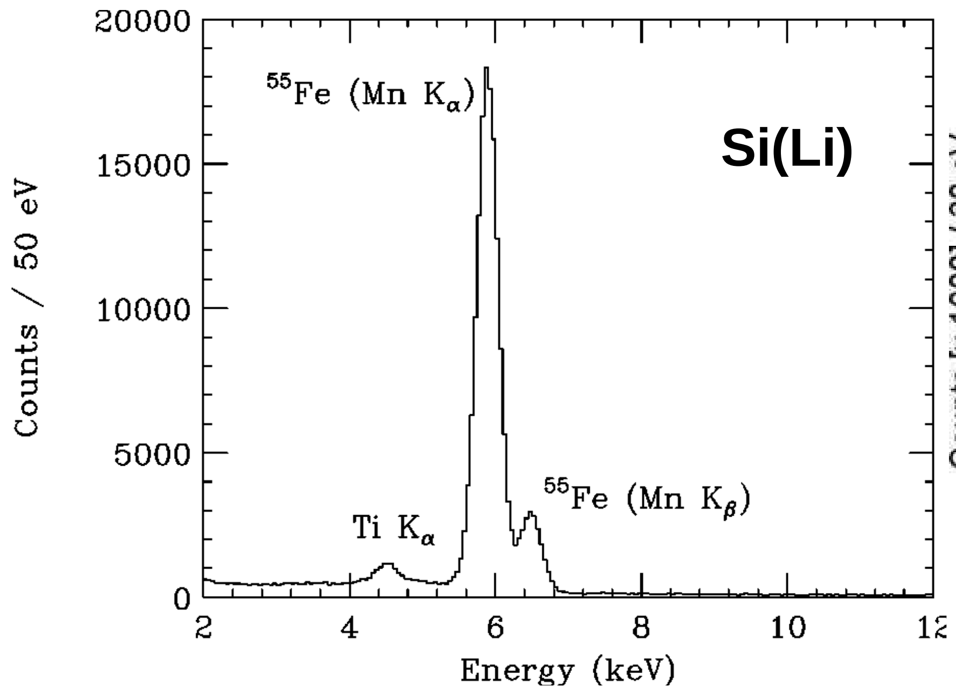


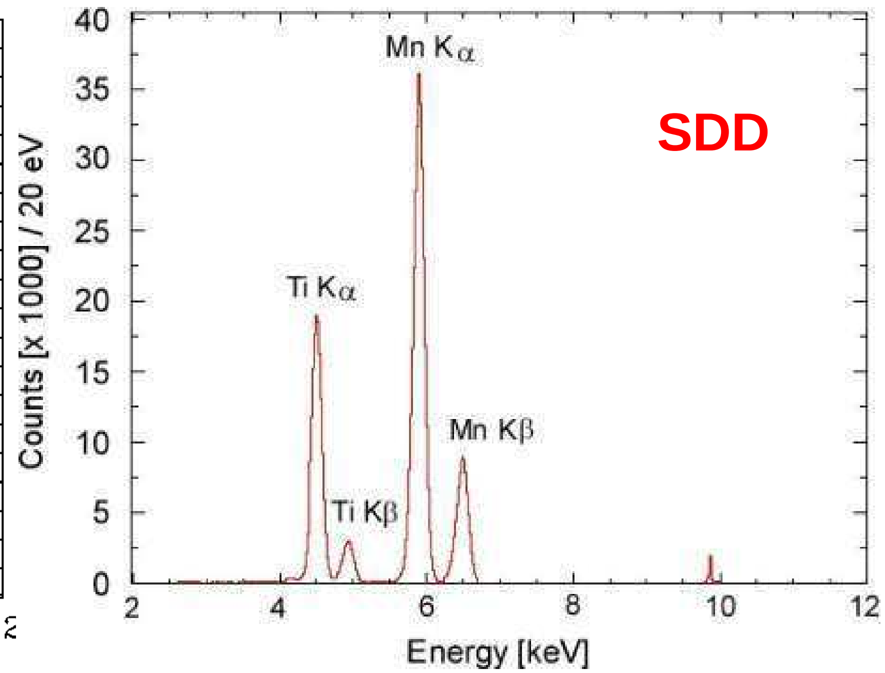
CCD

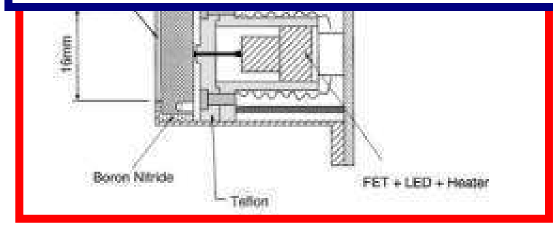


experiment		KpX	DEAR	E570
Detector		Si(Li)	CCD	SDD
Area	[mm2]	200	724	100
Thickness	[mm]	5	0.03	0.26
Δ E (FWHM)	[eV]	410	170	185
Δ t (FWHM)	[ns]	290	-	430

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







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Δ E (FWHM)	[eV]	~~410~~	170	185
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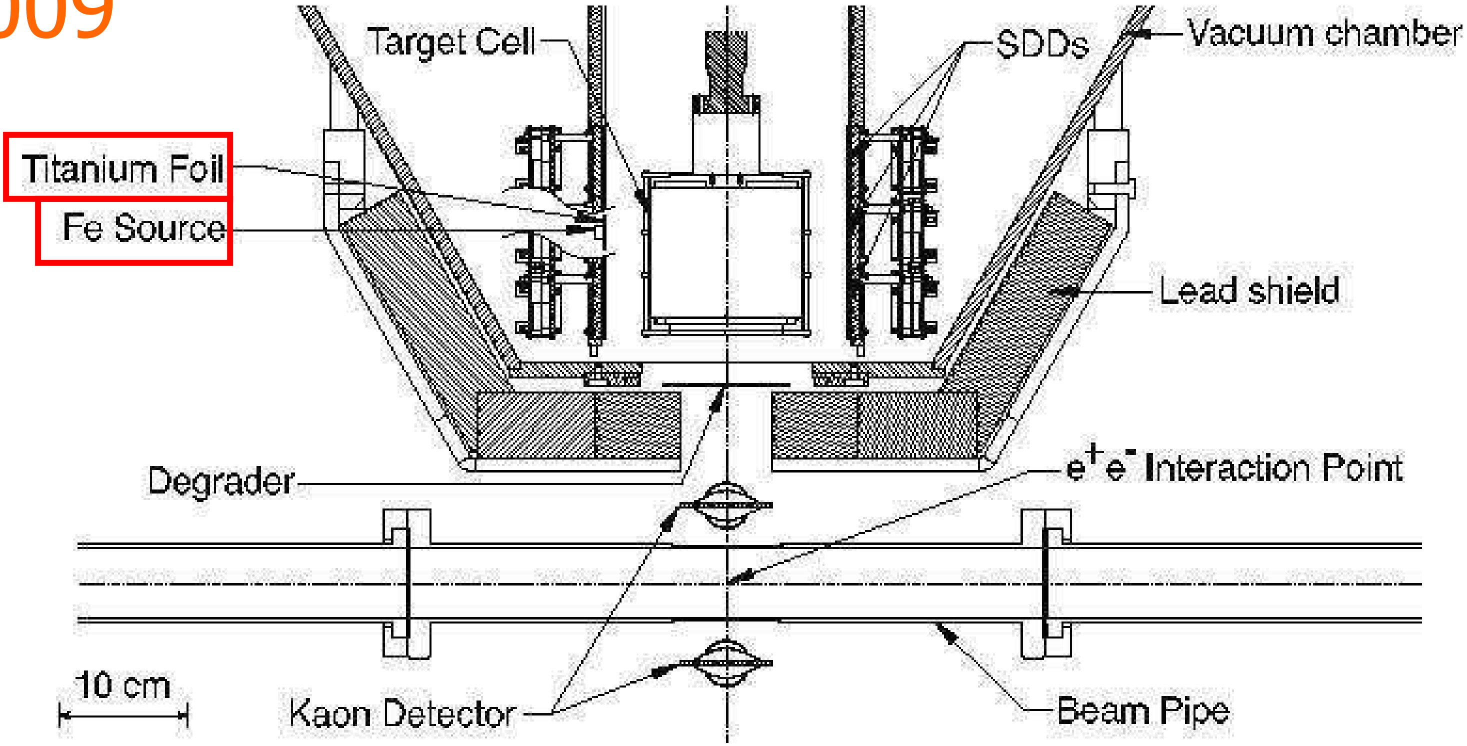
T.Ishiwatari,
Hyp. Int. 194(09)165

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

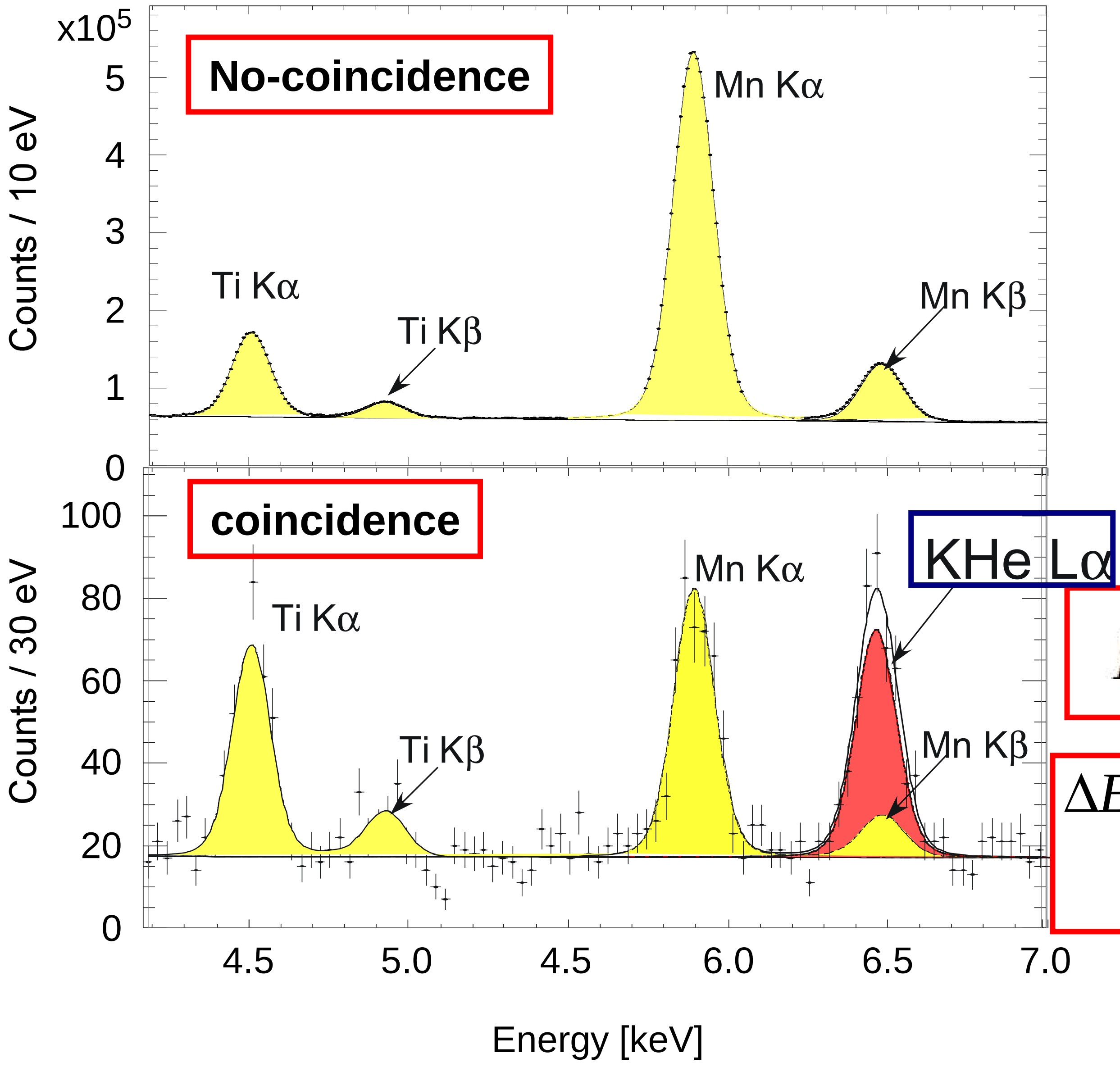
First measurement with gas target

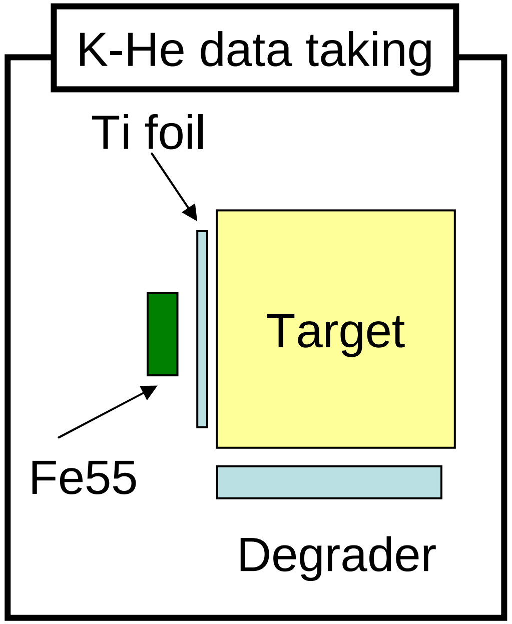
Installed SDD:144 cm^2, Used in Analysis: 60 cm^2
SDD operation temp. :170 K,
SDD Energy resolution: ~150 eV (at 6 keV)

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

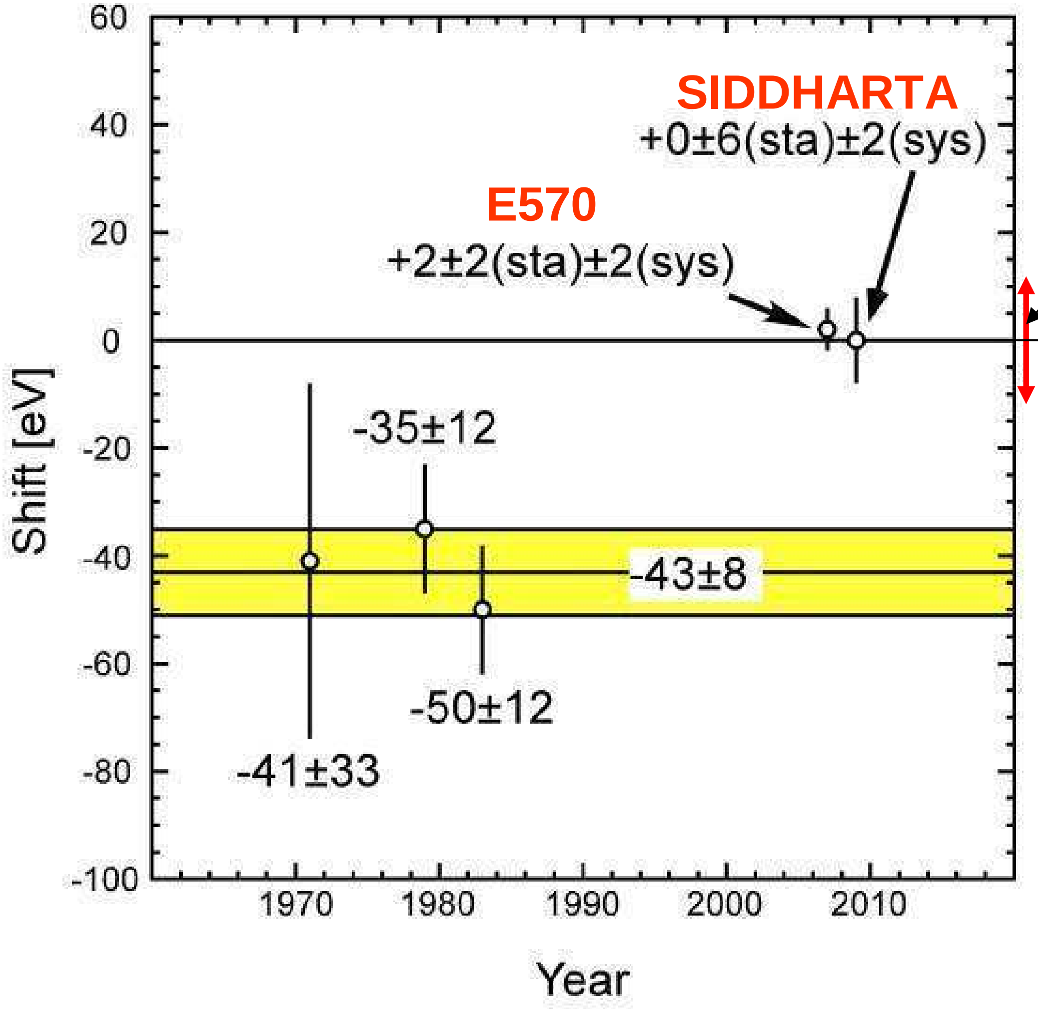




$$E_{\text{exp}} = 6463.6 \pm 5.8 \text{ eV},$$

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

Summary of KHe-4 shifts (up to 2007)



Akaishi Prediction
-10~ +10 eV

Optical model
~0eV

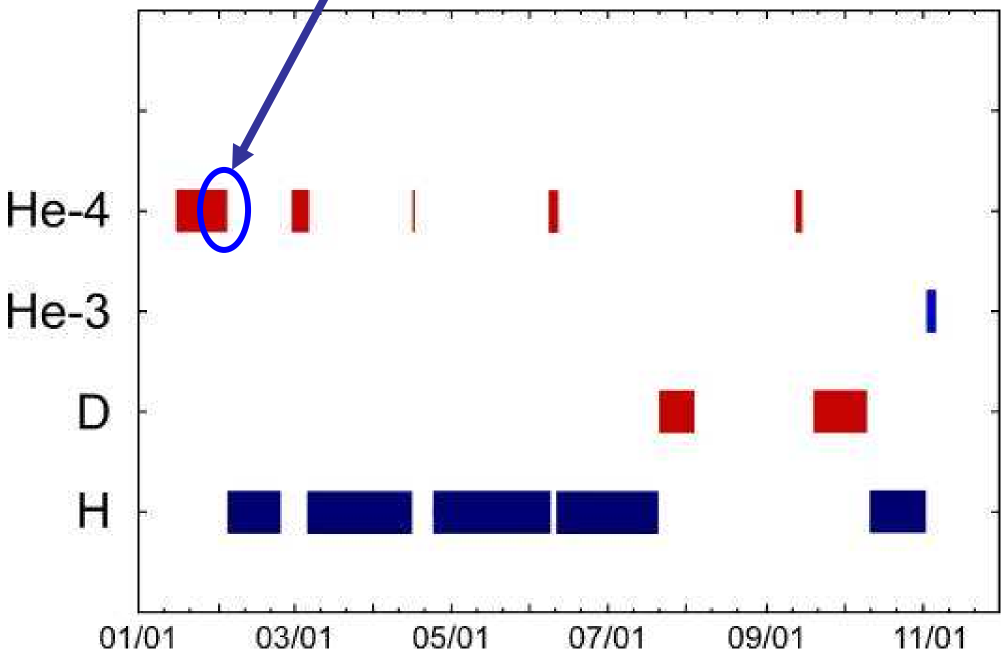
Optical model
Tiny (~ 0eV) ✓

K-nucl model
Small (<±10 eV) ✓

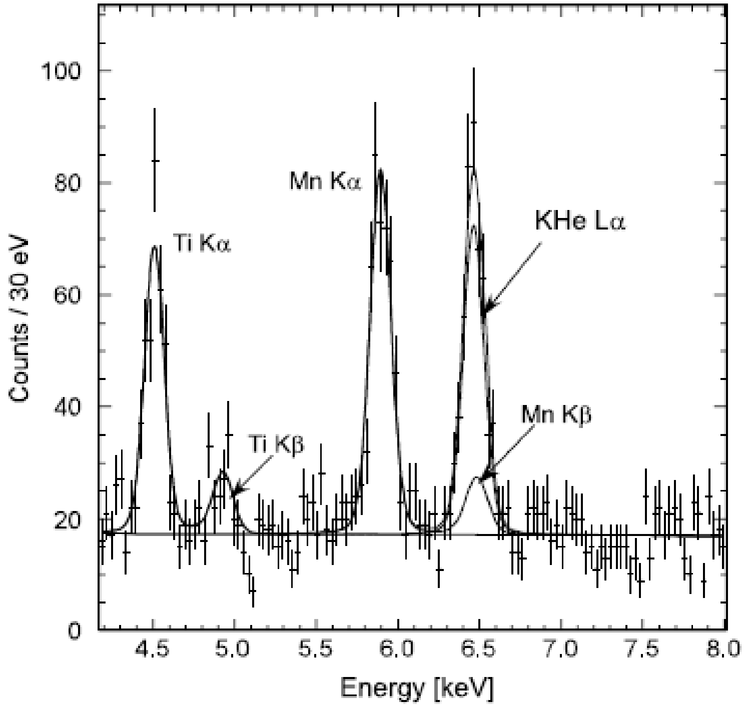
K-He4 exp
Large (-40 eV) ✗

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

Removed ^{55}Fe source in other data

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

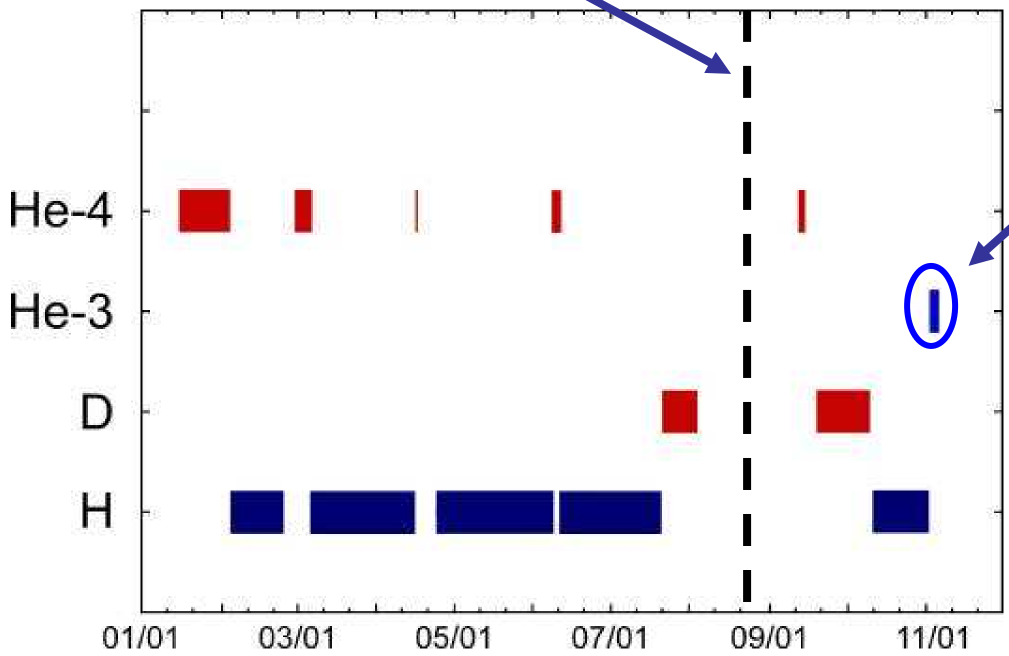
Systematic error = +/-2 eV

Data taking periods of SIDDHARTA in 2009

DAFNE shutdown in Summer

New alignment of setup
→Improve S/N ratio

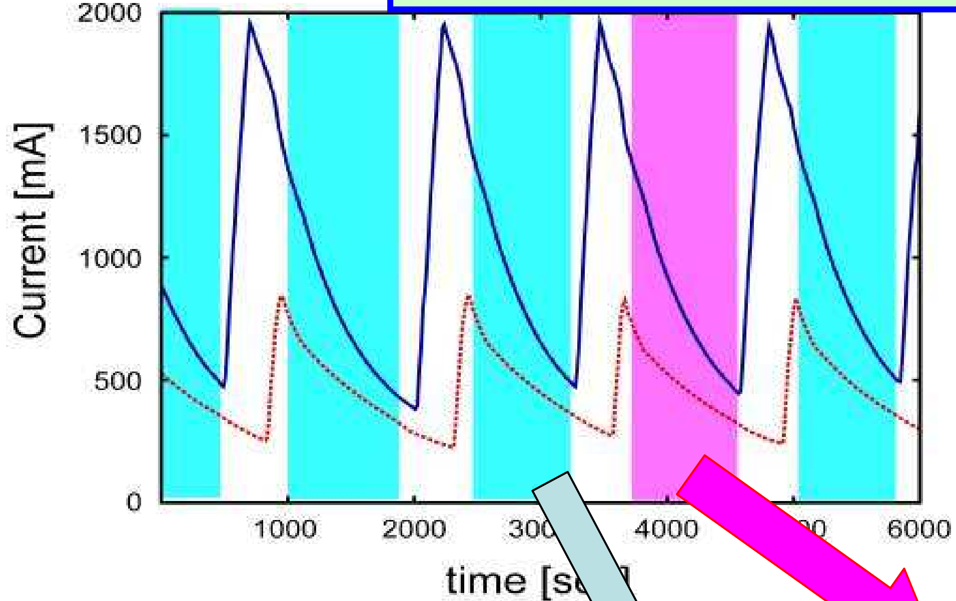
K-He3 data (~4days)



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

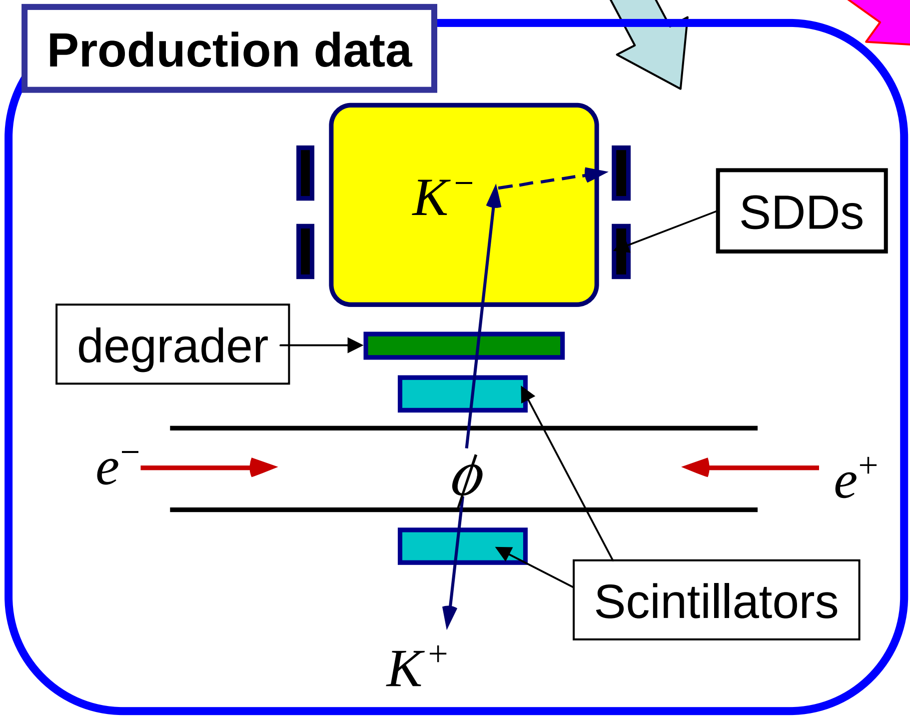
Removed ^{55}Fe source in other data

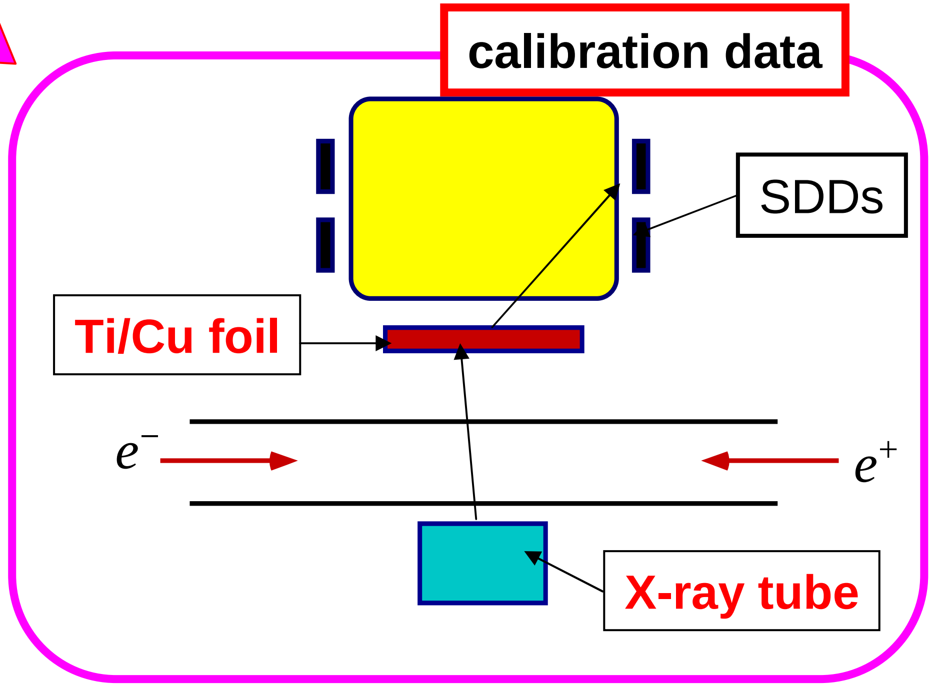
Data taking scheme at DAFNE



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

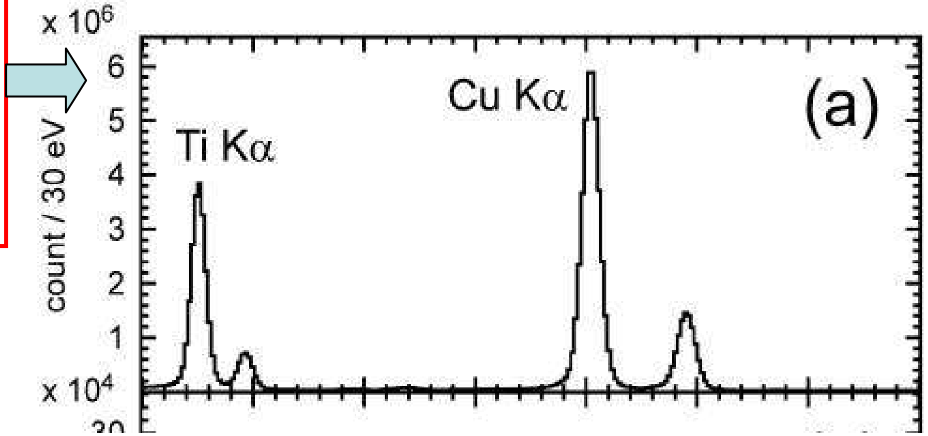
Estimated systematic error ~ 5 eV





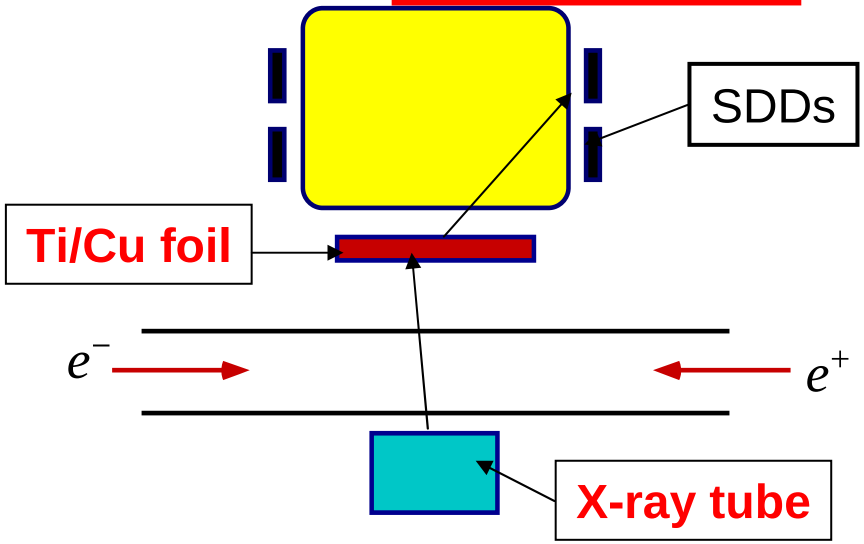
SDD X-ray energy spectra

Calibration data with **X-ray tube**



Calibration Ti&Cu

calibration data

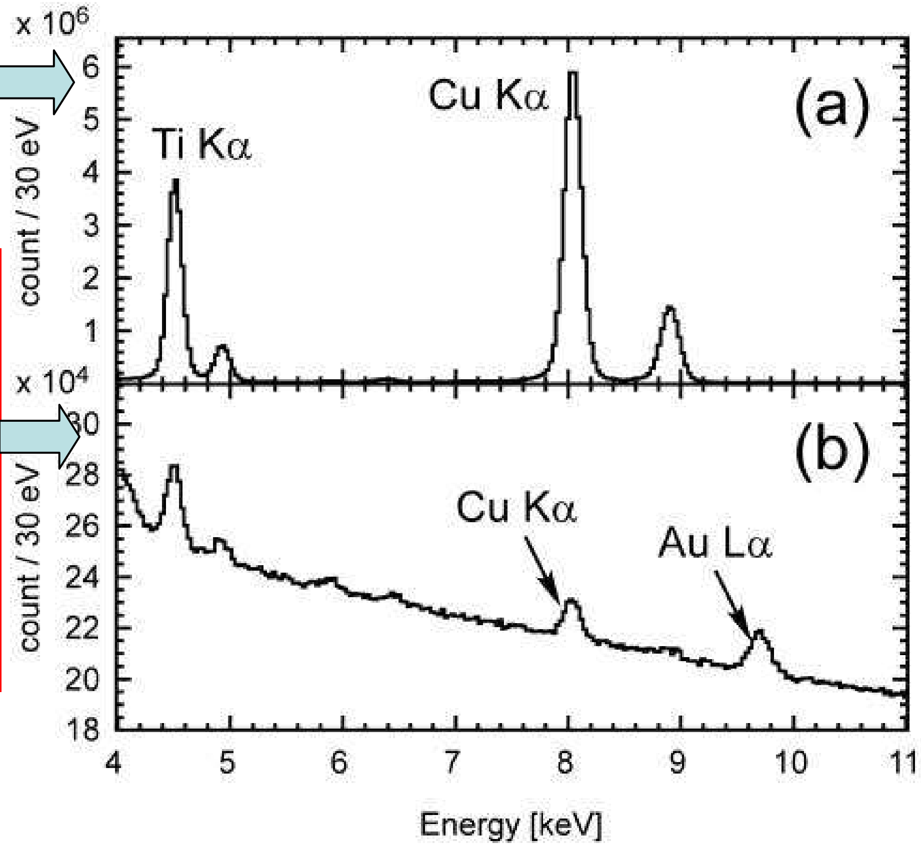


SDD X-ray energy spectra

Calibration data with **X-ray tube**

Not correlated to Kaon signals

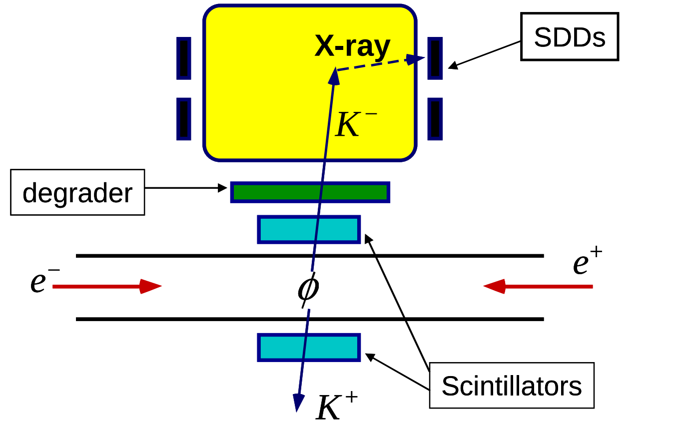
Production data



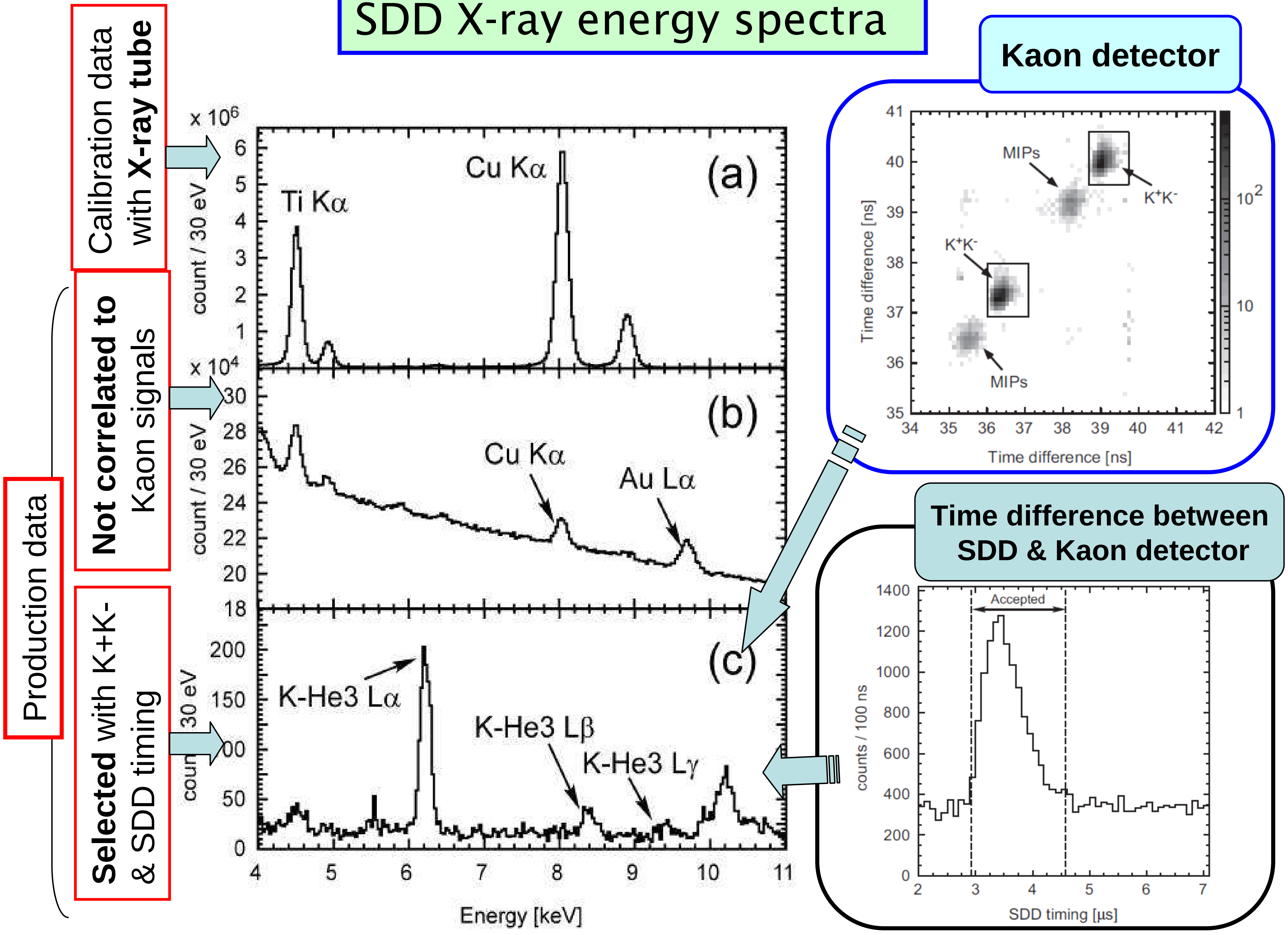
Calibration Ti&Cu

Energy scale determined by X-ray tube data

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



SDD X-ray energy spectra



SDD X-ray energy spectra

Calibration data with **X-ray tube**

Not correlated to Kaon signals

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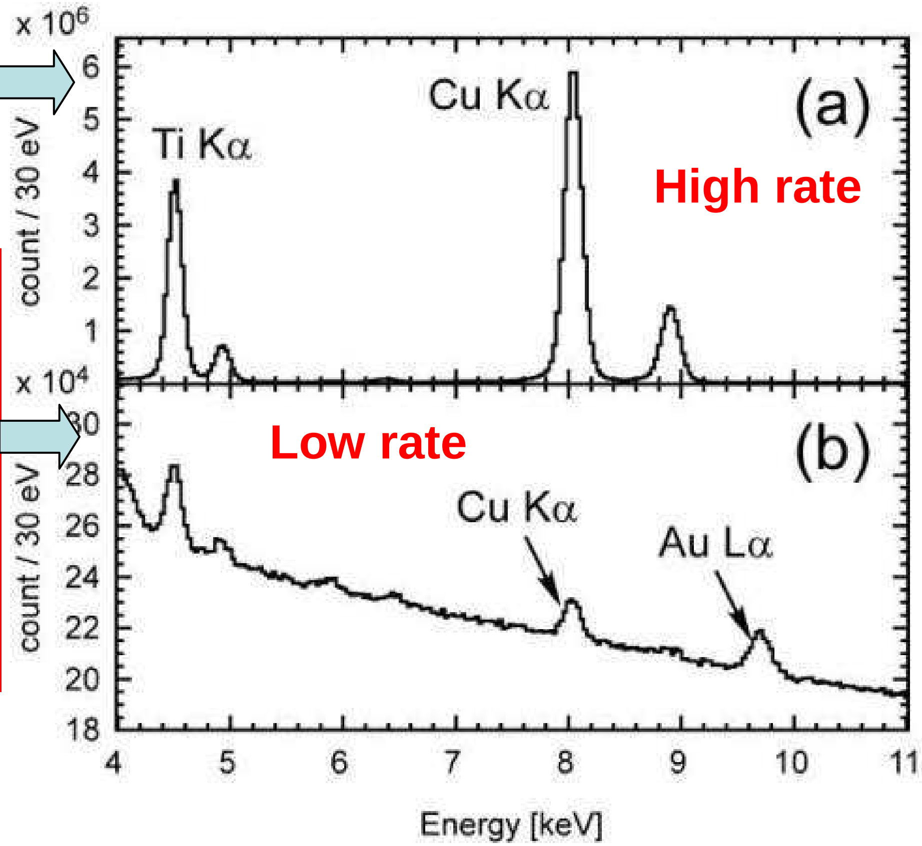
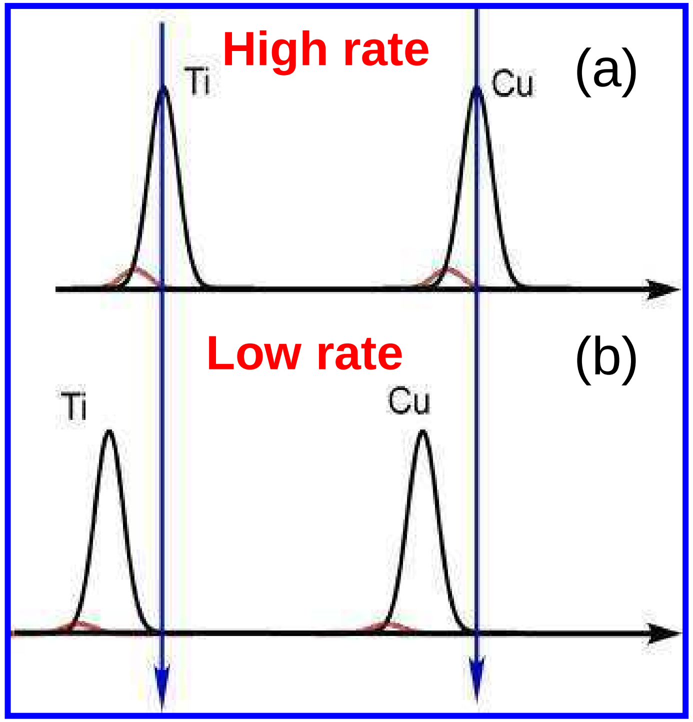




Rate dependency

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

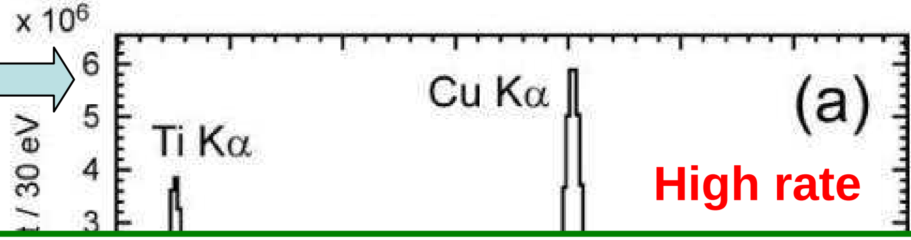
~10 eV peak shift compared to (a)

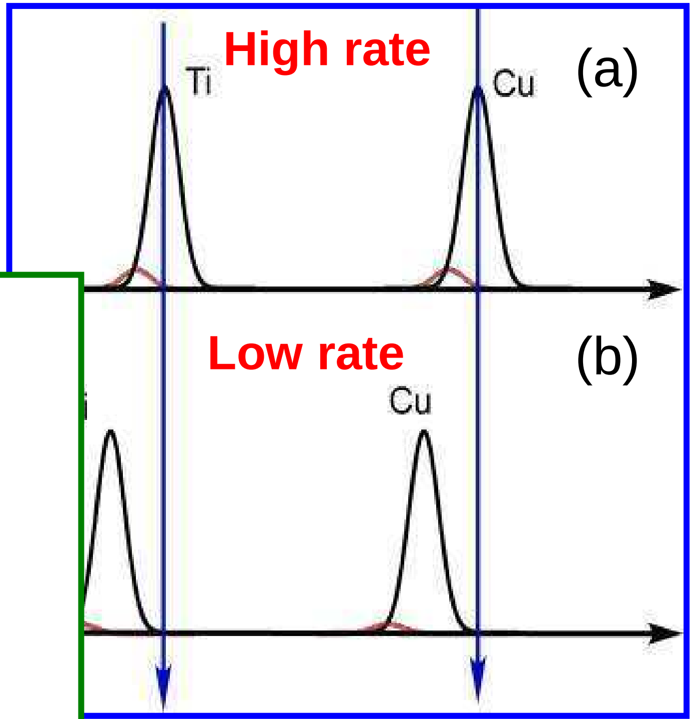
Calibration in (a): not reliable!

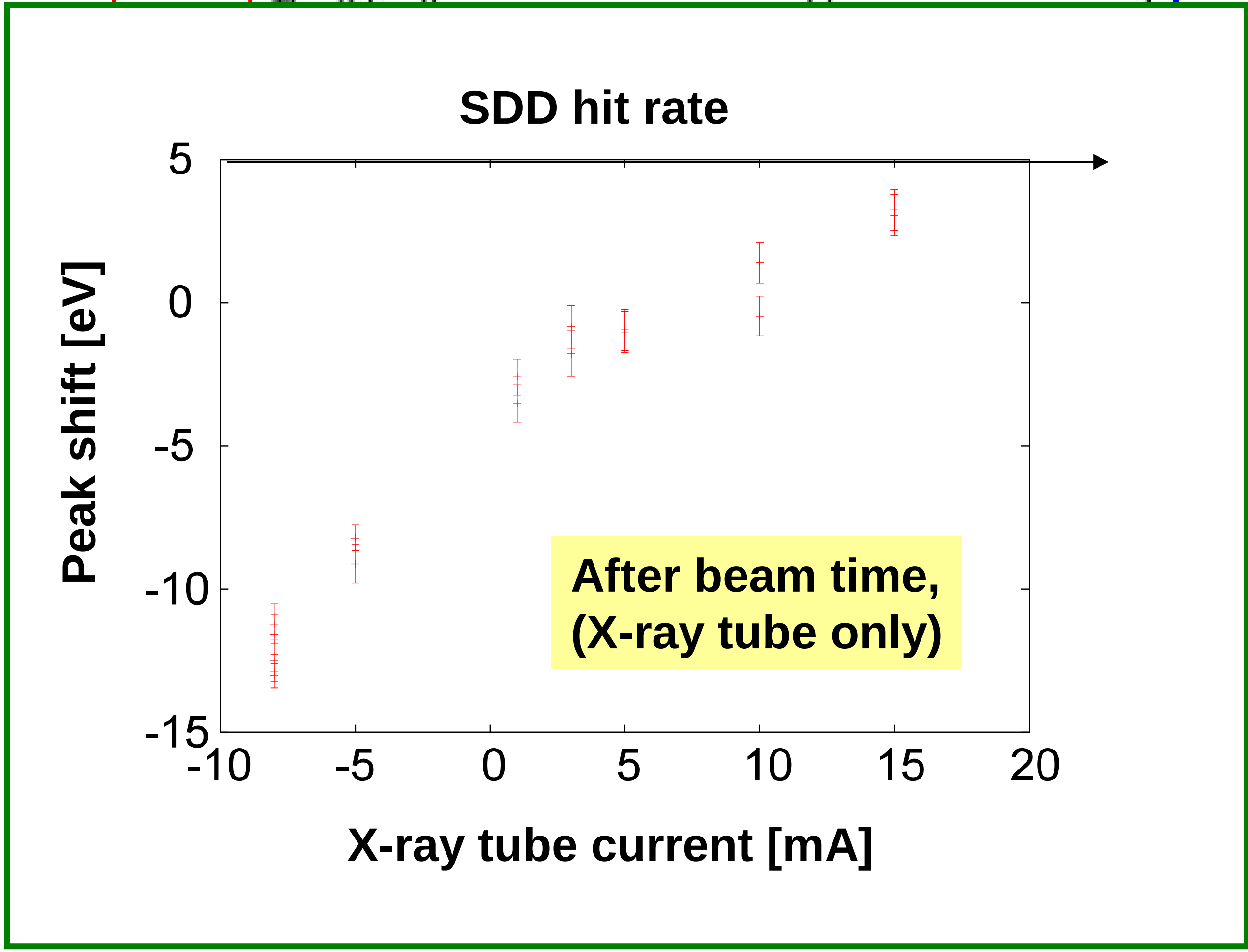
Significant for K-He measurement

SDD X-ray energy spectra

Calibration data with **X-ray tube**







~10 eV peak shift compared to (a)

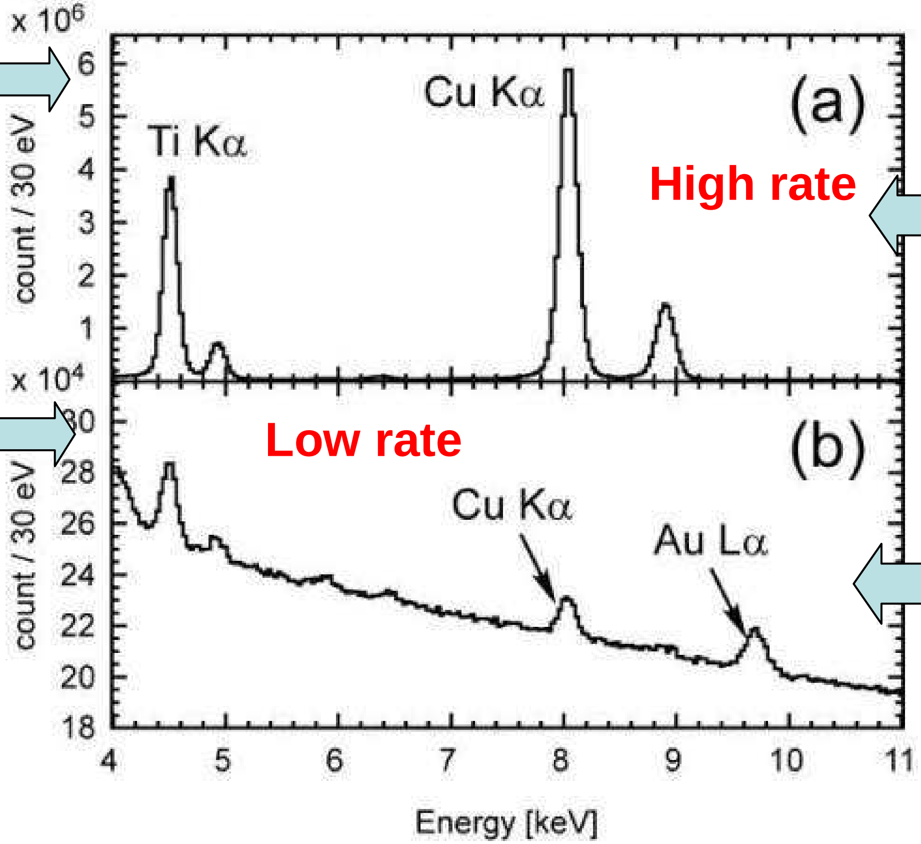
Significant for K-He measurement

SDD X-ray energy spectra

Calibration data with **X-ray tube**

Not correlated to Kaon signals

Production data



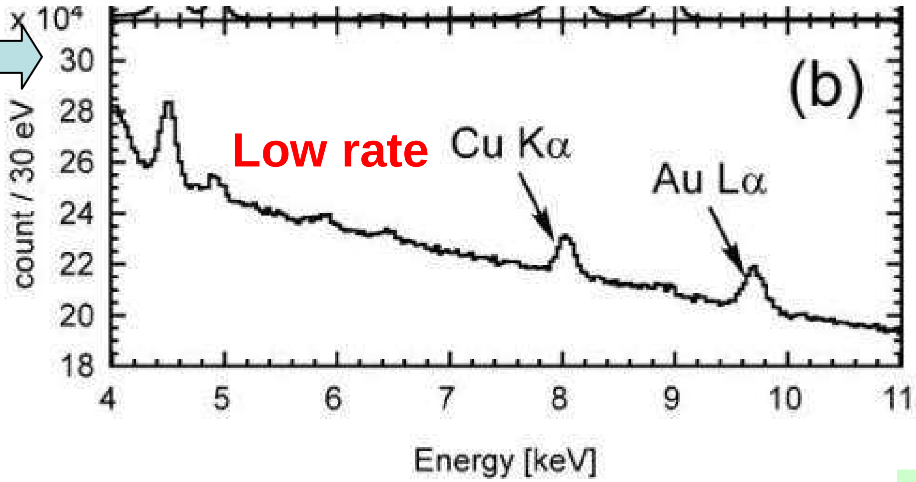
1. Good SDD selection
2. Gain adjustment,
3. correction of time-dependent fluctuation

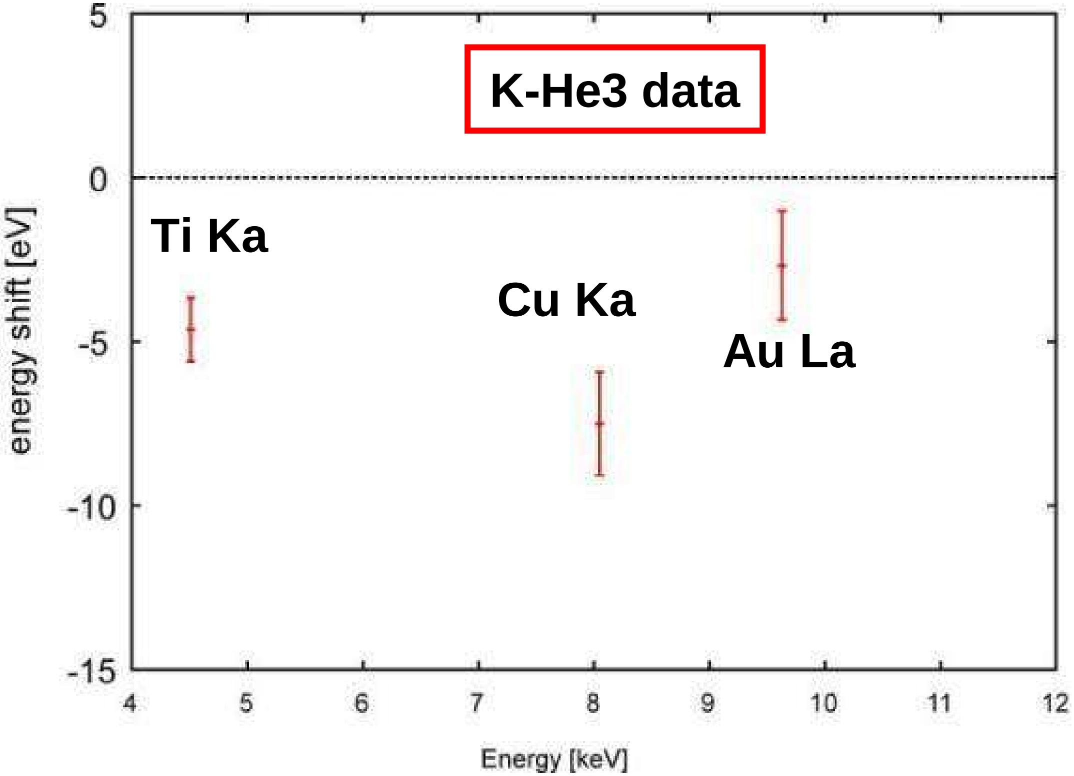
Precise energy calibration

SDD X-ray energy spectra

Production data

Not correlated to Kaon signals





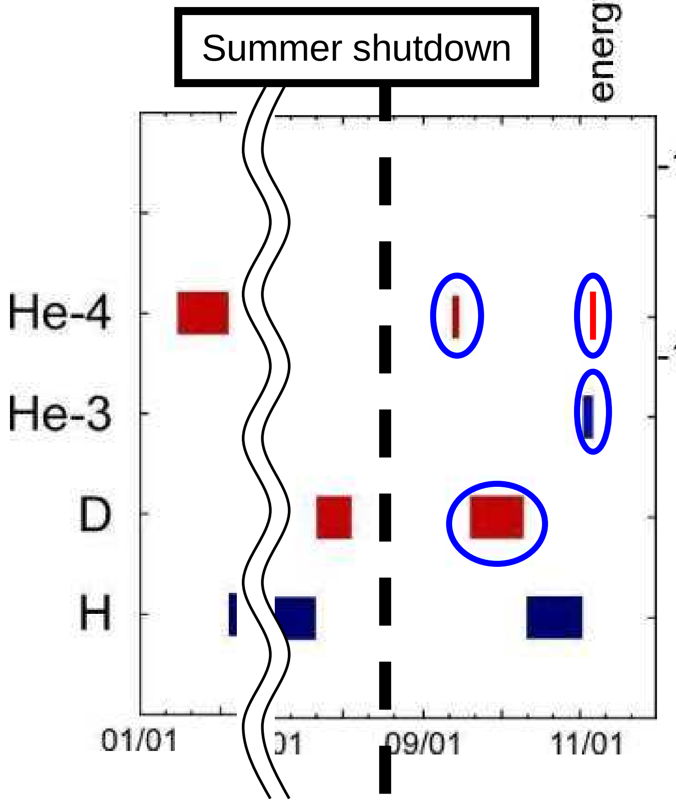
Ti/Cu/Au lines: compared to the reference values

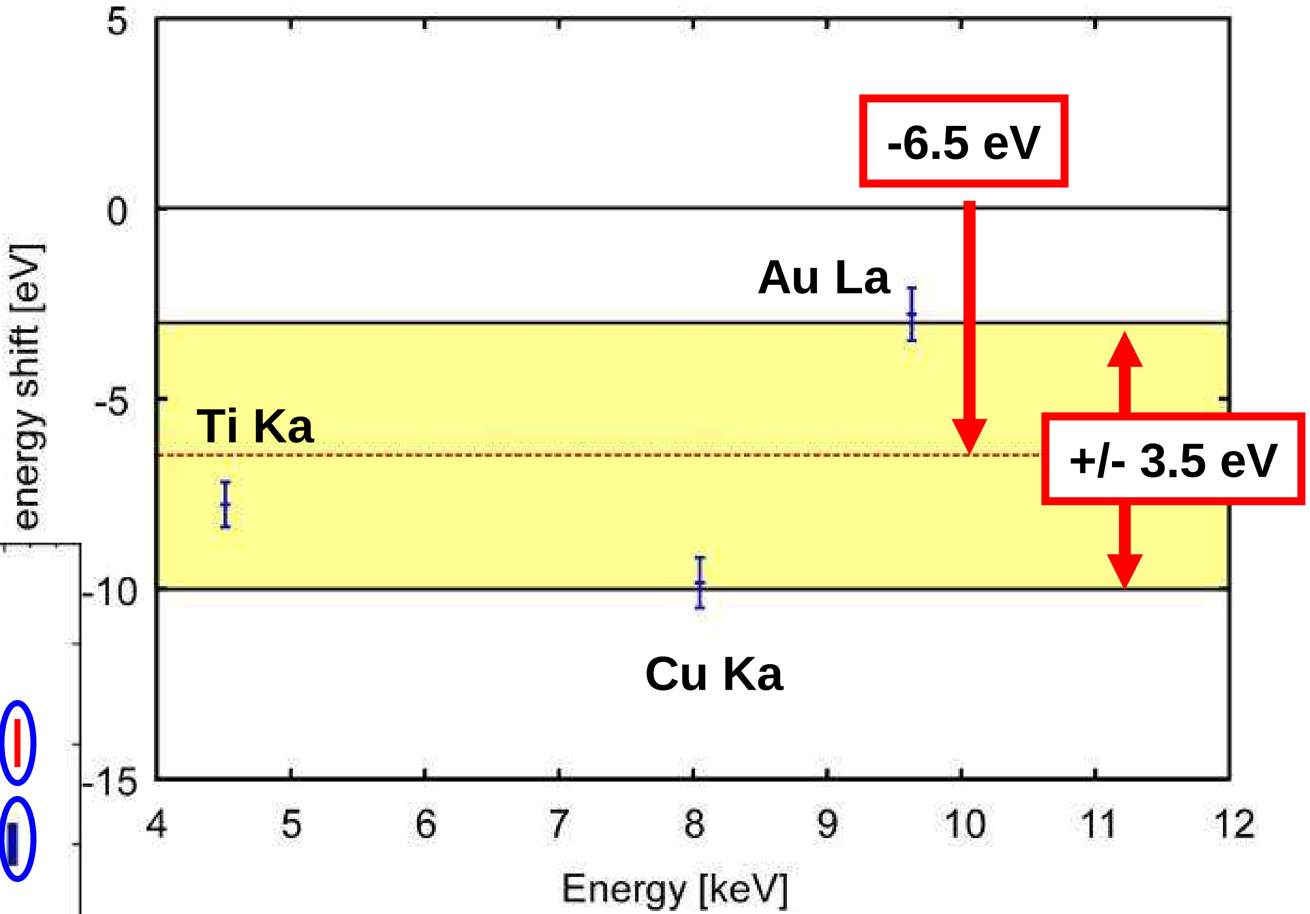
Average: shifted to lower
Systematic fluctuation??

Data analysis of other target

Evaluation of systematic error

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



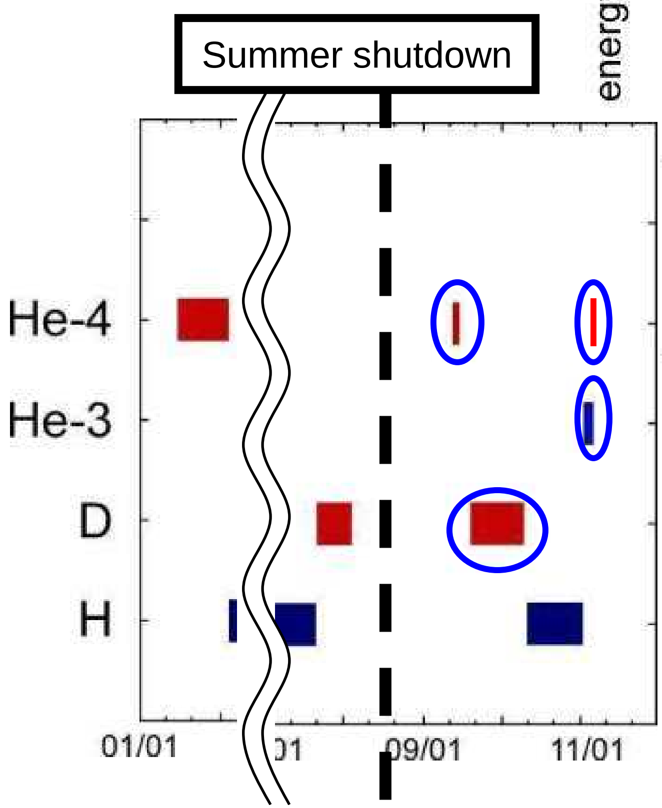


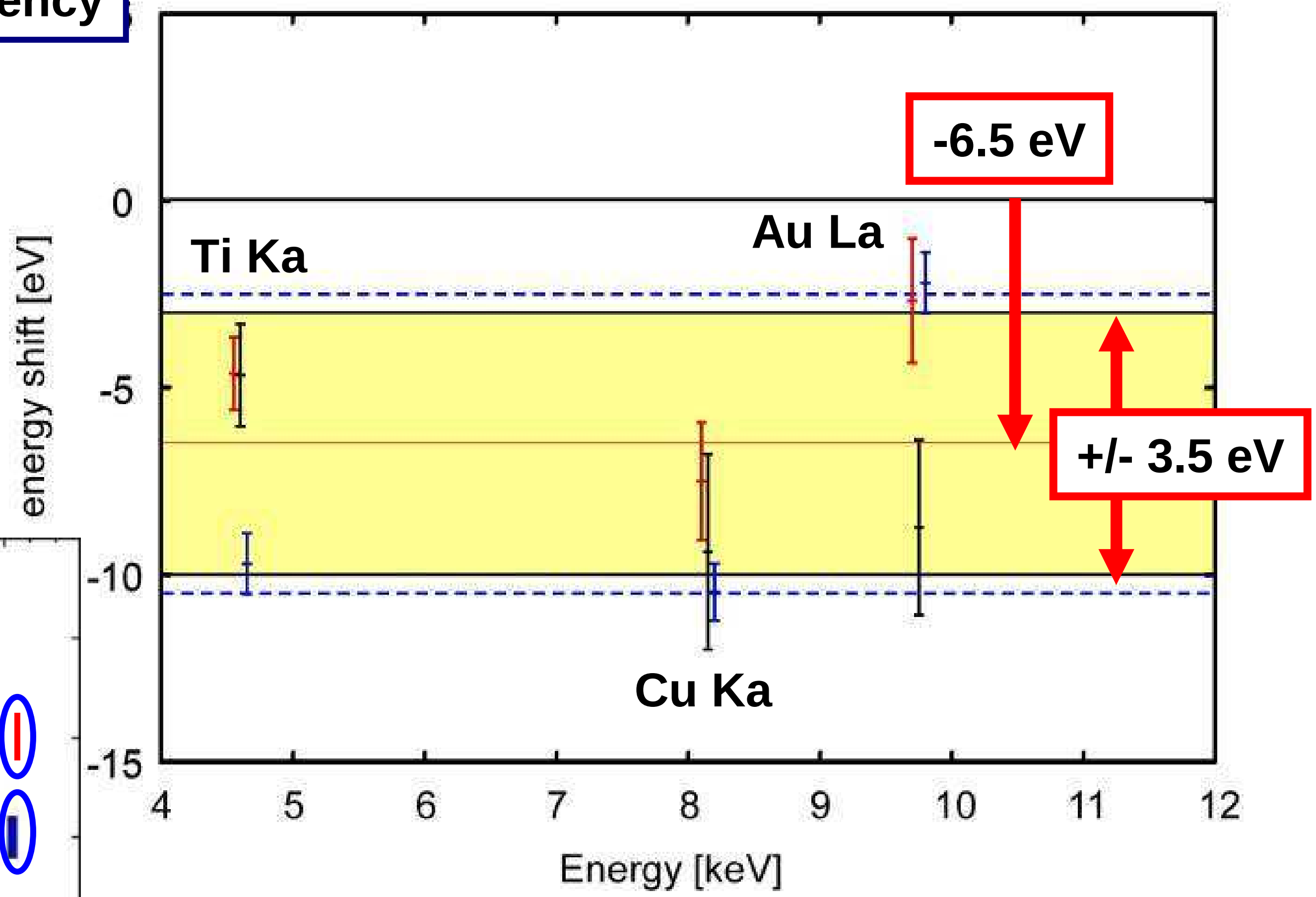
- **Peak shift: - 6.5 eV**
- **Accuracy of energy determination: +/- 3.5 eV**

Evaluation of systematic error

Time (or target) dependency

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





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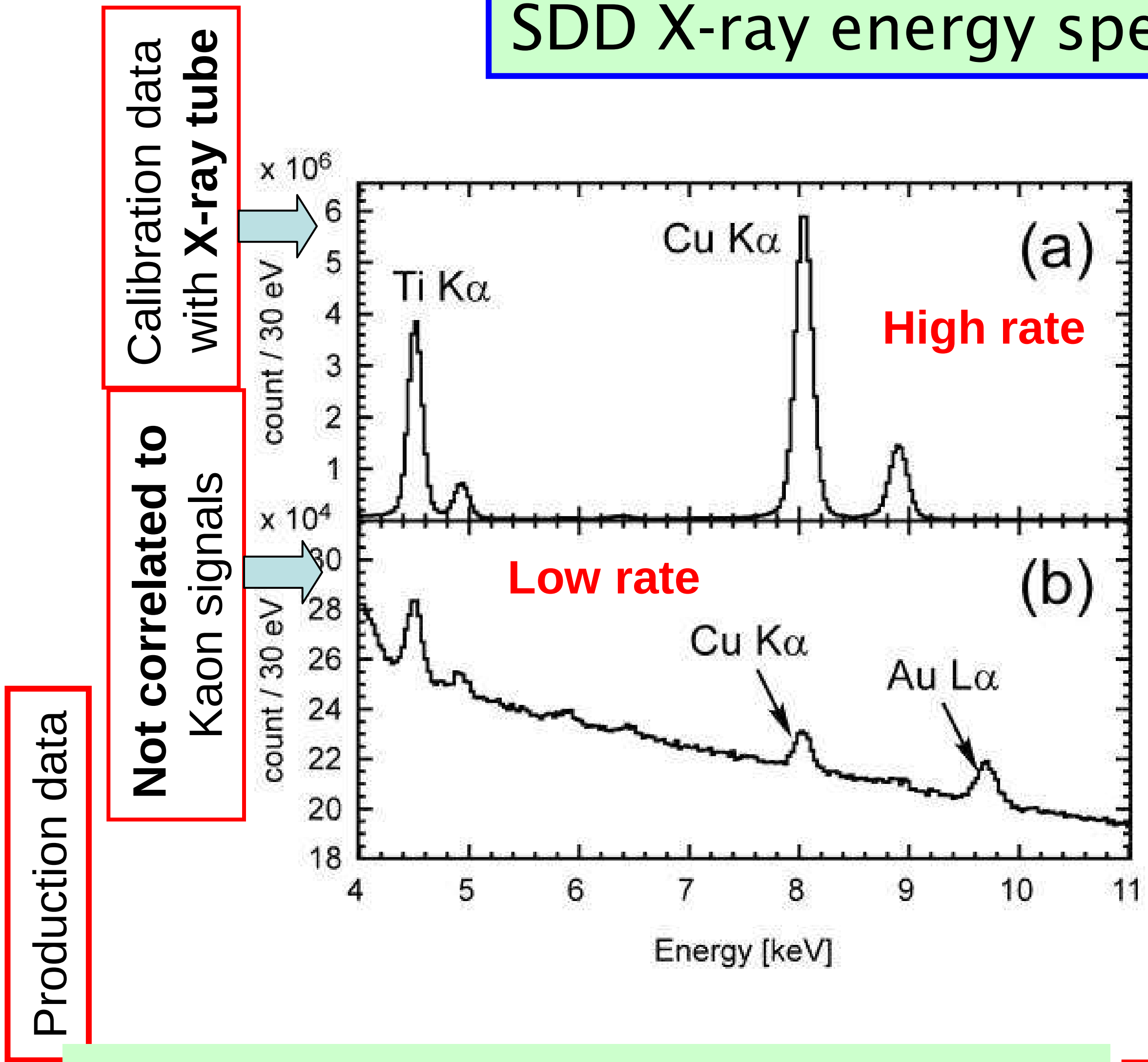
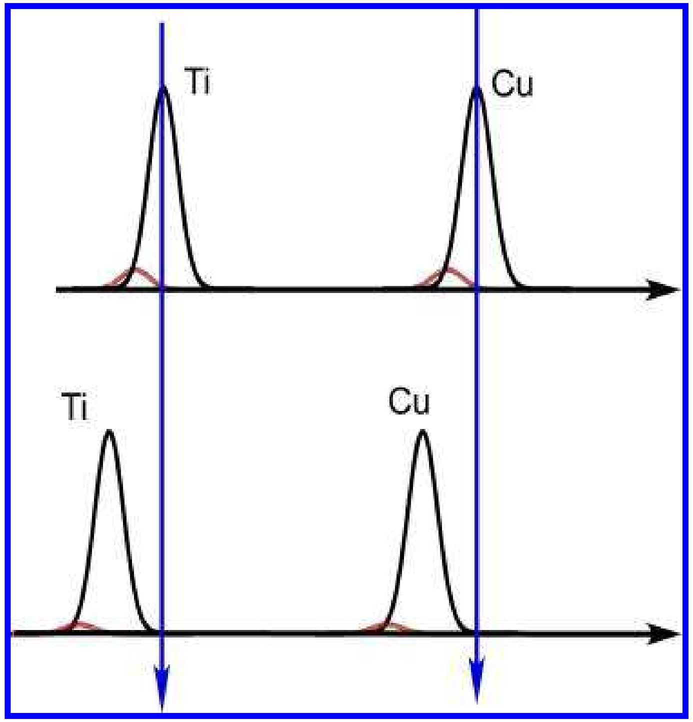
SDD X-ray energy spectra



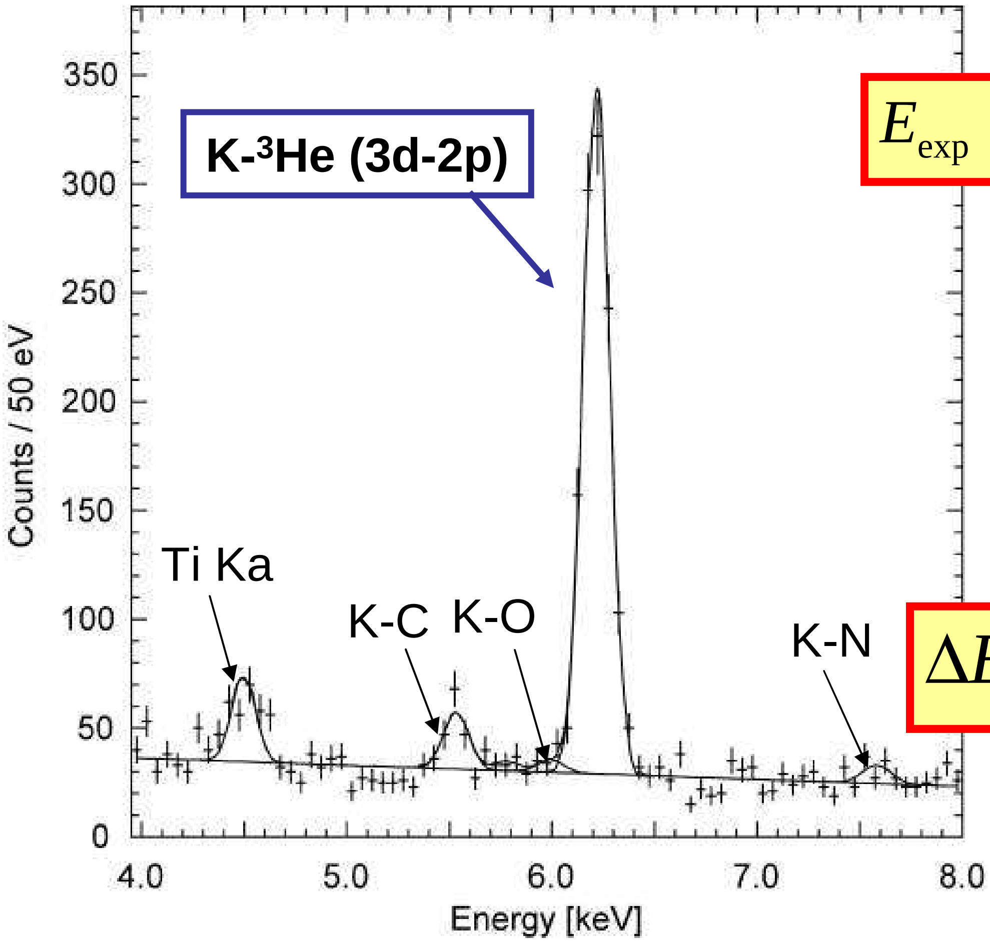


peak shift due to rate dependency: 6.5 eV
Precision of energy calibration : +-3.5 eV
evaluated from known X-ray energy peaks
(Ti, Mn, Cu, Au lines and kaonic C, O lines)

Correction term:

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

Kaonic Helium-3 energy spectrum



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

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

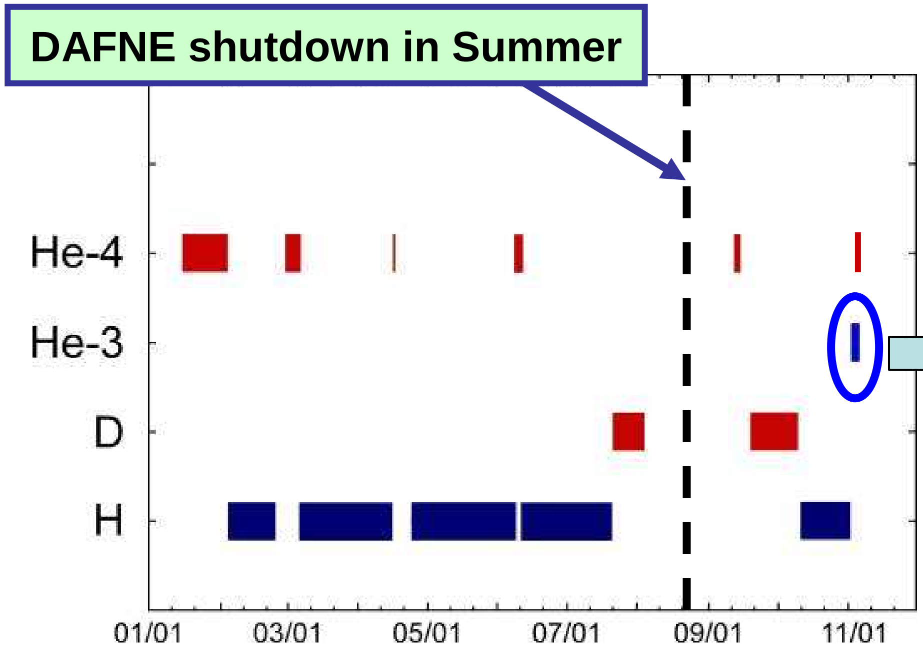
QED value: $E_{e.m.} = 6224.6\ \text{eV}$

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

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

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

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



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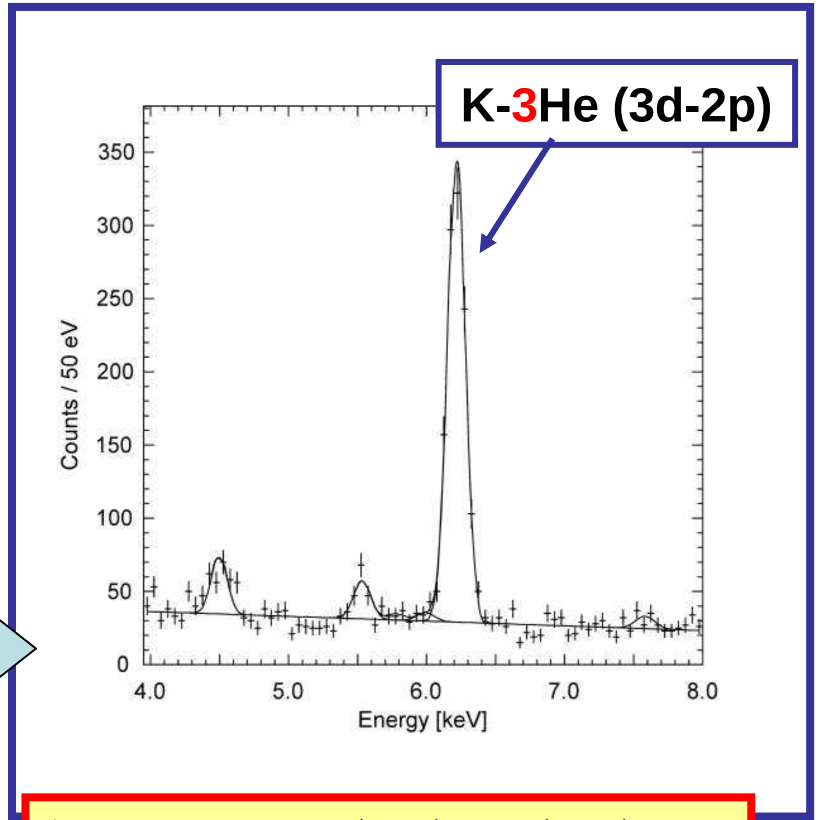
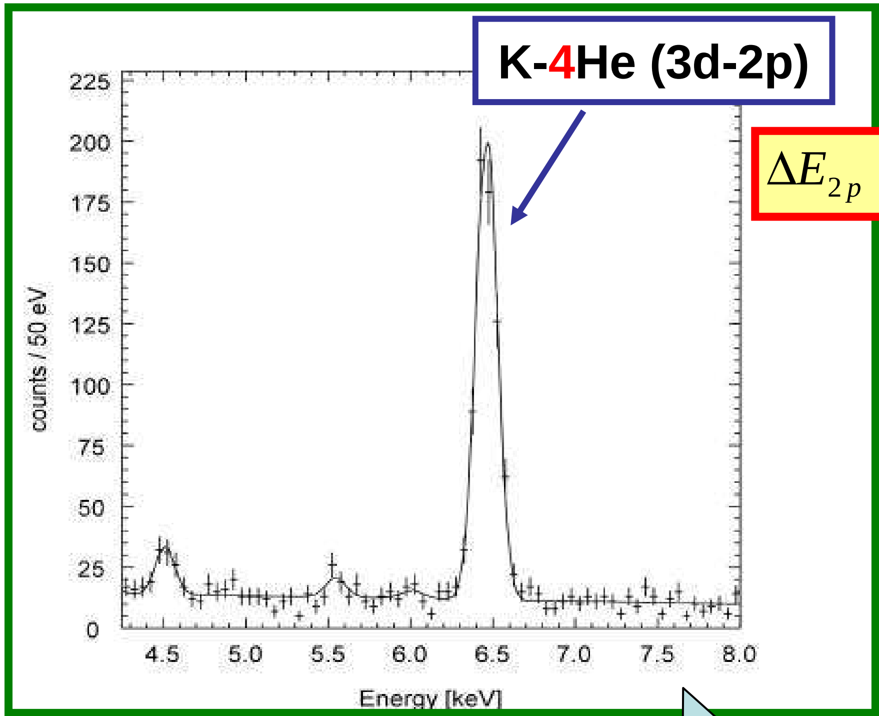
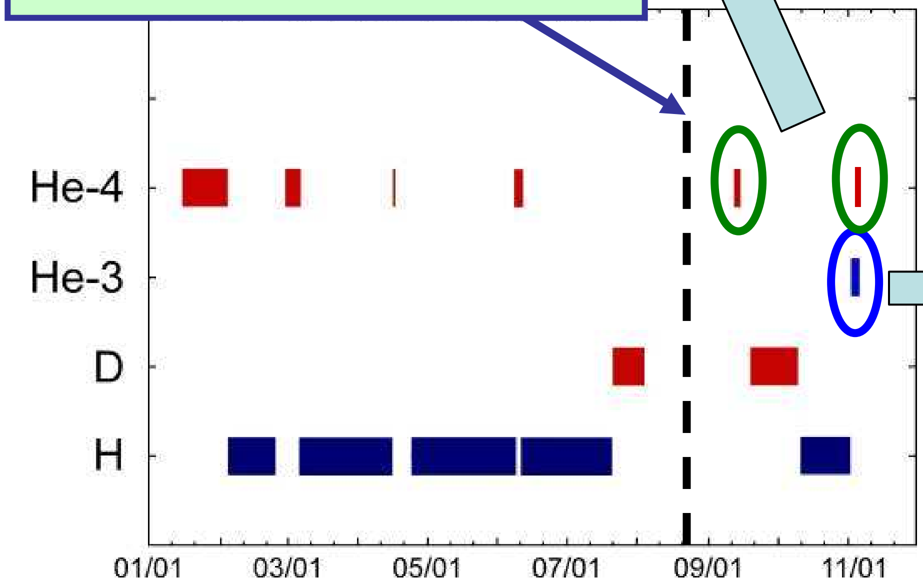


$$\Delta E_{2p} = -2 \pm 2(sta) \pm 4(sys)\ \text{eV}$$

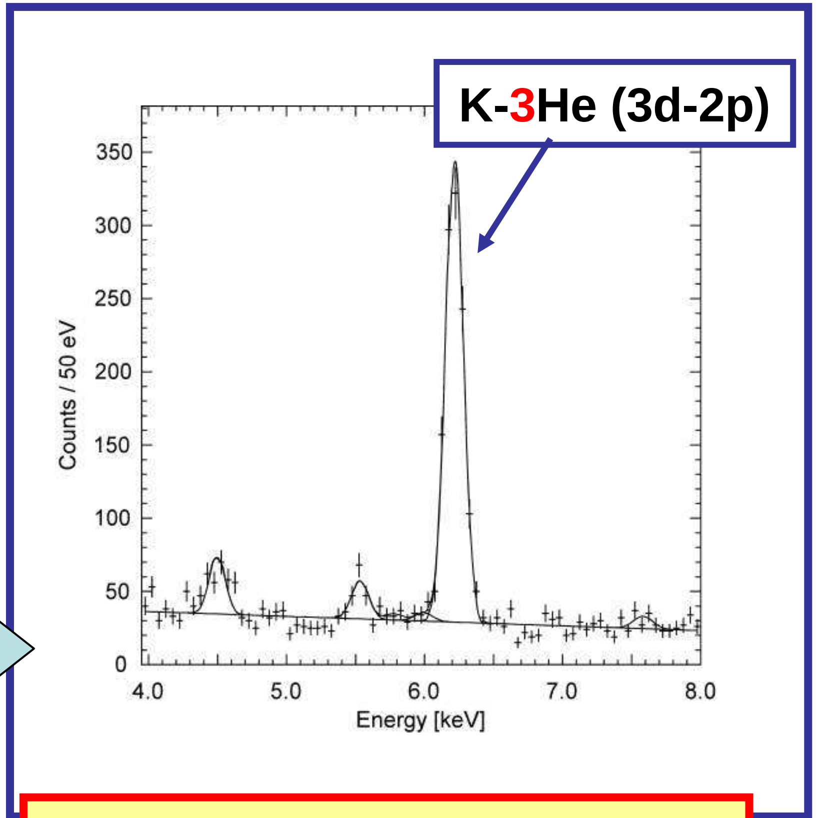


$$\Delta E_{2p} = +5 \pm 3(sta) \pm 4(sys)\ \text{eV}$$

DAFNE shutdown in Summer



PLB697(2011)199



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

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

$$\Delta E_{2p} > 0\,(\text{"attractive"}\,shift),$$

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

Comparison of results

PLB653(2007)387

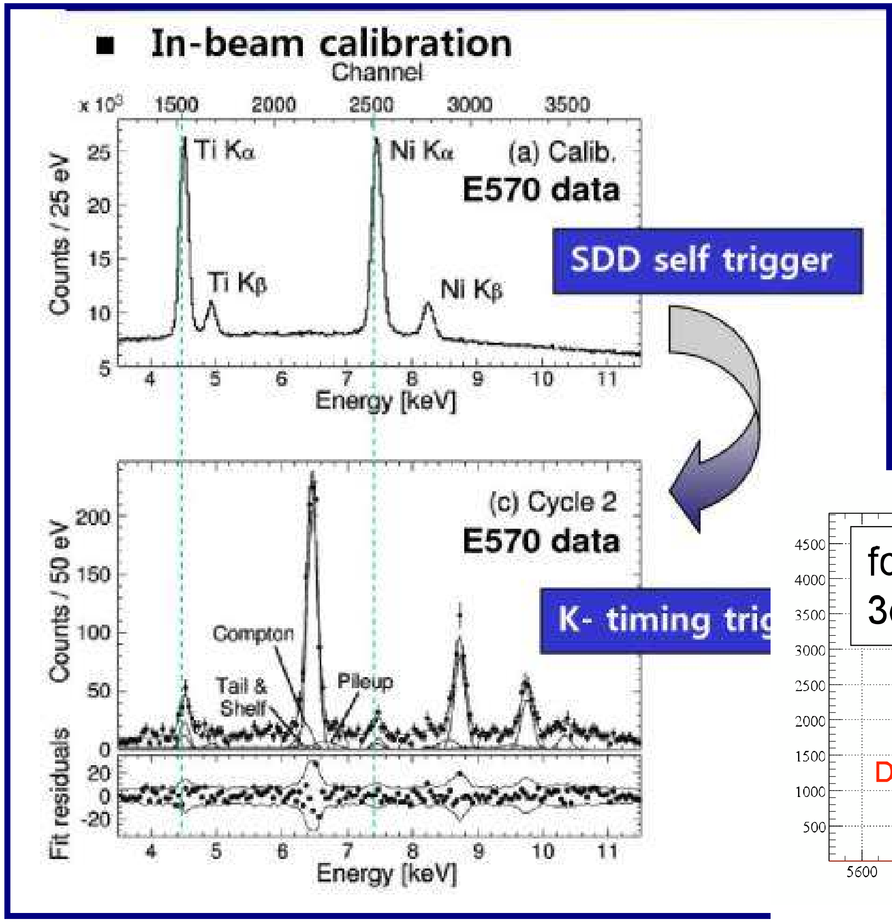
Kaonic 4He 2p level shift

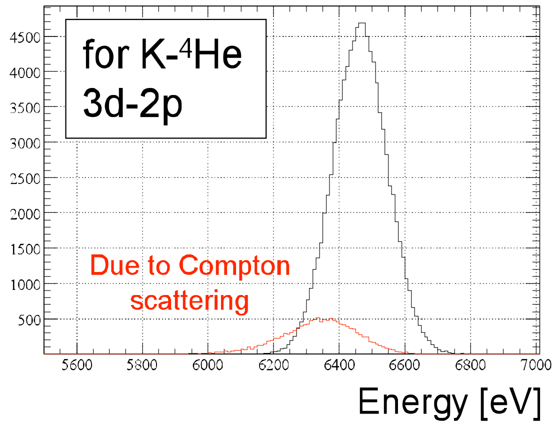
	Target	Shift [eV]
KEK E570	Liquid	+2±2±2 eV

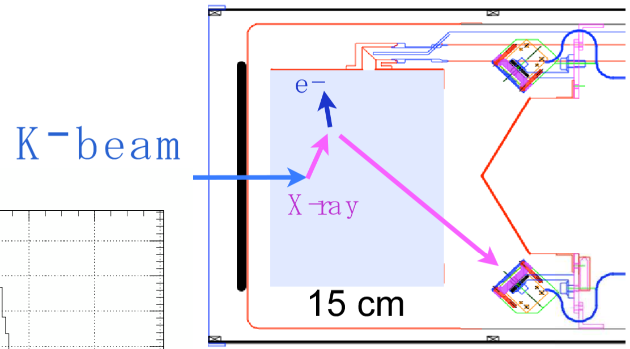
1. calibration/ and peak shape from Ti (4.5 keV) and Cu (8.0 keV). Apply for K-4He (6.4 keV)
2. Simulation of Compton tail using measured kaon stopping distribution.

Sys err = uncertainty of above

Sato, ECT* Workshop 2009







Comparison of results

PLB681(2009)310

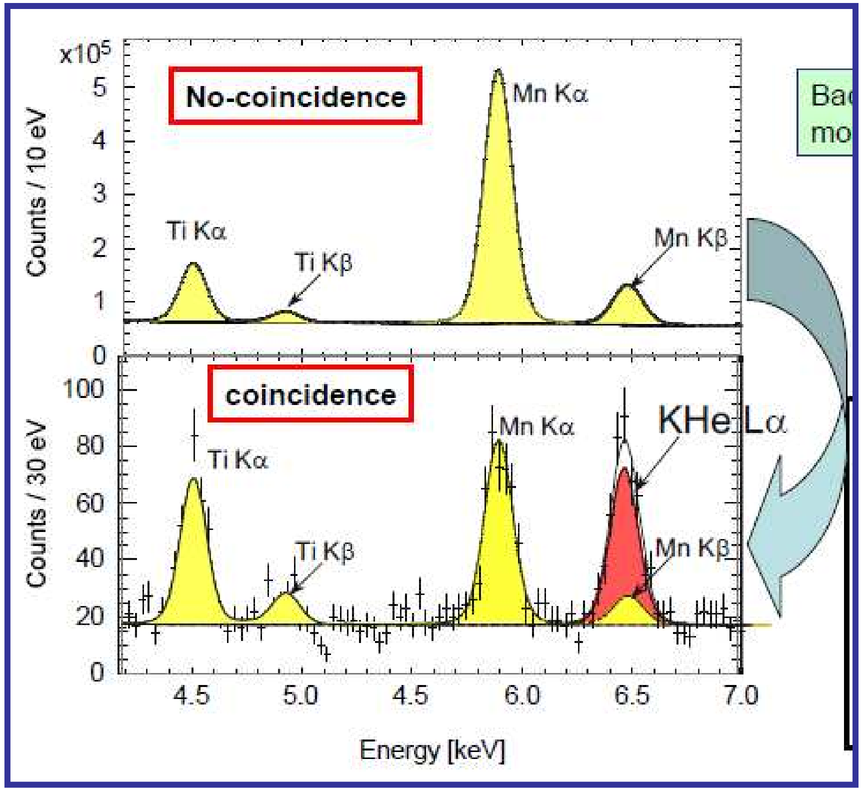
Kaonic 4He 2p level shift

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

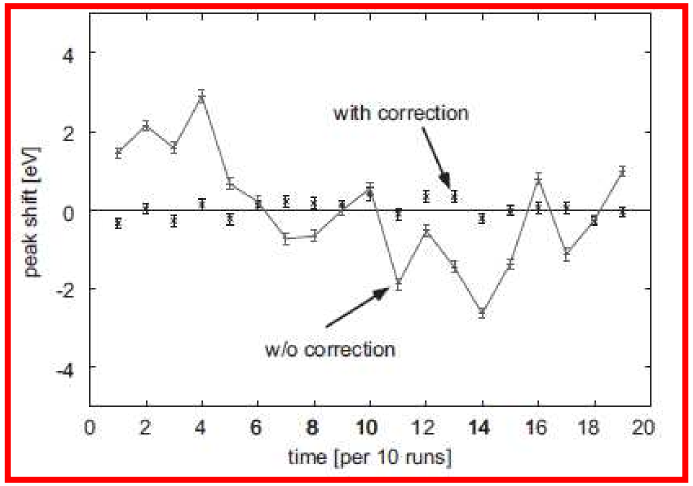
1. Calibration and peak shape from Mn (5.9 keV)

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

Ishiwatari, ECT* Workshop 2009



NIM A 628(2011)264



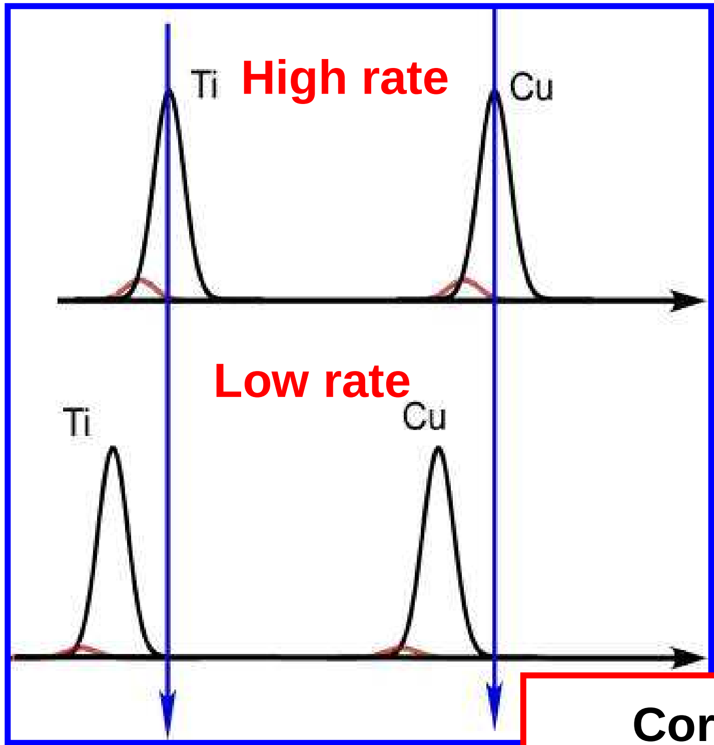
Comparison of results

PLB697(2011)199

	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

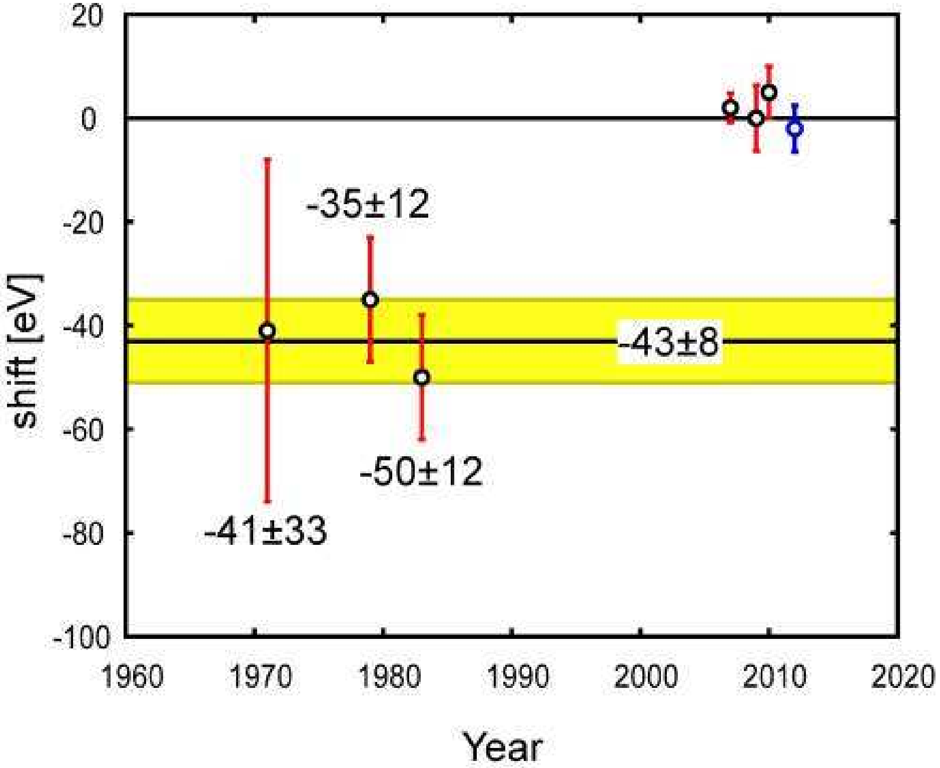


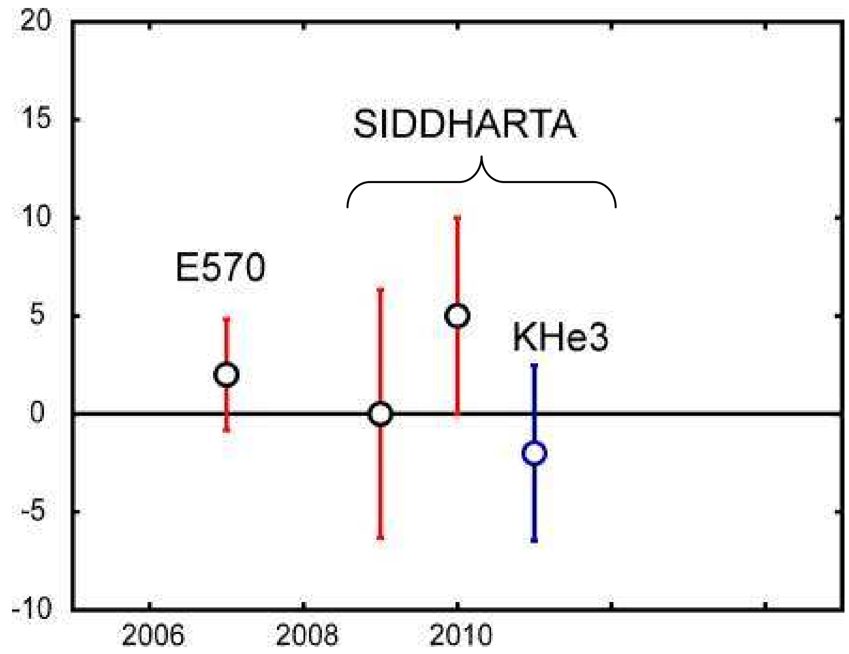
Correction term:

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

Comparison of results

	Shift [eV]	Reference
KEK E570	$+2\pm2\pm2$	PLB653(2007)387
SIDDHARTA (He4 with 55Fe)	$+0\pm6\pm2$	PLB681(2009)310
SIDDHARTA (He4)	$+5\pm3\pm4$	arXiv:1010.4631, PLB697(2011)199
SIDDHARTA (He3)	$-2\pm2\pm4$	





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

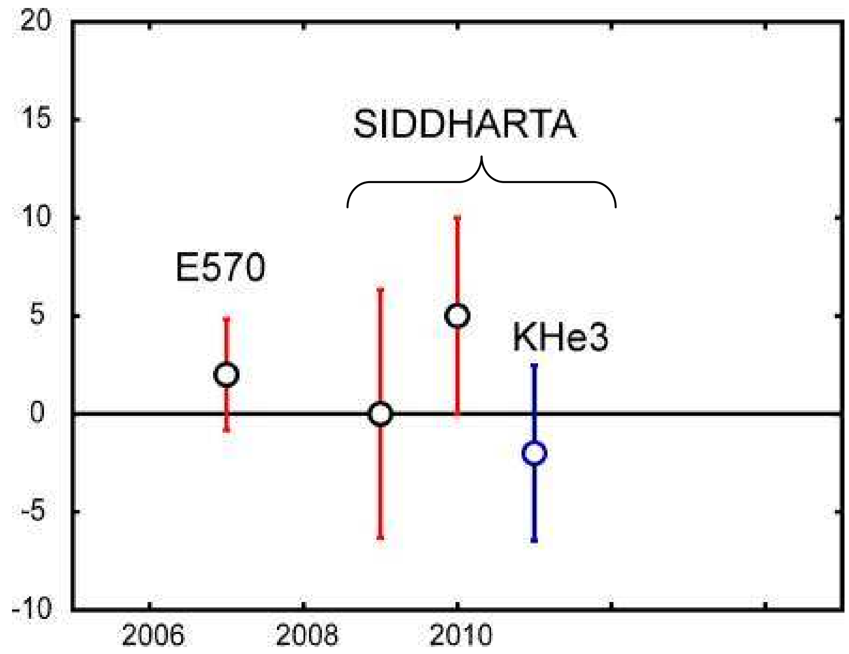
Comparison of results

	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

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)	$+0 \pm 6 \pm 2$	PLB681(2009)310
K-He4	$+5 \pm 3 \pm 4$	arXiv:1010.4631, PLB697(2011)199
K-He3	$-2 \pm 2 \pm 4$	

Outlook

- Isotope shift between He3& He4??
- Determination of width
- Determination of X-ray yields between gas &liquid
- Further kaonic atom measurements with Z>=3

	Shift [eV]	**Reference**
K-He4 (with 55Fe)	**$+0\pm6\pm2$**	**PLB681(2009)310**
K-He4	**$+5\pm3\pm4$**	**arXiv:1010.4631, PLB697(2011)199**
K-He3	**$-2\pm2\pm4$**	

Supported by

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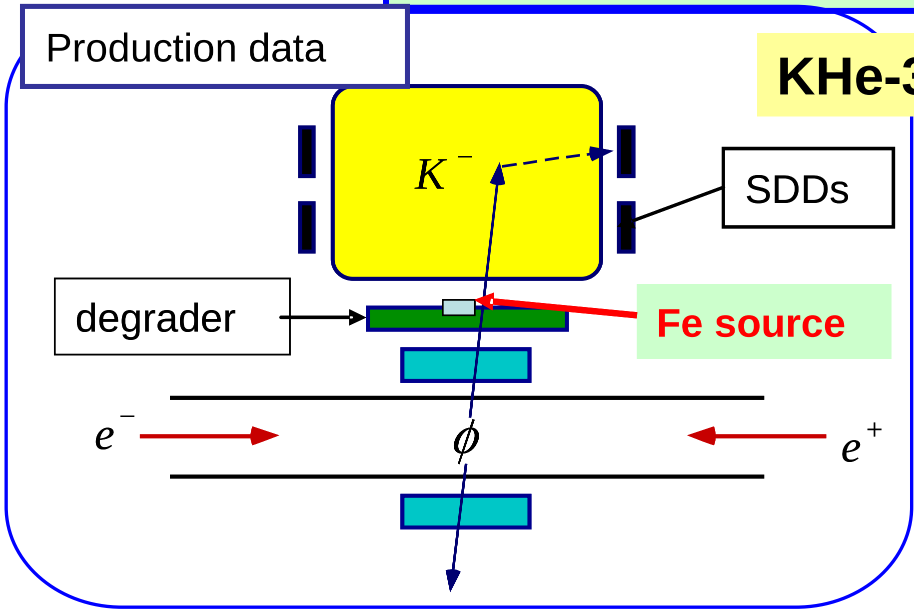
Austrian Federal Ministry of Science and Research BMBWK [650962/0001 VI/2/2009]

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

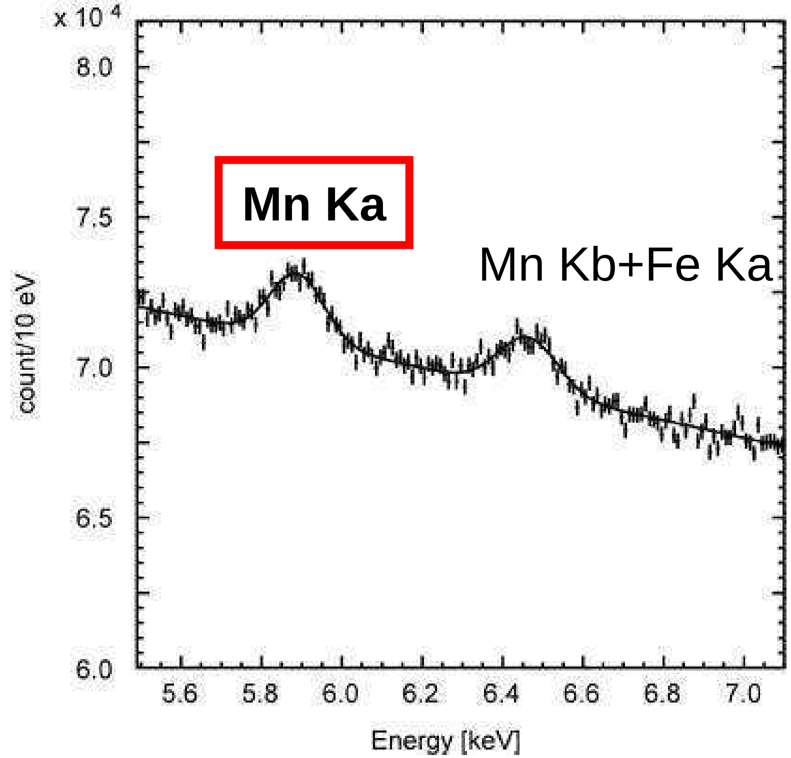
Grant-in-Aid for Specially Promoted Research (20002003), MEXT, Japan

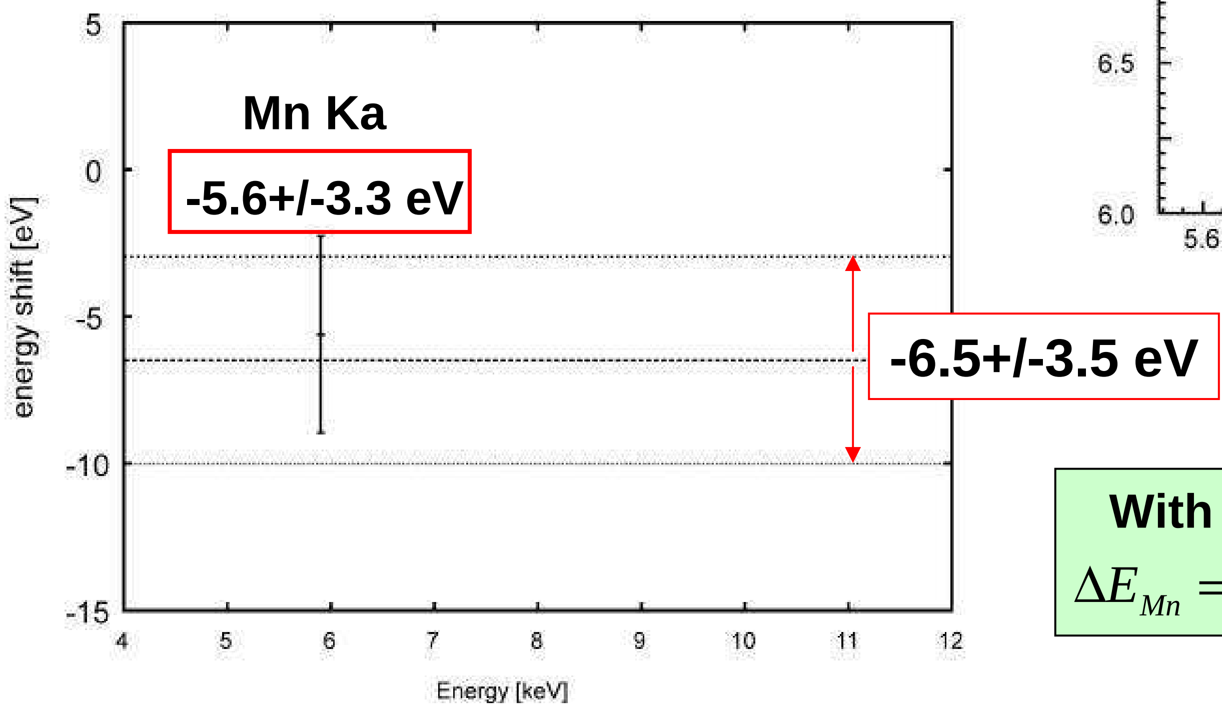
Austrian Science Fund (FWF): [P20651-N20]

Evaluation of systematic error



KHe-3 data with Fe source





With correction, Mn position

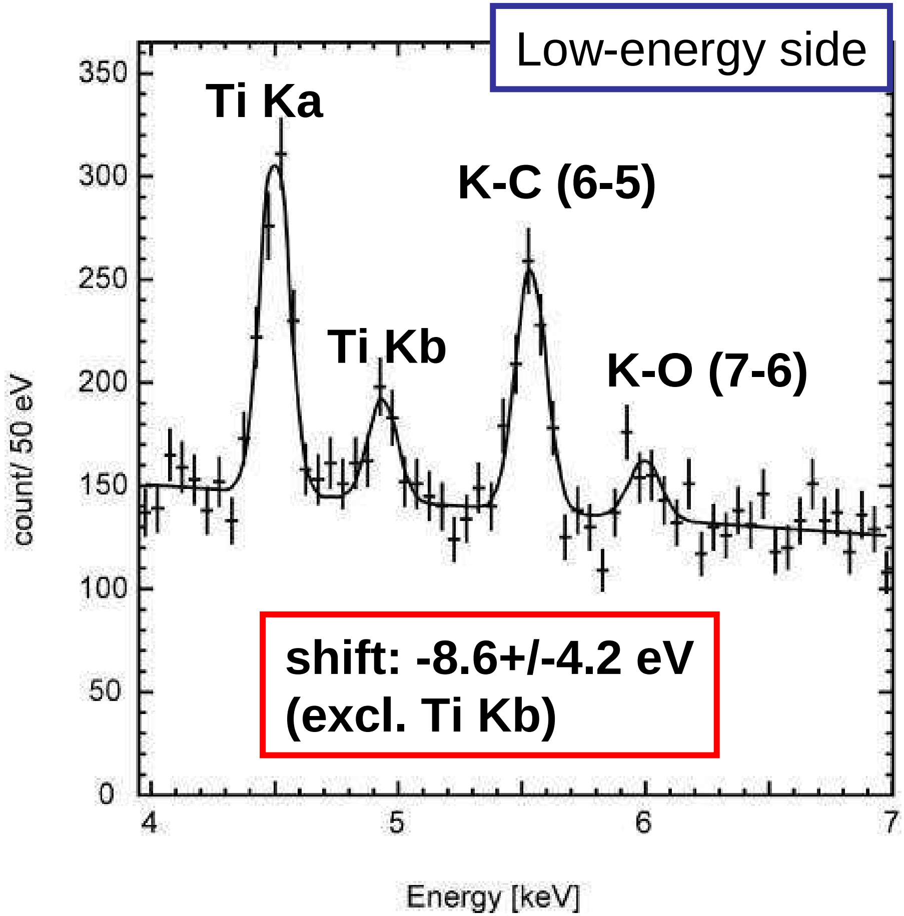
$$\Delta E_{Mn} = +0.9 \pm 3.3(stat) \pm 3.5(syst)\,\mathrm{eV}$$

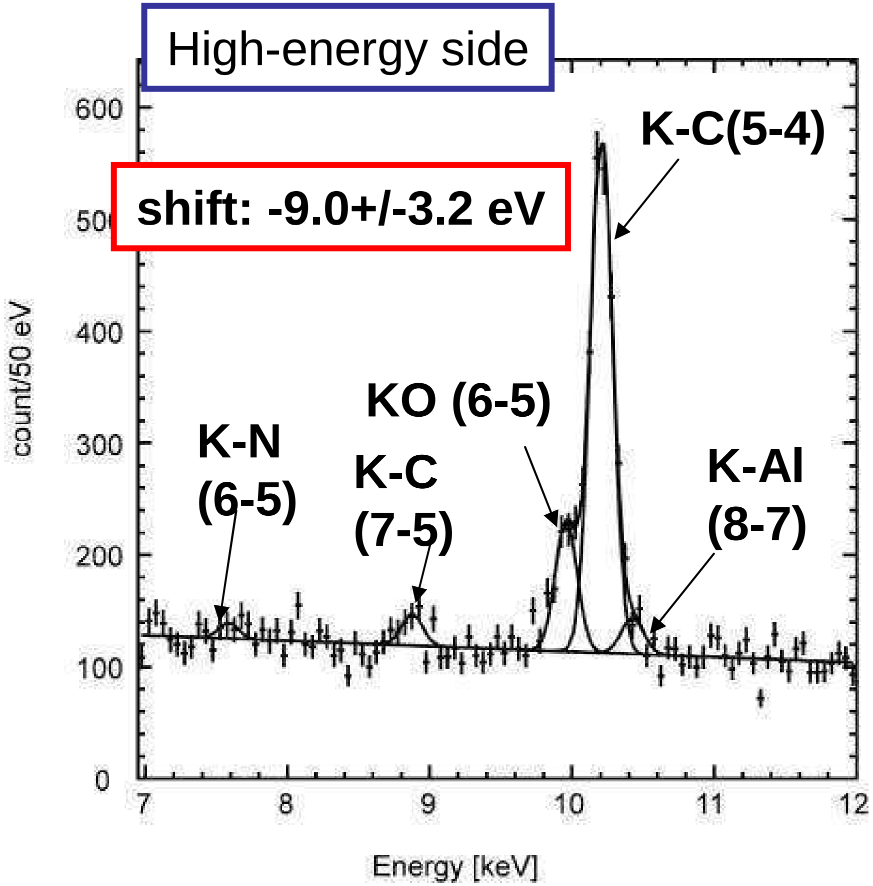
Evaluation of systematic error

“kaon-coincidence” with K-d data

Kapton window (C22H10N2O5)

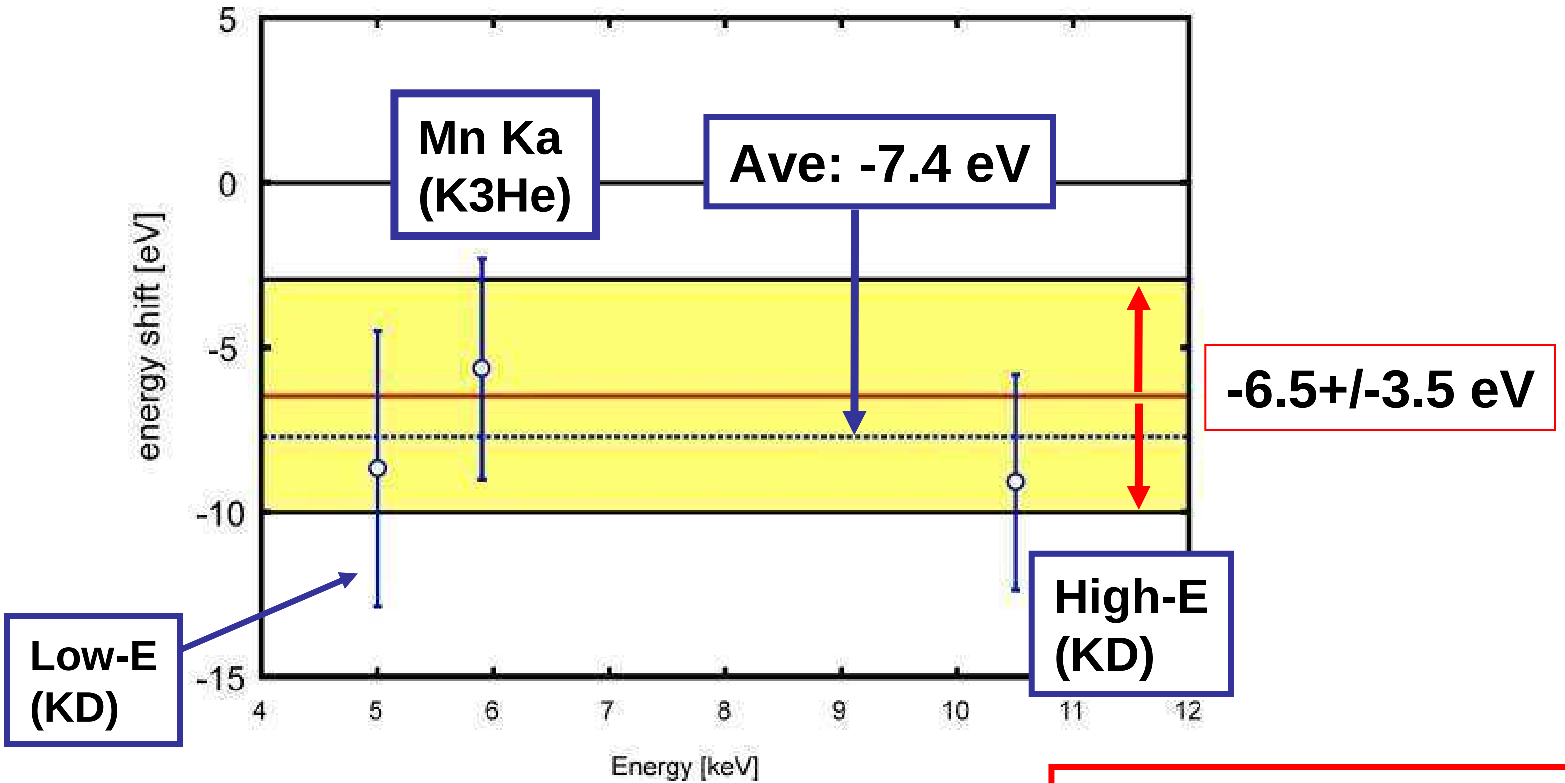
Fit of kaonic (C/O/Al) atom X-ray lines with known energy





Evaluation of systematic error

confirmation of the accuracy of energy determination & peak shift



Average of three points: consistent with the systematic error band

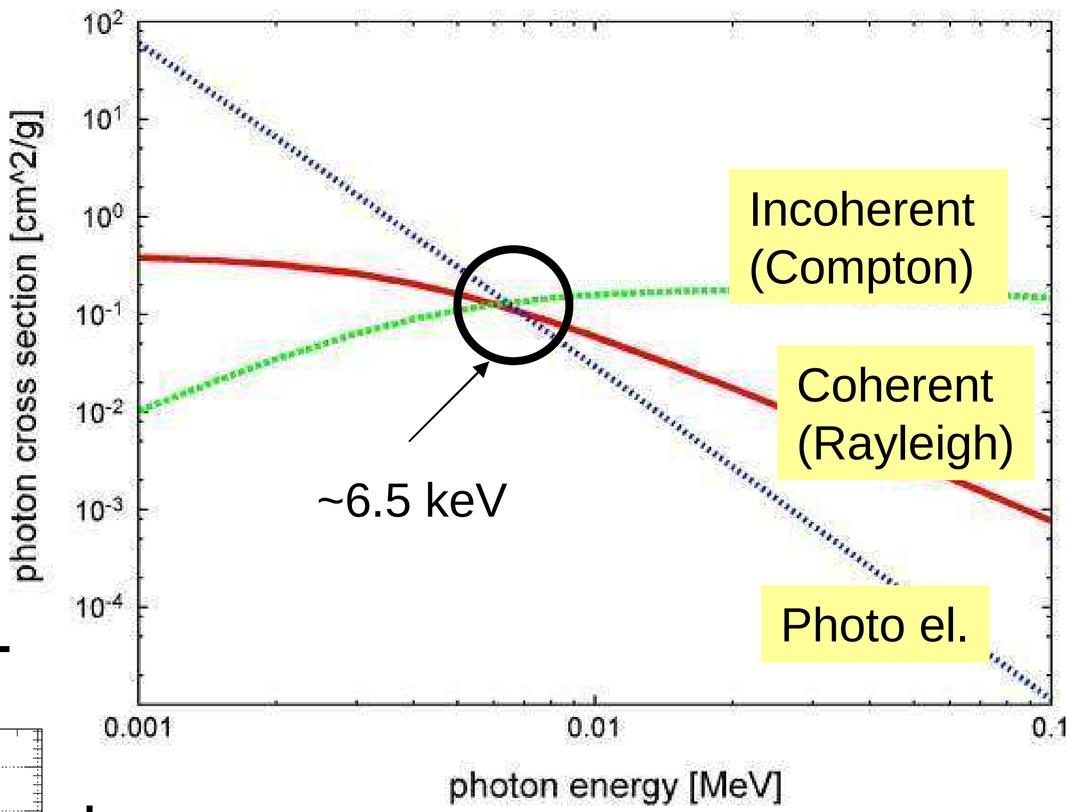
To obtain absolute energy from a fit value,

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

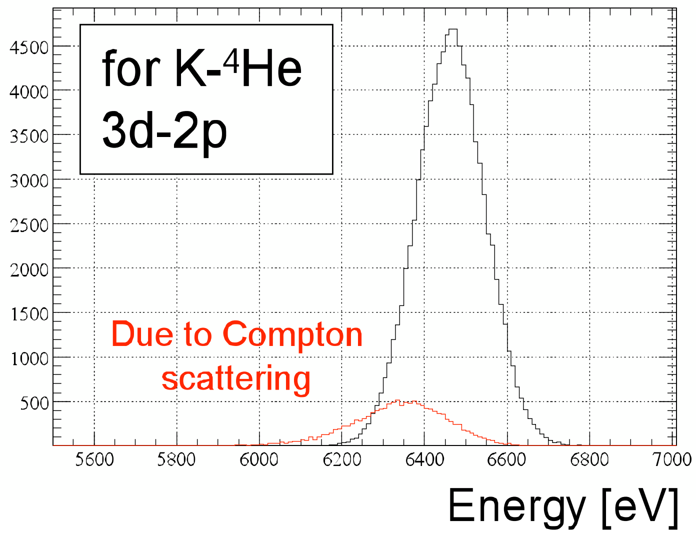
$$\varepsilon = +6.5 \pm 3.5 \text{ eV}$$

Photon cross section in helium

In helium, cross section of Compton effect is significant even in low-energy photons (~6.5 keV).
1/3=Compton effect



Liquid He (E570)



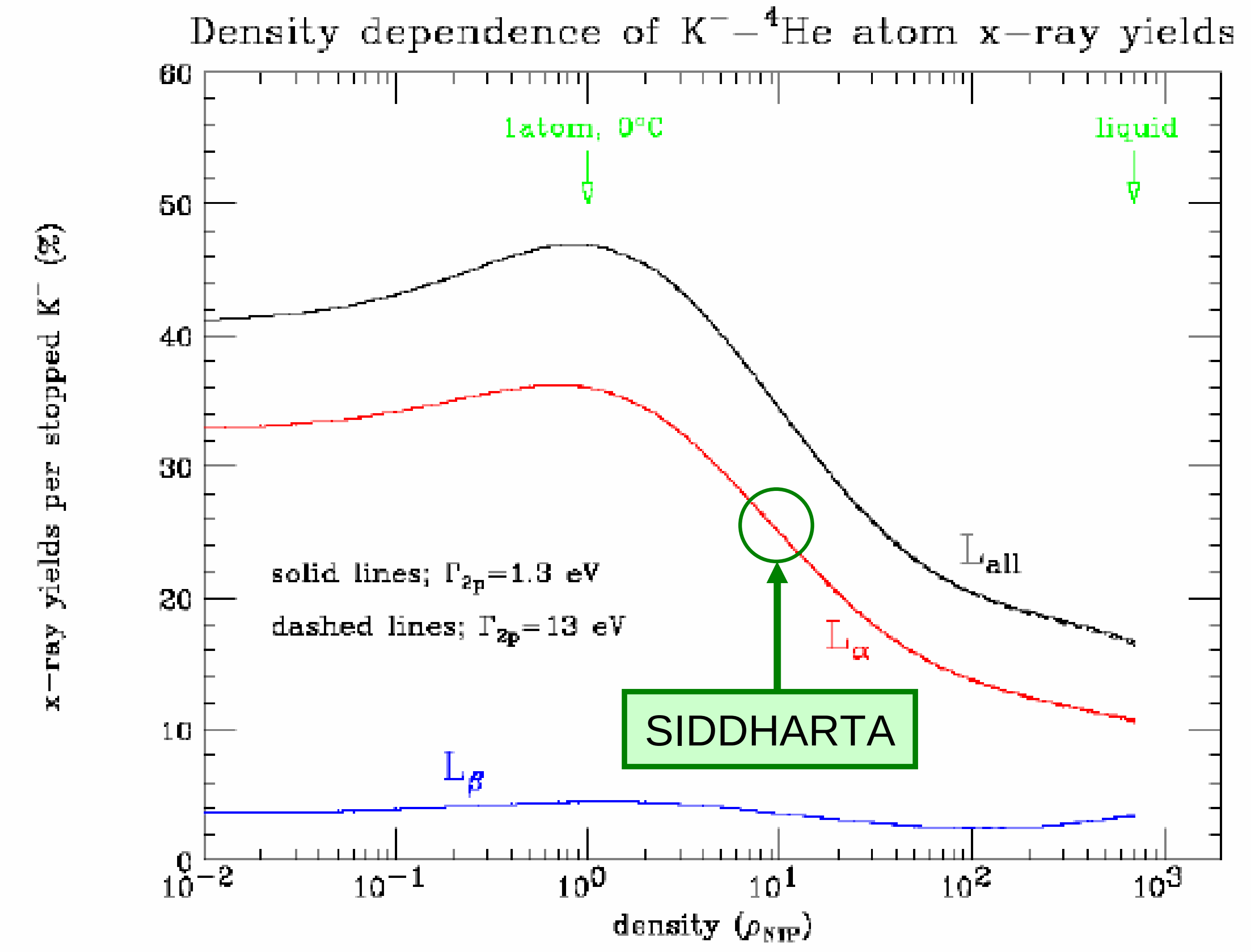
10% of X-rays in Liq. He (E570)
→ 10 eV peak shift (if Compton neglected)

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

Expected X-ray yields in helium gas

Y. Akaishi (EXA05 Presentation)

Calculated by T. Koike



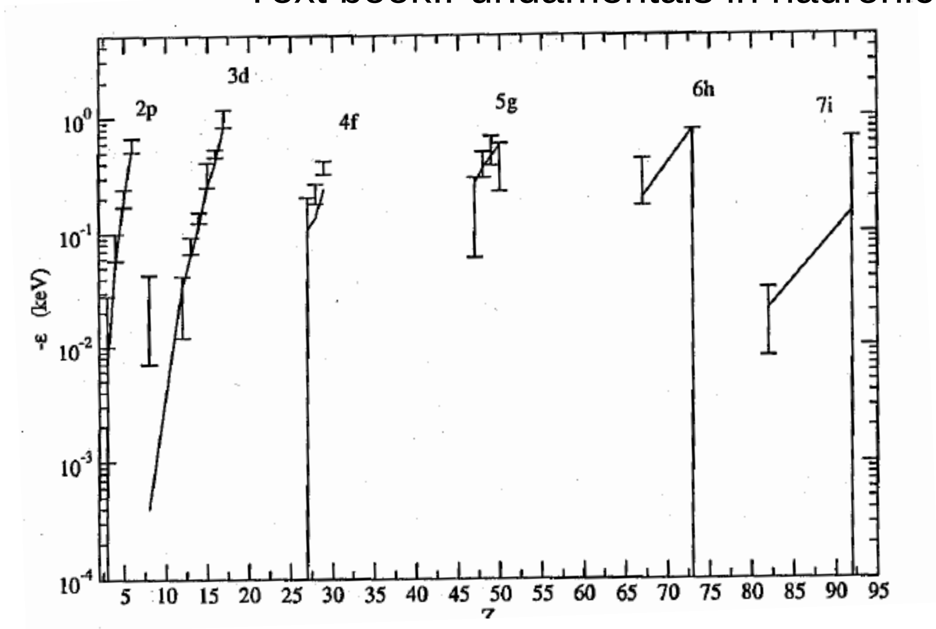
~2 times of
X-ray yields
in gas, compared
In liquid

Need to check!

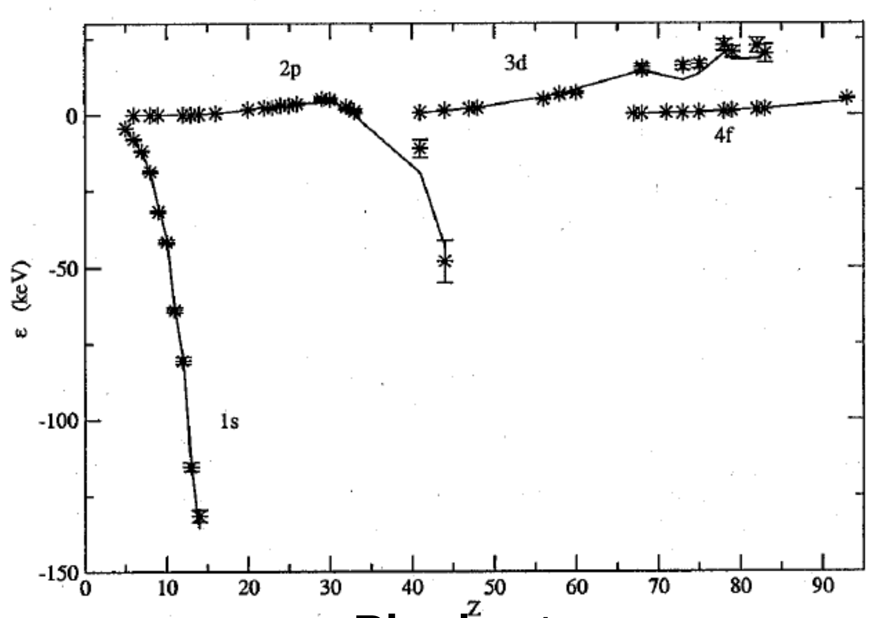
Kaonic atom data with Z>3

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)



Kaonic atom



Pionic atom

Kaonic atom data with Z>3

E. Friedman et al. / Nuclear Physics A579 (1994) 518–538 521

Table 1
Compilation of K^- atomic data

Nucleus	Transition	ϵ (keV)	Γ (keV)	Y	Γ_u (eV)	Ref.
He	$3 \to 2$	-0.04 ± 0.03	–	–	–	[15]
		-0.035 ± 0.012	0.03 ± 0.03	–	–	[16]
Li	$3 \to 2$	0.002 ± 0.026	0.055 ± 0.029	0.95 ± 0.30	–	[17]
Be	$3 \to 2$	-0.079 ± 0.021	0.172 ± 0.58	0.25 ± 0.09	0.04 ± 0.02	[17]
^{10}B	$3 \to 2$	-0.208 ± 0.035	0.810 ± 0.100	–	–	[18]
^{11}B	$3 \to 2$	-0.167 ± 0.035	0.700 ± 0.080	–	–	[18]
C	$3 \to 2$	-0.590 ± 0.080	1.730 ± 0.150	0.07 ± 0.013	0.99 ± 0.20	[18]
O	$4 \to 3$	-0.025 ± 0.018	0.017 ± 0.014	–	–	[19]
Mg	$4 \to 3$	-0.027 ± 0.015	0.214 ± 0.015	0.78 ± 0.06	0.08 ± 0.03	[19]
Al	$4 \to 3$	-0.130 ± 0.050	0.490 ± 0.160	–	–	[20]
		-0.076 ± 0.014	0.442 ± 0.022	0.55 ± 0.03	0.30 ± 0.04	[19]
Si	$4 \to 3$	-0.240 ± 0.050	0.810 ± 0.120	–	–	[20]
		-0.130 ± 0.015	0.800 ± 0.033	0.49 ± 0.03	0.53 ± 0.06	[19]
P	$4 \to 3$	-0.330 ± 0.08	1.440 ± 0.120	0.26 ± 0.03	1.89 ± 0.30	[18]
S	$4 \to 3$	-0.550 ± 0.06	2.330 ± 0.200	0.22 ± 0.02	3.10 ± 0.36	[18]
		-0.43 ± 0.12	2.310 ± 0.170	–	–	[21]
		-0.462 ± 0.054	1.96 ± 0.17	0.23 ± 0.03	2.9 ± 0.5	[19]
Cl	$4 \to 3$	-0.770 ± 0.40	3.80 ± 1.0	0.16 ± 0.04	5.8 ± 1.7	[18]
		-0.94 ± 0.40	3.92 ± 0.99	–	–	[22]
						[21]

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