Decay data measurements using MMCs at CEA-LNHB

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MiND Workshop, June 28, 2023

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Outline

- Introduction
  - Presentation of the CEA-LNHB
  - Short history of the MMCs at LNHB
- Decay data by decay energy spectrometry
  - Beta shape of ^{63}Ni and ^{241}Pu
  - BR and end-point energy of ^{151}Sm
  - Electron capture probabilities of ^{55}Fe
- Absolute L X-ray emission intensities of actinides
  - The MMC SMX3
  - L X-rays from the decay of ^{238}Pu, ^{244}Cm ^{233}Pa, ^{237}Np
  - L X-rays from the decay of ^{241}Am

1. Introduction

The Laboratoire National Henri Becquerel Activity Metrology

Conventional methods for activity standardization

- 4πβ-γ coincidence
- α-particle counting by defined solid angle
- Liquid scintillation (TDCR method)
- Triple internal gas counting
- And others…

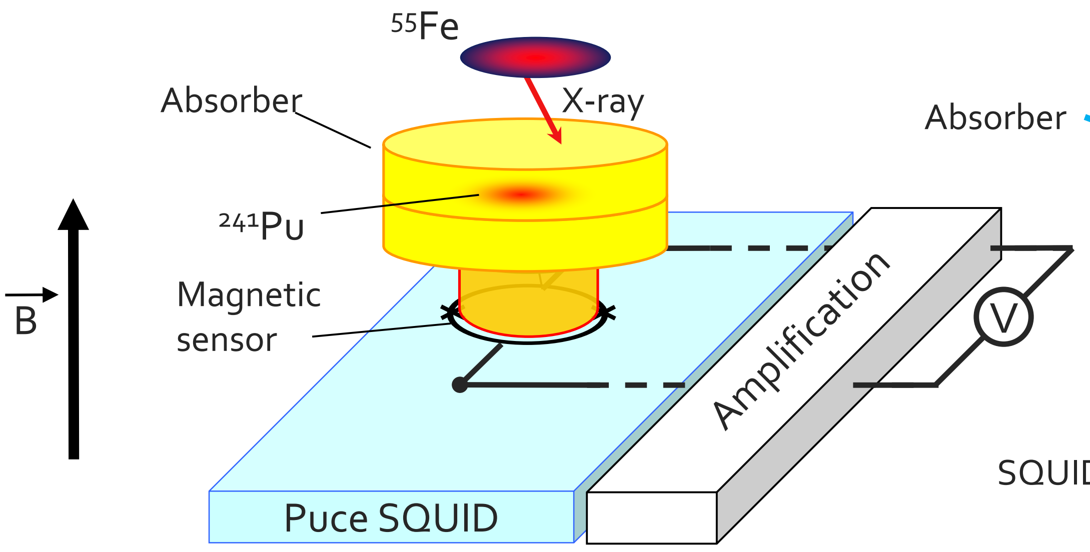
Decay data measurements and evaluations

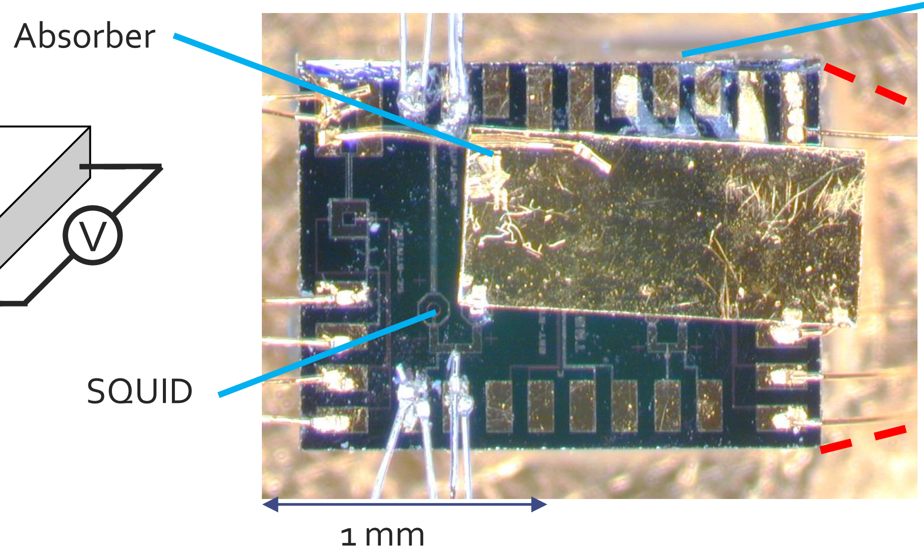
- Beta and gamma-ray spectrometry
- Monochromatic sources of photons
- Code Beta shape
- DDEP Decay Data Evaluation Project (Data recommendation dissemination of data http://www.lnhb.fr/donnees-nucleaires/module-lara/)
- **Metallic magnetic calorimeters**

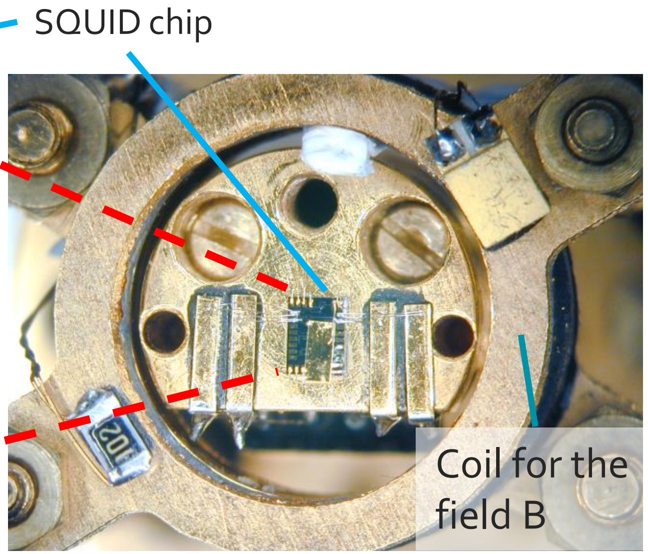
Radioactive source preparation

- Authorizations to prepare and to measure many radionuclides with large activity,
- Liquid, solid or gaseous radioactive source
- Radiochemical separation
- Source activities with low uncertainties

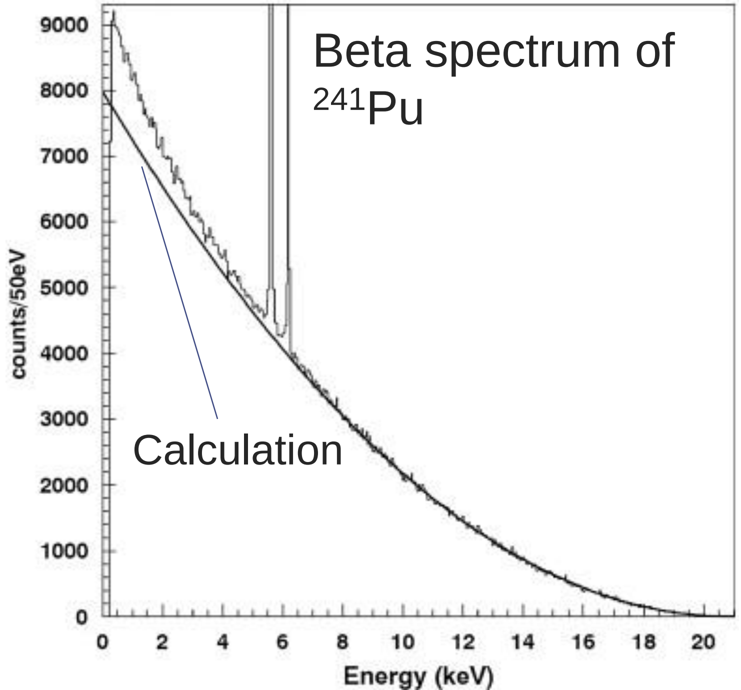
MMC at LNHB: started in 2004 with the direct coupling







- Electroprecipited ^{241}Pu source (8 Bq) between two 12 µm thick gold foils
- Energy calibration: external ^{55}Fe source
- Data recorded continuously 2.6 days @ 16 mK



Applied Radiation and Isotopes 68 (2010) 1454–1458

Contents lists available at ScienceDirect

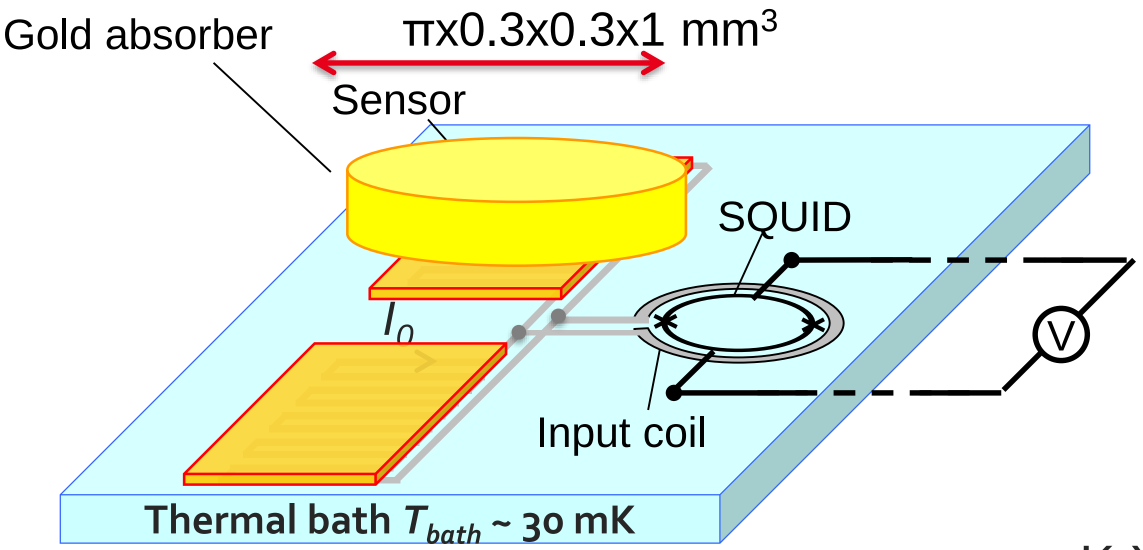
Applied Radiation and Isotopes

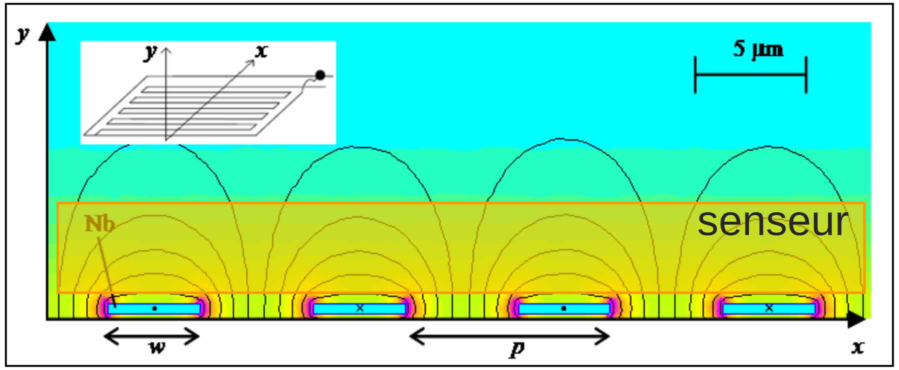
journal homepage: www.elsevier.com/locate/apradiso

First measurement of the beta spectrum of ^{241}Pu with a cryogenic detector

M. Loidl *, M. Rodrigues, B. Censier, S. Kowalski, X. Mougeot, P. Cassette, T. Branger, D. Lacour

MMC at LNHB : 2008,
Coupling with meander shape pick-up coil

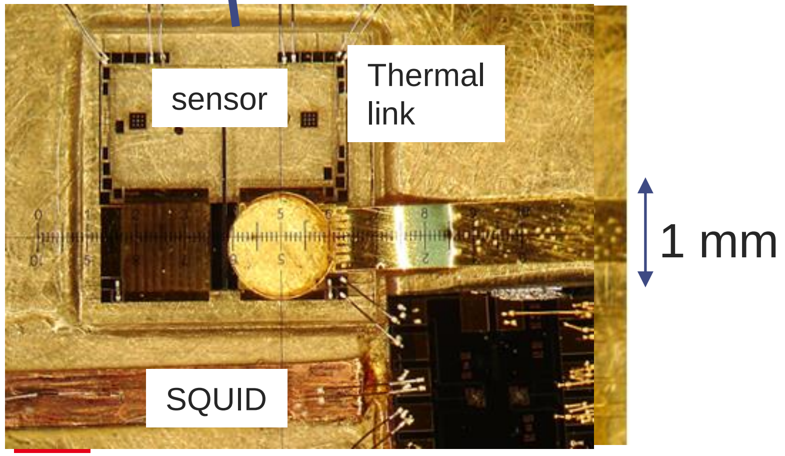




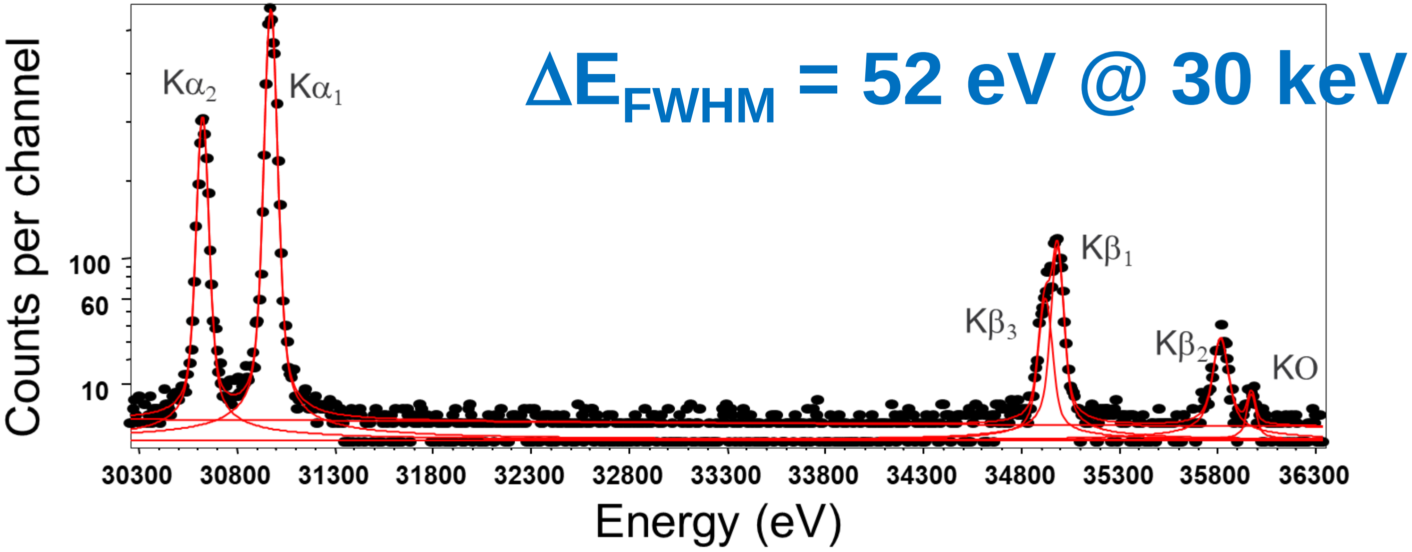
A. Burck et al., J Low Temp Phys (2008) 151: 337–344

MMC chip produced by the KIP Heidelberg

KIRCHHOFF-INSTITUT FÜR PHYSIK



K X-ray spectrum of ^{133}Ba



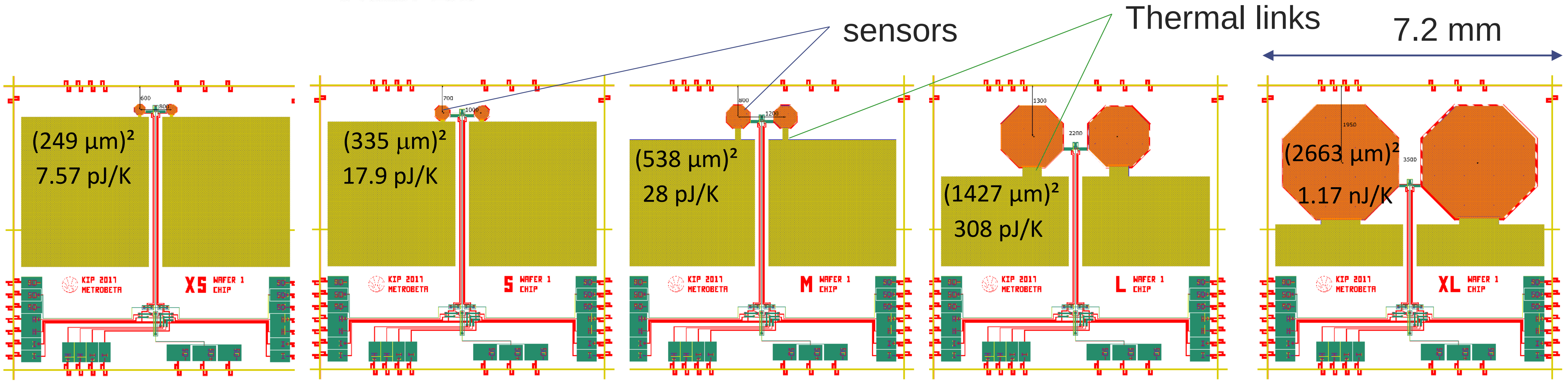
MMC chips produced in collaboration with KIP Heidelberg 2010-2021 and KIT Karlsruhe 2021-now

Different MMC sizes produced to address different projects (European project of metrology MetroBeta, MetroMMC, PrimA-LTD)

PrimA-LTD

MetroMMC — Measurement of fundamental nuclear decay data using Metallic Magnetic Calorimeters

MetroBeta — Radionuclide beta spectra metrology



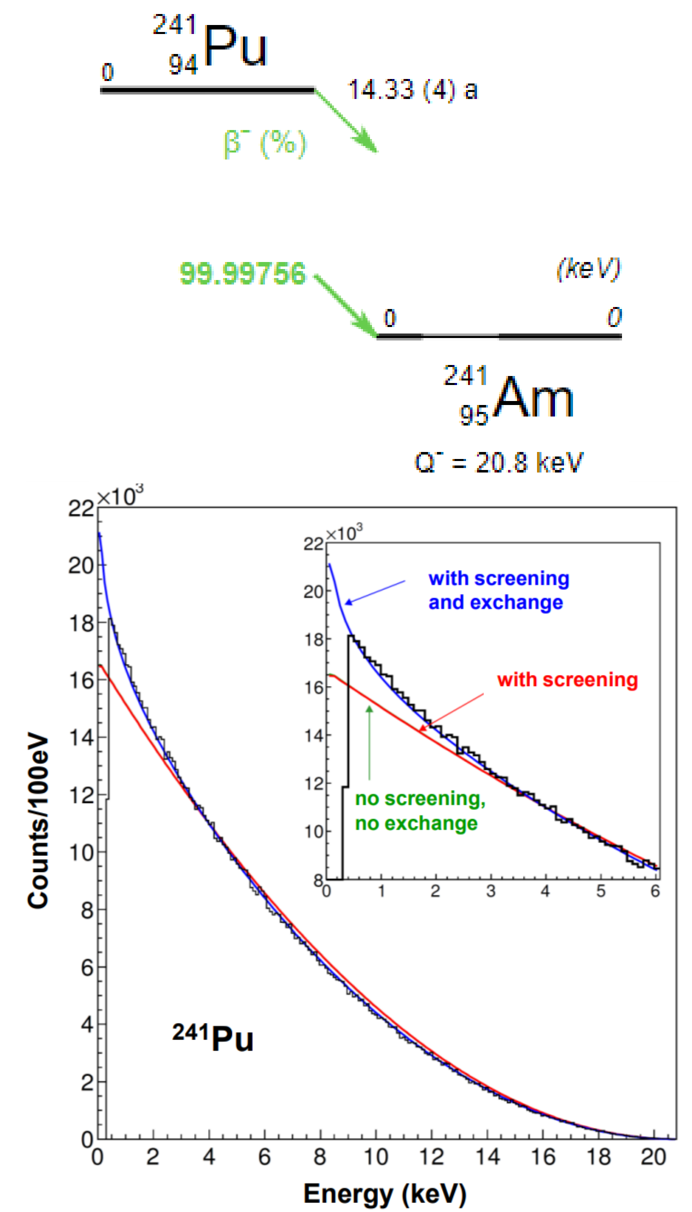
For a given radionuclide and a given spectrometry, absorber sized is to achieve the required efficiency.

→ The sensor MMC size chosen such as the sensor matches the absorber heat capacity

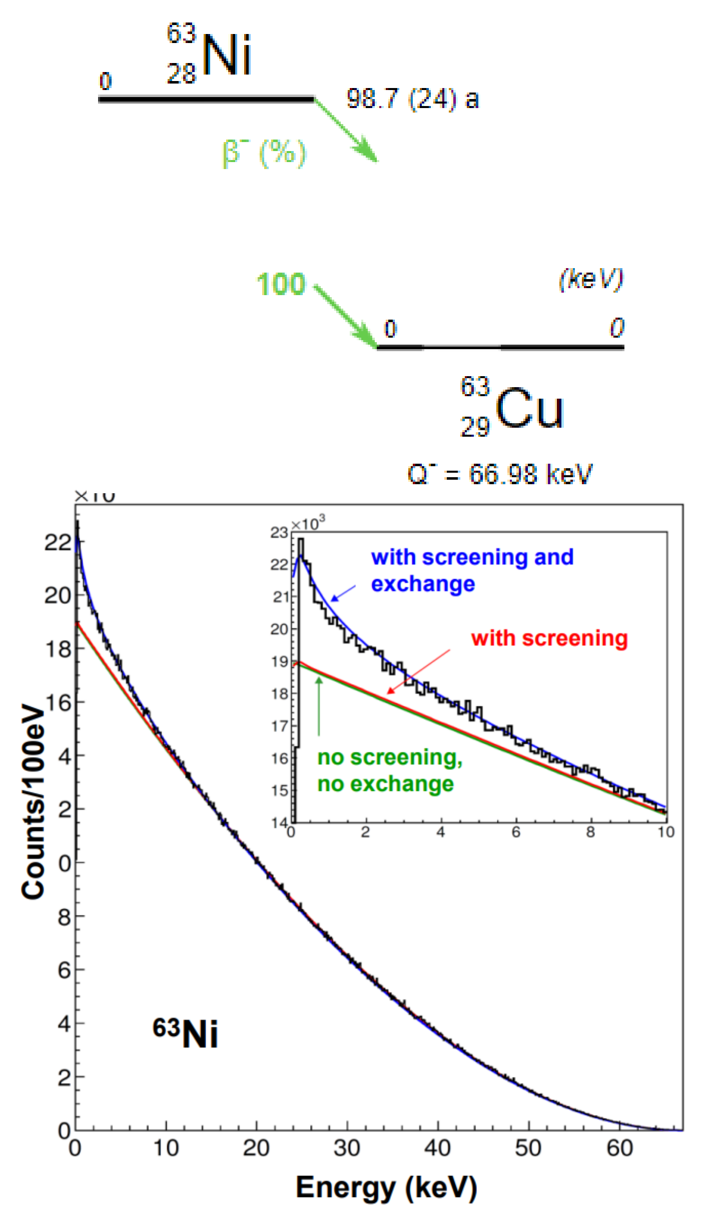
→ The source+absorber prepared at LNHB and attached to the sensor by gluing

2. Decay data by decay energy spectrometry

Beta spectrum shapes of ^{241}Pu and ^{63}Ni



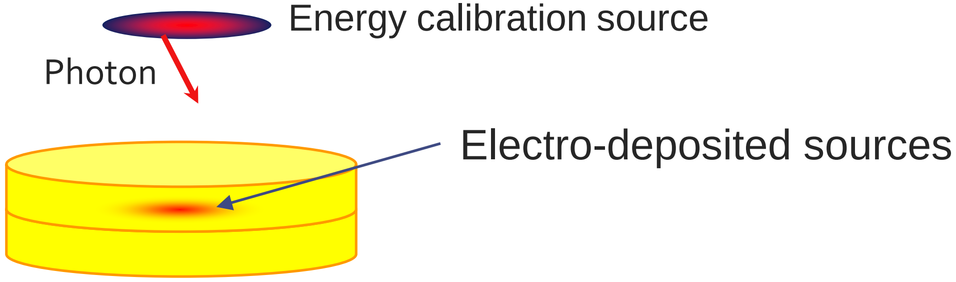
M. Loidl *et al.* ARI Vol. 68 P1454, 2010
https://doi.org/10.1016/j.apradiso.2009.11.054



M. Loidl, *et al.* ARI Vol. 84, P302, 2014
https://doi.org/10.1016/j.apradiso.2013.11.024

^{241}Pu and ^{63}Ni are pure β emitters to the ground state (GS)

- Activity measurements only is achieved by LSC
- The knowledge of the β shape is needed



The measured spectra have:

- 100% detection efficiency
- Energy threshold
  - 200 eV for ^{63}Ni, 300 eV for ^{241}Pu
- FWHM energy resolution
  - 51 eV for ^{63}Ni, 29 eV for ^{241}Pu
- shown evidence of the exchange effect
- validated the theoretical code BetaShape

X. Mougeot, EPJ Web Conf. Vol. 146, 2017
https://doi.org/10.1051/epjconf/201714612015

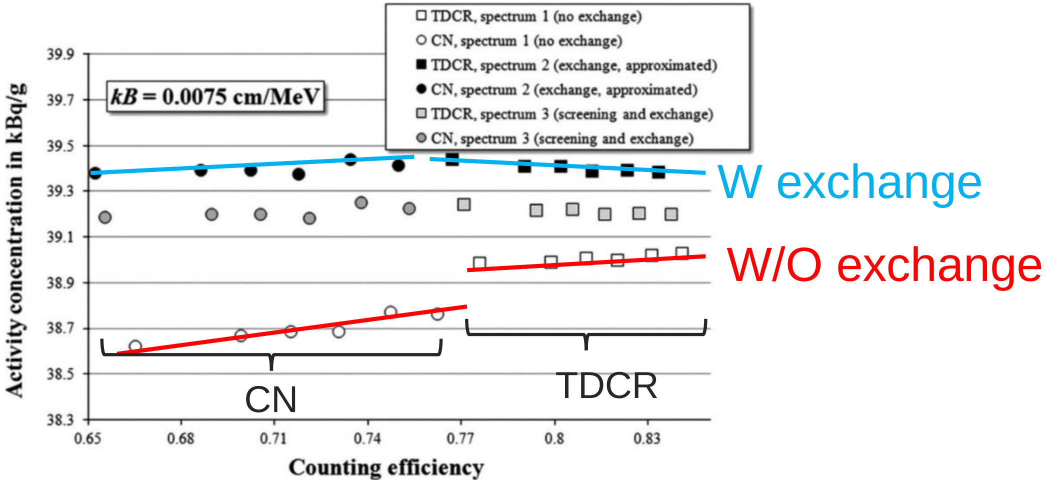
Impact on the activity measurement by LSC

Counting efficiency in liquid scintillation depends on the beta spectrum for the 2 LSC methods:

- CIEMAST/NIST (CN) (2 PMTs) $\varepsilon = \int_0^{E_{max}} S(E)(1-e^{-\eta})^2 dE$

- TDCR (triple to double coincidence ratio) (3 PMTs) $TDCR = \frac{R_T}{R_D} = \frac{\int_0^{E_{max}} S(E)(1-e^{-\eta})^3 dE}{\int_0^{E_{max}} S(E)((3(1-e^{-\eta})^2 - 2(1-e^{-\eta})^3))dE}$

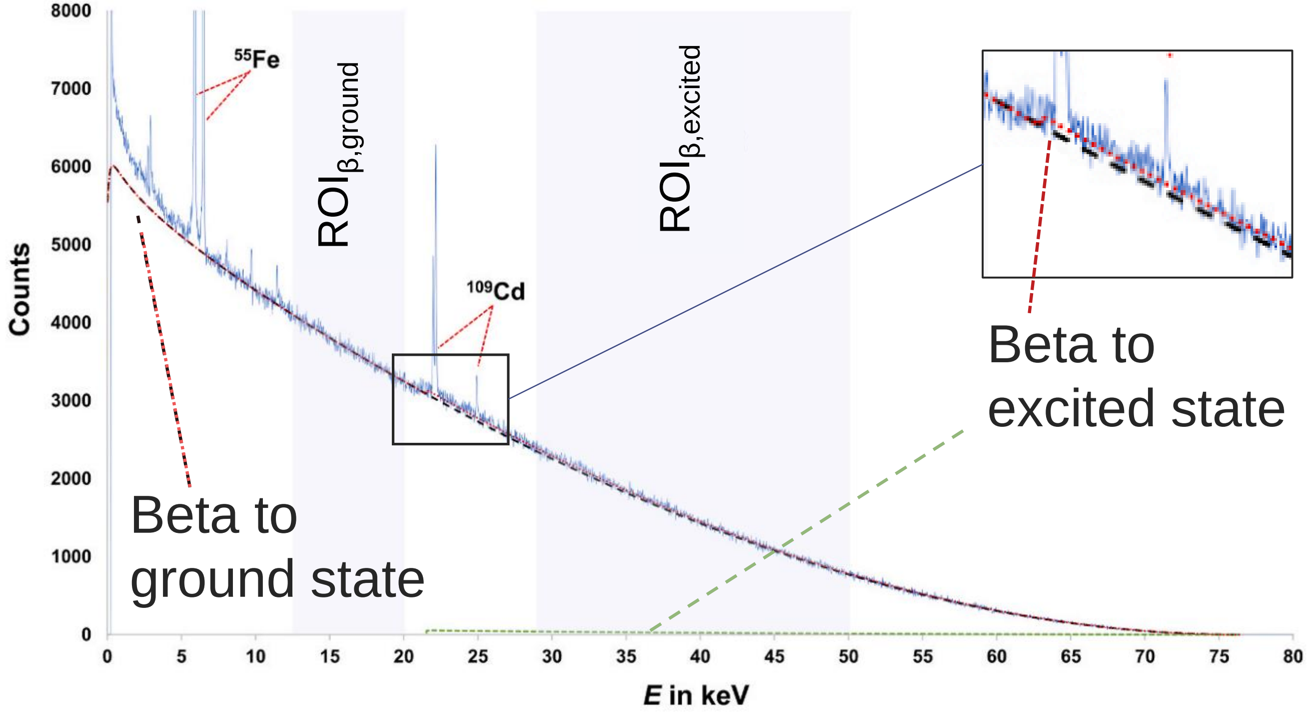
$$\eta = \frac{v}{n}\int_0^E \frac{A\,dE}{1+kB\frac{dE}{dx}}$$ Birks's expression

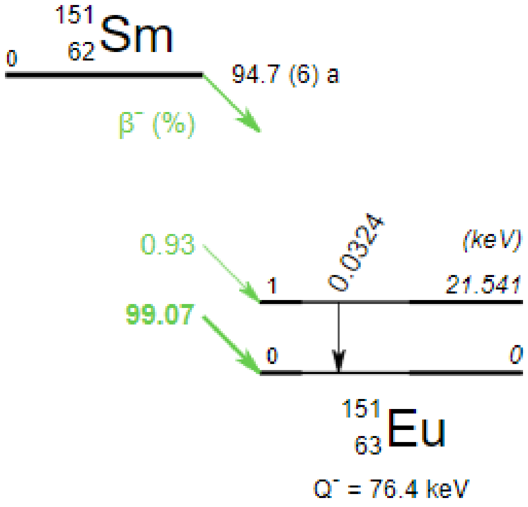


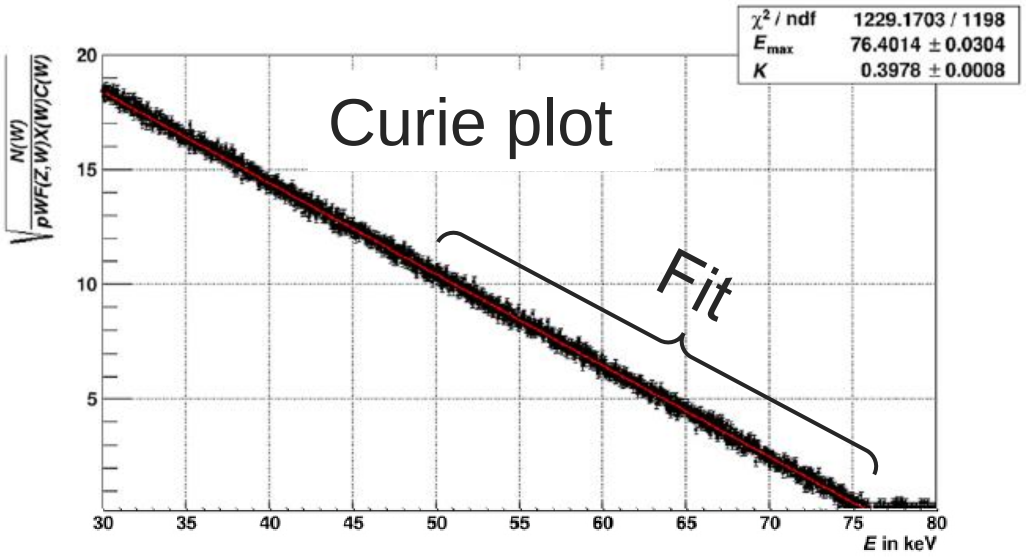
→Better agreement between the 2 LSC methods taking into account the exchange effect

K. Kossert, X. Mougeot, ARI Vol 101, 2015, P40-43
https://doi.org/10.1016/j.apradiso.2015.03.017

Beta spectrum of ^{151}Sm branch probabilities and end-point







- Measured $P_{\beta,ground}$ = **99.31 (11)%** and $P_{\beta,excited}$ = **0.69 (11)%**

  Recommended value DDEP: **99.07 (4)%** and **0.93 (4)%**

- Measured E_{max} = **76.430 (68) keV.**

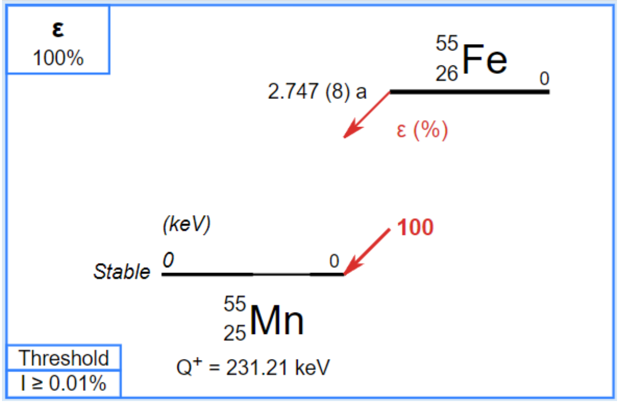
  Recommended value AME2020: **76.5 (5) keV**

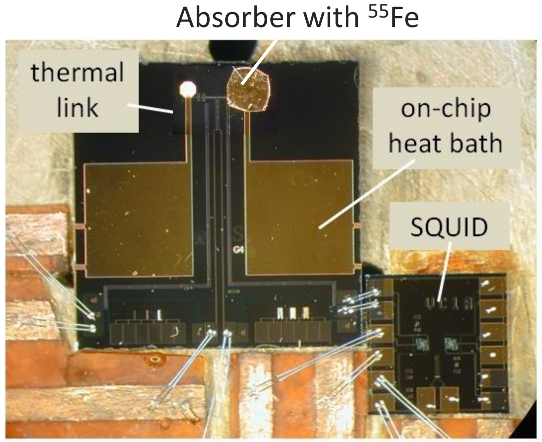
K. Kossert, ARI, Vol. 185, 110237, 2022
https://doi.org/10.1016/j.apradiso.2022.110237

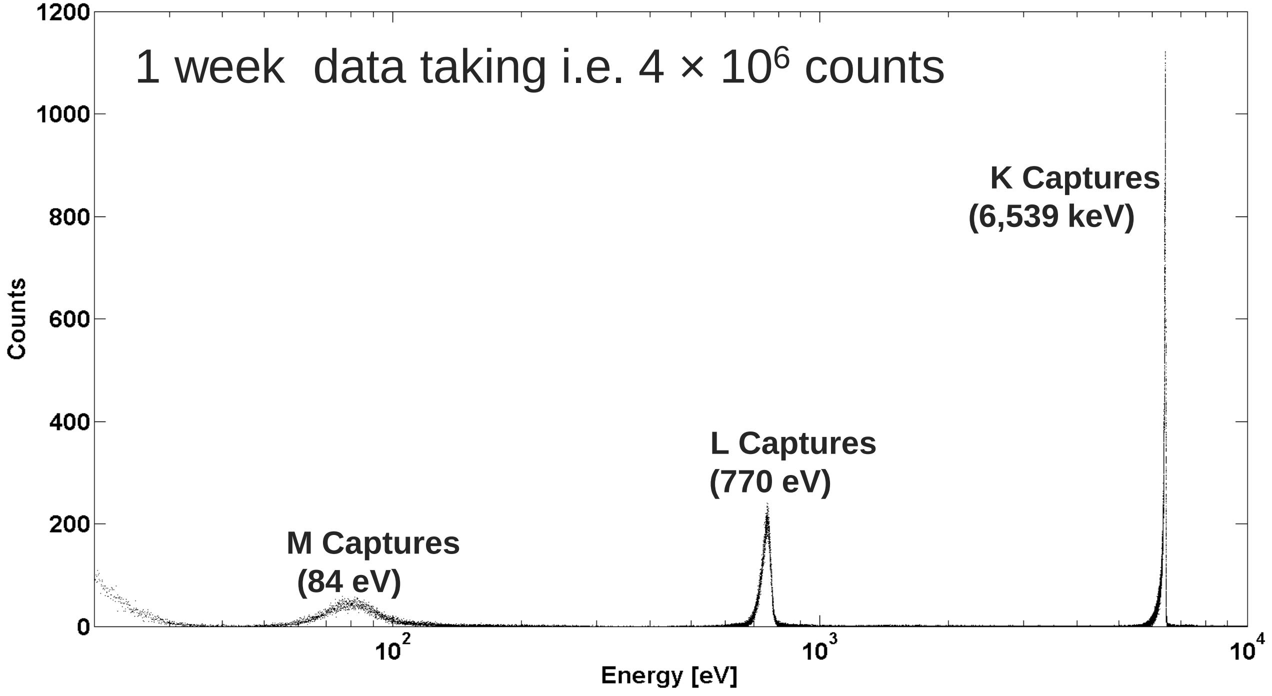
Electron capture probabilities (EC) of ^{55}Fe

Like pure beta emitters to the GS, EC radionuclides to the GS can only be measured in LSC
→ EC probabilities is required.

- Source prepared by electroplating on Au foil
- Source foil with ~ 10 Bq of ^{55}Fe between two Au foils
- Absorber dimensions 600 µm × 600 µm × 24 µm







EC probability	Calculated Value	Pengra *et al.* 1972	Loidl *et al.* 2018 P_N = 0.0014 ($\sigma_{stat.}$)
PK	0.8853 (16)	0.881 (4)	0.8833 (26)
PL	0.0983 (13)	0.103 (4)	0.1001 (22)
PM	0.0157 (6)	0.0161 (8)	0.01515 (38)

M. Loidl, et al. ARI, Vol. 134, P395, 2018
https://doi.org/10.1016/j.apradiso.2017.10.042

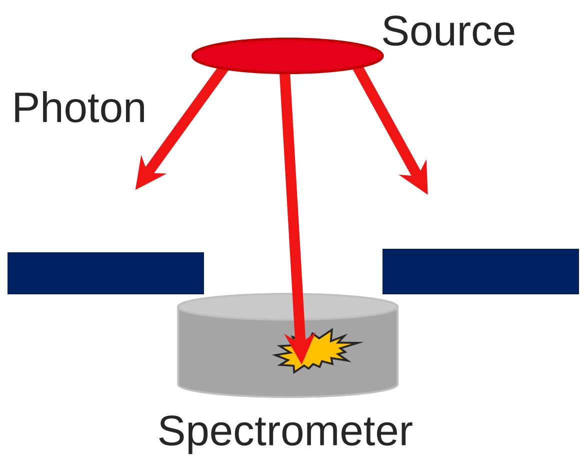
3. Decay data by photon spectrometry

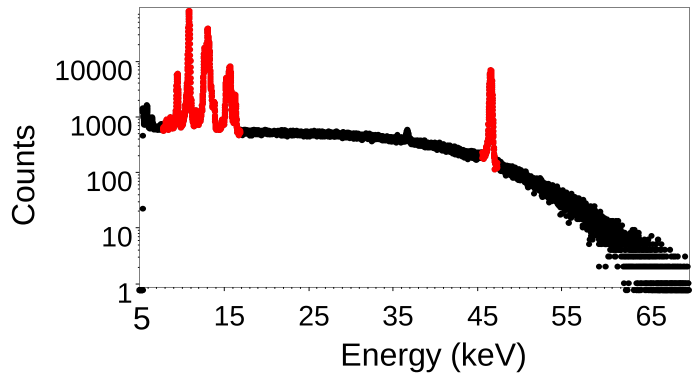
“Absolute” photon emission intensities (PEIs)

- Absolute PEIs: I = number of photons at E per 100 decays
- Essential decay parameter for quantitative analysis by photon spectrometry
- Absolute PEIs are challenging to measure accurately with standard deviation < 1%...

$$I(E) = \frac{N_{FEP}(E)}{A(t) \cdot \varepsilon_{FEP}(E) \cdot \Delta t}$$

N_{FEP}: counts in the Full Energy Peak (FEP)
ε_{FEP} : FEP detection efficiency
$A(t)$: source activity
Δt : live time



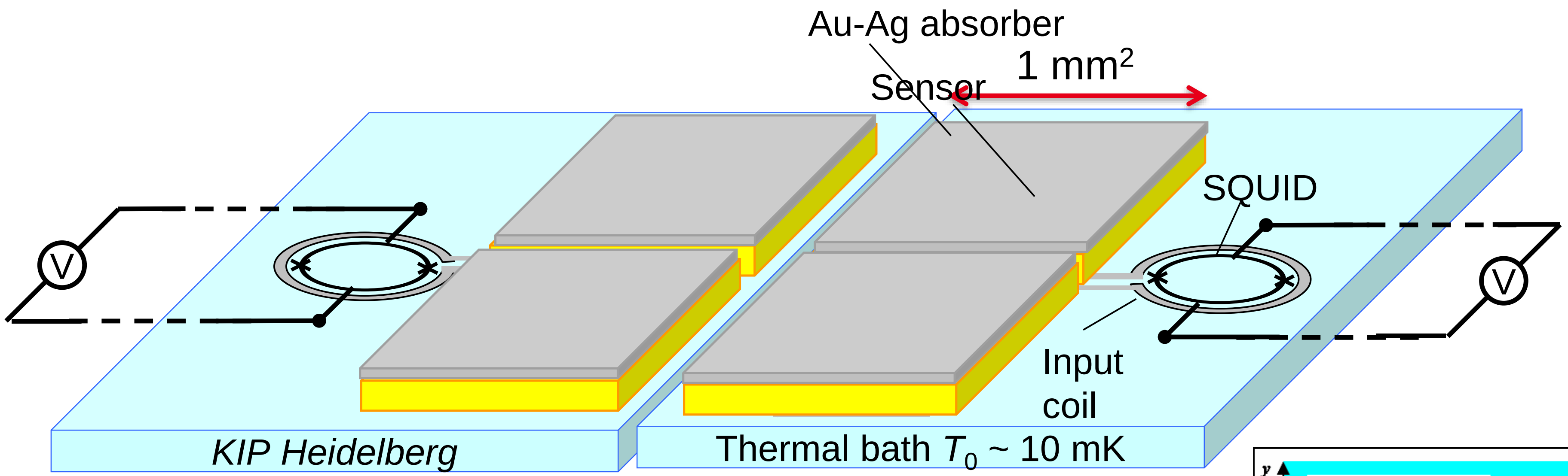


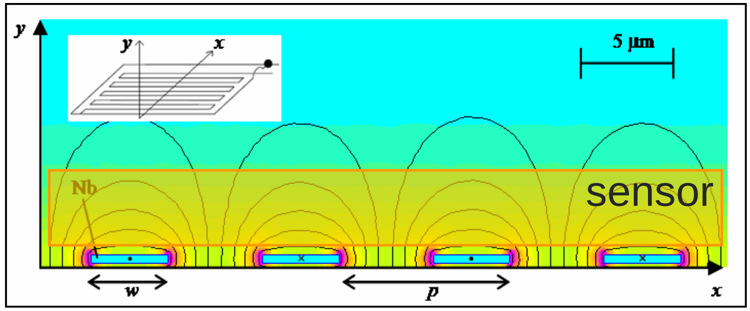
- $\varepsilon_{FEP}(E)$ is the product of $\varepsilon_{int.}(E) \times f_{geo}$ where $\varepsilon_{int.} = f(E) < 1$

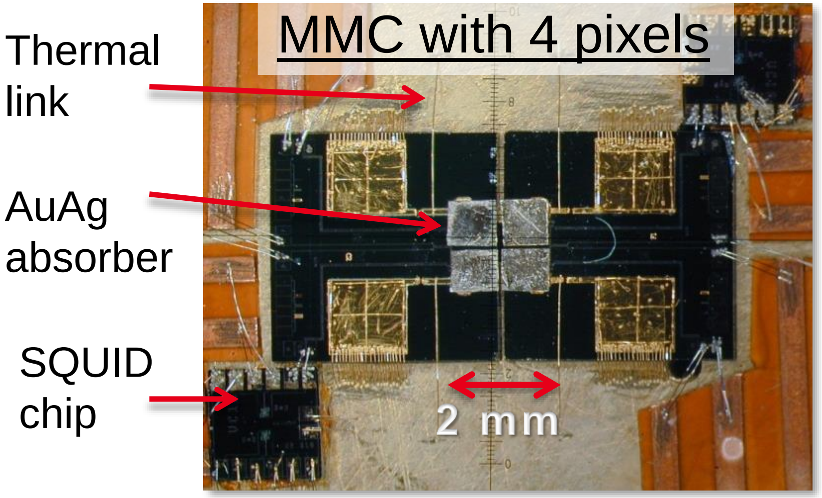
f_{geo} : geometrical factor between source-collimator-absorber
$\varepsilon_{int.}$: intrinsic detection efficiency

- ε_{FEP} and $\varepsilon_{int.}$ are difficult to calibrate accurately

SMX3: A dedicated MMC for L X-ray spectrometry of actinides



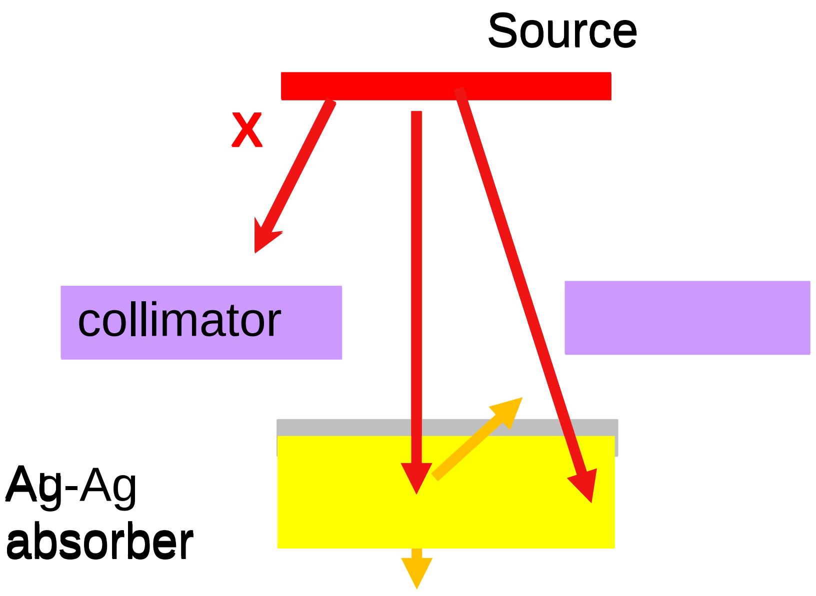


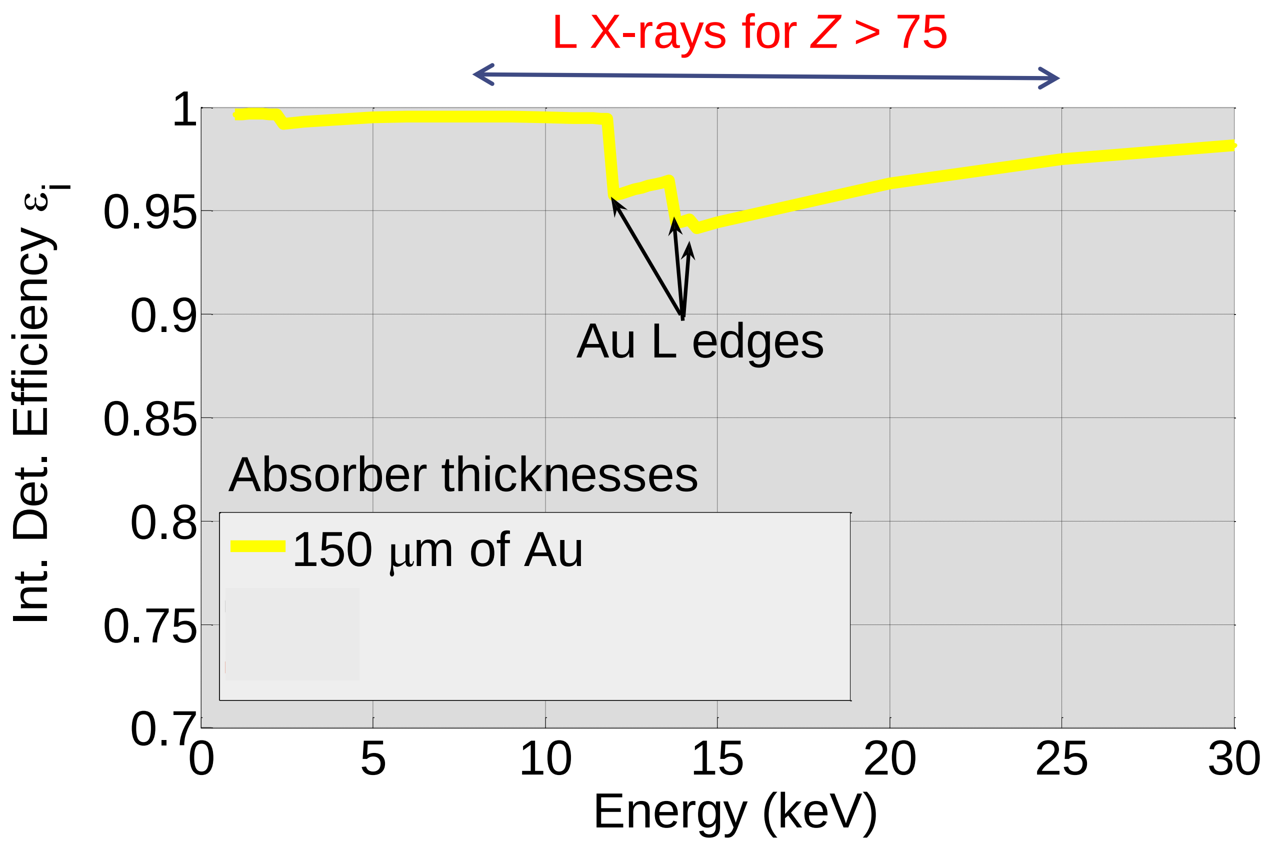


- 4 absorbers of 1 mm^2

  50 µm of Au + 17 µm of Ag thick
- Intrinsic efficiency > 99% between 10-25 keV
- 10 – 20 s^{-1} ($\tau_d \approx$ 4 ms)
- Energy resolution FWHM of 22 - 40 eV

Intrinsic Detection efficiency of AuAg absorbers





→ Quasi-constant intrinsic efficiency below 25 keV, $\varepsilon_{int.} \sim 1$

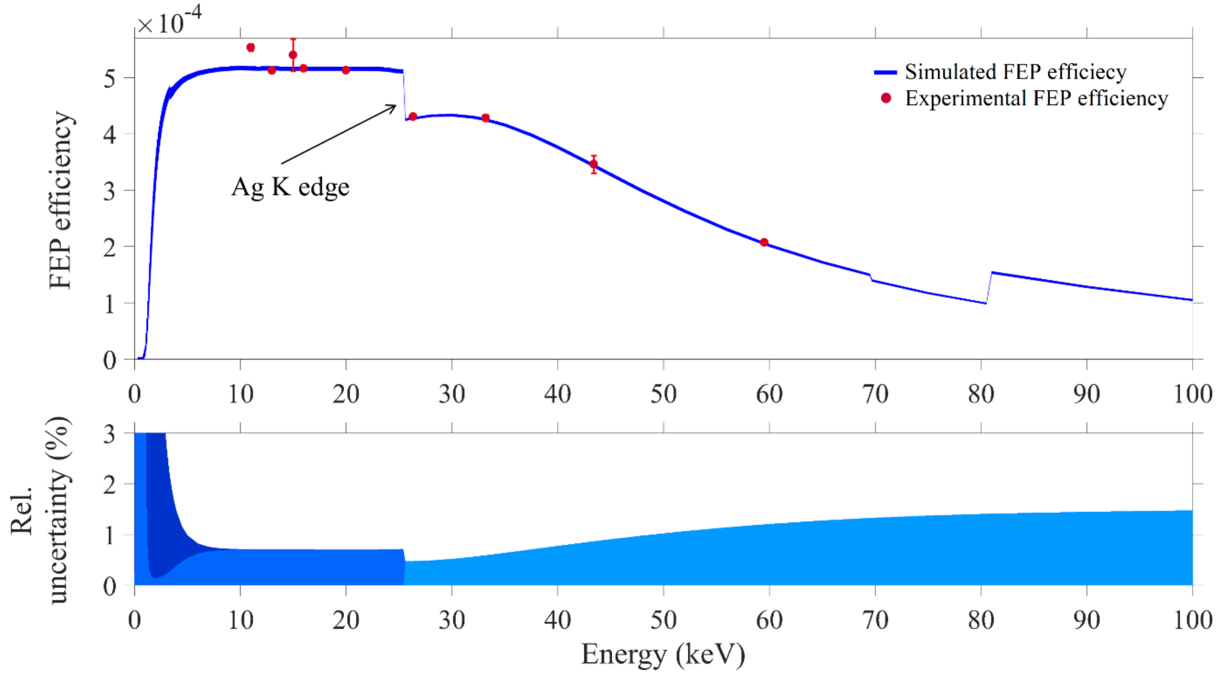
→ Minimize the efficiency correction

Full energy peak detection efficiency calibration using ^{241}Am and MC simulations

$$\varepsilon(E) = \frac{N(E)}{\Delta t \cdot A \cdot I(E)}$$

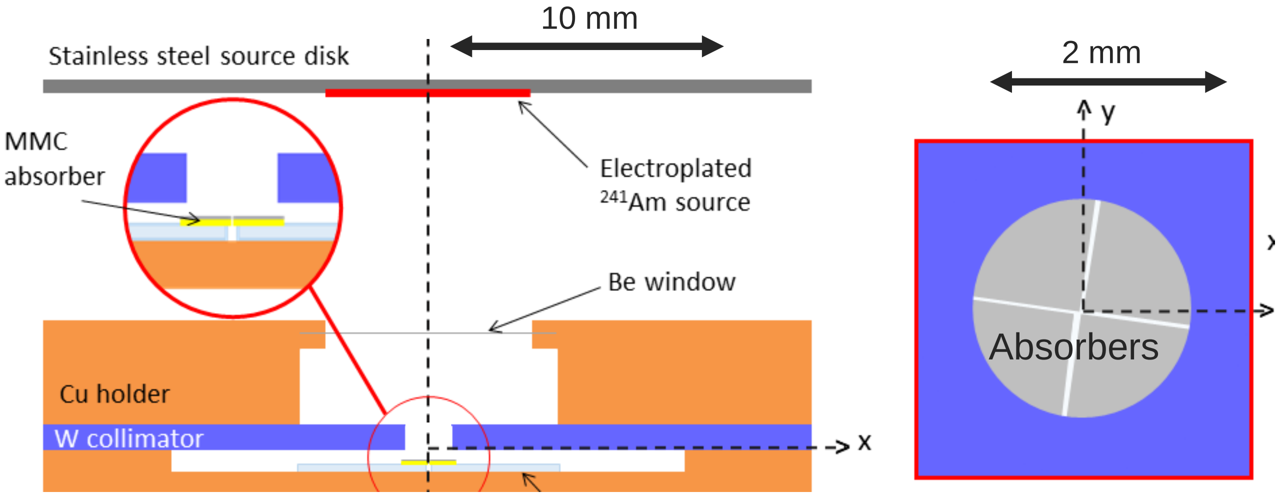
Efficiency calibration

- ^{241}Am spectrum to establish experimental data of
- Extendable dead applied to MMCs to determine Δt
- Definition of a meta-geometry by and for Monte Carlo simulations



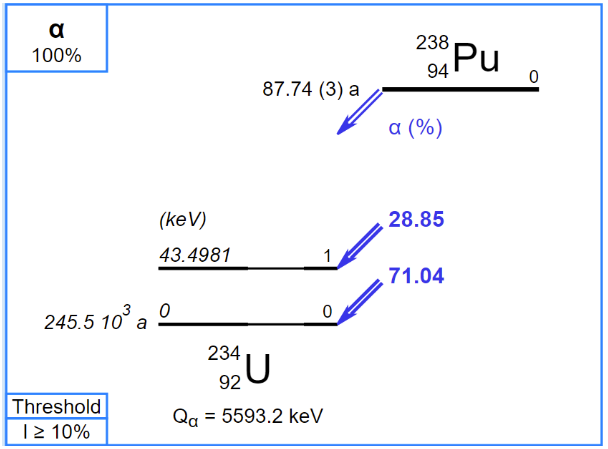
Efficiency uncertainty

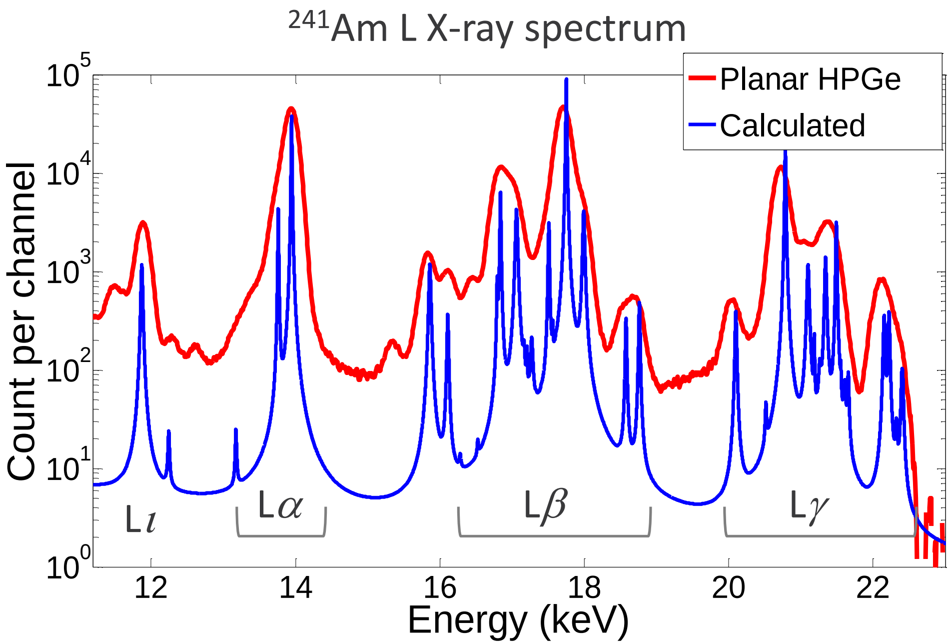
- < 10 keV
  ~ 4% uncertainty at 2 keV given by Be window
- 10 keV < E < 25 keV
  0.7% uncertainty given by $I(XL\beta)$
- > 25 keV
  1.2% to 2.4% uncertainty given by $I(59.5\ \mathrm{keV})$



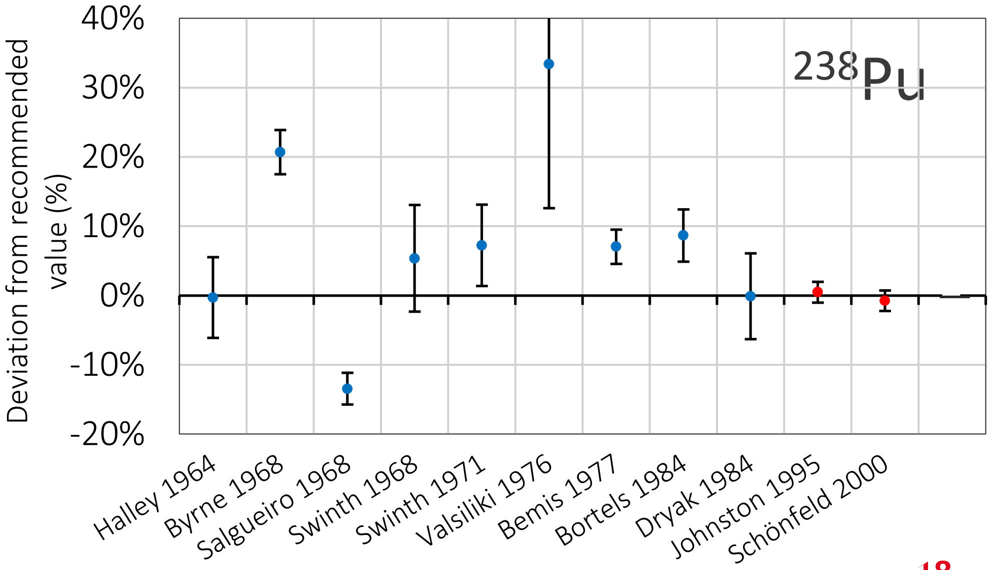
L X-ray emission intensities of actinides

- Many actinides decay by α-emissions and have intense L X-ray PEIs between 10-25 keV

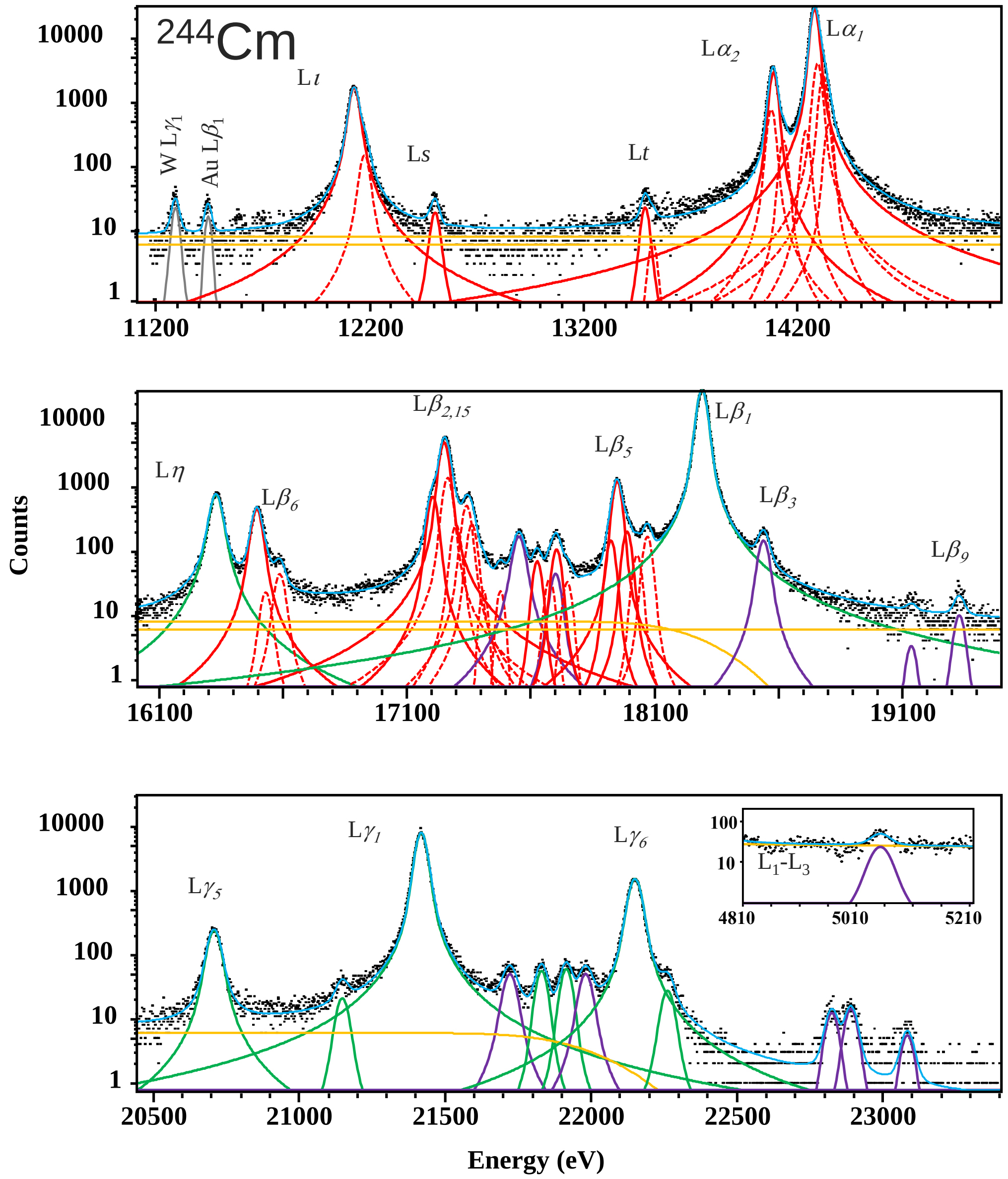




Nuclide	**LX-ray intensity / 100 dis.**	relative unc. (%)	Method	Number of measurements	**calc. vs. exp.**
Pu-239 → U-235+α	4.66	1.1	meas.	4	disagree
Pu-240 → U-236+α	10.34	1.5	meas.	6	agree
Am-241 → Np-237+α	37.66	0.5	meas.	9	disagree
Cm-242 → Pu-238+α	9.92	2.3	calc.	2	disagree
Cm-244 → Pu-240+α	8.92	2.6	calc.	1	agree
U-235 → Th-232+α	40.0	55.0	calc.	-	-



Data and spectrum processing



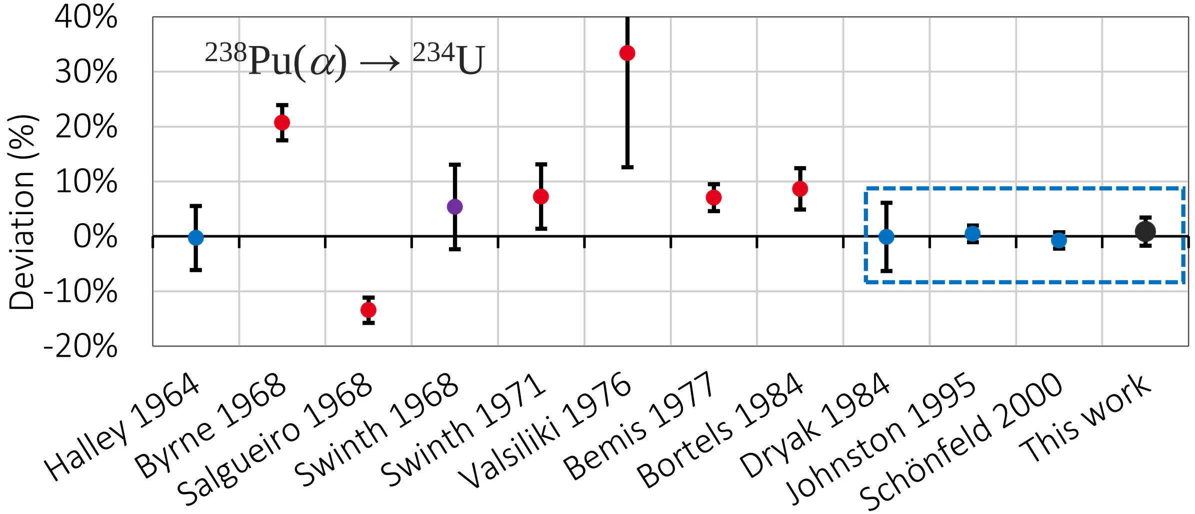
- Each spectrum measured during 10-15 days
- Data continuously recorded with a 16 bits resolution DAQ @ 250-500 kHz
- Data analyzed offline
  - Pulse triggering
  - Live time determination
  - Pulse energy estimation
  - Pile-up rejection
  - Temperature drift correction
  - Non-linearity correction
  - Energy resolution equalization
  - Spectrum co-adding
- Counting statistics of few 10^6 X-ray counts
  - FWHM at best of 22 eV and 32 eV between 0 and 166 keV)
- Spectrum processing
  - Diagram (solid lines) and satellites (dashed lines)

R. Mariam *et al.* Spectrochim. Acta B Vol. 187, 2022, 106331
https://doi.org/10.1016/j.sab.2021.106331

Comparison with PEIs in the literature

Total L X-ray emission intensity

Actinide	This work (%)	Evaluated or other measured values (%)	
^{238}Pu	10.72 (11)	10.62 (32)	[35]
		10.63 (8)	[34]
^{244}Cm	9.08 (16)	8.77 (6)	[34]
		9.44 (10)	[36]
^{237}Np	56.5 (7)	59.7 (32)	[9]
		54.8 (21)	[40]



Siegbahn group L X-ray emission intensities

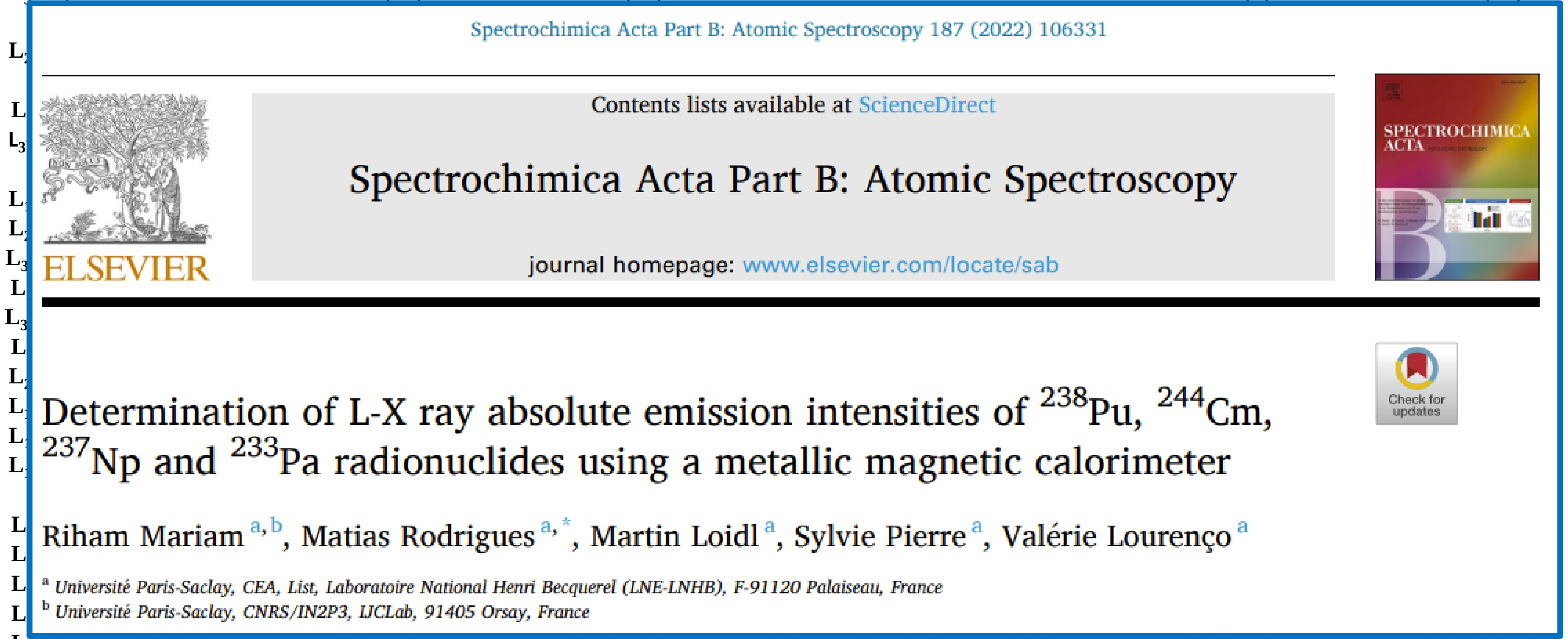
Group	$^{238}Pu(\alpha) \rightarrow {}^{234}U$ This work	$^{238}Pu(\alpha) \rightarrow {}^{234}U$ Johnston [34]	$^{244}Cm(\alpha) \rightarrow {}^{240}Pu$ This work	$^{244}Cm(\alpha) \rightarrow {}^{240}Pu$ Johnston [34]	$^{233}Pa(\beta^-) \rightarrow {}^{233}U$ This work	$^{233}Pa(\beta^-) \rightarrow {}^{233}U$ Calculated
$L\iota$	0.2418 (29)	0.231 (3)	0.2306 (35)	0.214 (3)	1.075 (19)	1.05 (4)
$L\alpha$	3.816 (43)	3.81 (3)	3.49 (5)	3.38 (3)	15.69 (20)	16.9 (6)
$L\eta$	0.1284 (16)	0.126 (2)	0.1002 (22)	0.102 (2)	0.235 (19)	0.272 (16)
$L\beta$	5.23 (6)	5.18 (4)	4.22 (6)	4.08 (3)	16.89 (25)	18.1 (6)
$L\gamma$	1.291 (14)	1.29 (1)	1.023 (15)	0.991 (8)	3.97 (6)	4.23 (14)

Agreement k = 1
Agreement k = 2
In disagreement

See references in https://doi.org/10.1016/j.sab.2021.106331

Tens of PEIs of individual L X-ray transitions

Line		$^{238}Pu(\alpha) \rightarrow {}^{234}U$						$^{244}Cm(\alpha) \rightarrow {}^{240}Pu$					
Siegbahn	IUPAC	Energy (eV)	X-ray emission intensity per 100 L X-rays	X-ray emission intensity per 100 decays	Rel. Unc. (%) u_1	u_2	u_3	Energy (eV)	X-ray emission intensity per 100 L X-rays	X-ray emission intensity per 100 decays	Rel. Unc. (%) u_1	u_2	u_3
-	L_1-L_3	4589.2	**0.0214 (44)**	**0.00229 (47)**	0.72	20	1.2	5054.63	**0.0267 (13)**	**0.00242 (13)**	0.37	5.0	1.6
$L\iota$	L_3-M_1	11618.4	**2.257 (11)**	**0.2418 (30)**	0.72	0.49	0.86	12124.4	**2.540 (13)**	**0.2306 (36)**	0.37	0.49	1.4
Ls	L_3-M_2	11982.0	**0.0227 (15)**	**0.00243 (16)**	0.72	6.6	0.86	12503	**0.0269 (20)**	**0.00244 (18)**	0.37	7.4	1.4
Lt	L_3-M_3	12864.7	**0.0286 (17)**	**0.00307 (18)**	0.72	5.8	0.86	13485.4	**0.0315 (16)**	**0.00286 (15)**	0.37	5.2	1.4
$L\alpha_2$	L_3-M_4	13439.8	**3.604 (7)**	**0.3862 (44)**	0.72	0.20	0.86	14074.5	**3.806 (11)**	**0.346 (5)**	0.37	0.29	1.4
$L\alpha_1$	L_3-M_5	13614.8	**32.007 (20)**	**3.429 (39)**	0.72	0.062	0.86	14237	**34.68 (7)**	**3.149 (47)**	0.37	0.21	1.4
$L\eta$	L										0.37	1.6	1.4
$L\beta_6$	L										0.37	1.2	1.4
$L\beta_{2,15}$	L_3										0.37	0.23	1.4
$L\beta_4$	L										0.37	1.9	1.4
$L\beta_{17}$	L										0.37	2.5	1.4
Lu	L_3										0.37	3.5	1.4
$L\beta_7$	L												
$L\beta_5$	L_3										0.37	0.81	1.4
	L												
$L\beta_1$	L										0.37	0.10	1.4
$L\beta_3$	L										0.37	1.4	1.4
$L\beta_{10}$	L										0.37	14	1.4
$L\beta_9$	L										0.37	6.5	1.4
$L\gamma_5$	L										0.37	1.1	1.4
-	L										0.37	4.4	1.4
$L\gamma_1$	L										0.27	0.27	0.3
$L\gamma_2$	L										0.37	4.6	1.4
$L\gamma'_8$	L_2-N_6	20556.1	**0.0616 (8)**	**0.00660 (11)**	0.72	1.3	0.86	21829.3	**0.0607 (21)**	**0.00551 (21)**	0.37	3.4	1.4
$L\gamma_8$	L_2-O_1	20625.7	**0.0910 (11)**	**0.00975 (16)**	0.72	1.2	0.86	21914	**0.0646 (18)**	**0.00586 (18)**	0.37	2.8	1.4
$L\gamma_3$	L_1-N_3	20712.4	**0.0594 (13)**	**0.00636 (15)**	0.72	2.1	0.86	21980	**0.0665 (18)**	**0.00604 (18)**	0.37	2.6	1.4
$L\gamma_6$	L_2-O_4	20842.0	**1.948 (6)**	**0.2087 (18)**	0.72	0.33	0.36	22149.1	**1.911 (9)**	**0.1735 (27)**	0.37	0.45	1.4
-	L_2-P_1	20904.0	**0.0117 (17)**	**0.00126 (18)**	0.72	15	0.86	-	-	-	-	-	-
-	L_2-$P_{4,5}$	20941.7	**0.03312 (50)**	**0.00355 (7)**	0.72	1.5	0.86	22260.9	**0.0343 (11)**	**0.00312 (11)**	0.37	3.2	1.4
$L\gamma'_4$	L_1-O_2	21498.1	**0.01838 (41)**	**0.001969 (49)**	0.72	2.2	0.85	22823.3	**0.0141 (7)**	**0.00128 (7)**	0.37	5.0	1.4
$L\kappa$	L_1-O_3	21564.0	**0.01345 (34)**	**0.001441 (39)**	0.72	2.5	0.85	22888.8	**0.0162 (8)**	**0.00147 (7)**	0.37	4.6	1.4


Spectrochimica Acta Part B: Atomic Spectroscopy 187 (2022) 106331

Contents lists available at ScienceDirect

Spectrochimica Acta Part B: Atomic Spectroscopy

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Determination of L-X ray absolute emission intensities of ^{238}Pu, ^{244}Cm, ^{237}Np and ^{233}Pa radionuclides using a metallic magnetic calorimeter

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Limits of previous measurements

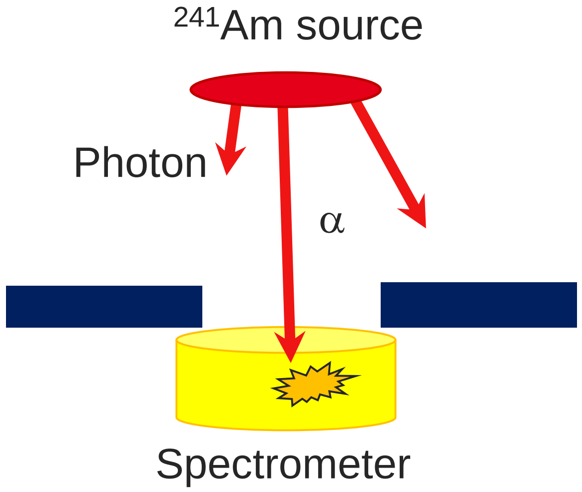
- Previous PEI measurements limited by the uncertainty on the FEP detection efficiency
- Itself limited by the recommended values of the PEIs of ^{241}Am used for the efficiency calibration

$$I(E) = \frac{N_{FEP}(E)}{A(t) \cdot \varepsilon_{FEP}(E) \cdot \Delta t}$$

$$\varepsilon_{FEP}(E) = \frac{N_{FEP}(E)}{I(E) \cdot A(t) \cdot \Delta t}$$

PEIs are ultimately interdependent and correlated to some extent

Absolute L X-ray PEIs of ^{241}Am independently of other PEIs



$$I(E) = \frac{n_{FEP}(E)}{n_{\alpha}} \cdot \frac{\varepsilon_{\alpha}}{\varepsilon_{FEP}(E)}$$

n_{FEP}: rate of photons in the FEP
n_{α}: rate of α-particle n_{α} in the FEP
ε_{FEP}: FEP efficiency for photons
ε_{α}: efficiency for α particle

ε_{int}: intrinsic efficiency
$f_{geo,ph.}$: geometrical efficiency

$$\varepsilon_{\alpha} = f_{geo,\alpha} \cdot \varepsilon_{int,\alpha}$$
$$\varepsilon_{FEP} = f_{geo,ph.} \cdot \varepsilon_{int,ph.}$$

Conditions:

- ✓ $f_{geo,\alpha} = f_{geo,ph.}$
- ✓ 100% decay by α-particle emission
- ✓ $\varepsilon_{int,\alpha} \approx \varepsilon_{int,ph.} \approx 1$

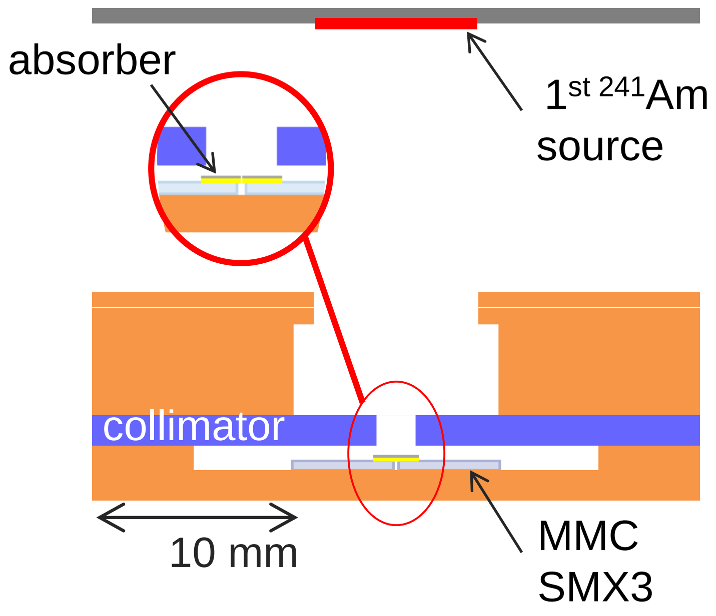
However measuring α-particles and photons in the same spectrum is not possible:

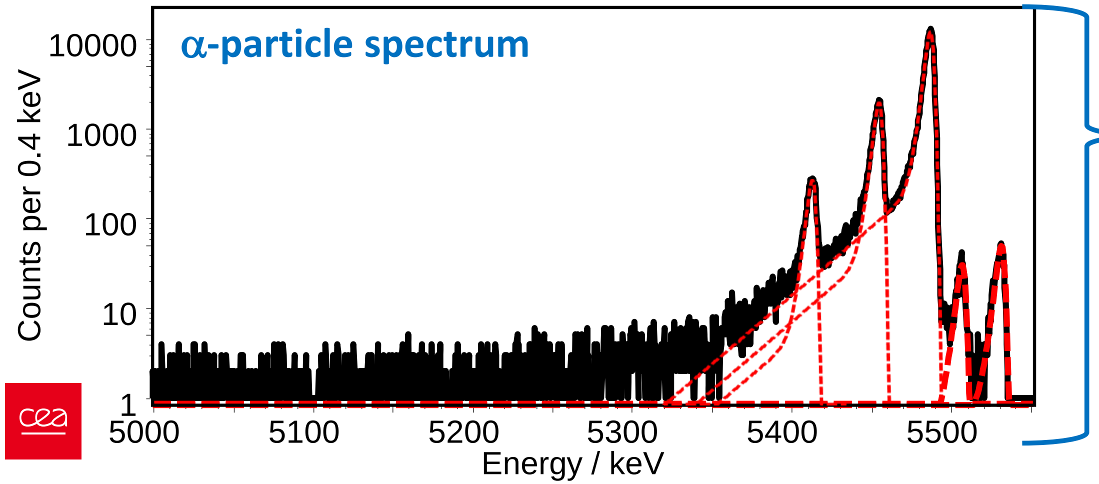
- ✗ MMC sensitivity for α-particles (few MeV) and X-rays (10s of keV) must be different
- ✗ Ten times as many emitted particles per decay as there are X-rays
  - → Many pile-up or reduced counting statistics, electrons/X-ray interferences

Measurements of two ^{241}Am sources with different activities

1st measurement: α spectrum

- ^{241}Am source of 1.8 kBq
- Lower MMC sensitivity
- No Be window
- FWHM resolution of 3.3 keV





$\rightarrow n_{\alpha}$

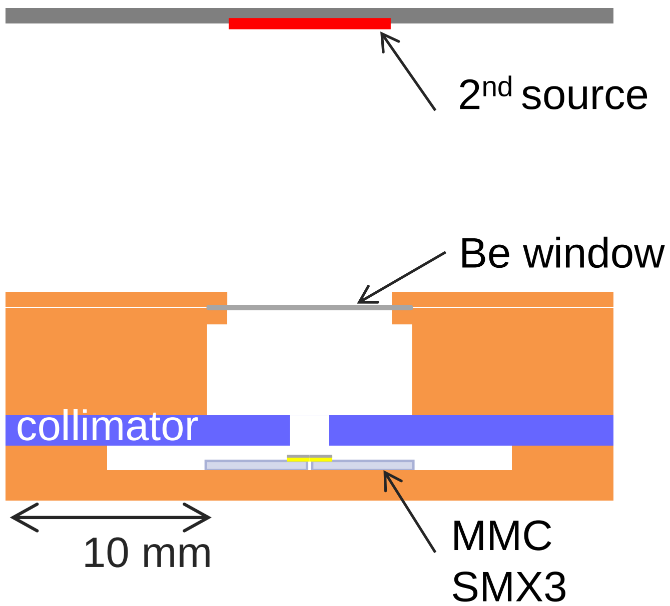
Measurements of two ^{241}Am sources with different activities

1st measurement: α spectrum

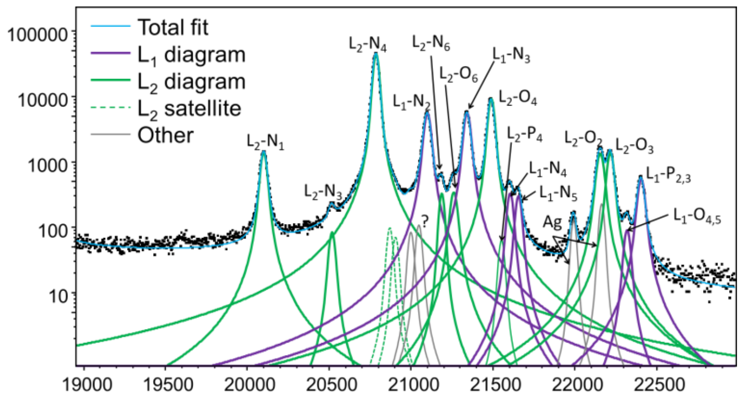
- ^{241}Am source of 1.8 kBq
- Lower MMC sensitivity
- No Be window
- FWHM resolution of 3.3 keV

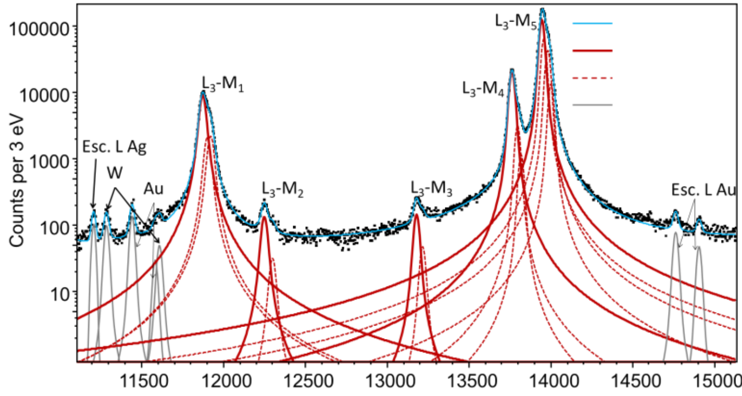
2nd measurement: X-ray spectrum

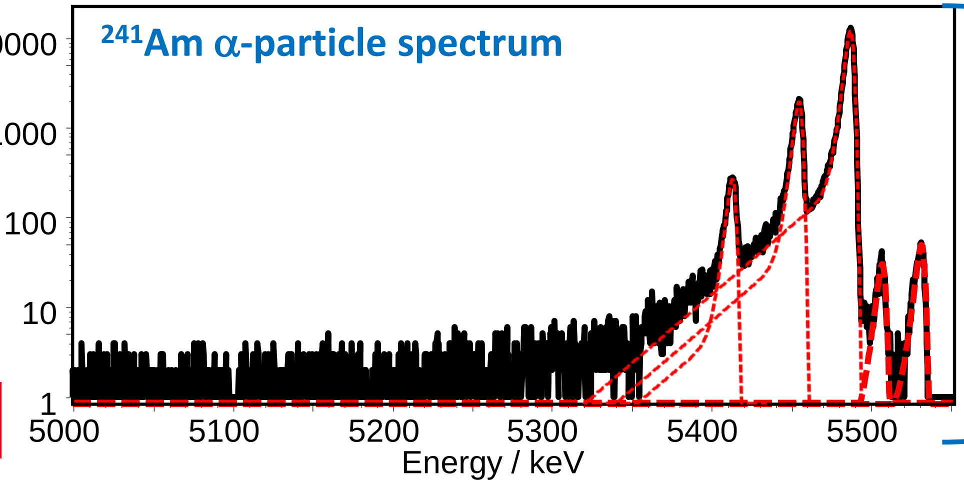
- ^{241}Am source of 32 kBq
- High MMC sensitivity
- Be window to stop the α-particles
- spectrum FWHM resolution of 28 eV



L X-ray spectrum of ^{241}Am(α) → ^{237}Np

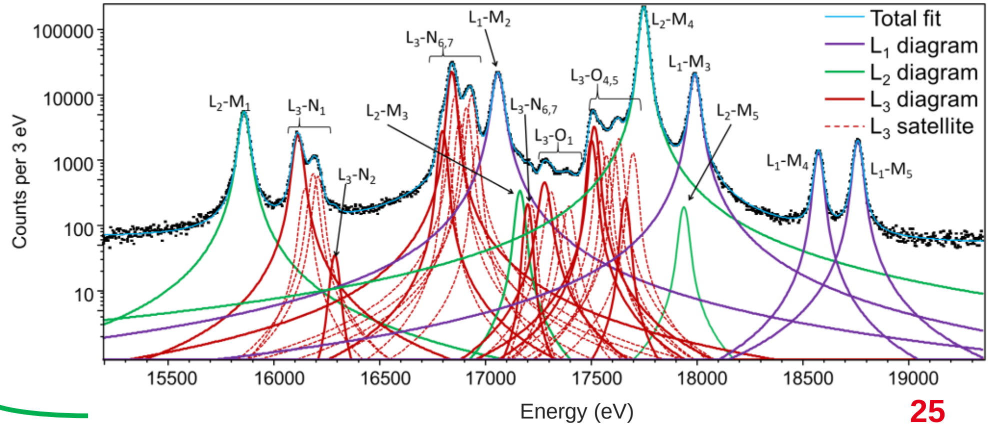






$\rightarrow n_\alpha$

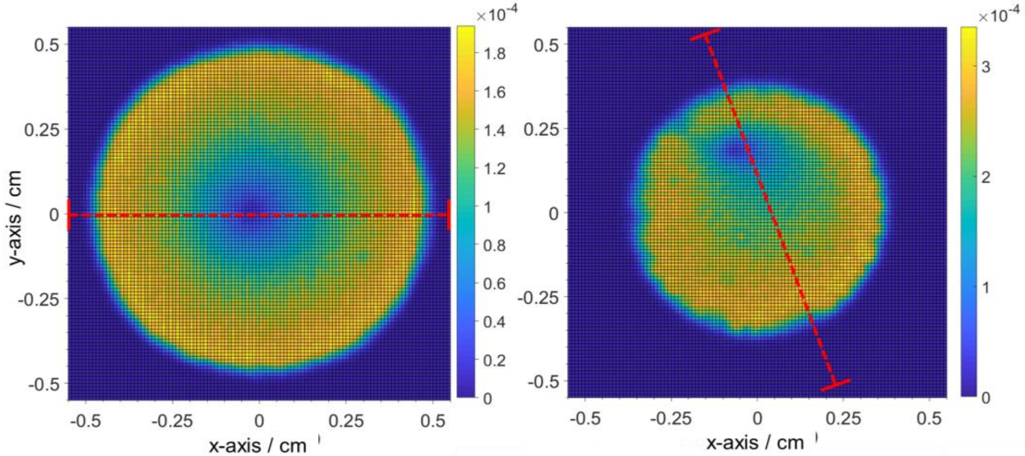
$n_{FEP} \leftarrow$



Additional corrections due to the measurement of 2 sources

$$I(E) = \frac{n_{FEP}(E)}{n_\alpha} \frac{F_A \cdot F_{source} \cdot \varepsilon_{int,\alpha}}{\varepsilon_{int,ph}(E) \times t_{Be}(E)}$$

- n_{FEP} and n_α from energy spectra
- F_A ratio between source activities determined by conventional α-particles spectrometry
- F_{source} correction factor for the inhomogeneity of the surface source activitiy determined by radioactive source imager.

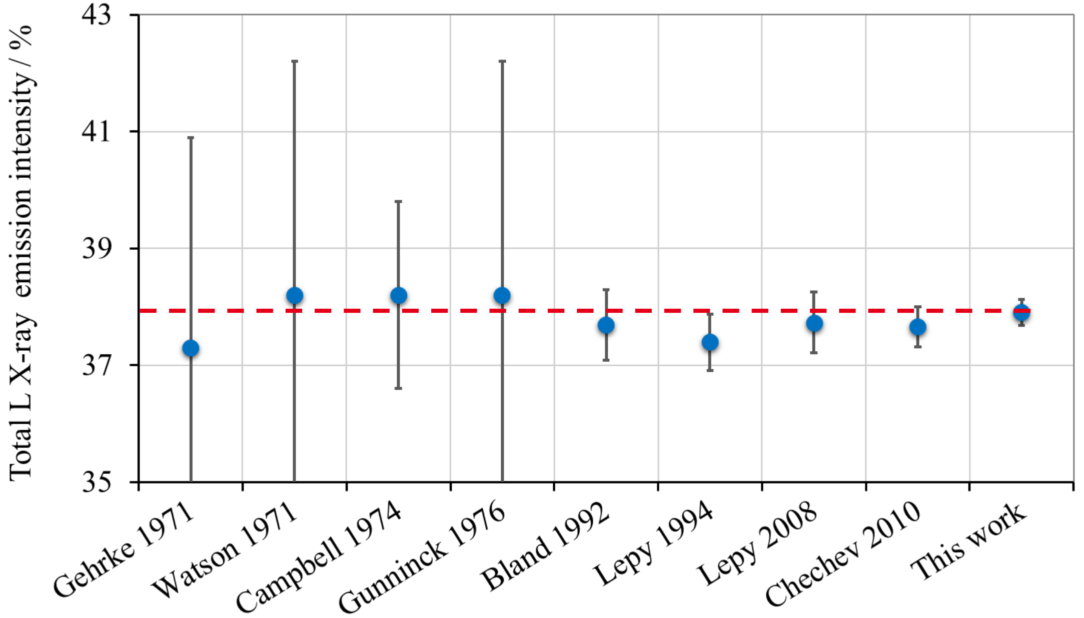


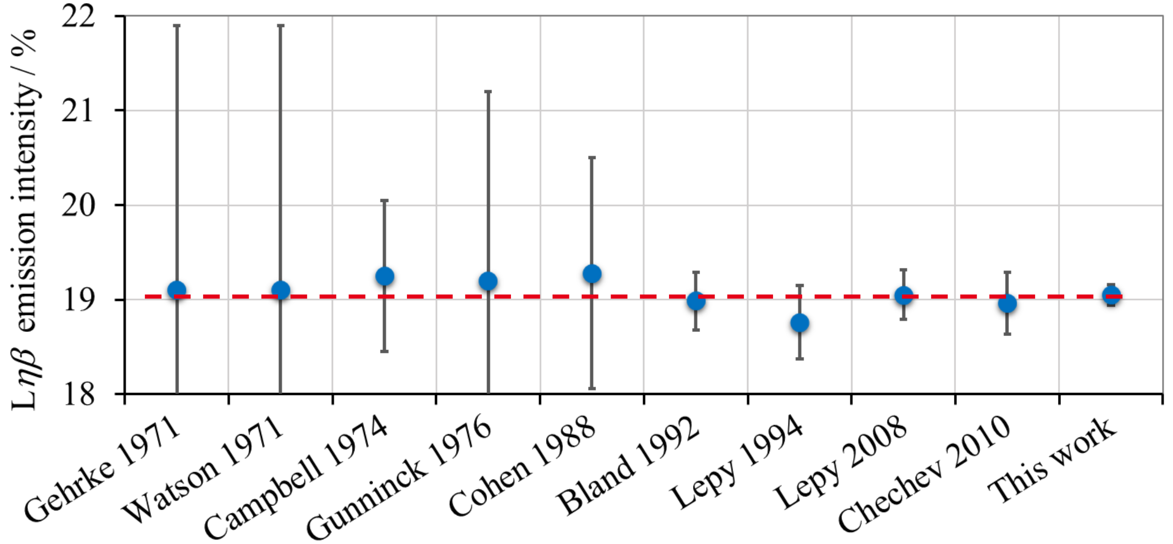
- $\varepsilon_{int,\alpha}$ and $\varepsilon_{int,ph}$ intrinsic efficiencies ~ 1, determined by Monte Carlo simulations.
- t_{Be} transmission through Be window, calculated.

Results of L X-ray PEIs from $^{241}Am(\alpha) \rightarrow {}^{237}Np$

Total L X-ray and Siegbahn group (Lα, Lβ, Lγ…) PEIs

- Good agreement with all the previous published data
- Relative uncertainty (0.32%) 2 times lower than the most precise measurement





Results of L X-ray PEIs from $^{241}Am(\alpha) \rightarrow {}^{237}Np$

33 PEIs of individual X-ray transitions are provided

X-ray transition UIPAC	X-ray transition Siegbahn	Energy (eV)	PEI per 100 decays	Relative uncertainties Total	Fitting procedure	Counting statistics	Siegbahn group	PEI per 100 decays	Relative uncertainties Total	Fitting procedure	Counting statistics
L_1-L_3	-	4820	**0.2289 (15)**	0.65%	0.41%	0.42%					
L_3-M_1	$L\iota$	11873	**0.8989 (38)**	0.42%	0.13%	0.21%					
L_3-M_2	Lt	12250	**0.01024 (26)**	2.57%	0.64%	1.96%					
L_3-M_3	Ls	13179	**0.0101 (8)**	7.59%	7.33%	1.98%					
L_3-M_4	$L\alpha_1$	13762	**1.2581 (49)**	0.39%	0.19%	0.18%	$L\alpha$	13.046 (41)	0.31%	0.084%	0.069%
L_3-M_5	$L\alpha_2$	13944	**11.788 (38)**	0.32%	0.13%	0.06%					
L_2-M_1	$L\eta$										
L_3-N_1	-										
L_3-$N_{4,5}$	$L\beta_{2,15}$										
L_1-M_2	$L\beta_4$										
L_3-$N_{6,7}$	$L\beta_7'$										
L_3-$O_{1,2,3}$	$L\beta_7$										
L_3-$O_{4,5}$ - L_3-$P_{1,4,5}$	$L\beta_5$									64%	0.058%
L_2-M_4	$L\beta_1$										
L_2-M_5	-										
L_1-M_3	$L\beta_3$										
L_1-M_4	$L\beta_{10}$										
L_1-M_5	$L\beta_9$										
L_2-N_1	$L\gamma_5$										
L_2-N_3	-										
L_2-N_4	$L\gamma_1$										
L_1-N_2	$L\gamma_2$										
L_2-N_6	$L\gamma_8'$										
L_2-O_1	$L\gamma_8$	21260	**0.02841 (48)**	1.69%	1.17%	1.18%					
L_1-N_3	$L\gamma_3$	21341	**0.4363 (20)**	0.46%	0.20%	0.30%					
L_2-O_4	$L\gamma_6$	21489	**0.6260 (30)**	0.48%	0.28%	0.25%	$L\gamma$	4.883 (20)	0.41%	0.26%	0.11%
L_2-P_1	-	21555	**0.00386 (16)**	4.02%	2.41%	3.20%					
L_2-P_4	-	21595	**0.02246 (31)**	1.39%	0.28%	1.33%					
L_1-N_5	-	21656	**0.02041 (30)**	1.46%	0.32%	1.39%					
L_1-O_2	$L\gamma_4'$	22155	**0.1139 (8)**	0.67%	0.15%	0.59%					
L_1-O_3	$L\gamma_4$	22216	**0.1057 (7)**	0.70%	0.15%	0.61%					
L_1-$O_{4,5}$		22319	**0.00639 (16)**	2.58%	0.61%	2.49%					
L_1-$P_{2,3}$		22404	**0.04361 (46)**	1.05%	0.34%	0.95%					

IOP Publishing | Bureau International des Poids et Mesures — Metrologia

Metrologia **60** (2023) 025005 (18pp) https://doi.org/10.1088/1681-7575/acb99f

Determination of absolute Np L x-ray emission intensities from ^{241}Am decay using a metallic magnetic calorimeter

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Conclusions and perspectives

MMCs are useful tool to provide accurate decay data in metrology of ionizing radiation

- MMCs are suitable for decay data measurements by DES (< 200 keV)
  - Beta spectrum shape
  - End point energies
  - Beta branch probabilities
  - EC probabilities

  → We are currently developing multiple MMC channels to achieve high statistics (108 counts) for beta spectrum of ^{129}I

- MMCs are suitable for precise and detailed absolute PEI determinations (<100 keV)
  - L X-ray PEIs for ^{238}Pu, ^{244}Cm, ^{233}Pa and ^{237}Np with relative uncertainties of ~ 0,8%
  - L X-ray PEIs for ^{241}Am without efficiency calibration based on other PEIs with relative uncertainties of ~0.3%
  - γ-ray and X-ray PEIs in the range 25 keV-100 keV with relative uncertainties of ~ 0,8%-1%

  → We are currently developing an MMC array for absolute PEIs of photons < 10 keV

- Measuring these decay data at higher energies is challenging:
  - due to loss of Bremsstrahlung photons for electrons
  - due to loss of efficiency for photons

Thank you for your attention

Matias Rodrigues