Reference-free X-ray spectrometry: photon emission intensities and self-attenuation effects

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INTRODUCTION

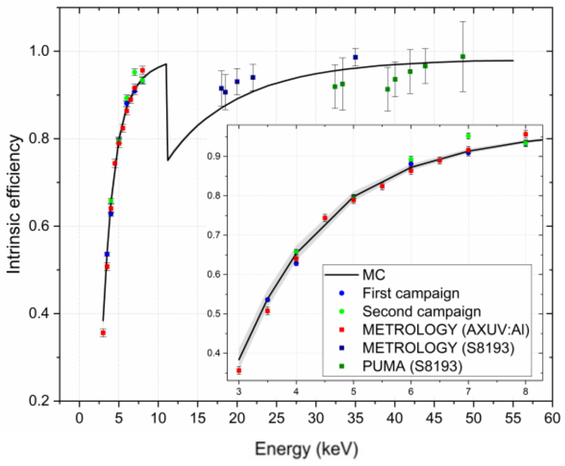
Reliable photon emission intensities and self-attenuation corrections are essential for radionuclide metrology, reactor dosimetry and detector calibration. To avoid correlations with tabulated decay data, we applied a reference-free efficiency calibration to a high-purity germanium detector (HPGe) and used it to determine X-ray and selected γ-ray emission intensities for a new set of standard radionuclides (^{241}Am, ^{152}Eu and ^{210}Pb), as a continuation of an ongoing measurement series [Utepov, *ARI*, 226, 2025, 112159]. In addition, self-attenuation corrections for *K* X-rays emitted in the decay of ^{93m}Nb were determined experimentally, and compared with calculation-based methods.

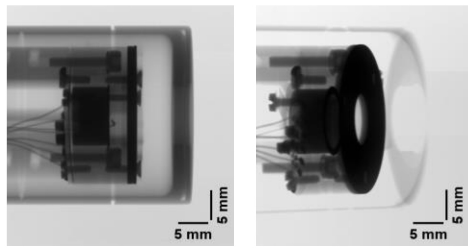
EFFICIENCY CALIBRATION WITHOUT REFERENCE TO RADIONUCLIDE DECAY DATA

Absolute efficiency determination:

$$\varepsilon_{abs}(E) = \varepsilon_{int}(E) \cdot \varepsilon_{geom} = \varepsilon_{int}(E) \cdot \Omega/4\pi$$

- **Intrinsic efficiency**, $\varepsilon_{int}(E)$
  - Monochromatic photon beams
  - Cryogenic radiometer + calibrated transfer photodiodes
  - Calibration established up to 55 keV [Elvira, *ARI*, 203, 2024, 111087]
  - **New measurements for independent verification**
- **Geometrical efficiency**, ε_{geom}
  - Detection solid angle Ω
  - Radiographically characterized detector geometry
  - External W collimator diameter: calibrated vision machine
  - Source-to-collimator distance: linear scale or calibrated laser



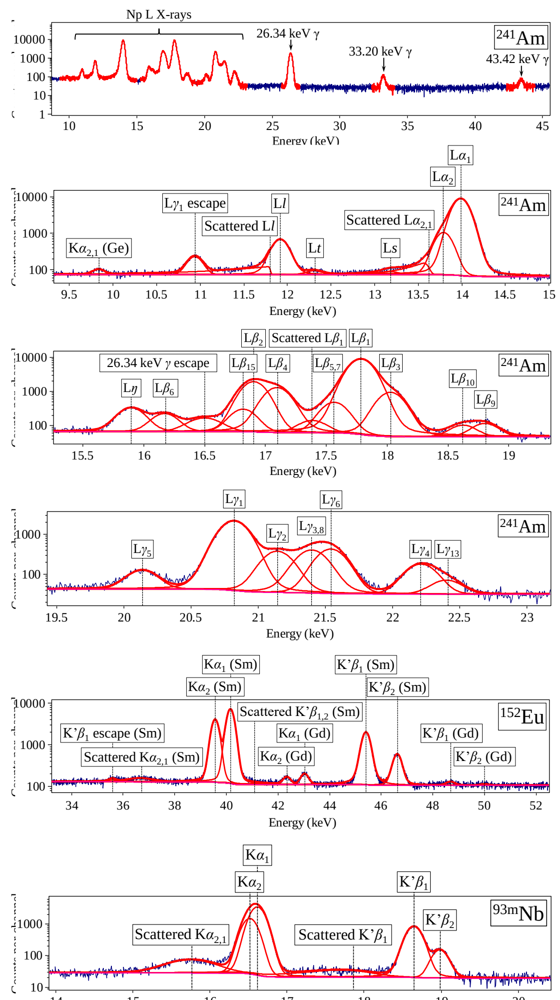


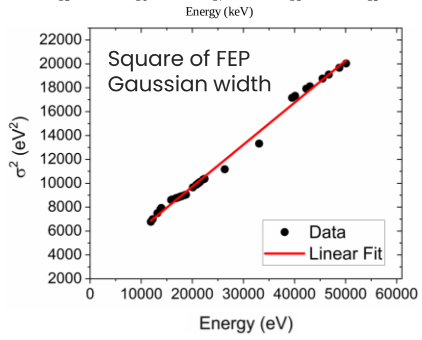
HPGe detector	Manufacturer	Radiography
Crystal thickness	6 mm	6.116(43) mm
Crystal diameter	10 mm	9.786(43) mm
Dead layer thickness	-	1 µm [Elvira, *ARI*, 203, 2024, 111087]
Beryllium window thickness	125 µm	131(7) µm
Internal collimator diameter (W/Cu/Al: 0.4/1/1 mm thick)	8 mm	7.7(9) mm
Crystal-to-window distance	10 mm	12.46(10) mm
Window-to-collimator distance	-	10.409(22) mm

X/γ-RAY SPECTROMETRY

Spectra analysis (COLEGRAM software)

- Voigt function for X-ray Full-Energy Peaks (FEP)
  - Gaussian: detector response
  - Lorentzian: natural linewidth
- Gaussian+left tail for Compton scattered "bumps"
- Gaussian for γ-ray peaks





PHOTON EMISSION INTENSITIES

Absolute X/γ-ray emission intensity determination:

$$I(E) = \frac{N(E) \cdot \prod_{i=1}^{n} C_i}{\varepsilon_{abs}(E) \cdot A \cdot t}$$

$N(E)$: Net peak area by X/γ-ray spec. on point sources

A: Source activity, standardized by methods available at LNHB

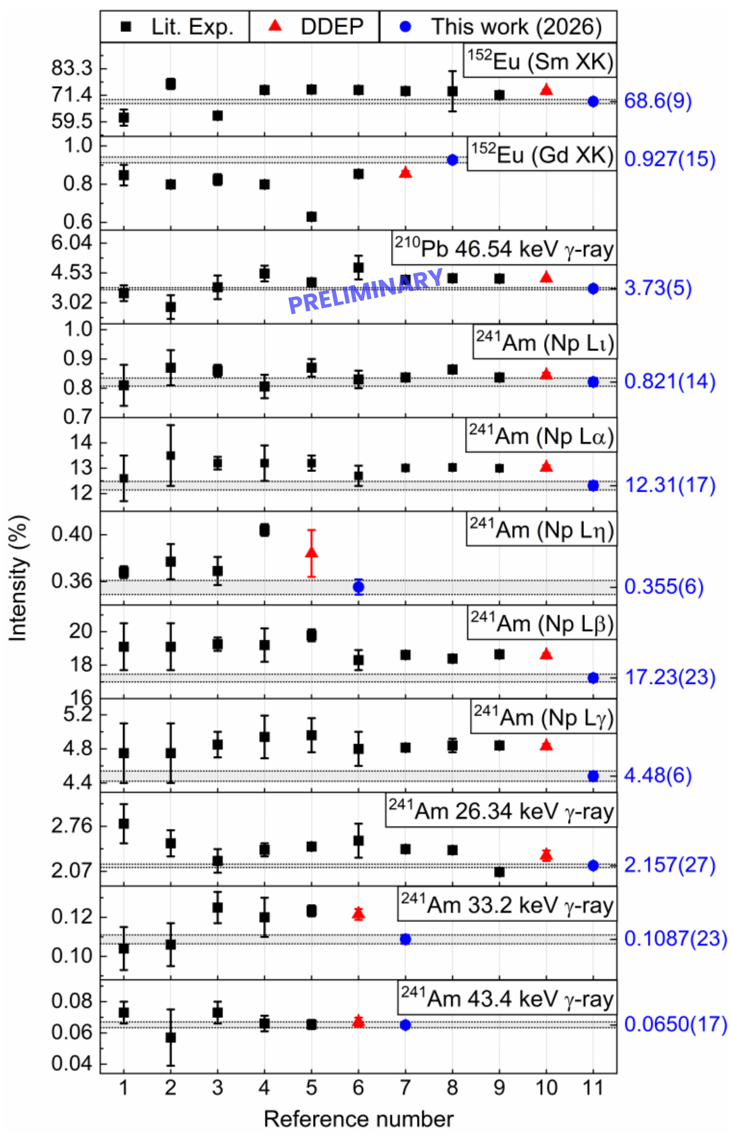
t: Acquisition live time (345 600 s – 2 332 800 s)

$\varepsilon_{abs}(E)$: Reference-free HPGe efficiency

C_i: Correction factors (transmission, reference date, ...)

Results of this work compared with those in the literature

(see [Utepov, *XRS*, 2026 (to be publsihed)] for numerical values)



SELF-ATTENUATION CORRECTIONS

Self-attenuation correction validation:

$$C_{self}^{-1}(E) = \frac{N(E) \cdot \prod_{i=1}^{n} C_i}{\varepsilon_{abs}(E) \cdot A \cdot t \cdot I(E)}$$

A: ^{93m}Nb activity by TDCR LSC [Utepov, *ARI*, 226, 2025, 112135]

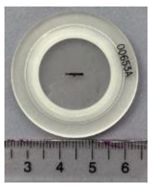
$I(E)$: reference-free *K* X-ray emission intensities by X-ray spec. on point source [Utepov, *ARI*, 226, 2025, 112135]

$N(E)$: Net peak area by X-ray spec. for Nb dosimeter

t: Acquisition live time (481 500 s)

$\varepsilon_{abs}(E)$: Reference-free HPGe efficiency

C_i: Correction factors (fluorescence, transmission, ...)



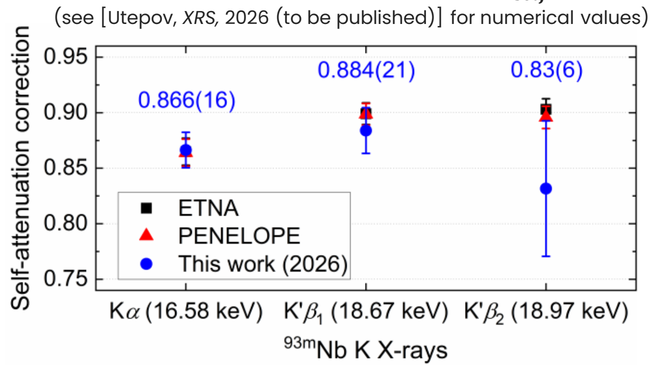
Niobium dosimeter	
Mass	0.7048(13) mg
Surface area	4.278(17) mm²
Thickness	**19.22(8) µm**
Irradiation site	OSIRIS reactor (70 MW)
Impurity	^{94}Nb (2.7%), ^{60}Co (0.01%)

Commonly used methods for the $C_{self}^{-1}(E)$ modelling:

- ETNA: Efficiency transfer calculation from a point source to the niobium dosimeter
- PENELOPE: Monte-Carlo simulation for the complete source-detector geometry

Experimental vs model-based $C_{self}^{-1}(E)$

(see [Utepov, *XRS*, 2026 (to be published)] for numerical values)



UNCERTAINTY BUDGET

Origin	Relative standard uncertainty	
	$I(E)$	$C_{self}(E)$
Activity	≤ 0.37%	≤ 0.49%
Counting statistics & Spectra deconvolution	≤ 4.9%	≤ 1.8%
Decay during measurement	≤ 0.01%	
Decay correction to a reference date	≤ 0.11%	
Geometrical efficiency	0.94%	0.83%
Intrinsic efficiency	≤ 0.64%	≤ 0.28%
Transmission through Mylar foil and air	≤ 0.36%	≤ 0.11%
Fluorescence correction	-	≤ 0.02
Photon emission intensity	-	1.30% – 7.04%
Combined uncertainty	**1.3% – 5.0%**	**1.8% – 7.3%**

CONCLUSION

- Reference-free photon emission intensities were determined for ^{241}Am, ^{152}Eu and ^{210}Pb using an HPGe detector calibrated independently of decay data.
- Fully traceable uncertainty budgets were provided for all reported quantities, and combined uncertainties were derived following the GUM recommendation [JCGM, 2008].
- The obtained intensities tend to be lower than previously reported values, while remaining consistent within uncertainties in most cases.
- Experimental self-attenuation corrections for ^{93m}Nb X-rays validate ETNA and PENELOPE calculations.
- New synchrotron measurements independently confirmed the intrinsic efficiency calibration established up to 55 keV.