ADVANCED REACTOR SAFEGUARDS & SECURITY

TRISO NDA Measurements for Burnup

Mark Croce, Christine Mathew, Daniel McNeel, Rico Schoenemann, Katherine Schreiber, Emily Stark Teti, Sophie Weidenbenner (Los Alamos National Laboratory)
Callie Goetz, Jianwei Hu, Craig Gray, Nick Termini, Robert McElroy (Oak Ridge National Laboratory)
Ammon Williams, Brian Bucher, Edward Seabury (Idaho National Laboratory)
Daniel Becker (University of Colorado)

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PRESENTED BY

Emily Stark Teti, *Los Alamos National Laboratory*

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Project Objectives

- Enable cost-effective safeguards for advanced reactors by understanding exactly how **nondestructive analyses** can be used
- **Directly measure NDA uncertainty** to provide a comprehensive set of validated measurement capabilities for safeguards models
- Current focus is burnup measurement of TRISO fuels for pebble bed reactors to support:
  - On-line burnup measurement system
  - Safeguards of used fuel

Isotopic Signatures of Burnup

uCal

Europium

- ^{154}Eu to ^{155}Eu
  - 123.07 keV (yield: 40.41%)
  - 86.55 keV (yield: 30.70%) or 105.31 keV (yield: 21.12%)

Americium

- ^{241}Am to ^{243}Am
  - 59.54 keV (yield: 35.9%)
  - 74.66 keV (yield: 67.2%)

HPGe

Cesium

- ^{134}Cs to ^{137}Cs
  - 604.72 keV (yield: 97.62%)
  - 661.66 keV (yield: 85.13%)

Fluorescence X-ray Signatures of Burnup

- U K_{α} at 98.44 keV
- Pu $K_{\alpha 1}$ at 103.73 keV
- Pu $K_{\alpha 2}$ at 99.529 keV (approximately ⅔ the strength of the Pu $K_{\alpha 1}$)

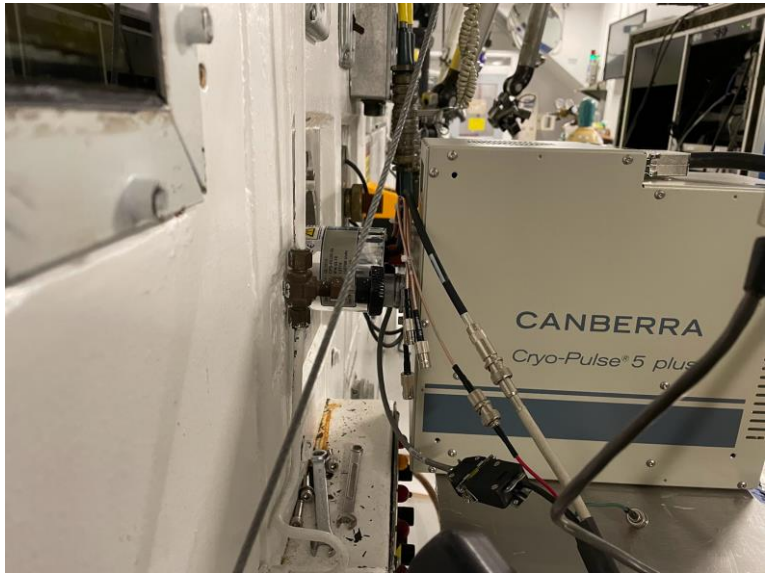
- Directly corresponds to the U to Pu content of the fuel
- Only 4 keV energy range to consider at max

Measurement Campaigns

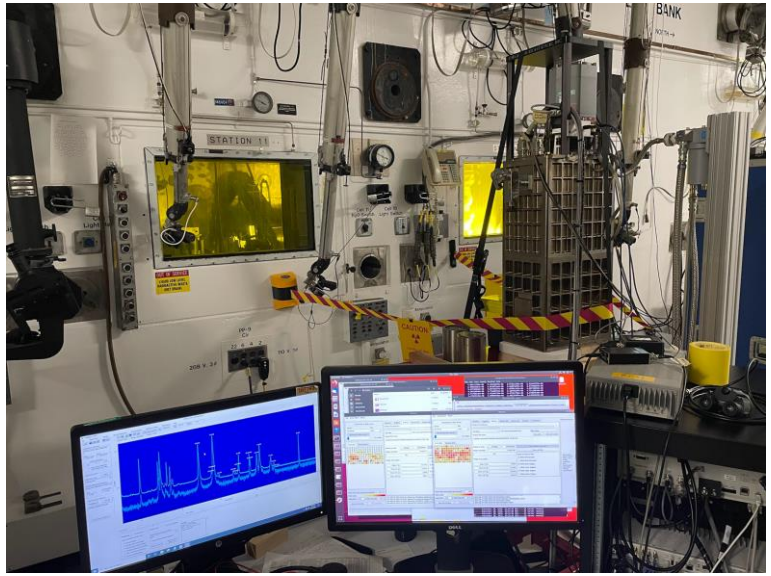
AGR2 and AGR5/6/7 TRISO fuels

Measured Sept 2023

ORNL Hot Cells



Irradiated at INL



Solid TRISO Fuels

ID	Burnup	Notes
AGR5/6/7 Compact 223	14.33%	Intact compact
AGR2 Compact 211	12.5%	Intact compact
AGR2 Compact 542	12.03%	~90% of compact
AGR2 subsamples	7.3-12.7%	11 samples with ~150-235 particles
AGR5/6/7 subsamples	9.3-14.3%	4 samples with ~235 particles

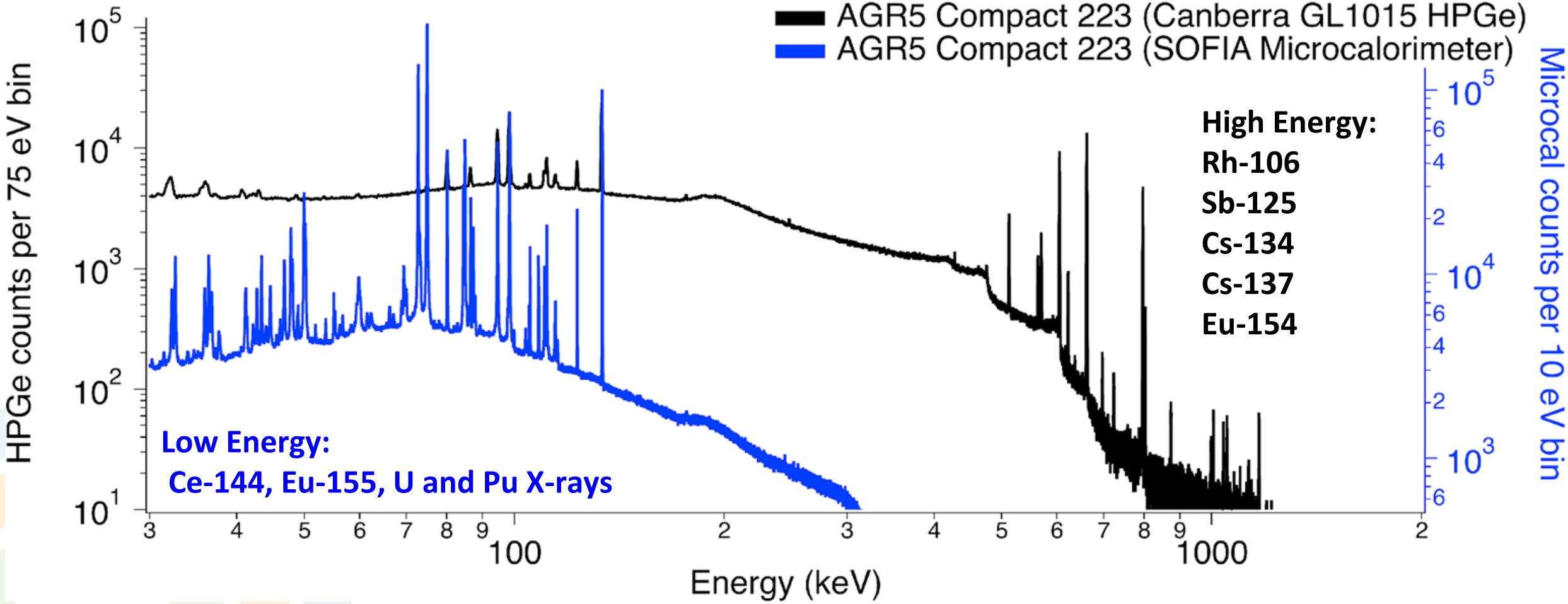
AGR2 Irradiations: June 2010 to October 2013
AGR5/6/7 Irradiations: February 2018 to July 2020

Dissolved TRISO Fuels

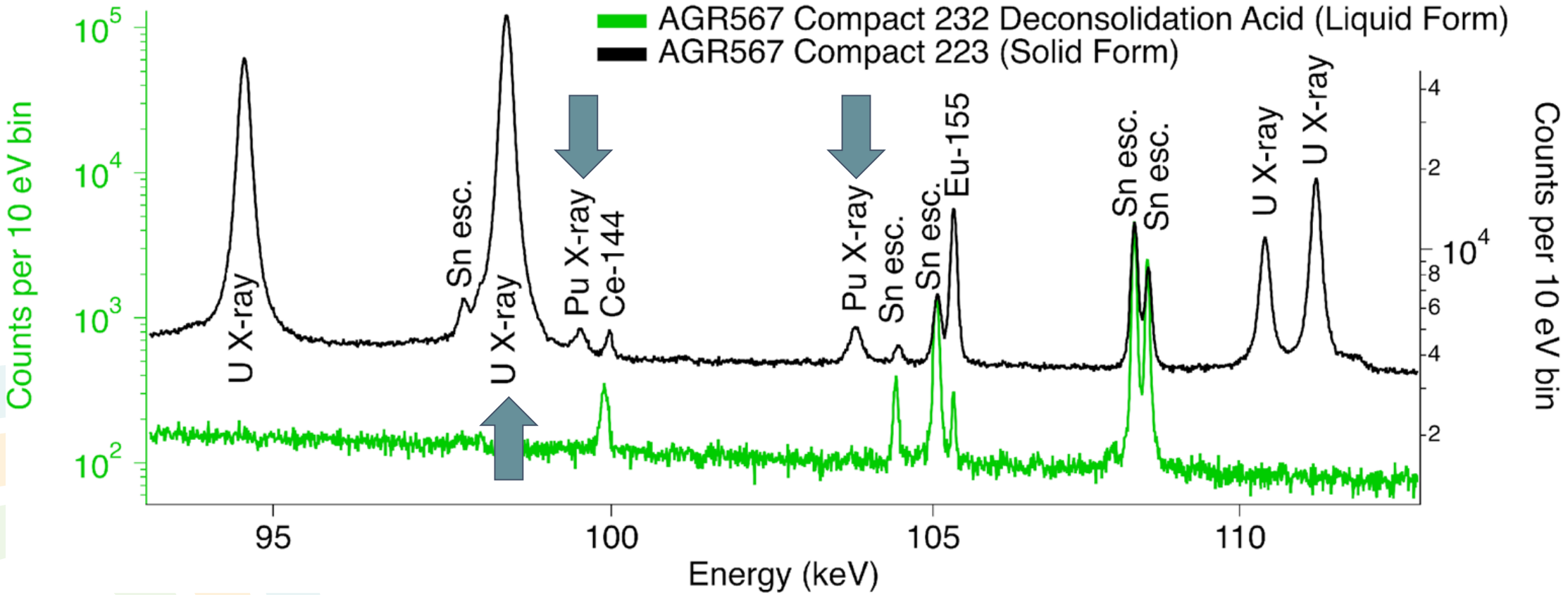
ID	Burnup	Notes
AGR2 Compact 642	9.26%	3 samples prepared for burnup DA
AGR5/6/7 Compact 232	14.36%	Fuel holder leach solution
AGR5/6/7 Compact 232	14.36%	Deconsolidation acid

AGR2 Irradiations: June 2010 to October 2013
AGR5/6/7 Irradiations: February 2018 to July 2020

HPGe and µCal Spectra



Liquid vs Solid Samples: Fluorescence X-rays



Insights from Measurements

- We can fully resolve the Pu x-rays from the U x-rays using μCal to directly quantify the U to Pu ratio in solid form TRISO fuels
- Measurement configurations can present unique challenges to simultaneous measurement with SOFIA and HPGe
- Variable background from hot cell operations and port alignment was a significant issue for quantitative analysis

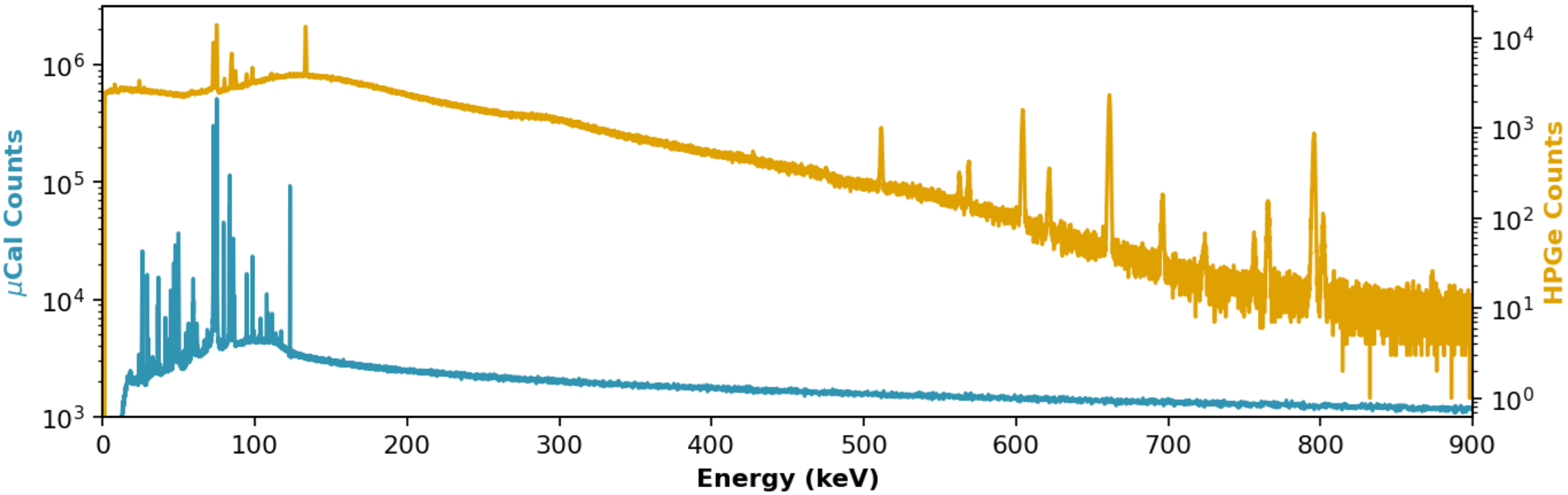
KP223 Fuel Compact

December 2023
ORNL Hot Cells

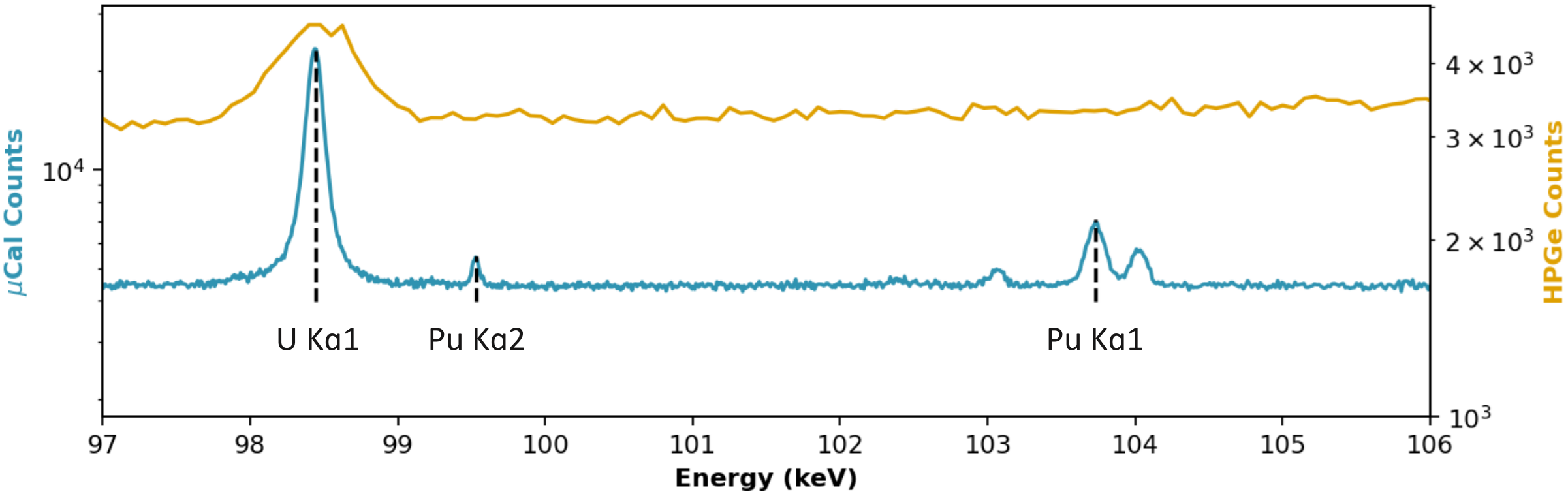
12.43% FIMA Burnup
20 particles in Minifuel compact
22 months since irradiation

Fuel made at LANL
Irradiated at ORNL
Made for Kairos Power

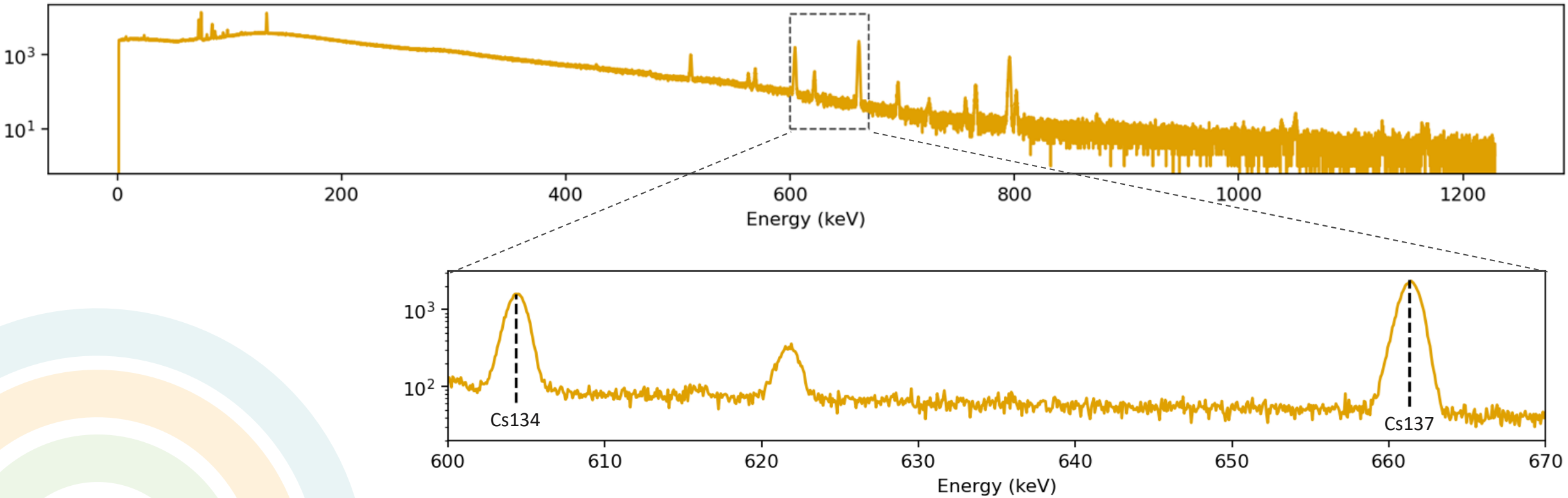
SOFIA and HPGe Spectra of KP223



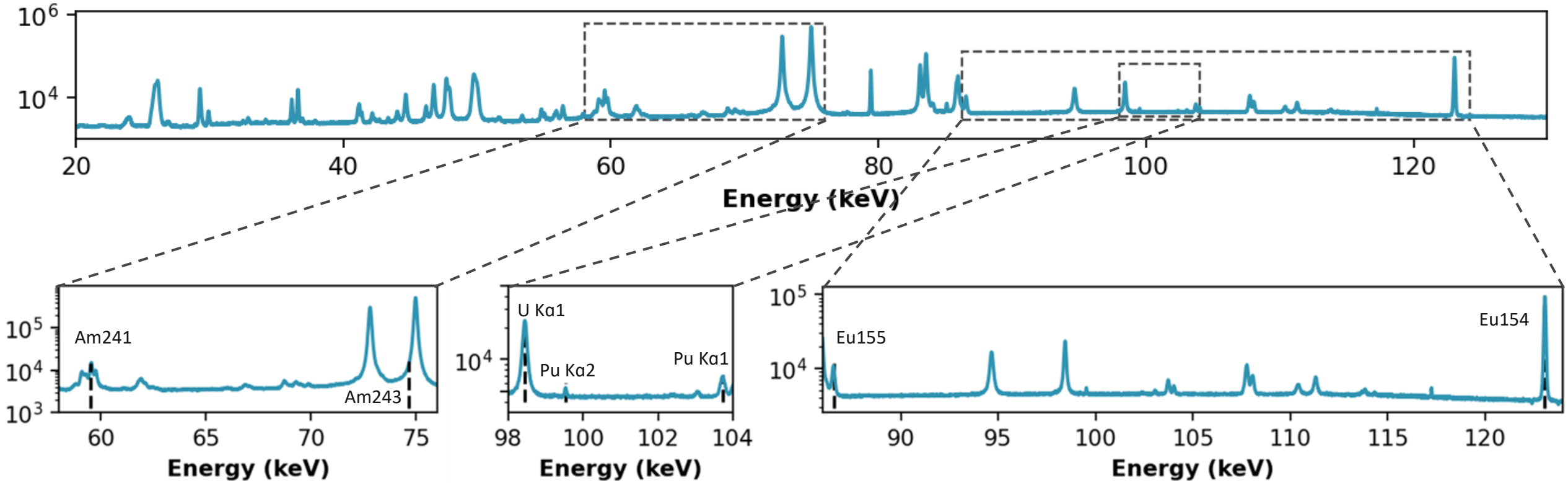
U, Pu X-Ray Region



HPGe Region of Interest

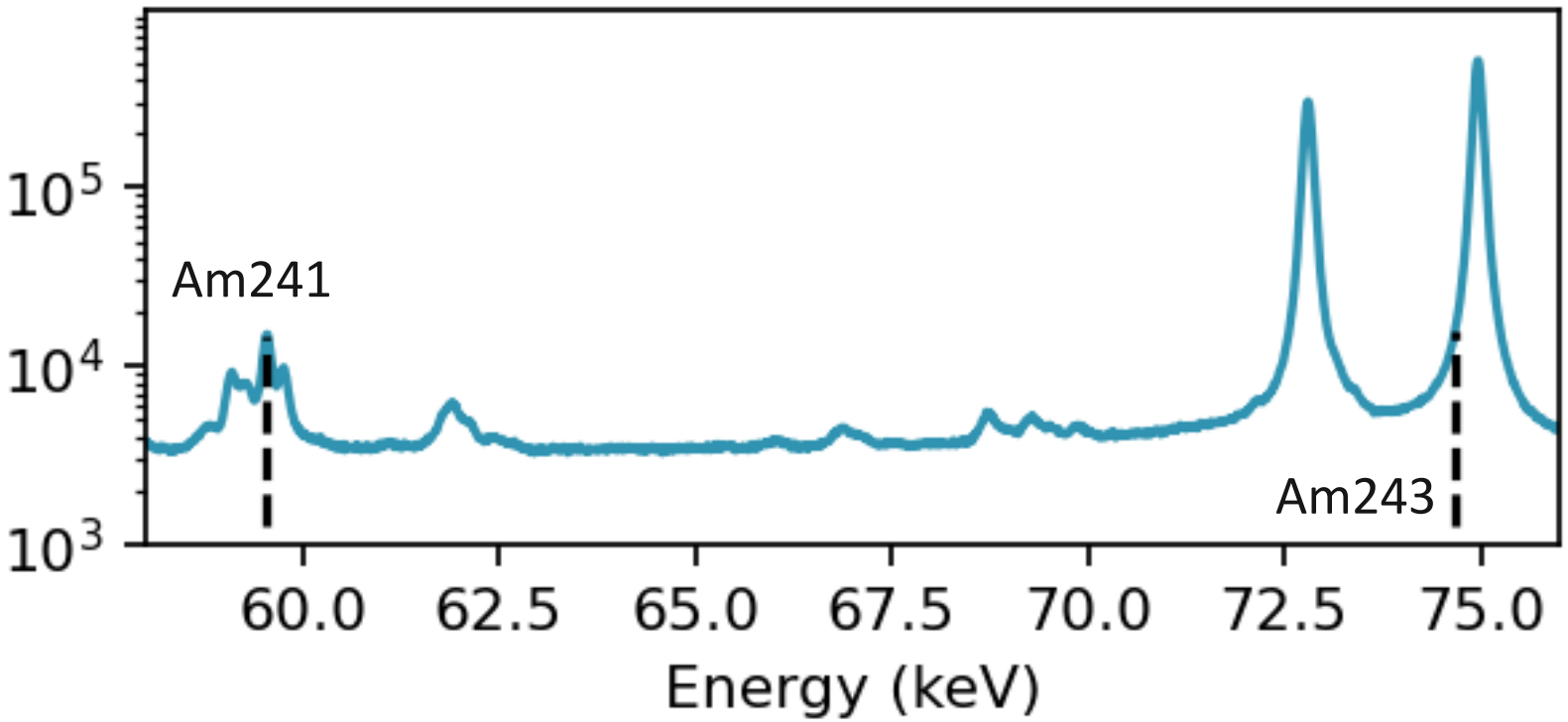


SOFIA Regions of Interest



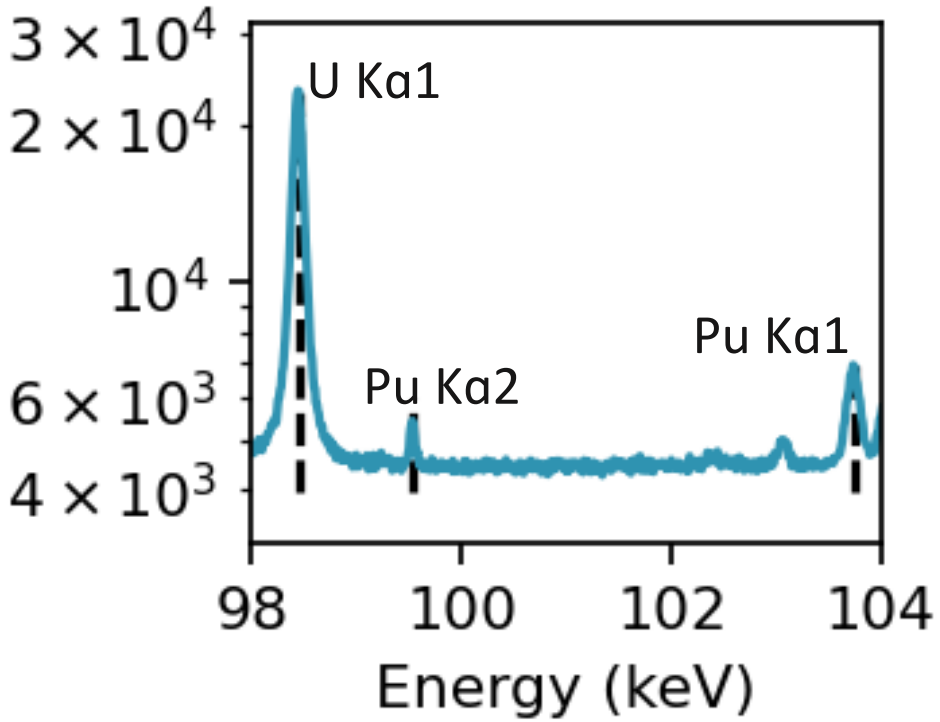
Americium ROI

The ^{243}Am peak is completely overpowered by a Pb x-ray (primarily from Pb collimator in hot cell)



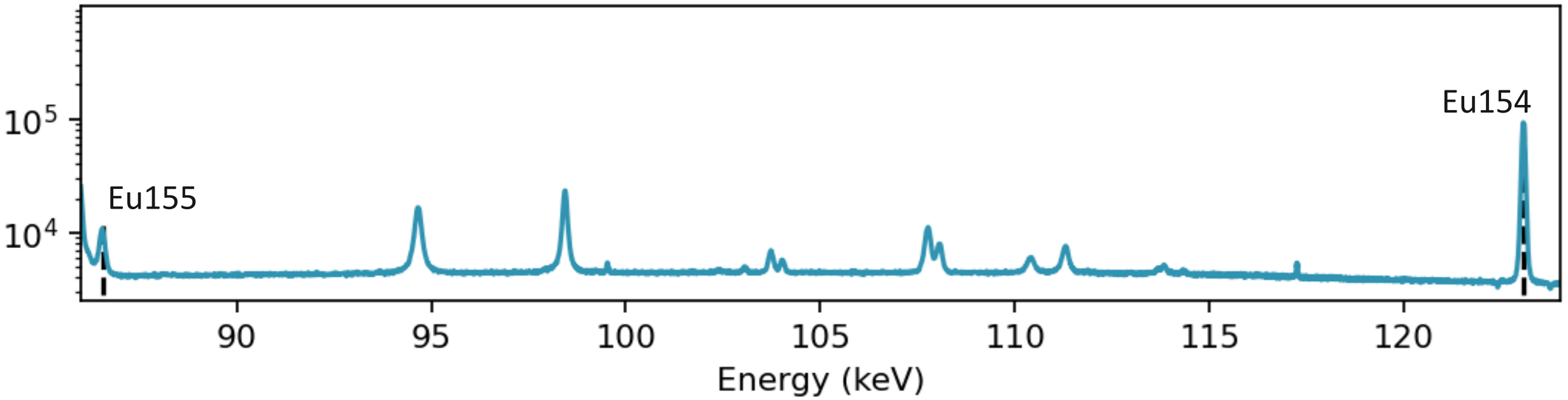
X-ray ROI

The x-rays are able to be completely resolved but the choice of which Pu x-ray to use must be considered.



Europium ROI

The Europium lines are present, but the calculation will rely more on an efficiency correction due to the wide energy range between peaks.



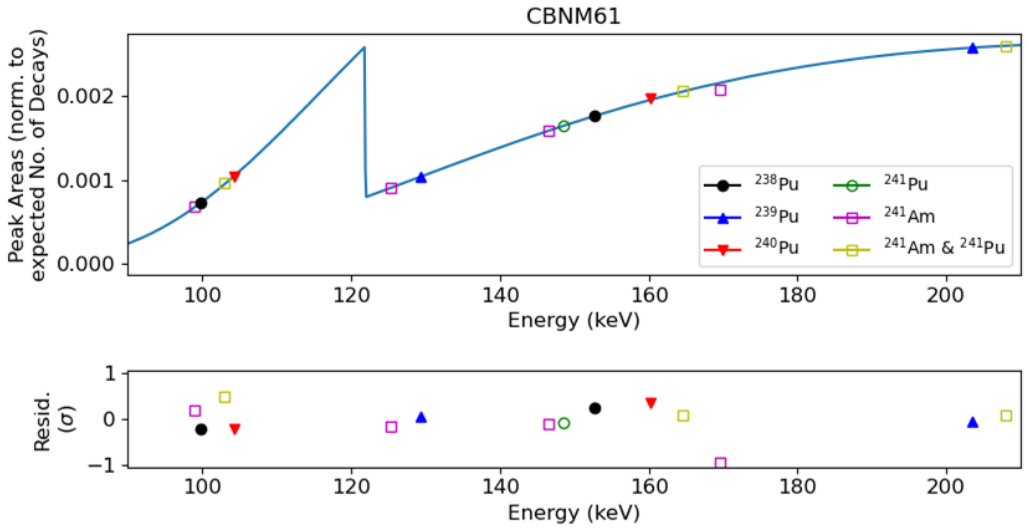
Planned Measurements

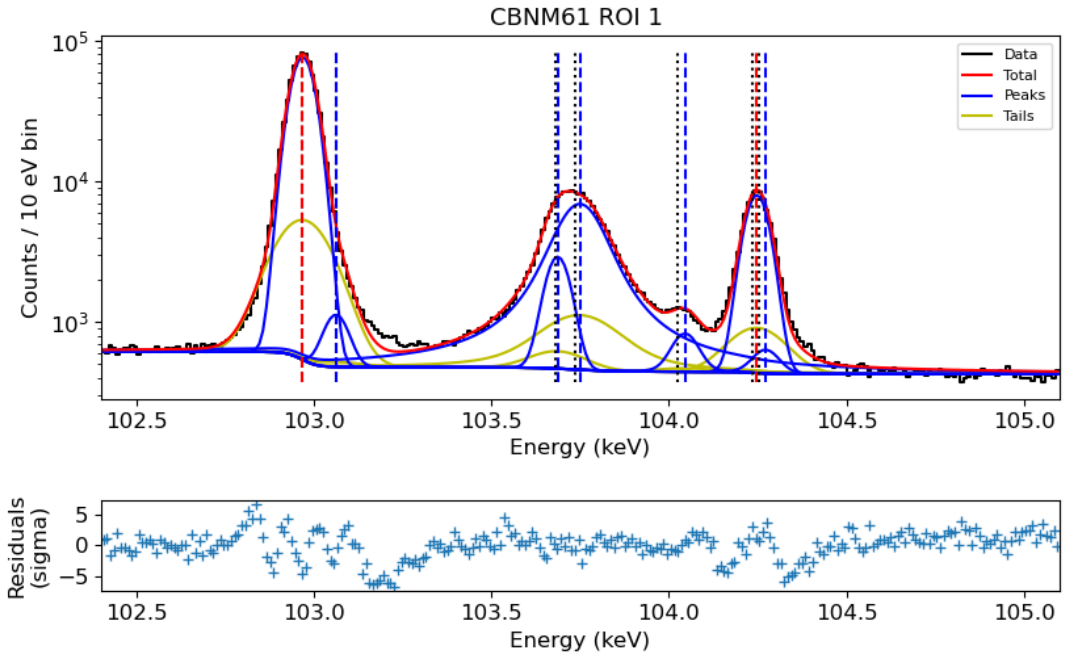
- Simultaneous measurement with SOFIA and HPGe to head-to-head comparison
  - Cannot compare spectra shown as the geometries differ dramatically
- Measurements with lower background radiation for higher signal-to-noise ratios
- Additional measurements at INL of irradiated TRISO with shorter cooling time

Quantitative Analysis

Uncertainty Quantification

- Using SAPPY we can extract peak fits and correct for efficiency
- Limitation of SAPPY: does not report uncertainty in relative efficiency curve





χ^2_{red} = 5.15 | Main FWHM = 78.1 eV | Tail FWHM = 180.0 eV

Line Centroid (keV) Ref.	/ fit	Source	Area (uncert)	Lorentzian FWHM (eV)
102.966 /	102.967	Pu241 *	723522.9 (0.131 %)	
103.060 /	fixed	Pu239	6162.4 (5.792 %)	
103.680 /	+0.005	Pu241	23272.4 (2.812 %)	
103.734 /	+0.013	x-ray	170851.4 (0.535 %)	121.0 (0.8 %)
104.025 /	+0.020	Sn esc	4174.8 (3.487 %)	11.1 (fixed)
104.234 /	+0.013	Pu240 *	71872.8 (0.425 %)	
104.252 /	fixed	Sn esc	2212.7 (fixed)	11.1 (fixed)

Dotted Lines above indicate tabulated peak locations

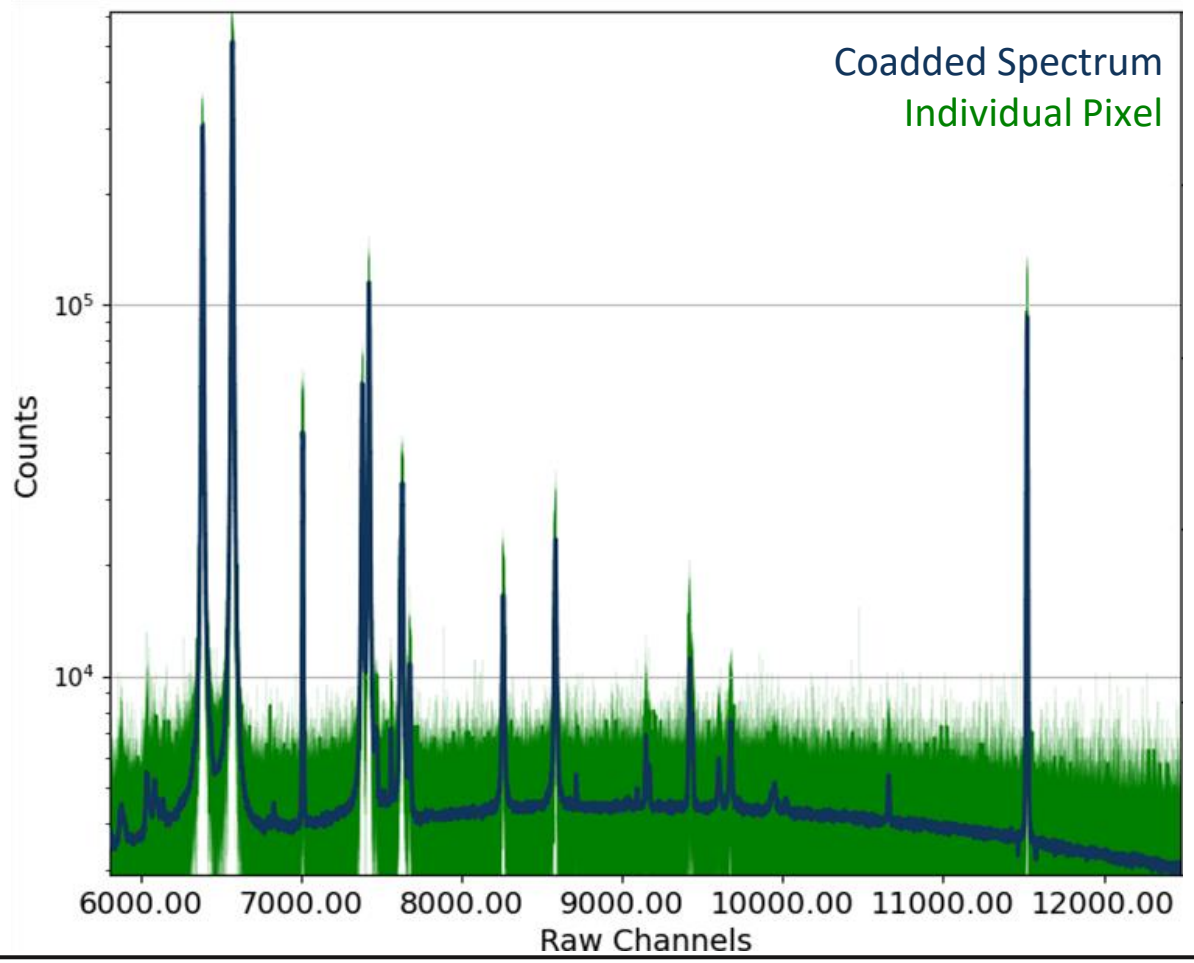
Dashed lines above indicate best-fit locations

* and red indicate peak used in efficiency curve fit

Plots from a reference standard

Comparison of Efficiency Calculation

- SOFIA is a multipixel array rather than a single detector
- Each pixel is processed individually and then coadded to give the final spectrum
- We can estimate the uncertainty in the relative efficiency curve by calculating the relative efficiency curve of each pixel



Next steps

- Measurements in progress will produce a series of spectra with well-controlled geometries and backgrounds to use for quantitative analysis

- FY24 M3 Milestone Report: Gamma Spectroscopy Performance for Irradiated Solid Form TRISO Fuel

Thank You