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Annual Report

X-GAMMA: Revealing the Nuclear Fingerprint with Cryogenic Detectors

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LA10-ADuCal-PD12

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1. INTRODUCTION

Technical work in the area of gamma-ray spectroscopy based on ultra-high resolution microcalorimeter spectrometers has focused on three areas: (1) In depth study of the sources of systematic uncertainty, (2) hardware upgrades to increase the stability and speed of spectrometer operation, and (3) measuring plutonium-containing SNM samples to test the hardware system and to inform further development of our spectral data analysis tools and methods.

2. **In depth study of sources of systematic uncertainty.** This effort has been lead by Dr. Andrew S. Hoover. We anticipate publication of new article (in draft form now) to be published in early 2014. A major peer-review and critical assessment of this work on the sources of uncertainty was held August 2013 at LANL. The review covered in-depth topics peak-fitting algorithms, spectral modeling, background models, replicate uncertainty, self-extraction of relative efficiency curves, model discrepancy, use of constraints, non-traditional choices for free parameters, impact on statistical uncertainty, comparison of HPGe and microcalorimeter results, and how to make fair comparisons between them. This is a very involved and complicated topic. Measurement data have been assessed for random (statistical) uncertainty on five different SNM materials. Systematic uncertainty has been partially assessed using measured data from three SNM materials. This work shows that the very small uncertainties in tabulated gamma-ray peak energies (~5 to 20 eV) lead to large uncertainties in HPGe-derived isotopic ratios (~1 to ~3%). In striking contrast, the exact same uncertainties in peak energies lead to >10X smaller uncertainties in microcalorimeter derived isotopic ratios (0.01-0.08%) because the peaks are so well separated. This is an important result indicating that the resolution of microcalorimeters is key to obtaining a large improvement in a critical component of total uncertainty. There is much more theoretical and practical work to be done in this area. Some results of these analysis are summarized in Table 1.

Constant	Ratio	PIDIE-1 (σ_s %)			PIDIE-3 (σ_s %)			PIDIE-6 (σ_s %)		
		HPGe Case 1	HPGe Case 2	μcal	HPGe Case 1	HPGe Case 2	μcal	HPGe Case 1	HPGe Case 2	μcal
Branching Fraction ($\sigma \approx$ 0.5-3.8%)	$^{238}Pu/^{239}Pu$	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
	$^{240}Pu/^{239}Pu$	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
	$^{241}Pu/^{239}Pu$	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
	$^{241}Am/^{239}Pu$	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24
Half Life ($\sigma \approx$ 0.04 -0.14%)	$^{238}Pu/^{239}Pu$	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
	$^{240}Pu/^{239}Pu$	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
	$^{241}Pu/^{239}Pu$	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
	$^{241}Am/^{239}Pu$	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Energy ($\sigma \approx$ 0.0007 -0.24%)	$^{238}Pu/^{239}Pu$	6.9	1.6	0.15	3.2	0.68	0.022	1.9	0.18	0.015
	$^{240}Pu/^{239}Pu$	2.7	3.1	0.051	3.2	1.4	0.024	2.7	0.96	0.038
	$^{241}Pu/^{239}Pu$	1.6	1.1	0.051	1.7	0.72	0.013	0.92	0.20	0.020
	$^{241}Am/^{239}Pu$	5.4	2.2	0.052	4.3	1.2	0.041	3.0	0.37	0.048

Table 1. Summary of sources of systematic uncertainty using a sensitivity coefficient approach and Monte-Carlo calculation. A key difference is now clear. For plutonium isotopic ratios, the systematic uncertainty due to peak energy centers is between ten and sixty times superior for our microcalorimeter-based spectrometers compared to HPGe. This is a direct consequence of energy resolution.

The intentional variation of normally-fixed parameters (e.g. half lives of Pu isotopes, branching ratios for specific gamma-ray peaks) has lead to improved understanding of a subset of sources of systematic uncertainty. For the analysis so far, a single set of spectral data from an individual Pu sample (PIDIE-3) for both HPGE and microcalorimeter system is analyzed with variable parameter sets. The parameter set variations explore a distribution whose widths are taken from the absolute uncertainties for each tabulated parameter. The effect of these changes on output values (isotopic fractions or ratios) provides direct access to sensitivity coefficients. Parameters considered so far include branching fractions, half lives, gamma-ray energies, X-ray energies, X-ray line widths, material density, and mass attenuation coefficients. The tentative conclusion is that gamma-ray and X-ray energies centroid values have a strong effect isotopic composition extracted from HPGE spectra (~0.6 to 5 % RSD), whereas they have almost no effect on isotopic composition extracted from microcalorimeter spectra (<0.05 % RSD). This is a direct consequence of spectral resolution. Common sources of systematic uncertainty include branching fractions and half lives, which are responsible for ~0.8 to 1.2 % RSD systematic uncertainty. Conducting these analysis is a major endeavor. Significant work is still required in this area.

3. H**ardware and firmware upgrades to increase the stability and speed of spectrometer operation**

This work has focused on substantial changes in room-temperature electronics that are integral to array operation and readout. Key features of the multiplexing (MUX) system have now been upgraded, most importantly the digital feedback (DFB) cards, on-board firmware, and control software. The main goal for these changes was to reduce settling time after MUX switching between readout rows.

The upgrades have substantially shorter settling times allowing for higher total event rates per pixel and across the array. Data have been taken with greater system stability at over 1000 events per second. Firmware upgrades under test also included saturation (unlock) detection and recovery (relock) being integrated into the pipelined DFB algorithm. Concurrently work continued on signal processing for retaining high resolution at high event rates (10 cps/pixel) and on software for spectral data analysis. Of particular note, improvements in feedback stability and automatically restoring the feedback subsequent to a flux jump. The example shown in Fig. 2 shows the new auto-re-locker in action. On the leading edge of a pulse, a flux jump occurs (red circle) and the fast firmware relock logic has responded to the pixel trying to settle to a sub-baseline value. The time interval between the flux jump and relock in this is example is approximately 4 ms.

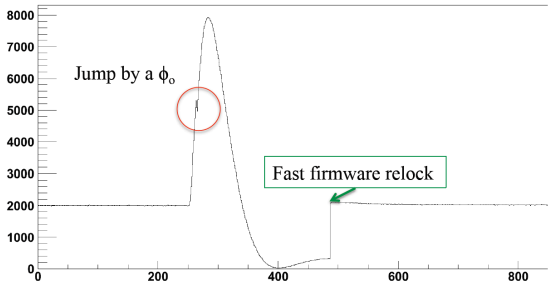

Figure 1. Example of successful automatic relock of pixel using firmware-based (pipelined) feedback algorithm.

4. Measuring plutonium-containing SNM samples The key result of the upgrades discussed above is substantially improved system stability allowing data collection over the entire array without cascade unlock and wit high likelihood of achieving 60-80 eV resolution with stable feedback systems settings on a run-to-run (day-to-day) basis. An example is shown in Fig. 2. The material analyzed is low-burn-up Pu and the relative amounts of the minor Pu isotopes (238, 240, 241) are also low. Hence the associated peaks for these isotopes have low relative peaks. This makes for a maximally difficult calibration.

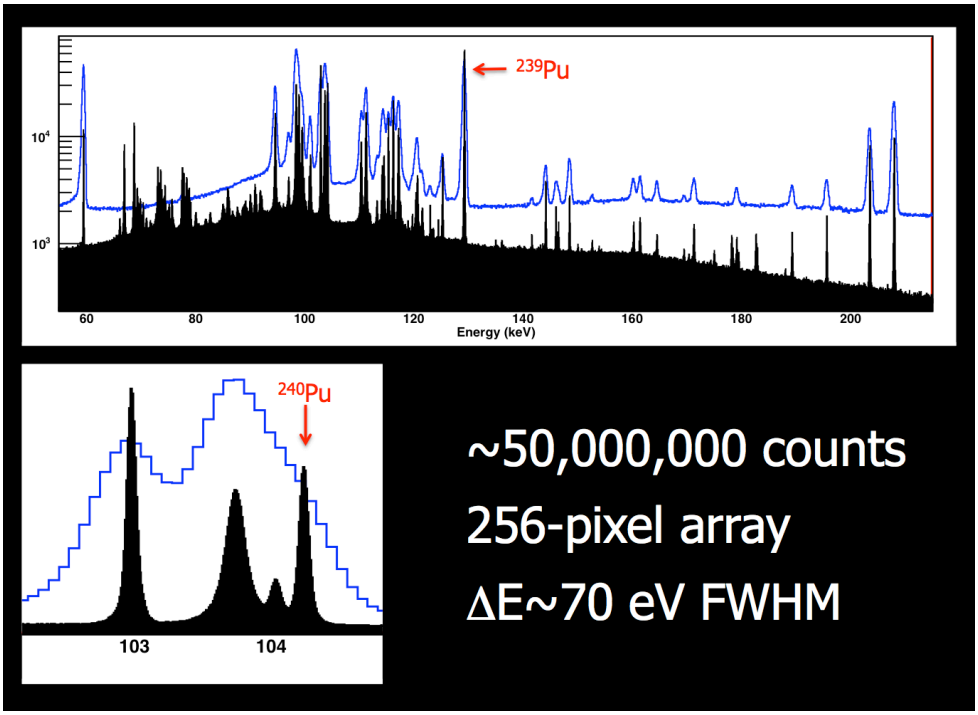

Figure 2. Recent ultra-high-resolution gamma-ray spectrum of plutonium.