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Magnetic Microcalorimeter Gamma Detectors for High-Precision Non-Destructive Analysis Fact Sheet

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Magnetic Microcalorimeter Gamma Detectors for High-Precision Non-Destructive Analysis

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Description:

- Precise measurements of gamma (γ) energies from radioactive decays provide an accurate non-destructive assay (NDA) of the isotopic composition of nuclear materials.
- Magnetic microcalorimeters (MMCs) are one class of detectors that operate at very low temperature to provide more than 10x higher energy resolution (precision) than conventional high-purity Ge detectors currently used for NDA of nuclear materials [Bühler 1994].
- MMCs detectors measure γ-energies from the change in magnetization of Er ions at ultra-low temperatures (<0.1 K) upon γ-absorption (inset figure 2).
- This project develops MMCs based on erbium-doped gold as ultra-high resolution γ-detectors for high-accuracy NDA (figure 1).
- Ultra-high resolution γ-detectors may allow e.g. direct detection of γ-emissions from Pu-242, reducing limiting systematic errors in Pu isotopics, especially for high-burn-up fuel [Bates 2014].
- MMCs may prove superior to γ-detectors based on superconducting transition edge sensors (TESs), because a) MMCs are expected to be more linear and b) TESs are constrained in high-resolution operation to a few counts/second per pixel.
- The main challenge of this project is to attain an energy resolution <100 eV FWHM with MMCs.
- Small detector volume and low count rates necessitate the development of γ-detector arrays.
- TRL = 6

Figure 1: Liquid-cryogen-free cryostat with compressor (on floor) and MMC γ-detector (behind round Be window). 19" rack with electronics not shown.

Applications:

- Nuclear Safeguards: Improved accuracy verification of Pu isotopics during nuclear fuel cycle
- Waste Management/Materials Storage: Accurate non-destructive analysis of nuclear materials
- Nuclear science: High-precision measurements of nuclear properties

Performance:

Two-pixel γ-detectors based on the Heidelberg design of magnetic microcalorimeters (MMCs) are currently in the initial stages of testing at LLNL. Despite the early stage of this project, the detectors have already achieved an energy resolution of 150 eV FWHM, or 4x better than the high-purity germanium detectors currently used for high-resolution NDA (figure 2). This is already enabling the detection and separation of γ-rays that have previously been obscured due to line overlap of background fluctuations.

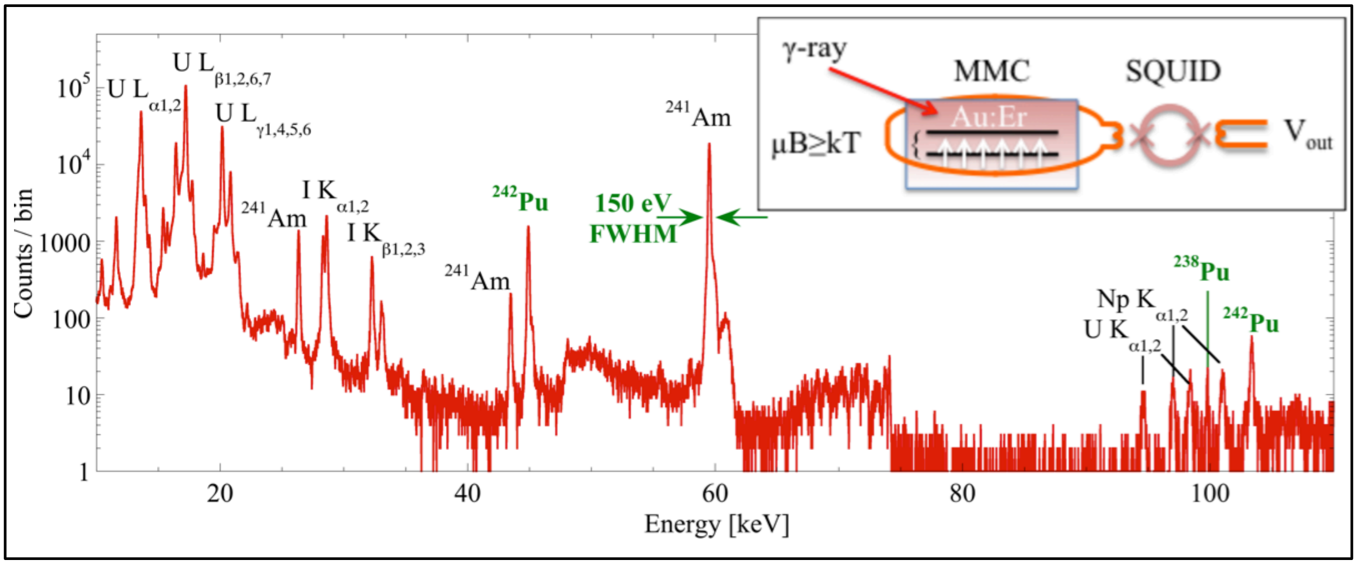

Figure 2: Composite spectrum of a Pu-242 source with an energy resolution of 150 eV FWHM. It consists of the sum of 32 spectra from the same MMC detector taken over several weeks. The visibility of lines at 100 keV after calibration using low-energy lines demonstrates very good linearity of this MMC detector. [Bates, to be published in 2015]

Cooling the γ-detectors to their operating temperature <50 mK is currenlty done in a two-stage adiabatic demagnetization refrigerator (ADR) with pulse-tube precooling. The cooldown is fully automated and does not require liquid nitrogen or helium. Gamma-rays sources are held outside the cryostat in front of a thin aluminum or beryllium window (figure 1). Weak sources can be mounted inside the cryostat for higher efficiency.

We collaborate with several groups at LLNL and beyond who provide us samples for detector testing and NDA analysis, and are open to expanding this range of collaborations.

Physical Specifications:

- Note: The detector itself is quite small, with pixel volumes of order ~mm^3. The largest portion of the instrument is the refrigerator and the associated compressor and electronics (figure 1).
- Weight: ~ 100 lbs. (refrigerator), 175 lbs. (compressor), ~200 lbs (rack with electronics)
- Footprint: ~4 sq. ft. (refrigerator), ~ 4 sq. ft. (compressor), ~4 sq. ft. (electronics)
- Power requirement: ~ 10 kWatts (primarily ~ 7 kW compressor, water-cooled, 240V 3-phase)
- User interface: Custom-written data acquisition program (in Python)
- Data acquisition features: Trapezoidal and cusp filtering; drift corrections; off-line analysis

Operational Specifications:

- Setup time: Precooling to a temperature of ~3 K overnight
- Repeated ~1h cooling cycle to the < 50 mK base temperature currently required every ~12 hours. (A refrigerator with continuous cooling to <50 mK is being developed as part of this project).
- Current compressors require water-cooling. (An air-cooled version is being built as part of this project).

Background:

- High-resolution X-ray spectrometers based on magnetic microcalorimeters (MMCs) first proposed and developed in the early 1990s [Bandler 1993] [Bühler 1994].

• MMC detector development since then mostly driven by Prof. Christian Enss' group at the University of Heidelberg (Germany), and by NASA Goddard for X-ray astronomy
• Adaptation of Heidelberg MMC X-ray detectors for high-accuracy gamma spectroscopy proposed by LLNL in 2012 (this project). Generous help by the Heidelberg group led to rapid advances in detector performance.

Future Development Goals:

- Further improvements in energy resolution require the current adiabatic demagnetization refrigerator with a ~35 mK base temperature to be replaced by a ~15 mK dilution refrigerator. For example, the MMC γ-detectors from the same wafer as the one used for the Pu-242 spectrum in figure 2 have an energy resolution of 46 eV FWHM when operated in a dilution refrigerator at a temperature of 18 mK (Figure 3 vs. Fig. 2), as the MMC signal increases with 1/T (Curie law).

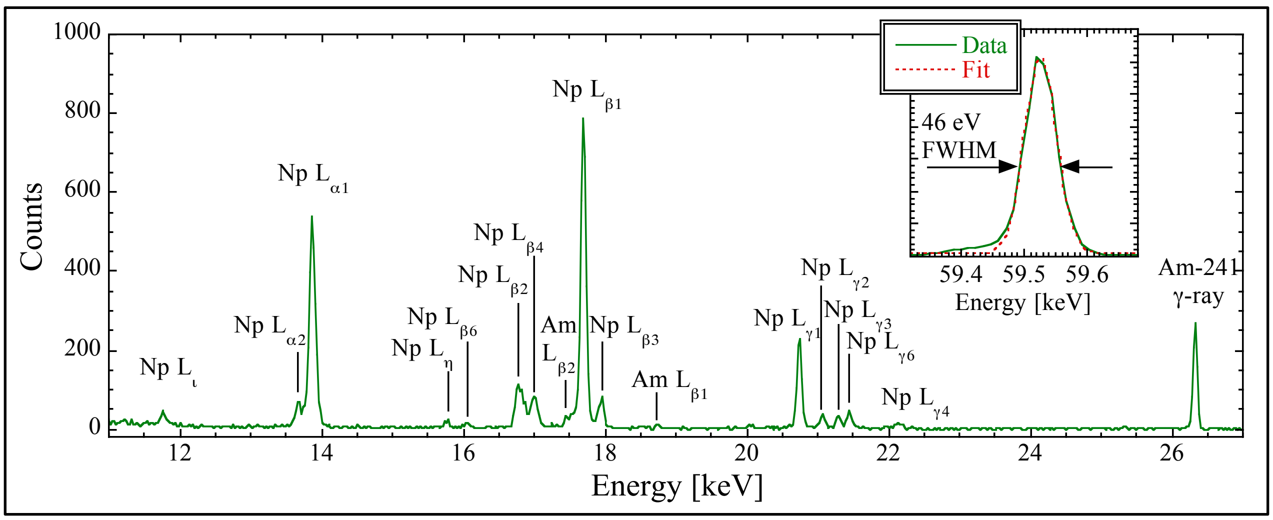

Figure 3: An Am-241 spectrum of an MMC detector from the same wafer, taken at the University of Heidelberg in a dilution refrigerator with a lower base temperature of 18 mK, has even higher energy resolution. [Bates, 2015]

- Increases in sensitivity (highly desirable) require the development of MMC γ-detector arrays. Arrays of several tens of pixels can be developed mostly by scaling existing detector technology. Significantly larger arrays require a multiplexed readout, which is currently being developed by the Heidelberg and the NASA Goddard group.
- Additional improvements in the user-friendliness of detector operation, real-time pulse processing and analysis software are very desirable.

References:

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