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A Novel Approach using Sapphire Crystals and Magnetic Microcalorimeters for Nuclear Material Analysis

Alexander R.L. Kavner, S.T.P. Boyd, Robin H. Cantor, Owen B. Drury, Stephan Friedrich, Igor Jovanovic, Dongwon Lee, and Geon-Bo Kim

***Abstract*— Magnetic microcalorimeters (MMCs) operating at milli-kelvin temperatures offer ultra-high energy resolution in radiation measurements. A key advantage of MMCs compared to transition edge sensor (TES) microcalorimeters is the ability to achieve excellent energy resolution over a wide energy range. We are developing a novel detection approach that couples sapphire absorbers to MMCs for larger detection area and volume, faster detector response, and broader energy range. This approach should benefit analysis of nuclear materials having multiple types of radioisotopes. Using this new approach we have successfully simultaneously measured keV-scale X-rays, sub-MeV heavy ions, MeV-scale beta particles, and several-MeV alpha particles.**

***Index Terms*—magnetic microcalorimeter, nuclear material analysis, nuclear forensics, nuclear safeguards**

I. Introduction

Magnetic Microcalorimeters (MMCs) [1] employ paramagnetic materials (typically Ag:Er or Au:Er) and superconducting wiring and electronics to perform high energy-resolution radiation spectroscopy. The paramagnet is magnetized by a superconducting coil and has a strong temperature dependence. A radiation deposition within the MMC's absorber produces heat and increases the temperature of the paramagnet. The resulting magnetization change is measured by a second superconducting coil connected to a very sensitive current sensor, a "superconducting quantum interference device" (SQUID). The SQUID converts the magnetic signals to readable voltage signals.

The theoretical limit of an MMC's energy resolution is a simple function of temperature and the heat capacity of the detector,

$$\Delta E_{\mathrm{rms}} = (\tau_r/\tau_d)^{1/4}\sqrt{8k_B C T^2},$$

where τ_r and τ_d are rise- and decay-times, k_B is Boltzmann constant, C is heat capacity, and T is temperature. MMCs therefore typically couple small paramagnetic samples to small, high conductivity Au foil absorbers, for fast thermalization and small heat capacity, and are operated at very low temperature T < 0.05 K. These Au-absorber MMCs offer ultra-high energy resolution and are employed in high resolution X-ray, gamma-ray, and decay-energy spectroscopies [2-4]. However, such gold-absorber MMCs have very small absorber volumes and detection areas, which is a substantial limitation.

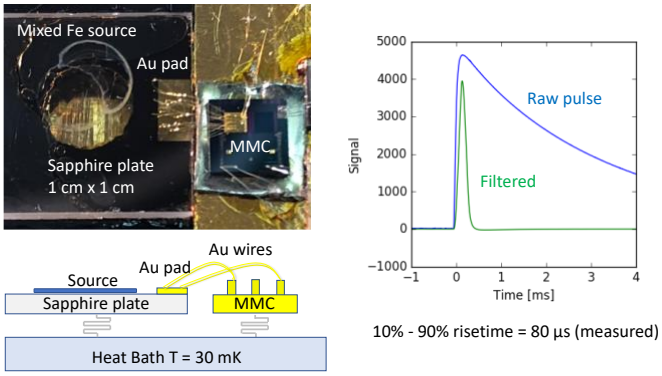

Fig. 1. (Left-top) A picture of the detector set-up with a source-embedded sapphire plate and an MMC sensor [5]. (Left-bottom) A schematic drawing of the detector. (Right) A raw and filtered pulses measured by the MMC. The pulse can be as fast as ~80 µs with trapezoidal filtering.

We are developing a new approach that replaces the Au absorbers with cm-scale sapphire single crystals for high precision radiation and nuclear material analysis. Sapphire crystals have significantly smaller specific heat than Au, therefore relatively large plates can be used without significant loss of energy resolution.

These sapphire-absorber MMCs offer large detection area, faster detector response, and broad energy range from sub-keV to several MeVs, due to their smaller heat capacity and higher signal to noise ratio. We expect these sapphire-absorber MMC detectors to benefit the analysis of composite nuclear materials having different types of radiation emissions over broad energy ranges, such as mixed Fe sources, Pu, and environmental samples containing various radioactive isotopes.

II. Detector Details

As shown in Fig. 1, our detector consists of a cm-scale single-crystal sapphire plate with a Au pad on its surface, an MMC sensor, and Au wires for the thermal link between the Au pad and MMC sensor. Radiation absorptions into the sapphire produce high-energy "athermal" acoustic phonons. These phonons are collected by, and thermalize the electrons in, the

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gold pad, which in turn thermalizes with the MMC sensor. Sapphire crystals have a high speed of sound and low phonon attenuation, thus the measured energy loss during the phonon-collection process is only of order 50%.

This approach allows us to couple a large-area absorber to the MMC sensor, creating significant improvements in detection efficiency while simultaneously providing high-precision measurements of broad-range radiations from sub-keV to several MeVs by a single detector.

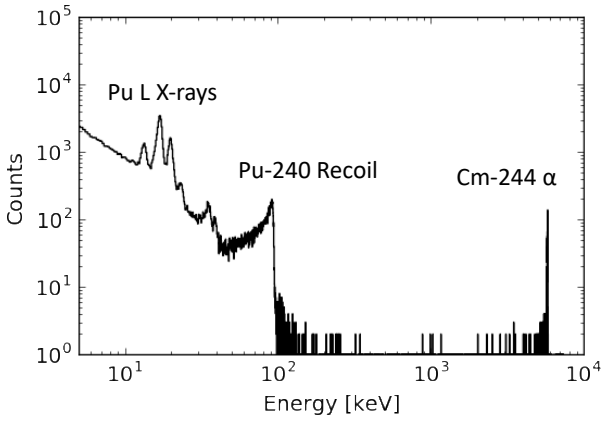

Fig. 2. Experimental Cm-244 spectrum measured with a sapphire-absorber MMC detector. X-rays, Pu-240 recoiled ions, and alpha radiations ranging from a few keV to several MeV are simultaneously measured in a single acquisition.

III. Results

A. Cm-244 source

A sapphire plate was exposed to a commercial Cm-244 source [5], at an event rate of ~30 counts/s. This source produces alphas, Pu-240 ions, Auger and conversion electrons, and x-ray emissions from its decays. Our sapphire-MMC detector can simultaneously measure all of these radiations ranging from a few keV to MeV without loss in energy or efficiency, as shown in Fig. 2. Intrinsic efficiencies for charged particles are near 100% and for photons decreases at high energies. Full-width-half-maximum (FWHM) energy resolutions are measured as 0.4 keV, 2.0 keV, and 18 keV, for 20 keV X-rays, 97 keV Pu-240 recoiled ions, and 5805 keV alpha particles, respectively.

B. Mixed Fe source

A source combining Fe-55 (electron capture) and Fe-59 (beta) was placed on top of a sapphire crystal absorber. Mn-55 X-rays from Fe-55 decays and beta particles from Fe-59 decays were successfully measured simultaneously, and the resulting energy spectrum is compared with Geant4 simulation in Fig. 3. The 5.9 and 6.5 keV Mn X-rays are measured with 0.5 keV FWHM energy resolution. Three unknown peaks at 8 keV, 14 keV, and 20 keV are suspected to be fluorescence from the detector holder materials and are being investigated. The ratio of Fe-55 to Fe-59 can be directly estimated by integrating Mn-55 X-ray peak areas and Fe-59 beta continuum. The event rate decrease of the beta continuum was consistent with the Fe-59 half-life of 44.495 days.

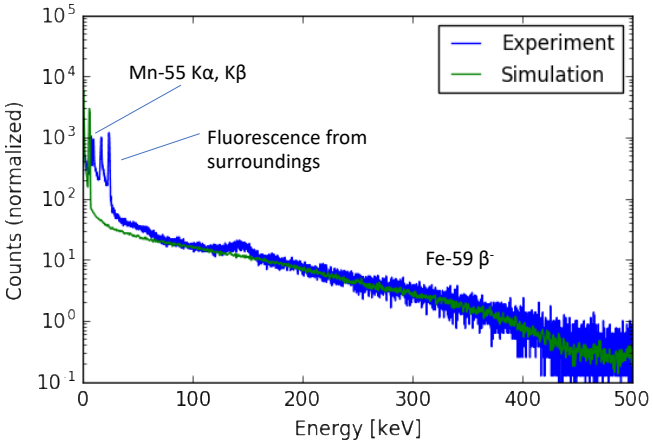

Fig. 3. An experimental spectrum of a mixed Fe source on the sapphire plate. Mn-55 X-rays and Fe-59 beta radiations are simultaneously measured, with half-keV FWHM energy resolution.

IV. Conclusion

We are developing a novel magnetic microcalorimeter by coupling cm-scale sapphire plates for large detection area, easy sample preparation, broad detectable energy range, and faster detector response. We have demonstrated that such detectors can simultaneously measure various types of radiations from the keV to MeV scale in a single experiment and acquisition, without significant loss in energy resolution or efficiency. Also, the sapphire-MMC detector can be operated at faster speed than current MMCs that use Au absorbers, which enables faster radiation counting at tens of counts per second per MMC. We anticipate these sapphire-MMC detectors could benefit analysis of nuclear materials that contain multiple isotopes and radiation types.

V. Acknowledgements

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