The modern microcalorimeter: a broadband, high resolution, high throughput detector for the x-ray sciences

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Transition-edge-sensor (TES) microcalorimeters are energy-dispersive detectors with energy resolving power of 1000 or more. Over the past decade, the NIST Quantum Sensors Group has developed a number of X-ray spectrometers based on multi-hundred-pixel arrays of TES microcalorimeters for a variety of measurement applications. These applications include tabletop time-resolved absorption and emission spectroscopy, synchrotron-based absorption and emission spectroscopy and energy-resolved scattering, metrology of X-ray-emission lines, spectroscopy of atomic transitions of ionized and hadronic atoms, gamma-ray spectroscopy of nuclear materials, and particle-induced emission spectroscopy.

The TES microcalorimeter uses the sharply temperature-dependent resistance of the superconducting-to-normal phase transition to measure the energy of individual x-ray and gamma ray photons. A single TES is a broadband, energy-dispersive area detector capable of eV-scale energy resolution with good quantum efficiency. With an array of hundreds or thousands of sensors, a TES-based spectrometer can have orders of magnitude higher throughput than wave-length dispersive instruments. Thus, microcalorimeter spectrometers built around arrays of TESs occupy an interesting region of the spectroscopy parameter space. They have good enough energy resolution to perform many types of X-ray emission spectroscopy (XES), or measurement of the positions, shapes, and relative intensities of emission features. TES arrays also have many of the best features of traditional energy-dispersive detectors (e.g., silicon-drift detectors): high collecting efficiency (large area, high quantum efficiency, and the possibility of a close sample distance), flexible observing geometries, and simultaneous sensitivity to all X-ray energies. Pixelated TES arrays also allow imaging. This combination of features is most useful in high-resolution applications that are traditionally photon-starved, involve radiation-sensitive samples, or in measurements where the science signal is obscured by large photon backgrounds. TES arrays are also enabling expansion of techniques to the lab bench that have been previously available only at synchrotrons or XFELs.

In this talk, I will introduce the basic principles of TES microcalorimeters, and discuss how TES thermistors are exploited to optimize microcalorimeter performance for a wide range of photon energies, from soft X-rays to gamma rays. Because the TES thermistor and the material that absorbs incoming radiation can be separate structures, we can use high-Z materials like tin and bismuth to stop photons with high efficiency up to 200 keV with $R > 1000$. For soft x-rays, using a thin film absorber with lower total heat capacity enables energy resolution of < 1 eV FWHM for $E < 1$ keV. This flexibility allows us to customize the TES array to the scientific goals and requirements of a particular light source and experimental configuration.

Additionally, I will discuss recent advances in TES design and high-bandwidth multiplexing readout that have enabled faster sensors ($\tau < 100$ μs) and larger arrays (>1000 pixels). By engineering the thermal time constant of the TES, the photon response time can be reduced to tens of microseconds, allowing a single sensor to count thousands of photons per second. With the success of microwave readout techniques, 3,000-pixel spectrometers are expected to arrive on the timescale of one to two years, and work is underway to expand to 10^5-pixel or larger arrays. This rapid expansion of capability will enable novel measurements both in the lab and at the world's most powerful light sources.