Microcalorimeter Detectors: Broadband, Efficient, High Energy-Resolution Detectors for Materials Science

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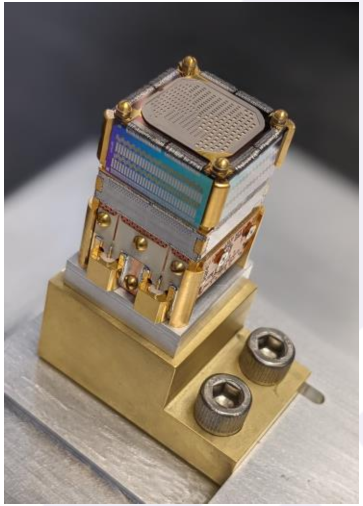
Outline

- Introduction to Low-Temperature Detectors (LTDs)
- Techniques/energy ranges and applications
- LTD applications to ultrafast techniques
- Discussion: where is the overlap and application between UED and LTD?

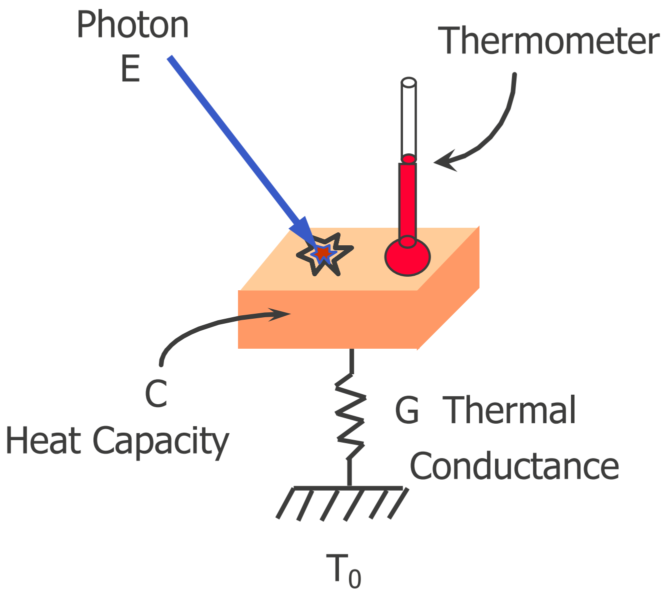
What do we mean by “low temperature”?

Room temperature: ~300 K
Liquid nitrogen: ~77 K
Liquid helium: ~4.2 K
Average temperature of universe (CMB radiation): ~2.7 K

Our detectors: ~0.1 K

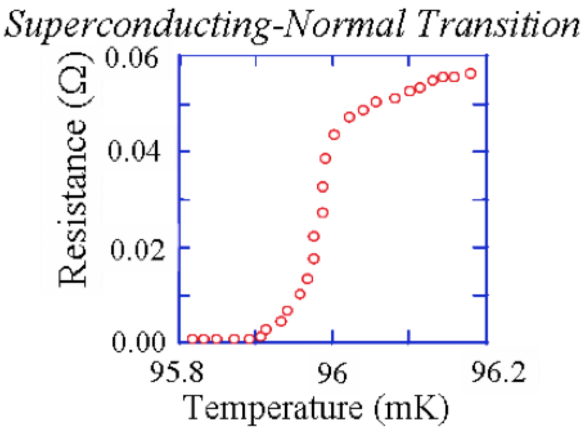


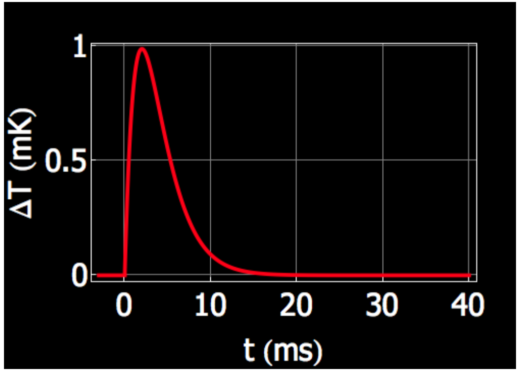
Why so cold? To overcome energy resolution limits.



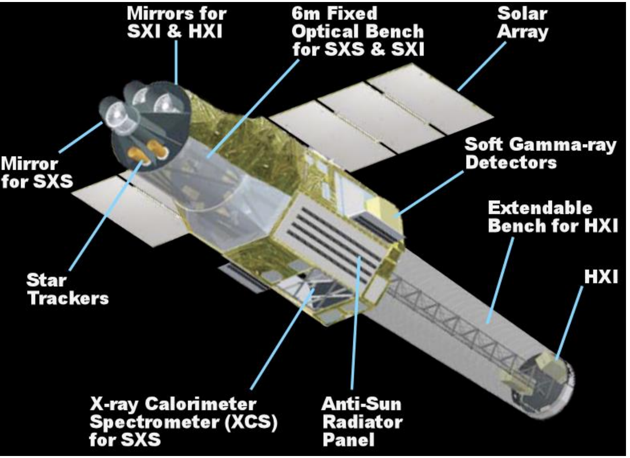
$$E = C \times \mathrm{D}T \qquad \mathrm{D}E \approx \sqrt{4kT^2C}$$

A microcalorimeter measures the thermalized energy of individual photons, nuclear decays, etc. to create an ultra-high resolution energy spectrum (10-50x better than semiconductors)

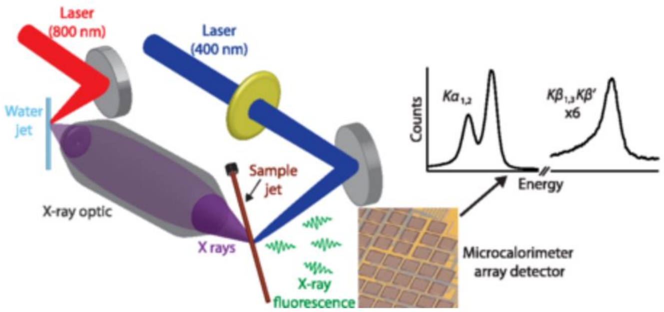




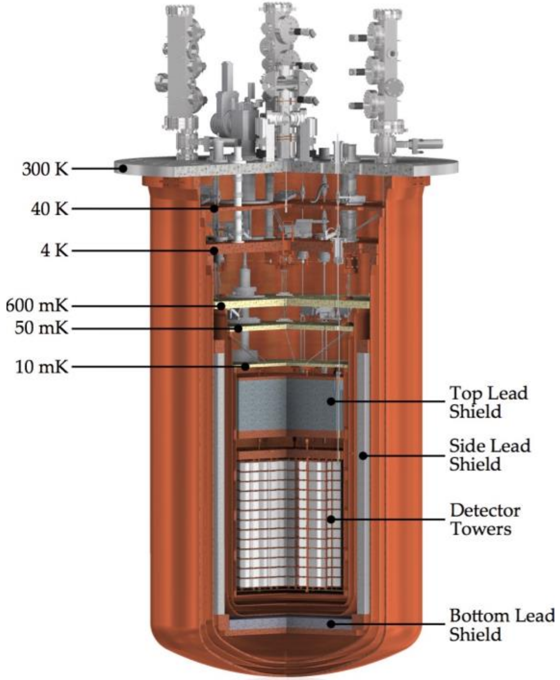
Many applications…



Hitomi (Astro-H) Soft X-ray Spectrometer (credit: JAXA/NASA)



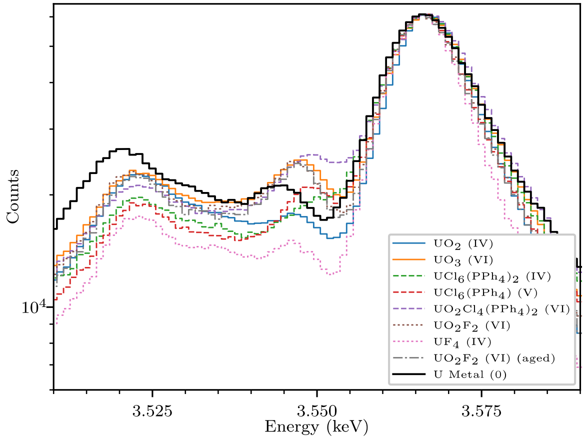
Picosecond tabletop X-ray spectroscopy to watch chemical reactions
L. Miaja-Avila et al., Phys. Rev. X, 2016



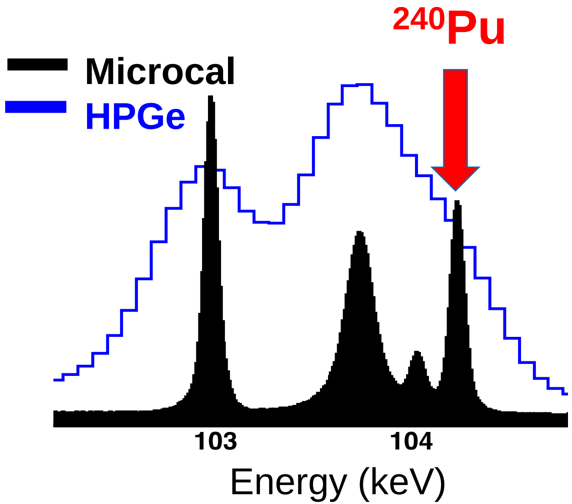
CUORE ^{130}Te 0νββ search (credit: CUORE collab.)

Our focus: nuclear material analysis

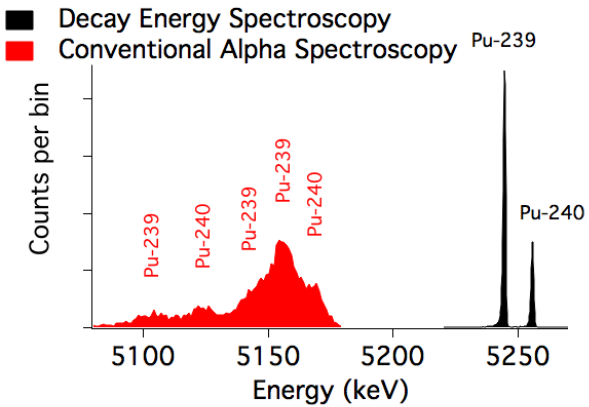
Low-temperature detectors are now creating real measurement capabilities that would be impossible with conventional detectors



X-ray spectroscopy



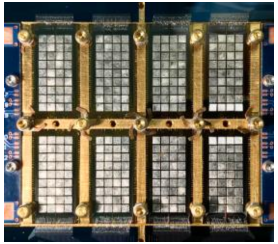
Gamma-ray spectroscopy

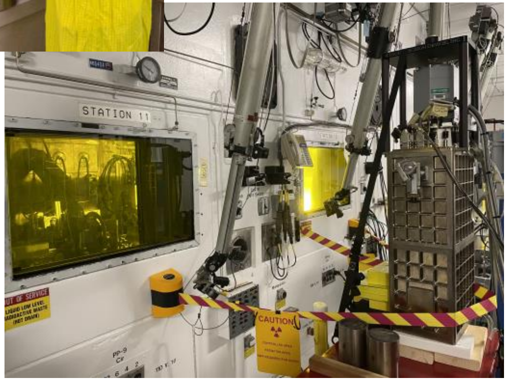


Decay energy spectroscopy

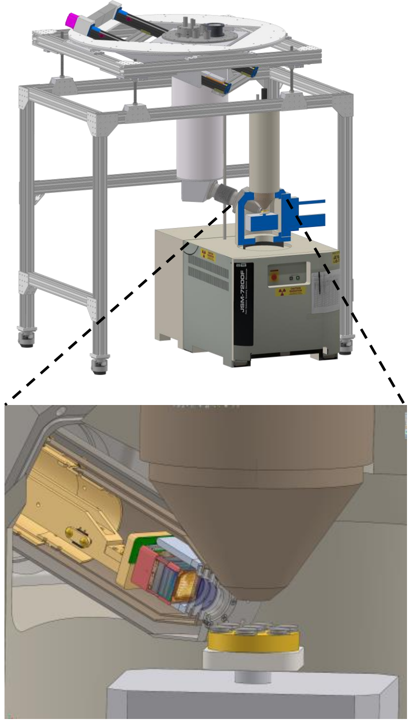
Different configurations/applications we have developed

Gamma-Ray: 10 – 300 keV
Hot cell deployment,
Pu facility deployment

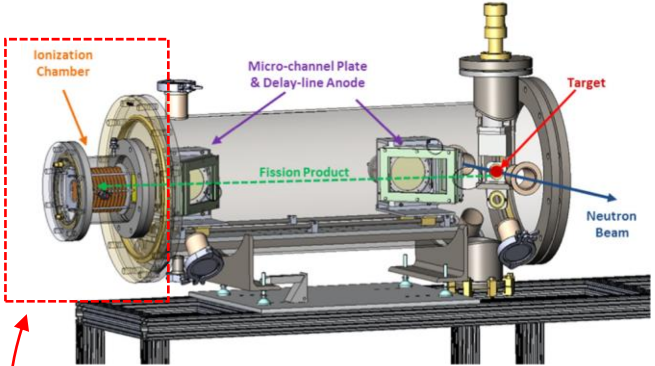




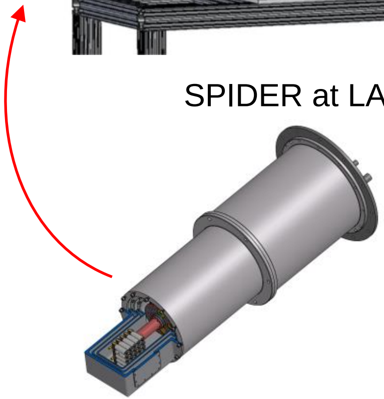
X-Ray: 0.1 – 20 keV
UHV/vacuum: Electron Microscope,
Synchrotron Beamlines

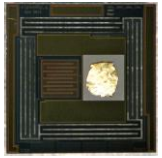


Alpha and Fission Fragment:
0.1 – 10 MeV/1 – 200 MeV
Plans for LANSCE integration

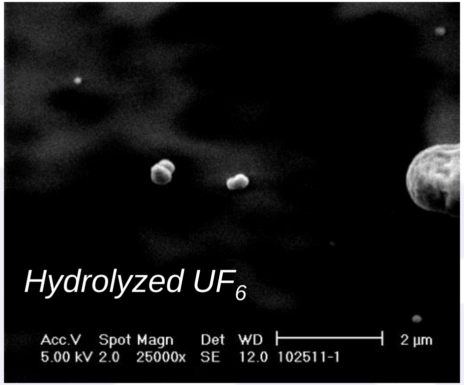


SPIDER at LANSCE





The Hyperspectral X-ray Imaging Project



The chemical form of actinide particles is an important signature for nuclear safeguards and forensics

How can you get this information?

Photons in	→	***Photons out***
Electrons in	→	***Electrons out***

- Nanoscale heterogeneity requires a nanoscale probe, which is only achieved in a small instrument with an electron beam
  - ➢ Optical spectroscopy (UV/VIS/NIR, Raman, LIBS…) or X-ray excited techniques (µXRF, XPS…) cannot provide nanoscale spatial resolution
  - ➢ Synchrotron X-ray absorption (e.g. XAFS) is an excellent probe of speciation with impressive spatial resolution (if you have a synchrotron)
- Electrons leaving a sample are easily perturbed. X-rays are less affected by the sample and more widely applicable.

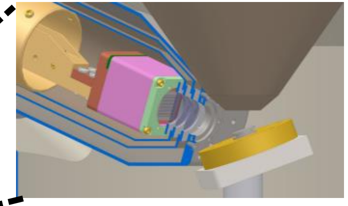
Our goal: high-resolution X-ray emission spectroscopy with nanoscale resolution in an electron microscope

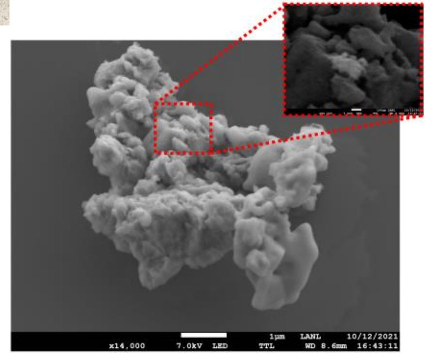
HXI Instrument

Linear Slide

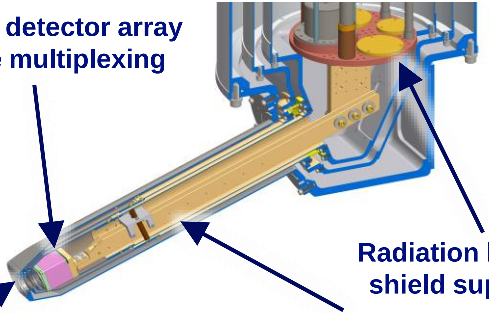
BlueFors SD cryogen-free dilution refrigerator

Rotary + XYZ stage





Microsnout with detector array
and microwave multiplexing



Radiation baffle and snout
shield support assembly

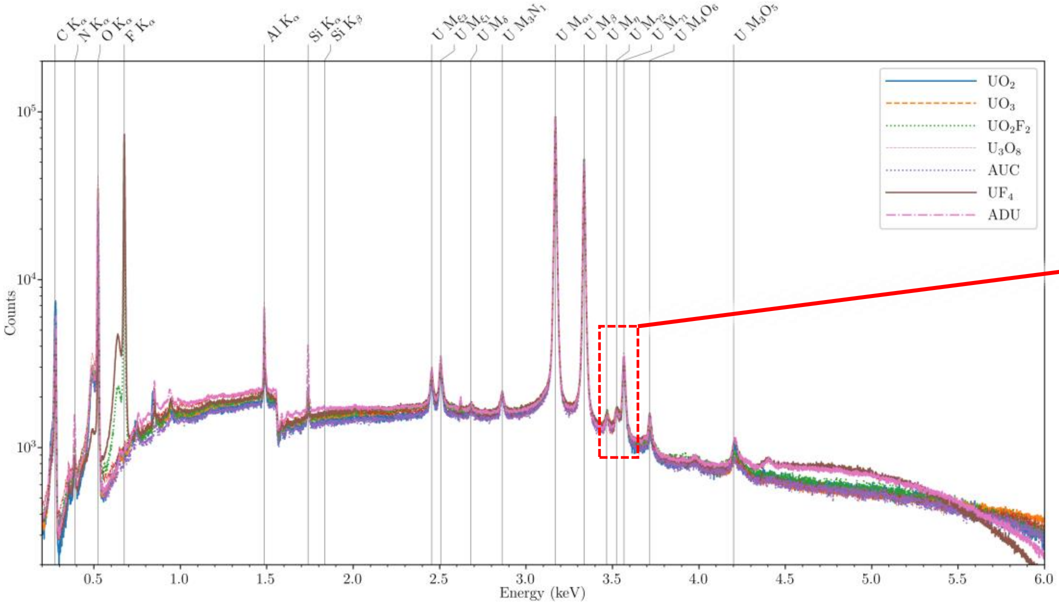
Cryostat fully decoupled from SEM,
Only mechanical contact through bellows

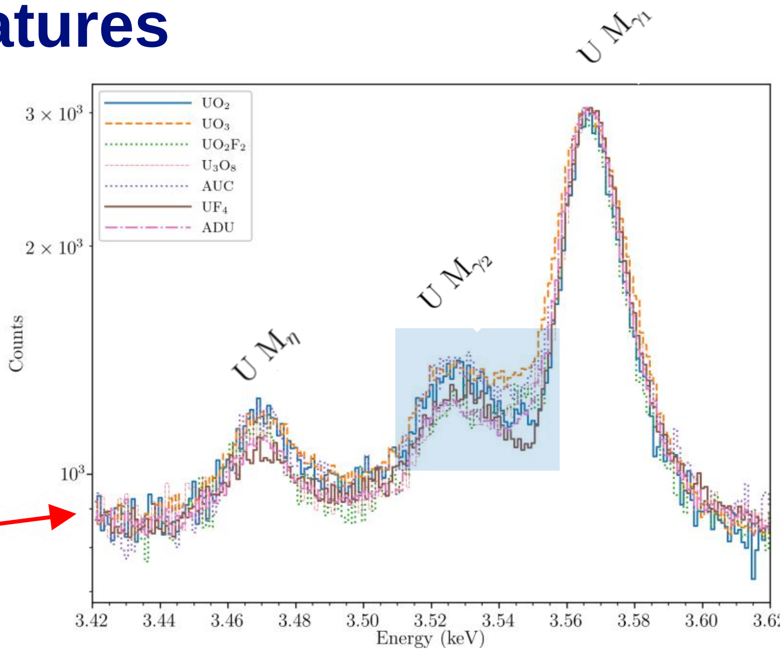
3X IR filters (100 nm Al)
+ Luxel vacuum window

Dual magnetic shields @ 50 K, 3 K

Studying actinide chemical signatures

Series of pure Uranium reference compounds



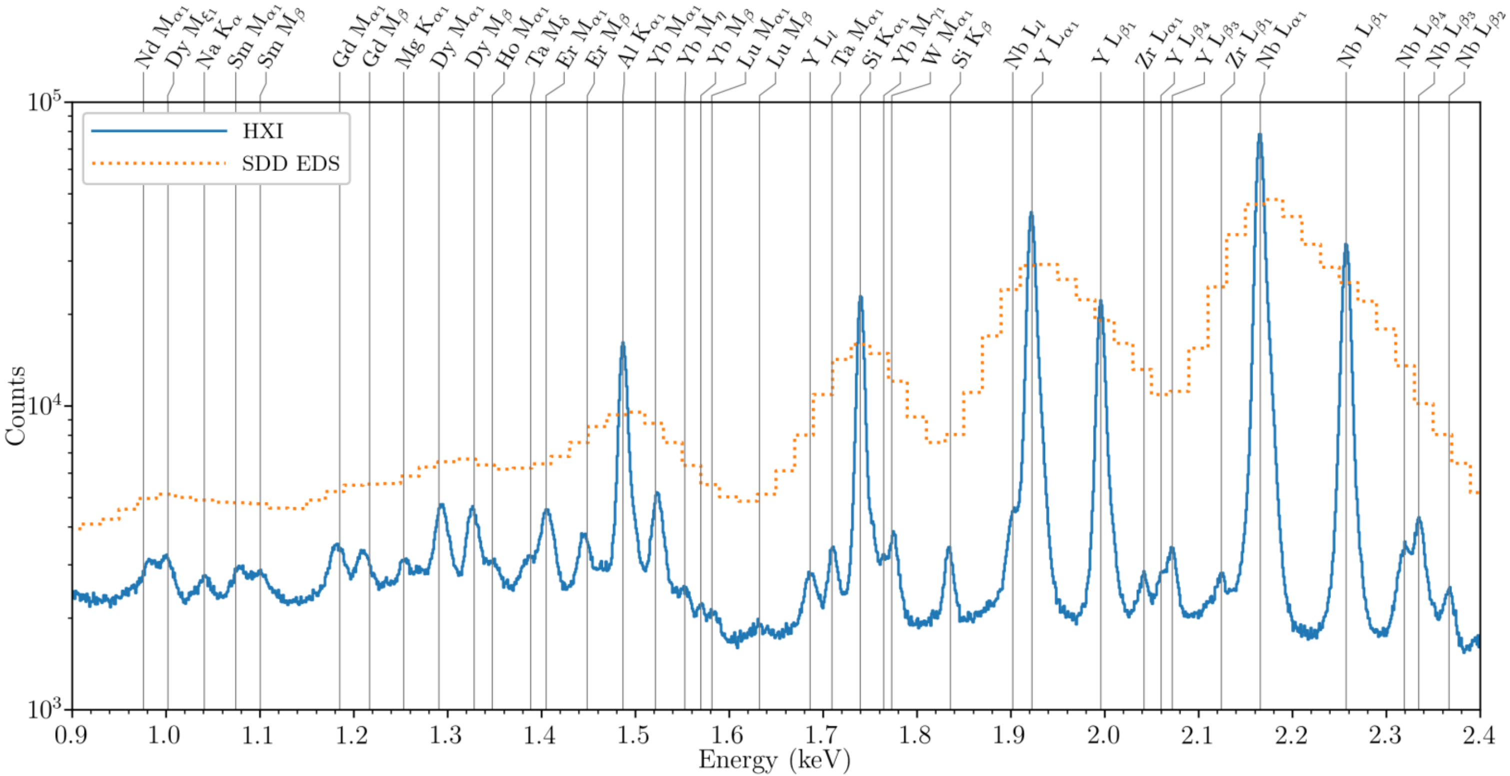


Line type corresponds to oxidation state

We focus on "M-gamma" region around 3.5 keV

Particle spectrum: HXI vs. Silicon Drift Detector

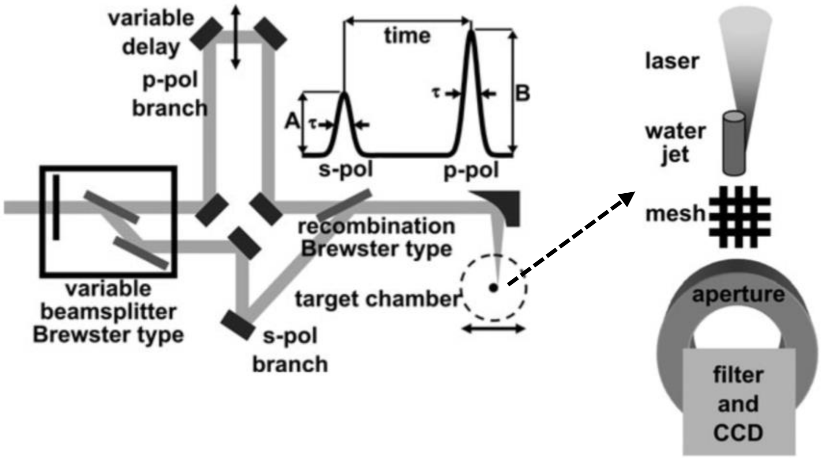
Zooming in around 1-2 keV region reveals many rare earth and refractory elements with HXI



Outside research: ultrafast time-resolved spectroscopy

Uhlig, J., et al. (2013). "Table-top ultrafast X-ray microcalorimeter spectrometry for molecular structure." *Physical Review Letters*, *110*(13), 138302.
https://doi.org/10.1103/PhysRevLett.110.138302

Laser water jet x-ray source



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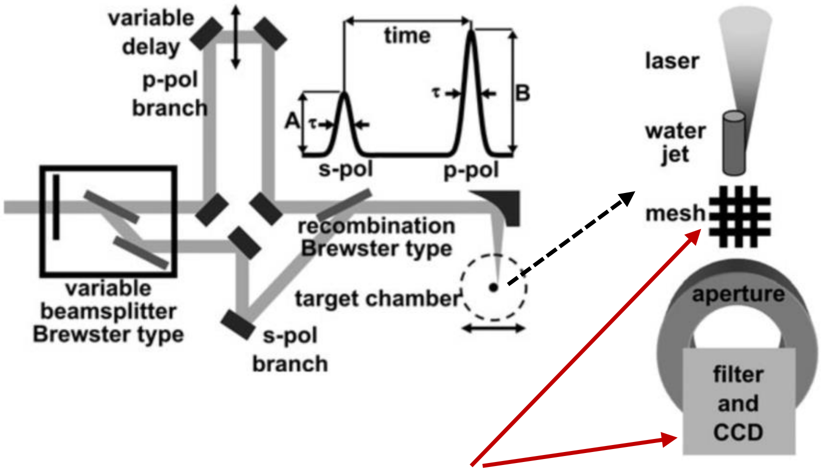
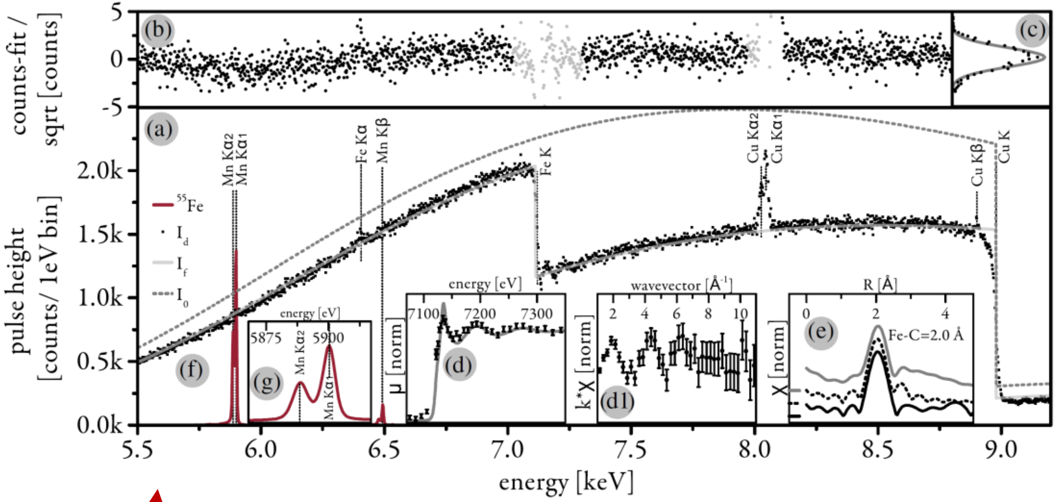


…Ultrafast transmission absorption spectroscopy



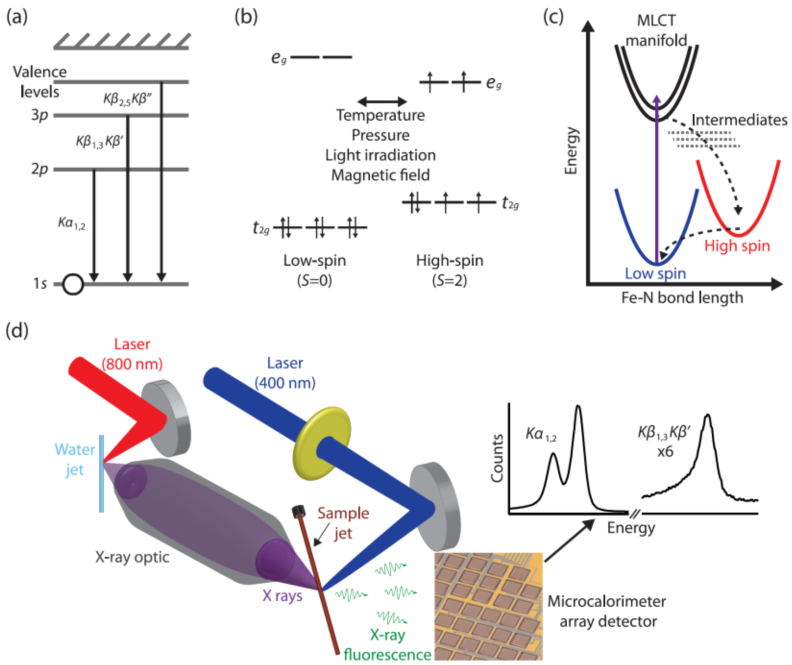
Replace "mesh" with sample,

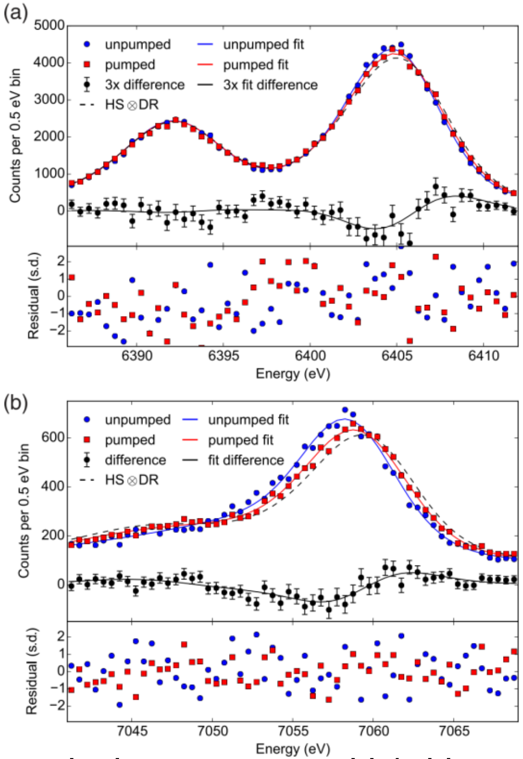
"CCD" with Microcalorimeter detector…

This is not time-resolved, but could be coupled to pump laser to give time-resolved spectra

Outside research: ultrafast time-resolved spectroscopy

Miaja-Avila, L, et al. (2016). "Ultrafast time-resolved hard X-ray emission spectroscopy on a tabletop" *Physical Review X*, *6*(3), 1–13. https://doi.org/10.1103/PhysRevX.6.031047

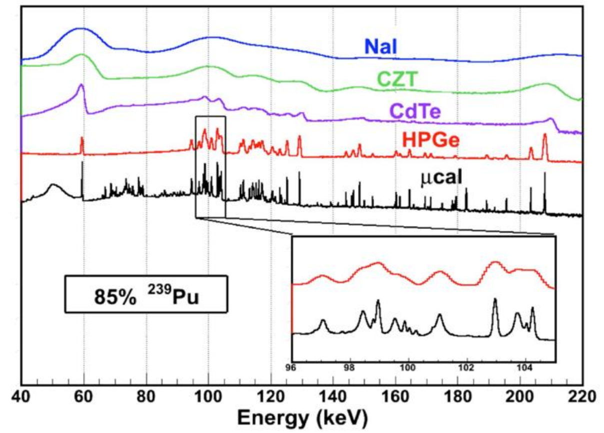


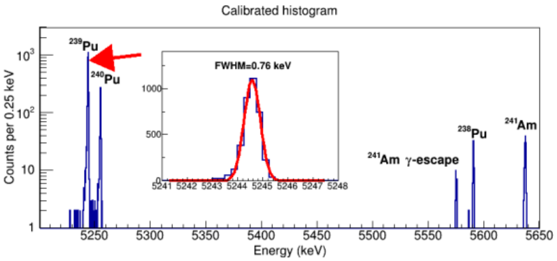


Iron Emission Spectra, with/without pump

Intersection with ultrafast electron source/UED?

- TES microcalorimeters can be tuned to practically any energy range, from microwave to 100+ MeV particles
- “Slow” detector: pulses with μs to ms decay times: time resolution comes from source timing/coincidence
- But: broadband, high efficiency, single photon counting (like high-purity germanium)
- X-ray emission spectroscopy?
- Electron spectroscopy?
  - We have measured beta decay (100s keV) with TES
- Electron pump/x-ray probe spectroscopy?





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