Superconducting Ultra-High Energy Resolution Gamma-Ray and Neutron Spectrometers

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Outline

- Historical Introduction:
  - Why low temperatures?
  - Why low-temperature detectors for safeguards and security?

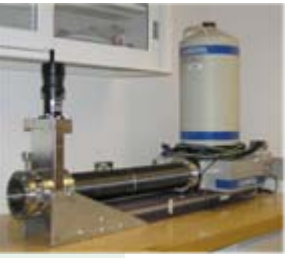
- Detector fabrication and low-temperature operation

- Cryogenic Microcalorimeters:
  - High-resolution Gamma detectors
  - High-resolution Neutron detectors

- Current work:
  - Increase sensitivity: Arrays
  - Increase User-friendliness: Pulse-tube refrigerators

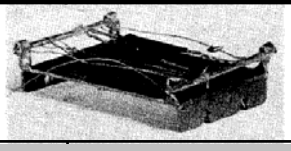
A Very Brief History of Radiation Detection

Decade	Technology	Active volume ⇔Carrier μτ	Operating temperature	Energy resolution ⇔Energy/carrier
~1930s	Gas detectors	Large	300 K	Low
~1950s	Scintillators	Large	300 K	Moderate
~1970s	Germanium	Medium	77 K	High
~1990s	Cryogenic:			
	Tunnel Jcts	Small	~0.4 K	Very high
	Calorimeters	Small	~0.1 K	Extremely high



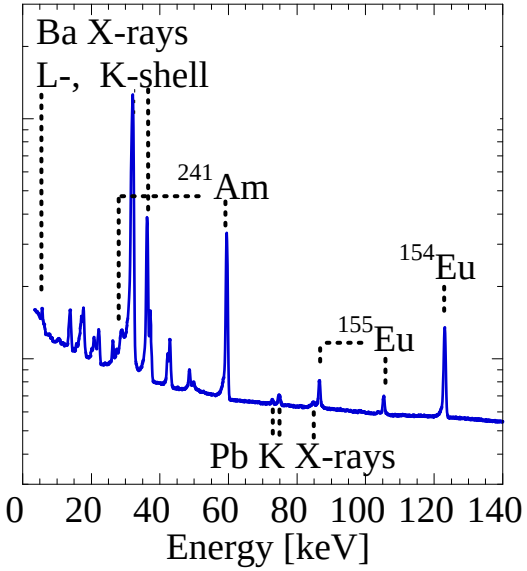
There is a trade-off between effective area, operating temperature and energy resolution.

A Very Brief History of Cryogenic Detectors

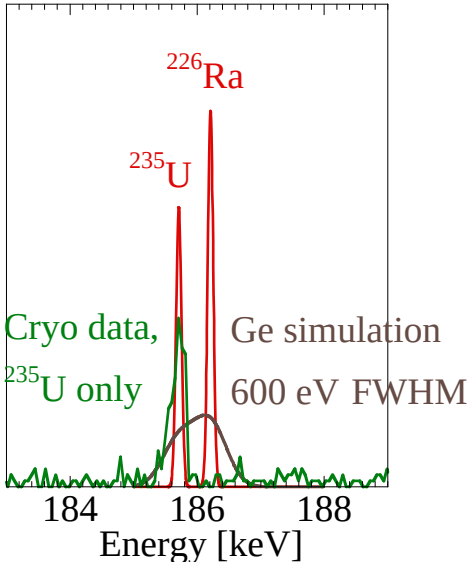
Decade	Microcalorimeters (Bolometers) Superconducting; Semiconducting; Magnetic	Superconducting Tunnel Junctions (STJs)
~1930-1940s Beginnings	Superc. TES bolometer (1942), α-detector (1949): Semiconductor p-n junctions (1949) 	
~1950-1970s Technology	Refrigeration: Adiabatic demagnetization, ^{3}He, dilution refrigerators Photolithography, integrated circuits	Tunneling in solids
~1980s Detector physics	Si X-ray calorimeters (H. Moseley, NASA, 1984) Dark Matter search proposed (E. Witten, Princeton 1985) ⇒ TES (CDMS, Stanford/Berkeley; CRESST, Munich/Oxford) NTD Ge X-, γ-ray calorimeters (E. Silver, LLNL 1988) Magnetic calorimeters (M. Bühler, 1988)	SIS X-ray detector proposed (M. Kurakado, 1982)
~1990s Single Pixels	X-ray TES calorimeters (K. Irwin, Stanford, 1995) γ-ray TES calorimeters (S. Labov, LLNL, 1998)	SIS (ESA, LLNL, Yale,…) NIS (M. Nahum, NIST,1993)
~2000s Arrays	Time-domain multiplexing (NIST, 1999) Frequency-domain multiplexing (Berkeley, 2002) Fast-neutron TES (T. Niedermayr, LLNL, 2002)	120-pix optical (ESA) 36-pix X-ray SIS (LLNL)

Nuclear Diagnostics with Cryogenic Detectors

High-precision analysis for nuclear safeguards

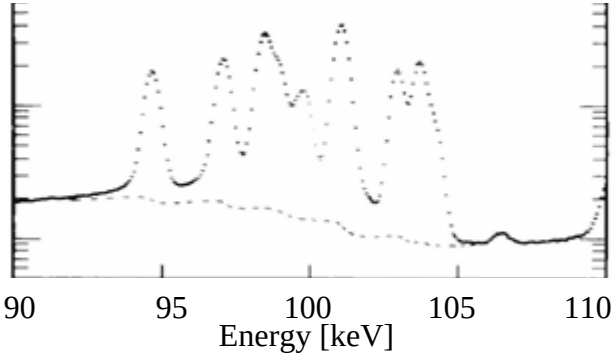


Monitoring illegal uranium mining



Nuclear forensics and attribution applications

Precision isotopics (e.g. MGA)

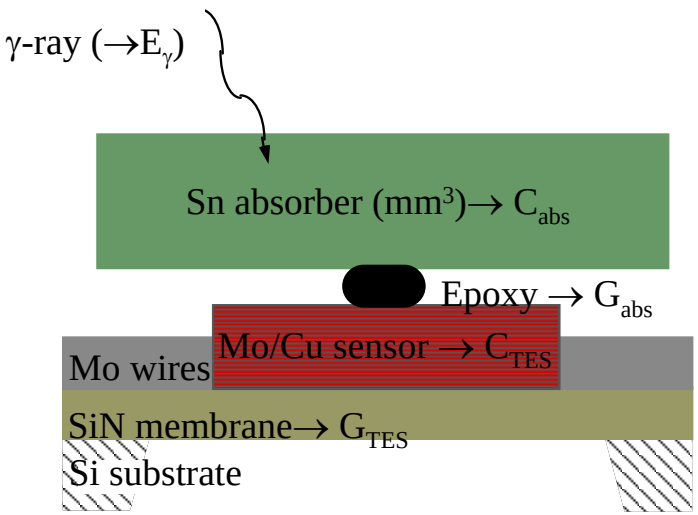


High-precision measurements of isotope ratios rely on closely-spaced lines and thus require high energy resolution.

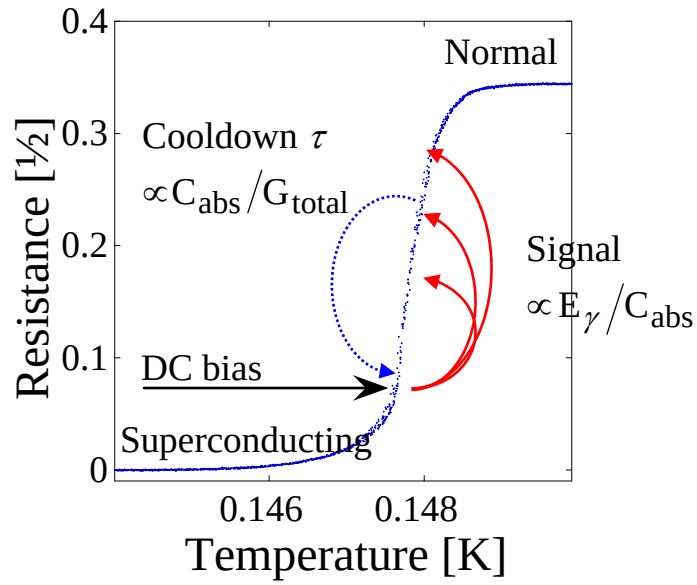
(Of course, detector requirements vary with application.)

Microcalorimeter Detectors

Detector cross section



Thermometer operating principle



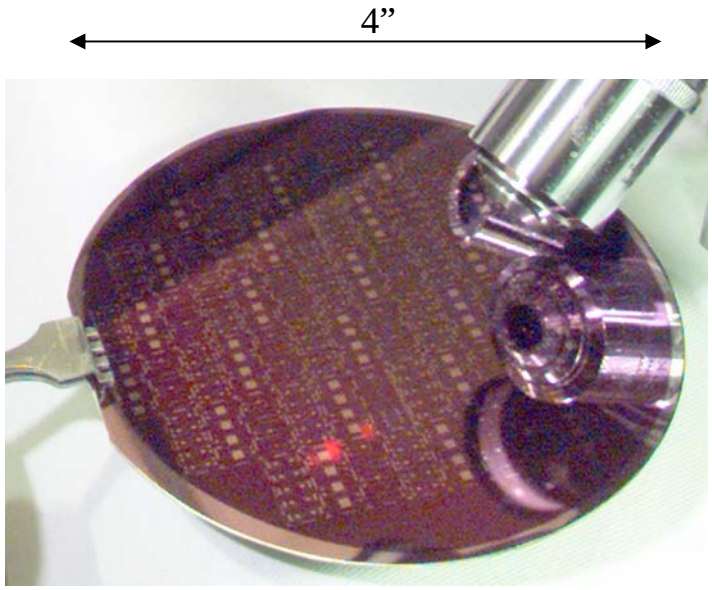
Energy resolution $\delta E_{FWHM} \approx 2.355\sqrt{k_B T^2 C_{absorber}}$

Speed $\tau \approx C_{absorber}/G$

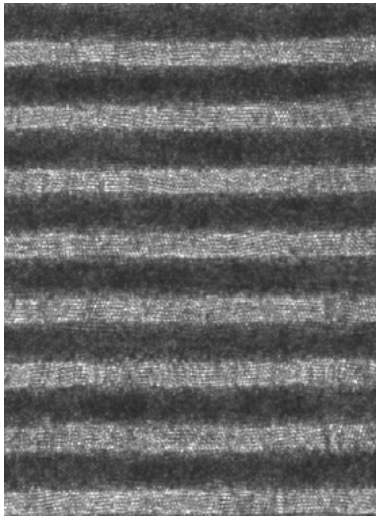
Ultra-high energy resolution thermal single photon detectors require low operating temperature T (~0.1K) and small volumes for low heat capacity C (~mm^3)

Detector Fabrication by Photolithography

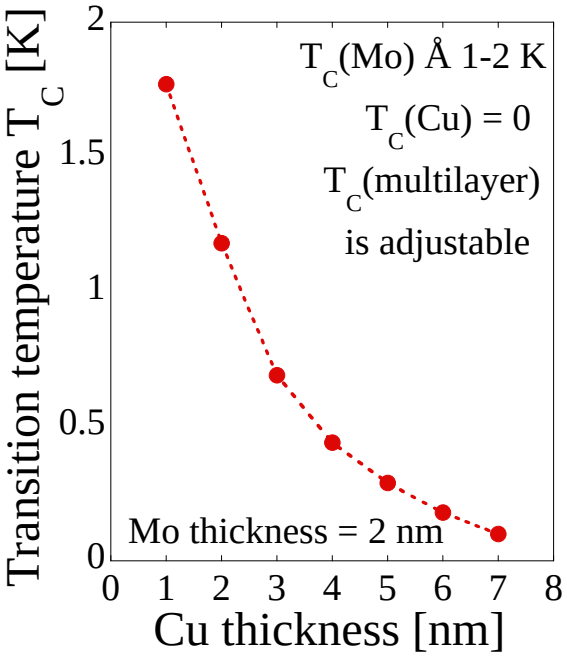
Photolithographic Mo/Cu sensor fabrication



TEM of multilayer



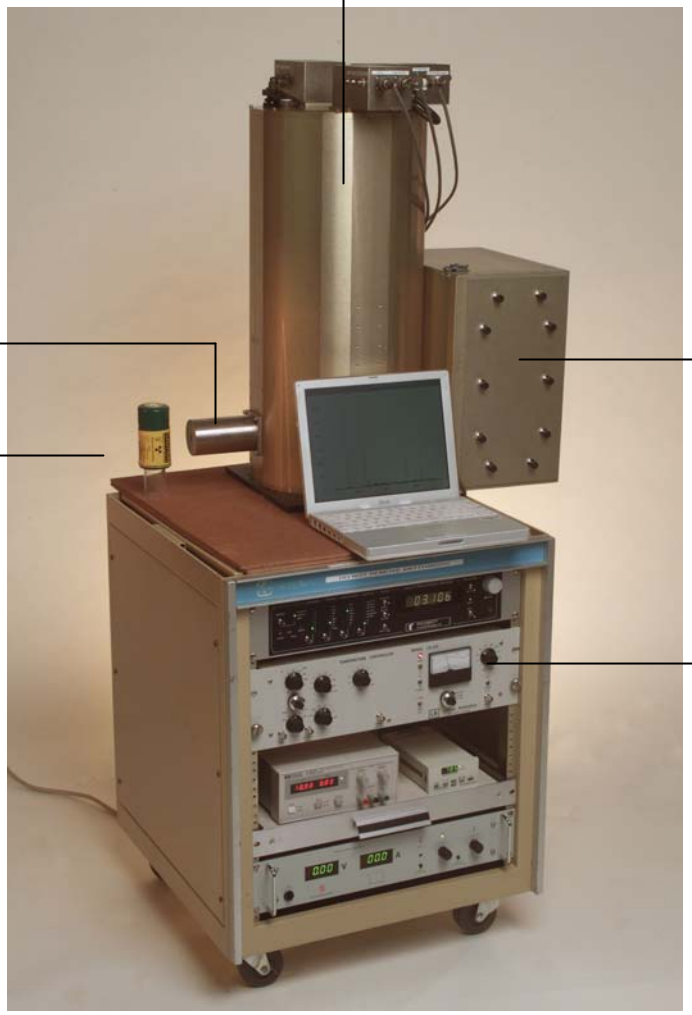
Mo/Cu ratio sets operating temperature



Superconducting Mo/Cu sensor, application-specific absorbers:
1) γ-rays: Sn foil 2) Neutrons: TiB_2 or ^6LiF crystal 3) X-rays: Au film

Superconducting Gamma Spectrometer (“UltraSpec”)

Nested design:
Liquid N_2 pre-cooling to 77 K
Liquid He pre-cooling to 4.2 K
Magnetic refrigeration to 0.1 K
Detector at end of cold finger



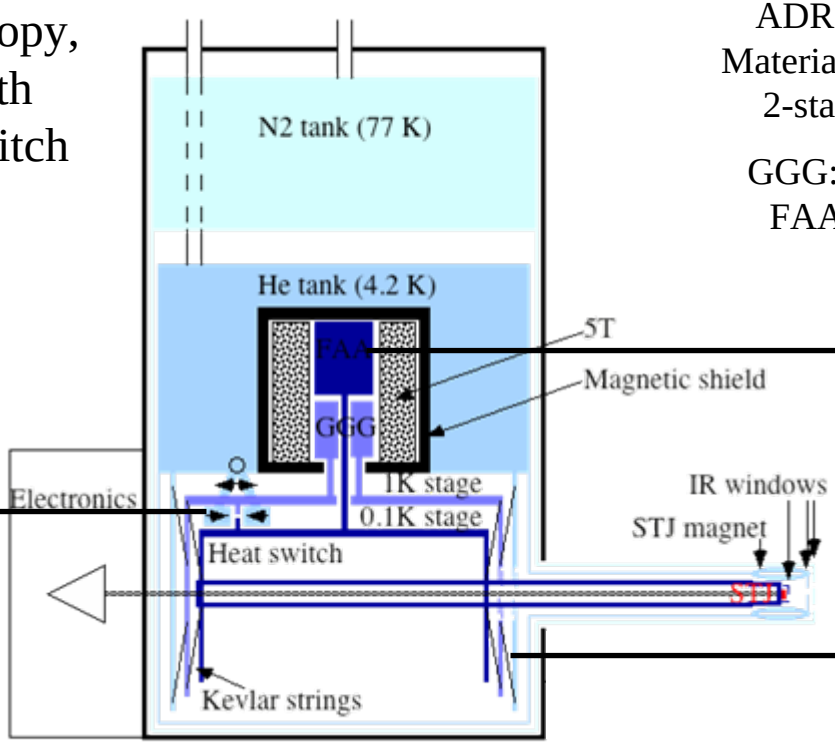
Adiabatic Demagnetization Refrigerators

Demagnetization cycle:
- Close heat switch
- Increase B to lower entropy, carry heat into 4.2 K bath
- Wait, then open heat switch
- Demagnetize to lower T

FAA paramagnet:

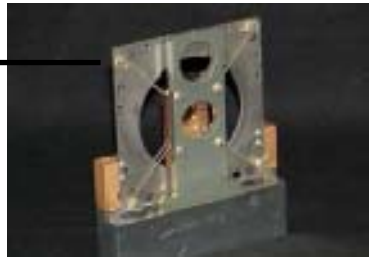
ADR idea: P. Debye
Materials: W. Giauque
2-stage: P. Richards

GGG: Laser material
FAA: Home-grown



Heat-switch:
No leaks, no dc power

Kevlar suspension:
Low heat load



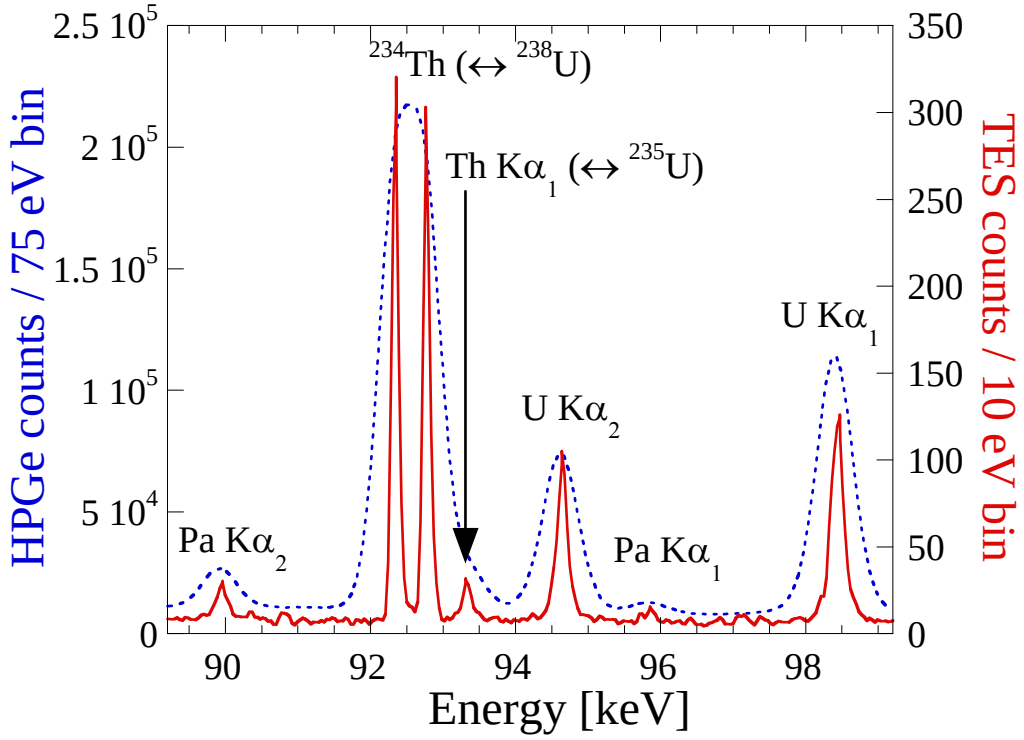
ADRs are compact, reliable, easy to use and to automate.

Superconducting γ-Detector Performance

LEU uranium spectrum at 92 keV

50 - 90 eV FWHM below 122 keV

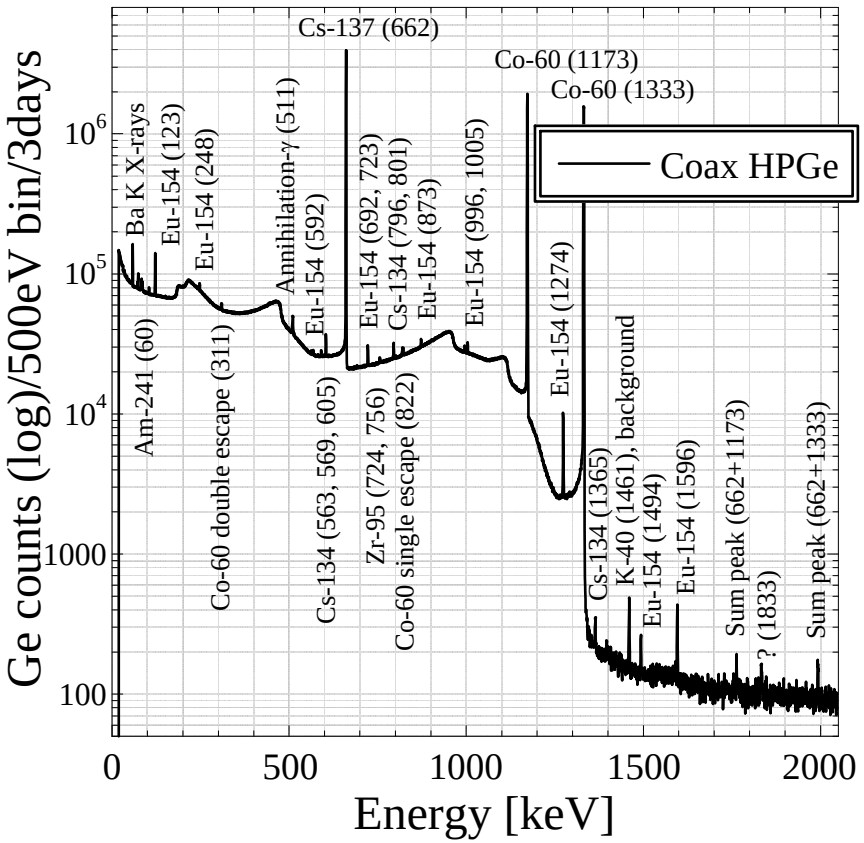
Superconducting γ-ray spectrometers enable high-resolution spectroscopy in cases where Ge detectors are fundamentally limited by device physics.



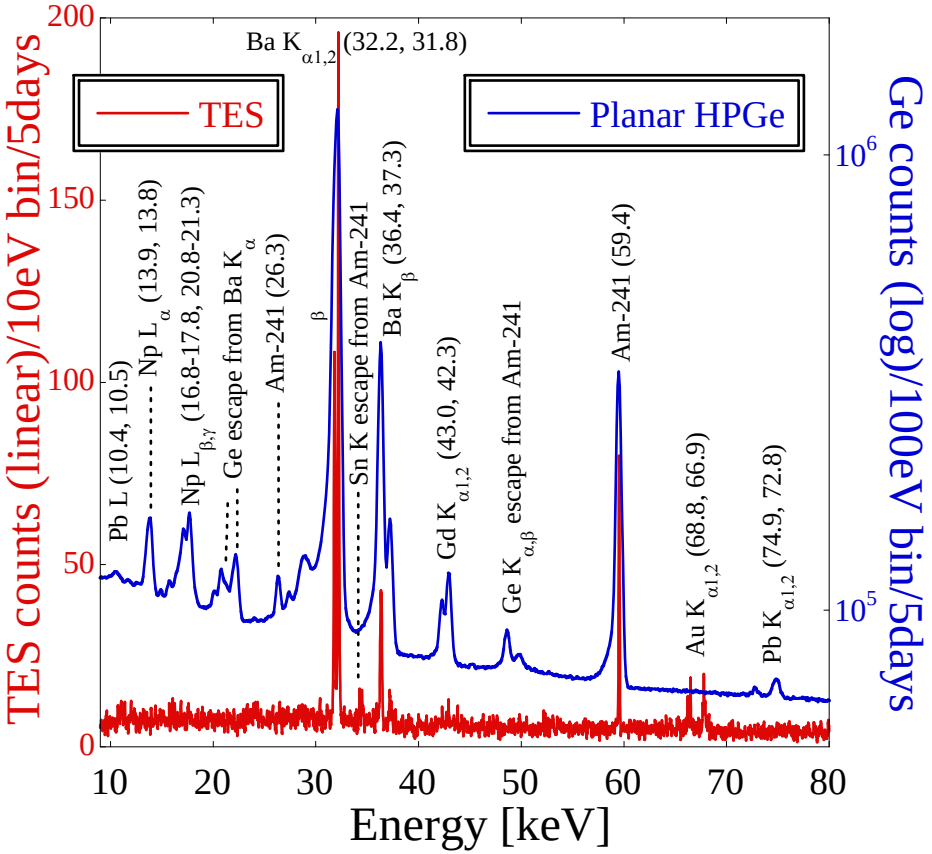
Analyzing closely-spaced lines reduces systematic errors in isotope analysis.

Fission Product Swipe Sample

Coaxial high-purity Ge detector



Planar HPGe and TES detectors

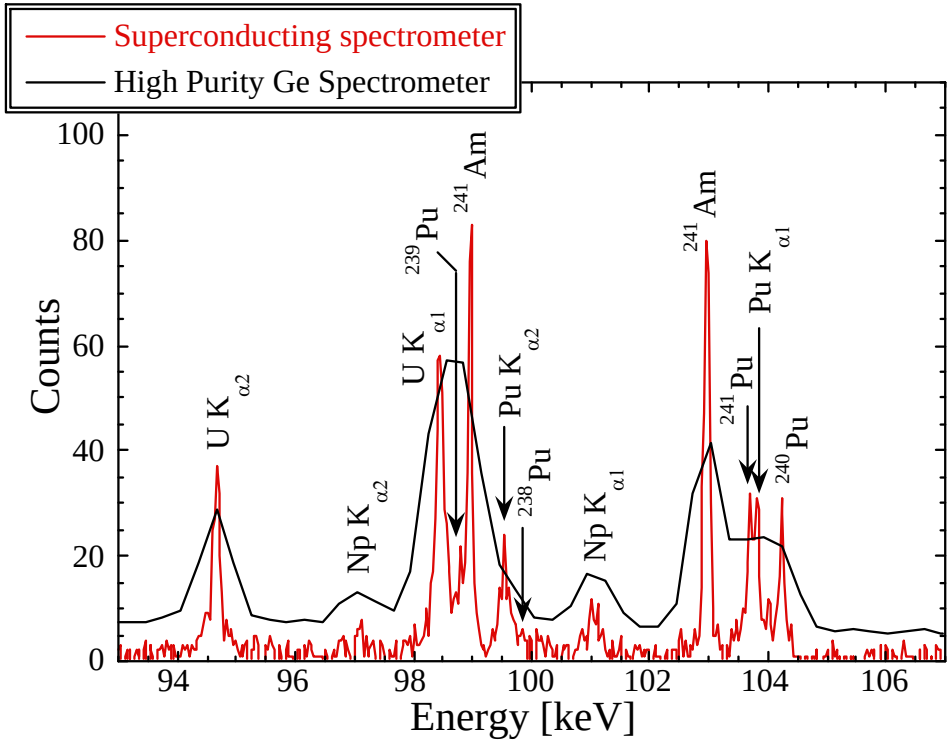


Typical γ-spectrum of fission products

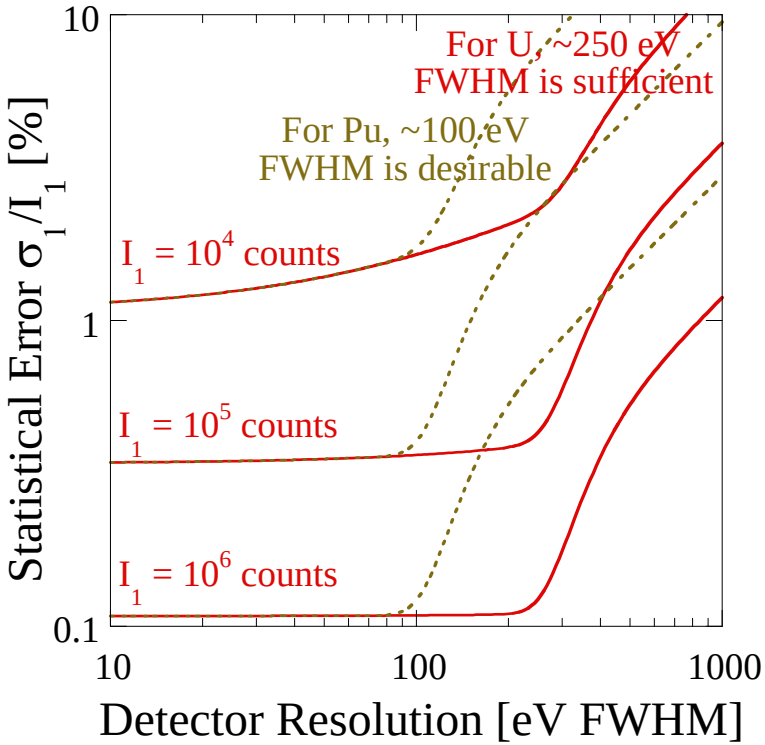
Details of low-energy γ-spectrum

Nuclear Diagnostics: Plutonium isotopics

WG Pu spectrum at 100 keV



Quantifying detector needs



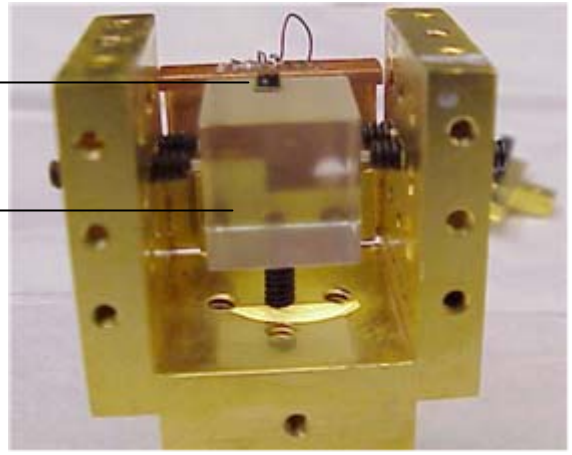
Resolution is great, counting statistics must be improved ⇒ Arrays

Cryogenic Fast-Neutron Spectrometers

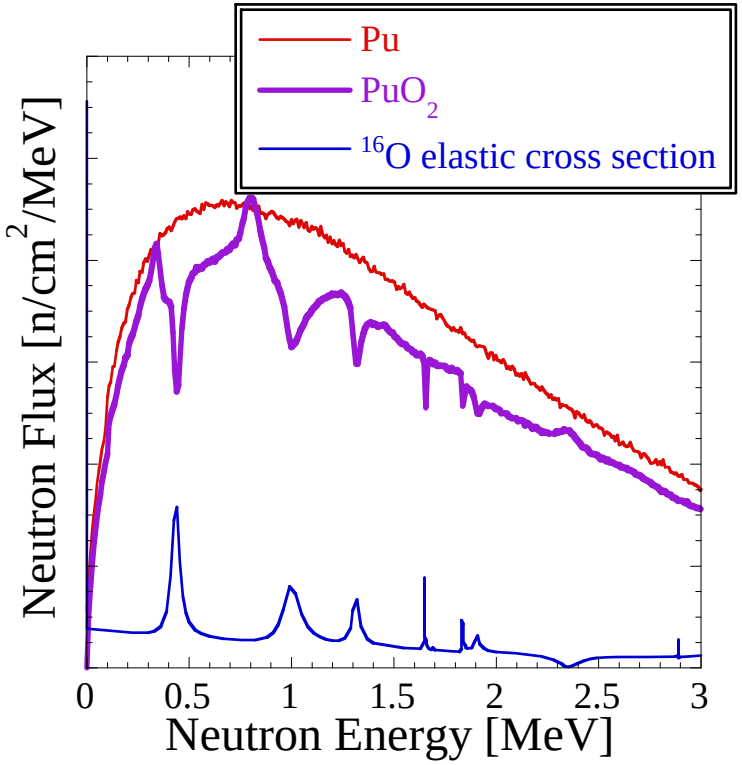
Fast-neutron detector:

Sensor

94% enriched ^{6}LiF absorber ~cm^3



MCNP simulation:

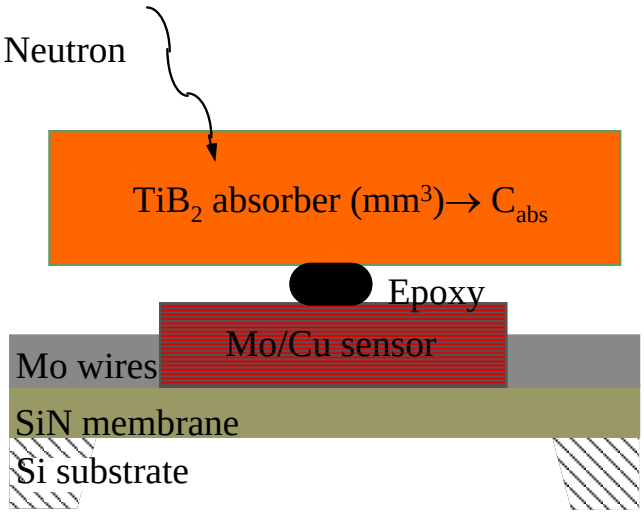


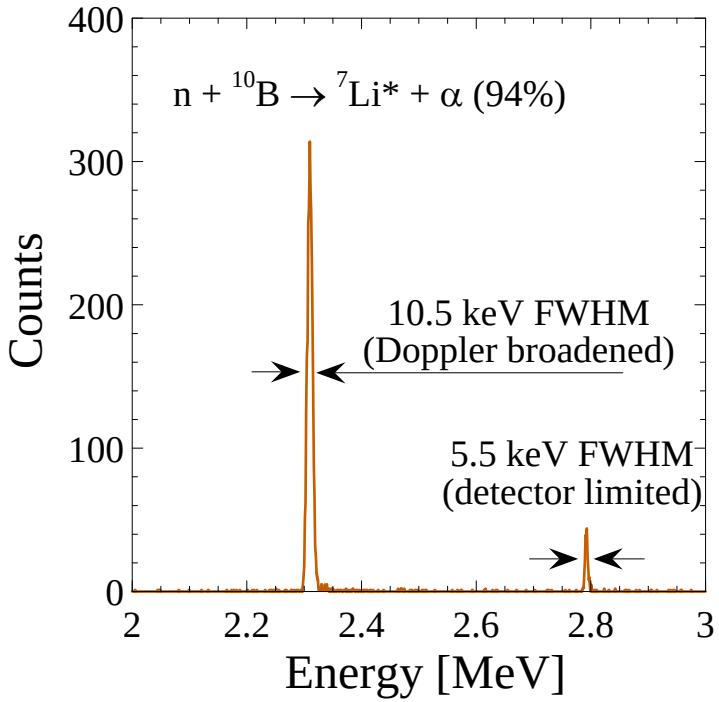
Same concept as before:
Optimize absorber for neutrons, measure $E_{total} = Q+E_n$ with superconducting sensor

High resolution for fast neutrons with Gamma discrimination and simple response function.

Neutron Spectrometer Demonstration Experiment

Metallic TiB_2 absorber, Mo/Cu sensor on membrane, thermal neutrons





High resolution, but low efficiency

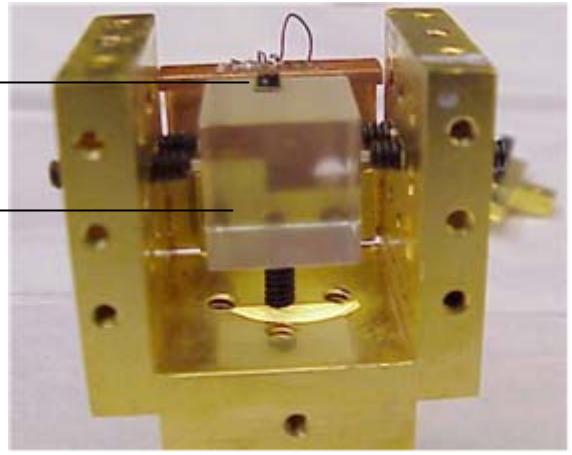
High-resolution neutron spectroscopy with cryogenic detectors is possible.

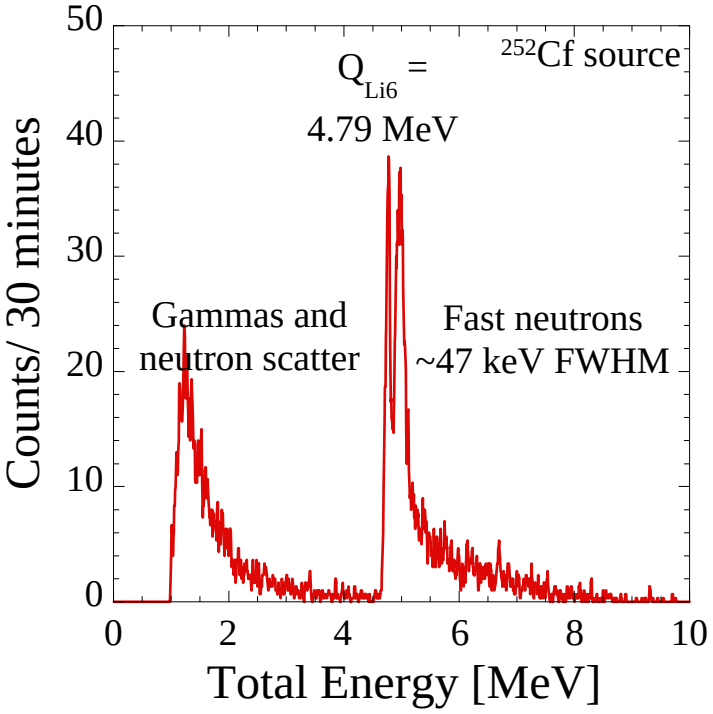
Fast-Neutron Spectrometer Performance

Dielectric ^{6}LiF absorber, cm^{3} (grown at Fisk U), Mo/Cu sensor on Si, fast neutrons

Sensor

94% enriched ^{6}LiF absorber





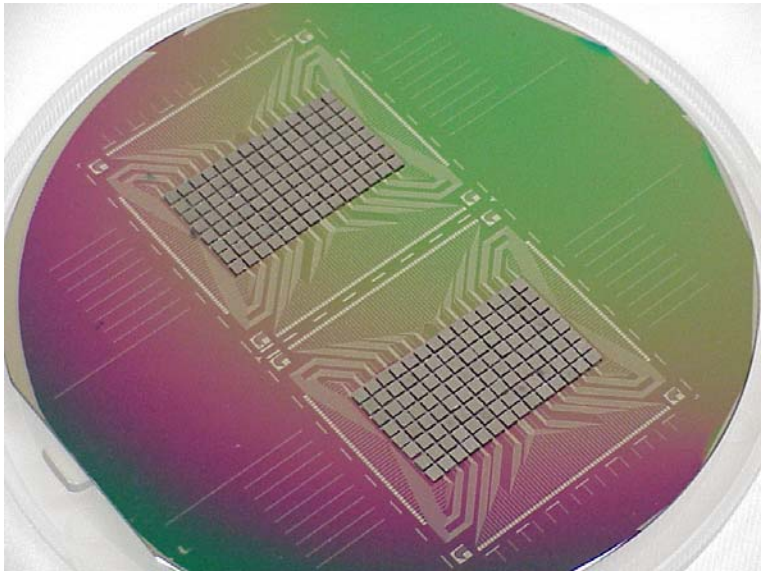
1cm^{3} ^{6}LiF has same C as 1 mm^{3} TiB_2, i.e. same limiting energy resolution, but much higher efficiency (~1% at 1 MeV)

Limiting resolution <10 keV

• High resolution • High efficiency • Simple response function • Easy Gamma discrimination

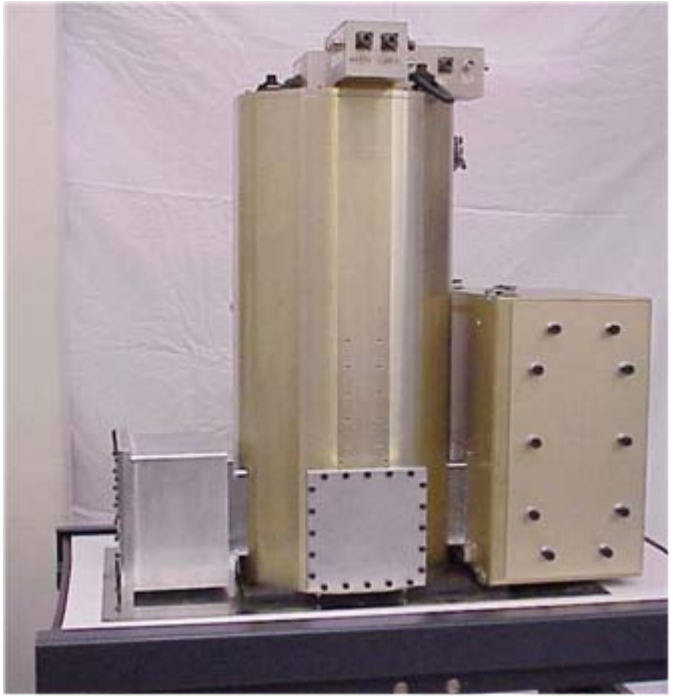
Current Work: Calorimeter Detector Arrays

112-pixel detector arrays on 4” wafer:



4”

Cryostat to operate large arrays:



Caveat: Fabricating arrays is easy (once you can make one), reading them out is not, because each wire introduces heat into the detector cold stage at 0.1K.

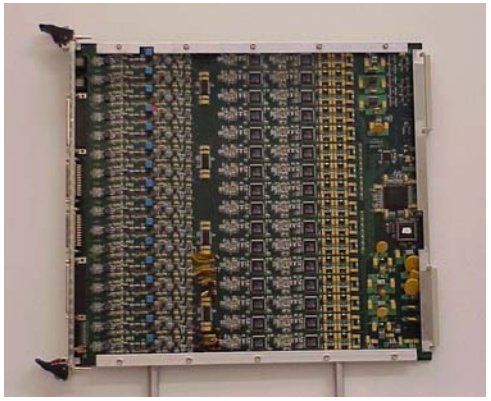
Current Work: Multiplexed Array Readout

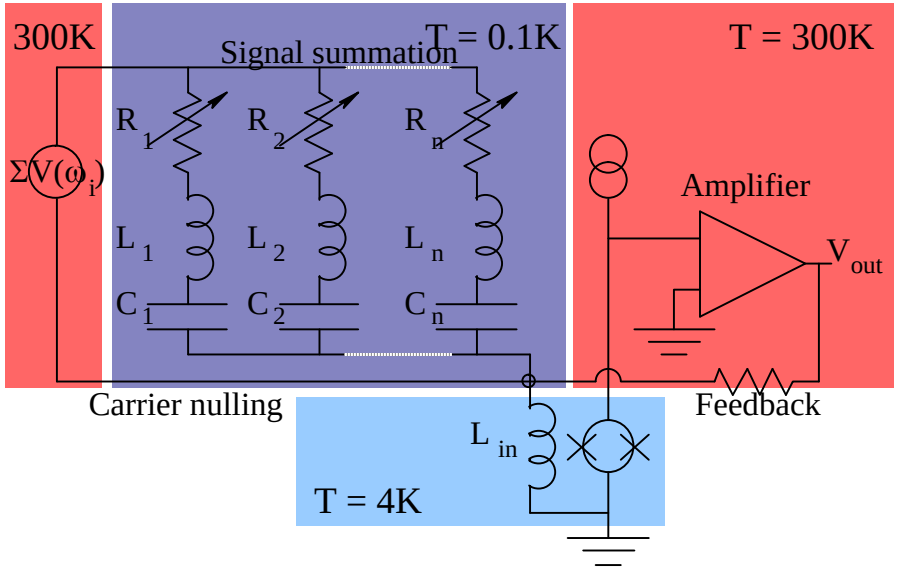
Frequency-division multiplexing (Berkeley/LLNL):

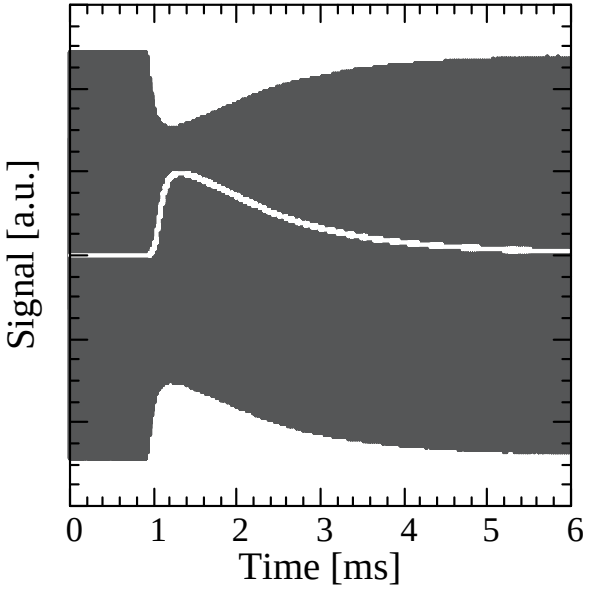
AC-bias sensor in LCR resonant circuit
⇒ Signal = Amplitude modulation ("AM radio")
⇒ Demodulate at room temperature.

Multiplexing is crucial to reduce the heat load.

16-channel MUX board



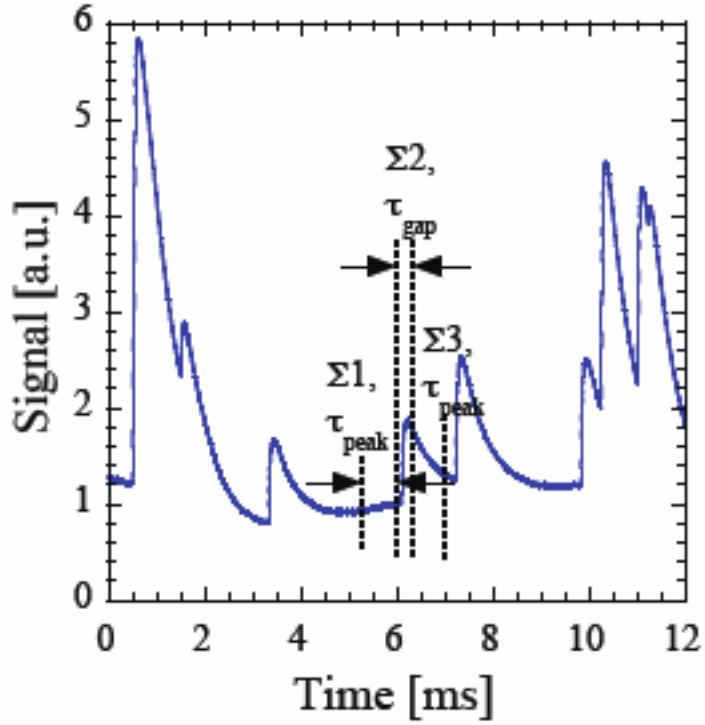




Current Work: Digital Signal Processors

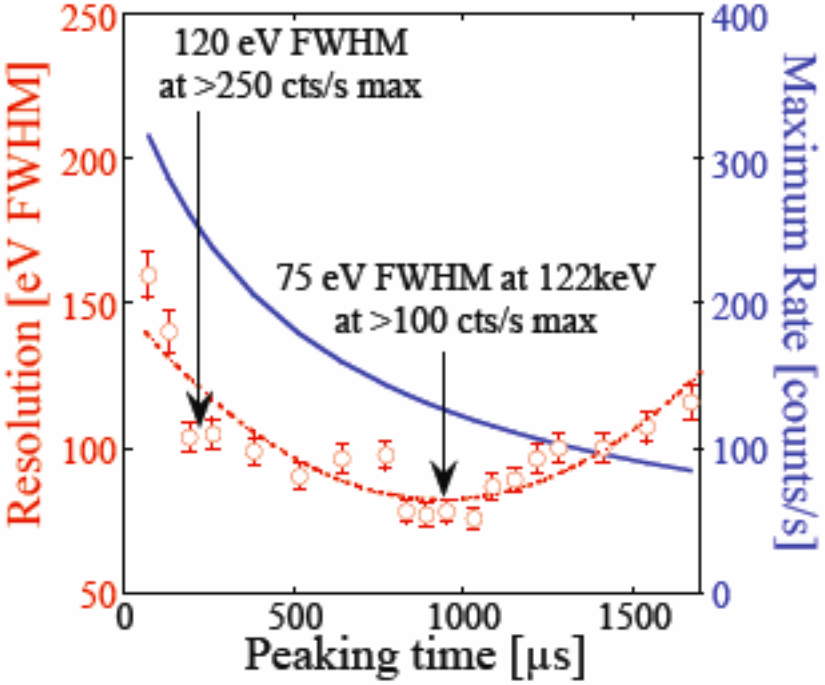
Previously: Optimum (Wiener) filtering, maximizes energy resolution, but is slow.

Now: DSPs, no need to wait for signal to decay Tests with ^{57}Co source at 122 keV



16-channel DSP Module

Collaboration with XIA LLC.



DSPs increase count rates by an order of magnitude without loss in energy resolution

Current work: 0.1 K without liquid N_2 and He

Push-button cool-down from room T to 0.1K

Award 2006

QuickTime™ and a
decompressor
are needed to see this picture.

Pulse tube refrigerator + ADR, developed in collaboration with VeriCold Inc.

Summary

- Cryogenic detectors offer extremely high energy resolution
- Gamma Detectors:
  - 50-150 eV FWHM at 100 keV
  - 100 cts/s per pixel with DSP
- Neutron detectors:
  - 5 - 50 keV FWHM for thermal - MeV neutrons
  - Simple response function, easy Gamma discrimination
- Current work:
  - 112-pixel arrays, 16-channel MUX and DSP modules, scalable
  - Push-button operation at 0.1K
- Applications: Precision isotope ratios for nuclear forensics and safeguards