

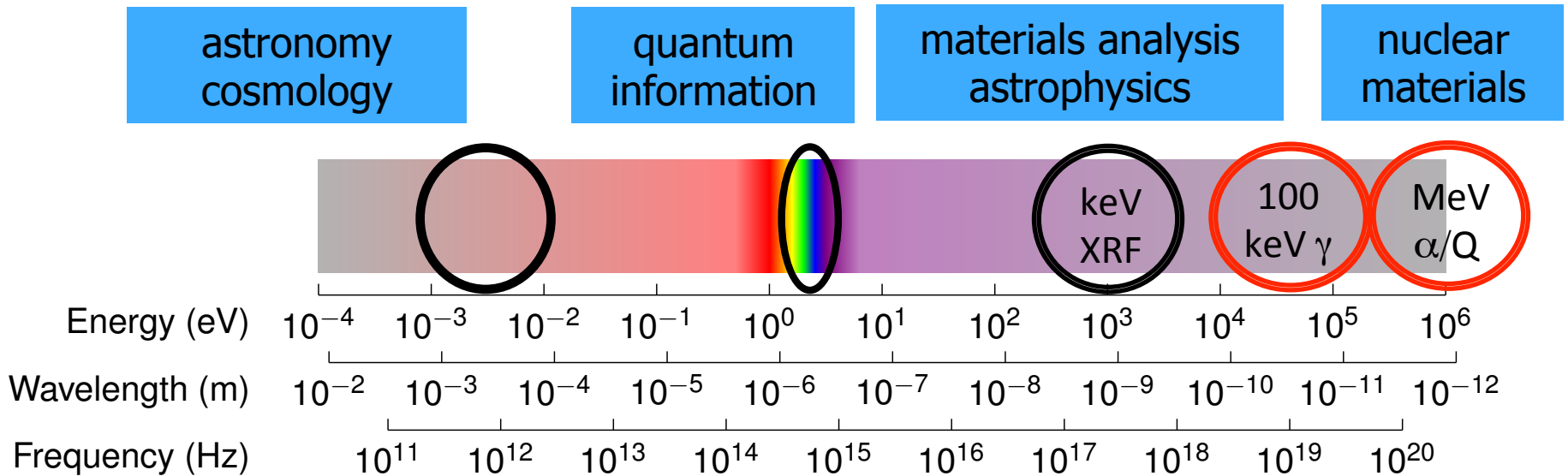
Radiation & Particle Detection with Superconducting Detectors

Andrew Hoover
March 6, 2014

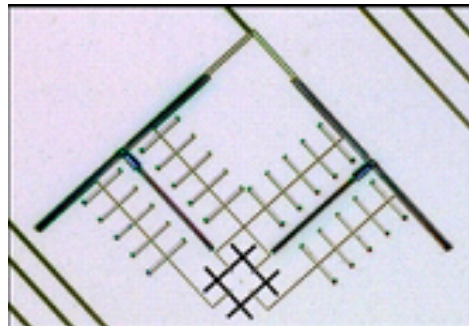


Applications of Low-Temperature Detectors

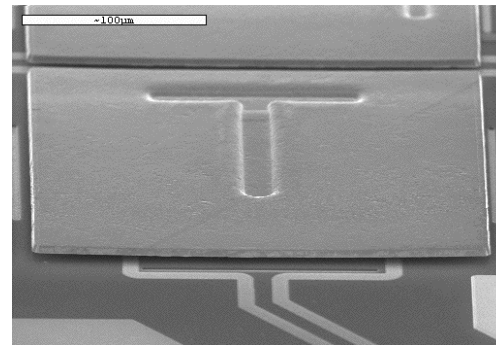
From microwaves to gamma-rays



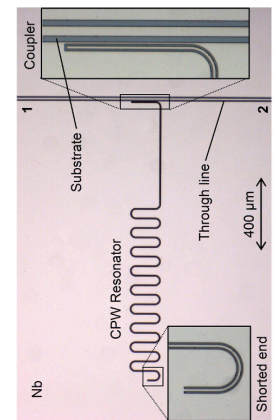
WIMPs (CDMS)



mm-wave (UCB)



soft X-rays (NASA)



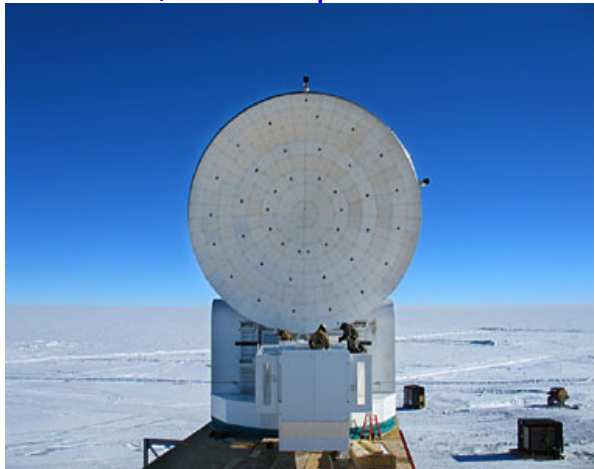
μ wave (SRON)

Precision Cosmology

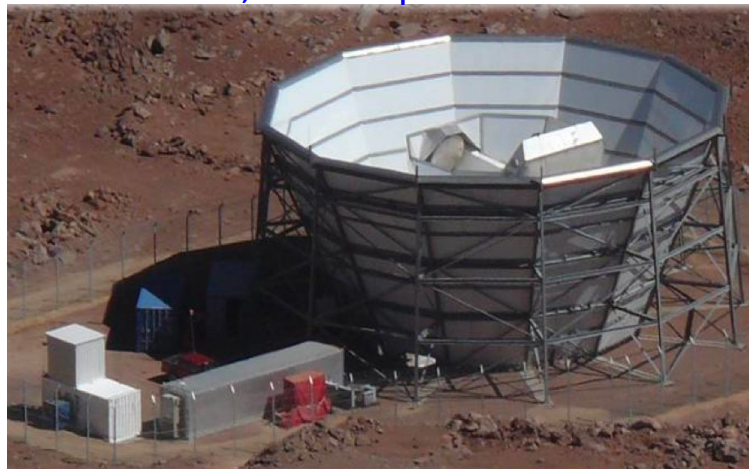
LTDs play large role:

- age of universe
- cosmic microwave background angular power spectrum
- searches for galaxy clusters
- polarization in the cosmic microwave background

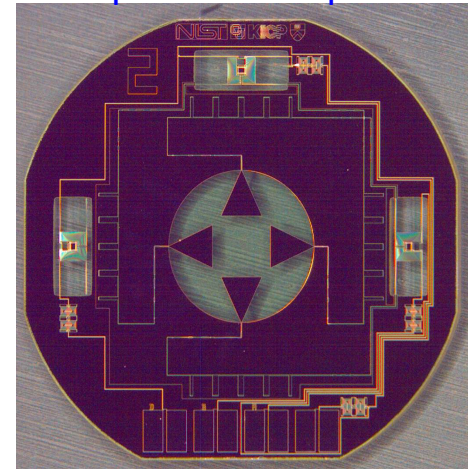
South Pole Telescope
~ 1,000 TES pixels



Atacama Cosmology Telescope
~ 3,000 TES pixels



B-mode search
polarimeter pixel



Many other instruments: SPIDER, PIPER, BICEP2, KECK, POLARBEAR, ...

Current Projects

1. X/ γ spectroscopy

Characterization of complex Pu spectra with overlapping peaks

Close performance gap between NDA and DA

2. α/Q spectroscopy

Characterization of trace-level Pu samples

Simpler/faster than mass-spec + alpha-spec

3. Electron capture spectroscopy (ECS)

Neutrino mass

Nuclear Analytical Methods

10^0 grams Pu



10^{-6} grams Pu



10^{-12} grams Pu

Material Control &
Accounting (fuel fab/
reprocessing facility
sampling)

Forensics/
Safeguards
(swipe)

Environmental
(air sample)

(Macro-)
Calorimetry

Gamma
Spec

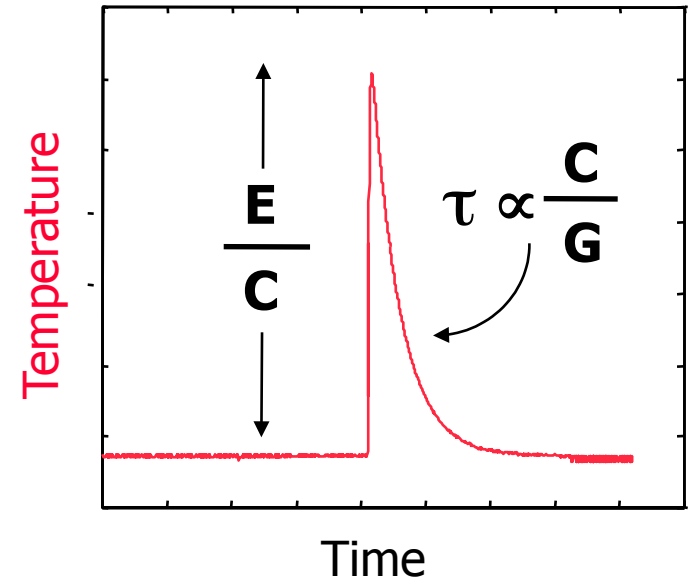
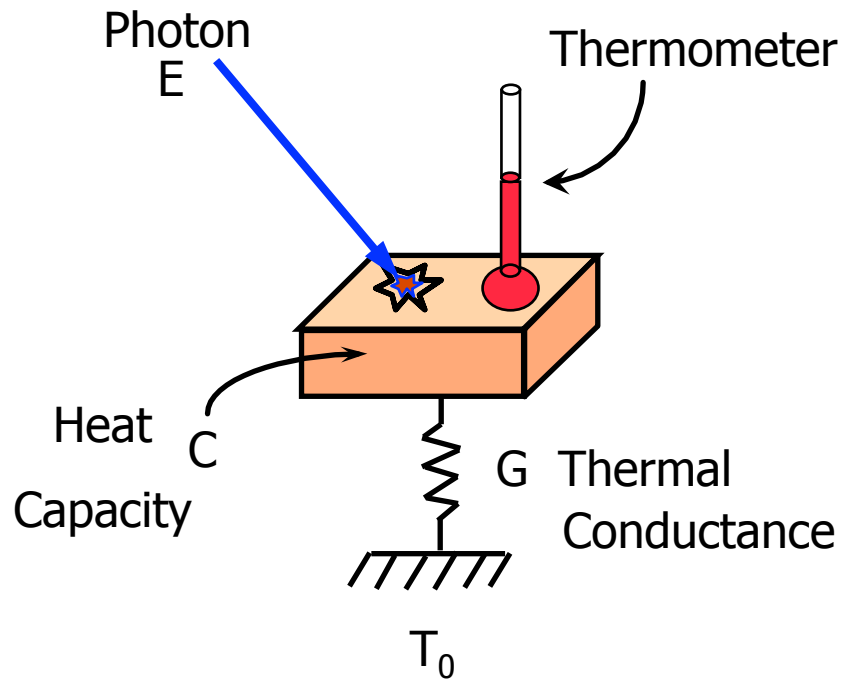
n-counting

Alpha Spec
Q-spec

Mass Spec

Thermal Sensors – Bolometers and Calorimeters

Measure temperature to determine absorbed power or energy

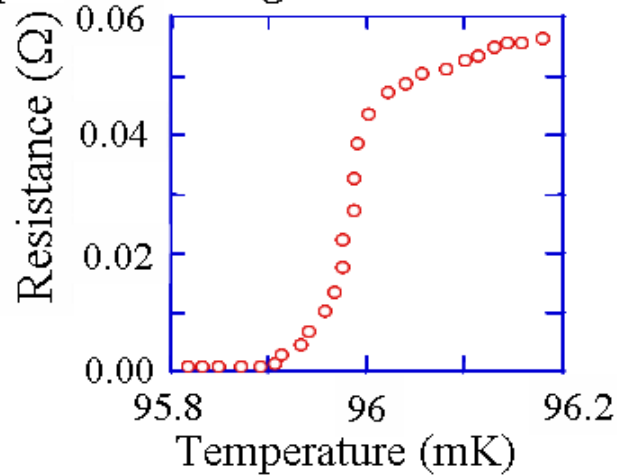


Transition Edge Sensor (TES)

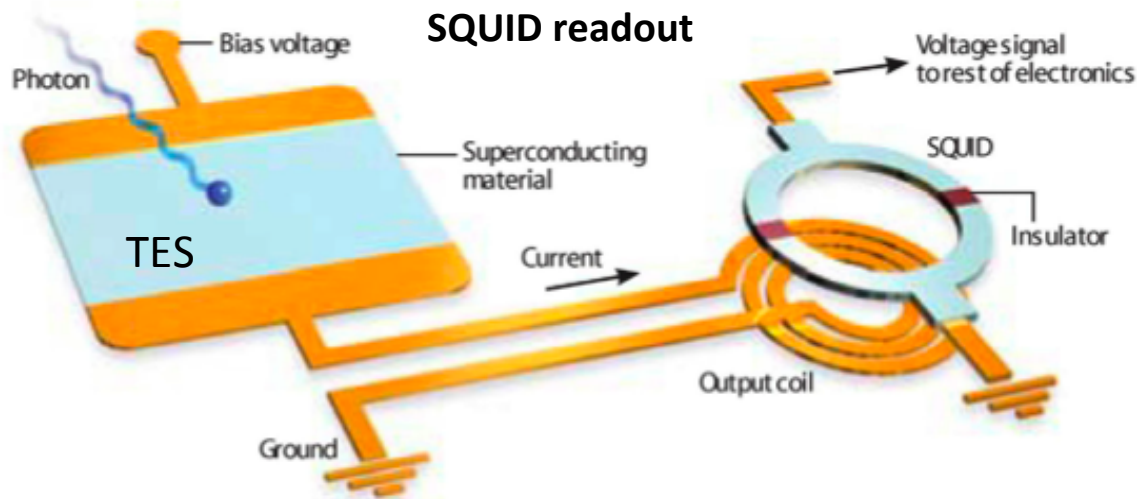
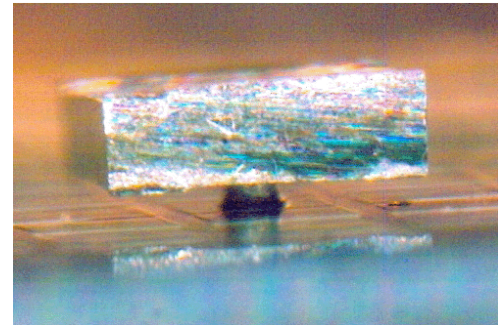
Low temperature → Low noise → High resolution

Thermometer:

Superconducting-Normal Transition



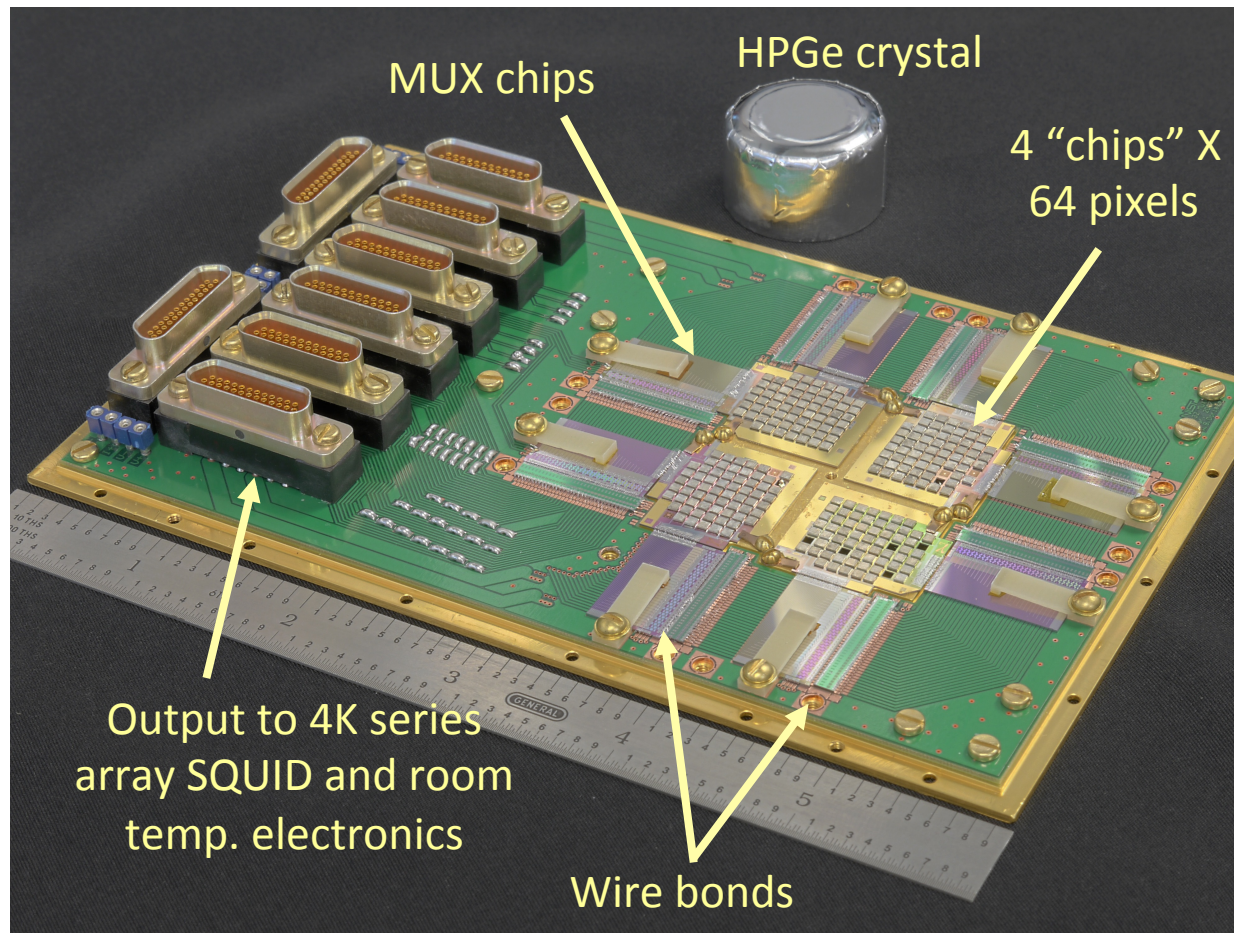
TES with absorber



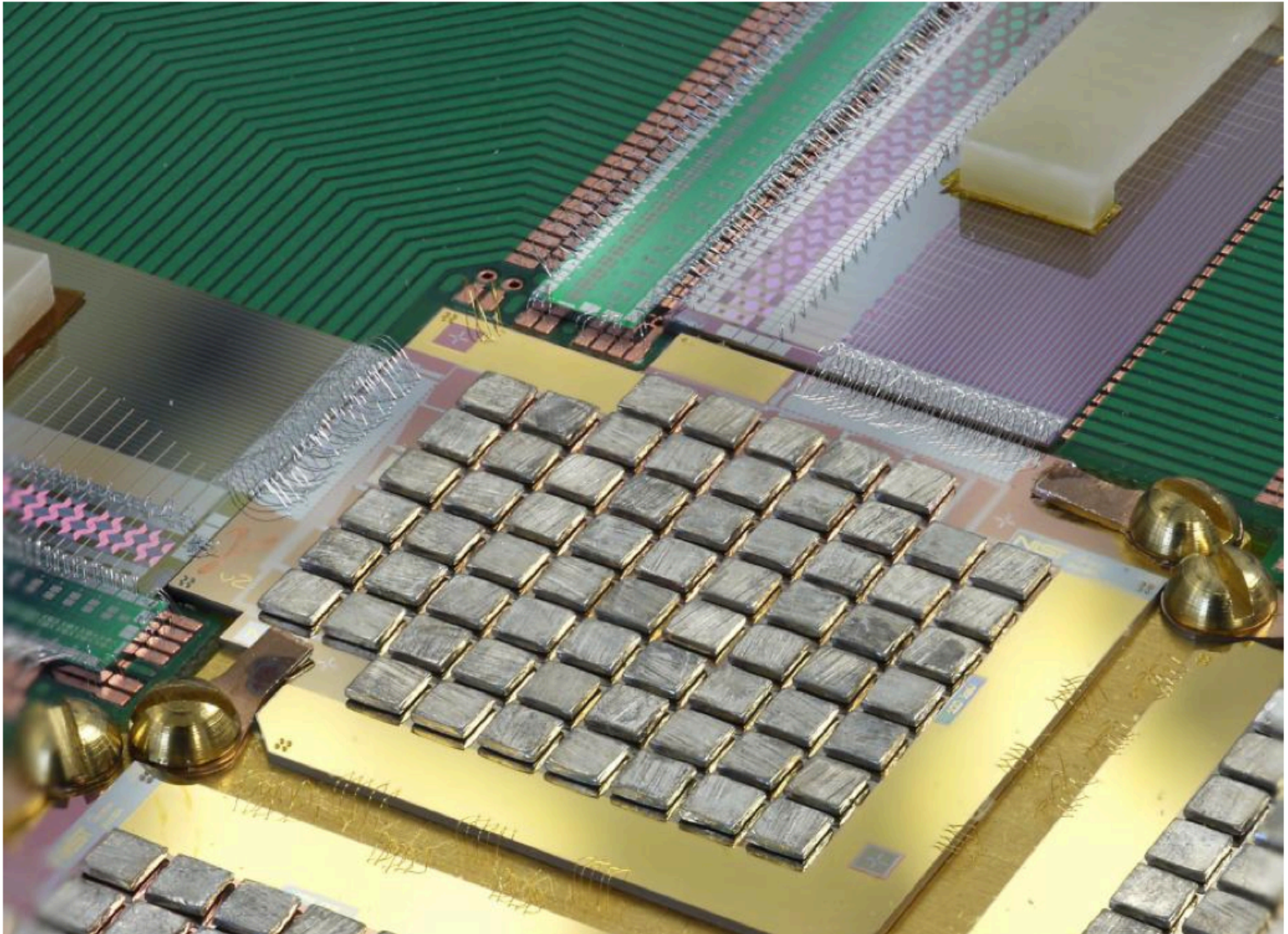
$$\Delta E \sim T(k_b C)^{1/2}$$

Microcalorimeter Gamma-Ray Array

- 256-pixel microcalorimeter array for X- & γ -ray measurement
- One pixel = $1.5 \times 1.5 \text{ mm}^2$ by 0.38 mm thick
- Total collection area = 576 mm^2 (compare to planar HPGe $\sim 200\text{-}1000 \text{ mm}^2$)



Microcalorimeter Array



Multiplexing

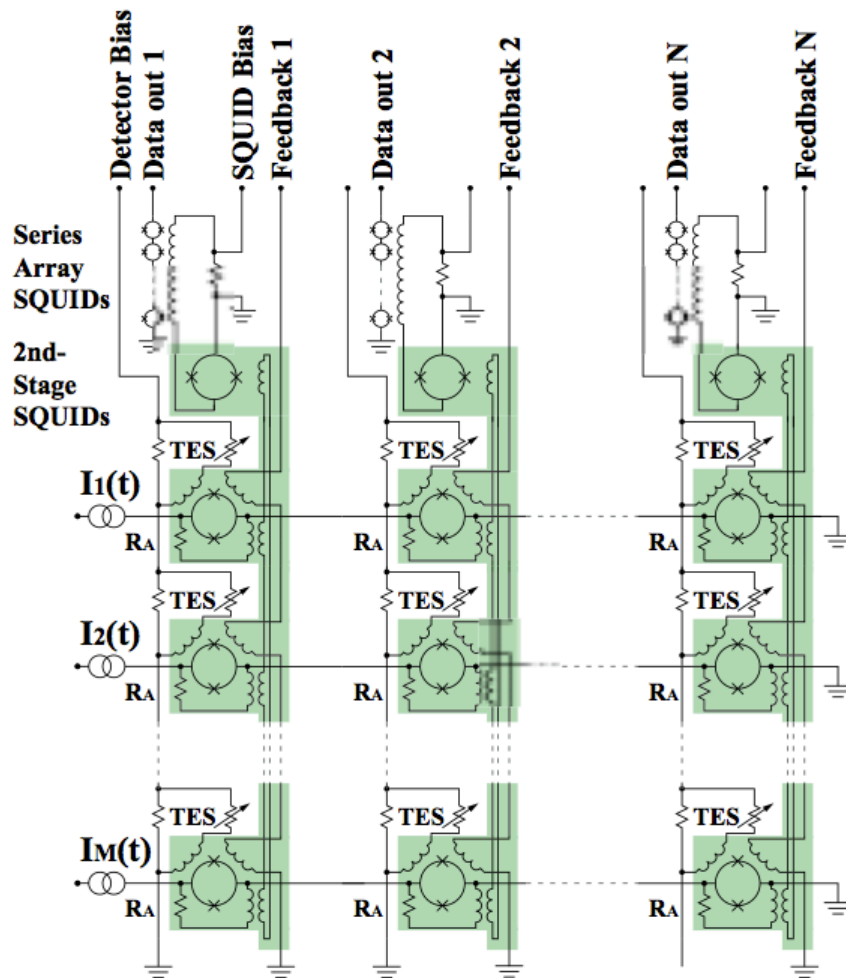
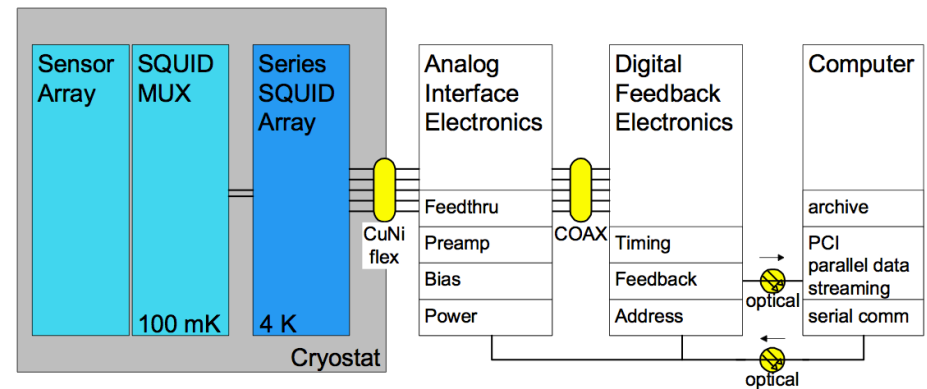


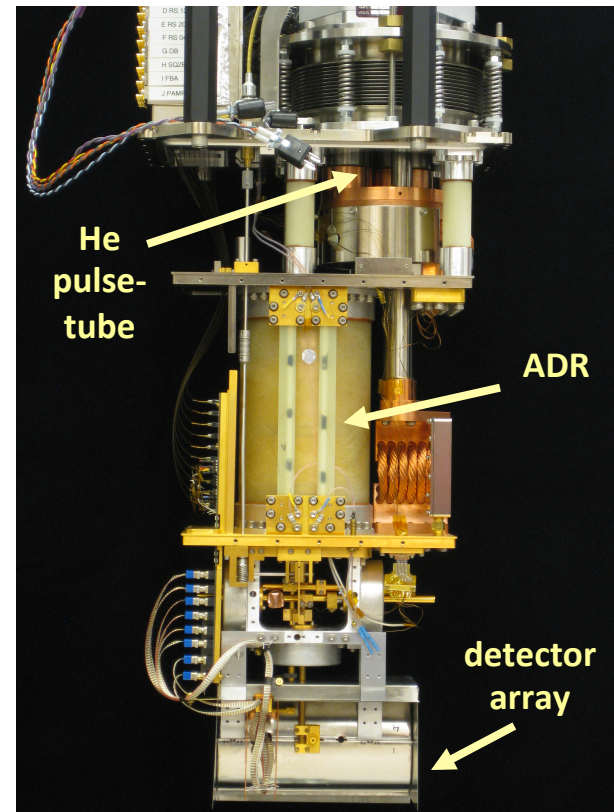
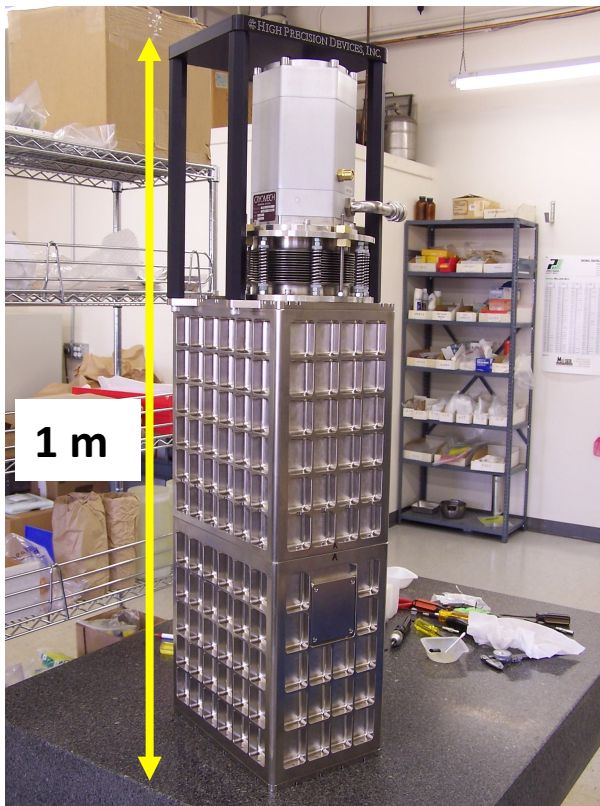
Fig. 1. Circuit diagram for time-division SQUID multiplexer with $M \times N$ pixels. In this version, the first-stage SQUIDs are coupled through a common transformer to the second stage.

- Channel count and power dissipation lead to multiplexing
- Time-division multiplexing



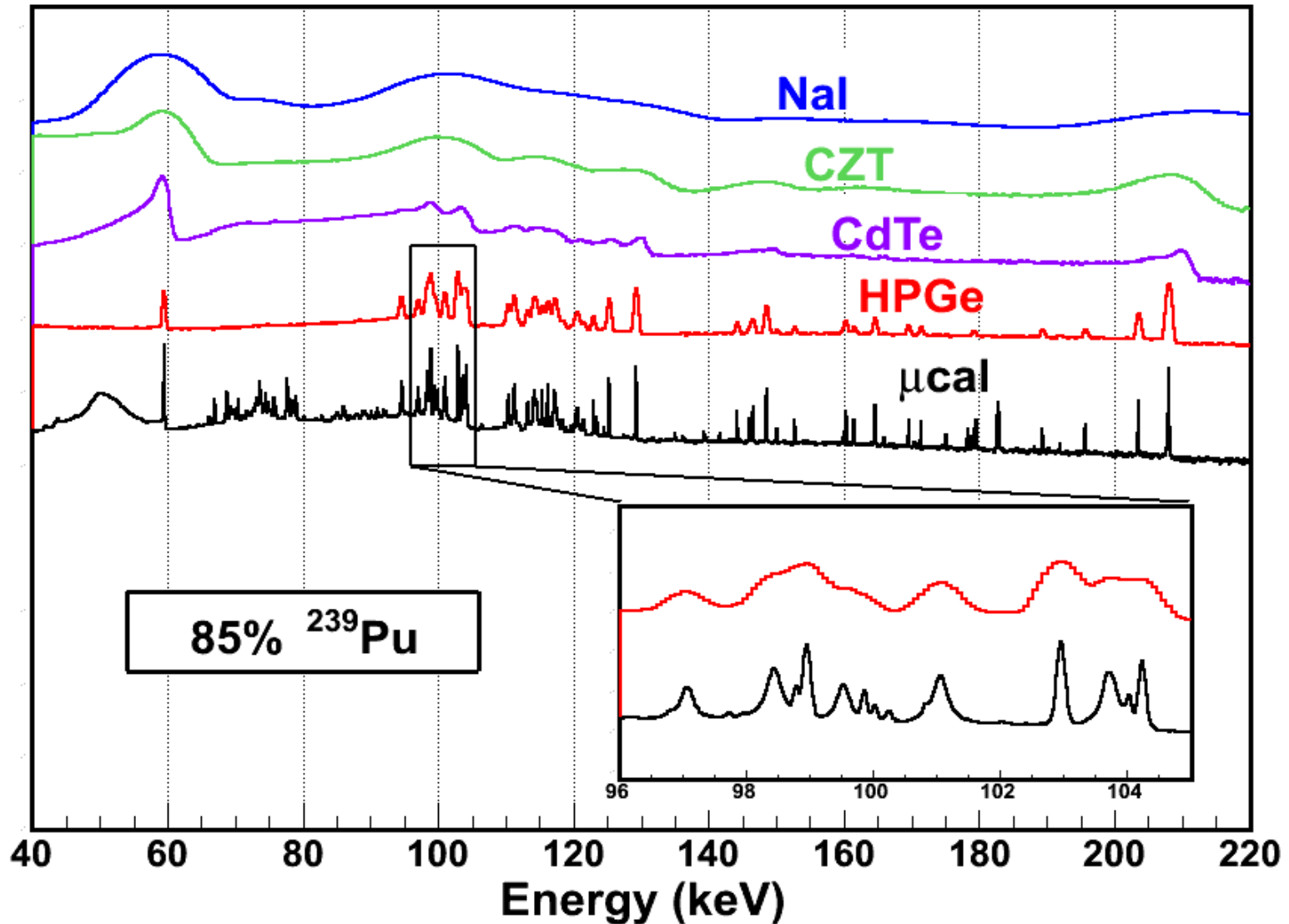
Cryogenic Operation

- ~ 50 mK with dry cryostat utilizing He pulse-tube and adiabatic demagnetization refrigerator (ADR) - no liquid cryogenics required



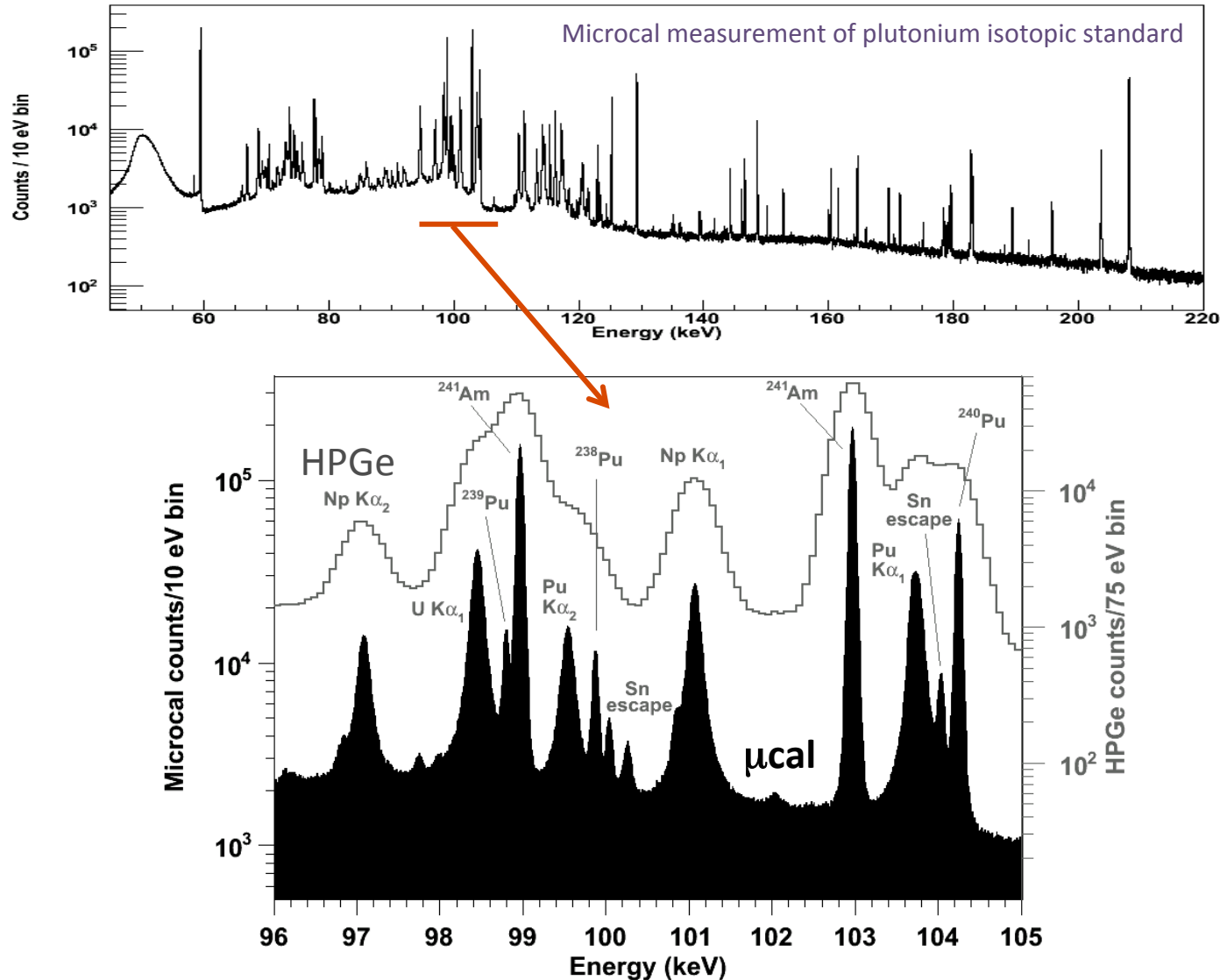
Energy Resolution for X- and γ -ray Spectroscopy

Factor of ten better than conventional semiconductor technology



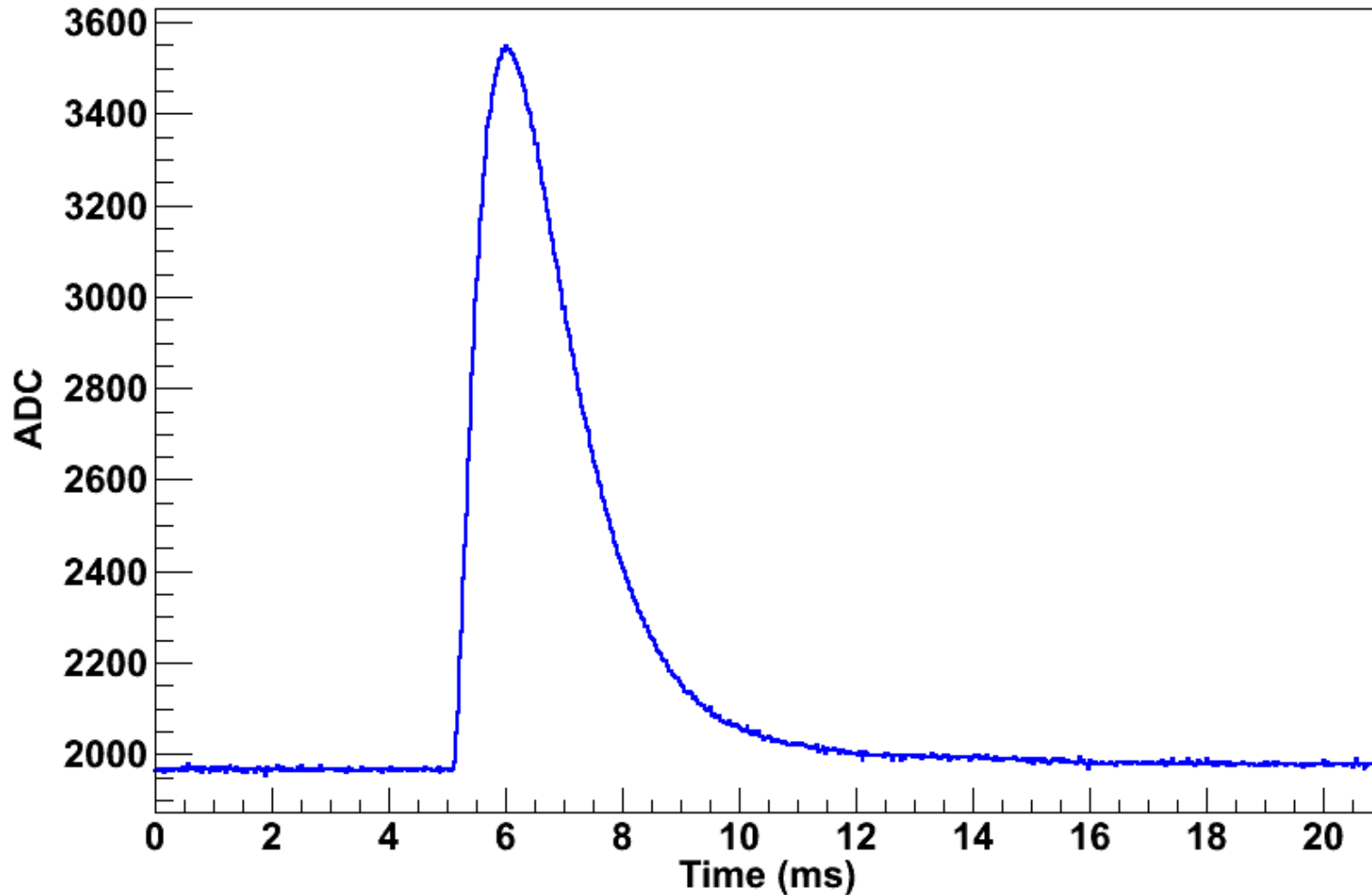
Gamma-ray Spectroscopy

- Microcalorimeter energy resolution up to 10 times better than HPGe; advantage for analysis of samples with high peak density and overlap



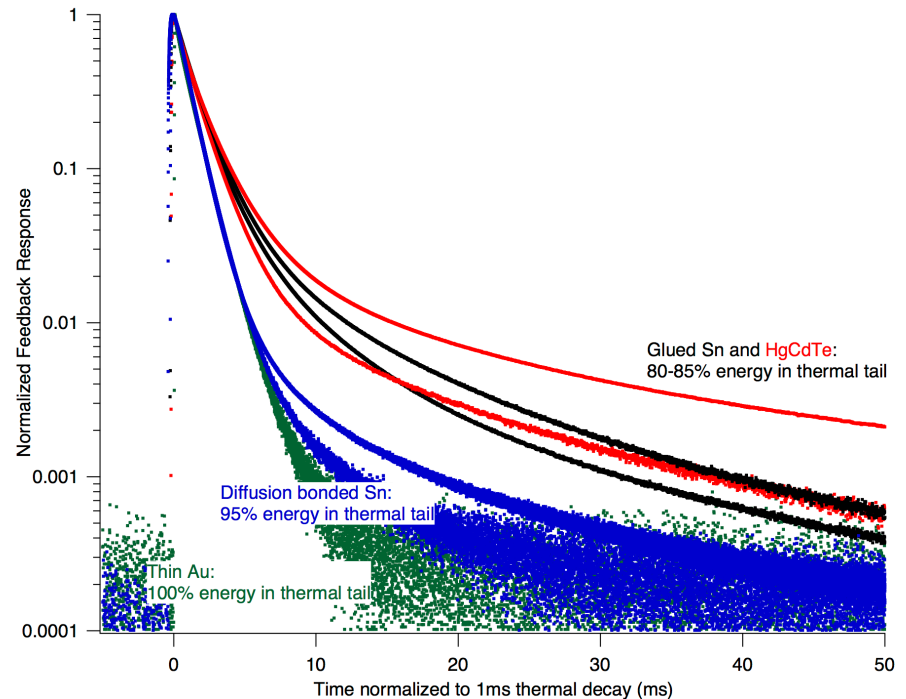
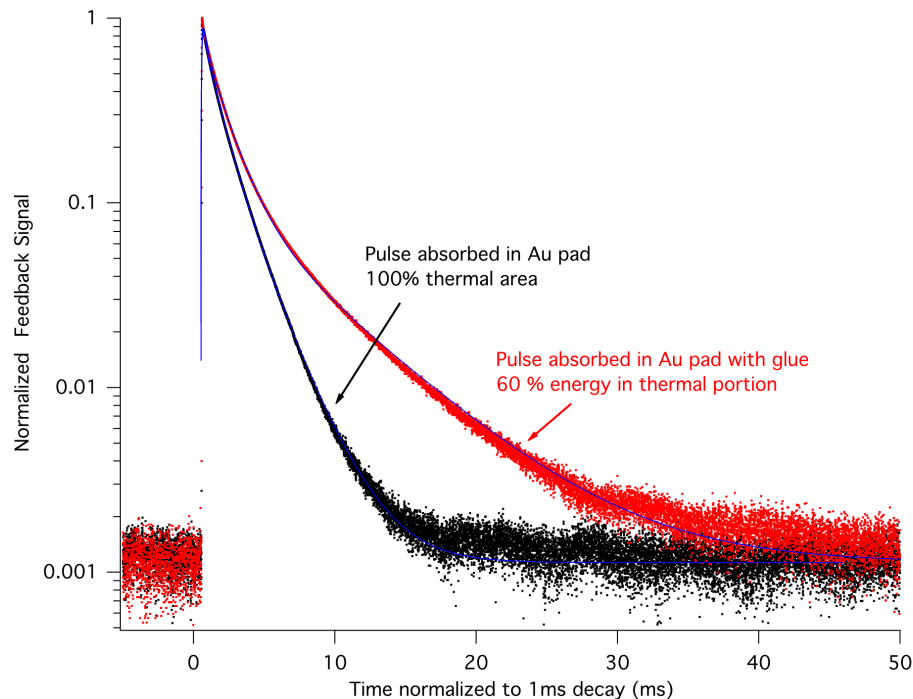
“Slow” Detectors

Challenge: similar counting speed as HPGe (tens of kHz) but retain resolution



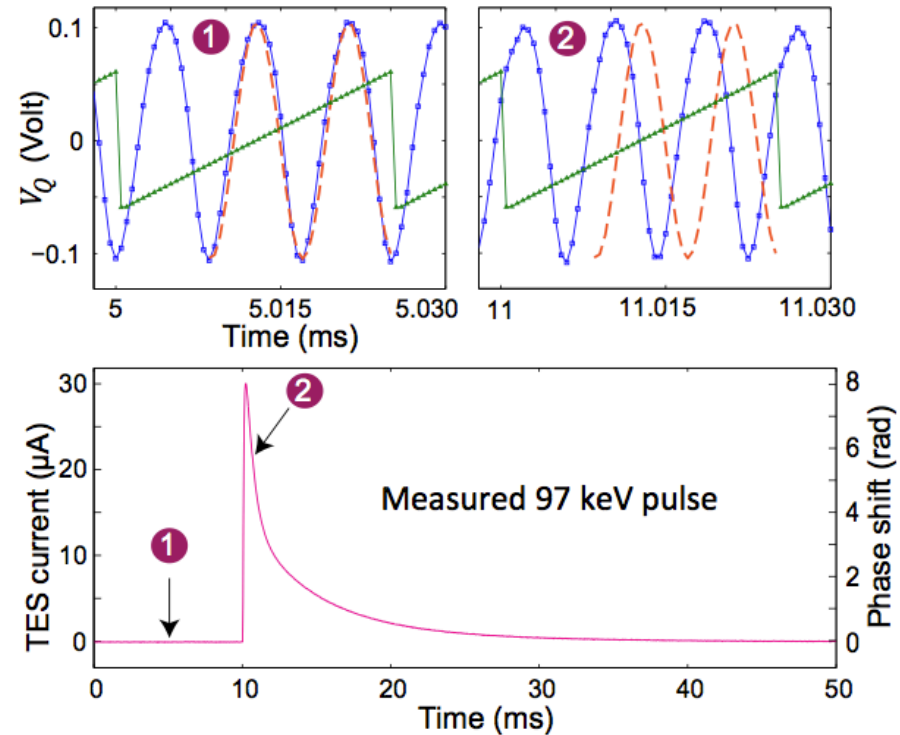
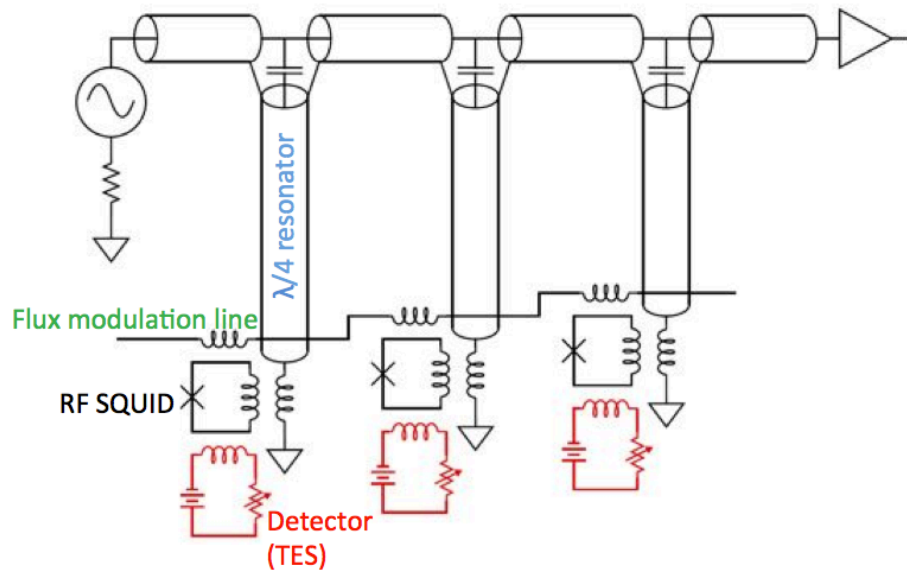
Reducing Pulse Decay Times

- Long secondary thermal decay times undesirable for high event rates
- Absorber attachment glue is suspect; Diffusion bonding looks promising



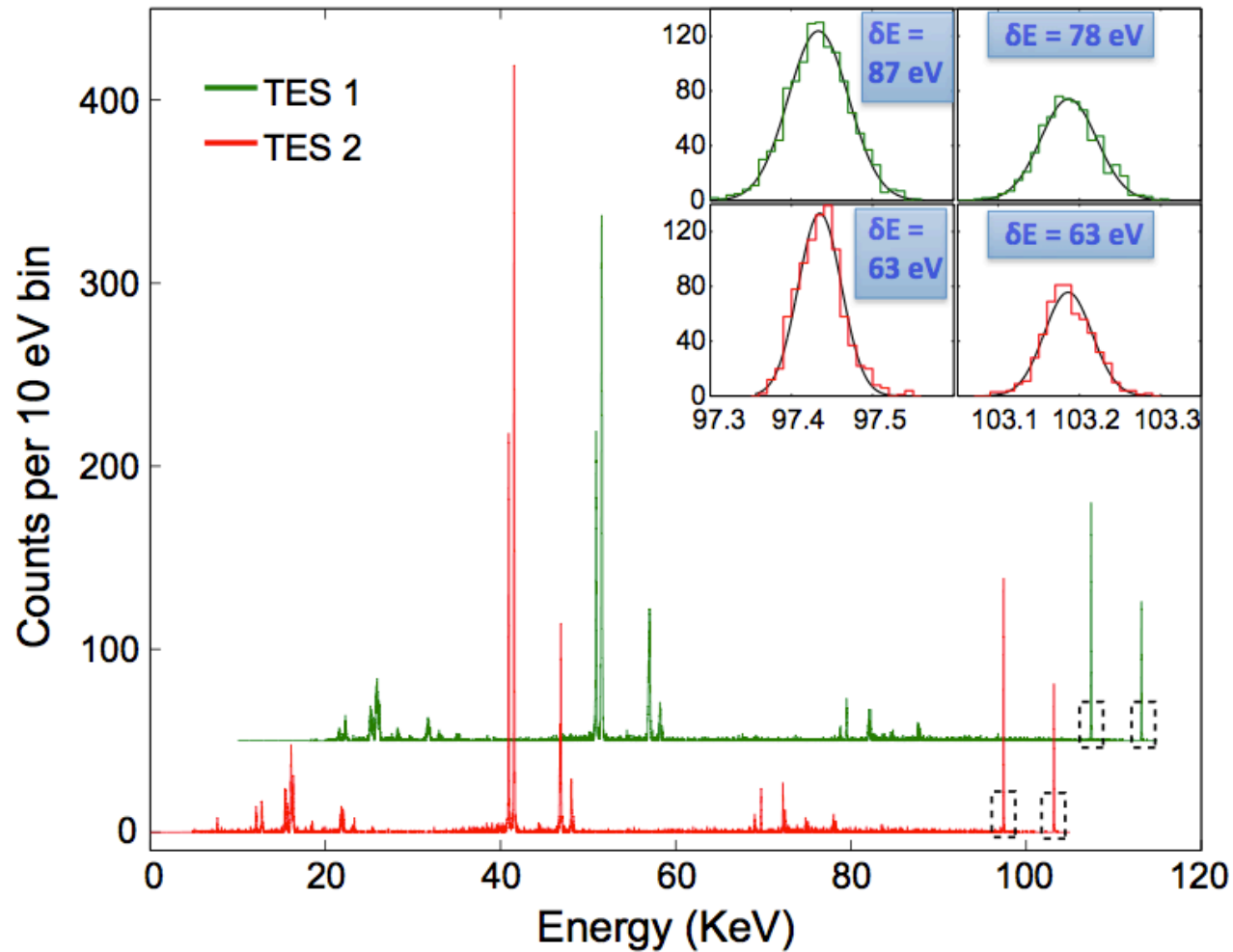
More Pixels

- Towards $10^3, 10^4$, or more pixels
- TDM at limits - microwave MUX could be enabling technology
- Change of inductance causes change in transmission of microwave resonator
- Readout thousands of pixels from a single line



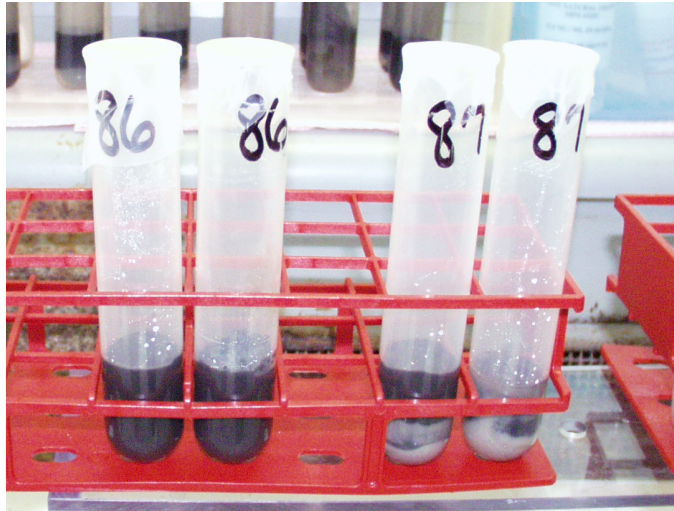
Microwave MUX

- Microwave MUX demonstrated on 2-pixel system (63 eV FWHM)



Nuclear Forensics & Alpha Spectrometry

- High emission/detection rate for alphas → analysis of trace samples (nanogram scale)

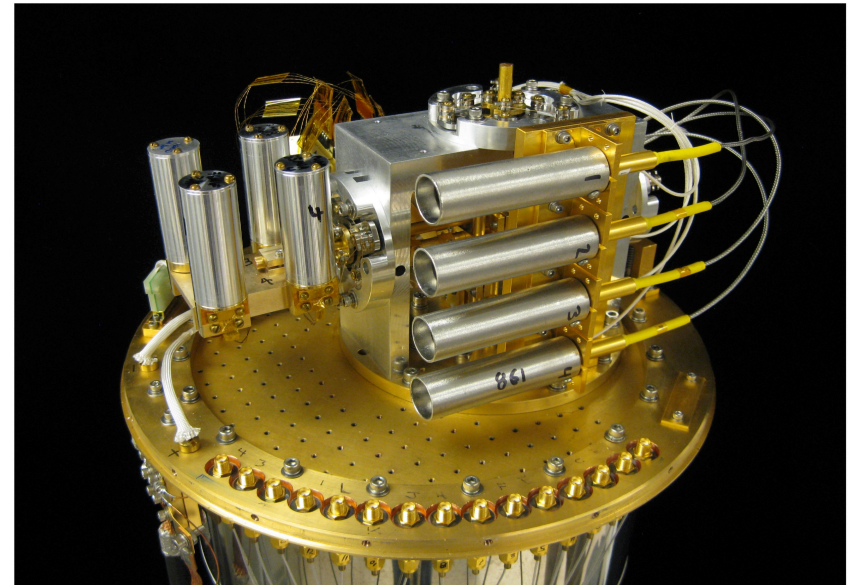
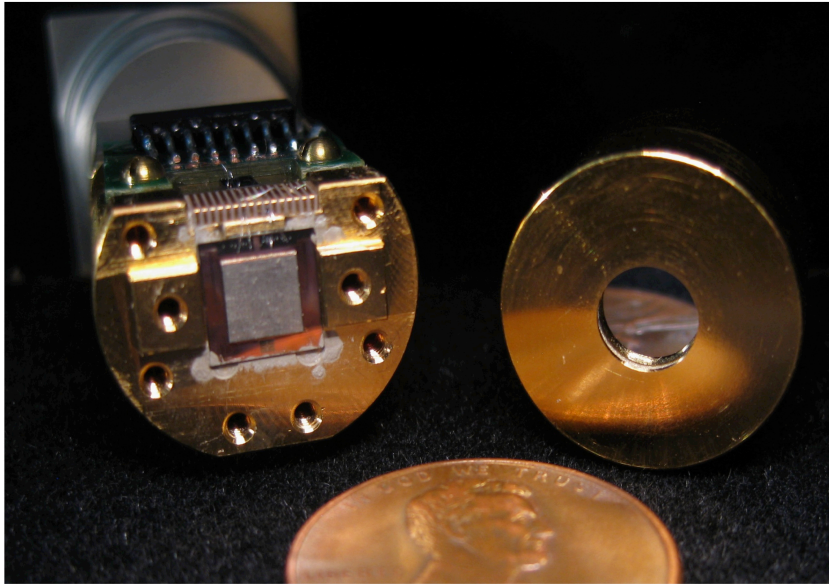


Limits on Current Alpha Spec:

- ~10 keV resolution with Si detectors; cannot resolve ^{240}Pu : ^{239}Pu ,
 ^{238}Pu : ^{241}Am
- Radiochemical isolation of each element to remove peak overlaps

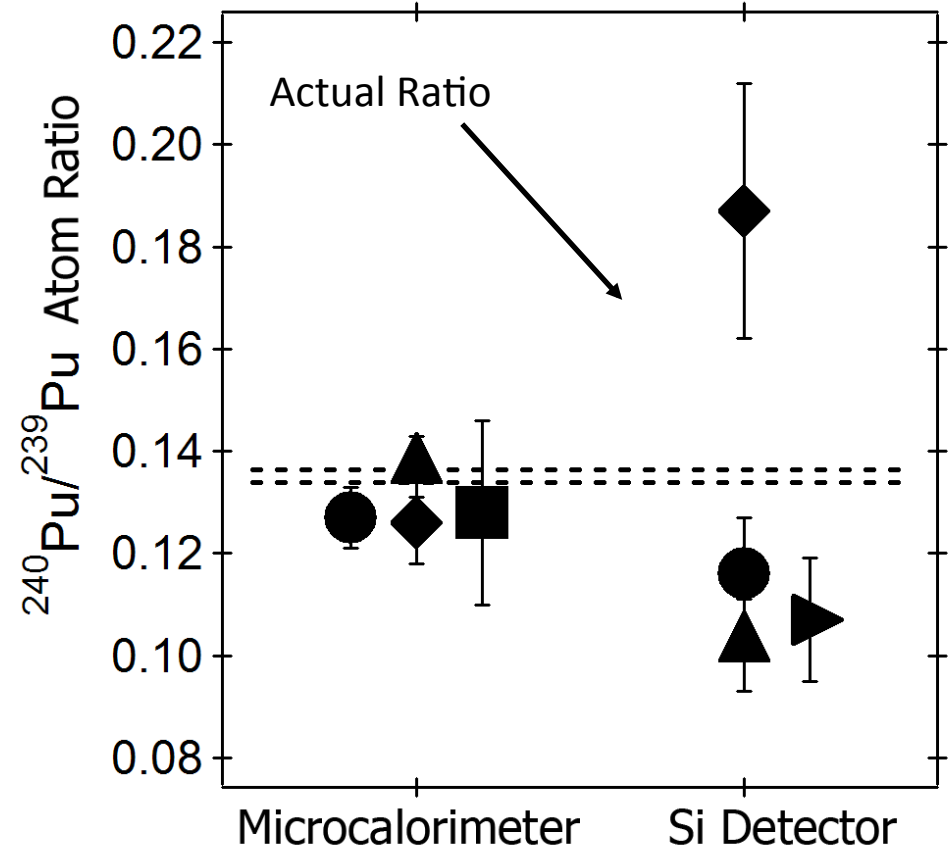
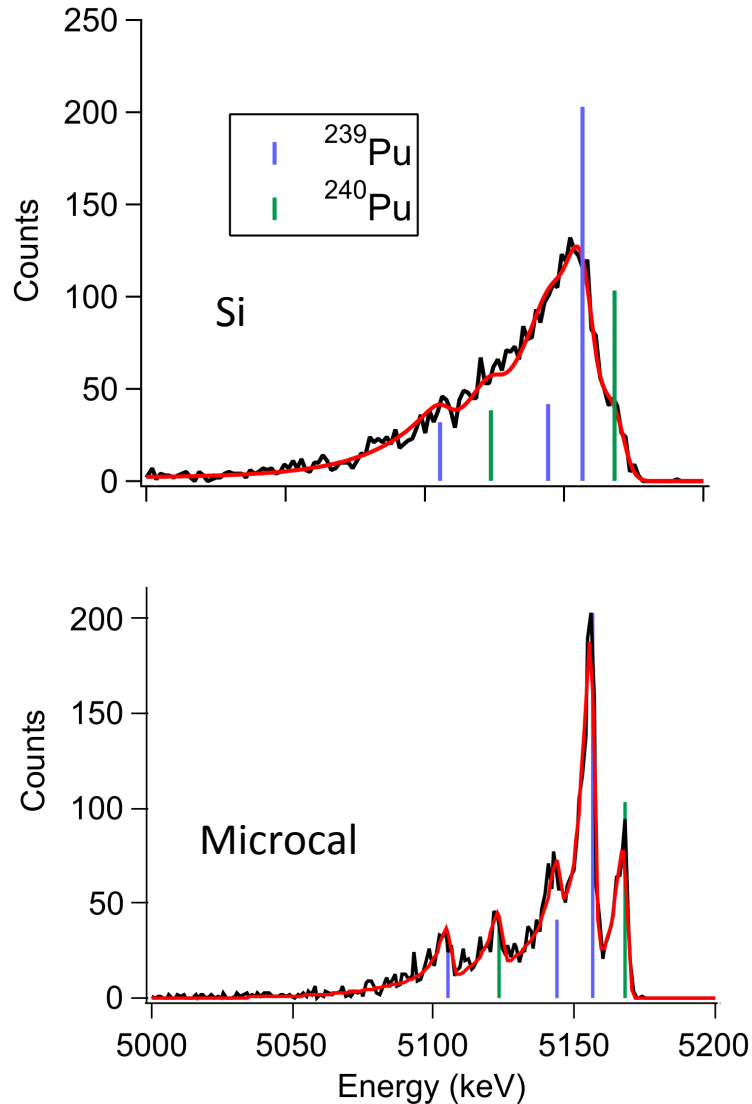
Microcalorimeter Alpha-Spec

- Similar core technology as gamma-spec (TES + absorber)
- Smaller channel count due to larger absorber and high detection efficiency for alphas



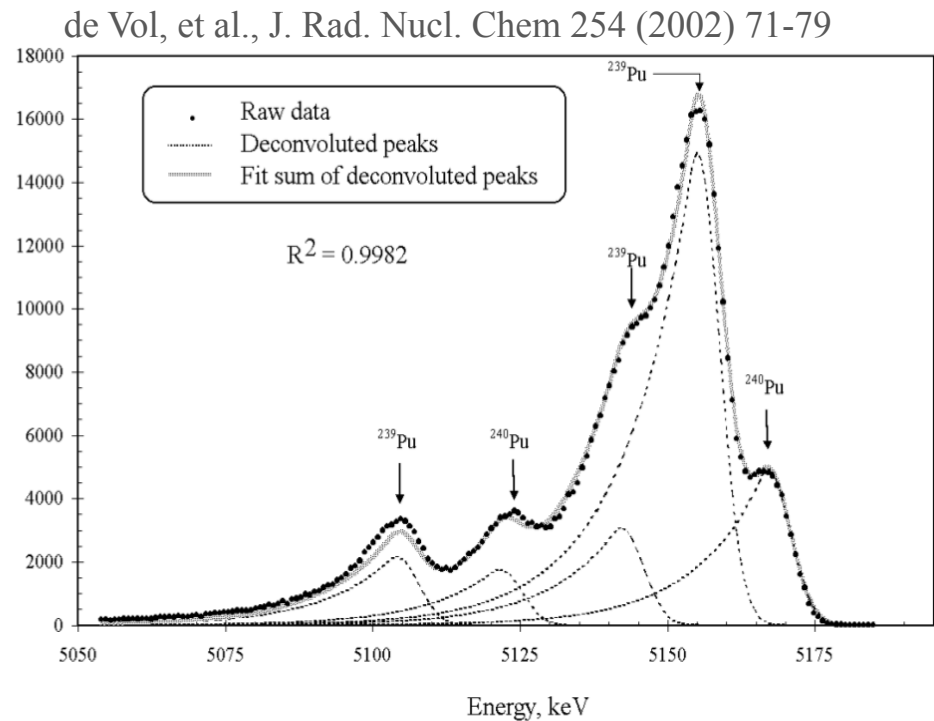
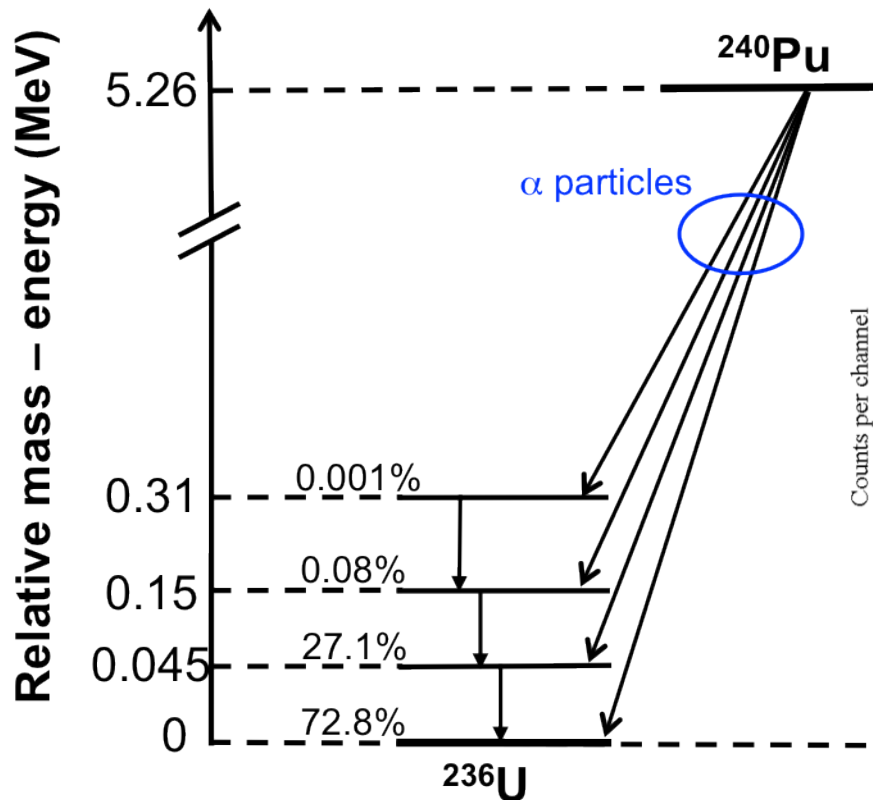
Application: Pu Isotopics

10x better resolution for microcalorimeter compared to Si



α -Spectroscopy Limits

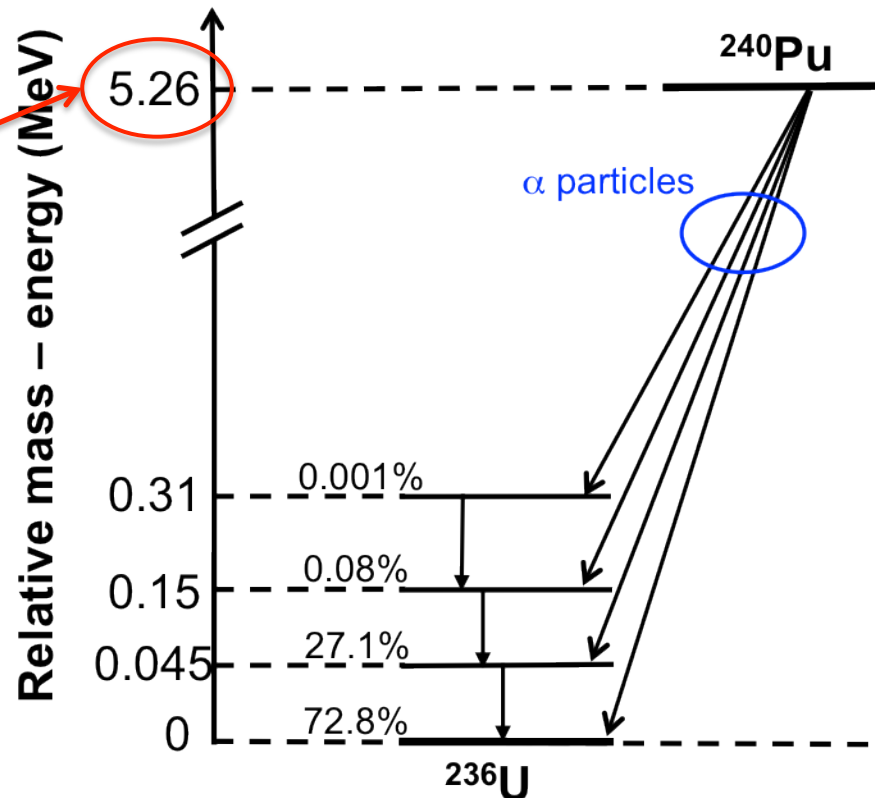
- Measure multiple α energies for single isotope due to fine structure of daughter nucleus



Q-Spectroscopy

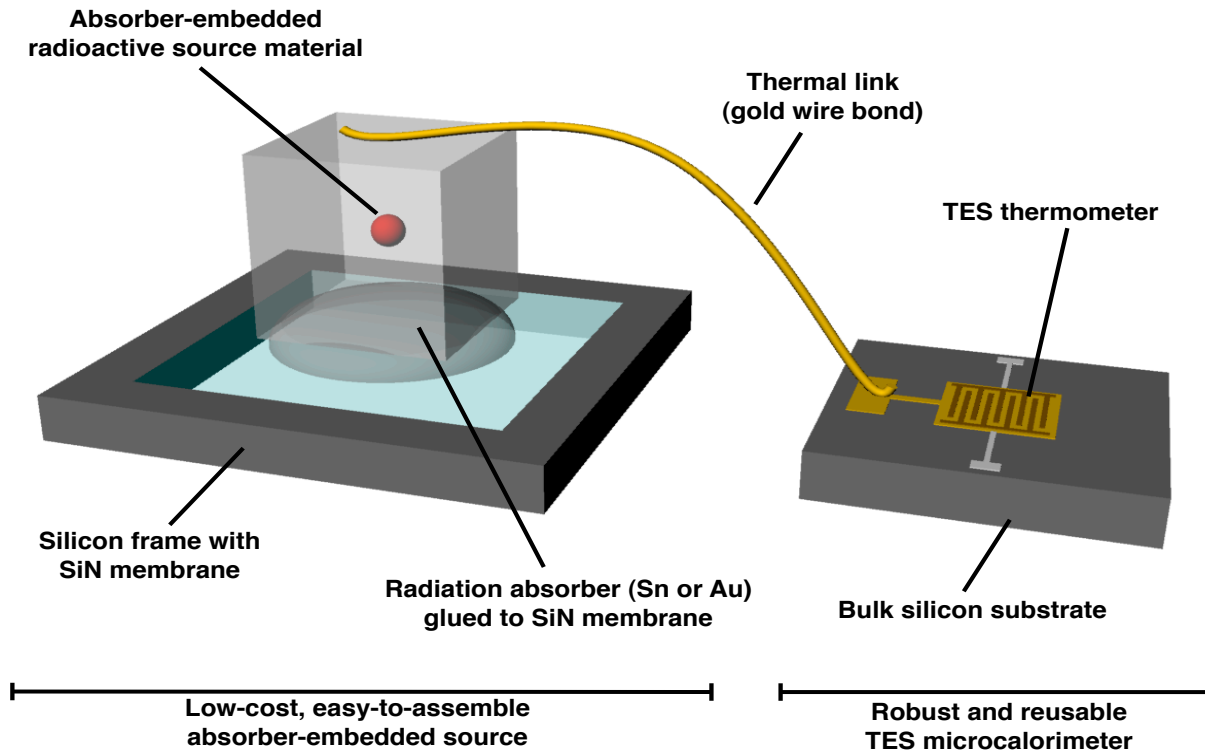
- Embed sample inside a detector
- Measure combined energy of all decay products (α , recoil nucleus, X-rays, γ -rays, e^-)
- Observe single energy peak at Q-value for each isotope

Q-value = 5.26 MeV
= Total energy release



Q Detector Concept

- Minimal chemical preparation; All elements/isotopes measured simultaneously; No electroplating; High efficiency; Sample is not destroyed during measurement; Bulk aqueous or single particle
- Separate sample and TES chips permit reuse of well-characterized detector for different samples

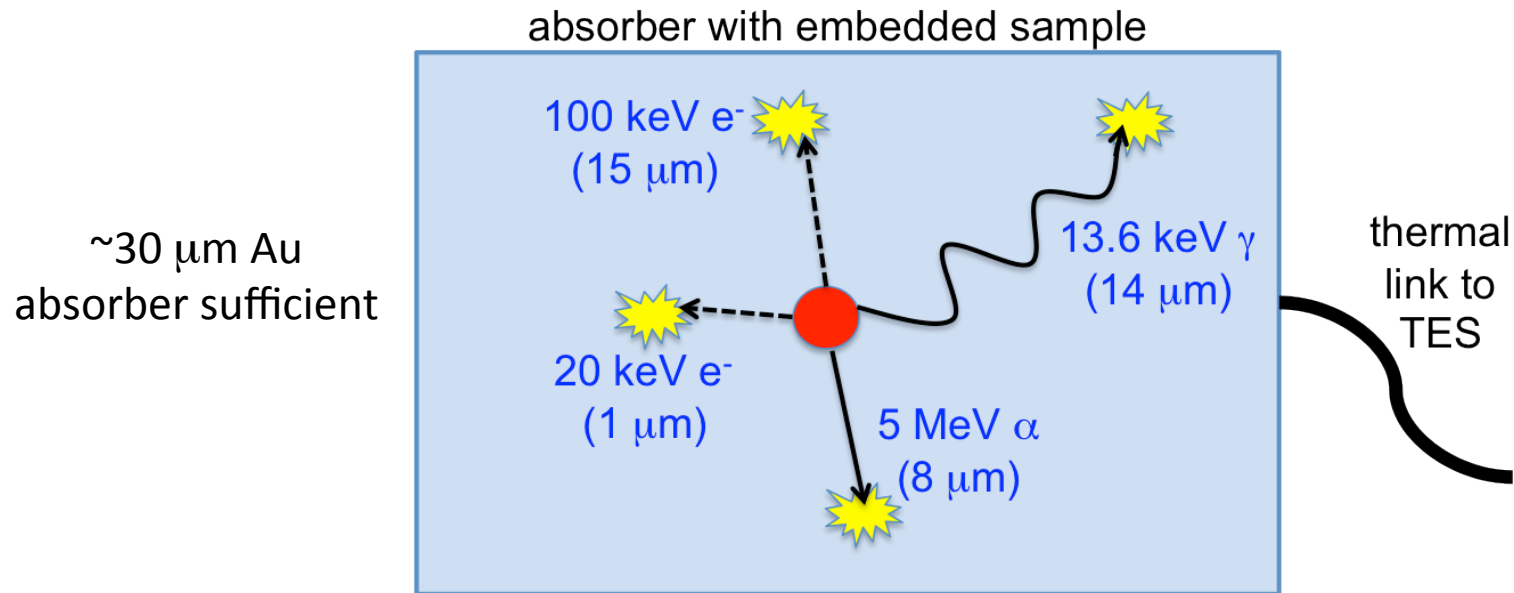


Absorber

Gold...

- Resists oxidation
- Malleable
- Amenable to diffusion welding
- Evidence that it works (*S-J. Lee, et al., J. Phys. G, 37 (2010) 055103*)

Path length of common decay products in Au...



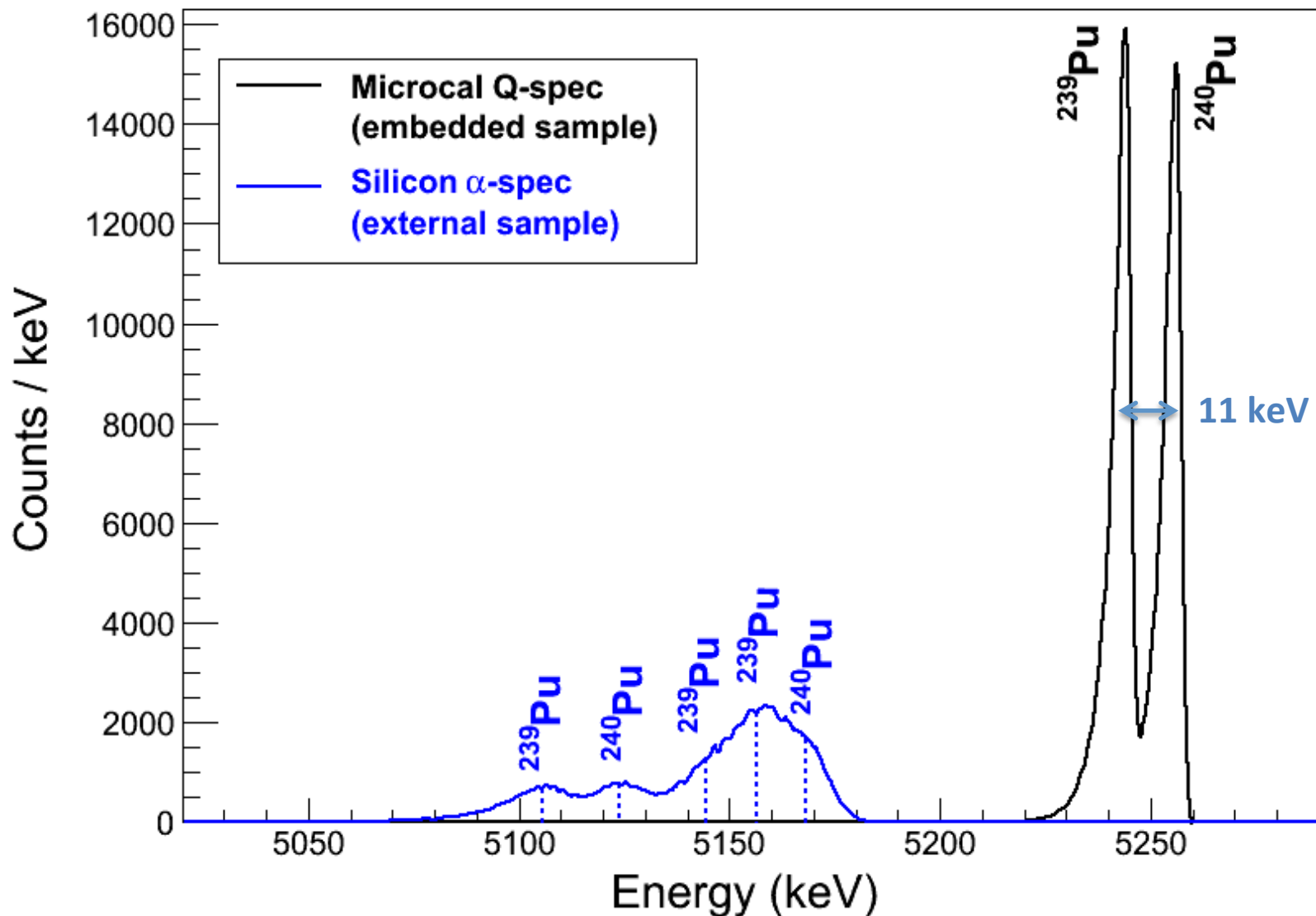
$^{239}\text{Pu}/^{240}\text{Pu}$

Synthetic data for illustrative purposes

1 Bq for 24 hours

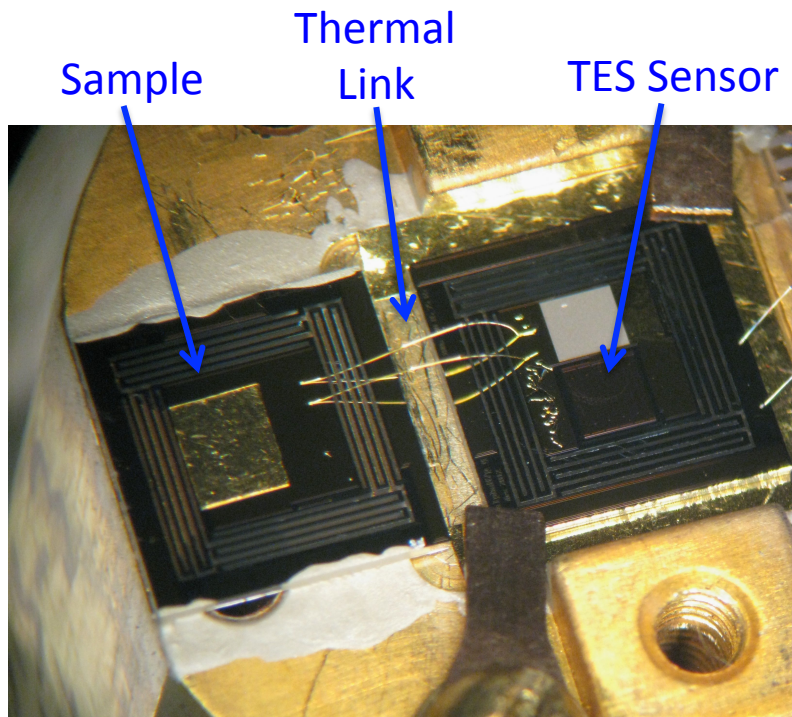
Si α -spec: 10 keV FWHM, $\epsilon=50\%$

μcal Q-spec: 2 keV FWHM, $\epsilon=100\%$



Q-Spectroscopy

- Successful Q measurements for 2-chip separated sample/sensor configuration

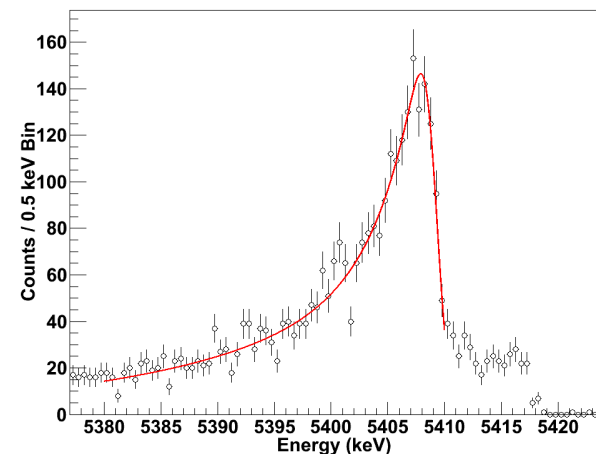
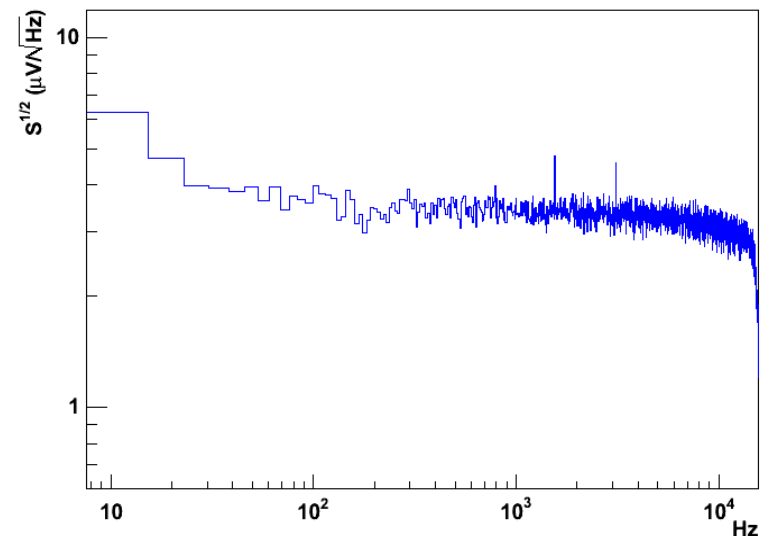


^{210}Po two-chip Si meander

$v_s \approx 0.73 \text{ V}$

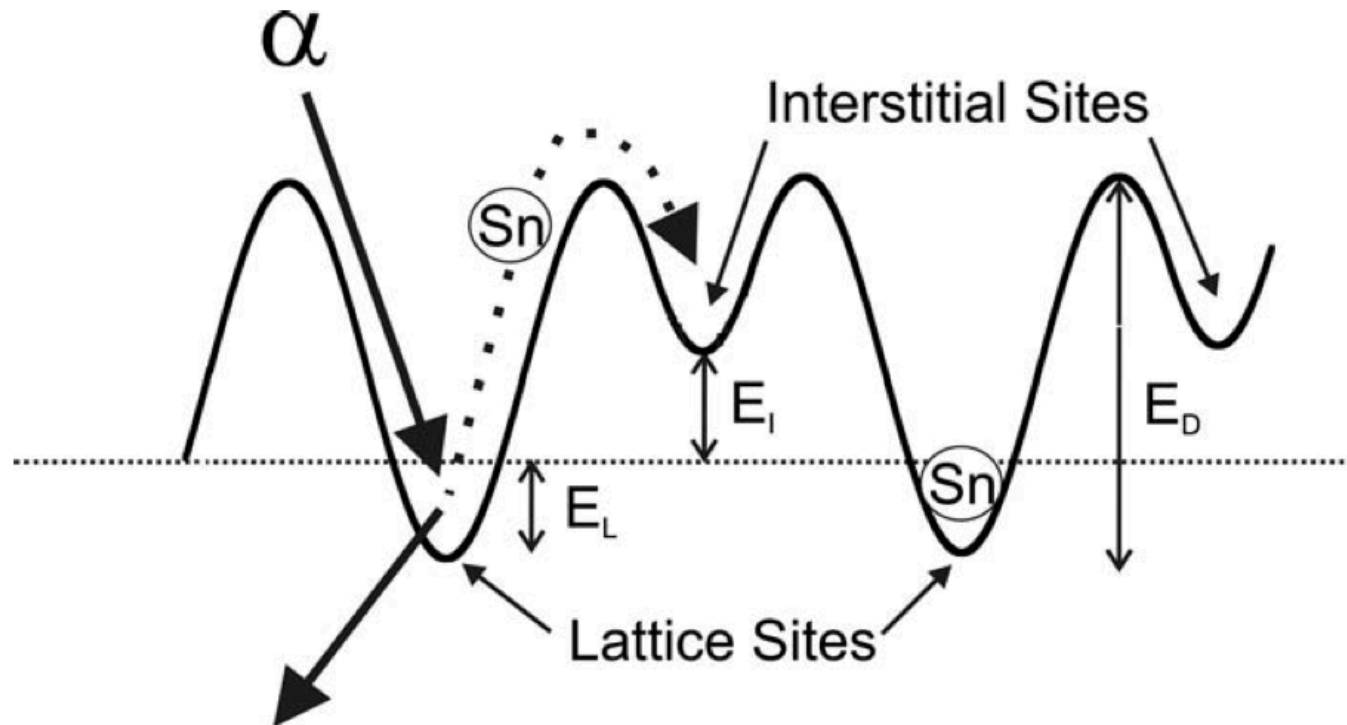
Predicted $V/\Delta V = 8561 \rightarrow 0.63 \text{ keV}$

Achieved $E/\Delta E = 2704 \rightarrow 2.0 \text{ keV}$



Lattice Damage

- Lattice damage – incident α moves atoms between lattice and interstitial sites
- Contributes to a mean energy loss, low-energy tail, and peak broadening



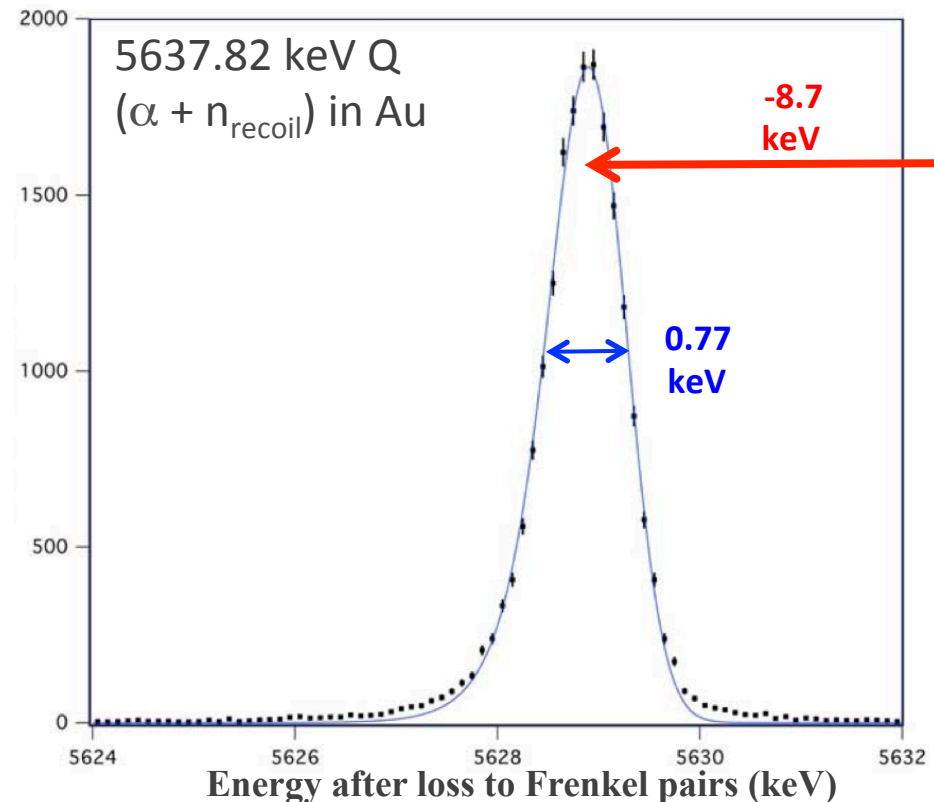
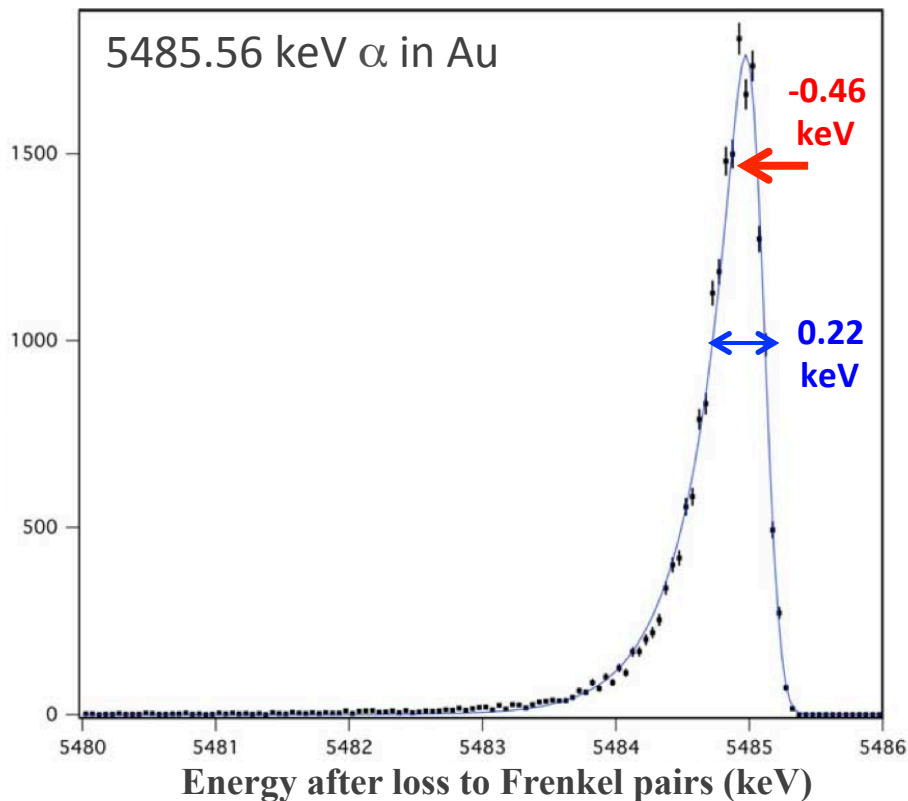
Lattice Damage

SRIM calculations (R.D. Horansky)

α in Au: 0.46 keV offset, 0.22 keV FWHM broadening

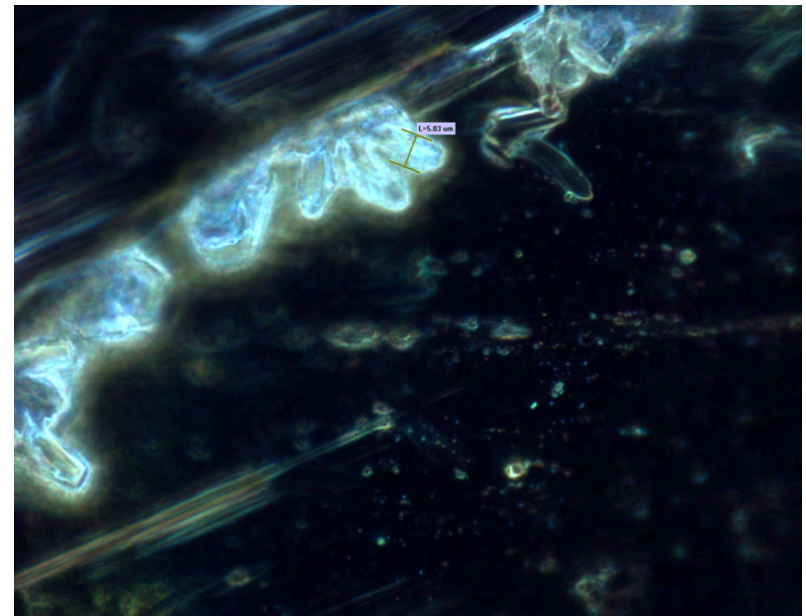
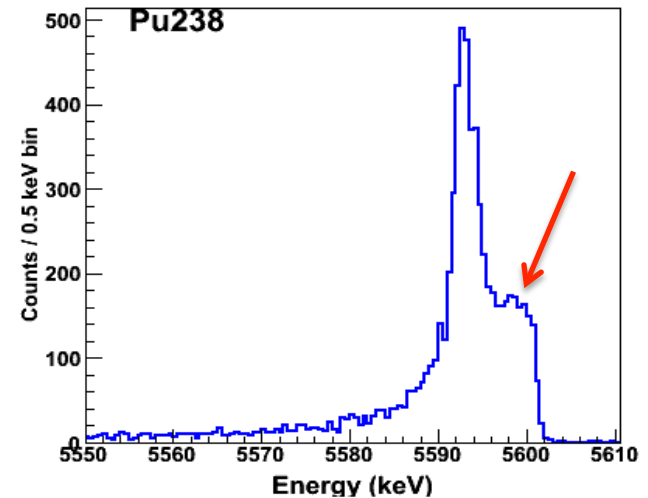
$\alpha + n_{\text{recoil}}$ in Au: 8.7 keV offset, 0.77 keV FWHM broadening

K.E. Koehler, et al., *IEEE Trans. Nucl. Sci.* **60** (2013) 624



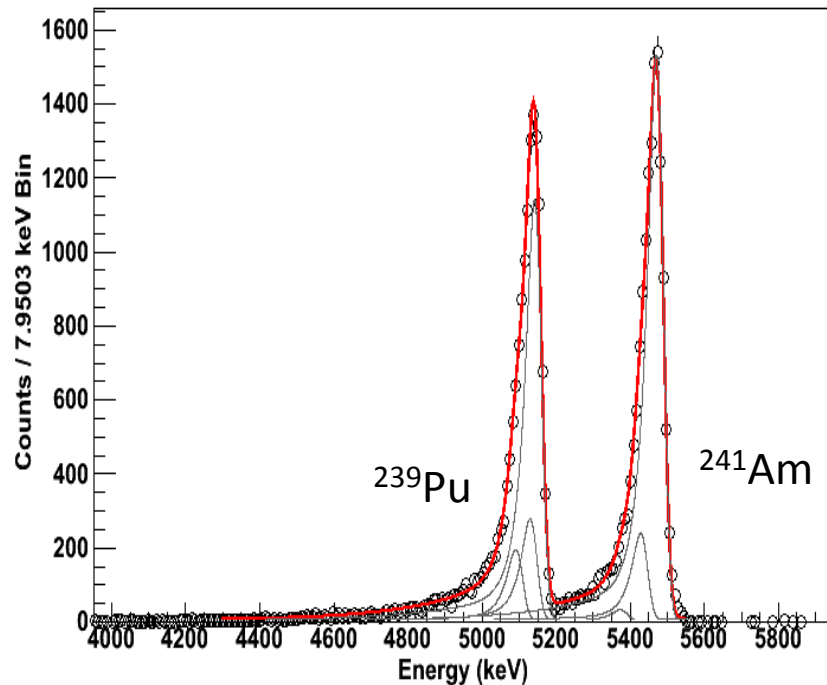
The High-Energy Feature

- Observation confirmed by KRISS researchers
- Present hypothesis: non-uniform radiation environment from residue left by droplet drying, perhaps leading to incomplete energy collection or lattice damage effects

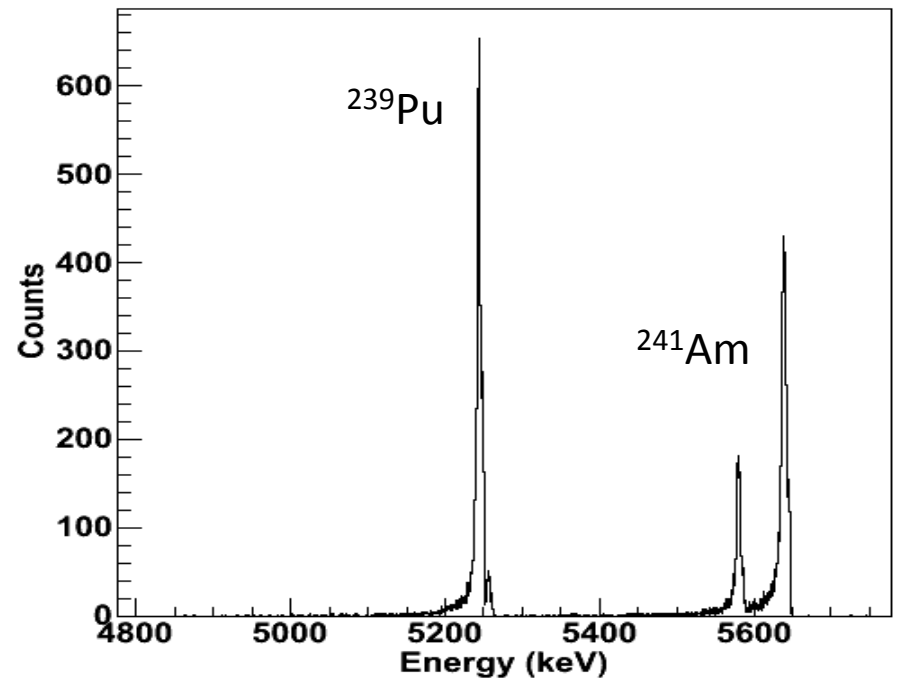


Quantitative Isotopic Analysis

Si α -spec data from $^{239}\text{Pu}/^{241}\text{Am}$ sample

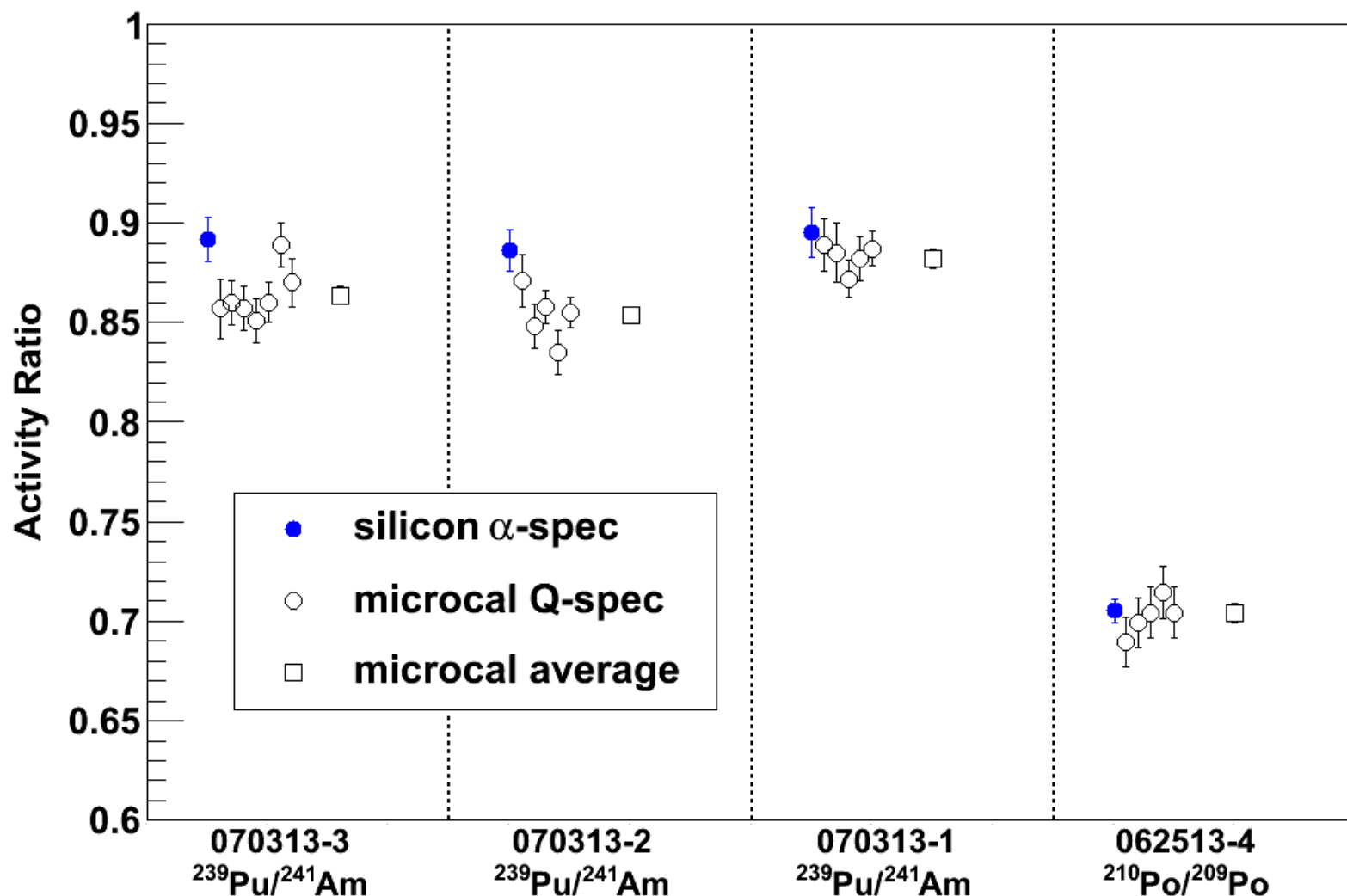


Microcal Q-spec data from $^{239}\text{Pu}/^{241}\text{Am}$ sample



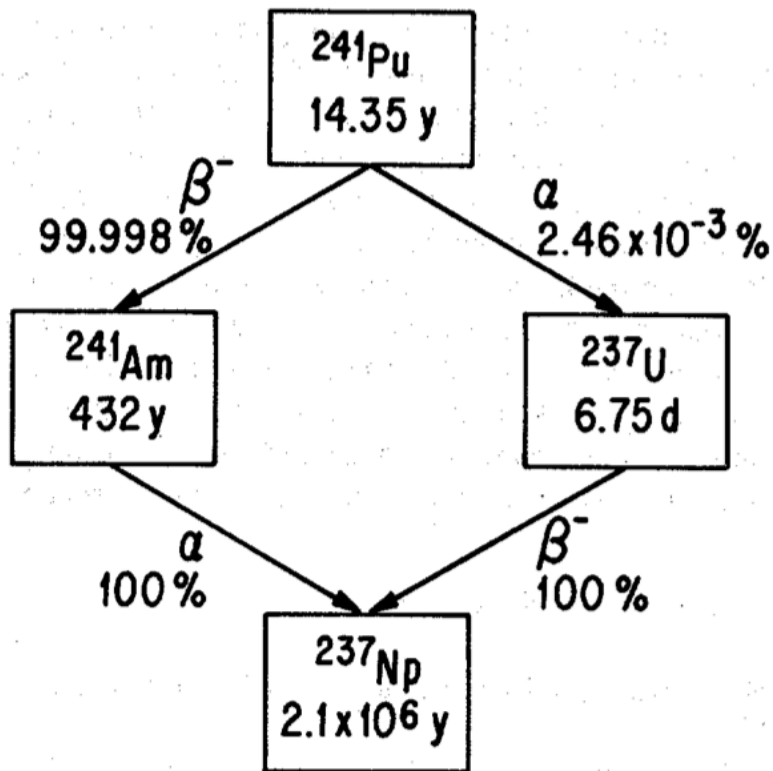
Quantitative Isotopic Analysis

- First demonstration of Q-spec quantitative analysis
- Presently looking at ^{240}Pu : ^{239}Pu vs. mass-spec



Chemical Age

- Time since chemical purification is important forensics/safeguards information

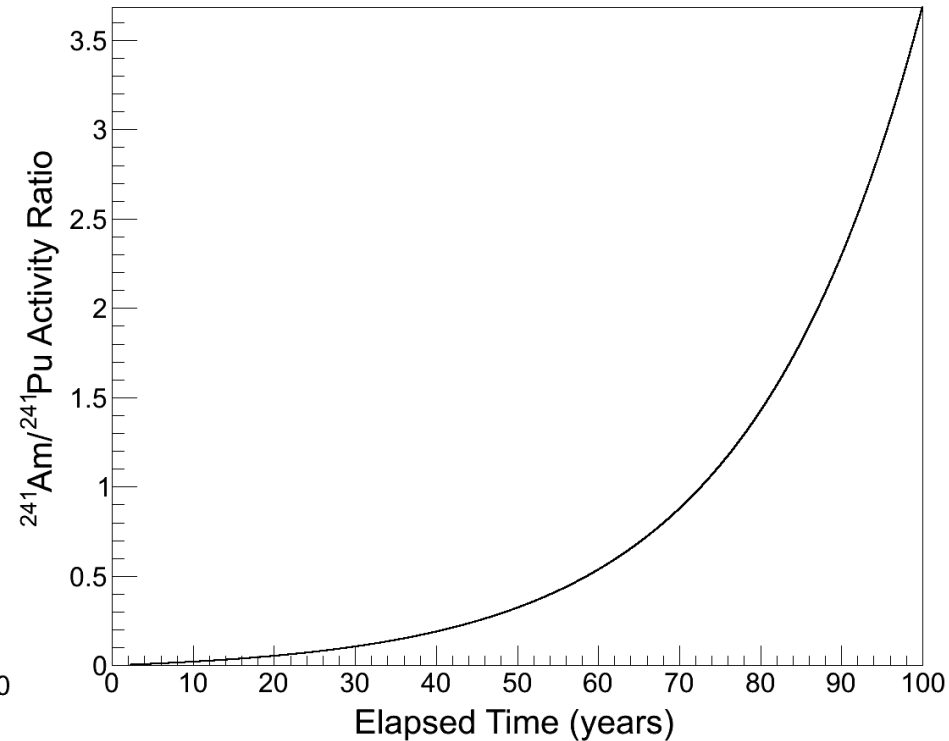
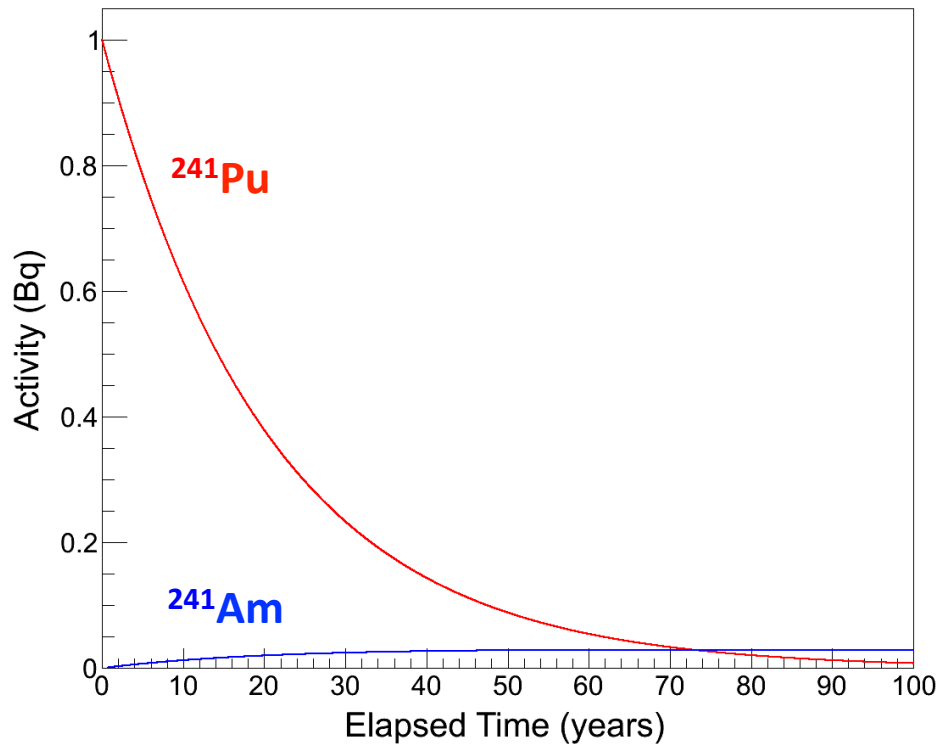


- Ingrowth of ^{241}Am daughter over time provides an “atomic clock” to determine time since purification using $^{241}\text{Am}:^{241}\text{Pu}$ ratio
- mass-spec isobar for $^{241}\text{Am}:^{241}\text{Pu}$
- γ -spectroscopy has low sensitivity
- α -spectroscopy insensitive to β -decay path
- Q-spectroscopy can perform the measurement with minimal chemical preparation and one measurement

Chemical Age

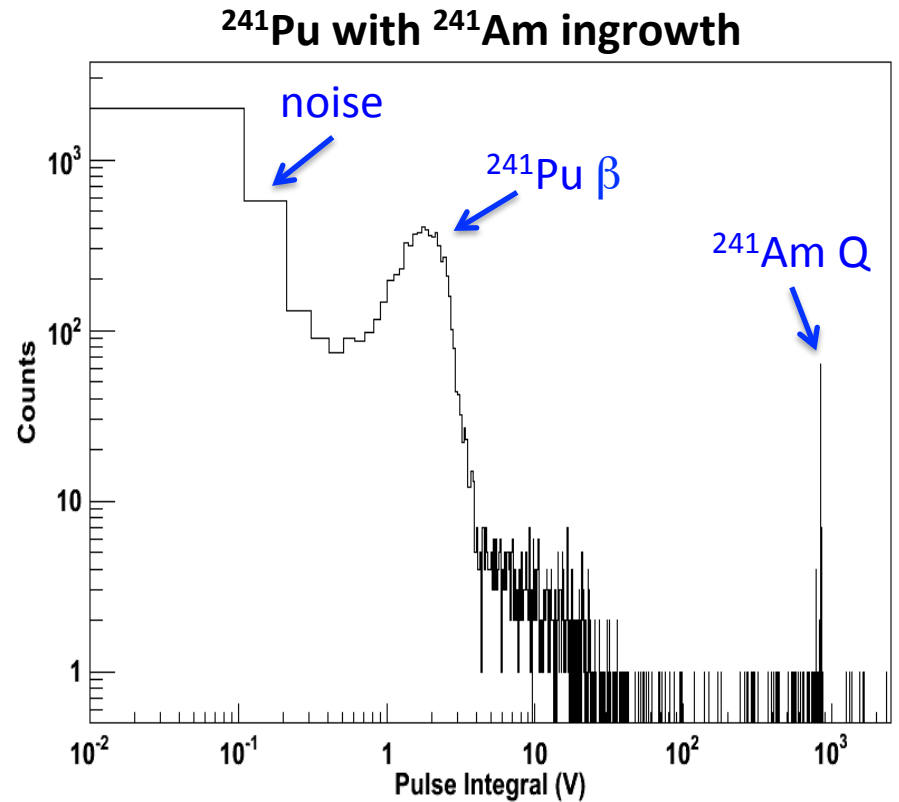
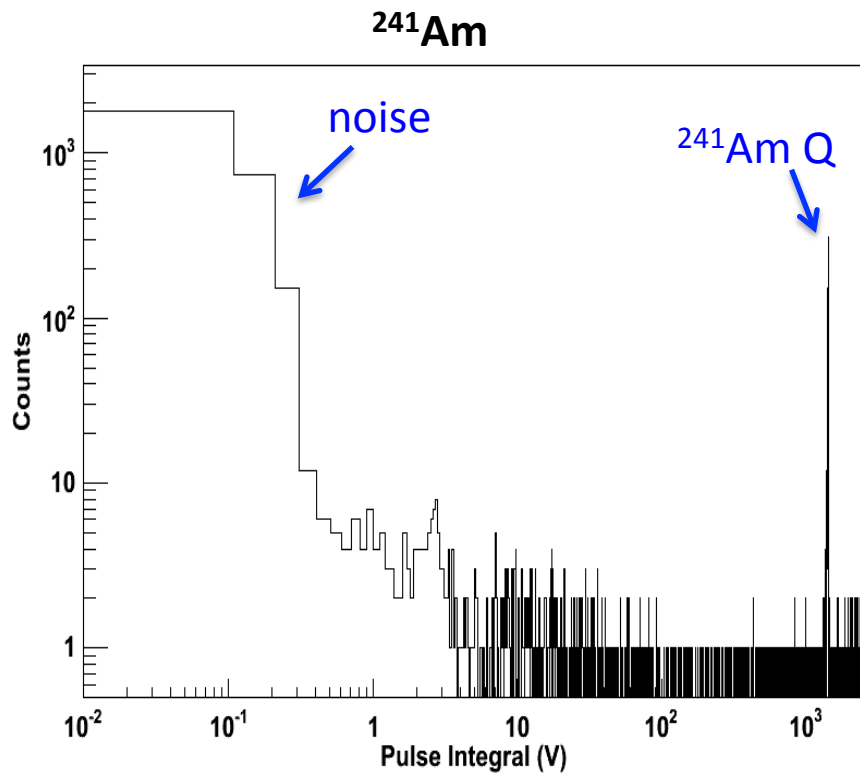
^{241}Pu parent: $A_t^p = A_0^p e^{-\lambda^p t}$

^{241}Am daughter: $A_t^d = \frac{A_0^p \lambda^d}{\lambda^d - \lambda^p} \left(e^{-\lambda^p t} - e^{-\lambda^d t} \right) + A_0^d e^{-\lambda^d t}$



$^{241}\text{Am}/^{241}\text{Pu}$ Analysis

- Can we simultaneously measure keV β and MeV Q?

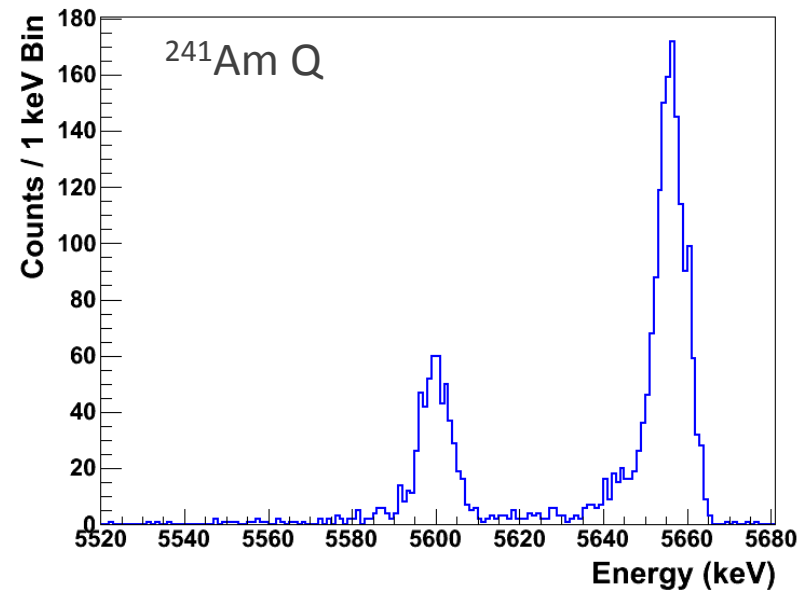
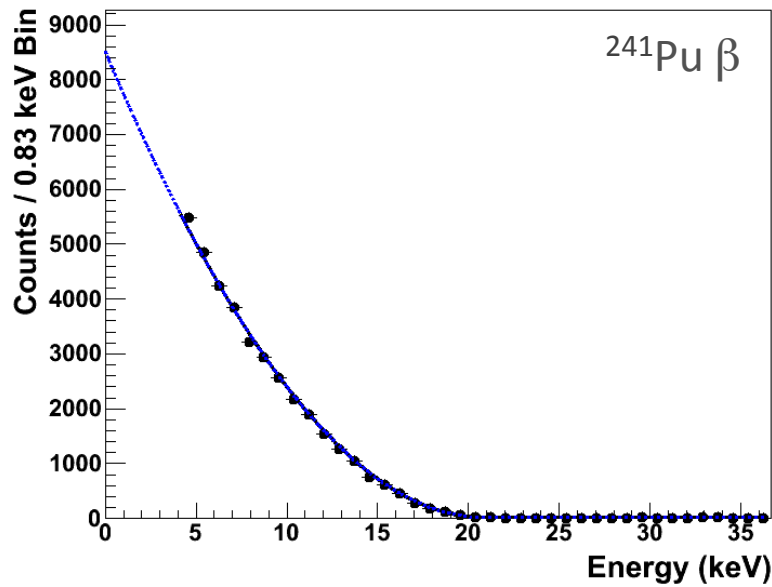


$^{241}\text{Am}/^{241}\text{Pu}$ Analysis

- For ^{241}Pu β -spectrum

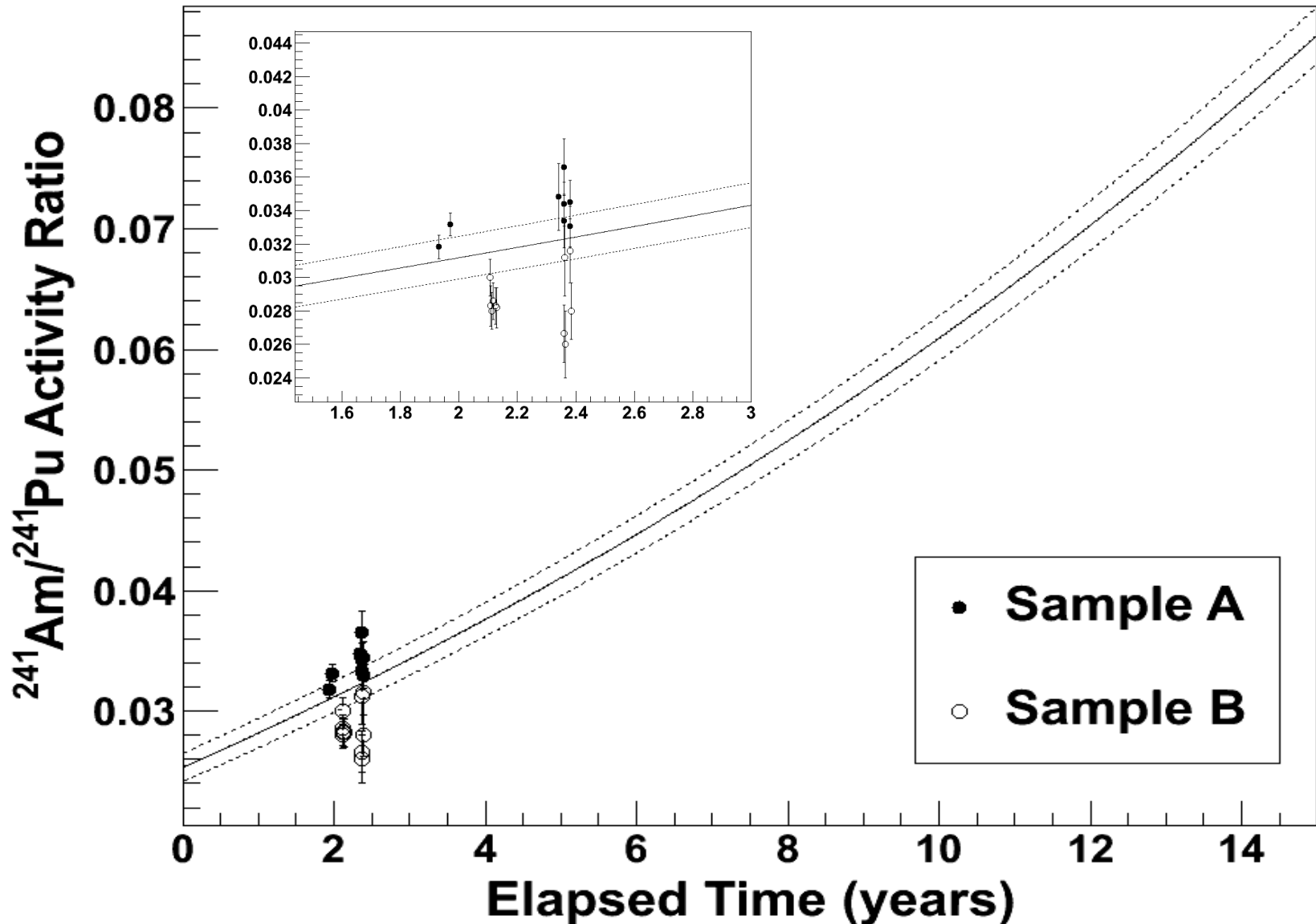
$$N(T) = CF(T)S(T)\sqrt{(T^2 + 2Tm)}(Q - T)^2(T + m)$$

- For ^{241}Am Q-value, just add up counts in the region of interest

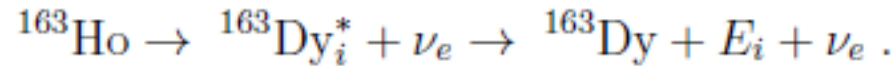


$^{241}\text{Am}/^{241}\text{Pu}$ Analysis

Measurements from 2 samples with known composition



^{163}Ho Electron Capture Spectroscopy (m_ν)



- ECS involves the emission a series of X-ray lines by the daughter atom. Each X-ray line is of energy $Q - E_i$, where Q is the mass difference of the two atoms in their ground states and E_i is the binding energy of the electron hole in the final atom. For Holmium the endpoint is only known to be between 2.2 and 2.8 keV.
- ~ 1 eV spectral resolution needed

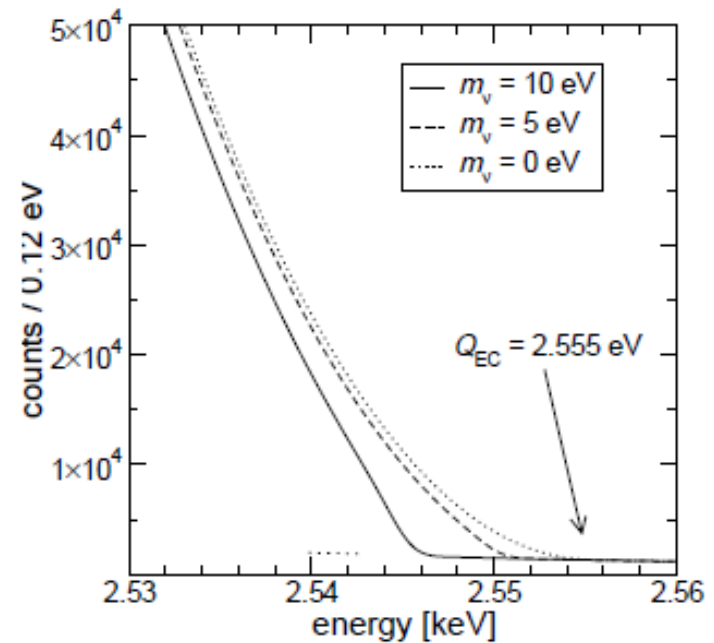
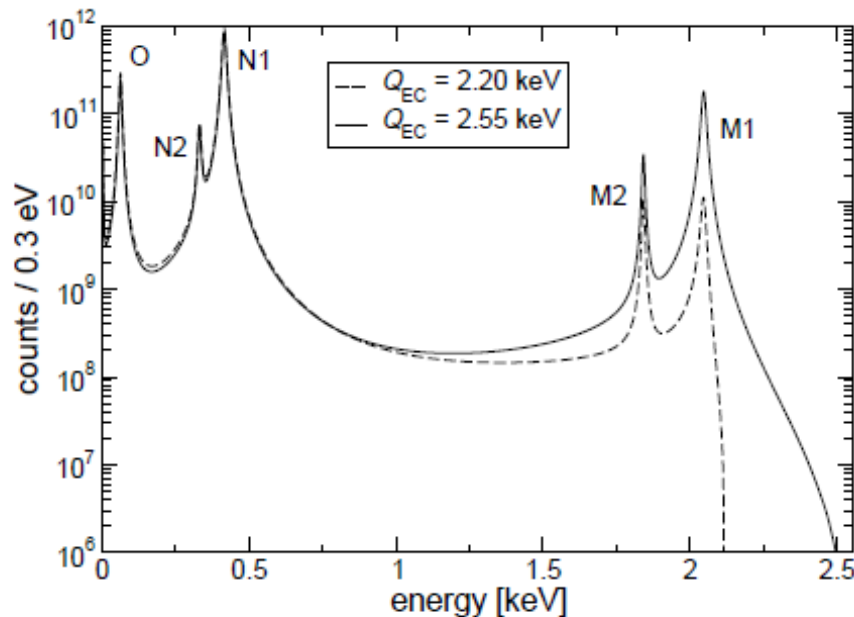
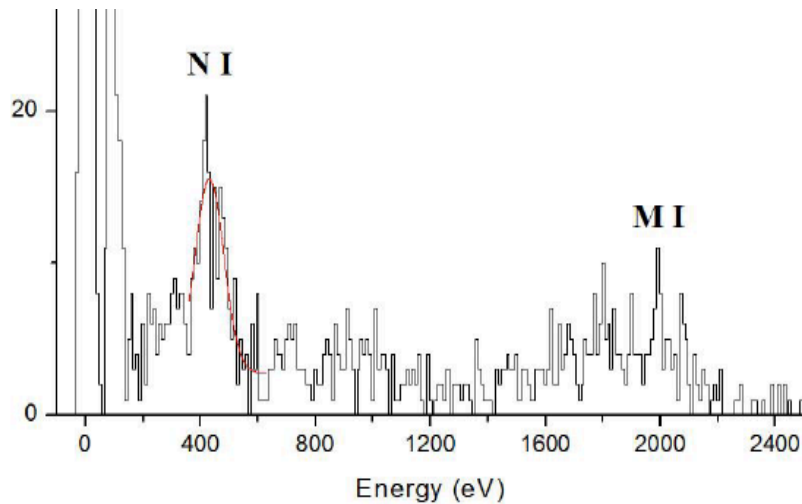
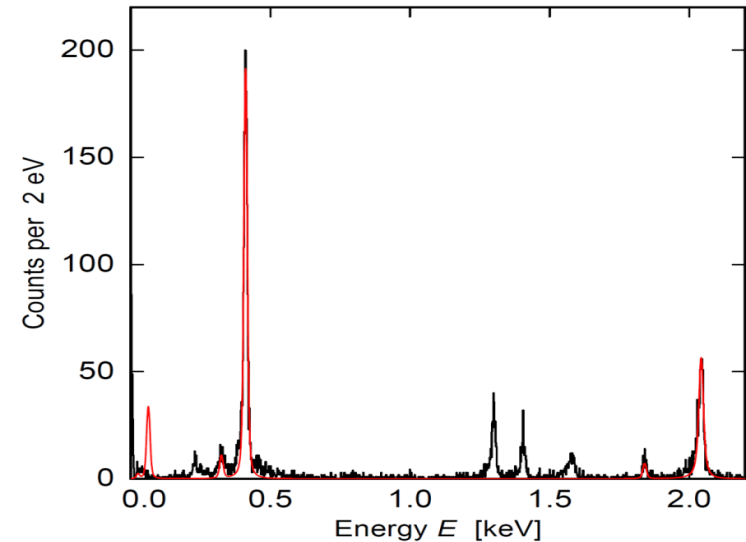


Figure 2: ^{163}Ho total absorption spectrum calculated for an energy resolution $\Delta E_{\text{FWHM}} = 2$ eV and a pile-up fraction $f_{pp} = 10^{-6}$.

MARE and ECHO



MARE (Rhenium) [Gatti 2011, Genoa, unpublished] After an experimental decade: low statistics, poor resolution



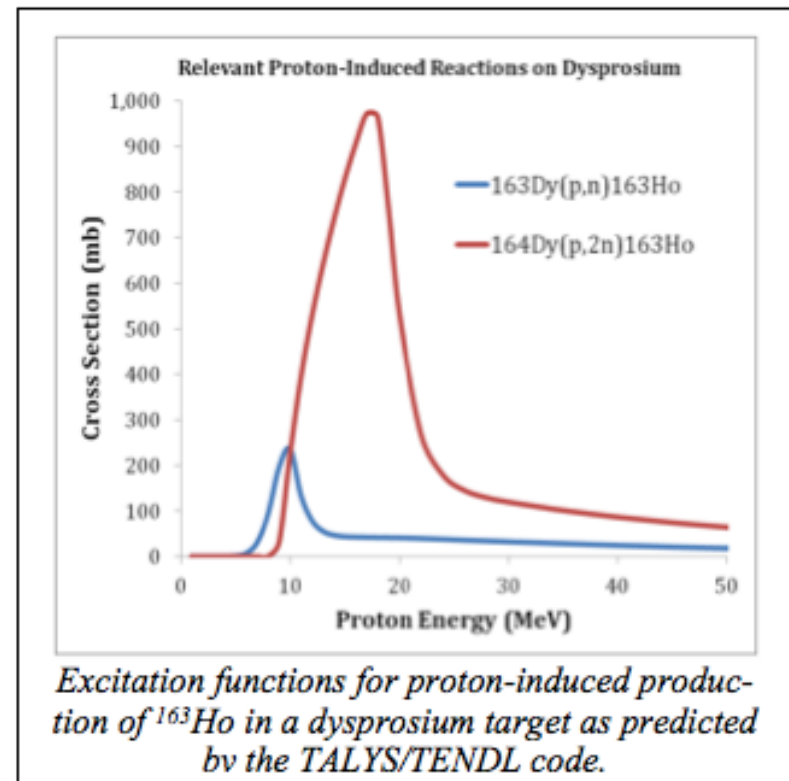
ECHO [Rantizsch 2011, Hiedelberg, JLT 2011] 12 eV resolution, no array readout

LANL advantages

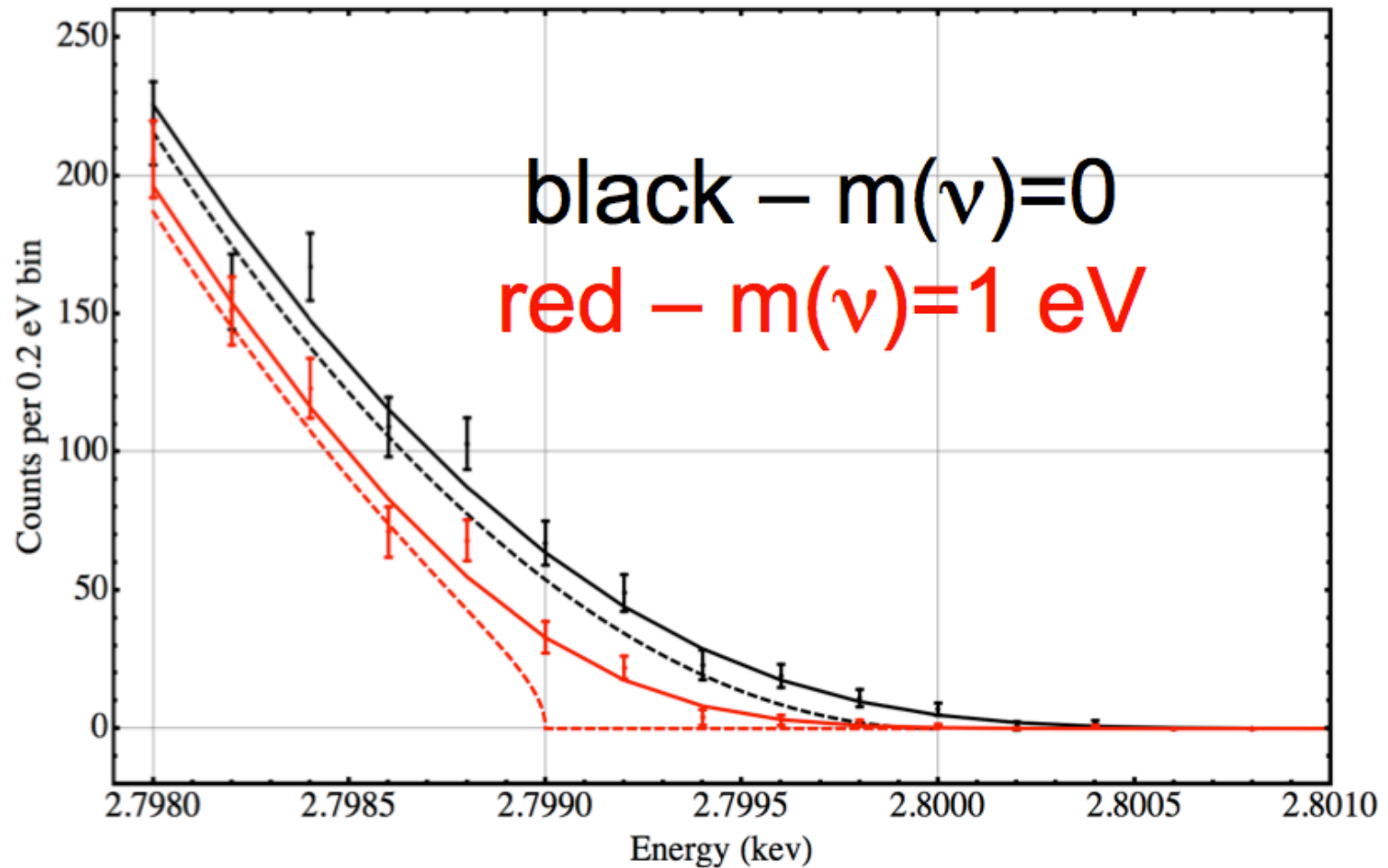
- Good isotope production method for ^{163}Ho
- Demonstrated high-resolution X, γ , α , and Q detectors
- World's largest microcalorimeter γ -ray array (256 pixels)
- Demonstrated radionuclide encapsulation with high resolution ($\sim 1\text{-}2$ keV at 5 MeV)

^{163}Ho

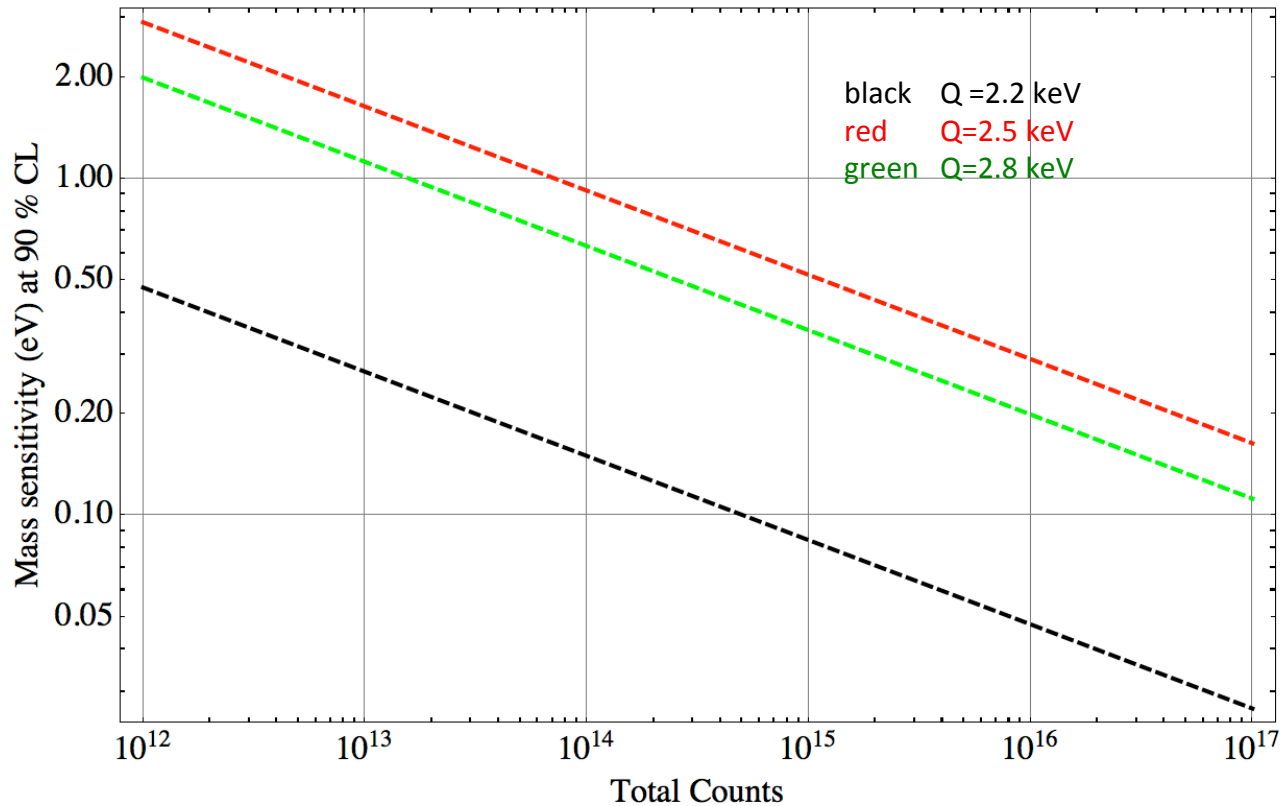
- Low Q-value (more sensitive to neutrino mass) and high activity
- The LANL Isotope Production Facility (IPF) can be used to produce ^{163}Ho via the $^{164}\text{Dy}(p,2n)^{163}\text{Ho}$ reaction
- Dy target with 30 hours irradiation expected to produce $\sim 10^{17}$ atoms of ^{163}Ho (30 μg , $\sim 10^5$ Bq)
- Recovery of the radio-holmium in TA-48 hot cell facility from the target material matrix by means of radio chemical separation procedures (column separation)



Predicted Spectrum Endpoint



Predicted mass sensitivity



Crucially dependent on Q, energy resolution, activity per pixel, number of pixels, experiment duration

Detectors for ECS

- 8-channel chip for scalability to large channel-count
- 9 eV resolution with ^{55}Fe source, working to improve

