Cryogenic High-Resolution X-Ray Spectrometer Development

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Cryogenic Detector Development at LLNL

Advanced Detector Group
Bill Craig, Group Leader

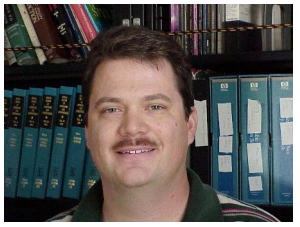
Cryogenic Detector Group
Stephan Friedrich

Radiation Detection Center
Simon Labov, Director

Microcalorimeters (TES) | Tunnel Junctions (STJ)







X-ray Detectors	Gamma Detectors	Neutron Detectors	X-ray Detectors
(S. Terracol)	(T. □Miyazaki)	(T. Niedermayr, D. Hau)	(S. Friedrich, O.Drury)
X-ray Astronomy (NASA) Atomic (ion) physics Prof. Briand, U Paris	Nucl. Non-proliferation (DOE NA-22) Prof. Freeman, UCD Dr. Vogt, IAEA	Nuclear Physics (DOE NA-22) Prof. Vujic, UC Berkeley Astrophysics Dr. Wang, LLNL	Biophysics (NIH-GM, DOE-OBER) Prof. Cramer, UC Davis Material Science (NSF-MRI) Prof. Opila, U □Delaware Prof. Harris, Stanford

Outline: Why Cryogenic Detectors?

- Why low T? → Low thermal noise, Small excitation energies → High energy resolution

- Which technologies?

	Tunnel Junctions	Microcalorimeters
Operating Principle	E → ΔQ	E → ΔT
Resolution (0.1 to 6 keV)	2 - 12 eV FWHM	2 - 5 eV FWHM
Max. count rate	~10,000 cts/s	~500 cts/s

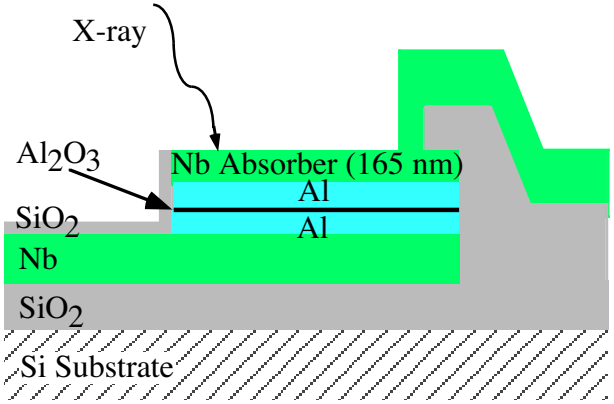
Both detectors have small pixel sizes $(\sim 0.2\ \mathrm{mm})^2$ and are operated around 0.1 K.

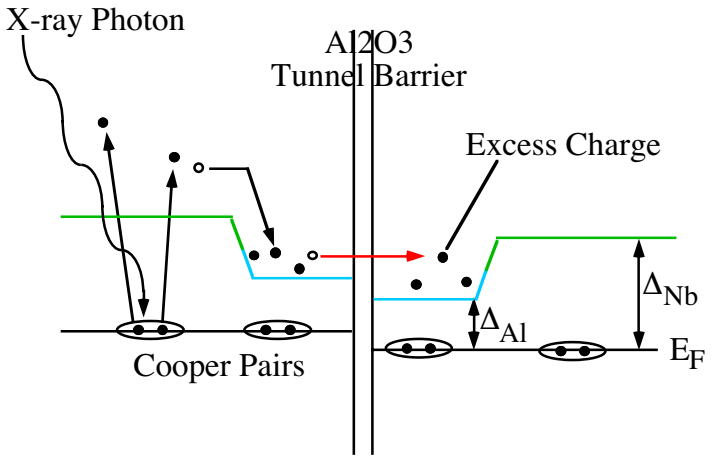
- What for?

Fluorescence-detected absorption spectroscopy of dilute samples

Superconducting Detector Technologies

Tunnel Junctions (STJ)

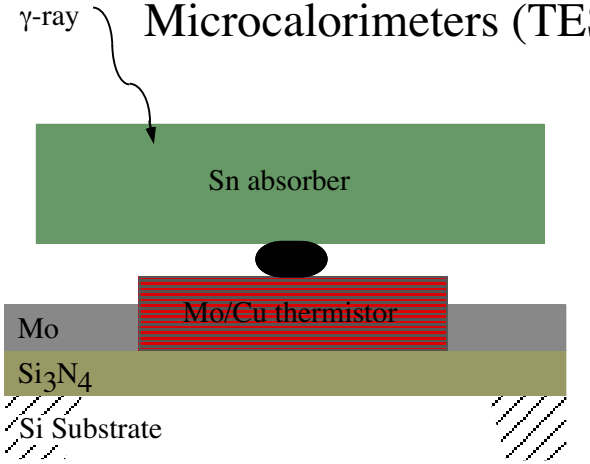


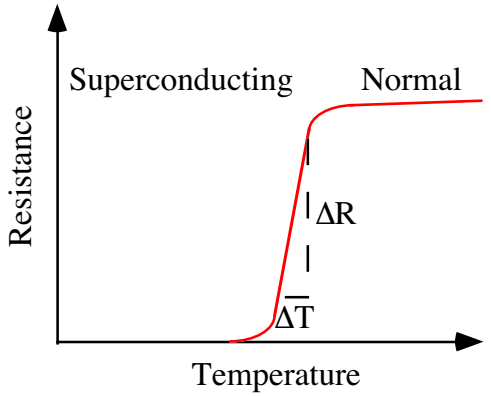


Signal = Current Pulse

High resolution, faster

Microcalorimeters (TES)

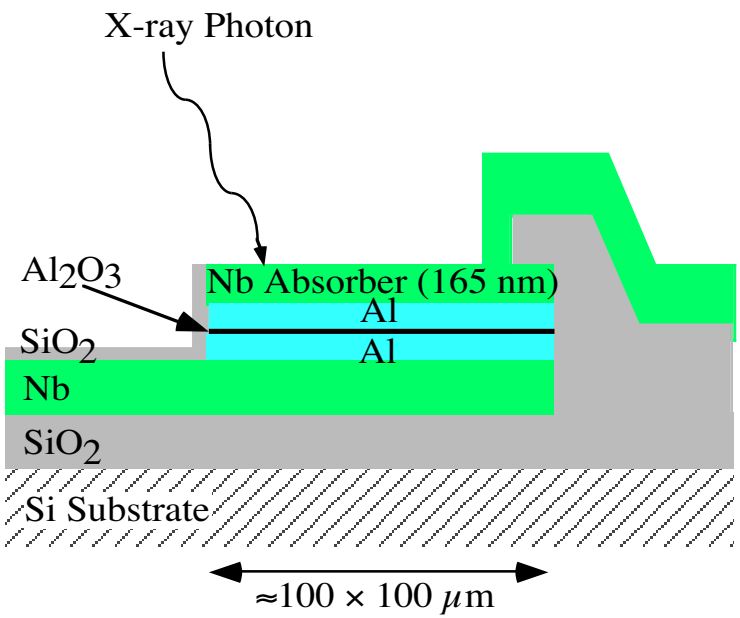


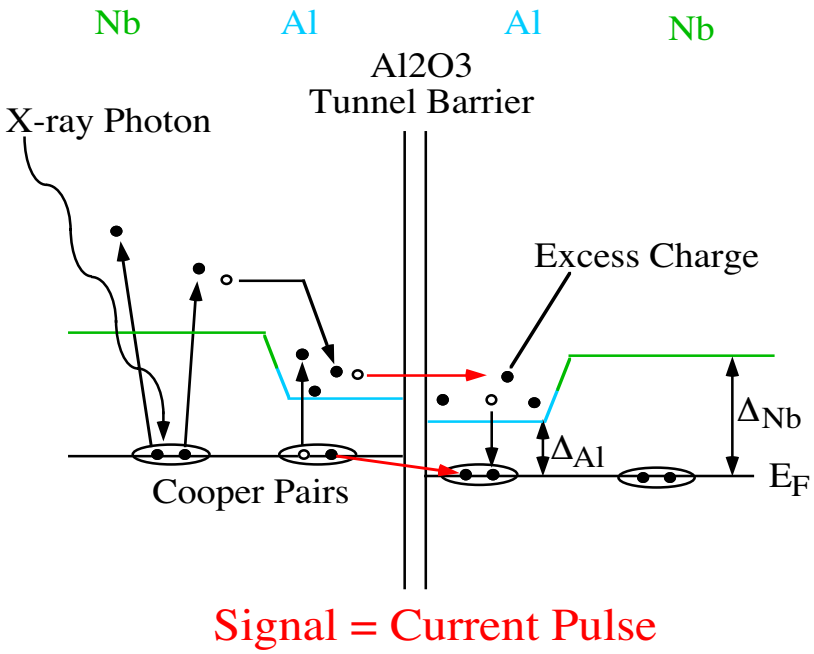


Signal = Resistance Change

Highest resolution, slower

Superconducting Tunnel Junction Detectors





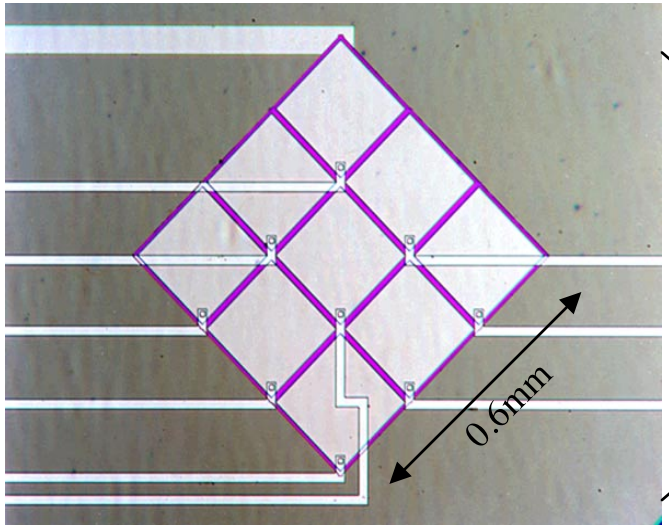
Signal = Current Pulse

$$\Delta E_{FWHM} = 2.355\sqrt{(\varepsilon E(F+1+1/<n>)}$$

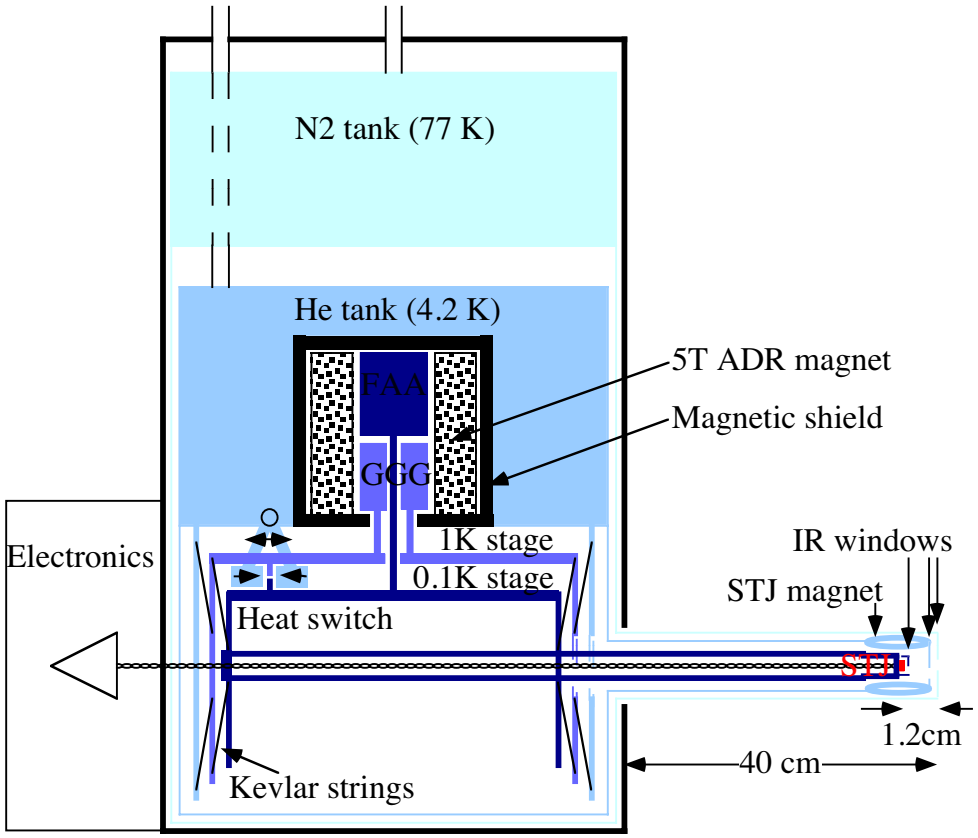
Small energy gap ($\Delta \approx 1$meV) ⇒High energy resolution (≈10 eV FWHM)
Short excess charge life time (μs) ⇒ (Comparably) high count rate (≈10,000 counts/s)

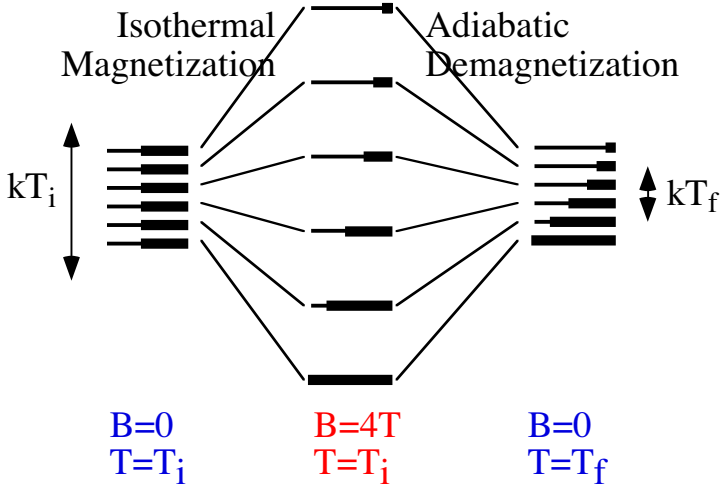
Two-Stage ADR with Cold Finger

- 70 mK base T, 20h below 0.4K
- 3×3 array at ≈15mm ⇒ $\Omega/4\pi \approx 10^{-4}$
- ≈15eV FWHM, >100,000 cts/s max



Adiabatic Demagnetization Refrigeration





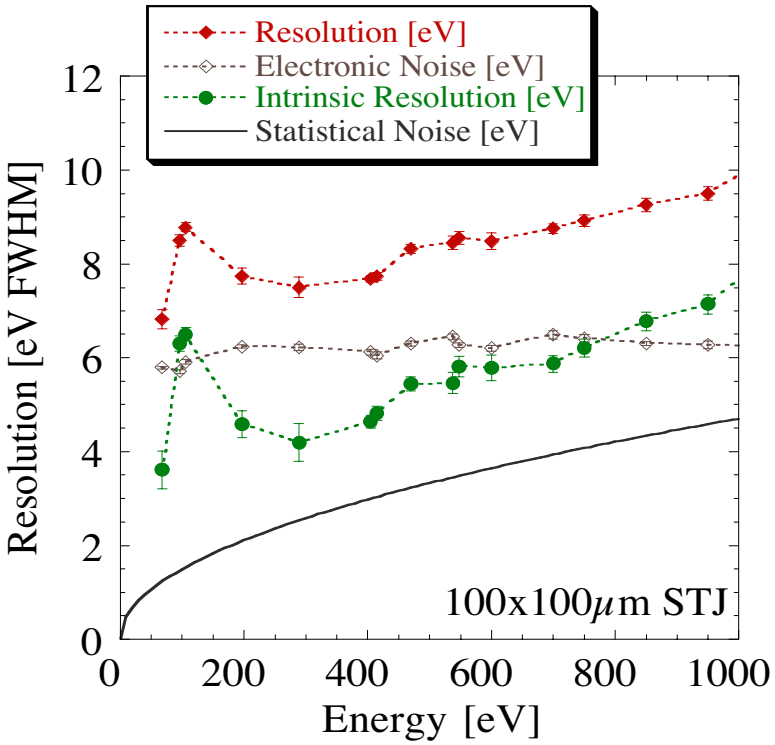
1) Close heat switch

2) Apply B (lower entropy S)

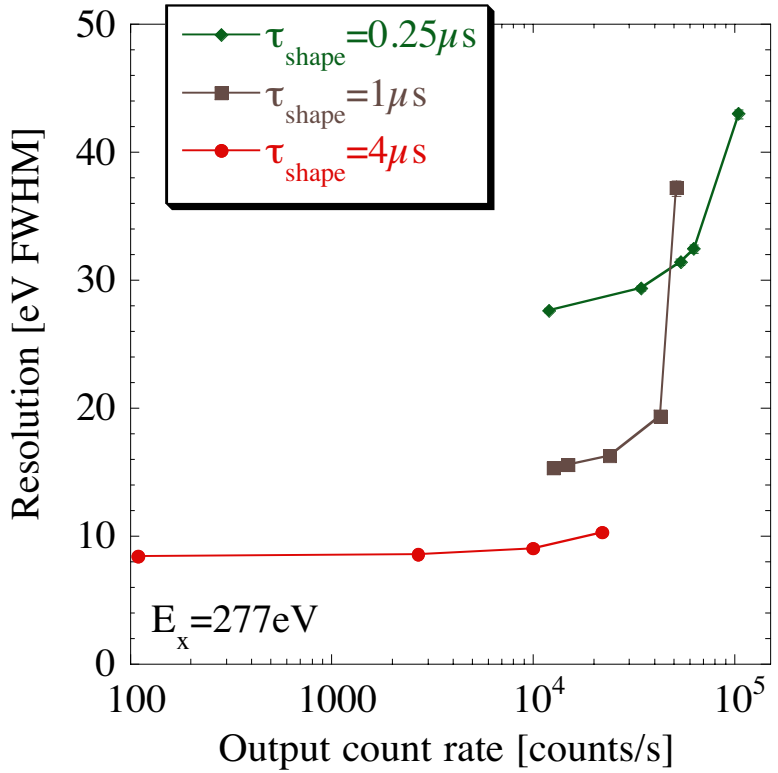
3) Open heat switch (decouple T)

4) Reduce B slowly (keeping entropy constant ⇒ reduce T)

STJ Detector Performance

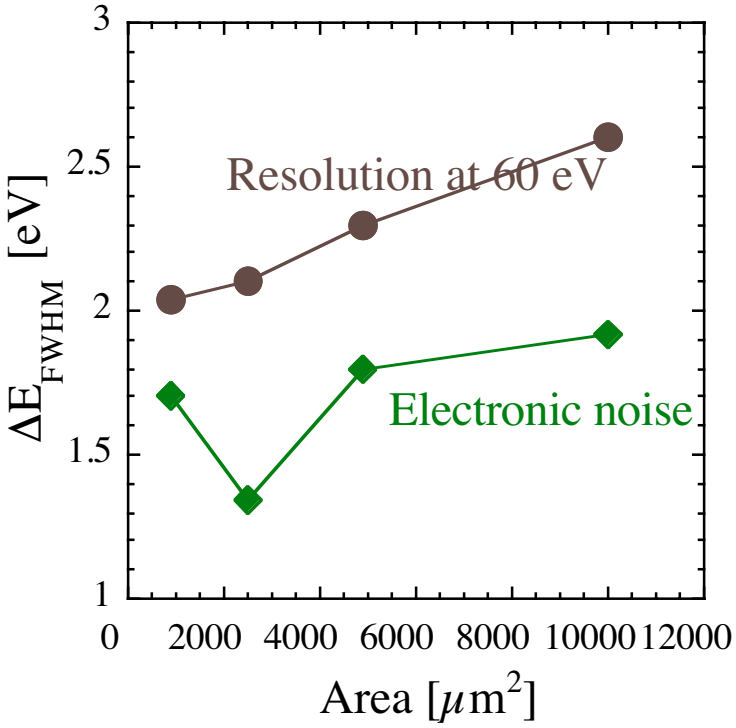


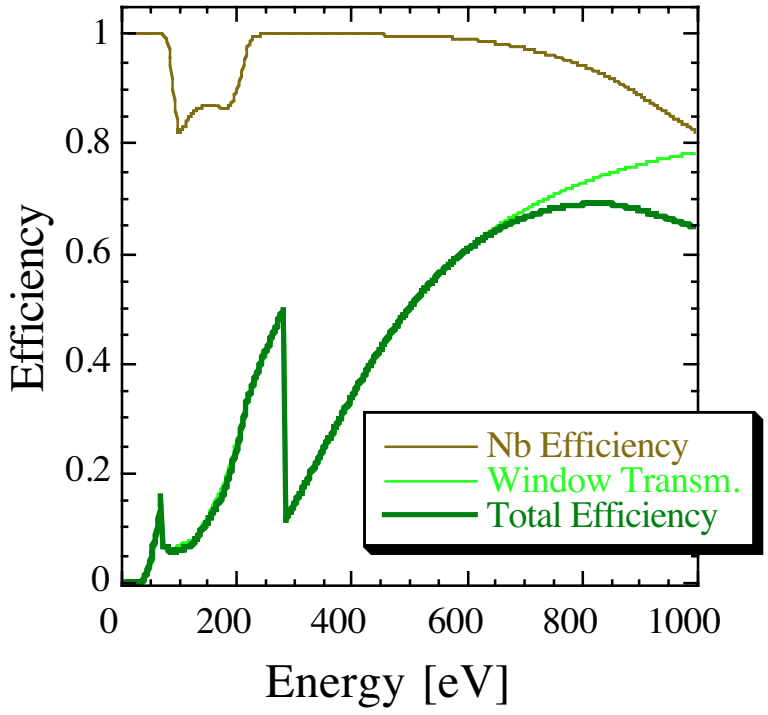
≤10eV resolution below 1keV



≥10,000 counts/s throughput

STJ Detector Performance





Trade-off between area and resolution

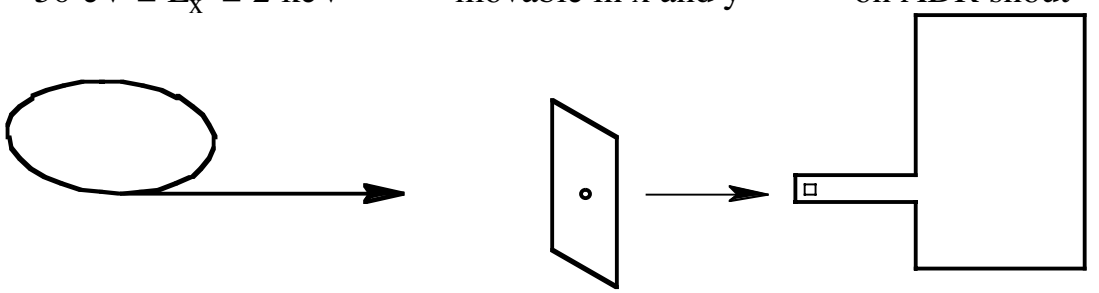
Trade-off between efficiency and resolution

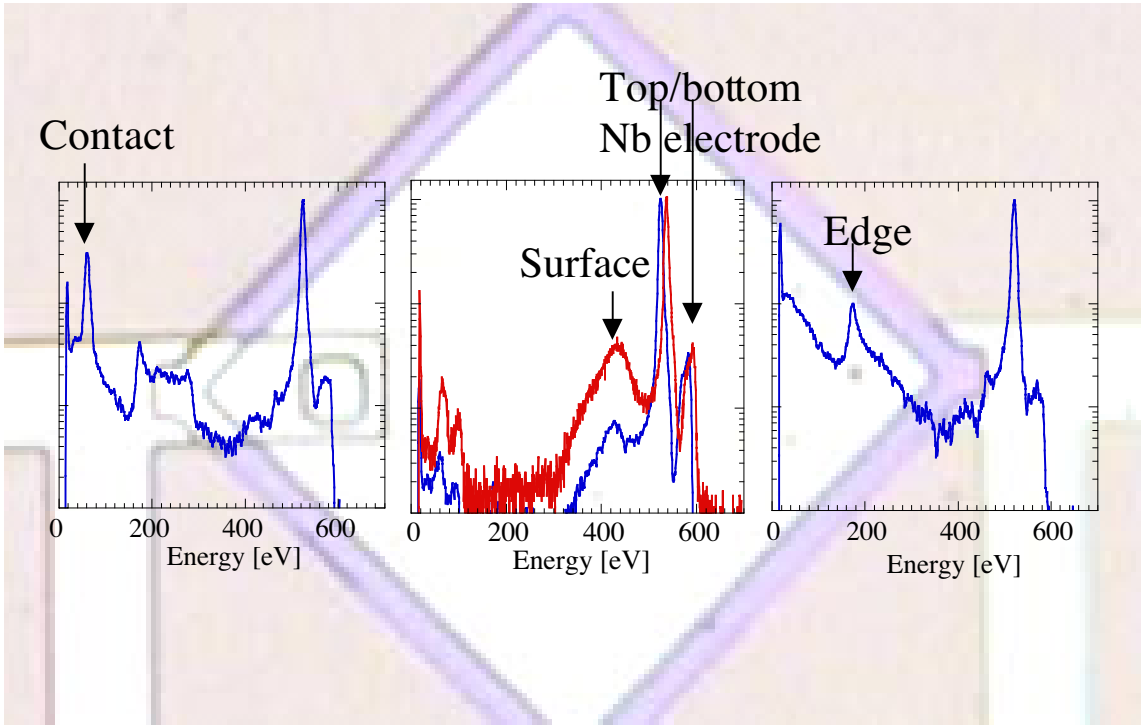
Lineshapes

Synchrotron beam
50 eV ≤ E_x ≤ 2 keV

Aperture
movable in x and y

STJ Detector
on ADR snout

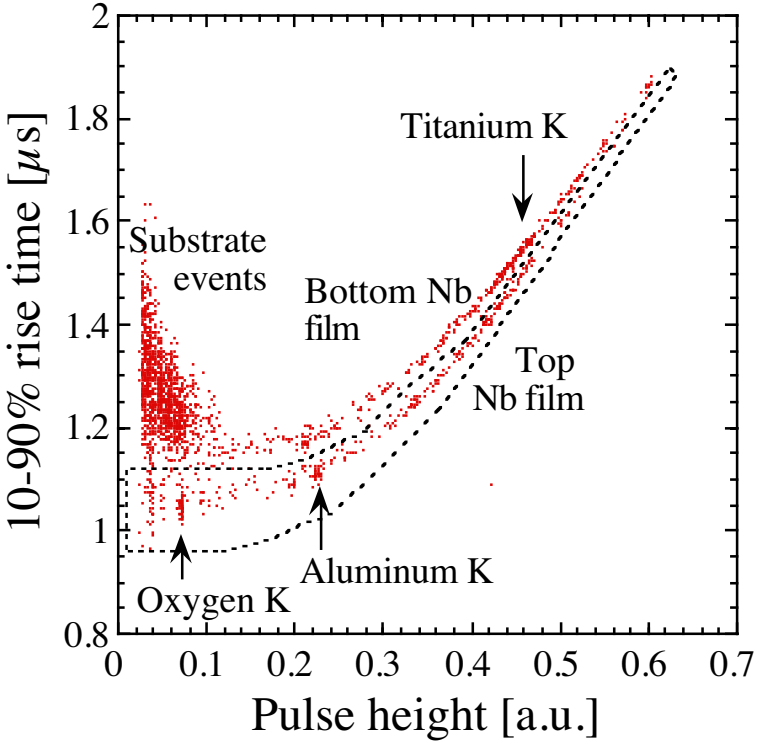




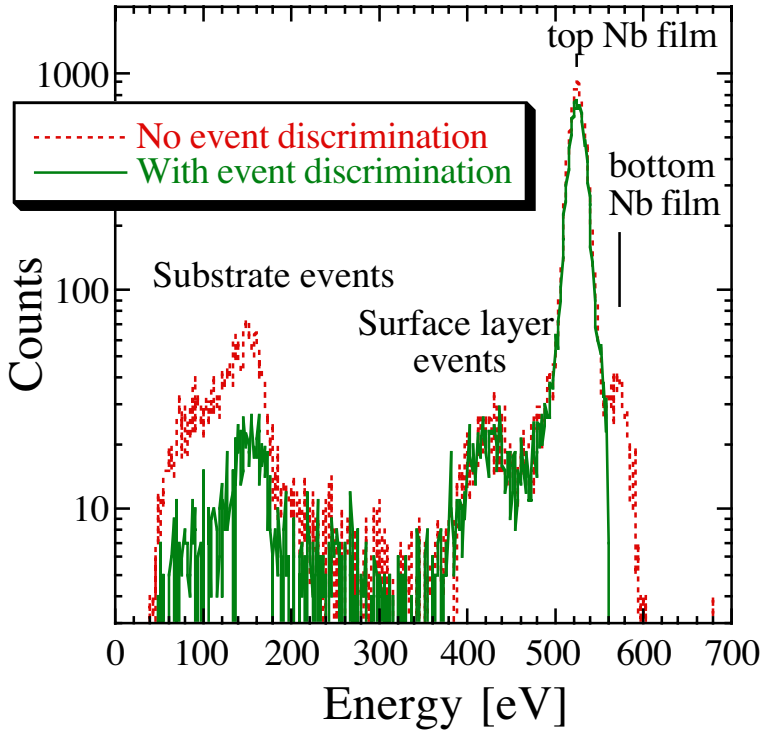
Artifacts can be greatly suppressed with apertures.

⇒ Peak/Backgnd ≈ 1000

Digital Signal Processing



Rise time differences between top and bottom electrode and substrate



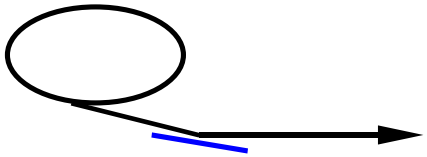
On-line event discrimination at 5000 cts/s to reduce artifacts

Digital signal processors courtesy of X-Ray Instrumentation Associates, www.xia.com

X-ray Absorption Spectroscopy

Synchrotron beam

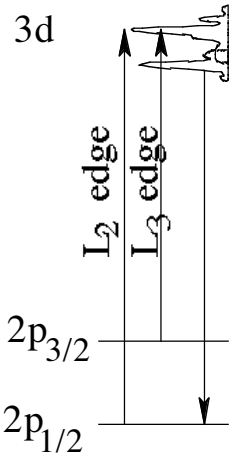
Intense, monochromatic, tunable
$I_0 \approx 10^{12}$ photons/s
$\Delta E = 0.1$eV



Monochromator

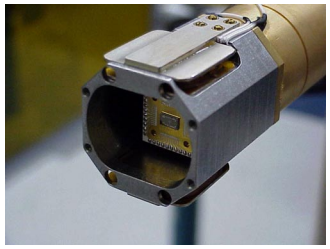
Sample x

Absorption $\mu_x(E)$



Detection

3) Fluorescence $\propto I_0 \cdot \mu_x$ (E)



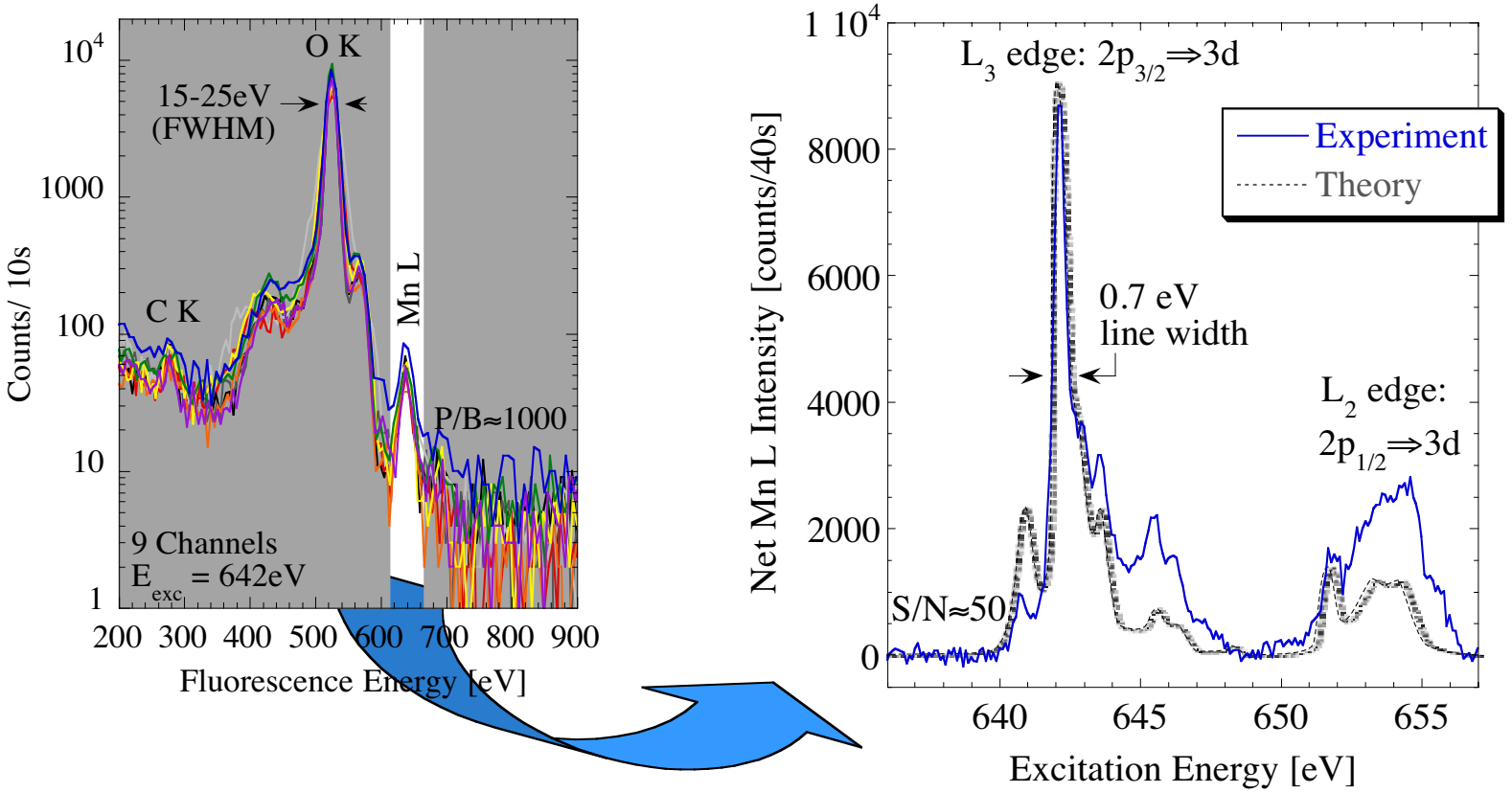
Photons
(Fluorescence)

1) Transmission $\propto I_0 (1-\mu_x-\mu_{bgnd})$
Thin samples
High background

Electrons
(Auger, photoelectrons)

2) Electron signal $\propto I_0 \cdot \mu_x$ (E)
Surface sensitive
Moderate background

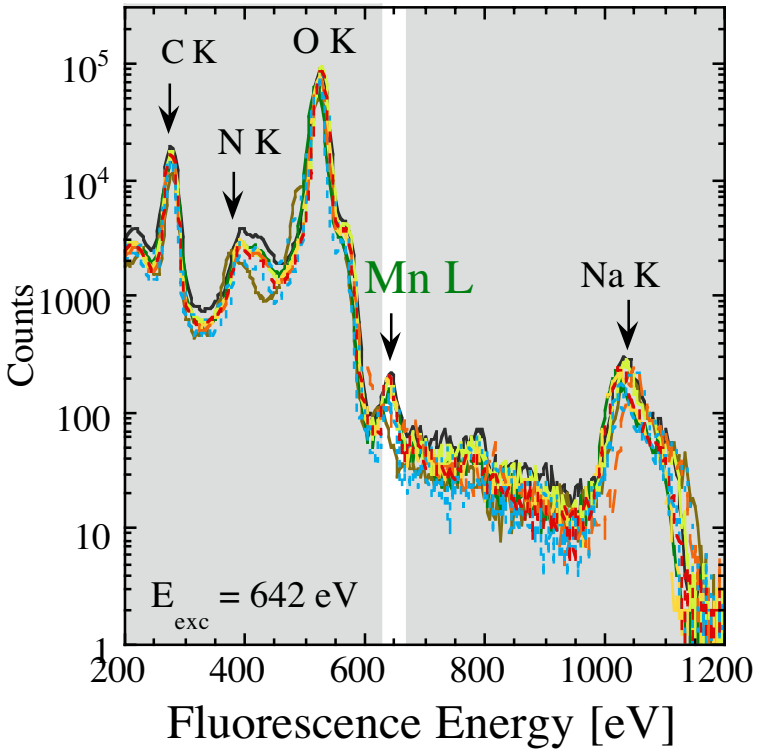
Absorption Spectroscopy on 840ppm Mn in MgO

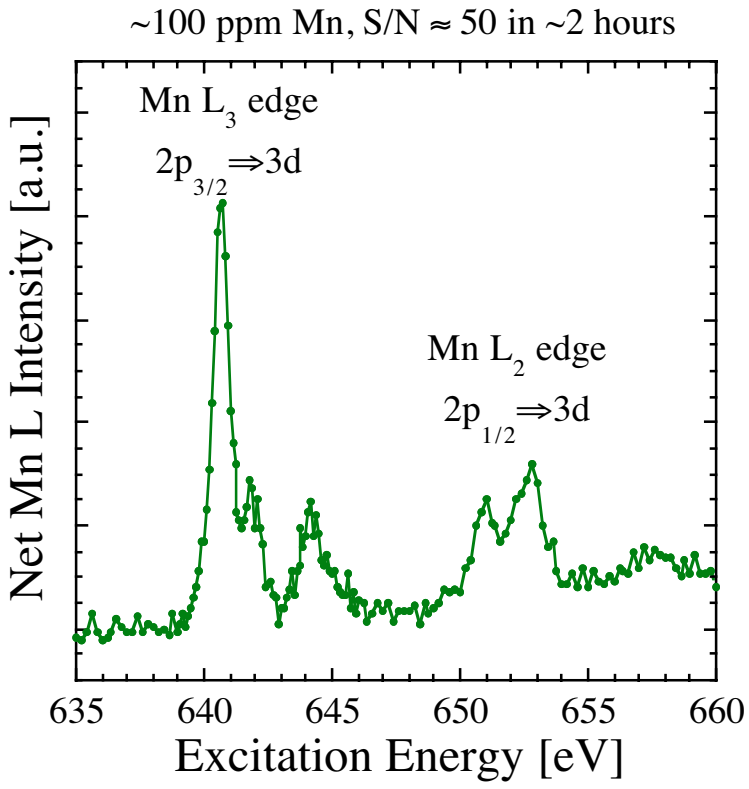


Mn L fluorescence intensity ∝
Absorption by Mn ∝
Mn 3d vacancies

Multiplet Simulations:
Fine structure indicative of Mn^{2+}
in cubic crystal field 10Dq≈1.4eV

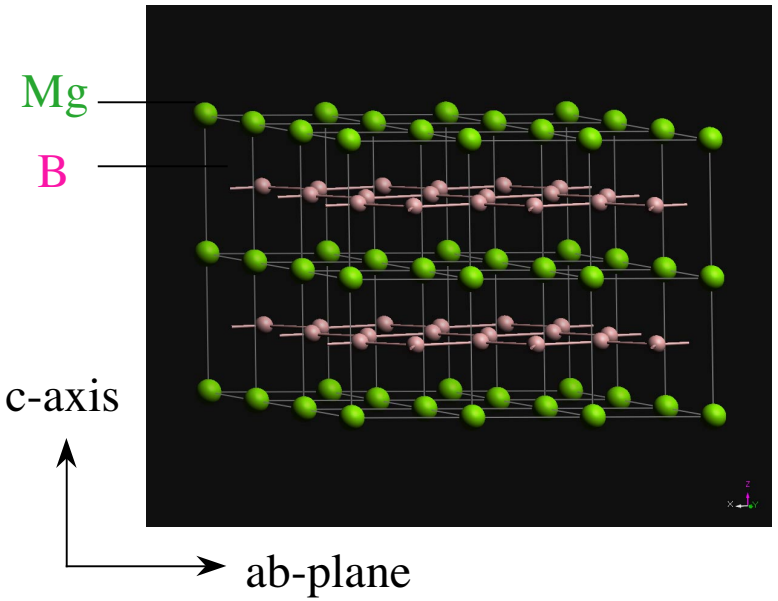
X-Ray Absorption Spectroscopy on Proteins

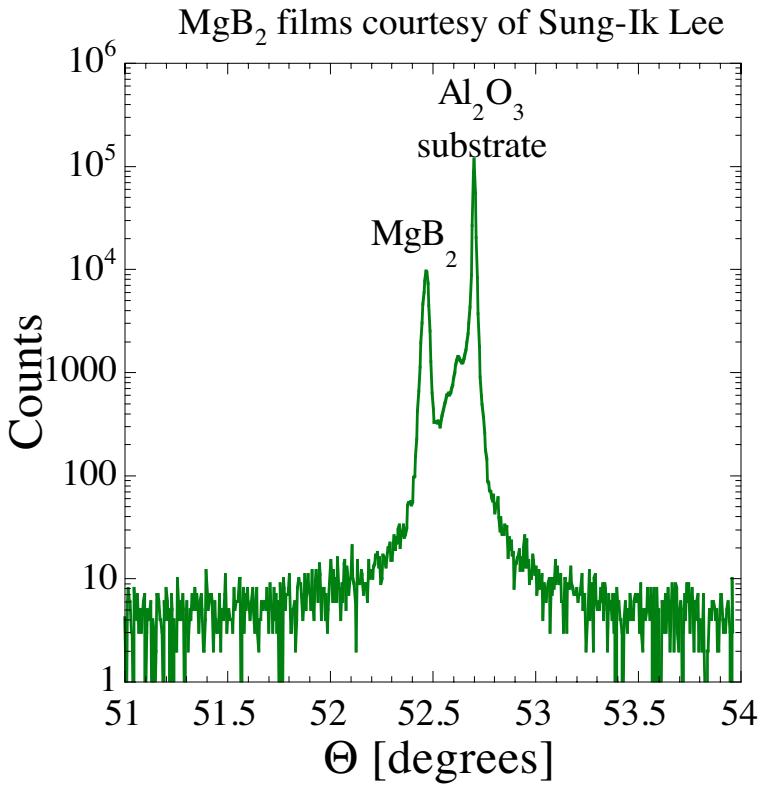




Spectrometer sensitivity is sufficient for ~100 ppm samples

MgB_2: Is the superconductivity anisotropic?

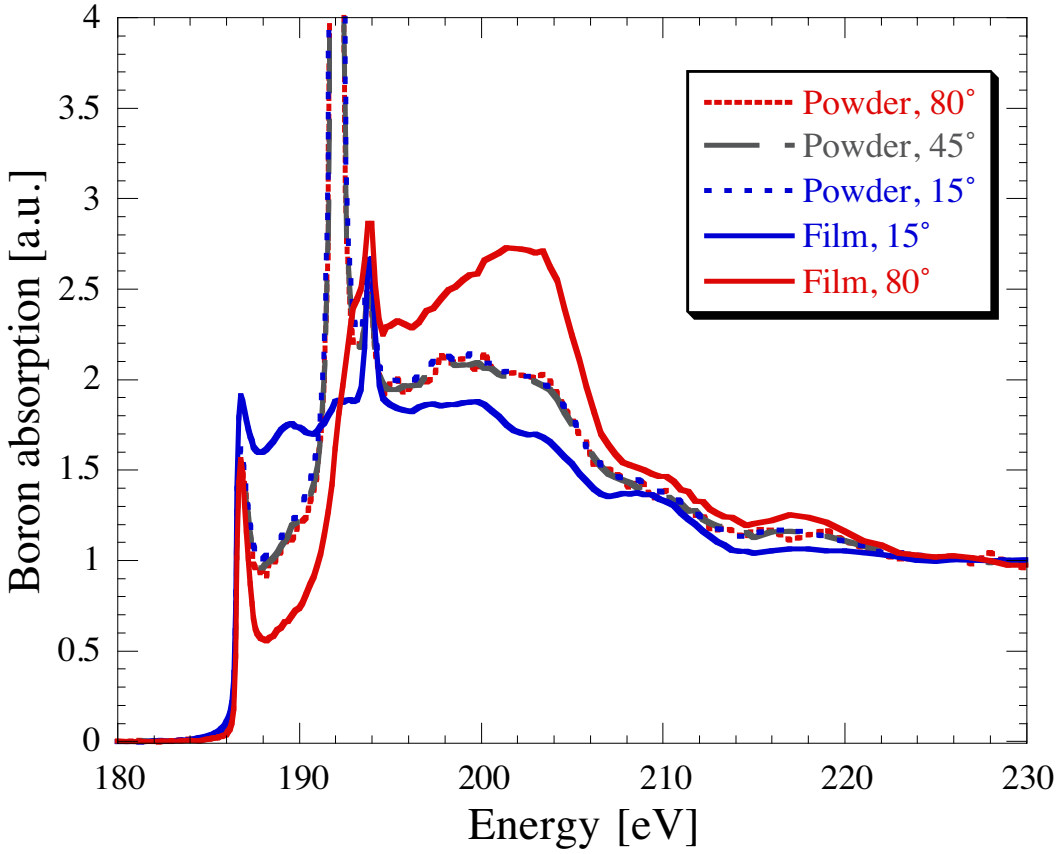




Mg donates ~2 electrons to the B sheets ⇒ $2p^3$ configuration
Hybridized sp_2 levels are half-filled ⇒ Fermi level

	Bulk	Thin Film
Al_2O_3	3.481 Å	3.481 Å
MgB_2	3.522 Å	3.496 Å

Angle dependence: MgB_2 film vs powder

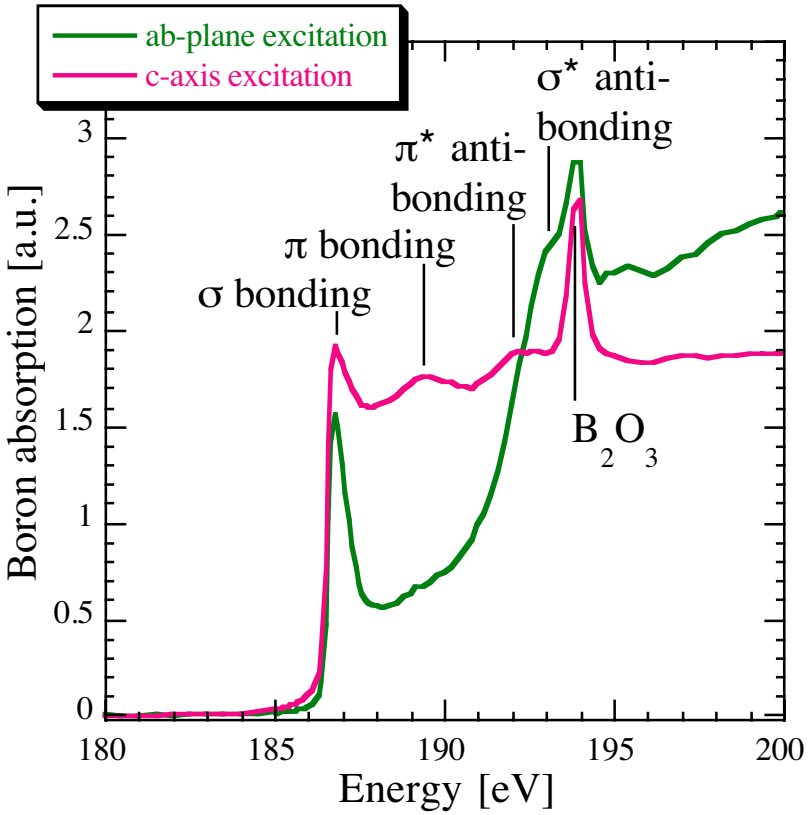


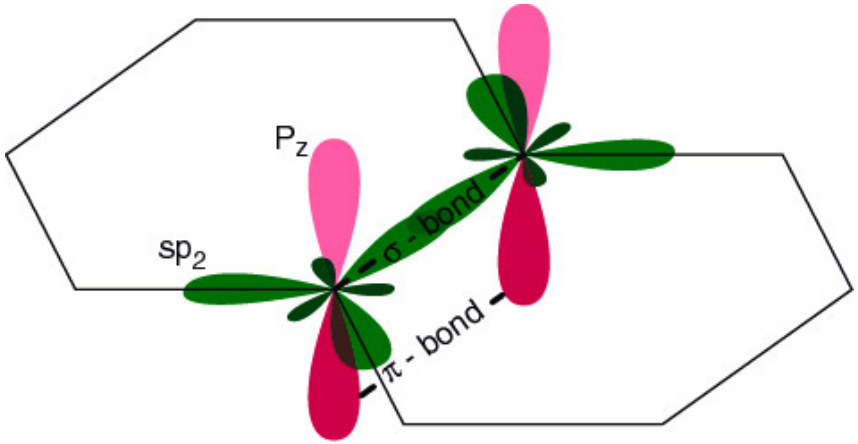
The angle of the horizontally polarized incident beam is measured relative to the sample surface, i.e. 80° means in-plane excitation.

The peak at 192 eV is due to an excitonic resonance. The peak at 194 eV is due to B2O3 at the surface.

The epitaxial MgB_2 film does show anisotropic absorption. The powdered MgB_2 sample does not, as expected.

In-plane vs. out-of-plane excitation





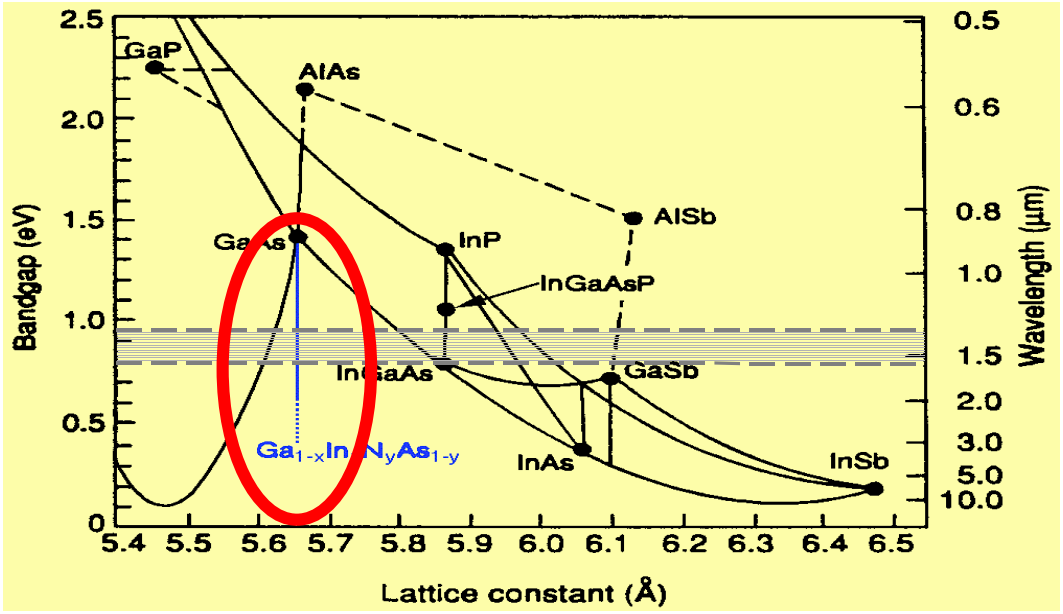
ab-plane: $p_x, p_y \Rightarrow sp_2$ hybridized
σ bonds, hexagonal

c-axis: $p_z \Rightarrow \pi$ bonds

The anisotropic electronic structure in MgB_2 is due to sp_2-hybridization.
Electronic density of states at E_{Fermi} is comparable in ab-plane and along c-axis.

GaInNAs: A material for 1.3-1.55μm lasers

Collaboration with V. Lordi from Prof. Harris' group at Stanford



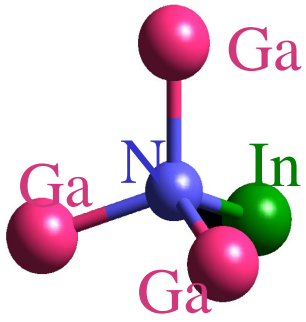
Telecommunications Application

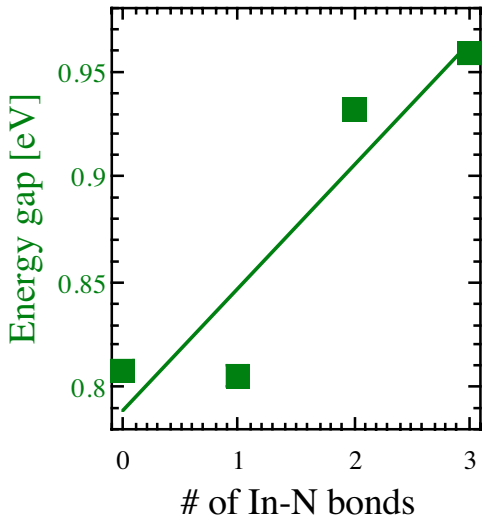
- $Ga_xIn_{1-x}N_yAs_{1-y}$ ($x \approx 0.70$, $y \approx 0.03$) has a bandgap of ~1.3 - 1.55 μm
- It is nearly lattice-matched to GaAs
- Fabrication of inexpensive surface-emitting lasers for optoelectronics
- Optical fibers best at ~1.3 - 1.55μm

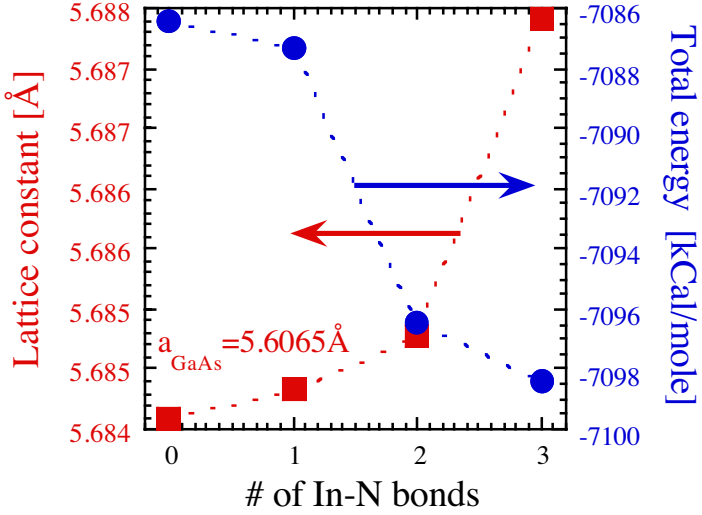
Anneal GaInNAs to increase luminescence.

Problem: Band gap increases upon annealing

Nitrogen nearest neighbors affect optical properties







- MBE, ~2% nitrogen
- III-V random alloy
- FCC lattice

- Anneal at 780 ˚C, 1min

⇒ Luminescence increases

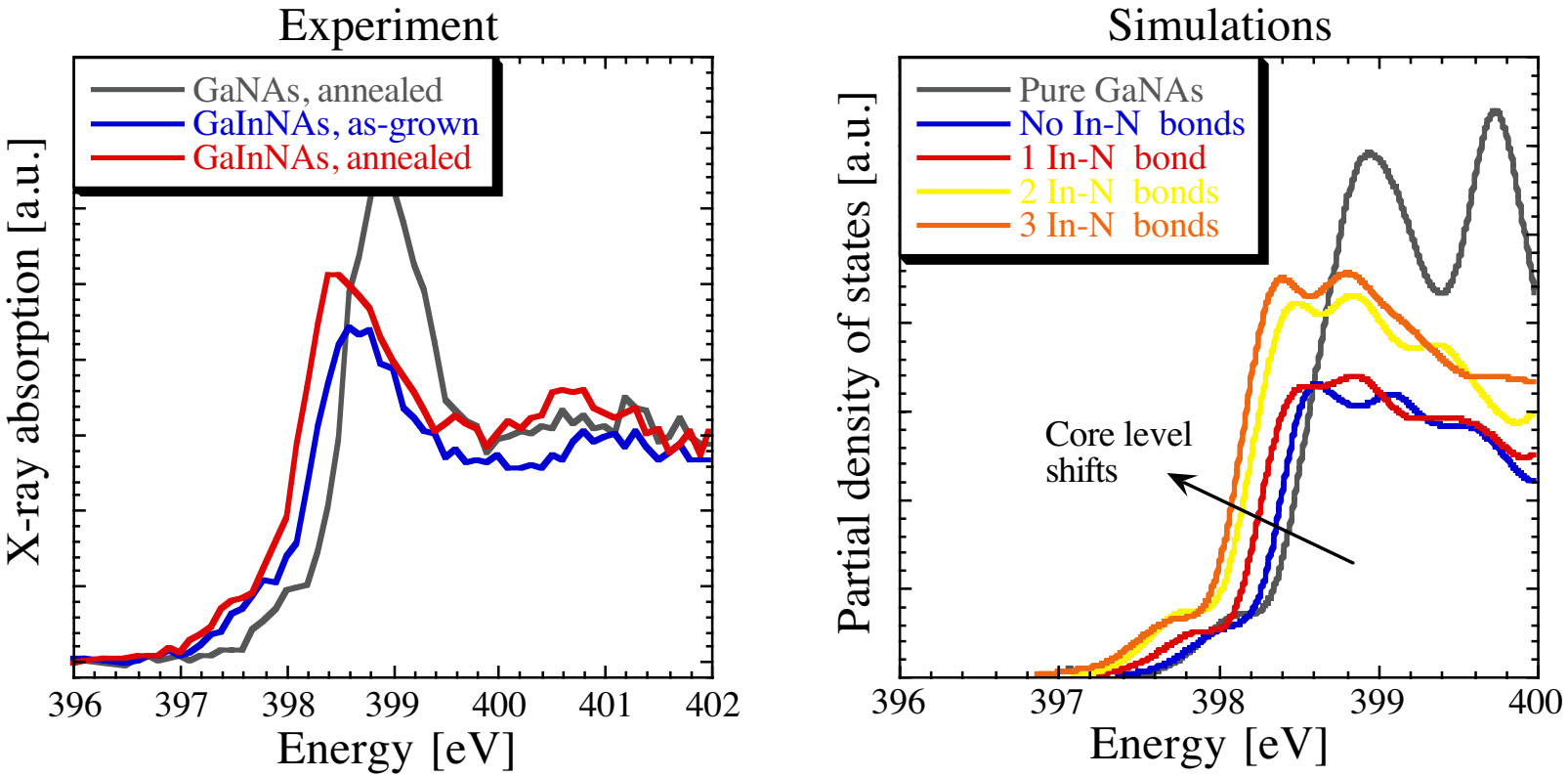
⇒ Bandgap increases

- Energy gap increases with # of In-N bonds

- Strain favors decreasing # of In-N bonds

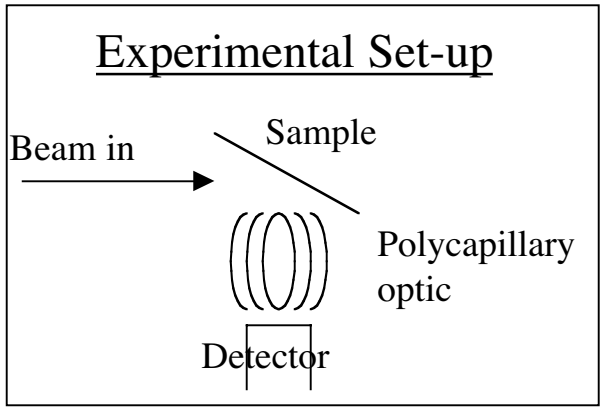
- Thermodynamics favors increasing # of In-N bonds

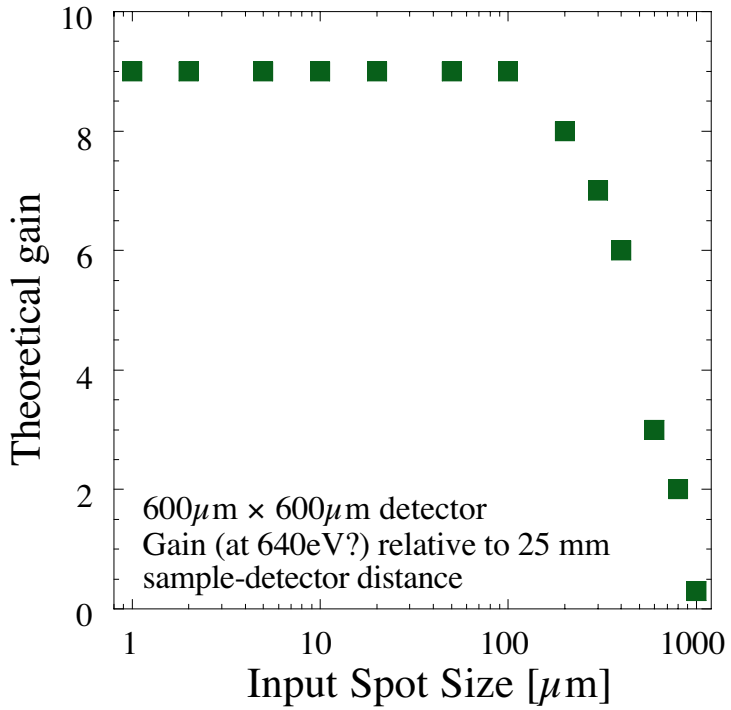
Nitrogen X-ray absorption fine structure



Absorption edge shifts show increasing number of N-In bonds
Nitrogen migrates towards Indium upon annealing

Current Work: Enhance Sensitivity

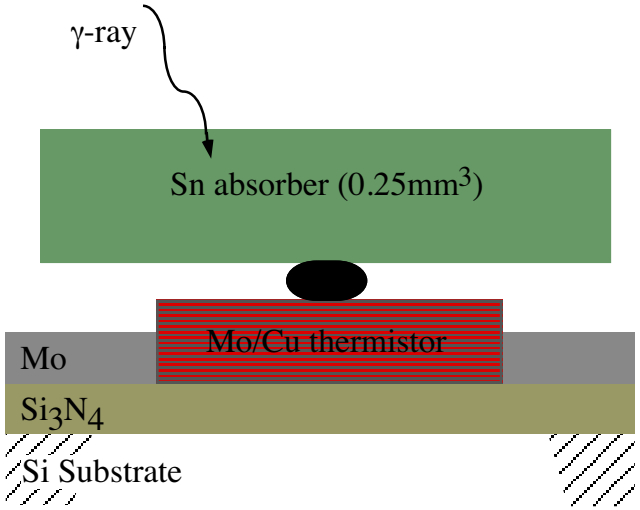




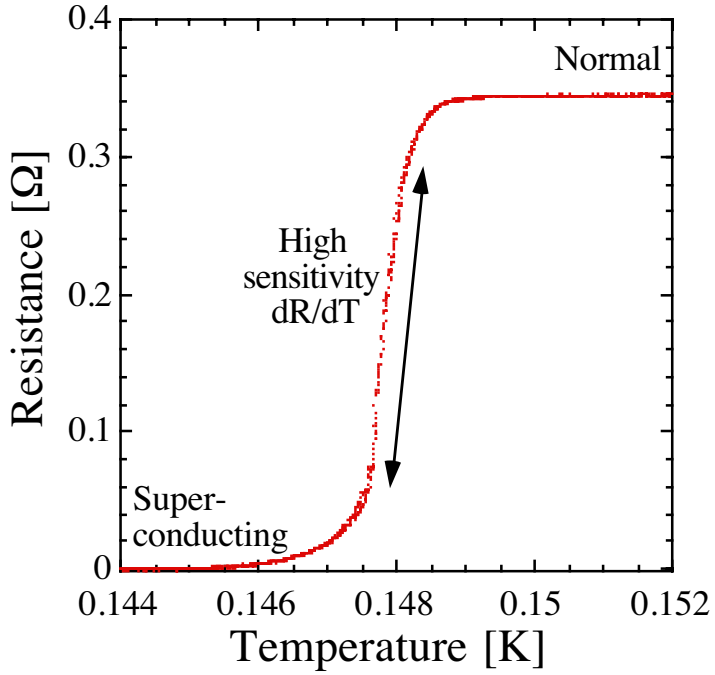
Spectrometer Development:

- Polycapillary Optic (courtesy XOS)
- Larger Arrays

Microcalorimeters



Energy resolution $\Delta E_{FWHM} = 2.355\sqrt{k_B T^2 C}$



Ultra-high energy resolution thermal detectors require low operating temperature T and small volumes for low heat capacity C

Microcalorimeter Fabrication

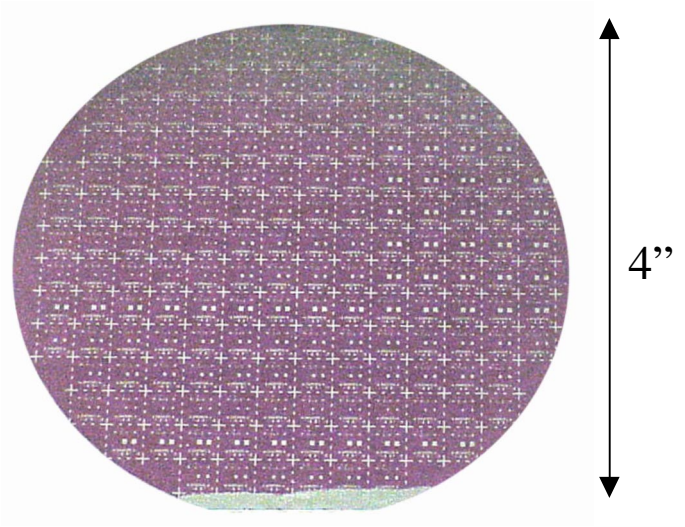
The Mo-Cu sensors are fabricated using photolithography like computer chips. Hundreds of identical devices are produced simultaneously on 4” wafers.

Mo/Cu thermal sensor:

- Fabricated at LLNL
- Stable, reproducible full-wafer process
- Flexible attached-absorber design

Application-specific absorbers:

- γ-rays: Sn crystal
- Neutrons: MgB_2, LiF crystal (so far)
- X-rays: Au film

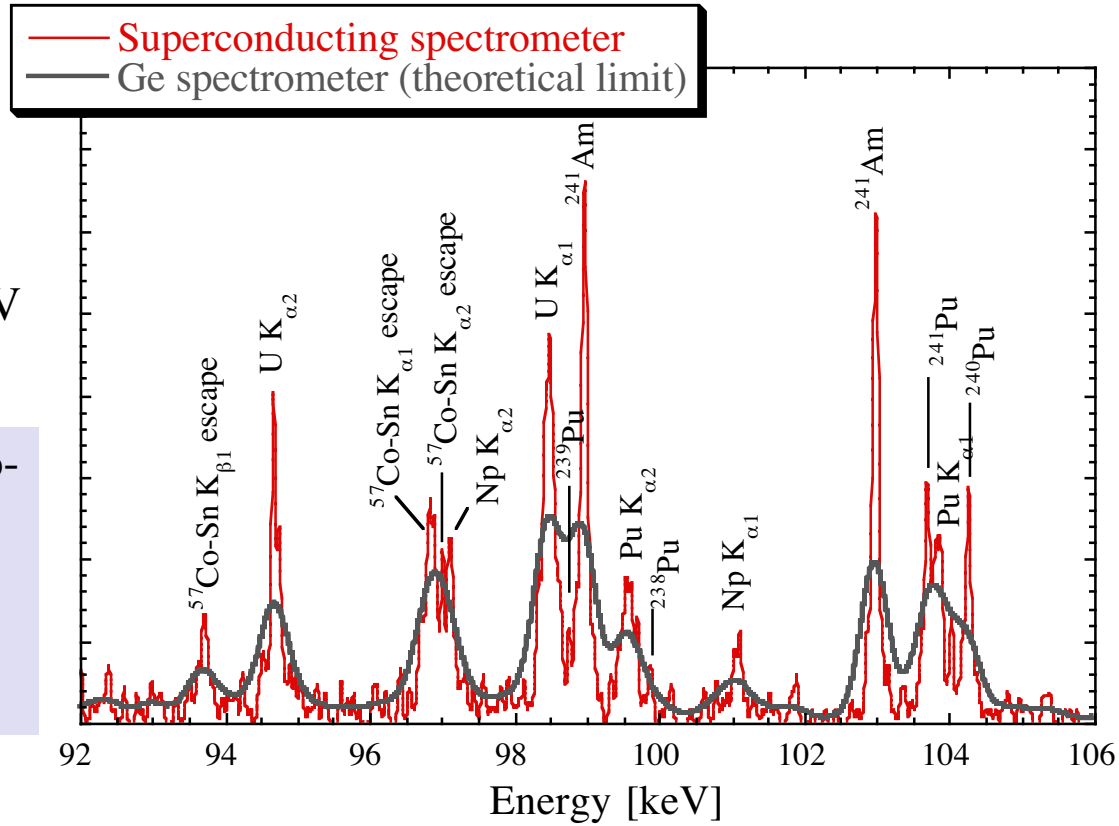


Gamma Ray Spectrometry

First measurements of SNM: Pu mixed isotope sample

$\Delta E_{FWHM} \approx$ 60-90eV at 100keV

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



Microcalorimeter Multiplexing

We can increase the area, count rate capabilities and sensitivity by frequency multiplexing many detector channels with a single SQUID preamplifier.

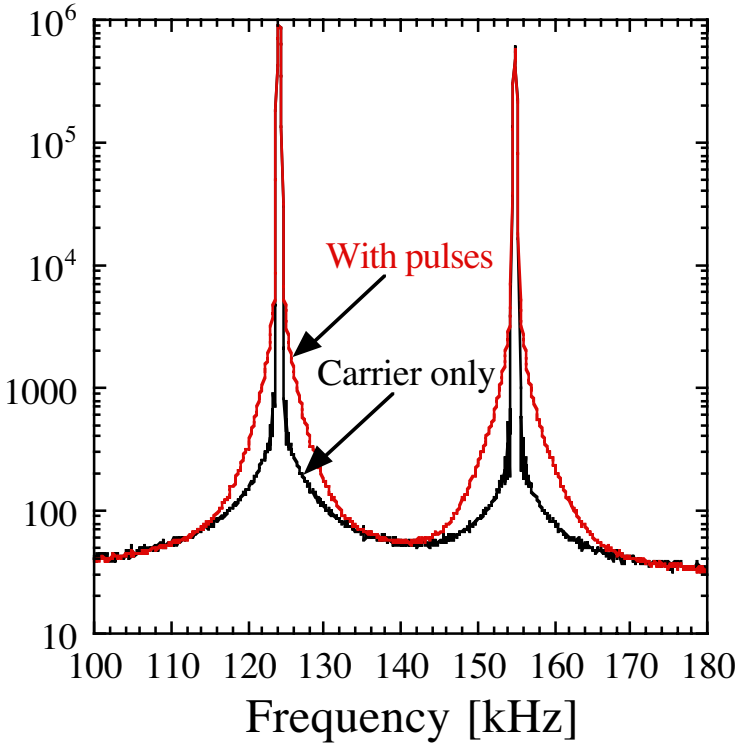
Present:

- dc and ac biased devices have same high resolving power $E/\Delta E \geq 1000$
- Single and multiplexed devices have same high resolving power $E/\Delta E \geq 1000$

Future:

- Single SQUID can multiplex ~30 sensors
- ~30 SQUIDs could offer three orders of magnitude improvement in sensitivity.

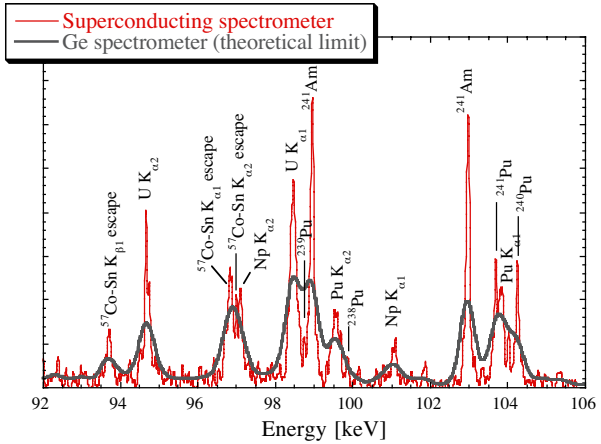
Cunningham et al, Appl. Phys. Lett. **81**, 159 (2002)



Summary

High-resolution cryogenic detector development

- Cryogenic spectrometer with cold finger
- 9-Channel STJ Arrays for synchrotron science
  < 10-20 eV FWHM up to 1keV, > 100,000 counts/s
- Microcalorimeters for nuclear analysis
  <100 eV FWHM for γ-rays below 100 keV
  Frequency-multiplexing



X-ray and γ-ray Spectroscopy

- Increased In-N bonding explains widened bandgap in GaInNAs upon annealing
- First γ-ray measurements on special nuclear materials (multiplexed).