XIII. Cryogenic Detectors

1. Motivation

a) Resolution

The statistical fluctuation of a detector signal

$$\frac{\sigma_E}{E} = \sqrt{\frac{F}{N}} = \sqrt{F\,\frac{\varepsilon_x}{E}}$$

improves with the energy ε_x required to form the signal quanta.

To form an electron-ion pair in gases requires of order 30 eV, formation of an electron-hole pair requires 3.6 eV in Si and 2.9 eV in Ge.

Other processes that do not rely on ionization have smaller excitation energies and would allow correspondingly smaller signal variances.

Examples:

The maximum phonon energy in Si is 60 meV. Roughly 2/3 of the energy required for electron-hole formation goes into phonon excitation, so many more phonons are produced for a given energy absorption.

In superconductors the energy gap 2Δ is equivalent to the band gap in semiconductors. Absorption of energy $>2\Delta$ can break up a Cooper pair, forming two quasiparticles, which can be detected. The gap energy is typically of order 1 meV.

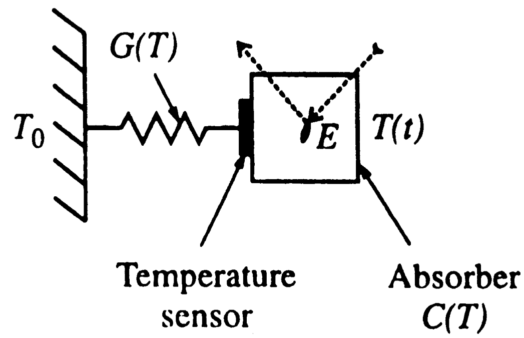
b) Detection of weakly ionizing particles

Many particles, very low energy molecules or nuclei, neutrinos, WIMPS, etc. do not interact by ionization.

Many of these particles interact primarily through elastic scattering on the absorber nuclei. The recoil energy is typically only a few keV, of which only 10% may go into ionization. Using non-ionizing excitation modes will provide a better signal.

2. Phonon Detectors

Basic configuration:



Assume thermal equilibrium:

If all absorbed energy E is converted into phonons, the temperature of the sample will increase by

$$\Delta T = \frac{E}{C}$$

where C the heat capacity of the sample (specific heat x mass).

At room temperature the specific heat of Si is 0.7 J/gK, so

E= 1 keV, m= 1 g $\Rightarrow$ ΔT= $2 \cdot 10^{-16}$ K,

which isn't practical.

What can be done?

a) reduce mass

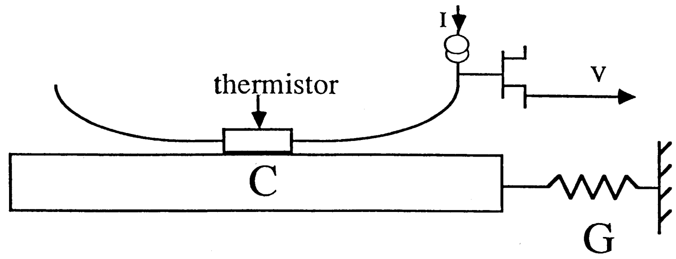
b) lower temperature to reduce heat capacity
"freeze out" any electron contribution, so phonon excitation dominates.

Debye model of heat capacity: $C \propto \left(\frac{T}{\Theta}\right)^3$

Example:	m= 15 µg		
	T= 0.1 K		
	Si	$\Rightarrow$	C= $4 \cdot 10^{-15}$ J/K
	E= 1 keV	$\Rightarrow$	ΔT= 0.04 K

How to measure the temperature rise?

Couple thermistor to sample and measure resistance change



(from Sadoulet at al.)

Thermistors made of very pure semiconductors (Ge, Si) can exhibit responsivities of order 1 V/K, so a 40 mK change in temperature would yield a signal of 40 mV.

Signal Fluctuations

number of phonons

$$\overline{N} = \frac{E}{\overline{E}_{phonon}} = \frac{CT}{k_B T}$$

Fluctuation in the number of phonons

$$\Delta E = \Delta N \cdot \overline{E}_{phonon} = \sqrt{\overline{N}} \cdot \overline{E}_{phonon} = \sqrt{\frac{CT}{k_B T}} \cdot k_B T = \sqrt{k_B T^2 C}$$

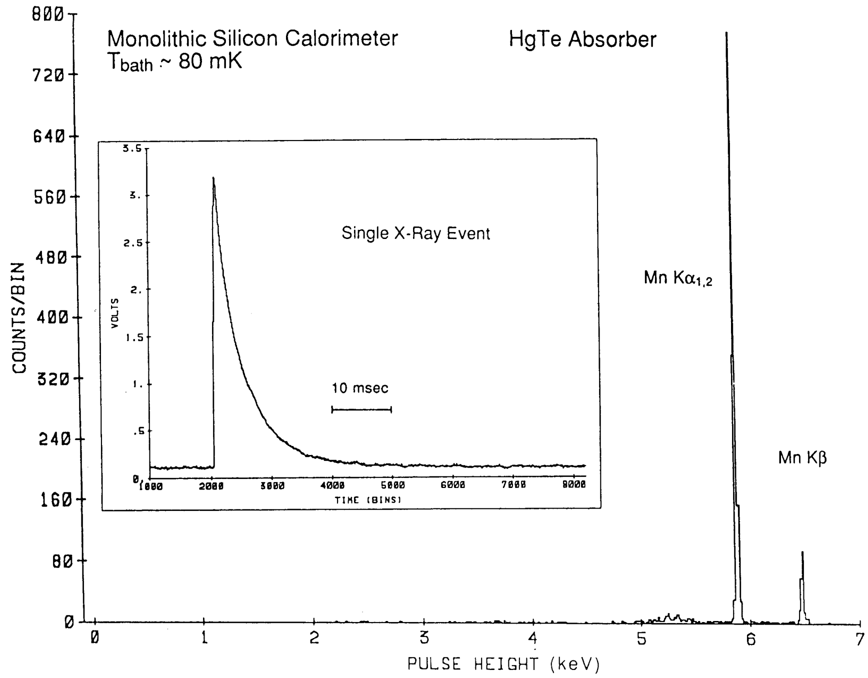
so for T= 0.1 K and C= 4·10^{-15} J/K

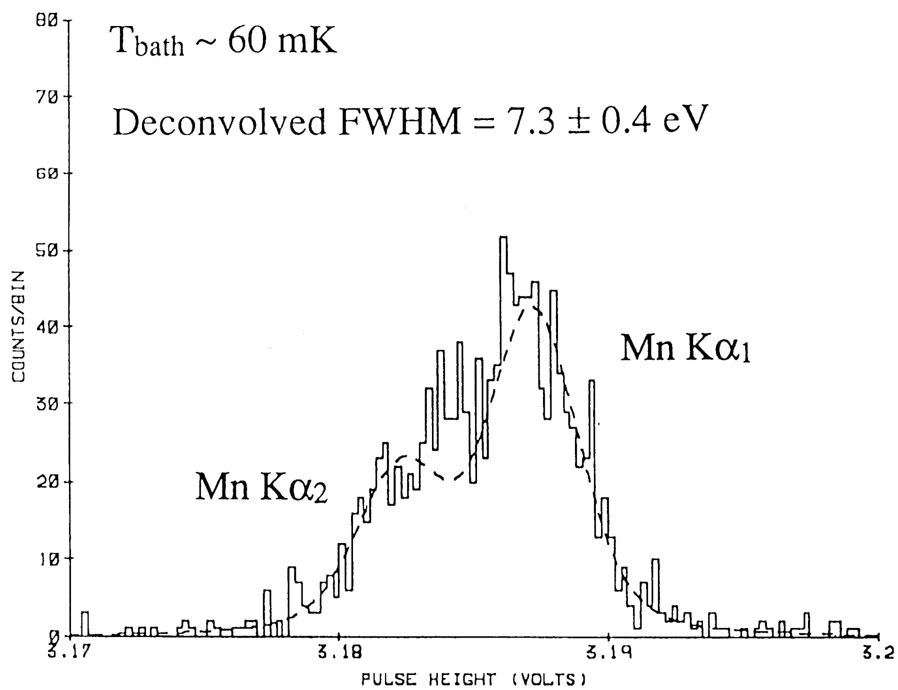
ΔE= 0.15 eV

Theoretical limit of Si ionization detector at 1 keV: ~20 eV rms

Experimental Results

Monolithic Si calorimeter: 0.25 mm wide x 1 mm long x 15 µm thick
(D. McCammon et al., NIM A326 (1993) 157-165)





Noise optimization

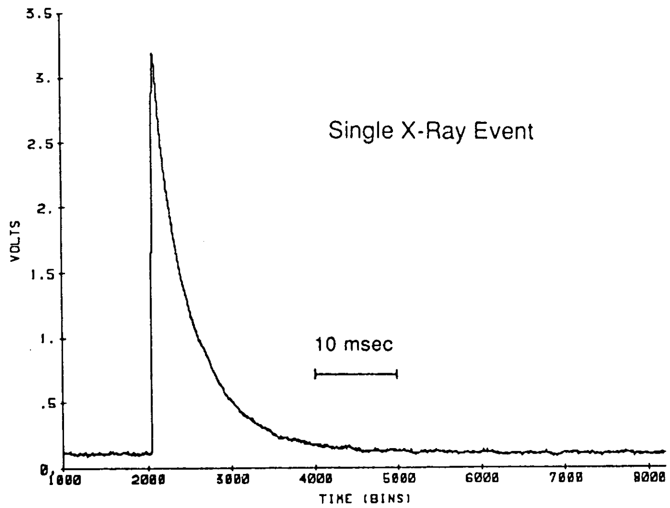
Absorber coupled to cold finger through thermal conductance G.

The signal pulse will rise rapidly by ΔT and decay exponentially

$$T(t) = \Delta T e^{-t/\tau}$$

with the decay time

$$\tau = \frac{C}{G}$$



Fluctuations in the phonon number in the absence of incident radiation will give rise to noise pulses with the same shape.

$\Rightarrow$ both the signal and the noise have the same frequency spectrum

$\Rightarrow$ S/N *of sensor alone* is independent of shaping time

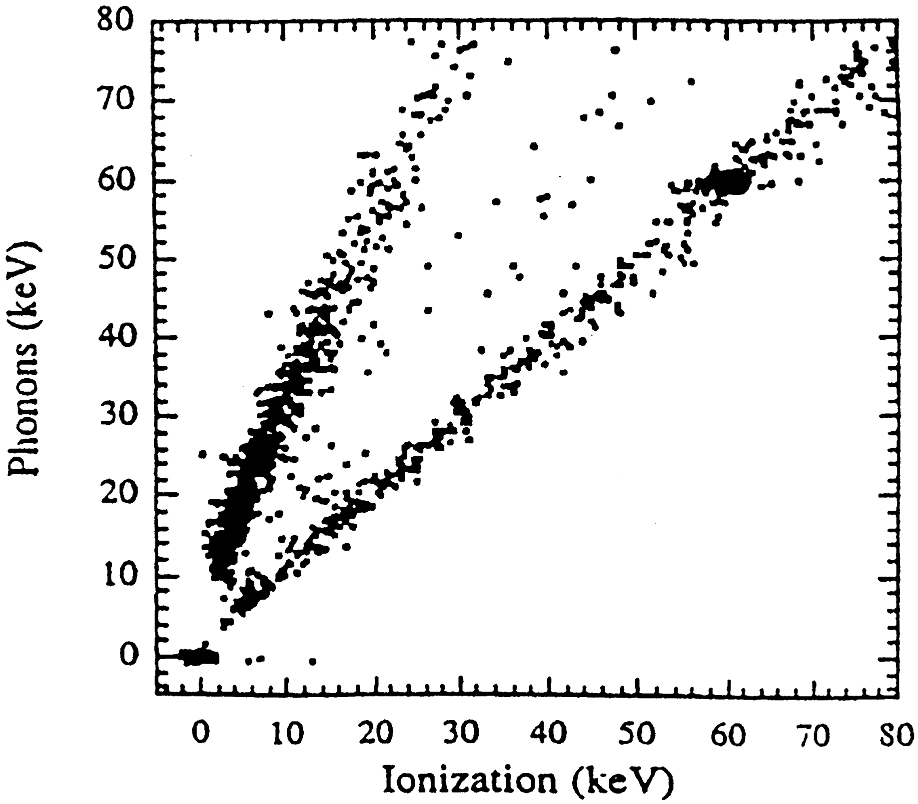
However, this does not apply to external noise sources, for example

- resistive sensor
- input transistor
- noise induced by mechanical vibrations

Ideally, front-end and shaper designed to contribute negligible noise, while providing suppression of low-frequency pickup.

Furthermore, phonon fluctuations are increased by fluctuations in signal going into ionization and ionization losses (e.g. trapping).

Silicon sensor can also be configured to measure ionization simultaneously with phonon excitation (P. Luke, LBNL)



(from Sadoulet et al.)

Upper branch: weakly ionizing nuclear recoils

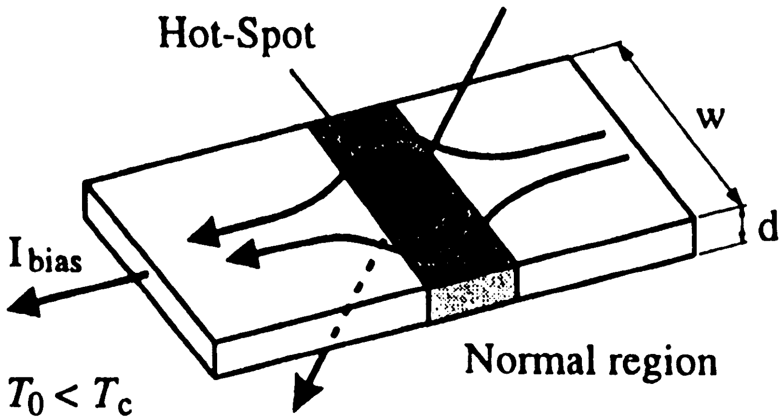
Lower branch: Compton electrons from incident gamma rays

Different responses can be used for background suppression.

3. Superconducting Strip Detectors

A thin strip of superconducting material is biased at a current just below its transition to a normal state (determined by local magnetic field).

When a particle deposits energy, a local hot spot forms. If sufficient energy is deposited, a normal resistance region spreads across the width of the strip and produces a voltage signal.



(from Booth)

Very narrow strips can be formed by photolithography.

⇒ improved sensitivity

⇒ position resolution

Binary device (on – off)

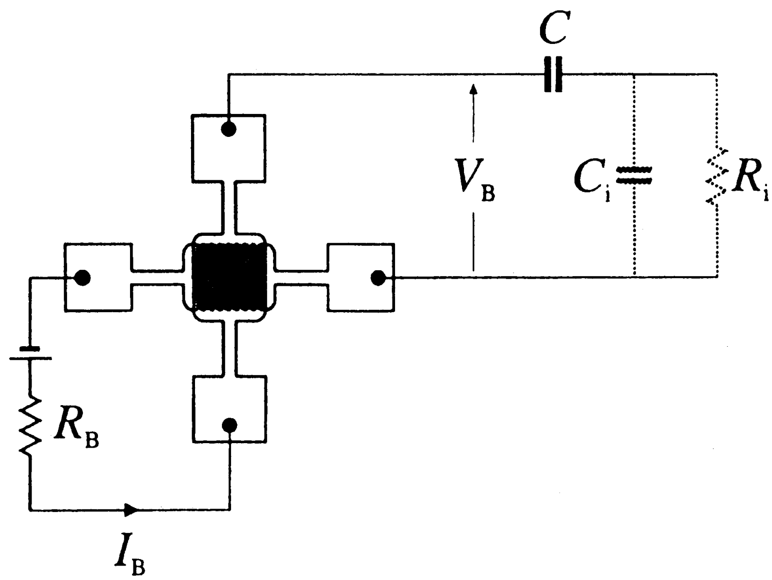
First demonstrated in 1971:
Crittenden et al., J. Appl. Phys. **42** (1971) 3182

4. Superconducting Tunnel Junctions

Sandwich of superconducting films with an intermediate thin insulator.

Junction is biased through lower-left contacts.

Signal current is measured through upper-right contacts



(from Booth)

Cooper pairs are broken by incident radiation forming quasi-electrons and quasi-holes.

The required energy 2Δ is 0.34 meV for Al and 3.05 meV for Nb.

In equilibrium two processes balance:

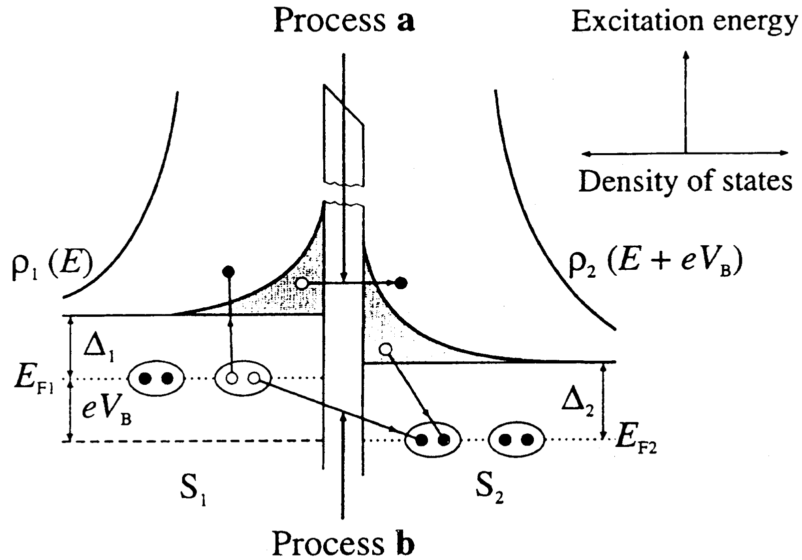
a) Cooper pair breaking by phonons

b) Recombination of quasiparticles forming a Cooper pair and emitting a phonon.

Absorption of radiation breaks Cooper pairs and increases the number of quasiparticles, leading to a change in resistance.

The voltage transition is measured.

Tunneling processes:



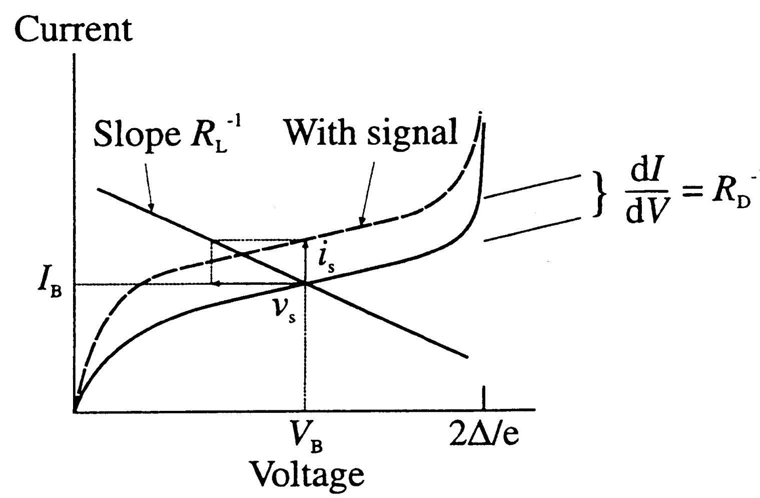
Breakup of a Cooper pair promotes a quasi-electron into the conduction band, where it tunnels from S_1 to S_2 (process a).

The corresponding quasi-hole can also tunnel from S_1 to S_2.

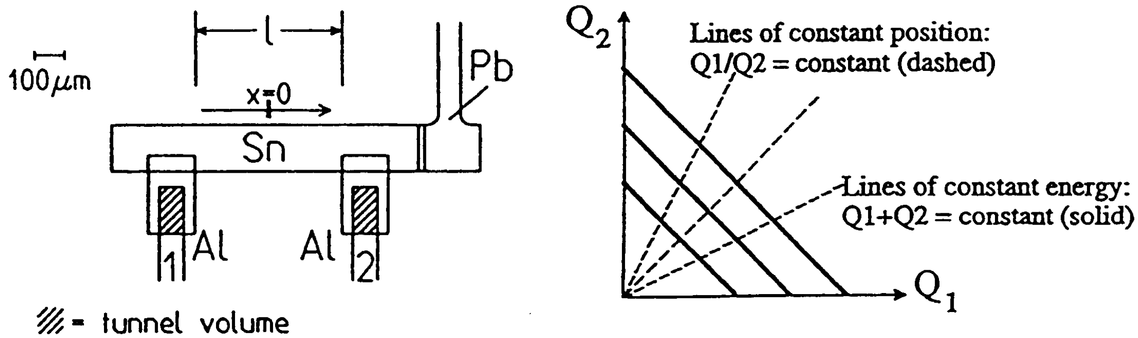
Electrons and holes in S_2 can form new Cooper pairs.

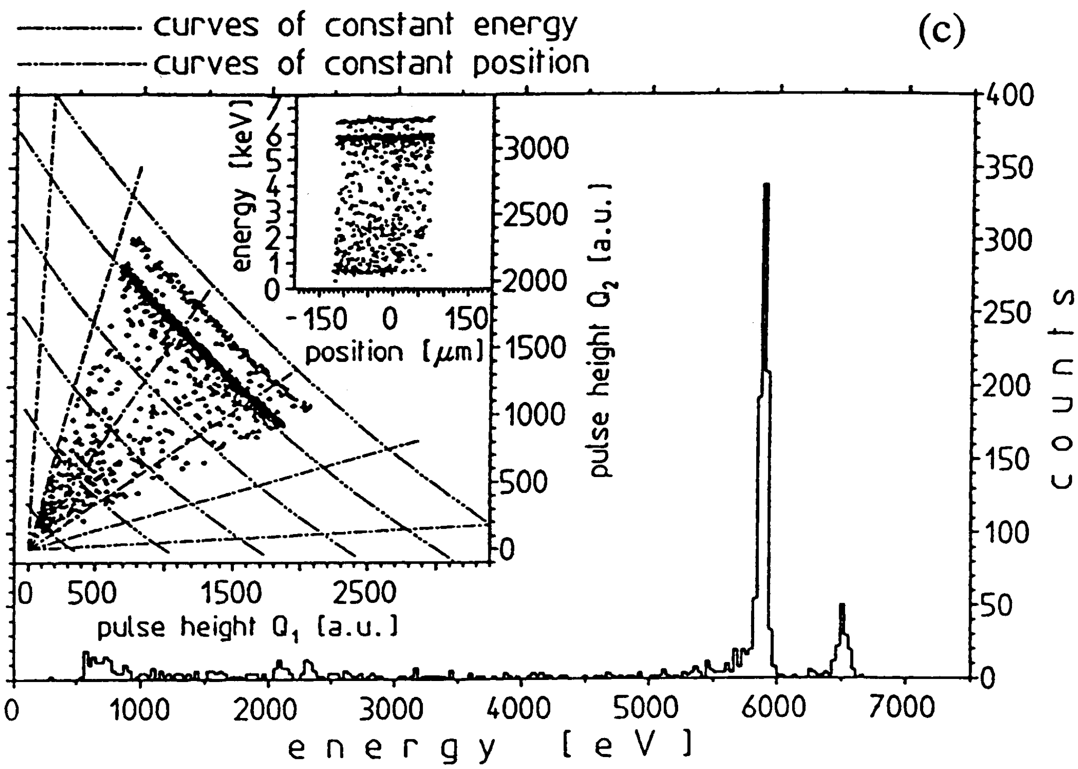
In equilibrium, the net flow of quasi-electrons and quasi-holes is zero, until it is upset by formation of new quasi-particles due to radiation.

The current grows with the number of quasi-particles and the voltage drop increases.



Detector utilizing superconducting tunnel junctions
(Kraus et al.)

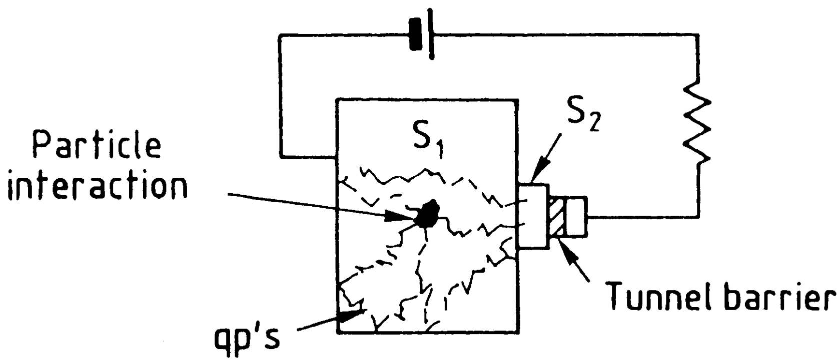




Radiation is absorbed in the Sn strip and the change in quasiparticle number measured in the two Al tunnel junctions.

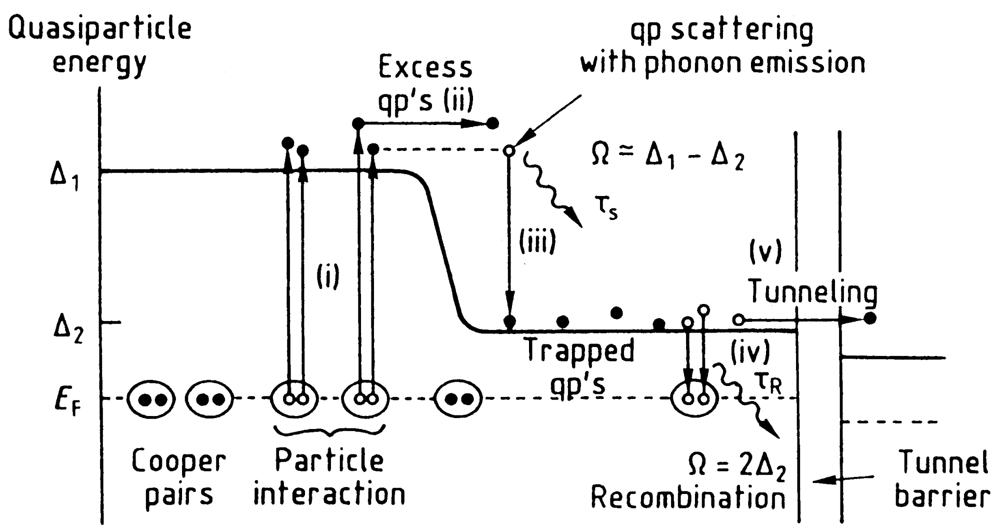
The charge signals from the two tunnel junctions are used to determine the full energy deposition.

Tunnel junctions can be coupled to large absorbers to increase the detection efficiency. A large volume absorber S_1 is coupled to a thin layer of superconductor S_2 with a lower energy gap. The tunnel junction is formed on S_2.



(from Booth)

Quasiparticles from S_1 are trapped in S_2, so tunneling proceeds form the thin trap S_2 rather than the thick absorber S_1.



(from Booth)

Superconducting tunnel junctions can also be used as thermometers to measure the temperature increase of crystals (instead of resistive bolometers).

Phonons from heat released due to radiation increase the number of quasiparticles, thus increasing the current in the tunnel junction.

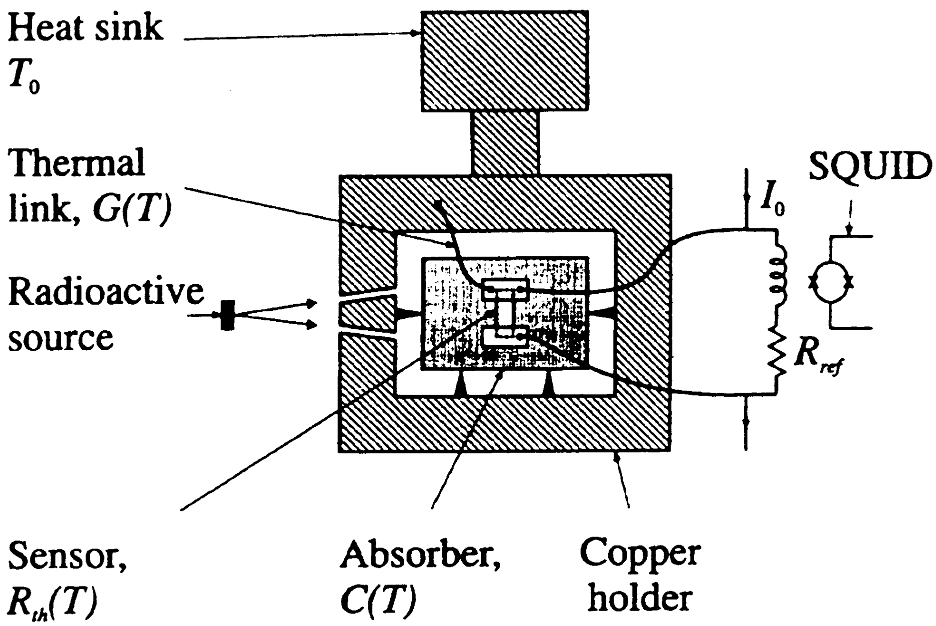
5. Transition Edge Sensors

Voltage is applied across a thin superconducting film at a temperature near the middle of the normal-to-superconducting transition.

The current is set so that Joule heating of the film is balanced by heat flow to the substrate.

When excitation reaches the film, the resistance increases.

The resistance change can be measured by a SQUID.



(from Booth)

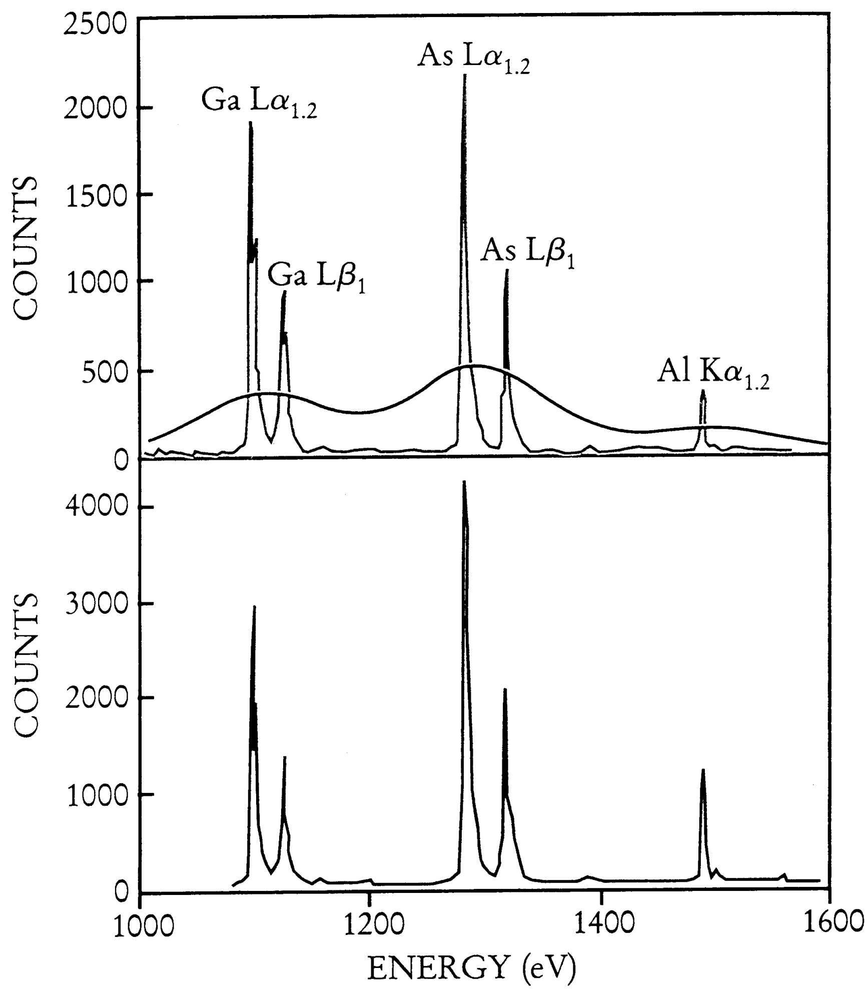
Very sensitive systems can be made using a feedback system.

When the resistance increases, the current decreases, so less power is dissipated for heating, which moves the operating point back towards the superconducting regime.

The feedback signal is the change in heating power, i.e. the bias voltage times the current. The deposited energy

$$E = -V_b \int \Delta I(t)dt$$

Recent results from NIST group, using transition edge sensors (Martinis et al., see Physics Today, July, 1998)



Upper plot: microcalorimeter spectrum (4 eV resolution) with superimposed spectrum from conventional Si detector

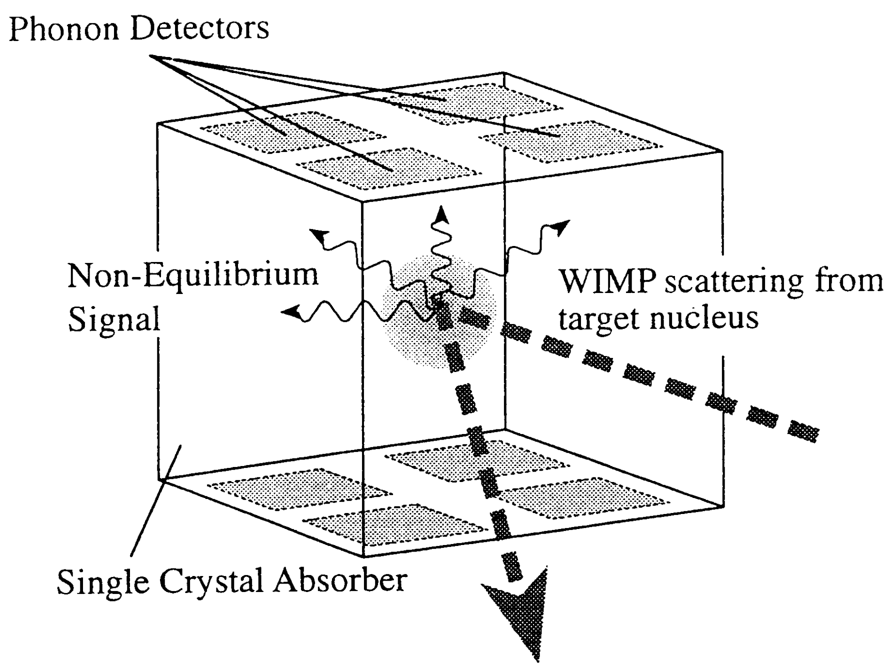
Lower plot: crystal diffraction spectrometer

6. Non-Equilibrium Phonon Detection

The cryogenic calorimeters discussed up to now utilize the equilibrated phonon signal, i.e. the temperature change of the absorber after phonons have propagated throughout the crystal and established a uniform energy density.

Detection of the equilibrium signal entails long time constants.

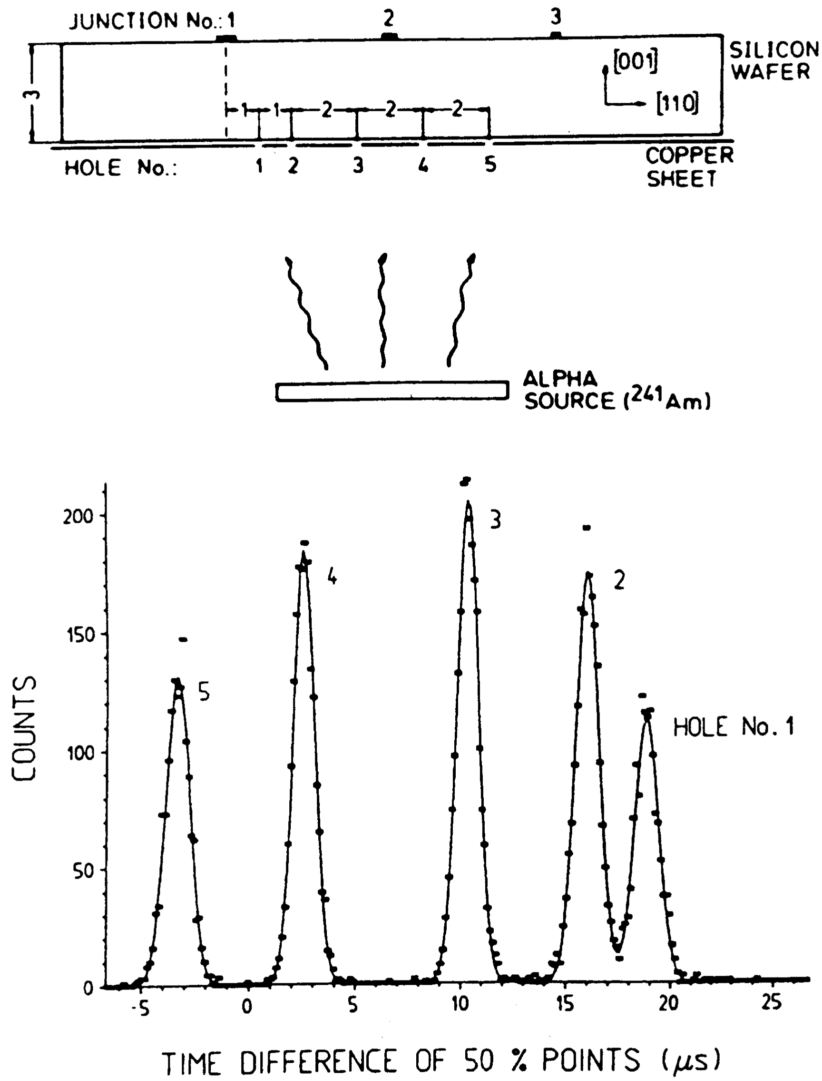
The phonons emitted from an excitation can be detected immediately (non-equilibrium phonon detection).



(from Booth)

An array of phonon detectors absorbs the phonons before they are reflected (and re-reflected) at the crystal boundaries.

This allows faster detection of the signal (~100 μs) and also provides position information.



(Petereins et al.)

The time difference in signals from the individual detectors can be used to reconstruct the radiation pattern.

7. Conclusion

Cryogenic detectors are still in development and – to some degree – a laboratory curiosity, but cryogenic detection systems are already providing data in ongoing experiments.

Substantial development still needed to exploit the potential of these devices, but current results and progress are very encouraging.

Some review articles on cryogenic detectors:

N.E. Booth and D.J. Goldie, Supercond. Sci. Tech. **9** (1996) 493 - 516

N.E. Booth, B. Cabrera, E. Fiorini, Ann. Rev. Nucl. Part. Sci. **46** (1996) 471 – 532

D. McCammon, *Cryogenic Detectors for Dark Matter*, in G. Herrera Corral and M. Sosa Aquino (eds.), *Instrumentation in Elementary Particle Physics*, AIP Conference Proceedings 422, Woodbury, NY 1998

Also see publication list of the Center for Particle Astrophysics at http://cfpa.berkeley.edu/preprints/cdms/cdms.html