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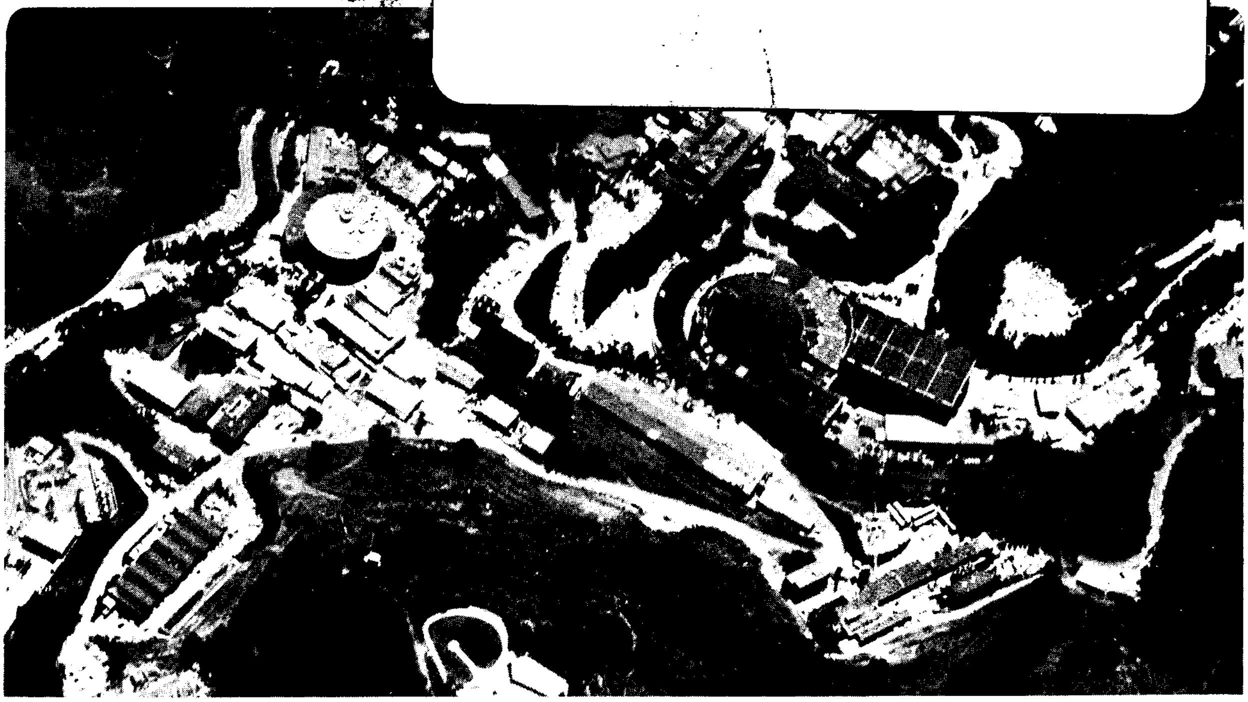
B. Sadoulet

November 1987



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CRYOGENIC DETECTORS OF PARTICLES: HOPES AND CHALLENGES[1]

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CRYOGENIC DETECTORS OF PARTICLES: HOPES AND CHALLENGES

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Abstract

We review the various methods proposed for cryogenic detection of particles, the current status of their development and their potential applications.

1. Basic Concepts

Historically, particle detection has progressed through the use of quanta of decreasing energy. In proportional chambers, particle interactions with the gas produce electron-ion pairs with binding energies of typically 10 eV. Scintillation detectors involve excitation energies of roughly 5 eV. Semiconductor ionization detectors rely on electron-hole pairs involving energies of the order of 1 eV, and this lead to a very significant improvement in threshold and resolution. For instance, state of the art silicon detectors of small dimensions reach an energy resolution of 100 eV FWHM for 6 keV X-rays.

It seems therefore natural to attempt to use quanta of even smaller energies: Cooper pairs in a superconductor have binding energies of the order of 10^{-3} eV and phonons in a crystal at 100 mK have energies of 10^{-5} eV (if they are thermalized). Infrared astronomers have been using these facts for a long time. It is Niinikoski and Udo [1] who recognized in 1974 the potentialities of thermal methods for particle detection. The potentials of superconductivity have been recognized even earlier (1962 [2]). If efficient detection schemes using broken Cooper pairs ("quasiparticles") or phonons could be implemented, the large number of quanta involved could lead to very low thresholds and excellent resolution, **on the order of one electron volt.** In order to prevent thermal excitation of the quanta to be detected, such detectors have to be maintained at very low temperature, typically much below one Kelvin, and are thus called **cryogenic detectors.**

Recent results show that these hopes are not totally unrealistic. In 1985 McCammon, Moseley, and coworkers [3] obtained a resolution of 100 eV FWHM for a 6 keV X-ray using a phonon detector and even more impressively a baseline FWHM of 11 eV indicating the possibilities of having a very low threshold. By decreasing the amount of energy trapped on impurities, they have achieved recently a resolution of 17 eV FWHM (Fig. 1). (See their contribution at this conference [4]). Zehnder now obtains 50 eV FWHM using quasiparticle detection in superconducting tunnel junctions (Fig. 2) [5].

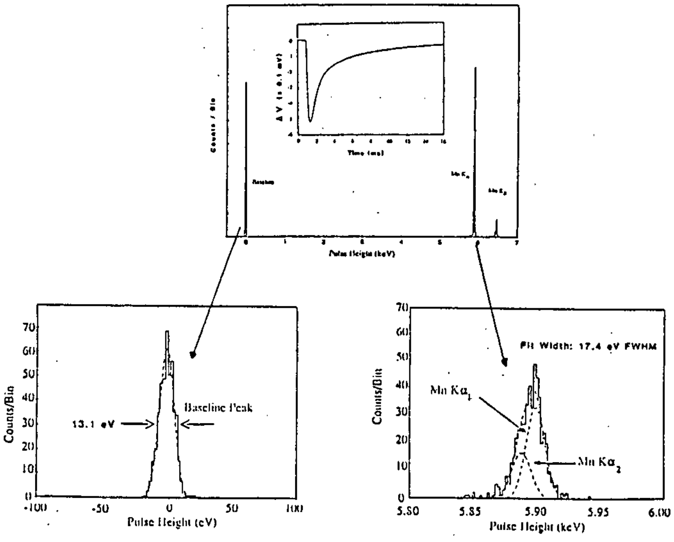

Fig. 1 Resolution obtained with a silicon calorimeter for 6 keV X-rays (from [3]).

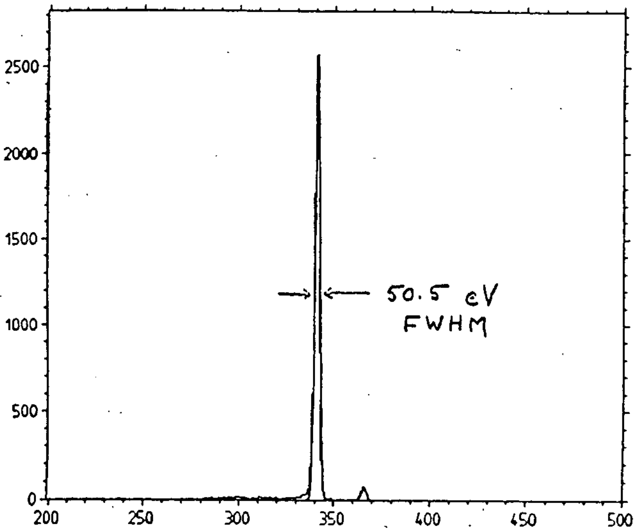

Fig. 2 Resolution obtained with a tin tunnel junction for 6 keV X-rays (from [5]).

2. Potential Applications

2.1 Interesting Properties.

Cryogenic detectors have several interesting properties which make them particularly attractive:

a) Such detectors are sensitive in the bulk and allow any material to be used. Present detectors have volumes of the order of $(100\mu)^3$ but scaling laws indicate, as we will see in sections 3 and 4, that masses of tens of grams (even kilograms) may be reached. Therefore devices with large stopping power and high density could potentially be built for neutrons and gamma ray detection. This is also very interesting for rare processes (neutrino and dark matter particle scattering).

In some schemes (superconducting granules, ballistic phonon detectors), this volume sensitivity is nicely complemented by position resolution, an important property for imaging and background rejection. Submillimeter position resolution has been demonstrated by granules [6].

b) Very low thresholds can be reached. The (tiny) X-ray detector of the Goddard-Wisconsin group [3,4] could be operated with a threshold of 20 eV. If the Debye Law remains valid at very low temperature, similar thresholds may be possible at 15 mK with 10 to 100g of (high Debye temperature) materials.

c) High resolution may be possible as demonstrated by the results quoted above. This is more demanding than getting low threshold because, in addition to having quanta of low enough energy to decrease statistical fluctuations, high resolution requires very low trapping of the energy into undetectable states.

d) Finally, cryogenic detectors may allow for the first time an unambiguous signature [7] that the energy is released by a recoiling nucleus of low energy. Below a few 100 keV of kinetic energy, the ionization yield is much smaller for a recoiling nucleus than for a recoiling electron with the same kinetic energy. Simultaneous measurement of ionization and heat deposition may allow discrimination between the two events. This may be important for background rejection in dark matter searches and in some nuclear physics experiments.

2.2 Applications

Such properties are quite attractive for many purposes and explain why many groups are now engaged in the development of cryogenic detectors (Table I). Let us list some applications.

2.2.1 **In particle physics** [8], thresholds below 1 keV would allow the study of coherent scattering of neutrinos [9]. The high accuracy which may be reached, for instance with superconductors, may be essential for progress in neutrinoless double beta decay [10,8]. Resolution may be interesting for the measurement of the electron neutrino mass. In tritium end point experiments, pile up problems exclude a simple measurement with a tritium implanted calorimeter [11]. However, cryogenic calorimetry may be beneficial to a magnetic or electric separation scheme. The "BONUS" collaboration is interested in using calorimetry for a ν_e mass measurement using the internal bremsstrahlung spectrum in the electron capture decay of ^{163}Ho [12].

2.2.2 **In nuclear physics**, <u>excellent X-ray energy resolution</u> obtained with microcalorimeters already allows [13] much more detailed study of levels [Fig. 3]. The low energy thresholds may open the possibility of measuring <u>nucleus recoil</u>, e.g. in internal capture of ^{7}Be $\rightarrow$ ^{7}Li where the recoil energy is 40 eV. <u>High resolution γ spectroscopy</u> may allow both an accurate mapping of the level structure and, combined with position resolution, a measurement by Doppler shift of the <u>direction</u> of nuclear recoil, important for instance in nuclear magnetism experiments. Finally, cryogenic techniques could be used in high resolution <u>neutron detection</u> with high efficiency and position resolution.

2.2.3 **In astrophysics**, many groups are interested in the high resolution and high efficiency that calorimeters or junctions can provide for 1-10 keV X-rays. Imaging is in principle feasible with several detector elements or by pulse division. Another important application is the detection of weakly interacting massive particles which may constitute the dark component of the universe [14,8,7,15]. These detectors must have targets of several kilograms, thresholds of a few 100 eV, and very low radioactive backgrounds. Even more demanding is the detection of solar neutrinos by coherent scattering [9], or through the indium reaction [16,17], where 1 ton detectors are necessary.

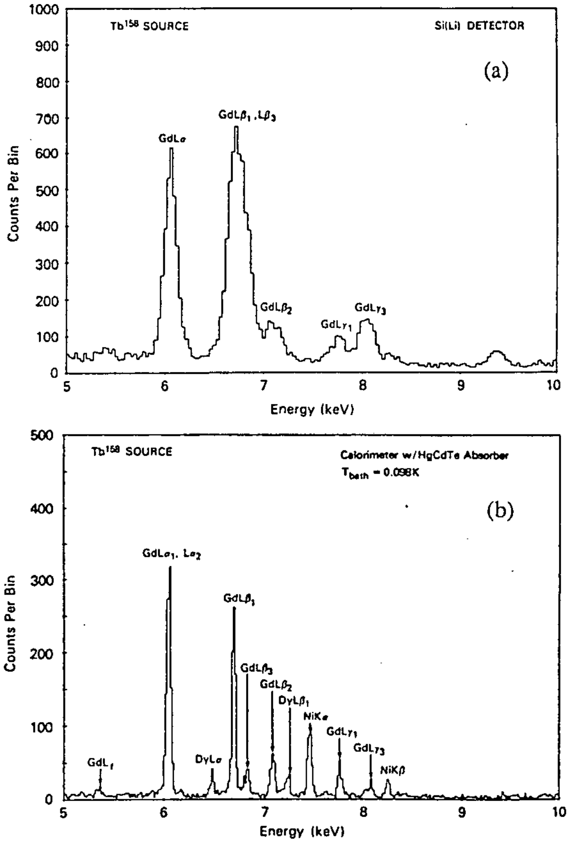

Fig. 3 Improvement in resolution on Tb^{158} source (from [12]).

a) Spectrum obtained with Conventional silicon ionization detector

b) Spectrum obtained with a 35 eV FWHM silicon calorimeter

2.2.4 **Other Scientific Fields.** The accurate simultaneous measurement of energy and position may find applications in <u>X-ray diffraction studies</u> in material science and biology, especially when low fluxes have to be used. A demonstration of high position resolution in the detection of <u>ultracold neutrons</u> [18] would open new possibilities in solid state physics.

2.2.5 **Industrial and Medical Applications.** It is clear that if these techniques are successful in the laboratory, in the long run they will be transferred to the industry, e.g. for nondestructive quality control, or to the hospital for X-ray and γ-ray imaging. Granules are already used at an experimental stage in industry [6].

It is important however when reviewing such a list not to delude oneself. There are also significant penalties for using cryogenic detectors. Even forgetting about the amount of development needed, practical problems with cryogenic operation, size, solid angle coverage, etc..., will certainly limit use of cryogenic detection to problems where no other technique can compete and where the scientific potential rewards outweigh the amount of effort needed.

3. <u>Quasiparticle Detectors</u>

Cooper pairs in a superconductor have a binding energy of 2Δ (the energy gap). Since 2Δ is of the order of 3.5 kT_c where T_c is the critical temperature, and ranges from 4.10^{-5} eV (Ir) to $3 \cdot 10^{-3}$ (Nb), the deposition of even a modest amount of energy in a superconductor leads to a large number of broken Cooper pairs (quasiparticles). Detection of these quasiparticles may lead to very sensitive or accurate devices.

3.1 <u>Breaking of Superconductivity</u>.

One way to detect quasiparticle is to make a detector element small enough for the superconductivity to be broken by the energy deposition.

3.1.1 **Superheated Superconducting Granules.** As proposed originally by a Orsay group [19], latter joined by Waysand and Drukier [20], the detector can be made of many small spheres of a few microns diameter. If they are immersed in a magnetic field, the transition of a single sphere from the superconducting to the normal state can be detected through the suppression of the Meissner effect and the variation of magnetic flux in a loop surrounding the spheres (Fig. 4 and 5). Position resolution may be obtained with crossed loops or by comparing the flux variation in separated loops ("flux division"). α particles are relatively easily detected by spheres of 60μ diameter and detection of X-rays of 60 keV have been reported with spheres of 10-15μ. Granules of 3μ are sensitive to minimum ionization particles [20].

The main technological problems may be summarized as follows.

a) Manufacturing of regular enough spheres [21]. In addition to the obvious dependence of the heat capacity of spheres on the cube of their radius, there may be variation of sensitivity due to the internal structure and the orientation of the grains [22]. Interaction between grains may also change their sensitivity as their relative distance fluctuates.

With current, admittedly crude, methods, a large number of granules seem to be insensitive, leading to low <u>overall</u> quantum efficiency even though high efficiency has been claimed for the sensitive grains [23]. But rapid progress in manufacturing and packaging is claimed by some of the groups involved [21].

b) The sensitivity of the amplifier attached to the loop is also a problem for very small spheres, since the flux change goes as the cube of the radius. Two directions are being explored: The use of (RF) SQUID's, which have been demonstrated by the University of British Columbia group [23], and the measurement of the derivative of the flux variation with respect to time which goes at the square of the radius [6].

Overall, although spheres of very small diameter can obviously be made very sensitive, this method appears (at least to this reviewer) unlikely to achieve very low thresholds in a consistent way. Its resolution at low energy will always be poor since the energy measurement relies on the number of spheres which are driven normal. But the scheme may have advantages in specific situations:

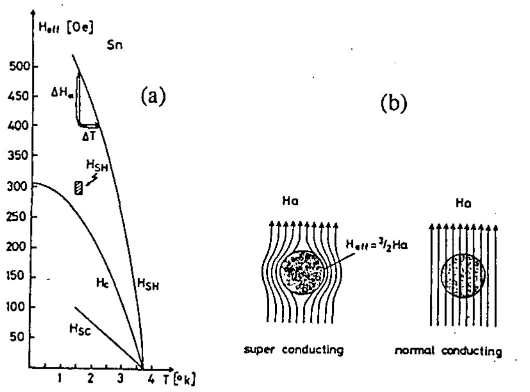

Fig. 4 a) Phase diagram of Sr granules.
H_{sh} = super heating field
H_{sc} = super cooling field
H_c = critical thermodynamic field

b) Meissner effect (from Ref. [22]).

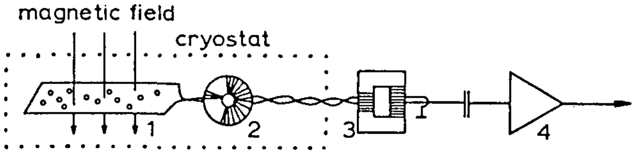

Fig. 5 Detection of superconducting-normal transition with a sensing loop (from [30]).

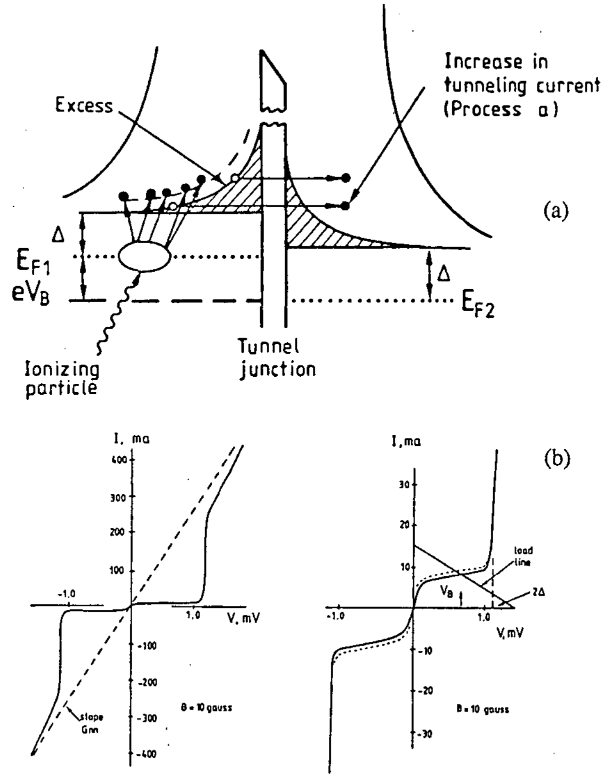

Fig. 6 Principle of tunnel junction operation (from [16]).
a) Level diagram
b) I V curve

a) Position resolution of 0.5 millimeter have already been achieved on industrial imaging devices [6] and the use of flux division with DC SQUID's may allow to reach a few tens of microns [18]. This could be extremely interesting for X-ray crystallography and industrial and medical imaging (positron emission tomography). Range may also be measured by the number of normal spheres, which together with position measurement may bring some discrimination power against background for the detection of rare processes

b) Fast timing is presumably possible.

c) The device could be made insensitive to minimum ionization deposition. This may be interesting for transition radiation [21].

d) The metastability of these granules (in most configurations) prevents them from recovering when they have been struck, giving a built-in memory which can be read out after the fact, e.g. by flipping back the granules. Together with the natural radiation hardness, this may be interesting in specific high rate applications.

3.1.2 **Superconducting Film Methods.** Variations of the above method which use superconducting film have been suggested [2,24,25]. They may allow one to use well developed lithographic techniques to solve the problems of size and position variability.

In addition to the magnetic methods described for the granules, it is possible to detect the breaking of superconductivity electrically by the variation of the resistance of a thin and narrow superconductive film, when a small section of it becomes normal. As reported by Neuhauser at this conference [26], the Stanford group has tested this scheme. They operate their film below the transition (in contrast to transition edge thermistors (see below) which are usually biased on the center of the transition). This method may be promising because of its approximate linearity in the energy density deposited in the superconductor (above a certain threshold).

3.2 Tunnelling of Quasiparticles

A potentially much more sensitive and accurate method of detecting quasiparticles is to make them tunnel through an insulating barrier between two superconductors (SIS). Fig. 6 show the level diagram and the I V characteristics of a tunnel junction.

The absorber is made of a superconductor cooled down in such a way so as to minimize formation of magnetic vertices and maintained at low enough temperature for the quasiparticles to be very long lived ($\tau \sim e^{-\Delta/kT}$). In that way, the quasiparticles can diffuse through the medium (at velocity of a few 10^6 m/s) and make the many attempts (10^6 or so) which are necessary for them to finally tunnel. The junction is typically biased below $2\Delta/e$ (typically at $V = \frac{\Delta}{e}$) so that it is in the off state. A magnetic field parallel to the junction suppresses the Josephson tunnelling of Cooper pairs. The quasiparticles liberated by the initial interaction and tunnelling through the junction will generate an additional current.

After the pioneering work of Wood and White [27], of Kuratado and Nazaki [28], and of Barone and coworkers [29], recently very encouraging results have been obtained by Twerenbold and Zehnder at SIN [30] and the von Felitzch group in Munich [31,32]. Over the past year, Zehnder has succeeded in decreasing the diffusion of quasiparticles along the connecting electrodes (essentially by decreasing their section) and has been able to obtain 37 eV FWHM resolution with a $(50\mu)^2$ junction with a ^{55}Fe source. (cf Fig. 1b which was obtained with a slightly worse junction) [5].

Many teams are now investigating these devices. Although photo-lithographic techniques may be used very effectively for the manufacturing, outstanding problems still have to be solved.

a) The manufacturing of low leakage junctions. Many junctions have a poorly understood leakage current in addition to the normal tunnelling of thermally excited quasiparticles (which disappears exponentially when the temperature is lowered). This does not seem to be due only to "microshorts", and the granularity of the tin film used by Zehnder may be responsible for the good performance of his junctions. Till now, this manufacturing process remains to a large extent "black magic".

It is also very important for the junctions to be robust enough to stand many cool-downs. This has been, for instance, the main problem of the Oxford group when they attempted to make junctions on indium (for their solar neutrino project) [16]. Recently, they made a significant breakthrough by building the junctions first on a niobium substrate and then growing the indium crystal on top.

b) Another significant problem is to collect quasiparticles created in a large volume. If the junction attached is small (say $(50\mu)^2$ for a cube of 1 cm^3), quasiparticles will bounce against the barrier very seldom and may get absorbed before having a chance to tunnel. Such devices would be very slow. Increasing the size of the junction (to 1 cm^2) leads to an unacceptable increase of the noise due to the leakage current. A promising solution has been proposed by Booth [33]. If a small piece of superconductor of lower gap is attached to the original superconducting crystal (Fig. 7), it will trap efficiently quasiparticles in a much smaller volume. If the junction is constructed on the lower gap superconductor, the tunnelling time should be decreased significantly. Zehnder recently demonstrated [5] this mechanism in a very spectacular fashion. Covering a 0.15μ thick tin junction with 0.4μ of lead, he observed a decrease of the rise time from 20 μs for ordinary (0.6μ thick) tin junctions down to 0.5 μs (Fig. 8). However, for reasons not yet understood, the Mn lines from a iron 55 source were completely washed out.

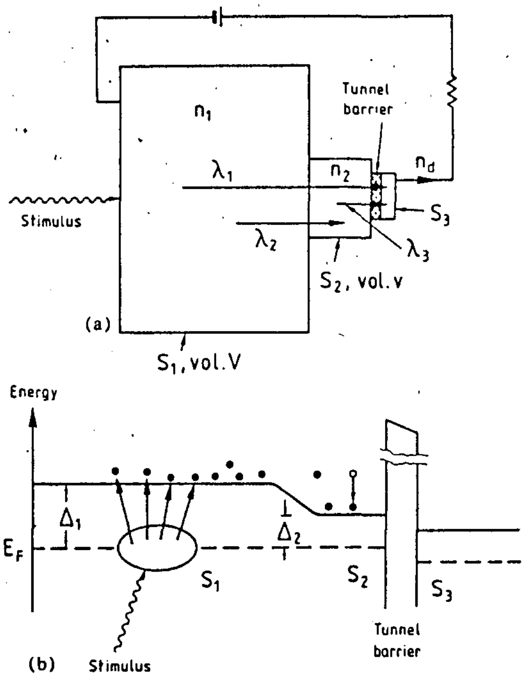

Fig. 7 Trapping of quasiparticles below the junction (from [24]).

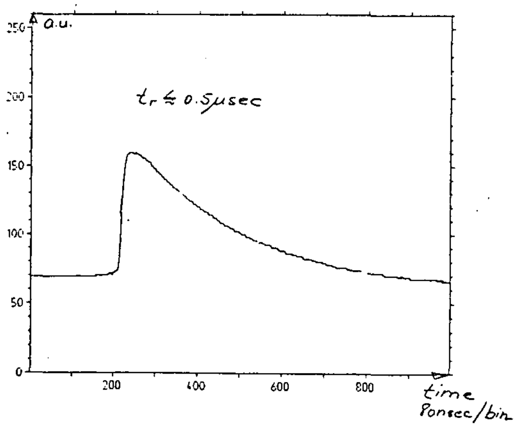

Fig. 8 Rise time obtained with a junction of $(50\mu)^2 \times (0.15\mu)$ using trapping (from [5]).

4. Phonon Detectors

We now turn to the detection of phonons which represent even smaller quanta of energy.

4.1 Calorimetry

One of the oldest methods for detecting energy is calorimetry, where the temperature rise ΔT resulting from the energy ΔE absorbed is measured

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

where C is the heat capacity. If this is done at low enough temperature for C to be very small, the method can be in principle very sensitive. This is a detector of thermalized phonons and, because of their discrete nature, the detector will experience thermal energy fluctuations

$$\delta E_{th} = \sqrt{k\ T^2\ C}\ .$$

This classical result of thermodynamics can be derived by computing the fluctuations in number and individual energy of the boson phonon gas.

Fig. (9) gives a schematic representation of a calorimeter designed for the detection of thermalized phonons. In order to allow a temperature rise to appear, the absorber has to be weakly linked to the heat bath. A small thermistor (to limit its contribution to the heat capacity) is fixed to or implanted in the absorber and is biased under, say, a constant current I. If the resistance of the thermistor is R, any rise of temperature ΔT will give a change of voltage across it:

$$\Delta V = \frac{\partial R}{\partial T}\ I\ \Delta T$$

$$= \frac{\partial V}{\partial T}\ \ \Delta T.$$

If the conductance of the link is G, our energy pulse ΔE will appear as a sharp rise

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

followed by an exponential decay of time constant

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

(if we neglect electro-thermal feedback [3]).

The detector is fundamentally limited by the thermal fluctuations which, averaged over a bandwith B would give an energy fluctuation

$$\delta E\ = \frac{\sqrt{k\ T^2\ C}}{\sqrt{2B\tau}} \sim \sqrt{k\ T^2 C}\ \text{for}\ B \sim \frac{1}{\tau}.$$

But on practical devices, we have to take into account in addition

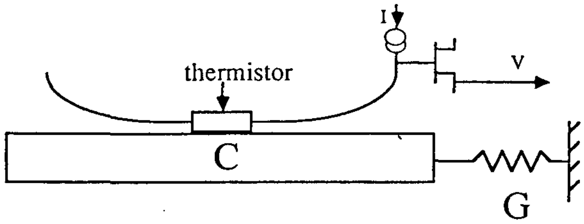

Fig. 9 Schematic representation of a calorimeter.

- The Johnson noise.
- The amplifier noise.
- Any excess noise.

Standard optimum filtering methods [34] give a final statistical uncertainty on the energy

$$\delta E = \xi \sqrt{k\ T^2\ C.}$$

At temperatures above 100 mK the best thermistors investigated so far are doped semiconductors. They have large responsivity $\frac{\partial V}{\partial T} \sim 1.5$ V/K, the last two noise contributions are negligible and ξ is of the order of 2. Another sensor known, as a "transition edge thermistor", is investigated by Von Feilitzch and coworkers [31]. A thin superconducting film is operated at T_c in the middle of its transition curve and its change of temperature measured by the change of resistance. Up to now, a detailed noise analysis has not been done.

4.1.1 **Large Mass, Low Threshold Devices.** The above formula indicates the obvious route for extrapolation to larger devices [1,10,9]. Since C is proportional to the mass, and for an insulator proportional to $(\frac{T}{T_D})^3$ where T_D is the Debye temperature,

$$\delta E \sim \xi\ T^{5/2}\ M^{1/2}$$

and a large augmentation in mass can in principle be compensated by a modest decrease in temperature. However, this relies on several assumptions.

a) The heat capacity is indeed decreasing with the cube of the temperature (the so called Debye Law). Impurities or surface effects may become dominant. In addition, as explained in the next section, the concept of heat capacity at low temperature may be inadequate.

b) The responsivity $\frac{\partial V}{\partial T}$ should not decrease appreciably with temperature so that ξ does not increase. If $\frac{\partial V}{\partial T}$ is too small, the energy noise δE is dominated by the amplifier and Johnson noises and the scaling law given above is incorrect. δE becomes proportional to

$$\frac{C}{\frac{\partial V}{\partial T}\sqrt{\tau}}$$

It is indeed the experience of many groups [4,13,35] that as the temperature decreases, parasitic effects in semiconductors prevent them from being optimally biased as if they were an increasing thermal decoupling between electrons and phonons or a increasingly strong field dependent resistance. Wang et al. [36] present at this conference the first evidence that an encouraging responsivity $\frac{\partial V}{\partial T} \sim$ 0.3 V/K can be achieved with neutron transmutation doped germanium thermistors [37] down to 20 mK.

In order to see the potential significance of this result, let us imagine attached to such a sensor an absorber made of 50g of boron. Even if no ballistic effect were present (see next section), their result would naively give a baseline fluctuation of 50 eV FWHM. This assumes that one can maintain the same heat conductance as they measure now and that no significant excess noise is present. Such a detector would allow a serious search for low mass dark matter particles!

c) Finally, perhaps because of the decoupling between electrons and phonons, the semiconductor thermistors appear to be intrinsically slow at low temperature. Wang et al. [36] measured a time constant of 4 ms around 25 mK.

Therefore, in spite of recent progress, there are still significant problems for enlarging calorimeters operated at low temperature.

4.1.2 **High Resolution Applications.** A whole new set of problems arises when a high energy resolution device is needed (e.g. for X-ray application). In that case, it is less the baseline fluctuation than the absence of loss mechanism for the released energy, which is important. For instance, in a semiconductor lattice, ionization electrons or holes can be trapped in metastable states, locking in quanta of energy of the order of the gap. The Goddard-Wisconsin group [3] has given convincing evidence that this is the dominating effect in the disappointing resolution they have first obtained with a silicon calorimeter. Switching to a low gap (but higher heat capacity) material, Hg Cd Te, they have reached 17 eV FWHM [4].

4.2 Ballistic Phonons

It should be noted, however, that very likely the picture outlined above is fundamentally incorrect, since the lifetime of phonons of energy E inside a crystal goes as

$$\tau = A(E)^{-5}$$

where E is measured in K and A is of the order of 1,000sK^5 for silicon [38]. So phonons originating from the interaction will stop thermalizing around 10K unless special surfaces or impurity effects play a significant thermalizing role. Such phonons are expected to be ballistic, that is to travel in straight lines and to bounce off surfaces. The concepts of temperature and heat capacity are inadequate to describe such a system.

This effect, first emphasized in this context by Maris [38] and Cabrera and coworkers [39], is very well seen in experiments where laser beams are used to create phonons (see, for instance, Wolfe [38]). Several effects observed in calorimeters at low temperature (e.g. fast rise time with a 3.5-inch silicon rod [39], escape of heat along silicon support structure [13], detection of α pulses in a transition edge detector irridiated from the back of the wafer [25]) point to the existence of ballistic phonons. But up to now these evidences were somewhat indirect. The Munich group [32] is reporting at this conference the **first unambiguous evidence** for the production of phonons of high enough energy for detection in aluminum tunnel junctions. Although their results on focussing properties and time propagation cannot readily be explained by a simple ballistic behaviour, this important paper already shows the inadequacy of a thermalization model. Much more quantitative work is still needed in well defined geometry, to understand the share of energy deposited by a particle in ballistic phonons and the various diffusion and thermalization mechanisms in a crystal. Reflections at surfaces and interfaces have also to be characterized.

Instead of being a nuisance [38], ballistic phonons may ease the detection job [39]:

a) Instead of the heat capacity of the global crystal, what counts now is the efficiency of energy collection ε and the resolution δE_s of the sensor leading to an accuracy in the deposited energies

$$\delta\ \Delta E = \frac{\delta\ E_s}{\varepsilon}.$$

These detectors are more appropriately called acoustic detectors than calorimeters [39].

b) Because of the fast propagation, these phonons may allow a timing on several faces of the crystal (Fig.10a). This requires a fast rise time of the sensor signal. In addition, focussing will occur and may allow to localize the event within one millimeter by pulse division between several sensors [39]. Fig. 11 shows a Monte Carlo of the phonon distribution on a 1 kg silicon cube.

These ideas are quite attractive. However, it remains to be proven that they can be implemented. Two kinds of sensor can be envisaged.

a) Thermal ballistic phonon sensors. In this case the sensor (Fig.10b) is a large area thermistor such as that tested by Wang et al. [36]. The analysis given in section 4.1.1 could be repeated, but taking now into account the efficiency ε of coupling ballistic phonons to the sensor.

$$\Delta E = \frac{\xi}{\varepsilon} \sqrt{k\ T^2\ C_s}$$

where C_s is now the heat capacity of the sensor. This assumes that the large crystal is clamped solidly to the heat sink (without loosing phonons!). No measurement of ε has been made yet. Ballistic phonons may like to couple to the impurity electrons or holes in the thermistors, so it could act as an efficient trap. However, problems of transmission and thermalization at the interface between the absorber and the sensor may be important.

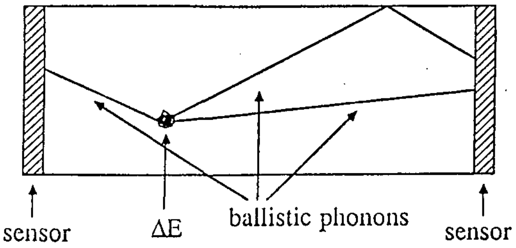

Figure 10a

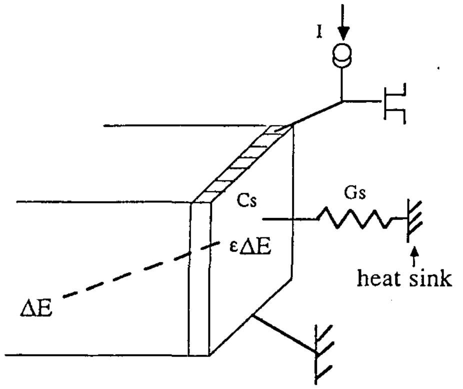

Figure 10b

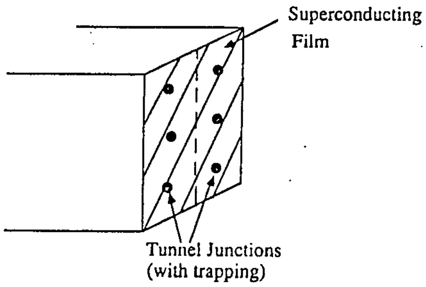

Figure 10c

Fig. 10 Schematic representation of a ballistic phonon detector.
a) General view
b) Thermal ballistic phonon sensor
c) Tunnel junction ballistic phonon sensor

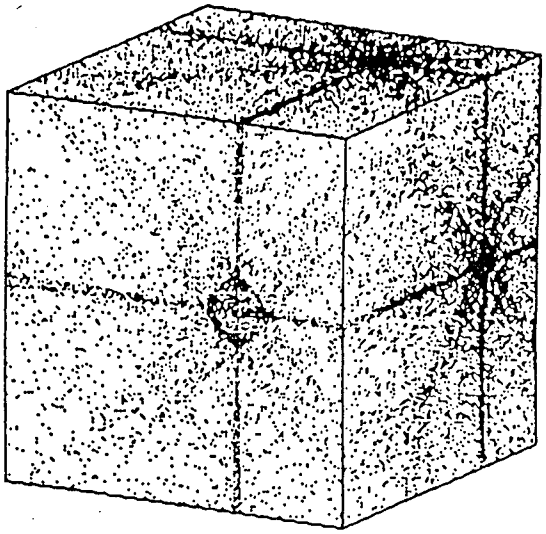

Fig. 11 Monte Carlo of ballistic phonon propagation in a 1 kg crystal of silicon (from [31]).

b) Superconducting film and tunnel junctions. The Stanford team [39] has proposed to use a superconductive film (Fig.10c) as a way to trap ballistic phonons, which are energetic enough to break Cooper pairs. The resulting quasiparticles could then be trapped in the way described in section 3.2, below tunnel junctions (in a material of lower gap) and then detected. This scheme is quite elegant in the sense that the detector is insensitive to thermalized phonons. It has been partially demonstrated experimentally by von Feilitzch and coworkers [32] and by Zehnder [5] This method involves, however, the development of relatively complex devices.

5. Conclusion

There is no lack of ideas in this new field of cryogenic detectors and some back of the envelope calculations give tantalizingly high sensitivity and resolutions. The experimental results are coming more slowly, as is natural in a field where the logistics (cryogenic techniques, low noise electronics) are not too easy. Some of them are quite encouraging, but it is clear that there is no lack of challenges either!

Table I Cryogenic detector developments

	Institutions	Physics Interests
Phonon Detectors		
Mc Cammon, Moseley et al [3,4]	Wisconsin, Goddard	X Ray Astronomy
Silver et al [40]	Livermore, UC Berkeley LBL, UC Irvine	X Ray Astronomy
Coron et al [12]	"Bonus" Collab. Meudon, CERN, Aarhus, NYU	Ho (163), X Ray
Niinikoski [41]	CERN	Neutrino
Fiorini et al [14]	Milano	Double Beta
Smith et al [14]	Rutherford, Imperial Coll.	Dark Matter
Von Feilitzsch et al [31]	Munich: Technical University	Instrumentation, Neutrinos
Sadoulet et al [35]	LBL,UC Berkeley	Dark matter
Lanou, Seidel, Maris [42]	Brown University	Solar Neutrinos (rotons)
Cabrera et al [39]	Stanford, San Francisco State	Coherent neutrinos (Ballistic Phonons)

	Institutions	Physics Interests
Superconducting Granules		
Waysand et al [17]	Paris VII/College de France	Imaging/ Solar neutrinos
Gonzales et al [21]	Annecy	Solar neutrinos, Dark Matter
Von Feilitzsch et al [31]	Munich: Technical University	Instrumentation, Neutrinos
Pretzl, Stodolsky [22]	Munich: Max Planck Institute	Coherent neutrino scattering
Drukier et al [23]	U. British Columbia U. South Carolina	Dark matter, Double Beta
Superconducting films		
Cabrera et al [25]	Stanford, San Francisco State	Instrumentation
Tunnel Junctions		
Von Feilitzsch et al [31]	Munich: Technical University	Instrumentation, Neutrinos
Zehnder [30]	SIN	Neutrino, Instrumentation
Twerenbold	ESA	X ray Astronomy
Barone,Gray [29]	Napoli,Argonne	Instrumentation
Booth [16]	Oxford	Solar neutrinos
Bland	San Francisco State	Solar neutrinos

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