Phonons and low temperature detectors: what is understood?

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Abstract. The great development of the Low Temperature Detectors either in the form of bolometer or as STJ was possible because most of the functioning is well studied. This has made possible the detection of radiations or particles from the sub eV range up to MeV particles. The size of the detectors range from a hundredth of a millimeter to masses up to nearly 1 kg. The standard functioning of these two devices will be outlined. Some fancy aspects, not so well understood, will be discussed. Finally a few choosen applications will be presented.

1. Introduction

Many things are understood in the cross play between phonons and low temperature detectors. Very good reviews exist on low temperature detectors and peculiarly an entire book edited on the subject by C Enss [1]. J Wolfe’s book on phonons is also highly recommended as reference on the subject [2]. The idea that low temperature could help in measuring energy goes back to Simon [3] who noted that heat capacities decreasing fast would allow small energy to be detected. That this could be extended to single particle was presented first by Ninikoski [4] in a somehow controversial experiment where cosmic rays were detected by their sudden heating of a Spear resistor (a rather complex medium!) used to measure temperature down to below 10 mK. The development remained hidden until Fiorini [5] realized the potential of these devices to the search of the double beta decay. The same year a paper by Moseley, Mather and McCammon [6] discussed with great detail the possibility of 1 eV resolution on a small X ray detector by reducing the temperature to 0.1 K. Note that, despite numerous efforts and progress, this optimistic statement is still not obtained after more than twenty years. Indeed the heat capacity of an insulating crystal (or a superconducting metal well below its $T_c$ temperature) is decreasing as $T^3$ so at a sufficient low temperature any heat would be in principle detectable. This leads to the simple scheme of one class of Low Temperature Detector: an insulating crystal with heat capacity $C$ is connected to a bath at temperature $T$ through a weak heat link with a conductivity $K$. When a particle of energy $E$ heats this crystal, after thermalization the crystal reaches a temperature $T + \delta T$ and $\delta T$ writes $\delta T = E/C$. The system will return to equilibrium with a time constant $\tau = C/K$. As quoted above a calorimeter is composed by an absorber which will transform as perfectly as possible the incoming radiation in heat. A first condition for this is that the size and composition of the absorber is suited to absorb the radiation which is measured. The larger the energy, the bigger the absorber and possibly in a heavy material if one is concerned by gamma rays. The size or weight of the calorimeters ranges therefore from a small fraction of a cubic mm to one kilogram for experiments with high energy gammas. The
assemblage of many bolometers (each around one kg) up to a total of a ton will be needed for double beta decay and dark matter experiments where the number of expected events is very small. The distribution of energy in this process of absorption is well summarized by the Andersen’s scheme [7].

Figure 1 shows that there are many ways for the energy to escape from the absorber, either as ejected electrons or atoms or defects which store energy, or also as light emission in some materials. As a general statement a normal metal is one of the best absorber because a true temperature equilibrium is expected. It has unluckily a large heat capacity and therefore a very small size is required.

Some thermometers are made of doped semiconductors, Si or Ge. A classical way to dope with a good uniformity Ge is to irradiate it with slow neutrons. Transmutation occurs and after decay of the radioactive nuclei a mixing of n and p impurities gives a Mott insulator with the opening of a gap. \( R \) writes:

\[
R = R_o \exp \left( \frac{T_o}{T} \right)^{1/2}
\]

A characteristic of the quality of a thermometer is

\[
\alpha = \frac{T}{R} \frac{dR}{dT}
\]

The electronic needed to measure the large resistance of doped Ge is an amplifier with a very low noise, usually using a first stage made of a Si FET cooled down to 100 K.

A second type of thermometer with a very steep slope is done with a thin strip of a superconductor either a pure one or a bilayer of a superconductor and a normal metal. One could make a choice in \( T_c \) from a few K down to 15 mK (pure W). This low impedance thermometer is measured using a SQUID and SQUID array as a cold low noise amplifier. To avoid any non linearity with the strip resistance and SQUID response, a feedback system keeps the temperature of the thermometer constant. The size of the feedback measures the energy deposited.

A third type of thermometer is a magnetic one with a rare earth ion embedded in a metal. With the interaction between electrons in the metal and the ions the equilibrium is reached quickly thus allowing a reasonable rate of counting. The magnetization is again measured with a SQUID, a feedback on the flux keeps the response of the SQUID constant.

2. Fundamental resolution

A bolometer can be considered as a canonical system (figure 2), that is a system thermally connected to a large ensemble at a fixed temperature \( T_0 \). By definition the temperature of the
Random transport of energy between heat sink and detector over thermal link $G$ produces fluctuations in the energy content of $C$. The magnitude of these can easily be calculated from the fundamental assumption and definitions of statistical mechanics:

$$\Delta E_{\text{rms}} = \sqrt{kT^2 C}$$

**Figure 2.** Fundamental fluctuation noise

**Figure 3.** Signal can still be measured to high accuracy in presence of thermodynamic noise by looking at the “corners”. Here the signal amplitude is equal to the r.m.s. of the fluctuations.

**Figure 4.** Energy resolution in units of the thermodynamic fluctuation noise

canonical system is fixed and equal to $T_0$ [8]. But the energy is fluctuating with a variance $\Delta E = \sqrt{kT^2 C}$. In the absence of incoming external energy this is the limit of the measurement of this energy. The spectrum of fluctuations is flat up to $1/\tau$ and decreases linearly with the frequency. On the other hand, when a particle heats the canonical system, supposing that the internal thermalization is very quick compared to $\tau$, this rapid variation of energy could be extracted taking advantage of this sudden rise of energy (figure 3). This needs naturally to have a large enough bandwidth and no additional noise. By this, one could beat the fundamental limit quoted above. A practical consequence is represented in figure 4 of the possible resolution compared to the thermodynamic limit. Large values of $\alpha$ and a peculiar range of bias power are needed to obtain these very good thermal results [9].
3. STJ (Superconducting Tunneling Junction)
An other class of detector is the STJ in which the tunneling current through the junction is enhanced if one electrode receives a radiation which breaks Cooper pairs in excited electrons. These detectors cannot be built as very large entities because one should keep these electrons for the measure before they decay by emitting phonons. The size of the best systems is around \( mm \) or below, well suited for low energy X rays or visible photons. A fine trick is also to concentrate those electrons by absorption in a large gap superconductor in contact with a smaller gap superconductor. There is an irreversible flux from the high to low gap superconductor and measurement of these electrons by tunneling through the junction (figure 5). By a well built absorber which does not loose phonons before they produce quasiparticles, very good resolutions have been obtained with a large spectrum of energy. See more details in [10].

4. Practical limits obtained in bolometers
We will review (very briefly) the very good results obtained with these detectors. Two extremes are now on the scene from nanowires to kilogram. The nanowires, newcomers, offer so far a very rapid response to optical photons but no energy discrimination [11]. The small bolometers are now detecting visible and infrared photons with remarkable energy resolution. The first on the market were the STJ of the ESA group [12], followed more recently by the raise of the TES (transition edge sensor) helped by the SQUID technology developed by the NIST [13]. The promising newcomers are the MMC with their normal metal absorbers [9]. The large bolometers have also very good results in term of resolution with the (nearly) one kilogram bolometers used in double beta experiments [14]. The alpha spectrum gave the best results in the past with 4.5 \( keV \), at that time twice better than any silicon detectors. This was recently overcome by a MMC detector with a much smaller mass. The CDMS, CRESST and EDELWEISS have also large masses in their bolometers but their qualities reside more in the ability to distinguish between a recoil and an electronic event by a double detection of heat and ionization or light. CDMS is also determining the impact point of the event to eliminate the spurious surface events.

5. Some limitations on the functioning of bolometers
5.1. Thermalization
The description which has been given above suffers from reserves on different points. One is that to speak of equilibrium in a dielectric solid is far from being reasonable. The lifetime of low energy phonons becomes rapidly longer than the measured time needed to return to original temperature. One has argued that it is the surfaces which at the end thermalize phonons, because of metallic depositions, or vitreous substances like glues. We do not believe this is the true explanation because estimations, from the known interaction between metal and phonons
Figure 6. Attenuation of phonons in copper for different phonon frequencies. One could remark the low attenuation of the phonons corresponding to \(10^{-1}\) K.

Figure 7. Energy levels of Al nuclei in a magnetic field applied along the c axis.

which have been done in the past (figure 6), does not support that idea [14]. We believe that the response of the thermometer is mostly given by high energy phonons. If a fine study is done on the thermal response one could see variations also on the shape of the signal except maybe in very small bolometers in which the size allows a large number of interactions on surfaces.

5.2. Extra heat capacities

The quality of the dielectric absorber is to have a heat capacity decreasing as \(T^3\). This is true providing that the crystal does not possess nuclear spin larger than 1/2 and cubic structure. For example in the sapphire Al\(_2\)O\(_3\), Al nuclei are 5/2 spins and a rhombohedral structure. Therefore the nuclei interact with the gradient of the crystalline field and give rise to quadrupolar structure, very well known [14] and studied. Figure 7 represents the energy level versus an applied magnetic field. One sees at zero applied field the quadrupolar splitting with energy of the order of MHz. A simple calculation shows that the heat capacity due to these levels grows as \(T^{-2}\) (Schottky anomaly) down to microkelvin temperatures. This heat capacity is equal to the phonon heat capacity at 250 mK. If in equilibrium at temperature below 250 mK the heat capacity will increase as \(T^{-2}\) rather than decrease. Such an anomaly was seen [16] at \(T = 50\) mK and attributed to glassy impurities!

The quadrupolar interaction will play a role only if the \(T_1\) (time constant of equilibrium between the spin and the lattice) is short enough. The problem is that this time is often not known and depends strongly on the purity of the crystal. Some studies have been done in the past [15] on sapphire which is nearly always slightly doped with paramagnetic impurities playing the role of links between the lattice and the spin of Al.
The same remark applies to metals for which the Korringa coupling gives a path from the quadrupolar energy to the bath. Bi is one of the metal commonly used as absorber and very little is known on his nuclear properties. For superconductors used as absorbers it is suppressed in principle but the spins near the surface may escape from this suppression.

5.3. Hydrogen and rotational compounds
A known additional heat capacity comes from hydrogen molecules which possess rotational energy. Again the relaxation time is not often well known and depends on the substrate. Other compounds like CH$_2$ are supposed to be deposited on surfaces and may gave extra heat capacities. Surface studies are needed to clear up these assumptions.

6. Friction phonons
The mechanical suspension of a bolometer is of primordial importance. Any slightly loose contact will produce heat by friction. In a way, it is remarquable that this phenomenon is seldomly observed. A question which does not received answer is the type of phonons which will be produced in such a process. The only quoted experiment on that was the first CRESST experiment in which a sapphire crystal was firmly hold by tiny spheres of the same material. Some cracks were produced in the main crystal and the propagation of these defects appeared like permanent heat bursts, random in time with a spectrum exponential in energy [17]. They were abundant and a more seldom appearance may occur in any suspended bolometer.

7. A few selected experiments
7.1. Cosmic Microwave Background
It was discovered a long time ago as a permanent noise on a microwave antenna. It was rapidly explained as the fossils photons of the expansion following the Big Bang, now at a temperature of 2.728 K. But after more debate on its fine structure, that is what difference should be measured when looking in different directions tracking the first seeds of accretion which gave galaxies, it was only the COBE experiment which showed this fine structure at a level of $10^{-5}$. This was obtain by (very) well designed heterodyne detectors. To make further refinements, bolometers for microwave at low temperature were among the best designs with balloons and satellite experiments (WMAP, ARCHEOPS) to provide more subtle details. The race is still running with for example the Planck mission which will track a sensitivity 600 times bigger than COBE. The analysis has now conforted the so call Standard Cosmological Model with a density of universe of 1 (that is the density just between expansion and recompression of universe).

7.2. Neutrino Physics
See figure 8. This is an old problem with new solutions. The neutrino is a very elusive particle, first theoretically predicted to account for the loss of energy and momentum in the beta decay. Its existence was proven experimentally by an experiment with 1400 liters of liquid scintillator near a reactor producing a very high flux of antineutrinos. Later on, the first underground experiment with 400 m$^3$ of perchlorethylene showed a deficit in the calculated neutrino flux from the sun ($6.5 \times 10^9$ cm$^2$s$^{-1}$). None of these experiments could measure directly if the neutrino carries a mass and if it is identical with its antiparticle. The possibility of non zero masses and exchange between different savours (mu and tau neutrinos) was proven by other deep underground detection of atmospheric neutrinos (Kamiokande 1998). The study of the end point spectrum of the beta decay could possibly measure the mass. An old experiment on $H^3$ (1952) with an endpoint of 19.6 keV claimed an upper mass of 200 eV !

Continuous progress were made and nowadays bolometers containing Re (end point 2.5 keV) could improve this value down to 2 eV with a total counting of $10^{10}$ events. An other side of the
neutrino physics is the Dirac (neutrino \neq\text{antineutrino}) or Majorana (neutrino = antineutrino) nature. If the later is true, a double beta decay is possible without emission of two neutrinos meaning that a single line with the sum of energy will appear. This type of study is a long track (see for example E.Fiorini [5] which needs very clean radioactive environment to reduce the noise in the surrounding of the line in the energy spectra. Choices are made with nuclei giving a high energy low noise line. A well designed bolometer gives the total energy with an unprecedented resolution. TeO\textsubscript{2} is a well suited material and experiments with near one ton is under preparation with individual crystal of 740 g cooled down to 10 mK. The real challenges are the purity of the material of the bolometer and surrounding supports, the experiment being done in deep underground laboratory together with pure lead and copper protection against the remaining radioactivity (rocks, radon neutron activation). The surfaces remain often a delicate problem, being polluted by various deposition, specially by the radon nucleus daughters.

7.3. Dark matter search
This is also an old problem, new insights and new solutions. It was first proposed by Zwicky in 1933 to account for the relative movement of galaxies. Later on, the rotational curve of objects far away from galaxies shows the presence of concentrate non luminous masses. The CMB experiment has conforted the existence of 25\% of the universe as non baryonic dark matter. A favourit possible candidate is a neutralino, fossil lightest particle of the supersymetric family, remnant of the Big Bang. The lightest in the supersymetric family insures its stability. This particle will be searched at the Large Hadron Collider as a missing energy and momentum (as the neutrino for the beta decay). Its interaction with matter, with a very low cross section, leaves a recoil nucleus after interaction. Apart rapid neutrons, all other radioactivities interact with electrons. The search of this elusive particle is done in a deep underground laboratory to suppress most of the cosmic muons. A heavy shielding of very pure copper and archeological lead (which
has lost his radioactive $^{210}$Pb by decay) removes the radiation from the rock. A polyethylene shield transforms any rapid neutron in slow neutron. Also a covering muon detector is used as a veto. Inside, a dilution cryostat cools down crystals but these bolometers are equipped also with detection of ionization (for Ge and Si bolometers) or detection of light for scintillating crystals. Either method discriminates against most of the standard radioactivity because a recoil produces less ionization or light by a quenching factor much less than one. At this stage, good results were obtain in the past (for example Edelweiss I) but it is not enough to scan the full area of masses and cross sections. A discrimination against surface events is necessary when the limit of the cross section diminishes. Various schemes are tried, detection of phonons before they are thermalized [18], or for ionization detectors interleave electrodes which sign surface events. At the end, the final success will depend on the total suppression of rapid neutrons produced inside the various shields (those coming from the natural fission of $^{238}$U always present in trace in copper or lead).

8. Conclusion
The unprecedented qualities of the low temperature detectors have rendered them unavoidable in many aspects of fundamental and applied physics, from astrophysics and particle physics to biological mass spectroscopy and surface physics. There is no doubt about vigorous development as well as active research in this area even though not all the details of functioning are fully understood.

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