Cryogenic Detection of Particles

Development Effort in the United States

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CRYOGENIC DETECTION OF PARTICLES *

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Abstract

We review the development of cryogenic detectors of particles in the USA, with emphasis on large mass devices. Most groups are still tooling up and exploring basic properties of sensors. We summarize the main discussion themes and describe some of the early experimental results.

1. PHYSICS MOTIVATIONS1.1 Potential Properties of Cryogenic Detectors

It has been realized recently [1] that it may be advantageous to detect particles through processes different from ionization. The break up of Cooper pairs in a superconductor (leading to formation of quasi particles) or the generation of phonons in a crystal provide several interesting properties.

-Detectors sensitive to these processes would be sensitive in the bulk and would be made quite massive (several hundred grams). Some methods may allow to implement good position sensitivity.

-Since the detected energy quanta is much smaller (1 meV for quasi particles, 10^{-6} eV for phonons at 10mk) than for electron-ion or electron-hole pairs (20 eV and 1 eV respectively). It may be possible to obtain very low thresholds and very good energy resolution.

-As explained under section 2.1.5 the combination of phonon and ionization detection may allow to give a signature that an interaction occurred on a nucleus, [2] providing in some cases a much needed rejection of the radioactive background [3].

Because these detectors have to work at very low temperature, they are usually referred to as cryogenic detectors.

1.2 Physics Applications

The above properties have attracted a large number of groups. (See table I for a tentative list of groups developing large mass cryogenic detectors in the USA).

* Talk given at the workshop on cryogenic detectors, Max-Planck-Institute, Munich, Rindberg Castle, March 13, 1987

Table I
Development of large mass cryogenic detectors in the USA

Group	Technique	Dilution Refrig?	Funding
NRL,UBC,PNL/USC BU Drukier et al	Granules,Squid	UBC	Operating funds
Stanford Cabrera,Neuhauser Martoff	Ballistic Phonons Tunnel Junctions +trapping	Yes +He ³	Operating funds
UC Santa Barbara Caldwell,Witherell	Quasiparticles?	No low temper.	$\beta\beta$ Decay
UC Berkeley/LBL Sadoulet,Haller,Lange Steiner,Wang,Park	Phonons. Semiconductor Thermistors	Parasiting now 20mK on order	UCB +LBL
Brown Univ. Maris,Seidel,Lanou	Rotons in He ⁴ Bolometers		Operating funds

The most developed application is the use of bolometer (i.e. phonon detectors) for **X ray astrophysics** [1c]. The goal is to obtain a resolution of 1 eV for each photon.

Cryogenic detectors are also quite attractive for searches of **dark matter** if it is made out of particles (see e.g. Ref. [3] and references therein). They may complement in an essential way [4] the current searches [5] using conventional technologies. This is the main motivation in the USA for the effort of the UC Berkeley / LBL team and of Drukier et al.

The detection of **neutrino coherent scattering** requires also such detectors [6]. This is the main driving force behind the Stanford effort; Cabrera et al. are interested both in detection of reactor and solar neutrinos. Detection of **solar neutrinos** (through neutrino-electron interaction) is the goal of the Brown University effort.

The potential energy resolution and the bulk sensitivity make these detectors very interesting for **double beta decay** [7,6]. UC Santa Barbara is particularly interested in this application.

This energy resolution may be also interesting for electron neutrino mass measurement [8] but as explained by Fiorini [9] at this workshop the problem of pile up is severe.

2. DISCUSSION THEMES

We are therefore witnessing in the USA as in Europe, a burst of interest for cryogenic detectors. However, in the States, most groups are still in the tooling up and exploration phase. It may be

interesting to describe some of the discussions going on.

2.1 What is the Best Sensor?

When launching a development, the first decision to take is the kind of sensor to choose, in order to get the low threshold, energy resolution and localization needed. Let us review the candidates.

2.1.1 Superconducting Granules. This method is pushed very actively by Drukier et al. and Kotlicki[10] has described at this workshop their interesting results. However, it is the opinion of this author that granules are too rough bolometers for many applications (including dark matter searches). At low energy they are basically threshold detectors not providing the much needed energy spectrum and the difficulty to make 10^{12} identical detector elements (in order to have 1 kg of sensitive material) may be enormous.

2.1.2 Quasiparticles Detectors. Quasiparticles detection with tunnel junctions [11,12] may provide in particular excellent energy resolution. Caldwell et al. are very much interested in the possible use of this method with ^{100}Mo for double beta decays. An Argonne group (in collaboration with Naples) is developing tunnel junctions and the effort of Cabrera et al. described below (2.1.1) may eventually be applied also to detection of quasiparticles created by particle interactions. Note that bolometry does not work very well with a superconductor since most of the energy is transformed in quasiparticles which have a long recombination time [12].

2.1.3 Phonon Detection through Bolometry.

A first method to detect phonons is basically to measure a temperature rise with a thermistor. This bolometric method is explored at very low temperature with semiconductor thermistors by the Berkeley team. Transition edge superconducting thermistors have not yet attracted any American group [13] because of the very narrow temperature range of operation, the difficulty of coupling with amplifiers because of their low impedance (100Ω) and the variability of film properties. A new bolometric method based on the variation of skin depth in a superconductor has also been proposed [14].

Let us refer finally the reader to the talk of G. Seidel at this workshop [15] for a description of the method proposed by the Brown University team to detect high energy phonon configuration in liquid helium (rotons) with bolometry.

2.1.4 Phonon Detection with Tunnel Junctions.

A second method to detect phonons of high enough energy (>1 meV) is to use tunnel junctions. Phonons break Cooper pairs in a superconducting film and the created quasiparticle produces a current in a junction. This has been the choice of Cabrera et al. in Stanford. However for this scheme to work, junction areas should be maintained small and quasiparticles will have to be trapped below the junctions in a way similar to that proposed by Booth [11].

2.1.5 Combination of Phonon and Ionization Detection.

A low energy recoiling nucleus is providing much less ionization than an electron of the same kinetic energy (for a review see e.g. [16]). The rest of the energy should appear in heat. If both components

can be measured, a powerful tool of rejection of interactions on electrons (due to background radioactivity) could be obtained. The Berkeley team is planning to explore this possibility. The main difficulty may be to prevent too large a trapping of ionization products on impurities.

2.2 What is the Importance of Ballistic Phonons?

A second major discussion theme is the role of ballistic phonons in phonon detectors at low temperature.

2.2.1 The Thermal Equilibrium Description .

In the usual description of bolometers [17] it is stated that the intrinsic limit is given by the energy fluctuation in the detector. If it is a crystal of heat capacity C at temperature T , it is given by:

$$\Delta E = \xi \sqrt{(kT^2 C)} = \xi \sqrt{(kT^5 C_0 M)} \quad (1)$$

where ξ is a factor of the order of 2.5 including the Johnson noise of the bolometer. In the second we have used the Debye law:

$$C = C_0 M T^3 \quad (2)$$

where M is the mass of the crystal. The basic idea [1] of large mass phonon detectors is then to compensate the increase of mass with respect to conventional bolometers by a much smaller decrease of temperature. This description however assumes that phonons are in thermal equilibrium.

2.2.2 Ballistic Phonons

As first noticed by Cabrera in this context [18], this is almost certainly wrong. At very low temperature the mean free path of phonons is very long (i.e. they are ballistic, see e.g. [19]) and the high energy phonons produced in an interaction will stop cascading down at an energy much higher than the crystal temperature because of the disappearance of anharmonic terms and because of phase space restrictions. The exact energy distribution is poorly known but their average energy is believed to be of the order of 10^{-3} eV.

2.2.3 Impact of Detector Design

Such a property can be helpful in the detector design. It is no more the total heat capacity of the crystal which is relevant but the sensitivity of the sensors. Therefore it may be possible to work at larger temperature or with larger volume. Devices sensitive only to high energy phonons such as tunnel junctions can be used. Finally good localisation may be obtained by timing or by focusing (Cabrera [18]).

However in spite of its positive aspects, ballistic propagation of phonons may have detrimental effects (see also [20]) such as a position dependence response due to focusing, a variation from event

to event of the non ballistic component due to e.g. fluctuations in the cascading down or the number of reflections on surfaces defects and isotopic impurities, escape of phonons along some crystal support made of the same material (an effect seen by Moseley et al. in their X ray detector design [21])etc...

Before experimental results are gathered with a variety of sensors, it is difficult to optimize a detector design.

2.3 Parasitic Effects

It should be realized that the extrapolation, say, from the result of McCammon et al [1c] which use crystals of 10^{-5} grams to 10 grams or 1 kilogram crystal is enormous and requires to work in a much lower temperature region, which is from the point of view of solid state physics, a nearly virgin territory! Let us discuss a few of the questions.

2.3.1 Is the Debye Law Valid at Very Low Temperature?

Note that of the ballistic phonons are indeed predominant the question may be irrelevant.

2.3.2 What is the Effective Phonon Coupling to the Sensors?

Most groups are leaning in the direction of composite detectors where there is a mechanical interface between the sensor and the crystal. Phonon velocity mismatch between the two sides and absorption on one side leads to a Kapitza resistance varying rapidly with temperature. Phonons may then be internally reflected, and not couple effectively with the sensor.

2.3.3 How does the Physics of the Sensors Evolve with Temperature?

For instance the results of Berkeley described below may indicate a decoupling of electrons of the thermistor from the phonons of the lattice, which may prevent proper biasing of the bolometer.

Another example is the problem of leakage current in tunnel junctions which in some case have a non temperature-dependent component which is poorly understood.

3. EXPERIMENTAL RESULTS

Let us finally turn to the few experimental results which have been gathered so far in the USA. A. Kotlicki [10] described results on superconducting granules and we will not cover them here. We will distinguish between three regions.

3.1 1.4 Kelvin

Such temperatures are easily obtained by pumping on helium and it is possible to have a fast turn around time which makes this region an ideal training ground to learn the basics of the technology and to test electronics.

Detection of α particles is relatively easy and have been achieved at least by three groups : B. Cabrera et al. in Stanford with transition edge thermistors (Fig 1), N. Wang et al. in Berkeley with NTD bolometer (Fig 2) and E. Silver at Livermore. Note in both figures the sharp rise time and the relatively small time constant of the decay.

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Fig 1. Detection of alpha particles with transition edge detector (from Neuhauser et al [18]).

- a) Typical pulse caused by an alpha particle incident on the superconducting film.
- b) Corresponding pulse height spectrum
- c) Typical pulse when the alpha particle is incident on the backside of the silicon wafer.
- d) Corresponding pulse height spectrum.

Figure 2. Pulses observed with alpha particle of 5.8 MeV in a bolometer of $6 \cdot 10^{-3}$ gram at 1.4K. (N. Wang et al, Berkeley)

Usually those results are limited by non-optimal design. For instance the Berkeley result could be theoretically improved by a factor 20 on signal height, a factor 3 by optimal filtering and a factor 10 on the electronics noise and reach eventually the thermal limit of 6keV r.m.s. It remains to be seen whether parasitic phenomena will not limit performance.

3.2 The 300 mK-100mK Region

The Stanford team is tooling up, assembling a 300 mK ^3He refrigerator and manufacturing tunnel junctions with lithographic techniques.

The best work for the time being is that of the Wisconsin-Goddard group [1c] working both at 300mK and at 100mK. Their best result so far as a FWHM of 11 eV of the baseline indicating potential threshold of 15 eV for a 10^{-5} gram crystal. However their resolution for 6 keV X rays is degraded presumably by metastable trapping of electrons or holes at impurity sites leading to a fluctuation of the prompt heat release. This effect is minimized by using a composite bolometer with Hg-Cd-Te of approximately zero gap. Their resolution at 6 keV is a record 35eV FWHM. However in the process, the heat capacity has been increased and base line fluctuation have similar width.

This group is now designing their final device with which they hope to go down to few eV FWHM. However they encounter three problems [21]:

- a) Escape of the phonons along the silicon supports of their detector [1c].
- b) Parasitic phenomena attributed to phonon electron decoupling or to electric field dependence of the resistance.
- c) Excess $1/f$ noise which does not seem to come from contacts.

3.3 The 20 mK Region

The Berkeley group decided to go directly to low temperature. While waiting for our own dilution refrigerator to be delivered in September, we borrow time on other refrigerators to use Neutron Transmutation Doped (NTD) germanium thermistors.

Our first attempt at low temperature, (confirmed since the workshop by additional measurements) indicated an extreme sensitivity of the thermistor resistance on the electric power dumped into it. 3.10^{-16} Watts are sufficient at 18 mK to induce a significant change of the resistance!

Because of the weak electric field involved (0.01 V/cm), it is tempting to neglect in first approximation the field dependence of the resistance and compute an effective electron temperature from the measured resistance. The derivative of the electric power with respect to this quantity gives an effective thermal conductance which is plotted in Fig 3 for different bath temperatures. These results are **very preliminary** but are suggestive of a very sharp break off of the coupling of electrons to the lattice at low temperature. Another explanation could be given in terms of a very strong dependence on the electron field.

We are currently checking in detail this unexpected result and evaluating its impact on the sensitivity

of NTD bolometers at very low temperature.

Figure 3. Effective thermal conductance between electron and lattice in a NTD germanium thermistor, as a function of the electron temperature. T_0 is the heat sink temperature. (N. Wang et al, Berkeley).

4. CONCLUSION

As shown above, there is a lot of enthusiasm rising in the USA for cryogenic detectors and many groups are tooling up and starting development.

It is clear however, that the questions to solve are as much at the frontier of solid physics as at that of technology, and several years of painstaking effort are ahead, before a working device of reasonable size could be made. This will require reasonable funding to escape the common pitfall of superficial, undercritical effort. Coordination and exchange of information will be essential between the various groups in the US and Europe.

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