Thermal Detectors for Underground Physics

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A review of developments and use of low temperature thermal detectors in underground physics is presented.

1. Introduction

Experiments performed in underground laboratories can make significant contributions to particle and astrophysics. Some goals of these experiments are the search for the 0vββ-decay, dark matter and the detection of neutrinos via the coherent elastic scattering on nuclei.

In searching for 0vββ-decay it is helpful to have a detector which is simultaneously the source. For background suppression the detector should have a high energy resolution. The classic type of detector for this experiment is the germanium ionization detector. For testing other ββ-decay candidates one wants to be able to build detectors of materials other than germanium.

The interaction of weakly interacting dark matter candidates or neutrinos in a detector would result in a low energy nuclear recoil. A dark matter search therefore requires a detector with a low energy threshold for the detection of nuclear recoils, which have a low ionization efficiency, limiting the energy threshold for classical ionization detectors.

To meet the demands of these experiments new detectors are being developed. In general a detector counts the excitations in a gas, liquid or solid created by the interaction with a particle. In conventional detectors these excitations are ions, electrons, photons, electron hole pairs, whose energies are on the order of eV. The energy resolution is ultimately limited by the statistical fluctuations in the number of excitations created. To improve the energy resolution one has to count other types of excitations which have lower energies, such as the particle-induced creation of phonons in solids, quasiparticles in superconductors, or rotons in liquid helium. These excitations have energies on the order of meV or lower. To avoid thermal excitation such a detector has to be at low temperatures.

Low temperature detectors should therefore be able to achieve lower energy thresholds, higher energy resolutions, and to cover a wider range of detector materials. The following types of cryogenic detectors might be applied to underground experiments.

1. Superconducting granules
2. Tunnel junctions
3. Calorimeters
4. SICAD
5. Hybrid detectors

This article will concentrate only on the first three types since the last two are covered in the article by Betty Young. For cryogenic detectors covering other applications the reader is referred to the literature [1-4].

2. Granule detector

The superheated superconducting granule detector (SSG or SSGD) consists of many spheres of a type I superconductor in a metastable state in a magnetic field. Ideally these spheres are all of the same size, with typical diameters ranging between 1 μm to 100 μm.

To understand how this detector works one has to look at the phase diagram of a single granule (fig. 1). A superconducting granule remains in the superconducting state up to a superheating field $H_{SH}$ larger than the thermodynamical critical field $H_C$. A granule in the normal conducting state can only become superconducting if the magnetic field is lowered under the supercooling field $H_{HC}$ which is lower than $H_C$. To use this as a particle detector one applies a magnetic field somewhat smaller than the superheating field boundary, the sphere can be driven nor-

invited talk at the 3rd Int. Conf. on Advanced Technology and Particle Physics, Como, Italy, June 22-26, 1992.
Figure 1. Phase diagram of a granule. $H_C$ is the thermodynamical critical field, $H_{SH}$ the superheating and $H_{SC}$ the supercooling field.

A granule detector is therefore a threshold detector providing some position information. The detector material is limited to type I superconductors. A list of some type I superconductors including their critical temperature $T_C$ and their critical field $H_C(0)$ at $T = 0$ K is given in table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_C$[K]</th>
<th>$H_C(0)$[gauss]</th>
</tr>
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<tr>
<td>Pb</td>
<td>7.2</td>
<td>863</td>
</tr>
<tr>
<td>Sn</td>
<td>3.7</td>
<td>305</td>
</tr>
<tr>
<td>In</td>
<td>3.4</td>
<td>293</td>
</tr>
<tr>
<td>Re</td>
<td>1.7</td>
<td>200</td>
</tr>
<tr>
<td>Al</td>
<td>1.2</td>
<td>99</td>
</tr>
<tr>
<td>Ga</td>
<td>1.1</td>
<td>51</td>
</tr>
<tr>
<td>Zn</td>
<td>0.85</td>
<td>53</td>
</tr>
<tr>
<td>Zr</td>
<td>0.8</td>
<td>47</td>
</tr>
<tr>
<td>Cd</td>
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<td>30</td>
</tr>
<tr>
<td>Ir</td>
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<td>16</td>
</tr>
<tr>
<td>W</td>
<td>0.016</td>
<td>1</td>
</tr>
<tr>
<td>Rh</td>
<td>0.0003</td>
<td>0.05</td>
</tr>
</tbody>
</table>

At present there are two main groups working on the granule detector. A group in Bern, Switzerland studies the dynamics of the phase transition of a granule [5]. Furthermore they perform irradiation experiments with 70 MeV neutrons at PSI as a test for the sensitivity of the SSG to nuclear recoils [6]. The latest results of this experiment are published elsewhere in these proceedings [7].

A second group in Vancouver, Canada tries to solve the sensitivity problem of the SSG. In a large sample of granules the superheating phase boundary is broadened (up to 30%) resulting in a high and poorly defined threshold. Two major effects are responsible for this spread:

First, crystalline effects in the granules, like defects acting as nucleation centers or an anisotropy of the superconducting gap cause different superheating fields. This means each granule has a different phase diagram.

Second, magnetic interactions between the granules cause that the field applied to a granule depends on the state of all other granules.
To reduce these problems the Vancouver group produces regular arrays of granules by evaporating an array of equally sized spots on a substrate [8–10]. After a melting procedure in the presence of some wetting agent the spots have become spheres. They call this type of set up "PASS" for “planar array of superheated superconductors”. The improvement over a colloid sample is about a factor 8.

Progress is being made with granule detectors. Nevertheless sensitivity is still a problem and a lot of work has to be done until a large (1 kg) detector can be realized.

3. Superconducting Tunnel Junctions

Superconducting tunnel junctions (STJ) consist of two layers of a superconductor separated by a thin insulating layer. When a voltage is applied across the junction, a current due to tunneling of quasiparticles can be observed. This voltage has to be smaller than $2\Delta/e$, where $2\Delta$ is the energy gap of the superconductor and $e$ the electron charge. In order to keep the dark current of the STJ as small as possible the operating temperature has to be much smaller than the critical temperature of the superconducting layers. If a particle interacts in one layer, it breaks up Cooper pairs and creates quasiparticles. This results in an excess tunnel current. The integral over this excess tunnel current is a measure of the energy deposited.

In order to keep the tunneling probability of the quasiparticles high the thickness of the superconducting layers has to be thin. This means one cannot make massive junctions, whereas for underground physics one usually needs to have massive detectors. The solution is to put the STJ onto a massive absorber which can be either a dielectric or a superconducting crystal. In a dielectric absorber a particle creates nonequilibrium phonons which can be detected by a STJ if the phonon energy is larger than $2\Delta$. This was shown to work by a group at the Technical University of Munich [11]. The critical temperature $T_C$ of a superconducting absorber has to be higher than that of the junction, so that quasiparticles created in the absorber can be collected by the junction.

Recent results in this field were published by a group in Oxford [12]. They work on dielectric and on superconducting absorbers [13, 14]. As a sensor they use many ($\approx$ 200) tunnel junctions in series, calling this a serial array of superconducting tunnel junctions (SASTJ). Thus they are able to enlarge the area covered by the sensor, while decreasing the capacitance and increasing the dynamic resistance at the same time. Both properties help to improve the noise performance of the sensor. (If one would try to cover a large area with a single STJ one would increase the capacitance and decrease the dynamic resistance of the sensor and therefore loose in noise performance.)

To test dielectric absorbers the Oxford group built a device which consists of a 0.5 mm thick slice of silicon with an aluminum SASTJ of 1 cm$^2$ area on one side. The operating temperature was 360 mK. The current pulses induced by the absorption of 60 keV and 25 keV photons show a fast leading edge and a long exponentially decaying tail (Fig. 2). The leading edge was found to be position dependent and was attributed to the first impinging burst of ballistic phonons. The
slow tail was interpreted as a signal from some kind of reverberation of phonons in the crystal. The integral over the slow tail was found to be a measure of the energy deposited giving an energy resolution of 700 eV (FWHM) for 25 keV photons (fig. 3).

For testing superconducting absorbers they used a niobium single crystal (15 mm long, 10 mm diameter, 12 g) and evaporated two SASTJs on each end. The SASTJs are made of 200 Al-oxide-Al junctions each. Each SASTJ covers an area of $3 \times 6 \text{ mm}^2$. The SASTJs on the same side are connected in series. The niobium crystal was irradiated with 5.5 MeV $\alpha$-particles. Between crystal and source was a collimator having five holes equally spaced over the length of the crystal. The detector was operated at 360 mK. Position information could be obtained from the pulse heights measured with the SASTJs on different ends of the absorber (fig. 4) as well as from timing information. The position resolution was estimated to be better than 0.5 mm. The energy resolution for illumination of the absorber through the center hole of the collimator was 170 keV (FWHM) for 5.5 MeV $\alpha$-particles. These results show that SASTJs can work on massive absorbers, providing energy and position information. Dielectric and superconducting absorbers can be used. Further improvements due to lowering of the operating temperature seem feasible.

4. Calorimeters

A calorimeter consists of an absorber in which the particle interaction takes place and a thermometer attached to the absorber (fig. 5). The basic idea of an calorimeter is to wait until the high energy phonons created by a particle interaction have thermalized, thermometer and absorber are in thermal equilibrium and the temperature of the calorimeter can be measured. The change in temperature $\Delta T$ due to an energy deposition $E$ is given by

$$\Delta T = \frac{E}{C}$$
where $C$ is the heat capacity of absorber plus thermometer. To cool down to its equilibrium temperature after an event the calorimeter is connected to a heat sink via a thermal link with thermal conductance $g$. The time constant $\tau$ for cooling, which is the decay time of a pulse is

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

One has to keep the heat capacity $C$ low in order to obtain large signals. To allow high absorber masses the specific heat capacity per unit mass of the absorber material has to be low. This is the case for dielectric solids or superconductors at a temperature far below their critical temperature $T_c$. Since the heat capacities of these materials decrease when one lowers their temperature, one can gain a lot in sensitivity if one runs a calorimeter at the lowest possible temperatures.

The essential part of a calorimeter is the thermometer. At present there are three different types of thermometers in use:

1. Doped semiconductors
2. Superconductors
3. Paramagnetic materials

4.1. Semiconducting Thermistors

Strongly doped semiconductors undergo a metal to insulator transition at low temperatures. Lowering the temperature their resistance rises steeply. They can therefore be used as thermometers. The most widely used semiconducting thermistors are neutron transmutation doped (NTD) germanium thermistors [15, 16]. Calorimeters with semiconducting thermistors can be operated over a wide temperature range. Since semiconducting thermistors have a high impedance they are well matched to conventional electronics. To avoid long RC time constants due to stray capacitances, the leads to the thermistors have to be short. This problem is usually solved by using preamplifiers with cold input stages. One also has to take care to suppress noise due to microphonics.

Several groups are working in this field. In France a group has built a detector consisting of a 24 g sapphire absorber with a 1.28 mm$^3$ NTD germanium thermistor [17, 18]. The device was operated at 55 mK. This detector showed a resolution of 3.7 keV (FWHM) for 60 keV photons (fig. 6). However the baseline noise corresponded to 600 eV (FWHM), showing that this detector does not behave as simply as the naive model of a calorimeter presented above. With this detec-
A tor the French group is presently performing first background tests in the Frejus tunnel.

A Italian group is already running an experiment with a low temperature calorimeter searching for the 0νββ-decay of 130Te [19-21]. They constructed a calorimeter with a 73.1 g single crystal of tellurium oxide as absorber and a NTD germanium thermistor. The operating temperature is 16 mK. They use a specially built low radioactive background dilution refrigerator surrounded by an outer lead shield. To minimize RF interference the cryostat is placed in a Faraday cage. The whole experiment is located in the Gran Sasso Underground Laboratory. The calorimeter shows an energy resolution between 5 and 10 keV at energies ranging from 300 keV to 6 MeV.

![Energy spectrum in the region of the neutrinoless double beta decay (2528.8 keV) obtained in 1389 h accumulated running time.](image)

Figure 7. Energy spectrum in the region of the neutrinoless double beta decay (2528.8 keV) obtained in 1389 h accumulated running time.

After an accumulated running time of 1389 hours they have seen no evidence for the 0νββ-decay of 130Te. Their lower limit for the lifetime in the 0ν-channel $\tau_{0\nu} > 2.5 \times 10^{31}$ years (90% c.l.). This result is three orders of magnitude more stringent than results for the same nucleus obtained with conventional detectors. This limit exceeds the value of geochemical measurements for inclusive $(2\nu + 0\nu - \beta\beta$-decay) lifetime; therefore the geochemically observed $\beta\beta$-decay of 130Te has to be attributed mainly to the $2\nu$-channel.

Very recently this group improved their shielding lowering their radioactive background by one order of magnitude. They are preparing an experiment with four tellurium oxide crystals of a mass of 350 g each. They also have enriched 130Te and plan to build a calorimeter out of this material.

These results show that calorimeters with semiconducting thermistors are up to now the best developed cryogenic detectors which are already highly competitive to conventional detectors. Nevertheless these type of calorimeters are still improving in performance.

4.2. Superconducting Thermometers

A superconductor shows a strong temperature dependence of its electrical resistance in a narrow region around its transition temperature $T_C$. In this transition region the resistance goes from the normal conducting value to zero in the superconducting state. A film made of a superconducting material can therefore be used as a thermometer. Such transition edge thermometers can be used in two different ways.

First, one can produce a long very narrow (some µm) film in the shape of a meander. The detector is stabilized just below the transition. A particle-induced burst of nonthermal phonons drives a small fraction of this film normal. If a current is run through the film this normal conducting fraction can be detected as a voltage signal with a conventional preamplifier [22]. This type of operation is used in a SICAD detector, which is explained in detail in another contribution to these proceedings.

Second, one can use short, wide films, both dimensions of some mm. The detector is stabilized within the transition. A temperature rise of the absorber heats up the whole thermometer. The particle-induced temperature rise of the thermometer is usually much smaller than the width of the transition. This type of thermometer is naturally a low impedance device and well matched to a SQUID as preamplifier [23].

This type of thermometer is used by two groups...
in Munich, Germany which work in collaboration. The group at the Technical University concentrates on superconducting absorbers, while the group at the Max-Planck-Institute of Physics uses dielectric absorbers. Both use the same facilities to produce their thermometers.

Superconductors can provide an interesting alternative to dielectric absorbers. It has been experimentally observed that in dielectric absorbers part of the energy deposited in the absorber gets trapped in some metastable states (e.g. electron-hole pairs trapped by impurities). The lifetime of these metastable states can be very long at low temperatures and the energy resolution can be strongly affected by the statistical fluctuations of this loss process [24]. The optimal solution to this problem would be a material without a band gap such as a metal. However metals have a very high specific heat capacity, which limits their use as absorbers. Superconductors operated at a temperature far below their critical temperature $T_C$ have a very low heat capacity and a small energy gap in the order of meV and should therefore be superior to dielectric absorbers.

The group at the Technical University of Munich built several calorimeters using vanadium (fig. 8) and molybdenum absorbers [25, 26]. The thermometers were iridium films with a critical temperature around 123 mK (fig. 9). With a vanadium absorber of 15 g mass they achieved an energy resolution of 70 keV (FWHM) for 5.8 MeV $\alpha$-particles (fig. 10). A second calorimeter consist-

![Figure 8. Experimental set up of a vanadium crystal with an iridium thermometer.](image)

![Figure 9. Transition curve of an iridium thermometer.](image)

![Figure 10. Energy spectrum obtained with a calorimeter consisting of a 15 g vanadium absorber and iridium thermometer. Irradiation was performed with a three-line $\alpha$-source.](image)
ing of a 35 g Molybdenum absorber showed a resolution of 10% for 5.8 MeV α-particles.

These experiments show that massive calorimeters can be built using superconducting absorbers. Lowering the temperature below the presently used value should bring substantial improvements in the resolution.

Lower operating temperatures are one of the goals of the work done at the Max-Planck-Institute. This can be done in three ways:

I. One can produce thermometers of pure metals with low critical temperature such as tungsten (Tc = 15 mK). The group at MPI succeeded very recently in producing a tungsten film showing a transition at 14 mK [27].

II. Alloying a normal and a superconductor can give a superconductor with reduced Tc. However, it is technically difficult to produce thin films of such a material.

III. When a superconducting film is overlaid with a normal conducting film, both act together as a single superconductor with a reduced Tc. This is called the proximity effect. In principle the critical temperature can be tuned by varying the thicknesses of the normal and the superconducting layer. This is being tested at MPI.

In the first attempt to build a calorimeter with an iridium/gold proximity thermometer on a silicon crystal the production process was not yet under control. As a result the thermometer showed a very broad transition, starting at 110 mK and still being not totally superconducting at 20 mK (fig. 11) [28]. Due to its flat slope such a thermometer is quite insensitive, but one has the chance to study the behaviour of the calorimeter over a wide temperature range. The absorber used for this calorimeter was a 19 g silicon crystal. In spite of the insensitive thermometer this calorimeter showed an energy resolution of 1 keV (FWHM) for 60 keV photons (fig. 12). This resolution was achieved at an operating temperature of 20 mK. The shape of the pulses could be fitted with three exponentials, one describing the rise time and two the decay of the pulse. The presence of two decay times is in disagreement with the simple thermal model of a calorimeter. Comparison of pulses taken at different operating temperatures led to the conclusion that the
fast part of the pulse is caused by high energy phonons and the slow part by thermal phonons. A more detailed description of this model can be found elsewhere [29].

The results obtained with this quite insensitive iridium/gold thermometer showed the importance of running this type of calorimeter at low temperatures. By using better thermometers an improvement of an order of magnitude seems possible.

4.3. Paramagnetic sensors

The magnetic susceptibility of paramagnetic materials shows a strong temperature dependence. Paramagnetic materials can therefore be used as sensors for low temperature detectors. These materials act not as temperature but as a thermal energy sensor. The energy deposited by a particle in the absorber splits up in sensor and absorber according to the ratio of the heat capacities. Therefore the heat capacity of the sensor must be much larger than the heat capacity of the absorber. The thermometer is read out with a SQUID without dissipating measuring power in the calorimeter. This work is done by a group at the Walter Meissner Institute in Munich [30, 31]. Using a 121 g silicon absorber operated at 28 mK they observe particle-induced pulses. The rise time of these pulses is \( \approx 40 \text{ ms} \). This group claims an extremely good signal to noise ratio but has not yet shown a spectrum. Therefore the energy resolution of this device is still unknown.

5. Other Detectors

There are many other ideas for low temperature detectors, which still need development.

One new type of detector which recently showed \( \alpha \)--particle induced pulses is being developed in USA at Brown University [32, 33]. It uses superfluid helium as an absorber. A particle interaction in the helium creates rotons. These can travel to the surface of the helium and evaporate helium atoms which are then detected with a calorimeter placed right above the surface of the helium bath.

6. Conclusions

At the present status of development of large mass, low temperature detectors, energy resolutions up to 1 keV and masses up to several hundred grams can be achieved. Such detectors are able to detect nonionizing events and are therefore in some applications already superior to conventional detectors. Furthermore they can be built out of a wide range of materials, providing a higher flexibility in the design of new experiments. The relatively slow pulses of low temperature detectors, are not a limitation when rare processes are to be investigated, as in underground physics.

Low temperature calorimeters are running successfully in the search for the \( 0\nu\beta\beta \) decay. Experiments searching for dark matter using calorimeters or detectors with SASTJ's seem feasible within the next years. These facts and the results of low temperature detectors in other fields show that cryogenic detectors are already competitive with conventional detectors. Since further improvements are expected, the contribution of cryogenic detectors to underground physics will grow within the next years.
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