Recent Results on Cryogenic Detector Developments

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Abstract

Recent developments on detectors operated at low temperatures are discussed. This includes new suggestions for dielectric and magnetic calorimeters and recent developments on superconducting grain detectors. In addition experimental results on phonon detectors and detectors based upon quasi particles in super conductors are presented.

Introduction

Among many other experimental developments in other fields of physics numerous attempts to explore the limits of the standard theory of electroweak interaction as well as new generation experiments in X- ray astrophysics physics and cosmology require detectors with considerably improved energy resolution and very low energy threshold. Presently used detection techniques based upon semiconductors or gas ionization have been developed since several decades. They are scarcely expected to be further improved considerably. It therefore seems advisable to search for new detection principles.

Generalizing one can understand a detector as a system consisting of a material in which the absorption of energy leads to detectable excitations. The amount of these excitations is a measure of the energy deposited. The minimal energy required for one excitation determines the detection threshold energy and the statistics of the excitations. This statistics for a given amount of energy absorbed finally limits the energy resolution if the detector operates in an idealized way.

For the operation of a detector one must require that no other radiation than the one which is supposed to be detect leads to an excitation of the detector. First of all to avoid thermal excitations this requires

$$KT << \Delta$$

where Δ is the energy gap for the excitations mentioned and K and T the Boltzmann constant and the operating temperature respectively.

Basically any solid state or atomic property showing a level structure with small energy gaps can serve as a basis for such a detector provided an adequate read out technique is available. There is in fact an increasing number of experimeters working on such new detection techniques. In this lecture I shall discuss briefly developments based upon magnetic two level spin systems, the temperature dependence of the dielectric constant and metastable superconducting grains. Further more phonon excitations and the detection of quasi particles in superconductors will be discussed.

1. Magnetic Bolometer

The detector consists of an radiation absorber which either contains ore is linked to a magnetic spin system. The absorption of energy than leads to a change of the relative population of the magnetic spin levels leading to a change of the magnetic susceptibility of the device. M.Bü hler and F. Umlauf /1/ have demonstrated this technique for the detection of 5.5Mev α-particles. The detector consisted of a sapphire crystal glued to a Y(Er) Al garnet serving as a temperature sensitive element. The Er^{3+} ions have a Kramers doublet and the magnetization of the garnet was measured with a superconducting quantum interference device (SQUID). The operating temperature was around 400 mK.

The energy splitting Δ of the Kramers doublet in a magnetic field H applied is

$$\Delta = 2\mu H,$$

where μ is the atomic magnetic moment. When the spin system absorbs the energy ΔE the number of induced spin flips is given by

$$\Delta N = \frac{\Delta E}{\Delta}.$$

The corresponding change of the magnetic moment of the sample than is $\Delta M = \Delta N \times 2\mu$ and therefore the energy sensitivity

$$\frac{\Delta M}{\Delta E} = \frac{1}{H}$$

which is independent on the operating temperature. The energy gap Δ can be tuned with the magnetic field applied. With a total detector mass of 7.5g (150mg for the Y(Er)Al sensor) they obtained a signal to noise ratio of 80. The signal decay time was 500 ms, the rise time short as compared to this ($\tau_r \sim 100ms$). This result was published as a demonstration of the detection principle and is claimed to have ample room for further improvements.

2. Dielectric Calorimeter

The dielectric calorimeter is based upon the temperature dependence of the dielectric constant of the radiation absorbing material. It was first suggested by Moon and Steinhard (1938)/2/ and recently reinvestigated by E.H.Silver et al /3/. The dielectricum serving as radiation absorber is sandwiched between the plates of a capacitor which is loaded with a given amount of electric charge. A change of the dielectric constant in turn manifests itself in a change of the bias voltage or in a charge flow depending on the read out device. For a given bias voltage the change of the charge is given by

$$\Delta Q = CV\frac{1}{\epsilon}\frac{d\epsilon}{dT}\Delta T$$

where C is the capacity without the dielectricum, V the bias voltage, ϵ the temperature dependent dielectric constant and ΔT the radiation induced temperature rise. Experimental values for the temperature sensitivity of ϵ are

$$0.3K^{-1} < \frac{1}{\epsilon}\frac{d\epsilon}{dT} < 0.8K^{-1}$$

within the temperature range of $0.1K < T < 0.3K$ using $SrTiO_3$ glass ceramic. This is relatively small as compared to other temperature sensitive devices but the signal scales with the bias voltage which might allow for a considerable amplification factor. An interesting advantage might be given by a low Jonson noise if leakage currents are neglectful. The authors predict for fast signal detection (peaking time $\sim 10\mu s$) considerably better energy resolution than for resistive thermometers with comparable time constants. They predict an energy resolution of several eV at 300 mK operating temperature for dielectric calorimeters with a heat capacity of $2 \times 1O^{-11} JK^{-1}$. First experimental tests were performed with infrared light pulses irradiated on to the detector.

3.Metastable Superconducting Grains:

One of the earliest suggestions for detectors operated at low temperatures were based on metastable superconducting grains /4/. Small superconducting spheres with diameters of several μm are exposed to a magnetic field and stabilized at a temperature where the sphere, made out of a type 1 superconductor, remains in a superheated superconducting state. Under this condition a very small amount of energy absorbed can lead to a phase transition into a normal conducting state. This phase transition changes the magnetic field distribution in its enclosure due to the vanishing Meissner effect,which in turn may be measured by means of a magnetic flux meter (fig.1).

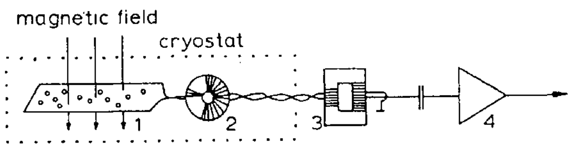

Fig.1: Schematic picture of the read out system of a superconducting grain detector with a flux consisting of a pick up loop (1), two transformers (2,3), and preamplifier (4).

The sensitivity of this detector was investigated by several groups leading to the conclusion, that it was essential to obtain samples of grains with well defined sizes and optimal spheric shapes which still seems difficult to achieve /5/. In addition it was shown that the orientation of the sphere relative to the magnetic field applied influences the temperature and magnetic field for which the phase transition occurs /6/. It is important to know whether the phase after energy absorption occurs in a state where the energy is homogeneously spread over the whole grain (global heating) or already when the energy is still locally concentrated at the spot of radiation absorption (local heating). In the latter case the sensitivity to radiation depends on the position where in the grain the energy is absorbed.

For the case of local heating it is to be expected that at the equator the grain should be most sensitive where as it should be less sensitive at the poles as there the magnetic field density is the lowest due to self shielding by the Meissner effect. It was shown by M.Frank et al. that in Sn and In a local heating where as in Zn and Al a global heating occurs before the phase transition takes place.This is mainly due to the different life times of quasi particles in a superconductor and the high speed of propagation of quasi particles as compared to phonons allowing for a fast energy transport.

In grains showing a global heating process a more homogeneous responds of all grains in a sample might be expected. The most sensitive sample of grains has been observed using Cd grains /5/ having the lowest critical temperature among those materials mentioned here, where as Sn and In, showing local heating, have the highest critical temperature.

4. Detection of Phonons

Phonons are lattice vibrations in a solid state crystal and can be excited by the absorption of radiation. The primary frequency distribution of the phonons depends upon the energy density at the point of absorption. High energetic phonons decay into low energetic phonons with a life time which strongly depends on the phonon frequency. Acoustic phonons for example decay spontaneously through the effect of enharmonic lattice potentials with a rate given by

$$\Gamma_{dec} = \gamma\omega_D\left(\frac{\omega}{\omega_D}\right)^5,$$

where $\gamma = 3.3 \times 10^{-4}$ for longitudinal phonons in Si and ω_D is the Debeye frequency.

During their life time the phonons propagate through the crystal and may be scattered on crystal defects of any kind. These may be impurities, lattice defects or isotopic atoms.

In a pure crystal low energetic phonons may propagate ballisticly with the speed of sound ($v \sim 5000m/s$) over long distances. Due to the anisotropy of the lattice structure of a crystal the ballistic phonons show preferential propagation in certain lattice directions (phonon focusing).

There are two possibilities for phonon detection. The detection shortly after their creation by radiation absorption in the detector consisting of an absorber and phonon sensors on top of it. In this case the phonons may not yet have reached a homogeneous spatial distribution nor a thermal frequency distribution. The second possibility is to measure the phonons at a later time when they have reached thermal equilibrium manifesting themselves as an increase in the temperature of the absorber.

In the first case they propagate as non equilibrium phonons undergoing decay, scattering, and ballistic propagation. During this time period using several phonon sensors on the surface of the absorber crystal the point of radiation absorption in the crystal can be determined. This can be achieved by means of the time differences between the arrival of the phonon wave front at the different phonon sensors.

An experiment demonstrating this possibility was performed by Th. Peterreins et al./7/.Three $Al/AL_2O_3/Al$ tunnel diodes were evaporated on one surface of Si mono crystals with the dimensions $10 \times 20 \times 3mm^3$ and $10 \times 20 \times 10mm^3$. The sensitivity to phonons of these tunnel diodes has an energy threshold due to the cooper pair binding energy Δ in the Al films. The minimal energy of phonons being detected is

$$\hbar\omega_{Ph} = 2\Delta_{Al},$$

which is estimated to be several meV.

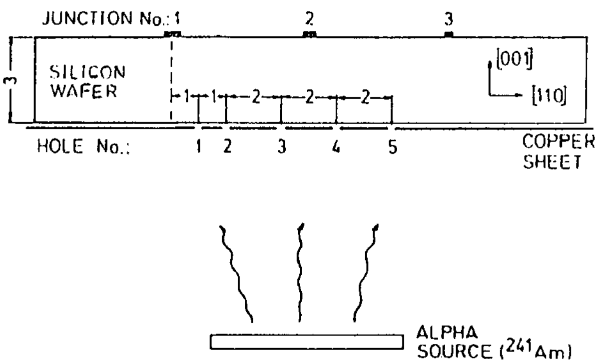

Fig.2: Geometry of the experiment to measure non equilibrium phonons with three superconducting Al-tunnel junctions /7/.

In fig.2 the geometry of this experiment is shown. The Si crystal was irradiated with 5.5 MeV α-particles at 5 different points opposite to the surface onto which the Al-tunnel diodes where evaporated. This way the time differences between the arrival of the α- induced phonon pulses as well as their pulse hights could be measured for each α-particle absorbed by the crystal. From the time measurement the effective speed of the phonon wave front was measured to be $520m/sec$ which is proximately ten times slower than what is expected for purely ballistic phonons. This indicates that scattering dominates the propagation of the phonons in the crystal.

Fig.3 shows the time correlation of the signals between diode 1 and diode 3 (see fig.2) for the 5 points of irradiation leading to a position sensitivity of $200\mu m FWHM$.

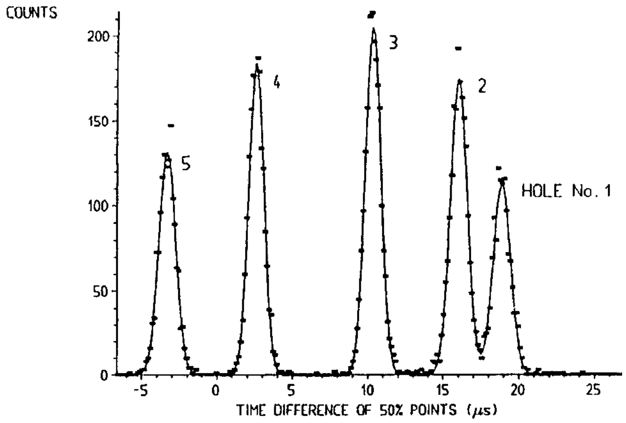

Fig.3: Time correlations of the signals between diode (1) and diode (3) (see fig.2) for 5 point of irradiation.

After an integration time of ca 1ms the phonons are approximately homogeneously spread over the whole crystal even though they still have not reached thermal equilibrium. This was measured by comparing the pulse hights between the different tunnel diodes for different integration times. A measurement of the rise times of the phonon induced pulses in the tunnel diodes allows for a distinction between focused phonons and phonons coming from other directions. This is depicted in fig.4 where the inverse rise time versus the pulse hight is plotted.

The signals stemming from phonons propagating along focusing directions are clearly separated from those stemming from other directions /8/.

For the detection of phonons in thermal equilibrium superconducting tunnel junctions are not adequate. In this case a sensor with an energy gap Δ being smaller than the energy of thermal phonons are required. For this essentially two systems

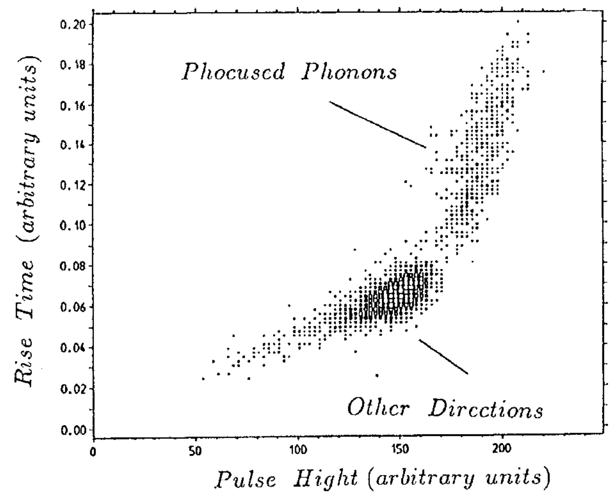

Fig.4: Separation of focused phonons and those from other directions.

have been explored recently being superconducting phase transition thermometers and specially doped semiconducting thermistors.

With a superconducting Ir phase transition thermometer the α-induced rise in temperature of a 280g sapphire was measured with an accuracy of 1.2% and an integral non linearity of smaller than 0.3% /9/. This accuracy corresponds to $54nK$ if the pulse is interpreted as being purely thermal.

In fig.5 the principle of detection with a phase transition thermometer is shown. The thermometer consisting of a thin superconducting stripe is thermally stabilized at its transition temperature where the electric resistivity changes from the superconducting to the normal conducting state .

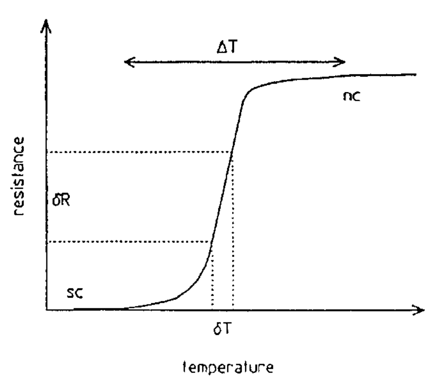

Fig.5: Principle of temperature measurement with a phase transition thermometer.

A measurement of its resistivity in this transition range is very sensitive to small changes in temperature. In the experiment mentioned above the resistivity was measured by means of a DC-SQUID system.

Another purely thermal measurement of radiation absorption was performed using a specially doped silicon thermistor with a small gap semiconducting absorber glued on top of the thermistor /10/. The signal was measured as a change in resistivity of the semiconducting thermistor by means of conventional electronics. The absorber with a mass of $\sim 10\mu g$ was irradiated with ^{55}Mn X-rays and showed an energy resolution of $7eV$ for the 5.9 KeV $^{55}MnK_{\alpha_{1,2}}$ line which is the best energy resolution obtained with a calorimeter up to now.

In fig.6 the measured spectrum is shown indicating already a separation of the K_{α_1} and K_{α_2} lines.

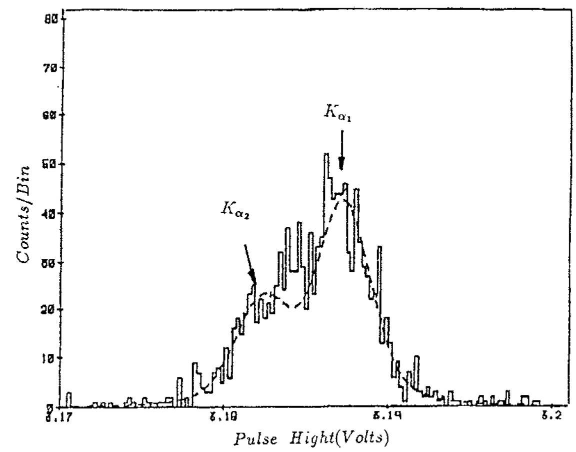

Fig.6: Energy spectrum of ^{55}Mn-X rays measured with the calorimeter of D.Mc Cammon /10/.

In a resistive thermometer due to the read out current heat is dissipated and a thermal noise is added to the signal. An increasing current leads to an increasing signal but also to an increasing thermal noise. In principle a capacitive or inductive read out might be more favorable from this point of few if they have sufficient sensitivity.

5. Detection of Quasi Particles in a Superconductor

In stead of the detection of phonons the breaking of cooper pairs in a superconductor can be detected directly if the radiation is absorbed in the superconductor. This was demonstrated in experiments where superconducting tunnel diodes were irradiated with α-particles and X-rays /11/. The radiation induced signal, represented by an increase of the quasi particle tunnel current in the diode, is proportional to the quasi particle density in the tunnel diode. Therefore large tunnel diodes are not favorable as they lead to a reduced quasi particle density for a given energy deposited and to a large capacity of the diode. On the other hand a detector may require a certain size for adequate detection efficiency and solid angle. To overcome this problem quasi particle trapping has been independently suggested and demonstrated by N. Booth and H. Kraus /12/.

Quasi particle trapping occurs from a superconductor(1) with Δ_1 into a superconductor(2) with Δ_2 if $\Delta_1 > \Delta_2$. This is schematically depicted in Fig.7 for a sequence of Pb, Sn, and Al.

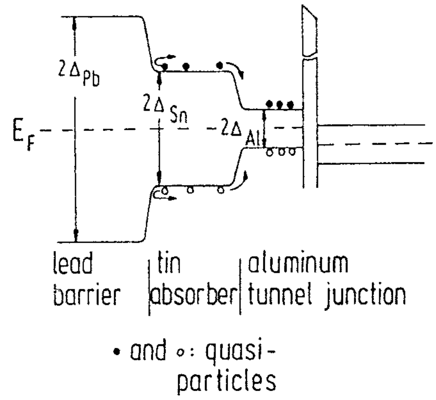

Fig.7:Quasi particle trapping for a sequence of the superconductors Pb, Sn, and Al. The decreasing energy gaps Δ, representing the cooper pair binding energies, are drawn. Quasi particle diffusion in the direction of decreasing Δ is possible, diffusion in the opposite direction is energetically forbidden.

H. Kraus used a superconducting Sn film as an absorber for radiation, $Al/Al_2O_3/Al$ tunnel diodes into which quasi particles were trapped for detection, and Pb films for electrical contacts. The geometry of this detector is shown in fig.8.

Quasi particles created in the Sn stripe can not diffuse into the Pb contact line but are trapped into the Al tunnel diodes. A comparison of the pulse hights in diode(1) and diode(2), as well as for diode(3) and diode(4), gives information on the position along the Sn stripe where the radiation was absorbed. The sum of the signals is proportional to the total amount of quasi particles created in the Sn absorber and hence proportional to the energy absorbed. The Sn absorber was irradiated with ^{55}Mn X-rays. This way a position resolution of better than $5\mu m$ and an energy resolution of $50eV$ were achieved.

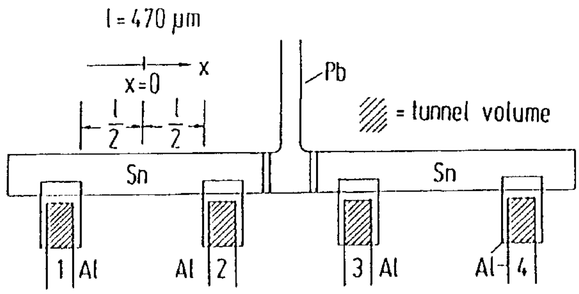

Fig.8: Geometry of the detector to demonstrate quasi particle trapping. The Pb serves as electrical contact and as barrier for quasi particles created in the Sn absorber. The quasi particles are trapped and detected in the $Al/Al_2O_3/Al$ tunnel diodes numbered with 1 to 4.

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References:

1) M. Bühler and E. Umlauf Europhys. Lett.5, 297,(1988)

2) P.Moon and L.R. Steinhardt, J. Opt. Soc. Am.28, 148, (1989)

3) H.Silver et al. N.I.M. A277, 657, (1989)

4) L.Stodolsky and A.K. Drukier, Phys. Rev. D30, 2295, (1984), and references there in.

5) W. Seidel, L. Oberauer, and F. von Feilitzsch, Rev. Sci. Instr. 58, 1471, (1987)

6) K. Pretzl, in 'Superconductive Particle Detectors', proceedings of the Workshop, Torino, Italy, 1987, ed. by A. Barone (World Scientific, Singapore, 1988), p.213

7) Th. Peterreins et al. Phys. Lett. B202, 161, (1988)

8) J. Jochum, Diplom Theses TUM, (1989)

9) W. Seidel et al. Phys. Lett. B236, 483, (1990)

10) D. Mc Cammon et al. in 'Low Temperature Detectors for Neutrinos and Dark Matter III' ed. by L. Brogiato, D.V. Camin, and E. Fiorini, (Editions Frontières, Gif sur Yvette Cedex France, 1990), and private communications.

11) H. Kraus et al. Europhys. Lett. 1, 161, (1986),
D. Twerenbold, Europhys. Lett. 1, 209, (1986)

12) N. Booth, appl. Phys. Lett. 50, 293, (1987),
D.J. Goldie et al. Phys. Rev. Lett. 64, 954, (1990),
H. Kraus, Diplom Theses, TUM, (1985)
H. Kraus et al. Phys. Lett. B231, 195, (1989)