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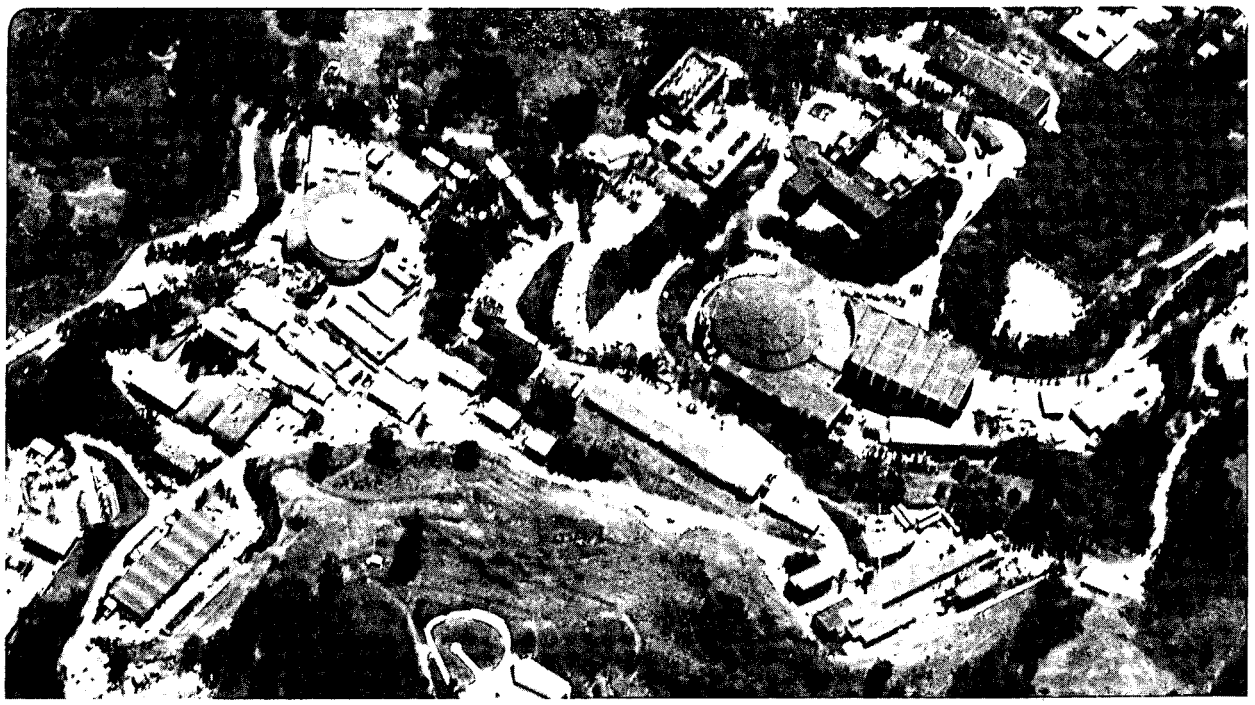

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PHONON DETECTION WITH SEMICONDUCTOR THERMISTORS

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Abstract

We give a status report of the development effort that we have undertaken in Berkeley to detect ballistic phonons with Neutron Transmutation Doped Germanium thermistors.

1. MOTIVATIONS

The hypothesis that dark matter is made out of exotic particles not yet discovered is rather natural and specific enough to allow a direct experimental test[1]. However, an exhaustive exploration of the available phase space requires[2] very low thresholds (of a few hundred eV's) in order to reach the lower part of the allowed mass spectrum. Perhaps more importantly, an excellent background rejection is also needed, since at larger masses the event rate is small compared to state-of-the-art levels of radioactive background.

Cryogenic detectors using quanta of small energies, such as broken Cooper pairs and phonons at low temperature, may provide both the low thresholds and the redundancy necessary to reject the background. Not only might the energy spectrum and the position be measured, but potentially a signature that the interaction has occurred on the nucleus and possibly the direction of the incident particle could be obtained. In addition, a wider range of materials may be possible than is allowed with ionization detectors. If they were demonstrated for some type of cryogenic detectors, the combination of all these advantages would make them the instrument of choice for dark matter searches.

Fascinated by both the fundamental nature of the dark matter problem and the promises of cryogenic detectors, we have formed a small team in Berkeley to develop a workable scheme. Our group includes E. E. Haller, A. Lange, R. Ross, H. Steiner and B. Sadoulet, with the first four still contributing a very small percentage of their time. An enthusiastic team of four students, Ning Wang, Tom Shutt, Alan Cummings, and Carol Stanton and the technical help of Jeff Beeman make this development possible. The present report is based on the work and ideas of this group.

2. THE PROMISES OF PHONONS DETECTION

Among the many possible versions of cryogenic detectors[3], we chose to explore the possibility of detecting phonons. There are at least three reasons for the choice we made.

2.1 Phonons represent the major fraction of the deposited energy.

A recoiling nucleus of a few KeV produced by a dark matter interaction will deposit more than $\frac{9}{10}$ of its energy into heat and only $\frac{1}{10}$ in ionization (for a review see, for instance, reference 4), and it would seem natural to detect the larger component.

Actually, however, it may be even better to detect both. At the same energy, a recoiling electron produced by photon or β interactions will deposit a significantly different amount of heat and ionization, roughly $\frac{2}{3}$, and $\frac{1}{3}$, respectively. We could then have a much wanted signature for an interaction on a nucleus in order to reject the radioactive background.

Such a scheme may not be too difficult to implement. The team of Brown University[5] has suggested that the ionization yield can be measured simply by measuring the heat produced by the drift of the carriers in an electric field. Independently, Paul Luke[6] has demonstrated this last possibility in a crystal of germanium at 1.4 K. It remains to be shown that it is possible to measure the heat and ionization component simultaneously (e.g. by pulsing the electric field once the primary phonon component has been measured) and to determine the experimental width of the distributions in order to get an estimate of the rejection power of the method.

2.2 Infrared bolometry and X-ray calorimetry provide existence proofs.

In particular, the beautiful results of McCammon, Moseley and collaborators[7] show that very sensitive phonon detectors can be made, at least for detector masses of 10^{-5}g by measuring the temperature rise of a crystal. However, if we assume a thermodynamics equilibrium and no excess noise, the threshold is proportional to[8]

$$\xi \sqrt{k\ T^2\ C}$$

where ξ depends on the sensitivity of the thermometer, T is the temperature and C the heat capacity. For an insulator $C \sim T^3\ M$, where M is the mass of the sample and the T^3 is predicted by the Debye law.

Assuming, in addition to the conditions stated above, that the Debye law stays valid, and that the thermistor characteristics do not degrade with energy (i.e. ξ is a constant), the threshold is expected to behave as

$$T^{5/2}\,M$$

and it is possible to compensate a large increase of mass by a much smaller decrease in the temperature[9]. Such an extrapolation indicates that, with these assumptions, thresholds of 100 eV may be reached with crystals of the order of 100 grams.

2.3 Phonons may be ballistic.

Although the foregoing discussion provides a strong motivation for starting a development effort, it may be fundamentally incorrect since it is very difficult to achieve thermalization at low temperature. In the bulk of the crystal at low temperature, the phonon lifetime against down conversion to lower energy increases[10] as the inverse of their energy to the 5th power. Thus, for practical time scales, the phonons produced in the primary interactions will stop thermalizing at an energy of 1 meV or an effective temperature of 10 K, which is much higher than the temperature of the crystal.

The discussion of section 2.2 only represents therefore the situation of a measurement made either in a dirty crystal, where defects of various types may thermalize the phonons rapidly (but in that case the defects will contribute to the heat capacity), or after a long time. In the latter case, the phonons will have made many bounces on surfaces and impurities.

If, on the other hand, the measurement is made rapidly to minimize the number of reflections, and proper precautions[11] are taken with surfaces and interfaces, the phonons may still be at high energy and to some extent ballistic that is, travelling in straight lines. Instead of measuring the amplitude of the normal vibration modes of the crystal, the problem is now to detect the wave front (the "ripple") originating from the interaction[12]. In this case, we can make the following observations:

- The crystal acts as a "phonon guide" and large detector sizes may be possible.
- Timing and, potentially, focussing properties[12] may provide position measurement. This is an important handle for background rejection, since it would allow one to define a fiducial volume and check the spatial distribution of events.
- Phonons of higher energy may be easier to detect, for then higher threshold detectors such as superconducting strips[13] or aluminum tunnel junctions[12] could be used. More generally, high energy phonons should couple more easily to the various types of sensors (see below).
- If the sensor is made to be insensitive to thermal phonons, the heat capacity of the crystal becomes irrelevant in the determination of the fluctuations of the detected energy. The detection challenge becomes one of phonon collection efficiency, uniformity of response and sensitivity of the sensors. It may then be possible to operate at slightly higher temperatures (100 mK or 300 mK), which simplifies the experimental set up.
- Last, but not least, the phonon flux may well remember the initial direction of the incoming particle. The "ripple" may be slightly higher in the forward direction than in the backward direction. Theoretically, this is a definite possibility since the initial momentum has to be conserved[14]. The amount of asymmetry depends on the importance in the down conversion process of umklapp processes which transfer momentum to the crystal as a whole. Such an asymmetry would be an exceptional signature for dark matter detection or solar neutrino studies, for instance. It remains to be seen, theoretically and experimentally, if this effect is strong enough to be useful.

The high energy and ballistic character of phonons originating from a high energy deposition is well established by Solid State physicists[10,11], for crystals up to 1 cm^3. Recently, such phenomena have been unambigously observed with X-ray interactions by the von Feilisch group[15]. But it remains to be seen, experimentally, if these phenomena can be used efficiently in practical detectors. Phonons are not particles in the usual sense, and they are very "fragile" and fragment easily. Therefore, reflections on surfaces and propagation through interfaces are problematic[11], and, in the end, only a small proportion of the initial energy may be collected in the form of high energy ballistic phonons. In

practice, we may have a mix of ballistic and partially thermalized phonons, and hence the detectors able to see both components may be advantageous.

3. THE DEVELOPMENT EFFORT IN BERKELEY

This is the main motivation of the Berkeley effort to explore the properties of semiconductor thermistors. These are generally highly doped semiconductors which are very close to the metallic limit, and whose resistivity varies very rapidly with temperature. The doping technique, Neutron Transmutation Doping, developed by a member of our team[16] is particularly interesting: A crystal of germanium is exposed to a thermal neutron beam in a nuclear reactor. This produces the dopants Ga, As and Se in a very uniform fashion, which is important because of the proximity of the metallic limit.

Our initial program is therefore to explore the properties of NTD Ge thermistors, and the next section gives a status report of our present understanding based on studies made in parasitic runs that Profs. Packard and Clarke have allowed us to do in their dilution refrigerators.

In parallel, we are setting up our own low temperature laboratory. Our fridge should soon be operational, allowing us a much faster turn around time.

Ballistic phonon detection with thermistors requires low noise and fast electronics adapted to the 1-10 MΩ resistance of thermistors. In order to limit the input capacitance, the FET has to sit as close as possible to the sample, presumably in a 4 K environment and dissipate as little power as possible. Using standard techniques from infrared astronomy, we have developed[17] a 1 nv/$\sqrt{HZ}$ preamplifier (based on the 2N 6453 epitaxial Si-As FET from interfet) with an intrinsic 100 ns rise time, a gate capacitance of 15 pF and only 3 mW of power dissipated in the cold stage (Fig. 1).

4. PROPERTIES OF NTD GERMANIUM THERMISTORS

We now discuss the present level of our understanding of NTD thermistors at very low temperature. We have been studying mainly one doping level (Haller's No. 12) while the samples are typically $1\times 1\times 0.2$ mm^3 since we intend to use relatively large area sensors for ballistic phonon collection.

4.1 Electrical Characteristics.

The electrical characteristics have been described in our IEEE paper[18] and can be seen in Figs. 2a,b. To summarize our findings:

• Our thermistors display a very fast dependence on temperature. Between 20 mK and 70 mK, their resistance (extrapolated at zero bias current) changes by 4 orders of magnitude.

• Unfortunately, as soon as we apply a biasing current, the resistance decreases greatly. The maximum responsivity dV/dT is obtained with relatively low biasing power, and the sensitivity is much smaller than the zero bias current resistance would indicate. This parasitic phonomenon is present in semiconductor thermistors used at higher temperature[19], but is much more obvious at the very low temperatures at which we are working. It is usually described loosely as a "hot electron" effect.

4.2 Origin of the "hot electron" effect.

Two interpretations have been proposed for this hot electron effect. It is claimed that there is a strong dependence[20] of the resistance of the bolometer on the electric field, or alternatively that electrons thermally decouple[21] from the phonons. The last proposition is troublesome because we would like to detect phonons.

It turns out that it is experimentally rather difficult to distinguish between the two effects (which may be alternative descriptions of the same physics). For a given resistivity, the power per unit volume is proportional to the square of the electric field. In order to study this question, we used two thermistors sharing the same lattice (Fig. 3). We thermally clamped one side to the heat sink as solidly as we could (with 1 mm^2 of conductive epoxy). By injecting electric power in one thermistor and watching the temperature of the lattice with the other, we were able to measure the Kapitza thermal impedance between our sample and the heat sink. This allowed us to measure the effective field dependence or the effective thermal conductance between the carriers and the lattice.

The main difference between the two models in their most naive form is their dynamic behaviour. The thermal impedance phenomenon would imply a time delay when we electrically pulse one thermistor and monitor the other one. This is due to the fact that carriers have a finite heat capacity and therefore change temperature with a finite thermal time constant. We do observe such a delay and currently are analyzing a series of experiments between 18 mK and 36 mK to confirm this indication[22].

4.3 Sensitivity to phonons generated by particle interactions.

If this evidence is correct, we are observing the decoupling between electrons and phonons. Is this fatal to our goal to detect phonons by observing the change in electric current they generate in our thermistors?

We do not know yet the answer to this question. But at the moment we can offer two elements of hope:

• The reason why electrons decouple from phonons is not the fact that the matrix element is going to zero, but rather that at very low temperature the phase space available in the final state is extremely small. The transition probability is therefore also extremely small. If the phonons created in an interaction reach the thermistor with sufficient energy, this phase space volume problem should not exist, and they should couple quite easily. These thermistors may then work very well as high energy phonon detectors.

• Although our set up of clamped thermistors is not designed to detect particles, we do observe quite easily α and 60 keV X-rays (Fig. 4) with sharp rise time which would indicate, in particular, for the X-ray particles, a direct coupling of the phonons to the carriers. This evidence is not unambiguous and we need a few more months to substantiate it.

5. CONCLUSIONS

It is too early to conclude on the capabilities of semiconductor thermistors. They are certainly very sensitive, but the apparent decoupling between the charge carriers and the phonons is troublesome. Even if these devices are sensitive to high energy phonons, it remains to be seen if they can be efficiently coupled to a crystal.

On the other hand, two years of effort to learn the trade and to equip a low temperature laboratory are beginning to bear fruit. And the problem that is motivating us, the nature of the dark matter, is so fundamental that it deserves a long development.

It is remarkable and somewhat distressing, for an outsider such as myself, to encounter, in the course of this work, many problems which are at the current forefront of Solid State Physics: electron-phonon decoupling, out-of-equilibrium phonons, and highly doped semiconductors!

ACKNOWLEGMENTS

I would like to thank all the members of our team named in section 1, especially N. Wang who has patiently made the measurements that are mentioned in the text, E. E. Haller who proposed the double thermistor experiment, and J. Beeman who has prepared the samples.

The access that Richard Packard and John Clarke provided to their refrigerators has been invaluable and the help of their students, in particular Seamus Davis and Frederick Wellstood is gratefully acknowledged.

Discussion with J. Clarke, P. Richards, and F. Wellstood on the electron-phonon decoupling have been illuminating. They cannot be held, however, responsible for my naive view of Solid State physics.

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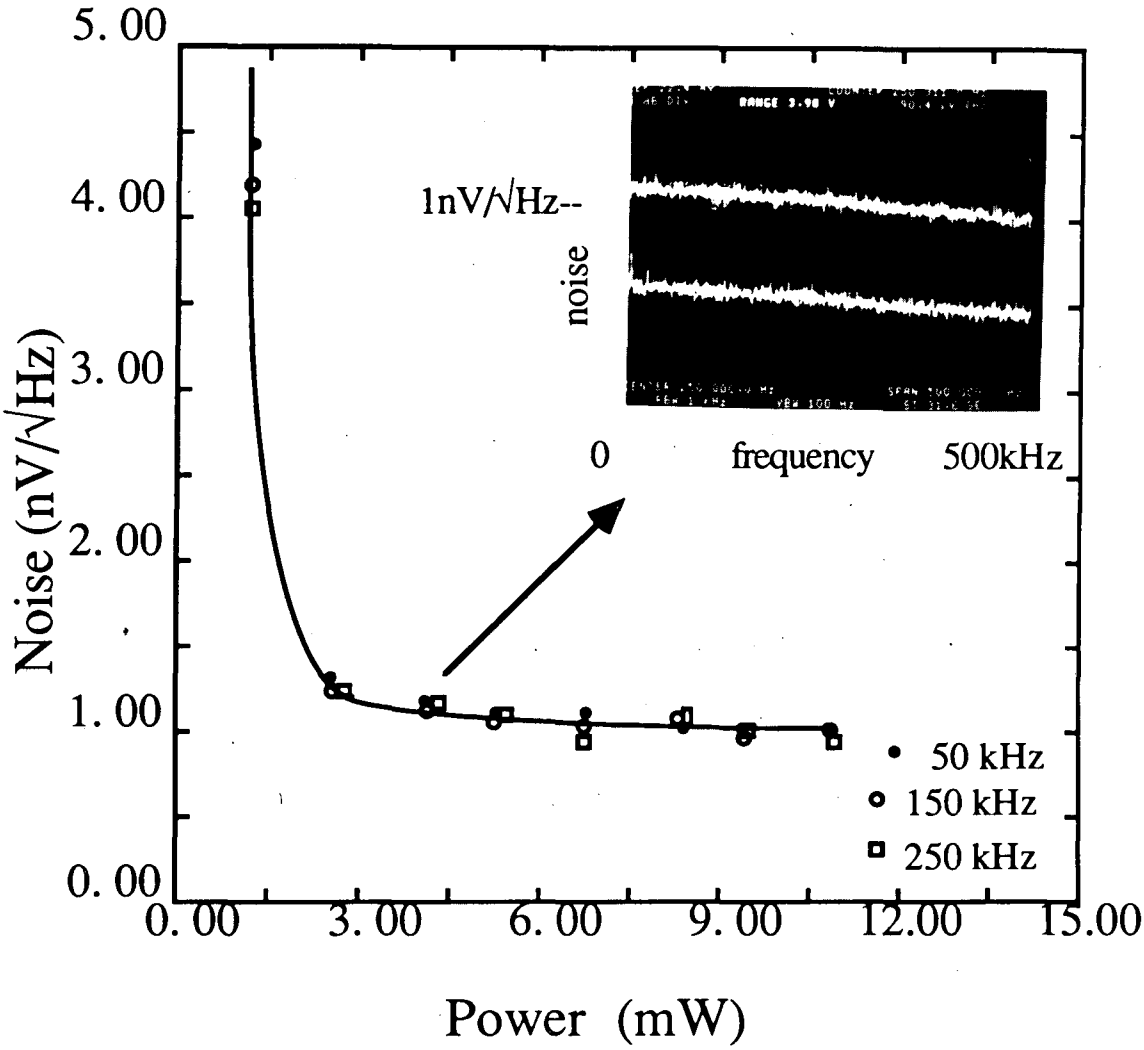

Fig. 1 Voltage noise power density of the amplifier described in the text as a function of dissipated power at 50, 150 and 250 kHz.The insert shows the uncorrected noise spectrum obtained without the amplifier(lower trace) and with the amplifier(upper trace) as a function of frequency. The slope is due to the varying gain of another amplifier used in the circuit.

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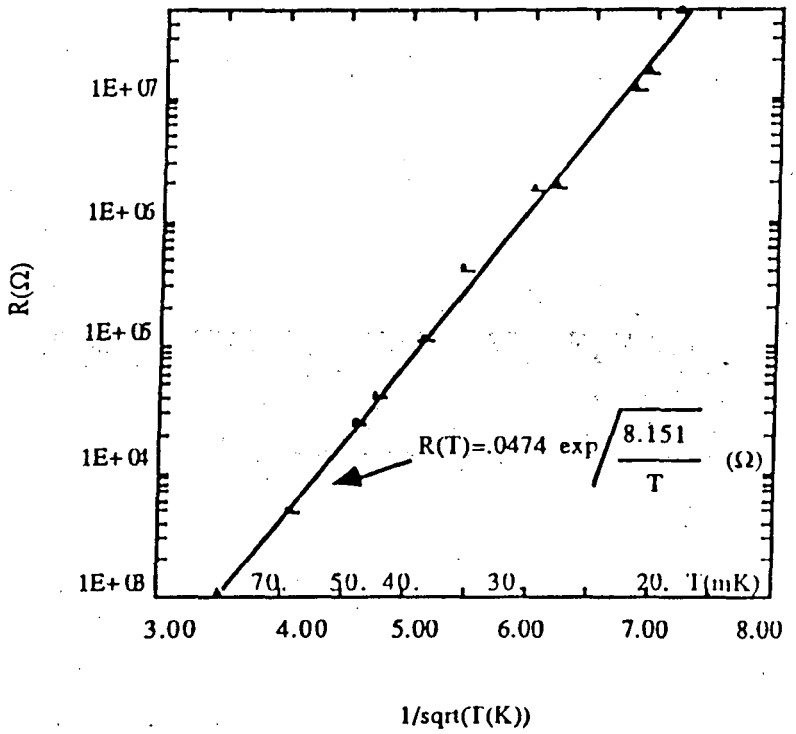

Fig.2 a) Resistivity (at zero bias current) as a function $T^{-1/2}$ (a form motivated by theoretical considerations).

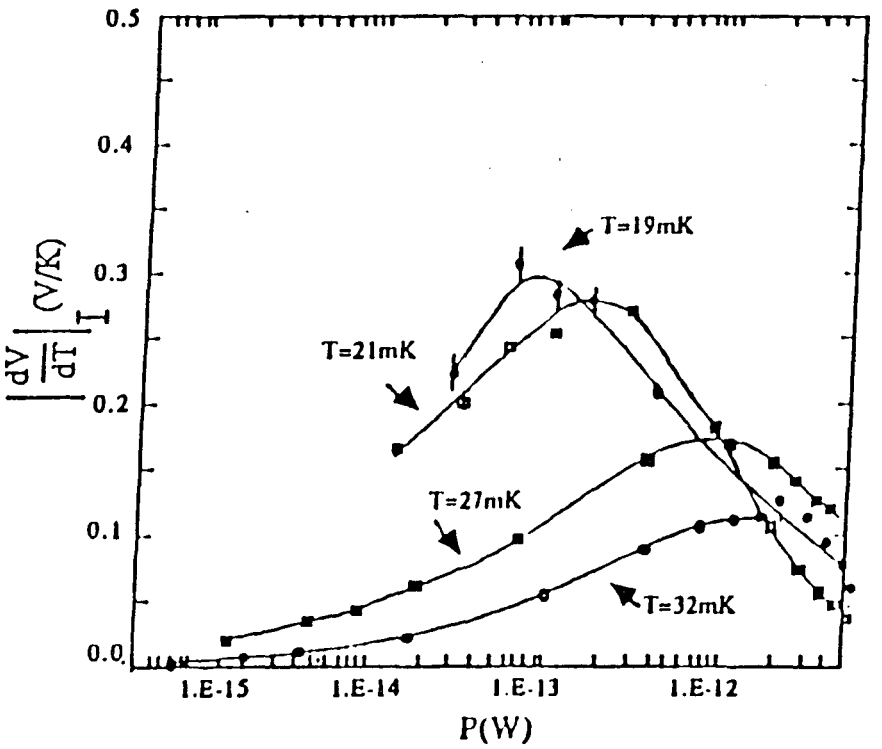

Fig.2 b) Responsivity dV/dT at constant biasing current as a function of biasing power.

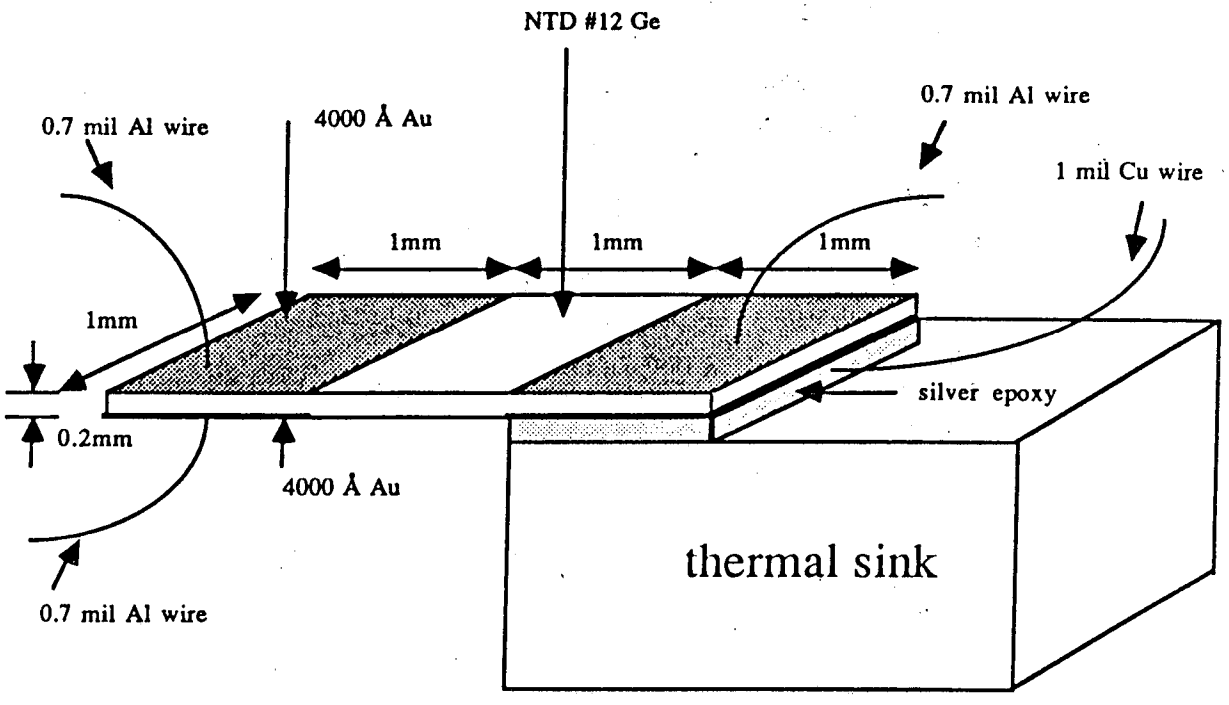

Fig.3 The double thermistor used in the measurement. It is made of NTD#12 Ge and is thermally clamped to the thermal sink as well as possible.

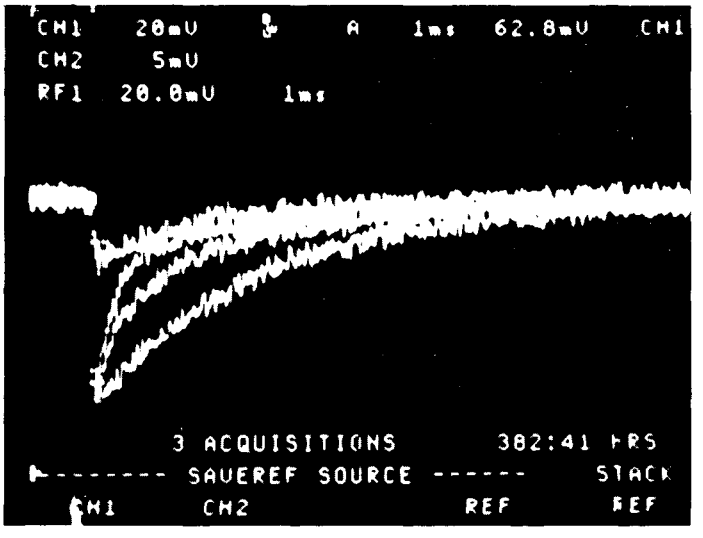

Fig.4 a) Pulses from alpha particles of ^{241}Am (E $\leq$ 6Mev) on a thermally clamped thermistor at 40 mK. The picture was taken with a digital storage oscilloscope, the amplifier gain on voltage was 100, and the bias current I_{bias} = 28.2nA.

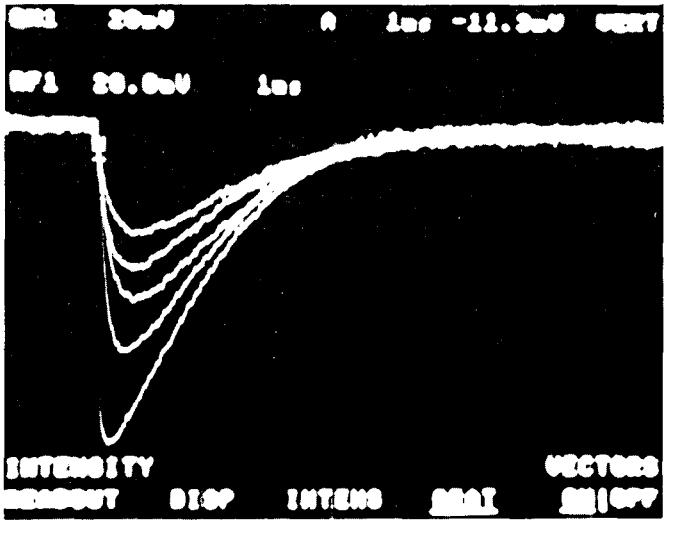

Fig.4 b) Pulses from X-rays of ^{241}Am (E$\leq$ 60 kev) on the same thermistor at 20 mK. The picture was taken with a digital storage oscilloscope, the amplifier gain on voltage was 100, and the bias current I_{bias}= 0.5 nA.

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