

DETECTION OF DARK MATTER PARTICLES WITH LOW
TEMPERATURE PHONON SENSORS

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ABSTRACT

Taking as an example our development effort in Berkeley, I discuss for nonspecialists (Astronomers and Particle Physicists) the promises of phonon sensing at low temperature for the detection of dark matter particles and the difficulties faced.

1. MOTIVATIONS

The hypothesis that dark matter is made out of exotic particles not yet discovered at accelerators is rather natural¹⁾, and specific enough to allow a direct experimental test²⁾. But as Rich has shown at this workshop³⁾, it is necessary to reach both lower thresholds and lower backgrounds that are presently available. The fundamental nature of the problem justifies a strong experimental development, and two directions are being explored:

- On the one hand, one could attempt to improve ionization detectors. Caldwell⁴⁾ discussed at this workshop the results obtained with solid state detectors and the developments which are being started. Low pressure gas detectors may also be promising^{3,5)}.

- On the other hand, many groups are launching development of cryogenic particle detectors⁶⁾. In the dark matter context, it is hoped that both smaller thresholds and lower backgrounds than conventional technologies allow, can be obtained.

The hope of reaching lower thresholds stems from the fact that much smaller quanta (broken Cooper pairs or phonons) are used in these detectors. Low thresholds are mainly interesting for investigating the low mass region of 2-4 GeV/c², which is not excluded by accelerators⁷⁾ and not accessible easily to ionization detectors. Another possible application of low thresholds is for the detection of dark matter particles trapped in the earth^{8,2)}. If their mass is right (≈ 12 GeV/c²), then their flux at the surface is enhanced and a 1 gram detector sensitive to 10 eV deposition would detect a few events per day!

In my mind, a more important justification for the development of cryogenic detectors is that at least some of the proposed techniques are able to provide much smaller background. It is obvious from Caldwell's discussion that it is essential to obtain the followings:

- a good spectral resolution in order to exclude X-ray lines and to recognize the spectral shape and the annual modulation expected for a positive signal.

- some position resolution to exclude short range radioactive products from the experimental surroundings.

In addition, it would be extremely useful to have additional handles:

- a wide variety of materials to check the behaviour of both the signal and the background. Note also that, at least in naive models⁹⁾, Majorana particles are expected to interact only with targets having nuclear spins¹⁸⁾.

- an unambiguous signature that the interaction occurred on a nucleus.

The main background is expected ultimately to be Compton scattering in electrons by stray γ -rays¹¹⁾, and β from radiogenically produced materials such as tritium. If one could measure simultaneously both the ionization and the amount of heat deposited^{12,11)}, one could then recognize a nuclear recoil and reject these background contributions.

- directionality; Since the sun velocity is of the same order of magnitude as that of dark matter particles, they are expected to come mainly from one direction¹³⁾.

Although it is unclear whether the phonon distribution will remember the direction of the initial particle, with phonons detectors, it may be possible to reach in particular, most of these objectives. This has been the main motivation behind the effort of our group in Berkeley. Other types of cryogenic detectors have been proposed for dark matter detection and are reviewed in reference 6). Perret-Gallix¹⁴⁾ discussed the potentialities of superconducting granules at this workshop. We limit our remarks to the phonon detectors.

2. AN EXISTENCE PROOF: LOW TEMPERATURE CALORIMETRY.

The hope that phonon detectors can indeed do the job is further boosted by the recent success of low temperature calorimetry.

2.1 Calorimetry and Bolometry

Calorimetry is probably the oldest method for measuring a deposition of energy. The rise of temperature of an isolated system in which an energy ΔE is dumped is given by

$$\Delta T = \frac{\Delta E}{C}$$

where C is the system's heat capacity. For an insulator, the heat capacity behaves as T^3 (Debye law), as the temperature T approaches the absolute zero. Thus for low enough temperature, the sensitivity could be excellent.

This method has long been used by infrared astronomers to detect the infrared light from a star. In their case, the technique is known as bolometry since an energy flux is measured. The temperature is usually measured with a thermistor. A small bias current develops a voltage difference across it which is sensed by a FET amplifier.

As early as 1974, Niinikoski and Udo¹⁵⁾ suggested that this technique could be used for the detection of particles. This concept has been marvelously established by the work of McCammon, Moseley, and Mather¹⁶⁾. They have achieved a resolution of 17.4 eV FWHM for 6 keV X-rays, and the base line fluctuations are only 13 eV, a very impressive value which indicates the possibility of thresholds of the order of 30 eV!

2.2 Naive Extrapolation to Larger Sample.

The only problem with the last result is that it was obtained with a crystal of 10^{-5} g, far from the kilogram of detection needed for a dark matter search.

However, at least superficially, it is possible to extrapolate this method to much larger samples. Mather and co-workers¹⁷⁾ have shown that the noise is ultimately limited by the thermal noise (both the energy fluctuation of the crystal and the Johnson noise of the thermistor) and is given by

$$\delta E = \xi \sqrt{k T^2 C}$$

where ξ is a constant depending on the sensitivity of the thermistor, and is of the order of 2.5 for the best ones currently available. But 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.

Therefore

$$\delta E \sim \xi T^{5/2} M^{1/2}$$

and if ξ is a constant (that is the thermistor efficiency does not decrease with temperature), if the Debye law is valid and if no other contribution dominates the noise, it is possible to compensate a large increase in mass by a much smaller decrease in temperature.

Extrapolating naively in this way¹⁸), and starting from the heat capacity that McCammon et al. have measured for their detection at 100 mK, we conclude that it could be possible to have 100 eV threshold with crystals of 300g of boron, 200g of silicon, or 100g of germanium at 15 mK. Even taking the experimental characteristics of the thermistors, that we have measured at 20 mK, 50g of boron should achieve this threshold. Let us emphasize again that this assumes the absence of any deviation from the Debye law and of any excess noise!

3. A TYPICAL ITINERARY

Fascinated by those numbers, our Berkeley group started enthusiastically experimenting with these low temperature calorimeters. We were not the only ones nor the first ones, but our trajectory is fairly typical of the experience of other groups who have started similar developments for dark matter searches (Cabrera and co-workers at Stanford, Lanou and collaborators at Brown University, E. Fiorini et al. in Milano, and P. Smith and co-workers at Rutherford). As such, the following description may be informative for groups attracted by the subject!

I began to gather a cross disciplinary team of people able to spend (for most of them) a small amount of their time on this interesting problem: E. E. Haller, a material physicist who brought to the team his knowledge of Solid State Physics and his know-how with Neutron Transmutation Doped thermistors; A. Lange, an infrared astronomer and an expert in bolometry; and two particle physicists R. Ross and H. Steiner.

My students and I knew nothing about low temperatures. We started to train ourselves at 1.3K^o (with a pumped ⁴He cryostat). Using the same type of bolometers used by infrared astronomers, Ning Wang, a graduate student, could relatively easily observe α pulses, and over time we improved the signal to noise.

This experience showed us clearly the need to have state of the art amplifiers. We embarked then to develop a low noise FET which could work in a 4K environment. Carol Stanton, an undergraduate, succeeded in obtaining $1 \text{ nV}/\sqrt{\text{Hz}}$ for a 3 mW dissipation and a total input capacitance of 15 pF.

Meanwhile, we borrowed time on existing dilution refrigerations. Profs. Packard and Clarke in the Physics Department offered us to run parasitically in their fridges. This led us to quickly discover the problems of very low temperatures and of our devices. For instance, RF shielding (not available in Packard's fridge) proved absolutely essential for devices of the sensitivity we were using, and we have also learned many tricks of the trade. In the process, we started to identify the fundamental difficulties of the enterprise that are summarized below in section 4.

But in spite of the kindness and patient help of our hosts, it became clear that no fast progress was possible without having our own low temperature facility, adapted and dedicated to our project. With the help of the University, we bought a dilution refrigerator from Oxford Instruments. Tom Shutt, a graduate student, began to design and construct a Faraday cage and a gas system, and a year later we are nearly operational.

The experience of Fiorini, for instance, closely parallels this trajectory a few months before us. And it is when his team finally had its own fridge working that rapid progress was made. They have observed¹⁹⁾, for instance, an α spectrum with 0.7g of germanium, and at the time of this writing they have a 10g calorimeter. The noise is still large (50keV FWHM) because of thermistors and electronics which are not optimized, but these devices clearly show great promise!

4. A DEVELOPMENT AT THE FRONTIER OF SOLID STATE PHYSICS

Although the practical problems linked to starting up and operating at low temperature should not be underestimated (it took us two years to reach our present status), the fundamental problems we are facing are of another nature. The behavior of

the detectors we are trying to build depends critically on phenomena, which are at the frontier of the understanding in Solid State Physics. We will sketch two examples. Interested readers will find a more technical discussion in reference 20).

4.1 Are the phonons ballistic?

Even the small energy deposited by dark matter particles is huge compared to the typical energies in the crystal, and the initial interaction creates a "fireball" which expands and cools off. It leads to optical phonons which down-convert eventually to transverse phonons. The energy of these, in turn, gradually decreases to an energy corresponding to the crystal temperature. However at low temperature, as well known to Solid State physicists²¹⁾, the phonon lifetime in the bulk of the crystal increases as the inverse of the 5th power of their energy and for practical time scales, they stop thermalizing at an energy of 1 meV, or an effective temperature of 10 K, much higher than that of the crystal. Such phonons are called "ballistic" since they travel in straight lines with mean free path of the order of 1 cm and scatter on impurities, the different isotopes and surfaces.

This description contrasts sharply with the picture that we painted in section 2, where we assumed implicitly a complete thermalization of the phonons. Therefore the scaling laws that we gave are presumably unrealistic. But is it so bad to deal with phonons out of equilibrium? As first emphasized by Cabrera and coworkers²²⁾, there may be a number of advantages⁶⁾:

- If phonons stay at high energy, we indeed could use higher threshold detectors, such as aluminum tunnel junction²³⁾ or superconducting strips²⁴⁾. Experimentally, such an assertion has been unambiguously proven by the von Feilisch group²⁵⁾. Even for thermistors, the higher energy of the phonons may improve their coupling to the sensor²⁰⁾.

- If the sensor is not sensitive to thermal phonons, the heat capacity of the sample is irrelevant in determining the fluctuations of the detected energy. The crystal then acts as a phonon guide and very large detectors may be possible.

- Last, but not least, there is the remote possibility that the phonon flux may remember the initial direction of the incoming particle. After all, the initial momentum has to be conserved²⁶⁾, and may introduce some asymmetry if the down conversion process is not dominated by umklapp processes which transfer the momentum to the crystal as a whole. This would be an exceptional signature for dark matter detection¹³⁾.

However, using these properties would impose the requirement of not thermalizing unduly the phonons, for instance on surfaces, crystal defects or the interfaces between the crystal and the sensor. These problems are extremely difficult, and, unfortunately, are at the present frontier of Solid State Physics²⁷⁾.

In a contribution to this workshop²⁸⁾, R. Lanou gives another example of the use of sophisticated Solid State phenomena, rotons in ⁴He liquid.

4.2 The Phonon Coupling Mechanism in the Sensor.

Many problems are also encountered in the understanding of the sensor.

Let us take, for instance, the example of our Neutron Transmutation Doped germanium thermistors²⁹⁾. In a series of experiments, around 20 mK, we have tried to characterize their behaviour^{30,20)}, and have found the following:

- They indeed display a very fast resistance dependence on temperature. Between 20 mK and 70 mK, their resistance (extrapolated at zero bias current) changes by 5 orders of magnitude.

- Unfortunately, a resistance cannot be measured without a current and as soon as we apply a current, the resistance decreases greatly and the devices severely lose their sensitivity. The carriers in the crystal (holes in our case) become hot for very low biasing power.

- We have been trying to understand the origin of this phenomena, which is to some extent present in all semiconductor doped thermistors¹⁶⁾. Our tests point to the possibility of decoupling between the carriers and the (thermal) phonons. If this is the

case, it is indeed very bad news, since we would like to use these detectors as phonon sensors!

- The situation may be saved by the lack of thermalization of phonons mentioned in section 4.1. Theoretical reasons²⁰⁾ lead us to believe that high energy phonons will not encounter this decoupling problem. The α and 60 keV pulses that we observe in our samples have very fast rise times (limited by our electronics), as is expected for good coupling. This does not constitute, however, an unambiguous proof for that process, and we are actively trying to obtain better experimental evidence. Our problem is that not very much is known on these processes as hot carriers and electron-phonon decoupling phenomena are at the forefront of Solid State Physics. Again, this is typical and if we had chosen to describe the development of tunnel junctions, we would have encountered similar fundamental problems of Solid State Physics³¹⁾.

5. CONCLUSIONS

We seem to have drifted far from our scientific quest on the nature of dark matter. However, the full testing of the hypothesis that dark matter is made of particles requires very sophisticated instrumentation, able of detecting weak energy deposition and providing the signatures necessary to distinguish the signal from the background.

Cryogenic detectors are good candidates for this important and challenging job. It is too early to know whether they will succeed. From our remarks, it should be clear, however, that in order to develop them it is necessary to master hosts of practical and Solid State Physics problems. It will clearly be a long haul, but the experimental challenges are fascinating. In addition to dark matter searches, there are many promising applications⁶⁾. And the fundamental nature of our initial scientific question certainly deserves a large amount of effort.

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