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D. Yvon, N. Wang, M. Chapellier, G. Chardin, P. Levêque, et al.. Bolometer's development, with simultaneous measurement of heat and ionisation signals, at Saclay. Journal of Low Temperature Physics, Springer Verlag (Germany), 1993, 93, pp.405-410. <hal-00125089>

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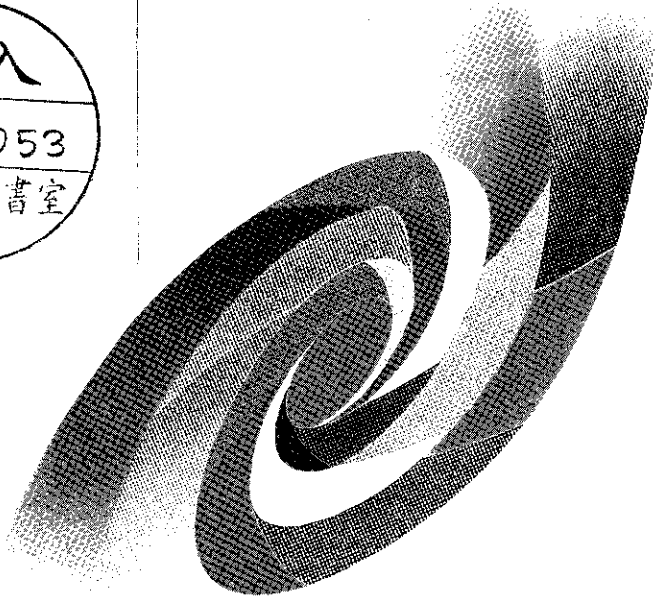

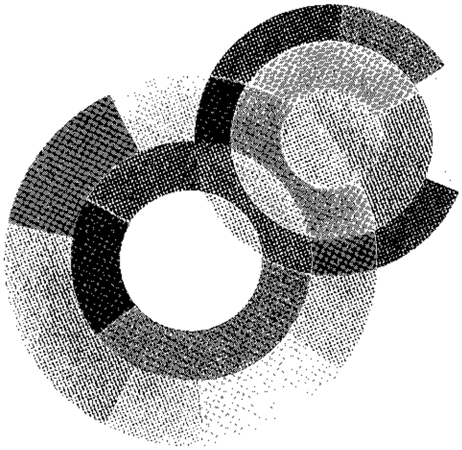

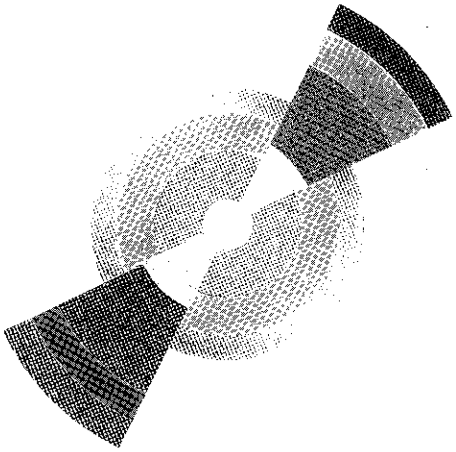

DAPNIA/SPP 93-11 August 1993

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Communication at the 5th Int. Workshop on
Low Temperature Detectors
for Neutrinos and Dark Matter (LTD5),
Berkeley, July 29 - August 3, 1993

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Adresse : DAPNIA, Bâtiment 141
CEA Saclay
F - 91191 Gif-sur-Yvette Cedex

Bolometer development, with simultaneous measurement of heat and ionisation signals, at Saclay

D. Yvon[1], N. Wang[1*], M. Chapellier[2,3], G. Chardin[1], P. Levêque[2], D. L'Hote[2], P. Pari[2], J. Soudée[2,3], G. Guerrier[2].

[1]*DAPNIA/SPP, CEA Saclay, 91191 Gif sur Yvette, France*
[2]*DRECAM/SPEC, CEA Saclay, 91191 Gif sur Yvette, France*
[3]*URA2, Université Paris Sud, 91405 ORSAY, France*
**Now at Caltech, M/S 320-47 Pasaneda, CA 91125,USA*

We report the latest developments of our work on bolometers. Low noise readout simultaneously in charge and heat channel was achieved. Tests were conducted using a 7 g bolometer build in Berkeley. Baseline widths 350 eV (1σ, phonon) and 1 keV (1σ, ionisation) were measured. But the 60 keV phonon width was found to be significantly larger than the baseline width. Also the amplitude of ionisation signal was found to drift with time. This effect motivated a detailed study of ionisation detectors at very low temperatures. Behavior of PIN silicon diodes (Hamamatsu) was investigated from room temperature to 3 K. First results are shown.

1. INTRODUCTION

A long standing problem of cosmology is the problem of Dark Matter. More recently, it was realised supersymmetry predicted the existence of unseen particles that could contribute significantly to the dark matter of the universe(1). These would be massive (1 GeV to TeVs) and would interact very weakly with ordinary matter. Goodman and Witten(2) suggested that these WIMPs (Weakly Interacting Massive Particles) could be detected through their elastic scattering on nuclei. The experimental challenge is tough, since the energy of recoiling nuclei would range from a few tens of eV to a few tens of keV. The event rate would be at best of the order of a few events keV^{-1} kg^{-1} day^{-1} of detector, most of them at low energy.

New cryogenic detectors, bolometers, were developed to detect those particles. They aimed to lower the threshold of other existing detectors and to allow simultaneous measurement of heat signal, and luminescence, or ionisation and thus reject photon like interactions which are known to be the major source of radioactive background.

T. Shutt et al (3) demonstrated that a rejection factor of 10 could be achieved on photon events relative to WIMPs like events (simulated by neutron scattering). To allow an unambiguous interpretation of future WIMP detection experiments, precise calibration of such bolometers, both for the ionisation and the heat signal is necessary. That was the purpose of the present work. The Berkeley group would provide us with an ionisation bolometer, and the Saclay group, in collaboration with Institut de Physique Nucleaire de Lyon, would test it in a neutron beam. Through kinematics of neutron scattering, we would determine the recoiling nucleus energy, and measure the corresponding heat and ionisation signal. Unfortunately, the bolometer showed an unexpected behaviour, which we will expose in this paper.

1.1. Test equipment

We used a cryostat(4) made in the cryogenic laboratory of P. Pari. This type of cryostat uses no 1.2 K pot, provides fast cooling and transportability, but does not allow yet large cooling power. The front end electronics were adapted from the one developed in Berkeley laboratory. Two silicon JFET(5) were mounted on a thermal impedance attached to the 4 K plate of the dilution unit. Manganin twisted cables were used to connect the drain and source of FETs to the top of the cryostat, where they are connected to the preamplifier board. The preamplifier cards used are fully described in D. Yvon et al.(6). Rejection of low frequency electrical noise in heat channel was achieved using a lock-in amplifier. This being done, the major excess noise contributions originated from electrical problems. Data acquisition developed under Labview(7) allowed online treatment of the incoming signals such as time space fit.

1.2. Bolometer

The bolometer, was designed to sustain a rate of few tens of Hz, when used in a neutron test beam. Build in Berkeley, it consisted of a 7 g high purity (≈ 3 10^{11} trap cm^{-3}) Ge disk. Face implants were chosen to be P^{+} (Boron 3 10^{14} at. cm^{-2}, 25 and 40 keV) and N^{+} (Phosphorus 5 10^{14} at. cm^{-2}, 25 keV), to be able to bias the crystal as a regular diode. Three Neutron Transmuted Doped (NTD12) thermal sensors (1*2*0.3) mm^{3} from Haller's group were eutectically bonded(8) on the P^{+} implant side of the crystal. The eutectic bound was made as thin as possible to allow good phonon transmission and reduce the pulse risetime.

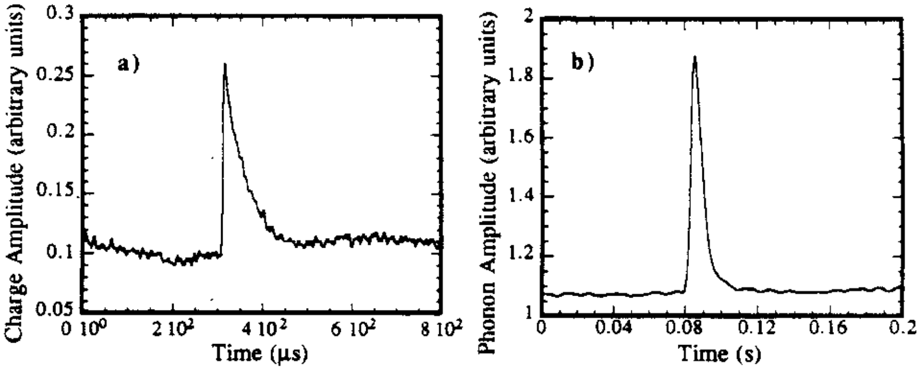

Figure 1 A typical γ-ray 60 keV event, as seen in charge (a) and in phonon (b) channels.

2. TEST RESULTS

The bolometer exhibits a remarkable diode like behaviour, even at the lowest temperatures. At temperature below 1K, we were able to revert bias the crystal up to 100 V without measuring a noticeable leakage current. The bias voltage is limited to 1V to minimize the heating induced by the drift of charges in the crystal. A typical 60 keV event is shown in figure 1. The baseline modulation of the charge signal is due to crosstalk from the modulation on the NTD. Unfortunately, the quality of the signal is rapidly degraded.

2.1. Ionisation channel studies

In this study, no biasing current is applied on the NTD sensor. The crystal has been irradiated with a 120 µC Cesium source placed at 10 cm from the bolometer for one night while both faces of the crystal were grounded.

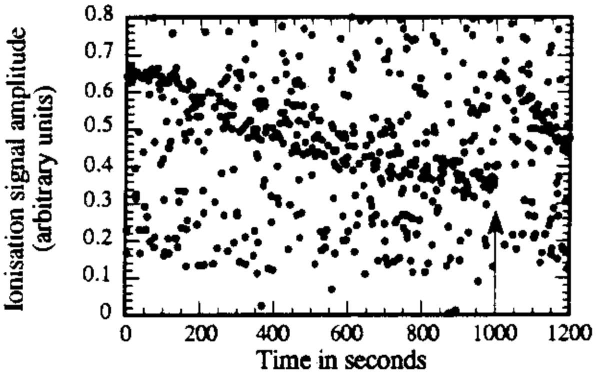

Figure 2: Drift of charge signal amplitudes with time. At t = 1000 s, indicated by the arrow, both faces of the crystal were grounded.

2.1.1. Stability tests

Figure 2 shows a scatter plot of the measured charge amplitude versus time, after the crystal has been (revert) biased from ground to 1V. The amplitude of the 60 keV γ -ray events from ^{241}Am seemst to be stable for approximately 2 minutes. Then the amplitude decreases and the resolution worsens. After 1000 s, the detector was grounded for ≈1 mn and then biased again. The pulse amplitude recovered and then drifted again. We made an automatic reset of the bias voltage, hoping it would allow us to run continuously, but this was insufficient. Further tests have shown that this detector cannot be run with optimal resolution, without at least 60% deadtime This is a very bothering effect :

- since, for timing reasons, we trigger on the charge channel, the trigger level increases with time, thus forbidding the study of the lowest energy events.
- although a software correction of the amplitude with time can be done, the resolution is degraded and a discrimination of gamma like events would only be possible at high energy.

These observations can be explained assuming that space charges slowly build up within the crystal. The effect had been observed in Berkeley with the E2 bolometer (60 g germanium), but with a much lower amplitude. However, the 7 g Ge crystal contains three times more active impurities and one of the contact implants is N+ (Phosphorus) type. Phosphorus implants are known to be more difficult to make than boron ones. Many deep levels would then allow charge trapping at the implanted surface. We will investigate these hypothesis in more details in the future.

2.1.2. Resolution tests

Baseline width as measured from random triggers is 1 keV (1σ). The trigger threshold, however, is as high as 10 keV, due to a spurious pick-up frequency at 100 kHz we could not completely suppress.

Since the signal amplitude is drifting, it is difficult to have sufficient statistics to make a good measurement of the 60 keV peak width. From the data we took, the FWHM $\leq$3.6 keV which is not very different from the baseline width we measured.

2.2. Phonon channel studies

Phonon data were taken in the following conditions : The two implanted contacts were kept to ground, while the charge amplifier was still in operation. Due to the diode-like behavior of the detector, we still observe a pulse on the charge channel, when an interaction occurs. The charge pulse height is one third of its nominal amplitude and allows to trigger on 60 keV gamma events. This is a convenient way to get good timing for phonon pulses.

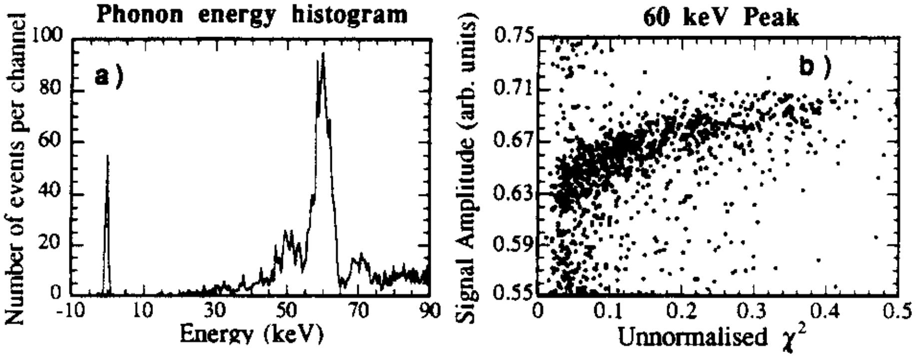

Figure 3: a) Energy histogram in phonon channel. The 60 keV peak FWHM is 2.9 keV. The baseline witdh is 350 eV.

b) Scatter plot illustrating the correlation between the computed amplitude of the 60 keV event and the χ^2 of the fit. This effect results from a position dependent athermal variation of the pulse shape from one event to the other.

Before taking data, a template is prepared from the average of 20 carefully chosen events (50 keV$\leq$E$\leq$ 250 keV). Event are then fitted to the template multiplied by the "fitted amplitude" plus a baseline constant.

Due to youth problems of our fridge, data were taken at 34 mK. This is not the optimal temperature for such a sensor, as determined by T. Shutt et al(3), so further progress on resolution are expected.

2.2.1. Resolution Tests

Six thousand events were taken. The 60 keV is clearly seen (figure 3a), though it displays a large witdh, 2.9 keV (1σ), compared to the pedestal width of 350 eV (1σ). Such a discrepancy has to be understood. We are clearly not limited by electronic or microphonic noises.

Figure 3b shows the fitted amplitude of the signal versus the (unnormalised) χ^2 of the fit. The amplitude is correlated to the measured χ^2 suggesting that incoming signals may have slight variations in shape leading to significantly different fitted amplitudes.

2.2.2. *Analysis.*

Such variations are expected to happen if the pulse shape is position dependent. This is likely to happen because NTD thermometers have been bonded with a much thinner interface than the 60 g Ge from Berkeley. In order to test this hypothesis, we builded two averaged pulses by selecting 60 keV events with "high" and "low" χ^2. The difference between the two pulse shapes was used as a template for the position dependent term. We then reanalysed the data using this additional function as a new parameter. The 60 keV width was reduced down to 2 keV (1σ). This is consistent with the athermal contribution hypothesis. The 60 keV width is still large relative to the baseline width. Future work is needed to test whether other effects degrade the resolution.

3. PIN DIODE IONISATION TESTS

The study of semiconductor detectors at very low temperatures is interesting in itself for solid state physics and is motivated by the results shown above. In this study, we used pin commercial photodiodes. Same qualitative behavior of the device was observed, though parameters of the crystals and of the fabrication process were very different.

We measured the charge signal induced by 5.58 MeV alpha particles in a 500 µm thick silicon pin diode, at low temperature (3K) and compared the measurements with 77 and 300K data. The results are shown on figure 4. Because of the thin (1 µm) p layer thickness, the irradiation on the p side generates almost all the carriers in the depletion region.

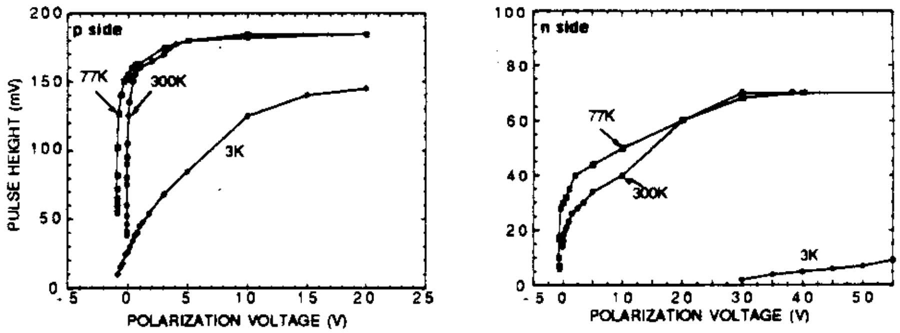

Figure 4 Pulse height as a function of the diode polarization voltage at T=3, 77 and 300K. The left (resp. right) part corresponds to an irradiation on the p (resp. n) side of the diode .

Figure 4 (upper part) shows that the drift of the electrons across the whole diode volume is achieved for polarization voltages above 5V at high temperatures. For T=3K, the smaller signal observed can be accounted for by an increase of trapping cross-sections, and a decrease of the detrapping probabilities. Also, it could be that the depletion region thickness is decreased, and the increase of the undepleted region resistance may slow down the drift of the carriers(9). The smaller charges collected for an irradiation on the n-side are due to the thicker (20 μm) n-doped dead layer. The much smaller signal at 3K could be due to the decrease of the hole diffusion which would forbid them to reach the depleted region if the latter does not extend across the whole diode volume. Finally, we observed that the resolution became worse at low temperatures or polarization voltages. The collected charge decrased with time (–40% in 15mn), suggesting that a space charge built up.

4. CONCLUSIONS

We have developed a low noise readout electronic system for bolometers with charge and ionisation readout. Unfortunately, the amplitude of charge pulses decreased with time. In addition, the phonon energy spectrum is degraded by a position dependent pulse shape. Work is continuing to improve these detectors. We plan to build a detector of larger mass with low radioactivity materials to be soon installed in the Fréjus underground laboratory.

ACKNOWLEDGMENTS

We are grateful to the Berkeley group for providing information and experience whenever needed. This work was funded by the Commissariat à l'Energie Atomique. Direction des Sciences de la Matière, Saclay, and Laboratoire de physique des solides, URA2, Orsay, France.

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