Nuclear Instruments and Methods in Physics Research A314 (1992) 595–601
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Gamma ray spectroscopy with high-Z thermal detectors

A. Alessandrello [a], C. Brofferio [b], D. Camin [a], O. Cremonesi [a], E. Fiorini [a], G. Gervasio [a], A. Giuliani [a], M. Pavan [a], G. Pessina [a], E. Previtali [a] and L. Zanotti [a]

[a] *Dipartimento di Fisica dell'Università di Milano and Istituto Nazionale di Fisica Nucleare, Milano, Italy*
[b] *Laboratori Nazionali del Gran Sasso dell'INFN, Assergi, L'Aquila, Italy*

Received 4 September 1991

A massive thermal detector to be used to search for rare decays and to detect high-energy γ-rays has been operated both at sea level and underground. It consists of a 20.9 g monocrystal of TeO_2 whose temperature is measured by means of a neutron transmutation doped thermistor. The detector was first operated in Milano at a base bolometer temperature of 22.5 mK and with a FWHM resolution of 90 keV, rather independent of the γ-ray energy. Much better results have been obtained when the detector was operated underground, under a suitable shielding against local radioactivity and inside a Faraday cage. The base bolometer temperature could be as low as 14.5 mK which, together with the elimination of pile-up, allowed to achieve FWHM resolutions of 1% for γ-rays above 2.0 MeV. The increase in the base temperature of the bolometer when exposed to a weak radioactive source is discussed in view of possible applications in the search for dark matter.

1. Introduction

Development of γ-ray detectors made with materials of high atomic number is of obvious interest in nuclear and subnuclear physics. In fact, the contributions to the cross section of high energy photons by photoelectric effect and pair production increase with Z much more rapidly than the contribution by Compton effect. As a consequence the peak-to-Compton ratio is strongly improved by large atomic number. High-Z detectors are also very important in specific searches in fundamental physics, like those on coherent interactions of massive particles which could constitute dark matter [1–3], or on double β decay [4,5]. Bolometers operated at very low temperatures have been suggested since 1984 [5,6] as detectors of single particles. When a particle delivers an energy ΔE in form of heat to a bolometer of heat capacity C, the rise in temperature is given by:

$$\Delta T = \frac{\Delta E}{C}. \tag{1}$$

For a pure crystal of diamagnetic and dielectric material the heat capacity is given at low temperature by:

$$C = 1944\left(\frac{m}{A}\right)\left(\frac{T}{T_D}\right)^3 \text{ [J/K]}, \tag{2}$$

where m, A and T are the mass (in grams), the atomic number and the temperature of the crystal, and T_D its Debye temperature. At very low temperature the heat capacity can be so small to allow a measurable increase of temperature even for the tiny energy delivered by a single particle. The energy resolution could in principle be extremely good as shown [6] by the expression:

$$\Delta E_{FWHM} = \xi\sqrt{kCT^2}, \tag{3}$$

which assumes complete thermalization. The nondimensional parameter ξ can be of a few unities in sensitive enough detectors.

Various bolometers, of different materials and sizes, are presently operating [7–10] with performances which are very good, even if still far from those predicted theoretically. Small bolometers, of masses of the order of a few tens of micrograms, to be used for detection of X-rays or in searches on the neutrino mass, have reached impressive resolutions [7–11]. Many massive bolometers made of low-Z crystals have been constructed, taking advantage of the very favourable Debye temperatures of materials like silicon, sapphire or lithium fluoride [7–10,12–14]. They are not suitable to detect high energy γ-rays or massive dark matter particles.

High-Z detector materials only rarely present high Debye temperature, which makes considerably difficult to realize thermal high-energy γ-ray detectors. An exception is represented by many superconductors, where however the Cooper pair broken by the incoming particle could not recombine in a time sufficiently shorter than the thermal relaxation time [15]. In fact the Milano group has recently found that a relatively large (2.4 g) crystal of molybdenum was yielding pulses an order of magnitude lower than expected for full energy thermalization [16]. The Genova group obtained good thermalization and detection of ^{60}Co γ-rays with a rhenium crystal, whose mass was however of 20 mg only [17].

Large germanium bolometers have been constructed by the Center for Particles Astrophysics (60 g) [18] and by the Milano group (190 g) [19], but their energy resolutions are much poorer than for germanium diodes. One has to note however that the former of these bolometers could measure at the same time ionization and heat, an essential feature to reduce background in experiments for the search of rare events.

We have constructed and operated bolometers of tellurium, a high-Z element which is very promising for the search of double β decay of ^{130}Te (33.87% isotopic abundance). After the use of a crystal made with 2.1 g of pure tellurium [20], which we found however very brittle at low temperatures, we have successfully operated a 5.7 g TeO_2 crystal. We report here the construction and operation of a much larger detector made with the same material and presently used in an underground experiment on double β decay.

2. Experimental details

The detector is shown in fig. 1. It consists of a TeO_2 crystal of $20 \times 16 \times 12$ mm^3 with a mass of 20.9 g. It is fastened to the heat sink of the dilution refrigerator by a frame made with oxygen free high conductivity (OFHC) copper. In order to reduce microphonic noise the crystal is suspended with 16 brass screws whose extremities have small tips which exert a pressure adjustable with springs. Springs also compensate the different contraction of crystal and frame when the temperature decreases. A sample of the OFHC copper used in the frame, screws and all materials surrounding the bolometer has been previously measured with our low radioactivity γ-spectrometer located in the Gran Sasso Underground Laboratory in order to ensure against detectable radioactive contaminations. The temperature of the crystal is measured with a neutron transmutation doped thermistor, provided to us by Prof. E. Haller, kept in thermal contact by means of Dow Corning high vacuum grease. The characteristic curve of this thermistor (fig. 2) follows the dependence:

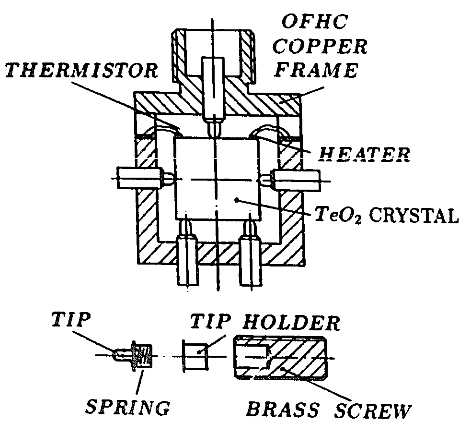

Fig. 1. Cross section of the frame used to hold the TeO_2 detector. A detail of the tip mounting is shown.

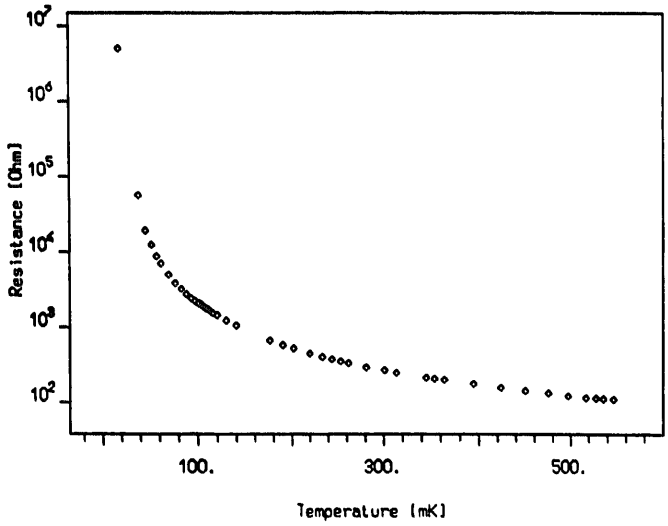

Fig. 2. Characteristic R–T curve of the thermistor obtained in Milano.

$$R(T) = R_0 \exp\left[(T_0/T)^{\gamma}\right], \tag{4}$$

with $R_0 = 22.5\ \Omega$, $T_0 = 1.4$ K and $\gamma = 0.57$ (close to the expected value of 0.5).

The detector was initially operated inside a standard dilution refrigerator with a cooling power of 200 μW at 100 mK, installed in our laboratory in Milano. The temperature of the mixing chamber was below 10 mK, but the detector temperature at zero bias was of 22.5 mK due to extra heating whose origin will be discussed below. The thermistor was biased to 2.6 mV using a battery and two 6 MΩ load resistors kept in thermal contact with the mixing chamber. The bolometer temperature was thus rised to 25.5 mK, where the resistance of the thermistor is of about 430 kΩ. In order to reduce the parasitic capacitance, the preamplifier has to be kept near the detector. The signal readout is realized using a differential configuration implemented with two cryogenic GaAs MESFET voltage sensitive preamplifiers [22] mounted in thermal contact with the helium bath of the dilution refrigerator and connected to the thermistor with wires of 50 cm length. The balanced readout greatly reduces the common-mode microphonic noise (a 100 dB rejection-ratio was measured) and the short-length connecting wires keep the parasitic capacitance low (~ 30 pF). Total noise contributed by both preamplifiers is of about 15 nV/$\sqrt{Hz}$ at 100 Hz with a $1/\sqrt{f}$ distribution. Measurements of noise power spectra have shown that total system noise is dominated by microphonic effects. The total power dissipated by both preamplifiers is about 100 mW. In order to test the stability of the system, thermal pulses corresponding to 15 MeV were generated every 30 s by injecting calibrated voltage pulses into a small nichrome resistor in thermal contact with the crystal.

The detector has been exposed to radioactive sources of ^{60}Co and ^{232}Th placed immediately outside the dilution refrigerator. A typical pulse produced by the ^{60}Co source (fig. 3) has a risetime of about 15 ms, much higher than expected from integration in parasitic capacitance (~ 30 μs). The risetime has therefore to be attributed to phonon thermalization and to thermal resistance between absorber and thermistor and possibly even between electron and lattice in the thermistor itself [23]. The thermal pulses have a long tail of about 2 s, but they are clipped by using ac coupling to reduce the pile-up in the acquisition system. The "electric" decay time ranges therefore between 100 and 200 ms. A threshold of ~ 800 keV was set for calibration purposes. Since the counting rate with the source is around 1.6 Hz and about 0.6 Hz without the source we clearly operate in undesirable pile-up condition. This shows the need to work underground and under a suitable shield against environmental radioactivity.

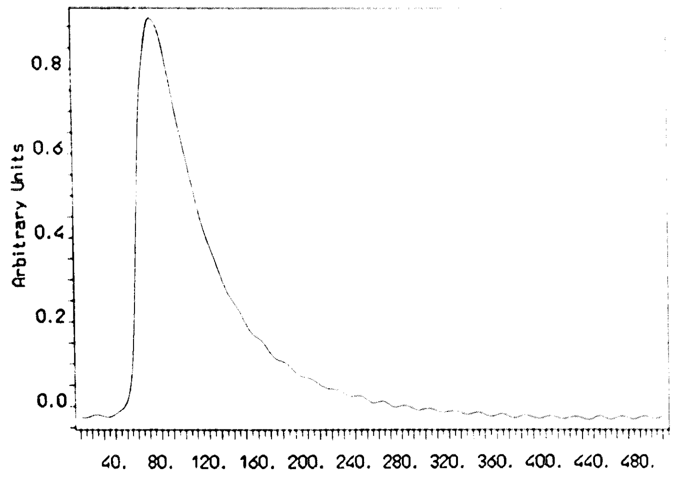

Fig. 3. Typical pulse obtained in Milano with a ^{60}Co source.

A second series of measurements have been performed after having installed the same detector in a dilution refrigerator with a cooling power of 1 mW at 100 mK operating in hall A of the Gran Sasso Underground Laboratory. The overburden of rock (about 1400 m corresponding to about 3500 m of water equivalent) suppress the background of charged cosmic rays

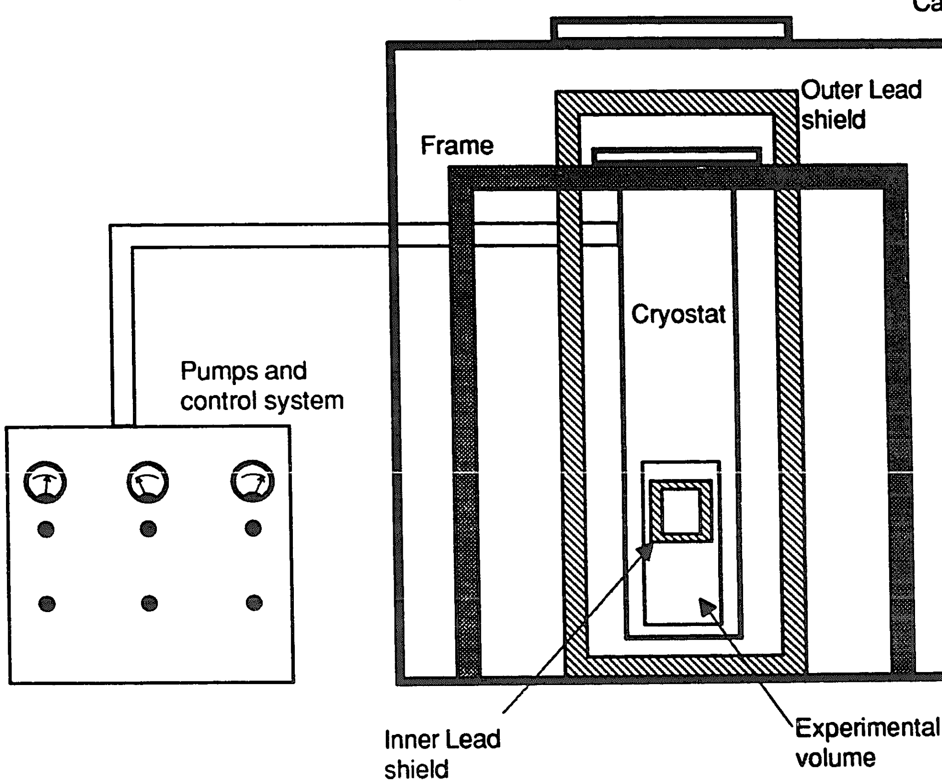

Fig. 4. The cryogenic setup in the Gran Sasso Underground Laboratory.

by a factor of $\sim 10^6$, while the flux both of thermal and fast neutrons is reduced by four orders of magnitude. This refrigerator, which can house a sample of up to 100 kg mass and up to 20 l volume has been specially constructed, in collaboration with Oxford Instruments, in order to reduce the contribution from its intrinsic radioactivity to the background of the detector. Most of it is therefore made with OFHC copper, and the amount of stainless steel has been reduced to minimum. All materials of the refrigerator have been previously tested and chosen for their low radioactive contamination. For all materials which were present with masses larger than 10 g, the intrinsic activity was less than 10^{-2} Bq/kg^{-1}, while for those with lower mass an upper limit of 10^{-1} Bq/kg was accepted. Despite the constraints due to this choice of materials the refrigerator could reach base temperatures as low as 5.7 mK similar to those obtained in Milano.

The refrigerator (fig. 4) is shielded against environmental radioactivity with a layer of low activity lead with a minimum thickness of 10 cm. The content of radon surrounding the refrigerator is reduced by enclosing it in a plastic bag which is fluxed with nitrogen. Electromagnetic interference of local origin is suppressed by means of a Faraday cage surrounding the refrigerator, while the radiofrequency interference generated by radio broadcasts is completely attenuated by the mountain. The detector biasing circuitry and a differential to single ended postamplifier are located inside the cage. All wiring traverses the cage walls through LC low pass filters, with the exception of the single pulse line which uses a BNC feed through.

The first and most impressive consequence of the operation in the Gran Sasso was that the detector base temperature was of 14.5 mK only. The thermistor was biased to 5 mV with a battery and its temperature thus raised to 16.5 mK, corresponding to a resistance of 6.5 MΩ. The stability was tested by injecting every 15 min thermal pulses corresponding to 770 and 2800 keV, separated by a time interval of 5 s. The detector was exposed through a small window in the lead shield to the same radioactive source as in Milano, with a threshold of 430 keV. The time structure of the pulses was similar to those in Milano, but the counting rate in absence of radioactive sources was much lower and any pile-up disappeared.

3. Results

We would like first to discuss the results obtained in Milano, even if those obtained underground are obviously quite superior. The voltage pulses and the increases in temperature corresponding to a γ-ray energy of 1 MeV are reported in table 1. The FWHM resolution is of about 90 keV, independently of the energy and can be fully accounted by the signal-to-noise ratio, which, as mentioned, is limited by microphonic effects.

Table 1
Voltage and temperatures increases corresponding to 1 MeV delivered to the bolometer and "apparent" heat capacities

Operating temperature [mK]	ΔV [μV]	ΔT [μK]	C_{app} [nJ/K]
25.5	17.9	32.0	5.2
16.8	150	97.0	1.6

In view of the comparison with the results obtained underground we have placed a 180 kBq ^{60}Co radioactive source in contact with the refrigerator, thus increasing by a factor of three the counting rate due to environmental radioactivity and cosmic rays. No measurable increase of the operating temperature of the detector was found ($\Delta T < 0.1$ mK).

In the experiment carried out in the Gran Sasso Underground Laboratory the lower temperature and the consequent much better responsivity of the detector considerably increased the signal-to-noise ratio. The changes of voltage and temperature corresponding to a γ-ray energy of 1 MeV are reported in table 1. The spectra obtained with the various sources are shown in figs. 5–7. The FWHM resolutions are around 20 keV, rather independent of energy, and can be almost entirely accounted for by the signal-to-noise ratio. We would like to point out that the resolution for the thermal calibration pulses and for the γ-rays at the same energy are similar.

One could extract in principle "apparent" values for the heat capacities from the voltage pulses and the sensitivity of the thermistor. The values, reported in

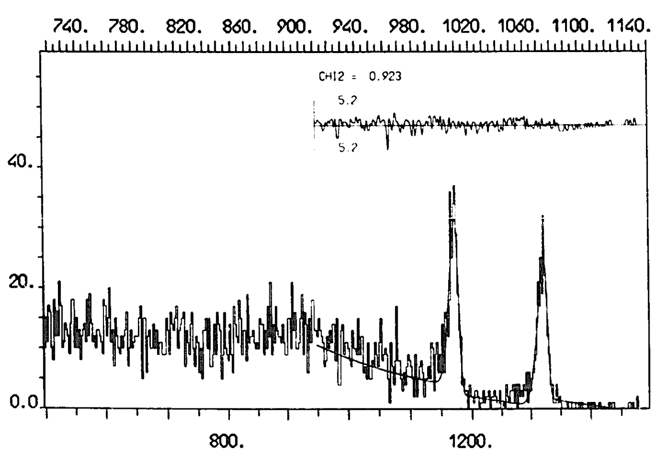

Fig. 5. Spectrum with a ^{60}Co source in the Gran Sasso Laboratory.

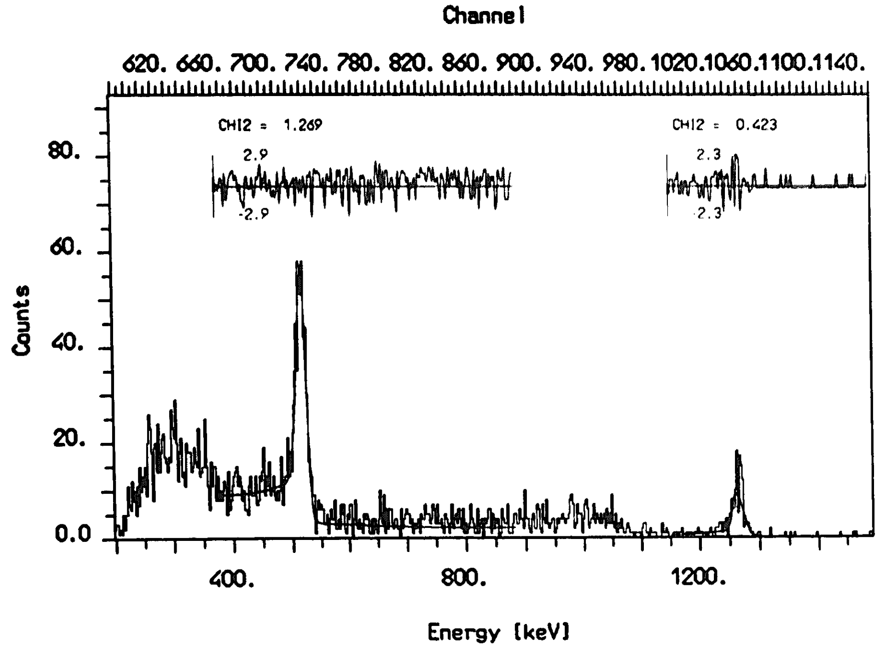

Fig. 6. Spectrum with a ^{22}Na source in the Gran Sasso Laboratory.

table 1, are larger by an order of magnitude than those which can be obtained on the basis of the recent measurements of the Debye temperature of TeO_2 [24]. This could be due to:

a) incomplete thermalization of the energy delivered by the particle;

b) incomplete transfer to the thermistor lattice of the heat delivered to the crystal;

c) incomplete transfer to the hopping electrons of the heat delivered to the thermistor lattice [23];

d) contribution to the heat capacity of the bolometer by the thermistor.

Measurements are in progress to clarify these points. We would like to point out however that heat capacities larger then expected by more than an order of magnitude have already been found for large crystals operating at low temperatures [12].

The resolutions in the energy measurements carried out in the Gran Sasso are the best obtained for high-energy γ-rays (> 1 MeV) with thermal detectors of this

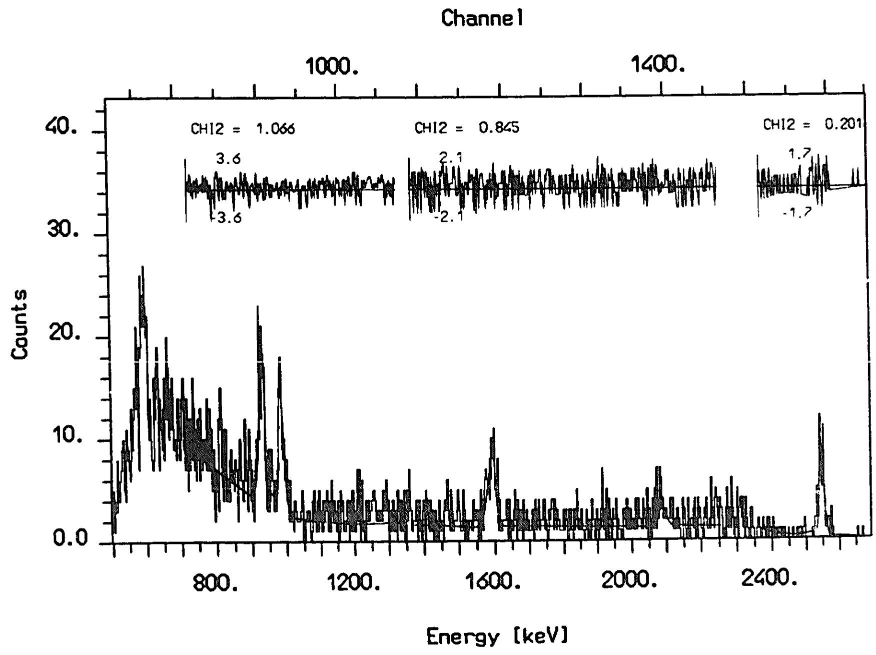

Fig. 7. Spectrum with a ^{232}Th source in the Gran Sasso Laboratory.

mass, despite the poor thermal properties of tellurium oxide. In comparison with the measurements carried out with soft γ-rays and with α-particles we would like to note that:

a) the source is placed outside the dilution refrigerator and is therefore separated from the detector by layers of aluminum and copper totalling ~3 g cm^{-2} producing Compton background. This background is not present when the "event" occurs near the crystal or inside it, as for experiments on double β decay or on interactions of neutrinos or WIMPS;

b) unlike in experiments with low-Z bolometers, where the detector is calibrated with α-particles incident in a well defined region, in the present experiment the interactions of the γ-rays are spread over the entire crystal. The response of the detector does not depend therefore on the position of interaction, within the resolutions obtained so far;

c) the detector has been operated for continuous runs of a few days with a small change in the overall gain which slightly affects the resolution. Good stability is essential in the experiments where rare events are to be searched.

The effect due to the high atomic number of the detector is shown by the counting rates in the full energy, single escape and double escape peaks of the 2614.6 keV line of ^{208}Tl (4.4, 1.5 and 6.4 counts h^{-1}, respectively). Their ratios are similar to those that can be achieved with a Ge diode of a mass larger by an order of magnitude.

We have experimentally investigated the heating of the detector due to cosmic rays and environmental radioactivity. We have first evaluated from the spectra obtained in Milano the heat delivered to the detector in absence of radioactive sources for calibration. The heat delivered by pulses above the threshold (800 keV) was found to be 0.7×10^{-14} W g^{-1}. When extrapolated to the entire energy interval using the well known spectra at sea level we found a value of 1.2×10^{-14} W g^{-1} in very good agreement with the value obtained with Ge diodes [2]. As mentioned before a ^{60}Co source corresponding to a counting rate three times larger than for environmental radioactivity did not produce any measurable increase of the temperature. In the Gran Sasso Laboratory we have evaluated that the heat delivered by the environmental activity (external radioactivity and cosmic rays) was from three to four orders of magnitude lower than in Milano. When placing the same ^{60}Co source in contact with the refrigerator we could measure an increase of temperature of 0.5 ± 0.1 mK, as shown by fig. 8. From the energy distribution in the spectrum and from its extrapolation below the threshold we have evaluated that the power delivered by the source to the crystal was 2.5×10^{-14} W g^{-1}, larger by a factor of 2 with respect to the heat delivered by radioactivity and cosmic rays in Milano. It

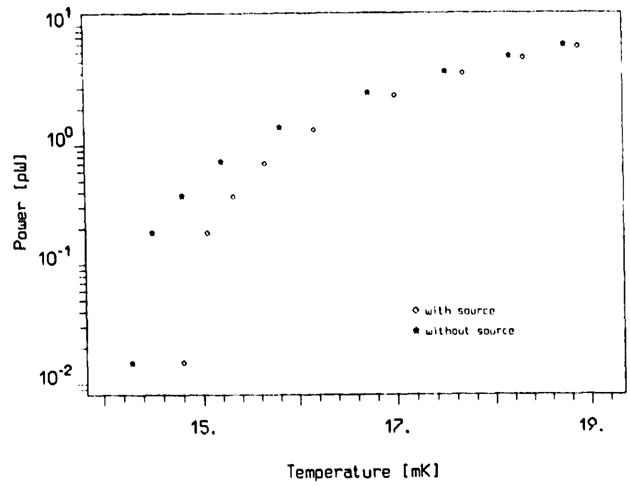

Fig. 8. Curves of power dissipated by bias current through the thermistor vs thermistor temperature, obtained in the Gran Sasso Laboratory. The upper and lower curves correspond to measurements without and with radioactive source, respectively. From extrapolation to zero bias power it is possible to obtain the crystal temperature in the two cases.

is therefore clear that the decrease in the operating temperature in the Gran Sasso Laboratory cannot be attributed to the lower environmental activity. We are presently investigating if this decrease is due to the improved suppression of the electromagnetic field by the Faraday cage and by the rock and/or by a different vibrational heating.

4. Conclusions

The main result of the present experiment is the excellent performance of a large TeO_2 thermal detector that can be very useful not only for the search of double β decay of ^{130}Te, but also for γ-ray spectroscopy. When operated underground the lower detector temperature, and the better pile-up conditions, allowed us to reach a FWHM resolution around 1% in the high energy γ-lines. The ratio of the counting rates in the full energy and double escape peaks is similar to the one that can be obtained with standard Ge diodes of mass greater by at least an order of magnitude.

We would like to note that the pulse heights are still an order of magnitude lower than expected theoretically. This could be due to unavoidable thermal difficulties, like violation of the Debye law at low temperatures, or thermal decoupling between lattice and electrons in the thermistor at low temperature. Some improvements in the performance of the detector can however still be achieved with a better thermistor and by increasing the fraction of heat transferred to it from the crystal.

We consider it quite important that underground, under strong reduction of electromagnetic interferences and better thermal operating conditions, we were able to detect a sizeable increase of the base temperature of the bolometer when it was exposed to a weak radioactive source. As we are sensitive to base temperature variations down to 0.1 mK, we can in principle monitor variations as low as 10^{-13} W in the background power delivered to the crystal. This indicates that searches on dark matter based on its integral thermal effect [2] on massive targets are indeed feasible.

Acknowledgements

We would like to thank the director and staff of the Laboratori Nazionali del Gran Sasso for their generous hospitality. The help of R. Benedet, R. Cavallini, S. Latorre, A. Nucciotti and S. Parmeggiano is gratefully acknowledged.

References

[1] P.F. Smith and J.D. Lewin, Phys. Rep. 187 (1990) 203, and references therein.
[2] E. Fiorini, Proc. of the Texas/ESO-CERN Symposium, Brighton, UK, December 16–21, 1990, to be published.
[3] D.O. Caldwell, Dark Matter Detection, Lectures given at the Int. School of Astroparticle Physics, The Woodlands, Texas, January 6–12, 1991.
[4] M. Moe, Nucl. Phys. B (Proc. Suppl.). 19 (1991) 158.
[5] E. Fiorini and T.O. Niinikoski, Nucl. Instr. and Meth. 224 (1984) 83.
[6] S.H. Moseley, J.C. Mather and D. Mc Cammon, J. Appl. Phys. 56 (1984) 1257.
[7] K. Pretzl (ed.), Proc. Low Temperature Detectors for Neutrinos and Dark Matter I (Springer, 1988).
[8] D. Gonzales-Mestres and L. Perret-Gallix (eds.), Proc. Low Temperature Detectors for Neutrinos and Dark Matter II (Edition Frontieres, 1989).
[9] L. Brogiato, D. Camin and E. Fiorini (eds.), Proc. Low Temperature Detectors for Neutrinos and Dark Matter III (Edition Frontieres, 1990).
[10] G. Ways and G. Chardin (eds.), Proc. Superconducting and Low Temperature Particle Detectors (Elsevier, 1989).
[11] D. Mc Cammon, private communication.
[12] W. Seidel, W. Christen, F.v. Feilitzsch, G. Forster, H. Gobel, F. Proebst and R. Moessbauer, Phys. Lett. 236B (1990) 483.
[13] N. Coron et al., in: Superconducting and Low Temperature Particle Detectors, eds. G. Waysand and G. Chardin (Elsevier, Amsterdam) pp. 115–126.
[14] P.F. Smith, G.J. Homer, S.F.J. Read, D.J. White, J.D. Lewin and N.J.C. Spooner, Phys. Lett. 245B (1990) 265.
[15] N.E. Booth, R.J. Gaitskell, D.J. Goldie, C. Patel and G.L. Salmon, Single crystal superconductors as X-ray detectors, OUNP-91-07, Preprint, to be published in: Proc. Workshop on Tunnel Junction Detectors for X-rays, Naples, December 1990, eds. A. Barone, R. Cristiano and S. Pagano (World Scientific, 1991).
[16] A. Alessandrello, C. Brofferio, D.V. Camin, O. Cremonesi, E. Fiorini, G. Gervasio, A. Giuliani, G. Pessina and E. Previtali, Nucl. Instr. and Meth. A289 (1990) 504.
[17] G. Gallinaro, F. Gatti and S. Vitale, Europhys. Lett. 14 (1991) 225.
[18] B. Sadoulet, Summary talk on Dark Matter, Proc. Texas/ESO-CERN Symposium, Brighton, UK, 1990, to be published.
[19] A. Alessandrello, C. Brofferio, D.V. Camin, O. Cremonesi, E. Fiorini, G. Gervasio, A. Giuliani, G. Pessina and E. Previtali, Proc. Topical Seminar on Experimental Apparatus for High Energy Physics and Astrophysics, S. Miniato, Italy, 1990 (World Scientific), to be published.
[20] A. Alessandrello, C. Brofferio, D.V. Camin, O. Cremonesi, E. Fiorini, A. Giuliani and G. Pessina, Phys. Lett. 247B (1990) 442.
[21] A. Alessandrello et al., Proc. Santa Monica Conf. on Astroparticle Physics, November 1990, to be published.
[22] A. Alessandrello, C. Brofferio, D.V. Camin, A. Giuliani, G. Pessina and E. Previtali, Nucl. Instr. and Meth. A295 (1990) 405.
[23] B. Sadoulet, N. Wang, F.C. Wellstood, E.E. Haller and J. Beeman, Phys. Rev. B41 (1990) 3761.
[24] G.K. White, S.J. Collocott and J. Collins, J. Phys. C: Condens. Matter 2, (1990) 7715.