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High-resolution bolometers for rare events detection

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Abstract

Since many years the Milano–Gran Sasso collaboration is developing large mass calorimeters for Double Beta Decay and Dark Matter searches, employing TeO_2 crystals as absorber elements. Recently, we have focused our attention on the improvement of the detector resolution: an efficient dumping suspension and the implementation of a new cold electronics device, have strongly suppressed the main sources of noise. The increase in S/N ratio has been of almost an order of magnitude and the resolution achieved is competitive with that of Ge diodes for γ-rays detection, while a FWHM of 3.2 ± 0.3 keV has been obtained for 5.4 MeV alpha particles, the best result with any kind of detector. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Since the introduction of bolometers as radiation detectors, one of their most important features has been recognized in their very high energy resolution. This characteristic, together with others, such as good-energy threshold, wide choice of materials such as absorber elements, sensitivity to non-ionizing events, makes them competitive or superior to conventional detectors in many applications, such as α, β, X and γ spectroscopy, Dark Matter and rare-events searches [1]. The Milano group is involved precisely in the search of neutrinoless Double Beta Decay (0νDBD) and WIMPs interactions employing tellurite bolometers operated in a dilution refrigerator, at a temperature of about 10 mK. In collaboration with the Gran Sasso Laboratories, an experiment with an array of 20 TeO_2 crystals (the MIBETA experiment) [2], is presently running and besides setting a limit of 1.4×10^{23} y (90% CL) on the ^{130}Te 0νDBD half life [3], has demonstrated the feasibility of arrays of large mass bolometers in

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order to have high sensitivities together with very good-energy resolutions. On the basis of the MIBETA results, we are developing a new detector, consisting of a tower of 54 TeO_2 crystals, organized in modules of 4 crystals each, for a total tellurite mass of about 42 kg. This new experiment, named CUORICINO, could reach the most stringent limits on neutrinoless DBD lifetime for tellurium and consequently on the so-called *neutrino effective mass*, presently obtained with Ge conventional detectors, by the Heidelberg–Moscow collaboration [4]. With such a big mass CUORICINO can also be a powerful detector for Dark Matter searches, owing to a high sensitivity to nuclear recoils induced by WIMPS interactions with the absorber nuclei. Excellent performances in terms of resolution have been obtained with the first CUORICINO module, after an accurate study of the mechanical link between detector and refrigerator, and the implementation of a cold front-end electronics device.

2. Resolution of bolometers

Measuring the energy released by a particle with bolometric techniques requires an absorber element, cooled down to a few mK in order to have a very small heat capacity, and a phonon sensor. The impinging particle, that can be a decay product or a nuclear recoil for example, looses its energy into the absorber, changing its phonon distribution and the phonon sensor converts the temperature variation into an electrical signal. In our case a dielectric and diamagnetic TeO_2 crystal is the absorber, while the phonon sensor is represented by a Neutron Transmutation Doped (NTD) Ge thermistor, whose electrical resistance has a steep dependence with temperature, when kept at about 5–10 mK. The resitance variations result in a change of the voltage applied on the thermistor through a bias circuit with two 100 GΩ load resistors. The presence of ^{130}Te into the absorber allows us to investigate its Double Beta Decay channels, measuring the energy of the 2 electrons produced in the decay. Resolution is limited both by intrinsic (of the bolometer itself) and by external factors. Among the first we can include thermodynamical fluctuations of the crystal internal energy, statistical fluctuations of the energy stored into reticular defects or metastable electronic states (and not converted into lattice vibrations in reasonable times) and the thermistor Johnson noise. As external noise sources we find load resistors (Johnson noise), JFETs, microphonic effects and vibration heating, that is thermal power dissipation induced on the crystals by mechanical vibrations of the cryogenic facility. The difficulty of reaching an extremely high-energy resolution (in the range of the eV for microdetectors and of hundreds of eV for macrodetectors), with low-temperature detectors, as in principle could be possible, lies often in these external factors, as in our case.

3. Vibration heating and macrobolometers behaviour

Mechanical vibrations of the cryogenic facility can induce heat dissipation on the detectors, through friction between them and their holding structure (in our case a copper frame with Teflon supports for the crystals, see Fig. 1) and eventually other mechanisms. This dissipation produces large

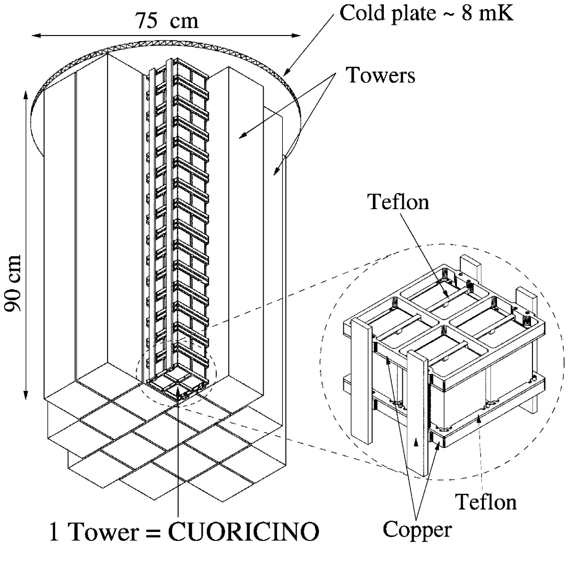

Fig. 1. The CUORE detector structure. One tower represents CUORICINO: the elementary module containing 4 crystals is in evidence.

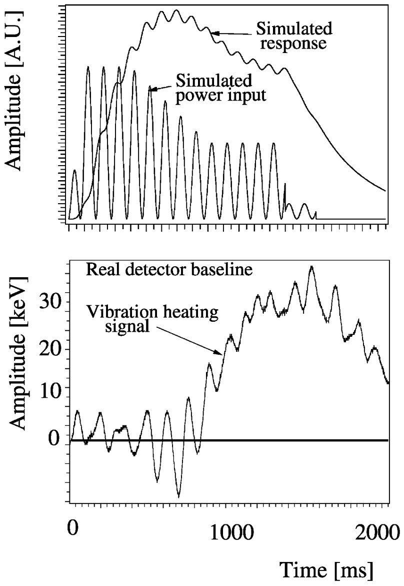

Fig. 2. Comparison between a simulated response of the bolometer to a 10 Hz power input and a typical detector baseline, obtained before the set-up improvements described in the text.

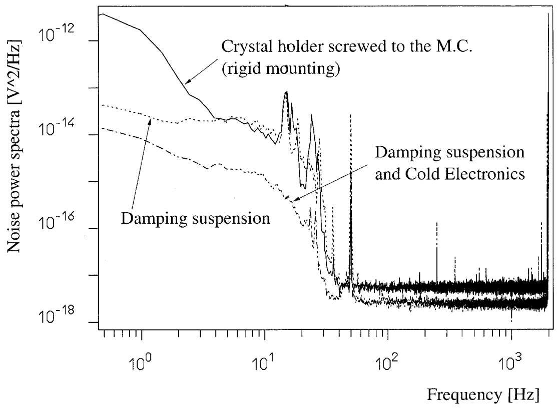

Fig. 3. Noise power spectra obtained with the old experimental configuration and with the modifications introduced.

and slow fluctuations of the detector baseline (its output signal, that is a measure of its temperature), even if the vibrational frequencies are high (a typical vibration source is the needle valve of the refrigerator 1 K-pot, with frequencies in the range of the hundreds of Hz), resulting in a rise of the low-frequency region of noise power spectra (see Fig. 3). We can explain this effect reminding that a macrobolometer is a slow-response detector, because of its large heat capacity and small coupling to the thermal bath: typical decay times for our 750 g crystals are of the order of some hundreds of ms. Therefore, even if a high-frequency vibration induces a power injection with the same frequency on the crystals, this input is integrated by the detector and converted into a slow and smoothed output signal as shown in Fig. 2. On the basis of this considerations we decided to study a mechanical suspension for our 4-crystal module, in order to damp the high-frequency oscillations of the refrigerator. In the previous configuration the crystal holder was directly screwed to the cryostat mixing-chamber (MC); now a spring, damped by a PTFE cylinder encapsulating it, suspends the module by means of two copper wires, in order to cut both the longitudinal and the transversal vibrations above a threshold of ~3.5 Hz. We can estimate in a factor 3–4 the improvement in terms of FWHM on the baseline, due to the introduction of this suspension. A comparison between the old and new noise spectra is given in Fig. 3.

4. Microphonic and front-end electronics noise reduction

The solution adopted to reduce transistors and load resistors noise is the introduction of a cold electronics stage inside the cryostat. A cold box, containing the circuit with transistors and load resistors is kept at about 4 K, inside the refrigerator, but owing to an accurate thermal link, the JFETs' power dissipation keeps them at 120 K. As the first important consequence, we reduced almost a factor 3 the white thermal noise due to resistors and the transistors leakage current. The second result is that we can now locate the front-end electronics at a much smaller distance from the high-impedance thermistors, so reducing that part of wires, responsible of microphonic effects. The improvement obtained with this set-up in shown in Fig. 3.

5. Conclusions

As a combined effect of the new suspension and the cold electronics device an improvement of a factor 10 has been achieved for the S/N ratio. The first results have been obtained with a 2-crystal module, as reported in Ref. [5]. A further improvement has come with the 4-crystal CUORICINO-like module: our 750 g TeO_2 bolometers are now competitive with Ge diodes in γ spectroscopy, with an energy resolution of 3.9 keV on the 2615 keV ^{208}Tl γ-line and are superior to any other detector for high-energy α particles: in a 19 h measurement, we obtained for the 5.4 MeV α-line of ^{210}Po, a typical contaminant of tellurium, a resolution of 3.2 ± 0.3 keV (see Fig. 4).

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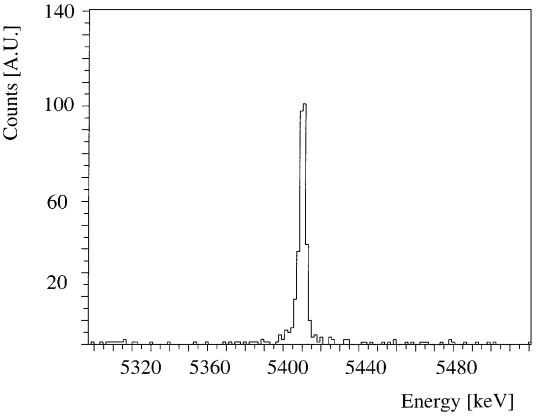

Fig. 4. The 5.4 MeV α-line of ^{210}Po, registered in a 19 h measurement with a 750 g TeO_2 bolometer.

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