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Section A

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A massive thermal detector for alpha and gamma spectroscopy

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Abstract

A massive bolometer with a 760 g TeO_2 crystal as energy absorber, the largest employed underground, has been realized and operated in the Gran Sasso Underground Laboratory for γ- and α-ray spectroscopy. A new system of mechanical suspensions was implemented to reduce vibration and thermal noise, and special care was put to the read-out electronics. As a consequence the FWHM resolution for high-energy γ-rays became comparable to that of Germanium diodes. The 4.2 keV average FWHM resolution for the 5407 keV line is the best ever obtained for α particles with any type of detector. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Alpha and gamma spectroscopy is playing an essential role not only in nuclear, subnuclear and astroparticle physics, but also in other fields of experimental science. Excellent performances are being obtained with semiconductor detectors. In γ-ray spectroscopy FWHM energy resolutions ranging from 1% to 0.1% have been reached with germanium diodes for energies ranging from hundreds of keV to a few MeV [1], even for long running times [2,3]. FWHM resolutions of about 8 keV have been attained for α-particles from 3 to 6 MeV with implanted and passivated silicon detectors [4,5]. Detectors made by different types of semiconductors or based on different techniques [1–13] are not competitive so far.

Due to their intrinsic properties, the energy resolution of semiconductor detectors is already approaching the physical limit [1,5]. The incident heavy ionizing particles, electromagnetic radiation and energetic electrons transfer their energy to the electrons of the detector by ionization and excitation and to the atoms by nuclear collision. This

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latter process yields additional electronic ionization and excitation, but also crystal damage and lattice vibrations.

In γ-ray spectroscopy the energy delivered to the atoms is negligible and the measured energy distribution should be Gaussian with a root mean square standard deviation

$$\Delta E_{\mathrm{RMS}} = \sqrt{\varepsilon E F}, \tag{1}$$

where ε is the average energy needed for an electron–hole pair and F the Fano factor.

In the case of α-particles the energy lost by nuclear collision becomes important and the role played by lattice vibration and crystal damage leads to an asymmetric distribution [4,5,14]. Additional asymmetry comes, for external alpha sources, from the finite thickness of the passive dead layer at the surface of the detector and from its thickness variations. As a consequence the distribution is no more Gaussian. The calculated contributions are in excellent agreement with the measured shapes of the alpha peaks [4,5]. In the best measurements, the energy resolution ranges from 7.6 to 8.5 keV for α-particle energies from 3 to 6 MeV, respectively. The contribution to this resolution from the intrinsic width of the source is negligible, since it does not exceed 1 keV [4]. The ultimate intrinsic resolution that can be expected from these detectors has been calculated assuming the absence of the dead layer and a negligible contribution (0.5 keV) from the read-out electronics. It has been shown that the FWHM resolution cannot be better than 6–7 keV in the above-mentioned α particle energy region, even under these extreme assumptions [5].

Better resolutions are expected from the use of cryogenic thermal detectors, which have been suggested since 1984 for searches on rare decays [15], for X-ray astrophysics [16], and for measurements on neutrino mass [15,16]. An intense technical activity for the implementation of these detectors is in progress and some experiments in subnuclear, nuclear and astroparticle physics are already being carried out. For recent results on thermal detectors see Ref. [17]. The principle of these detectors [18,19], in the bolometric approach, is as follows. The heat capacity of a diamagnetic and dielectric crystal at low temperatures is proportional to the cube of the ratio between its operating and Debye temperatures. As a consequence, at temperatures easily reachable with dilution refrigerators (tens of millikelvin) it becomes so small that even the tiny energy delivered by an elementary particle to the crystal can be measured by the increase of its temperature. An important figure of merit of bolometers with respect to conventional detectors is the efficiency in collecting the energy delivered by the particle. In fact, it is of about a third in conventional detectors for primary electromagnetic radiation or energetic electrons, but could be much less for slow particles like nuclear recoils [20,21]. On the contrary in the case of thermal detectors this fraction is much larger and could be near 100% if electron–hole pairs recombine within the time span of the thermal pulse.

Theoretically, the energy resolution of bolometers could be independent of energy and orders of magnitude better than for conventional detectors: below 1 eV for microbolometers for X-ray spectroscopy, and of fractions of keV for macrobolometers for α- and γ-ray spectroscopy. Unfortunately the actual performance of these detectors is limited by fluctuations in the gain due to thermal drifts and by the presence of nonintrinsic sources of noise. The main contributions are due to thermal noise, microphonics, electromagnetic interference and finite resolution of the read-out electronics. A FWHM resolution around 5 eV has been however obtained with microbolometers at energies around 6 keV in X-ray spectroscopy [22]. The resolutions obtained with massive (340 g) bolometers in the high-energy γ region (2.615 MeV) were of the same order of magnitude, but definitely worse, than those of germanium detectors [23,24].

The competition of thermal detectors with conventional ones should be more favorable in α-particle spectroscopy, since bolometers are sensitive over their entire volume without position effects inside the detector and with no dead layer. In addition some advantage could come from the above-mentioned full efficiency in the collection of the entire delivered energy. So far bolometers have reached [25–33], but not surpassed, the resolution of conventional detectors, even when the detecting mass was limited (a few grams).

We describe here the results obtained in γ and α spectroscopy with a massive tellurite bolometer, the largest presently operating underground.

2. Experimental details

The results reported here have been obtained in our preliminary work to improve the performances of massive thermal detectors in view of the recently approved experiment CUORICINO. The set-up will consist in an array of 56 cubic crystals of TeO_2 with 5 cm side and about 760 g mass. This experiment, mainly devoted to the search for double beta decay of ^{130}Te and for interactions of Weakly Interacting Massive Particles (WIMPS) and solar axions, represents a first step toward the planned construction of a much more powerful experiment, named CUORE, for Cryogenic Underground Observatory for Rare Events, based on an array of 1020 crystals of the same dimension [34]. An array of 20 crystals of lower size ($3 \times 3 \times 6\ cm^3$) is presently running in Hall A of the Gran Sasso laboratory for an experiment on double beta decay of ^{130}Te. This set-up consists in a tower with five floors of 4 detectors, each made by crystals of natural TeO_2 of $3 \times 3 \times 6\ cm^3$ with a total active mass of about 6.8 kg [23,24].

The results reported here have been obtained with a crystal of tellurite of $5 \times 5 \times 5\ cm^3$, similar to those to be operated in CUORICINO and CUORE. It is about 2.5 more massive than the previous ones. The crystal is fastened to a frame made of low-radioactivity Oxygen Free High Conductivity (OFHC) Copper by means of Teflon supports. The temperature sensor is a Neutron Transmutation-Doped Ge thermistor provided to us by prof. E. Haller. In order to decrease the thermistor operation resistance and to increase the electron–phonon thermal conductance we have adopted a thermistor considerably larger ($3 \times 3 \times 1\ mm^3$) than those used in the previously mentioned double beta decay experiments. It is thermally coupled to the crystal with 12 glue spots of ~ 0.6 mm diameter. A 50 kΩ resistor, realized with a heavily doped meander on a 1 mm^3 silicon chip, was attached to the absorber. A voltage impulse periodically delivered to the crystal heats the bolometer and allows to calibrate and stabilize its gain [35].

The detector is thermally connected via a copper cold finger to the mixing chamber of a dilution refrigerator, constructed with previously tested low radioactivity materials. The entire set-up is shielded with an internal layer of copper and an external layer of lead. Their minimum thickness are of 5 and 10 cm, respectively. The electrolytic copper of the thermal shields of the refrigerator provides an additional layer of 2 cm minimum thickness. The refrigerator is surrounded by a Plexiglas anti-radon box and by a Faraday cage to eliminate the electromagnetic interference.

A twisted pair of 60 μm diameter constantan read-out wires is connected to two copper pads on which a pair of gold wires are indium soldered, with the other ends being ball bonded to the thermistor. The constantan wires go, passing through four thermalizing stages, to the electronic read out. The first stage of it consists of a pair of differential JFETs which, in this new configuration, are kept at a temperature of ~ 120 K inside the refrigerator. JFETSs and load resistors are installed in a suitable box between the 600 mK plate and the 1 K-plot plate. The differential configuration reported in Ref. [36], and the location of the JFETs near the detector allows minimizing cross-talk and microphonic effects of the connecting wires. A further amplifying stage and a 4 pole antialiasing active Bessel filter at room temperature complete the analog read-out. The signal is acquired by a 16 bit ADC embedded in a VXI acquisition system. The data analysis is completely performed off-line.

Our previous experience with various arrays and particularly with the one with 20 crystals has shown that a considerable contribution to the noise and therefore to the overall detector resolution comes from thermal noise due to vibrations of the cryogenic system. We have first systematically studied these vibrations by placing four small piezoelectric accelerometers at the different temperature stages of the dilution unity: 1 K-pot, still, mixing chamber and crystal holder. These piezoelectric sensors enabled to investigate the correlation between vibrations and thermal noise induced by them in the bolometer. In order to reduce the contributions from the vibrations of high (in our scale) frequency (a few Hz) a two stage mechanical damp system was implemented. It consists of a damped steel spring hanging from the mixing chamber with the crystal holder suspended through two OFHC wires to its extremities. These wires, of 0.75 mm diameter and 7 cm length, provide both the mechanical suspension and the thermal link to the mixing chamber. The mechanical vibration spectra measured in this configuration on the crystal holder show a clear damp in the high-frequency region. Despite the lower thermal conductance of the wires with respect to the cold finger of the previous configurations, the crystal did not reach base temperatures substantially different from those of the previous runs.

3. Results

The calibration spectrum obtained in 47 h of effective running time with a mixed ^{232}Th and ^{238}U source placed immediately outside the shield (Fig. 1) shows a considerable improvement in the resolution at all energies with respect to those previously achieved by us with smaller detectors [23,24]. The FWHM resolution of the baseline is 1.4 ± 0.2 keV. The resolutions at various relevant lines are near to those of a 526 cm^3, 113% efficiency Ge diode directly exposed for 5 h to the same ^{232}Th source (Table 1). They are the best ever obtained with a thermal detector in this energy region and already comparable to those reachable with Ge diodes, despite the fact that the source had to be placed outside the shield of our bolometer, with a consequent poorer statistics and larger background. The spectra of our detector and of the Ge diode are compared in the region of the 2615 ^{208}Tl line in Fig. 2.

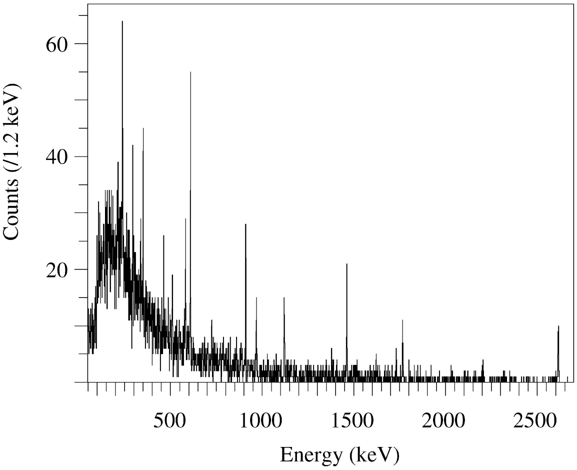

Fig. 1. Spectrum in the γ-ray energy region obtained with our bolometer exposed to a composite ^{232}Th and ^{238}U source.

Table 1
FWHM resolutions (keV) of a 113% Ge diode and of our bolometer

	Energy (keV)			
	238	583	911	2615
Ge diode	1.2 ± 0.1	1.4 ± 0.1	1.7 ± 0.1	3.0 ± 0.3
Bolometer	1.5 ± 0.2	2.0 ± 0.3	2.4 ± 0.2	3.9 ± 0.7

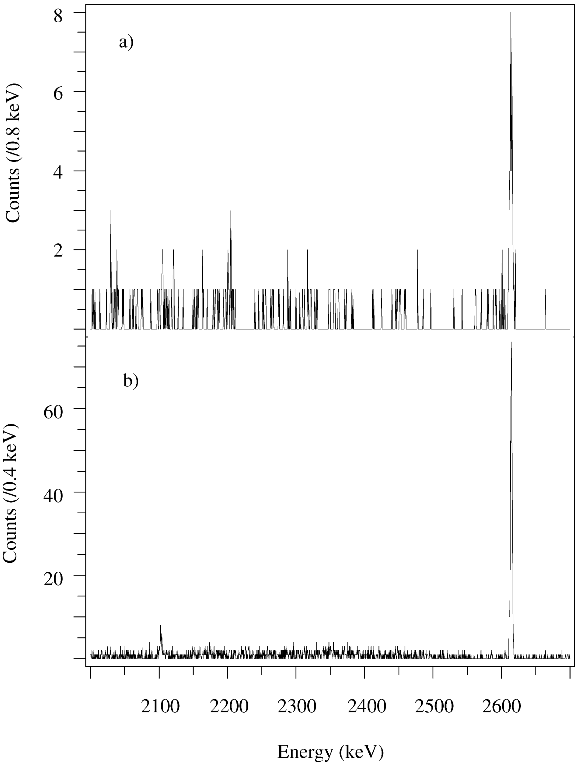

Fig. 2. Comparison of the spectra in the region of the ^{208}Tl line at 2615 keV obtained by exposing to the same ^{232}Th source our bolometer (a) and a 113% Ge detector (526 cm^3) (b).

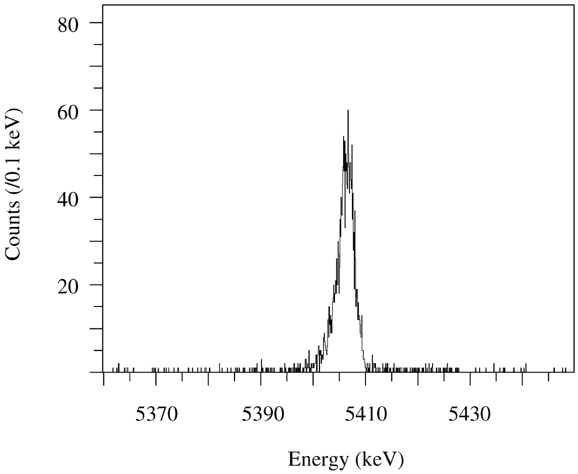

Fig. 3. The α peak of ^{210}Pb at 5407 keV.

In order to evaluate the resolution for α particles we have considered the line at 5407 keV (Fig. 3) due to the internal contamination of ^{210}Po, which is a common impurity in Te-based materials [23]. This line corresponds to the sum of the α particle and recoil energies.

The average FWHM resolution of our bolometer is of 4.2 ± 0.3 keV better than for any α particle detector. A considerable left–right asymmetry exists. It could be partly due to decays of ^{210}Po from the chain of ^{222}Rn, implanted by the decay of this nucleus in the detector. These decays would occur in a thin region very close to the surface. As a consequence a fraction of the α particles and of the recoils [37] would leave the detector before releasing all of their energies, thus simulating a lower decay energy.

4. Conclusion

The substantial reduction of vibration and thermal noise and of microphonics achieved with an improved suspension of the holder and by placing the FET near the bolometer has enabled us to reach a resolution of about 0.1% for high-energy γ-rays. This is compatible with those obtained with Germanium diodes. The average resolution on internally produced α particles is of 4.2 keV FWHM, the best ever obtained with any type of detector.

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