A cryogenic tellurium detector for rare events and gamma rays

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In view of a future experiment on double beta decay we have constructed and operated for the first time a bolometric detector made with an ultrapure tellurium crystal of about 2.1 gram. With this detector we have been able to measure high energy gamma rays from various calibration sources with an energy resolution of 2% in the region of neutrinoless double beta decay. The thermal properties of tellurium at very low temperature are determined for the first time in view of the construction of larger detectors.

Low temperature bolometric detection of single particles has been proposed for measurements of X-rays and neutrino mass [1,2] and for detection of rare processes like electron and double beta decay [1]. The operating principle of these detectors is based on the consideration that the heat capacity of a very cold pure dielectric and diamagnetic crystal is roughly proportional to the cube of the ratio between the operating temperature $T$ and the Debye temperature $T_D$. This capacity can therefore be made so small that even the tiny energy delivered by an incident particle in the form of heat can produce a sizeable increase of the temperature which can be measured by the change of the resistance of a suitable thermistor in thermal contact with the crystal itself. Exciting and very promising results have been recently obtained in the measurement of X-rays with small detectors [3] and, conversely, in the development of large mass detectors to search for rare events. In the latter case, many results have been obtained with the construction of large [3,5–7] bolometers of low-Z materials like sapphire, which present the advantage of a large Debye temperature and could be in principle very promising for searches on cosmic dark matter. Our group has developed the complementary approach of high-Z detectors suitable to investigate rare processes like double beta decay and to measure high energy gamma rays. In neutrinoless double beta decay [8], a very powerful tool to search for lepton number nonconservation, two electrons and no neutrinos are simultaneously emitted. Since the nuclear recoil energy is negligible, the spectrum of the sum of the two electron energies should present a peak corresponding to the transition energy [8]. In order to minimize the background of spurious counting in this very rare process it has been suggested [9] to use a double beta decay active material acting at the same time as source and detector of the decay. A series of experiments carried out with germanium semiconductors starting in 1967 [10] have in fact recently produced lower limits on the half-life of $^{76}$Ge exceeding $10^{24}$ yr [11,12]. Recent theoretical calculations have, however, indicated a suppression of the nuclear matrix elements for this process which seems to disappear [8] for nuclei of large atomic number, which are therefore more promising candidates for double beta decay. From a more practical point of view, high-Z bolometers are in addition excellent detectors of high energy gamma rays since the total photon cross section, and particularly the photoelectric one, increases strongly with atomic number.

Our group has recently developed bolometers made with large germanium crystals and thermally measured for the first time high energy gamma rays [13]. Despite the drawback of a Debye temperature for germanium lower by a factor of two with respect to materials like sapphire or silicon which are normally

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[1] Present address: Laboratori Nazionali del Gran Sasso, Assergi, L’Aquila, Italy.
[2] In a recent measurement the NASA–Wisconsin Collaboration has obtained a resolution of 7.3 eV on the 5.9 keV line of $^{55}$Fe [4].
used in low-Z bolometers, we were able to operate a 200 g gamma-ray detector with FWHM resolution around 5% in the region of 2000 keV and a 11 g one with a FWHM with 1% [14], the best obtained thermally in this energy region. The technical interest of these results, however, cannot obscure the fact that germanium detectors do not, at least for the moment, compete in mass or resolution with germanium diodes. We report here the construction and operation of the first thermal detector made of tellurium. The Debye temperature of this element is considerably low [15], but the atomic number is large (Z = 52). In addition 130Te is known to be one of the best candidates for double beta decay [8] for the large isotopic abundance (33.8%) and transition energy (2533 ± 4 keV). We would like to point out that tellurium detectors have never been constructed, while cadmium telluride diodes are normally used and were once employed in a double beta decay experiment [16]. Mass and resolution were so poor, however, that the obtained upper limit for neutrinoless double beta decay was 2.8 × 10^{18} yr only. We would also like to mention that some problems could arise from the presence of the naturally occurring beta radioactive nucleus 113Cd with an isotopic abundance of 12.22%. Also tellurium has a naturally occurring radioactive isotope, 113Te, with an isotopic abundance of 0.9%, but its decay mode is electron capture, obviously not so disturbing in a low background experiment. In addition we would like to stress the large cross section of cadmium for radiative capture of thermal neutrons.

After many attempts required by the intrinsic brittleness and by the unusual expansion properties of tellurium at low temperatures, we were able to operate a bolometer made with a monocrystal of a cross section of approximately 0.5 cm² and a thickness of about 0.7 cm [17]. The electronegative impurities of the tellurium are less that 10^{15} per mole. A commercial melt doped germanium thermistor of about half cubic millimeter is glued to the upper face of the crystal with an epoxy especially chosen among various ones for its large thermal conductance at low temperature. In order to reduce microphonic noise the bolometer is fastened to the heat sink of the dilution refrigerator at a pressure which is trimmed by means of two springs acting on two copper cylinders (fig. 1). The base temperature of the dilution refrigerator was at about 10 mK, but the detector base temperature was 39 mK, due to extra heating coming from mechanical vibrations of the crystal. The thermistor was biased to 1.45 mV using a battery and a 2200 MΩ load resistor. The bolometer temperature is thus raised to 44 mK where the resistance of the thermistor is about 1.34 MΩ. The signal from the thermistor is amplified using a low noise voltage-sensitive GaAs MESFET preamplifier [18] fully operating at liquid helium temperature. The preamplifier is mounted in the helium bath of the dilution refrigerator and connected with a short-length wire to the detector. The parasitic capacitance is in this way kept small, 25 pF approximately. The preamplifier dissipates 54 mW, has a gain × 50, a series noise level of 9 nV/√Hz at 100 Hz with a 1/√f distribution and a bandwidth of 8 MHz.

The detector has been exposed to radioactive sources of 60Co, 22Na and 232Th placed immediately outside the dilution refrigerator. A typical pulse due to gamma rays of 60Co after optimum filtering is shown in fig. 2, and the corresponding energy spectrum in fig. 3. The risetime (1 ms) is much larger than what can be expected from integration in the parasitic capacitance (74 ps) and has therefore to be totally attributed to phonon thermalization and to thermal resistance between absorber and thermistor. The decay time is a few tens of ms.

The heat capacity of the detector can be evaluated
from the height of the temperature pulses and is found to be $(2.1 \pm 0.2) \times 10^{-9}$ J/K for 100% thermalization. The contribution from the thermistor has been found in previous measurements to be $(0.3 \pm 0.1) \times 10^{-9}$ and can therefore be neglected with respect to the one of the absorber. The only results on the heat capacity of tellurium at low temperatures (1.5–20K) are so far those obtained by Leadbetter and Jeapes [15] and, when extrapolated to our temperature, yield a value of $(0.76 \pm 0.02) \times 10^{-9}$ J/K. We consider the consistency between these two values more than satisfactory if one takes into account that the extrapolation from the existing data to much lower temperatures can be only considered as tentative. This
comparison also shows that we are able to collect at least 40% of the total energy delivered by the gamma rays to the detector and ensures against a relevant decoupling between electrons and lattice [19]. The FWHM resolution is of about 50 keV rather independently on the energy of the gamma ray. It can be fully accounted for by the peak-to-noise ratio as shown in fig. 2. When considering this resolution we would like to note that

(a) the source is placed outside the dilution refrigerator and is therefore separated by the detector by about 3 g cm\(^{-2}\) of aluminum and copper which clearly produces Compton background. This background would not be present if the source would be placed in contact with or inside the absorber as is the case in double beta decay experiments;

(b) unlike low-Z bolometers our detector is not calibrated with alpha particles or low energy photons, but with gamma rays which interact uniformly inside the absorber. The resolution obtained does therefore imply that the response of the detector is not position dependent and the measured rates agree with those expected for a full sensitive volume. Both properties constitute essential conditions in double beta decay experiments;

(c) the detector has been operated continuously for runs of more than a day without a noticeable change in the gain. This stability is essential when rare decays have to be searched for.

In order to study the performance of the detector over a larger interval of energy we have exposed it to \(^{22}\)Na and \(^{232}\)Th. The spectrum of \(^{22}\)Na shows in addition to the lines at 511 keV and 1275 keV also a bump in the region of 1460 keV clearly due to \(^{40}\)K present in the walls and floor of the laboratory (fig. 4). The gain of the detector has been determined using the 583 keV line and the double and single escape peaks of \(^{232}\)Th (fig. 5) and found to be linear within our energy resolution.

This preliminary experiment carried out in our Milan laboratory with a small tellurium crystal used for the first time as detector, shows that this material, despite its rather poor Debye temperature, has good thermal properties and substantially behaves like "standard" bolometric materials such as silicon, sapphire and germanium. Our detector could already produce significant results on double beta decay of \(^{130}\)Te if mounted in a dilution refrigerator specially constructed with low radioactivity materials presently operating deep underground in the Laboratori Nazionali del Gran Sasso. We prefer, however, to wait for larger mass tellurium bolometers which are presently being tested.

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**Fig. 4.** Spectrum with a \(^{22}\)Na source placed outside the cryostat. The bump on the right is due to local contamination of \(^{40}\)K (1460 keV).
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