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A search for neutrinoless double beta decay of ^{130}Te with a thermal detector

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A 73.1 g TeO_2 bolometric detector has been operating for more than two months at about 16 mK in a specially constructed low activity dilution refrigerator installed in the Gran Sasso Underground Laboratory and shielded against environmental radioactivity. Its energy resolution is comparable with that of a Ge diode. A spectrum of the thermal pulses collected in 1389 h of effective running time shows no evidence for neutrinoless double beta decay of ^{130}Te. The corresponding lower limit of the lifetime is three orders of magnitude more stringent than those obtained for the same nucleus with conventional techniques. It also exceeds the value for the inclusive (two neutrino and neutrinoless) lifetime obtained by geochemical searches. Double beta decay of ^{130}Te has therefore to be attributed mainly to the two neutrino channel.

1. Introduction

Double beta decay (DBD) is a spontaneous radioactive process where a nucleus (A, Z) decays into the isobar $(A, Z + 2)$ with the contemporary emission of two electrons [1]. The process where two antineutrinos are also emitted (two neutrino DBD) is allowed by the standard electroweak theory, but it is very rare. Since the nuclear recoiling energy is negligible, the two electrons share the total transition energy E_0 with the two antineutrinos, and the spectrum of the sum of their energies presents a bump at about one third of E_0. In neutrinoless DBD, which would imply violation by two unities of the lepton number and transition energy delivered only to electrons, a sharp peak would appear in this sum spectrum in correspondence to E_0. In addition the neutrinoless mode would be strongly enhanced with respect to the two neutrino one by the much larger available phase space. As a consequence of these experimental implications, even a tiny violation of the lepton number could be revealed by neutrinoless DBD. Another lepton violating DBD where a massless Goldstone boson, named majoron, would be emitted [1] will not be considered here.

The uncertainties in the prediction of neutrinoless and two neutrino DBD rates are mainly due to difficulties in evaluating properly the nuclear matrix elements. Calculations have been performed for specific DBD candidates taking into account the previously neglected ground state correlation effects. The results agree well for the two neutrino DBD mode [1]. On the contrary a strong suppression which has been found in the neutrinoless mode by the Caltech group [2] is not confirmed by other authors [1,3]. There is however a general consensus on the need to investigate as many DBD candidates as possible, and especially those with large A, where the above mentioned suppressions should be lower.

Geochemical experiments on DBD [4,5] are based on the search for an anomalous abundance of the isotope $(A, Z + 2)$ in rocks with an abundant content of the nucleus (A, Z). While very sensitive, due to the long geological "running time" of the experiment, they do not allow to discriminate directly between the neutrinoless and two neutrino channels. Unambiguous evidence for DBD of ^{82}Se have been obtained, with comparable rates, by Heidelberg [4] and Missouri [5] groups. Evidence has also been found for ^{130}Te, even if there is some disagreement in the lifetimes: the "best estimate" in the most recent review

[5] is 8×10^{20} yr. Evidence for DBD of ^{128}Te presented by Missouri [5], is not confirmed by the other group [4].

Direct experiments where the two electrons are detected and their energies measured, have recently found [1] two neutrino DBD of ^{82}Se, ^{76}Ge and ^{100}Mo, even if some disagreement on the rates exists for the last nucleus [1]. No evidence has been found for neutrinoless DBD, with lower limits on the lifetime exceeding 10^{24} and 10^{23} yr for ^{76}Ge [1,6–8] and ^{136}Xe [9], respectively. All these experiments have been carried out with devices based on the ionization produced by the electrons (gas or solid state counters, scintillators, nuclear emulsions, etc). In many of them the "calorimetric" approach [10], where the detector itself is made with a DBD active material, has been adopted. The use of thermal detectors to search for DBD and other rare processes [11] as well as for X-ray spectroscopy [12] has been suggested since 1984, and many thermal devices have been implemented so far [13–18]. In the bolometric approach the particle is revealed by measuring the temperature rise of a crystal, which is proportional to the ratio between the energy lost by the particle in form of heat and the heat capacity. The latter, for a diamagnetic and dielectric crystal operated at low temperatures, is proportional to the cube of the operating to Debye temperature ratio. At tens of millikelvin the heat capacity can become so small that even the tiny heat delivered by the particle to the crystal can be revealed and measured by a suitable thermometer in thermal contact with it.

We report here the first result obtained in subnuclear physics with this new kind of detector: a limit on neutrinoless DBD of ^{130}Te. This candidate seems very promising since its isotopic abundance is very large (33.87%) and the transition energy to the ground state of the daughter nucleus (2528.8±1.3 keV) [19] is considerable and well determined. In addition the large atomic number should prevent strong suppression due to the ground state correlations.

2. The detector

Various tellurium detectors for γ-ray spectroscopy and searches in DBD have been developed by our group [20]. Our first approach consisted [21] in the use of crystals of pure tellurium which were however found to be quite brittle at low temperatures. Further measurements of γ-ray spectroscopy were carried out with crystals of 6, 21 and 34 g of TeO_2, a material with much better mechanical properties at low temperatures. After tests with α-ray and γ-ray spectroscopy on the intrinsic radioactivity of various TeO_2 samples we have chosen for the present experiment a $20\times20\times30$ mm^3 crystal having a mass of 73.1 g. The crystal is suspended with 64 gold covered copper tips in a frame of oxygen free high conductivity (OFHC) copper, which is fastened to the heat sink of the dilution refrigerator. The tips exert on the crystal an adjustable pressure by means of springs, thus allowing to compensate the different contractions of the crystal and frame at low temperatures. All materials in contact or surrounding the crystal have been previously tested against intrinsic radioactivity with our γ-ray spectrometer located in the Gran Sasso Underground Laboratory. The thermal pulses of the crystal are detected and measured by means of a neutron transmutation doped (NTD) thermistor developed by the group of Haller [22], kept in thermal contact by means of a nonconductive epoxy. The thermistor is biased using a battery and two load resistors. More details on the mounting of similar crystals and on the performance of the thermistors are reported elsewhere [20,23].

In order to attain a high sensitivity in the detector, the thermistor resistance has to be large. This may imply an excessive signal integration due to the parasitic capacitance of the detector–preamplifier link, with the consequent reduction of the signal-to-noise ratio. To prevent this effect, we use a low capacitance link connected to cryogenic voltage-sensitive preamplifiers based on GaAs MESFETs and operated at 4 K [24]. More details on the detector are reported elsewhere [25].

After tests in our dilution refrigerator in Milan [25] the detector was mounted and operated in the underground laboratory of Gran Sasso, at a depth of about 3500 metres of water equivalent, where the background of charged cosmic rays and of fast neutrons is reduced by 6 and 4 orders of magnitude, respectively [26]. The Gran Sasso dilution refrigerator was specially built, in collaboration with Oxford Instruments, with previously tested low radioactivity materials. In order to avoid the presence of an aluminum or stainless steel liquid nitrogen reservoir, the superinsulation technique was adopted. Base temper-

atures as low as 5.5 mK were achieved, similar to those reached in the standard refrigerator in Milan.

The entire dilution refrigerator is shielded against local radioactivity by a layer of lead with minimum thickness of 10 cm. The content of radon is reduced by surrounding the refrigerator with a plexiglas box and flushing it with nitrogen. To minimize electromagnetic interferences from local sources, the refrigerator and the biasing and post-amplifier circuits are located inside a Faraday cage. All control and power supply wires enter through LC low-pass filters while BNC feedthroughs are used for the signals. The 2 mm thick stainless steel Faraday cage walls are covered externally with sound absorbing and antivibrating materials, and with sound absorbing material in the interior for minimum reverberation.

The detector base temperature in the Gran Sasso was about 12 mK, and its zero-bias resistance 3.9 GΩ. The best operating conditions were obtained by applying to the thermistor a bias of 24.1 mV through two 2.5 GΩ load resistors. The thermistor resistance became 380 MΩ corresponding to a temperature of about 16 mK.

3. Results and discussion

The stability and the gain of the detector was routinely checked with ^{60}Co and ^{232}Th sources irradiating it through a small window that can be opened in the lead shield. A typical calibration spectrum with the ^{232}Th source is reported in fig. 1. The FWHM resolutions range from 4 to 7 keV in the 500–3000 keV energy region. We would like to note that the source, placed outside the dilution refrigerator, is separated by layers of aluminum and copper producing Compton background. Since weak sources were used, all calibrations last more than 12 h: there is therefore a considerable stability in the gain.

The voltage pulses corresponding to a 2615 keV γ-ray are of about 6 mV, from which an apparent heat capacity of about 1 nJ/K is deduced. Measurements carried out on the thermistor by exposing it to γ-rays, show that its contribution to the total heat capacity is negligible (<0.1 nJ/K). As a consequence the apparent heat capacity is five times larger than the value obtained by extrapolating to lower temperatures the existing data on TeO_2 [27] on the basis of the Debye

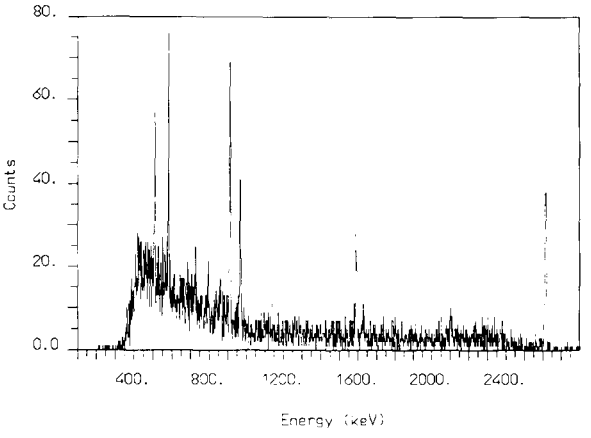

Fig. 1. A typical calibration spectrum obtained with a ^{232}Th source.

law. This extrapolation is not necessarily valid at very low temperatures. Losses of signal could however be due to (a) the above mentioned signal integration due to the parasitic capacitance; (b) incomplete thermalization of the energy delivered by the particle to the crystal; (c) incomplete transfer to the thermistor lattice of the heat delivered to the crystal; (d) incomplete transfer to the hopping electrons of the heat delivered to the thermistor lattice [22].

We show in fig. 2 the spectrum obtained in 1389 h of effective running time, an unusually long period for a thermal detector and even for a dilution refrigerator. This spectrum is similar to those obtained with Ge diodes and shows the γ-peaks due to the ^{238}U and ^{232}Th chains. The large peak at about 5.4 MeV is due to α-decay of ^{210}Po, a radioactive contaminant usually present in tellurium compounds [28]. We would like to stress that if this contaminant is inside the detector the position of the peak corresponds to the total transition energy, namely to the sum of the energies of the α-particle and of the nuclear recoil. A nonlinear fit to the γ-peaks has been carried out on the basis of a T^{α} dependence of the heat capacity, where α is a free parameter. By extrapolation to higher energies we obtain a value of 5413±10 keV for the position of the peak in excellent agreement with the figure of 5407.63 keV for the transition energy of ^{210}Po. The efficiency in the thermal detection of a nuclear recoil is confirmed by the presence, near the main peak, of a much weaker peak at 5315±10 keV, corresponding

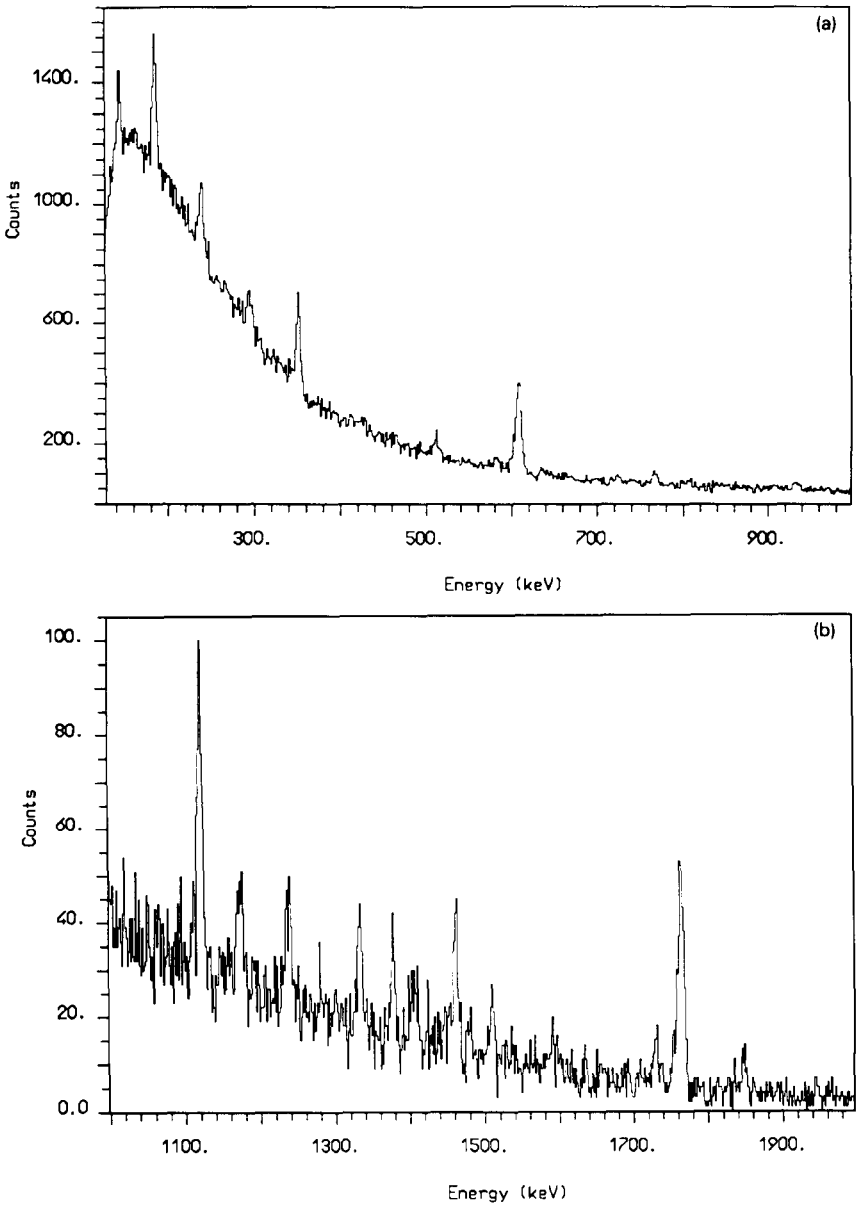

Fig. 2. Energy spectrum obtained in 1389 h of effective running time (1.5 keV/channel): (a) lower region; (b) central region; (c) region of neutrinoless DBD; (d) α-particle region. In the inset (10 keV/channel) the dominant peak at 5413 keV corresponding to the full transition energy of ^{210}Po, has been cut to show the satellite peak corresponding to the α-particle energy only.

to the energy of the α-particle alone (fig. 2d). It is due to a much smaller contamination of ^{210}Po on the surface or immediately outside the crystal. The distance between the two peaks obtained by a fit is 100±10 keV in excellent agreement with the calculated value of 103 keV for the energy of the recoiling nucleus. We confirm therefore our previous finding [29] that low temperature bolometers, unlike ionization detectors, can measure the energy of nuclear recoils with an efficiency compatible with 100%. This property is essential in searches for dark matter [30].

The counting rate for ^{210}Po (1.70±0.05 c/h) cor-

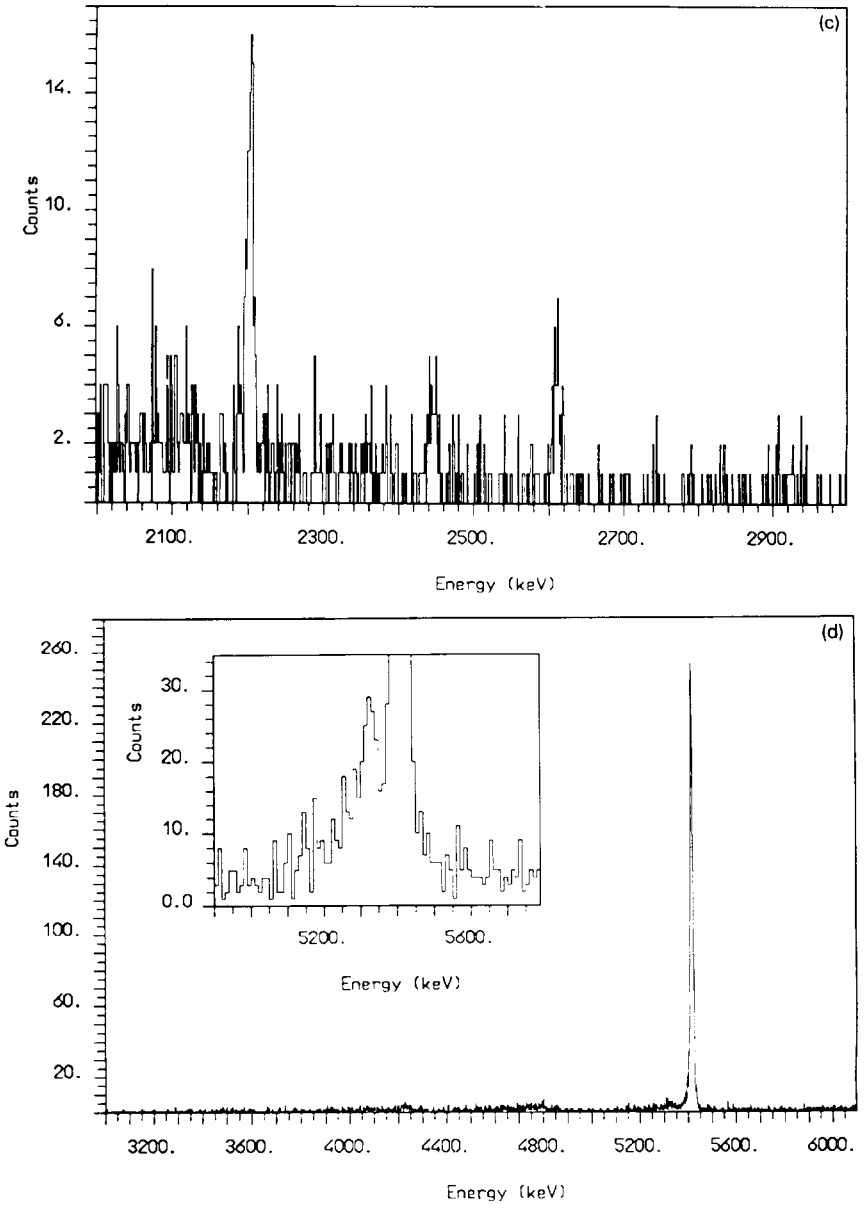

Fig. 2. Continued.

responds to a contamination of (6.5±0.2) mBq/kg namely to $(3.9\pm0.1)\times10^{-20}$ g/g of this nucleus, a low figure with respect to other materials [31]. It does not contribute substantially to the background in the DBD energy region since the α-particles are mainly emitted inside the detector and therefore not degraded by energy loss. Below and above the 5.4 MeV peak there are indications of different, even if lower, α-activities, but low statistics prevents to attribute peaks to single α-particles. Some internal activity due to the ^{238}U chain is however indicated by bumps between 4220–4300 and between 4700 and 4900 keV, produced by α-particles of 4149 and 4196 keV and 4621, 4688, 4723, 4777 and 4784 keV when the recoiling energy is added. The corresponding activities due to internal contamination by the ^{238}U chain in secular equilib-

rium are (0.18±0.04) and (0.13±0.02) mBq kg^{-1}. This is equivalent to a contamination of about 10^{-11} g/g of ^{238}U. There is no bump corresponding to the α-particles at 3952 and 4010 keV of ^{232}Th, when the nuclear recoiling energy is included. The corresponding 90% cl upper limits for the contamination from this nucleus are 0.08 mBq kg^{-1} or 2×10^{-11} g/g. The remaining counts above the 2.615 keV ^{208}Tl γ-peak are mainly due to external sources of α-particles.

No peak appears in the region of neutrinoless DBD, where the background counting rate is of $(2.9\pm0.4)\times10^{-4}$ counts keV^{-1} h^{-1}. The background is generated mainly by α-, β- or γ-decays outside the crystal or by β-decays inside it. It is of the same order as in the first experiments on DBD of ^{76}Ge, but definitely worse than in the present ones [6–8]. We consider it very satisfactory in this first experimental approach. TeO_2 is a material generally more contaminated than germanium, even if we have chosen the best commercially available crystals. In addition materials with considerable activities like stainless steel, silver compounds and electronic components cannot be eliminated in the interior of the dilution refrigerator. External shielding of the refrigerator is much more difficult than for a Ge detector, and could only be accomplished with antimony loaded lead, which has good mechanical properties. We are presently planning to test an internal shield of low radioactivity lead fastened to the mixing chamber of the refrigerator.

By applying the maximum likelihood analysis to our energy spectrum in the appropriate region we extract lower limits of 5.7×10^{21} and 2.5×10^{21} yr at the 68% and 90% confidence levels for (0^+-0^+) neutrinoless DBD of ^{130}Te. These limits are three orders of magnitude more stringent than those obtained by a previous experiment carried out with a CdTe detector [32]. The results of an earlier experiment [33] performed with scintillation counters cannot be used for comparison since it ignores the energy resolution of the detector. A limit of 10^{19} yr extracted from this experiment by Mitchell and Fisher [32] should not be considered, in our opinion, before a re-evaluation by the authors themselves. Our limit on neutrinoless DBD is definitely more stringent than the rate measured geochemically. This indicates that DBD of ^{130}Te is dominated if not totally accounted for by the lepton conserving channel.

The results of the present experiment constitute a first step in the thermal search for DBD of ^{130}Te. To improve we will use an array made by four crystals of 380 g each, surrounded by an additional shield of very low radioactivity lead mounted inside the refrigerator.

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