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A new search for neutrinoless $\beta\beta$ decay with a thermal detector

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Abstract

A 334 g TeO_2 crystal has been operated at a temperature of around 10 mK for more than one year in a low intrinsic radioactivity dilution refrigerator installed in the Gran Sasso Underground Laboratory. From the spectrum collected in 9234 h of effective running time we improve our limit on neutrinoless double beta decay of ^{130}Te by an order of magnitude with respect to our previous experiment. It is the most stringent on this nucleus and excludes a large contribution of the neutrinoless mode to the rate of double beta decay found in geochemical experiments. Upper limits on the effective neutrino mass and on the contributions of right handed currents are given.

1. Introduction

Double beta decay (DBD) is a rare radioactive transition of the even–even nucleus (A, Z) to its isobar $(A, Z+2)$ with the contemporary emission of two electrons [1,2]. According to the standard electroweak theory this process occurs with the emission of two electron antineutrinos (two neutrino DBD). Neutrinoless DBD where only the two electrons are emitted would violate lepton number conservation. In a third process, also without neutrinos, the electrons could be accompanied by a massless Goldstone boson, called majoron (majoron DBD). Other double beta decay process are possible [1,2], but will not be considered here.

Since the nuclear recoiling energy is negligible, the two electrons would share the transition energy with the two neutrinos and with the majoron, in the two neutrino and majoron channels, respectively. In neutrinoless DBD, on the contrary, they would share entirely the transition energy and a peak would appear in their sum energy spectrum. The phase space available to neutrinoless DBD would be much larger than for the two neutrino channel and, as a consequence, even a tiny violation of the lepton number could be in principle revealed. Neutrinoless DBD would therefore provide a powerful way to open a window beyond the standard model.

Neutrinoless DBD can be induced by a non zero value of the *average* [1,2] neutrino mass $\langle m_\nu \rangle$ or by the presence of a tiny impurity of right-handed currents in the weak amplitude. This latter possibility should however necessarily imply a non zero neutrino mass [1-3]. The difficulty to predict the DBD rates lies essentially in the evaluation of the nuclear matrix elements for individual candidate nuclei. The first detailed predictions of two neutrino DBD rates based on the shell model [4] were found higher than those measured

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experimentally. Nuclear ground state correlations were then introduced [1,2]. They lead to a strong suppression of the predicted rates, which depends very sensitively on the strength g_{pp} of the particle–particle coupling force. In the case of neutrinoless DBD this suppression is expected to be lower and less sensitive to g_{pp}. Considerable difference still remains among the theoretical predictions for the individual nuclei, and in some cases also between measured and predicted rates. DBD should therefore be investigated in as many nuclei as possible, especially on those of large atomic weight, where the above mentioned suppressions should be less severe [2].

DBD can be searched in geochemical experiments, looking for an excess of the $(A, Z+2)$ isotope in ores containing (A, Z). This method is powerful, due to the very long integration time, but does not enable to distinguish directly among the three DBD channels. Positive evidence for DBD of ^{82}Se into ^{82}Kr leading to lifetimes around 10^{20} yr has been obtained, with good agreement among the various experiments [5–7]. The situation for the DBD active tellurium isotopes is more complicated [6–10]. DBD of ^{128}Te seems now well established [9] with a lifetime of $(7.7 \pm 0.4) \times 10^{24}$ yr, later corrected in $(7.3 \pm 0.3) \times 10^{24}$ yr [10]. Evidence is confirmed for DBD of ^{130}Te, but measured lifetimes range from 7×10^{20} to 2.7×10^{21} yr. An overevaluation by a factor of three of the values obtained by the group of St. Louis [9] is suggested by the Rolla group [7] on the basis of the ratio between the rate of ^{130}Te and the much better measured rate of ^{82}Se. They recommend "average" values of 2×10^{24} and 8×10^{20} yr for ^{128}Te and ^{130}Te, respectively. Experimental values for the rates of ^{130}Te seem lower than the theoretical predictions for two neutrino DBD [1,2,4,11–14].

Indirect evidence for DBD of ^{96}Zr [15] and ^{238}U [16] has also been obtained recently in a geochemical and in a radiochemical experiment, respectively.

Direct evidence for DBD has been searched with two different approaches. One consists of the insertion in the detector of a DBD active source, generally in form of thin sheets. The *calorimetric* approach [17] consists on the contrary in the use of a detector made with a material which acts also as a DBD source. Two neutrino DBD has been found for ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, and ^{150}Nd. No evidence on the contrary has been obtained for the majoron and neutrinoless lepton violating channels. The most stringent limits for neutrinoless DBD have been obtained in calorimetric experiments with germanium diodes and with a TPC Xenon chamber [1,2].

The use of thermal detectors to search for neutrinoless DBD in the calorimetric approach has been suggested since 1984 [18]. Other thermal techniques have been proposed [19,20]. The source for DBD is a large crystal of a pure dielectric and diamagnetic material, operated at low temperatures. The heat capacity of this crystal is proportional to the cube of the ratio between the operating and Debye temperatures (T and T_D, respectively) and becomes very small at temperatures achievable with dilution refrigerators. As a consequence the heat delivered by a particle to the absorber yields a sizeable increase of the temperature, which can be transformed into an electrical pulse by a proper sensor in thermal contact with the crystal. Even if the extremely good performances predicted theoretically have not yet been reached, a thermal detector allows spectroscopy of high energy γ rays with a resolution already comparable with that of germanium diodes [21,22].

Among many materials with nuclear and thermal properties suitable for an experiment on neutrinoless DBD [18], we have chosen TeO_2 for the following reasons:

(a) natural tellurium contains 33.87% of ^{130}Te which can double beta decay into ^{130}Xe with a large transition energy (2528.3 ± 1.3 keV [23]);

(b) nuclear matrix elements for DBD of ^{130}Te are among the most favourable [1,2] and suppression for short range correlation are expected to be less severe due to the large atomic number;

(c) while crystals of pure tellurium are fragile [24], large crystals of TeO_2 with good mechanical properties can be obtained;

(d) extrapolation to low temperatures of the existing data [25] leads to predicted values of T_D which are reasonably large (265 K).

In a previous experiment [21] carried out in the Gran Sasso underground laboratory with a 73 g crystal of TeO_2 lower limits of 5.7×10^{21} and 2.5×10^{21} yr have been obtained at 68% and 90% confidence level, respectively. This indicates that the two neutrino mode is the dominant one if the geochemical results on ^{130}Te ($\tau_{1/2} \simeq 7 \times 10^{20}$ yr) obtained by the Rolla group [7] are adopted. This statement becomes marginal if the same comparison is made with the later geochemical results ($\tau_{1/2} \simeq 2.7 \times 10^{21}$ yr) by Bernatovitz et al. [9,10].

To increase our sensitivity and to clear up this point a new experiment with a 334 g bolometer, the largest thermal detector operated so far, was carried out. The results of partial measurements have already been reported [26,27].

2. Experimental details

The detector consists of a 334 g monocrystal of TeO_2 ($3 \times 3 \times 6$ cm^3) fastened to an oxygen free high conductivity copper frame by means of 13 spring loaded gold covered copper tips. In this way the different contractions of TeO_2 and copper at low temperatures are compensated. The frame is fastened to a heat sink of a dilution refrigerator operated in the Gran Sasso Underground Laboratory at a depth of 3500 m.w.e., where the fluxes of muons and fast neutrons are suppressed by six and three orders of magnitude, respectively [28]. The temperature sensor is a neutron transmutation doped (NTD) thermistor, provided by Professor E. Haller [29], kept in thermal contact to the crystal by means of a nonconductive epoxy. This thermistor is biased by a balanced network consisting of a battery and two 2.5 GΩ load resistances kept at 4 K in order to reduce the Johnson noise. The first differential stage of amplification consists of two identical GaAs MESFETs voltage sensitive pre amplifiers [30] whose outputs are connected to the second differential stage. The preamplifiers are mounted on the 4 K plate of the cryostat in order to reduce the length of the wires connecting the sensor to the front end electronics and, as a consequence, the parasitic capacitance. These wires are twisted together to reduce residual electromagnetic interferences and microphonism. The second stage consists of a differential amplifier operating at room temperature. The overall common mode noise rejection ratio is of 100 dB. The signal feeds a low-pass antialiasing filter and is digitized and recorded by a 12 bit ADC. Each recorded signal is processed off line with a software optimum filter.

The dilution refrigerator has been constructed in collaboration with Oxford Instruments with specially chosen low radioactivity components. All materials inside the refrigerator and especially those in immediate contact with the detector have been previously tested for radioactivity with a germanium γ-ray spectrometer operating in the Gran Sasso Laboratory. The refrigerator (Fig. 1) is shielded against external radioactivity with a layer of lead of 10 cm minimum thickness, placed immediately outside the cryostat. In addition the OFHC copper frame containing the detector is surrounded by an *internal shield* made with special low radioactivity Johnson & Matthey lead of 3.5 cm minimum thickness. This shield has a mass of 47 kg, is screwed to the mixing chamber and kept to the base temperature together with the detector. Radon contamination is reduced by fluxing nitrogen gas in a plexiglass box surrounding the cryostat.

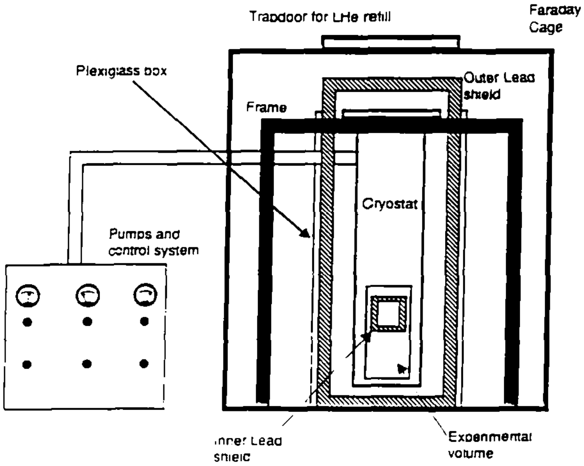

Fig. 1. The experimental setup.

The dilution refrigerator, the bias circuit and the read-out electronics are placed inside a Faraday cage to minimize electromagnetic interferences. Microphonism has been reduced by covering the cage walls with antivibrating materials, and by placing all tubes connecting the cryostat to the pumping system inside a box filled with sand.

3. Background considerations

In all experiments on DBD the background due to cosmic rays, environmental radioactivity and specially internal contamination has to be strongly suppressed. For germanium diodes this has been gradually accomplished [31–33] since the first DBD germanium experiment [34]. For the TeO_2 detectors this activity is just at the beginning.

One has first to ensure against lines due to natural or induced radioactivity which could mimic the peak at 2528 keV expected for neutrinoless DBD of ^{130}Te. No relevant γ-line is expected in this energy region [1]. A 2526 keV electron [2] could however be emitted from de-excitation by internal conversion of the 2615 keV state of ^{208}Pb produced by decay of ^{208}Tl [35]. This situation would require a very strong contamination of ^{228}Th directly facing the detector. This peculiar contamination should moreover be revealed by the presence of more intense lines due to electron conversions of lower energy. Another possibility [2] could be a large surface contamination of cosmogenically produced ^{208}Bi which decays by electron capture with lifetime of 3.7×10^5 yr. This contamination, which was however never revealed in low background experiments, should yield also a peak corresponding to the sum of the 2615 keV line and the energy of the de-excitation following this electron capture.

We have found no evidence for a line around 2528 keV in the analysis of about one hundred low activity germanium spectra obtained by ours and other groups. A peak in this region appears however in the published spectrum obtained in the Gotthard DBD experiment on ^{76}Ge [2,33]. Due to the relevance that this peak would have in the present and future experiment on ^{130}Te, we have re-analized this spectrum in collaboration with the Neuchatel group. The experimental set-up consisted of eight Ge detectors followed by individual electronic chains, a common ADC and a tagging system. Part of the events had no tag indication. The spectrum presented in Ref. [33] consisted of all, tagged and non tagged, events. By analysing these data we found unambiguously that a peak at 2527 keV was generated by non tagged events originated by the early saturation of amplifier number six, which was defective in the last part of the experiment.

An important source of background in the Ge diodes [31–33] is their cosmogenic activation while on surface and specially during air transportation. To investigate the corresponding background in our experiment we have exposed one of our TeO_2 crystals to fast and thermal neutrons from a Am–Be source. In addition to various short living nuclides which cannot contribute to the activity in an underground laboratory, where the neutron flux is weak, we detected the presence of ^{121m}Te, ^{123m}Te, ^{125m}Te, and ^{129m}Te, with lifetimes of 154.7, 119.7, 58.1 and 33.6 d, respectively. The role played by these contaminations will be considered later on.

4. Results

The experiment is running since January 1993 in the Gran Sasso Underground Laboratory. 9234 h of effective running time have been collected so far, with an efficiency of more than 90%, which we consider more than satisfactory for a thermal detector. The base temperature and zero-bias resistance of the detector were 8.7 mK and 1 GΩ, respectively. The best operating conditions were achieved by applying to the thermistor a bias of 6.15 mV thus rising its temperature to 10.5 mK and decreasing its resistance to 191 MΩ.

The detector was tested by means of ^{60}Co and ^{232}Th sources illuminating it through a window which could be opened in a wall of the lead shield. The pulses were slow, with rise and decay times of 75 and 700 ms, respectively, due to the thermal time constants [36]. By relating the height of the pulses to the corresponding energy without taking into account the loss of thermal signal due to the link between crystal and sensor, one can naively evaluate a heat capacity of ~3.5 nJ/K versus an expected value of 0.74 nJ/K. We would like to stress however that extrapolation to our temperatures of values of T_D which have been measured only above one kelvin can lead to considerable uncertainties. The FWHM resolution increases from 9 to 15 keV in the energy window from 100 to 2615 keV and is mainly due to microphonic and electronic noise and to instabilities in the operating temperature.

The final spectrum is shown in Figs. 2 and 3. As in the previous experiment [21] the high energy region is dominated by the peak at 5407 keV due to *internal* contamination of ^{210}Po usually present in tellurium [6]. It corresponds in fact to the *sum* of the α and recoil energies. The rate of this peak, initially of about 20 counts h^{-1}, was found to decrease during the experiment with a lifetime of 138 ± 1 d in excellent agreement with what expected for ^{210}Po. A much weaker satellite peak at an energy about 100 keV lower is due to the α-energy alone and indicates a ^{210}Po contamination on

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[1] We are grateful to Dr. B.H. Duchemin, of the Departement des Applications et de la Metrologie des Rayonnements Ionisants, for providing us an updated table of γ lines.

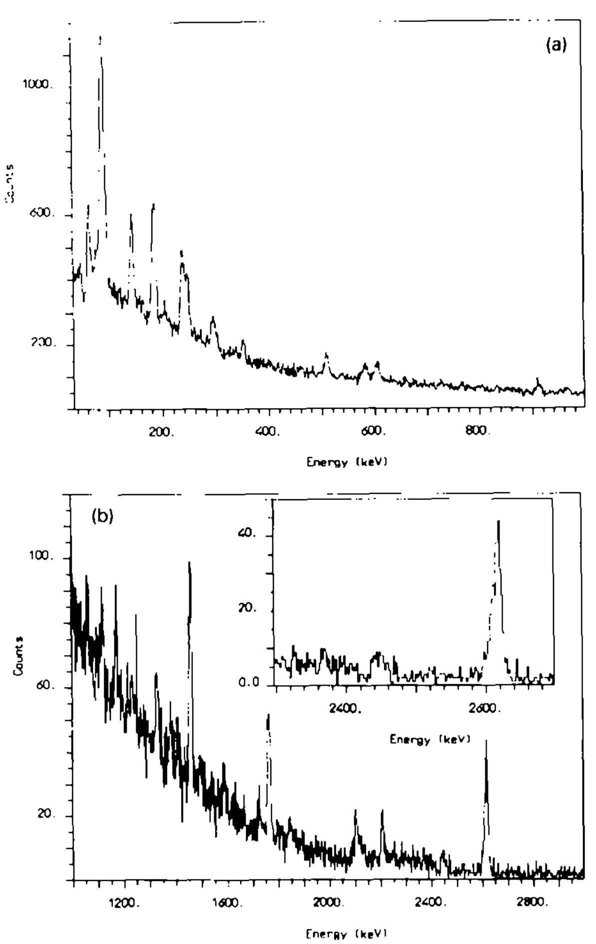

Fig. 2. The spectrum in the "gamma region". The region of neutrinoless DBD is shown in the inset of (b).

the surface. An accurate analysis of the time dependence of the counting rate of this peak shows that only a part of it decreases with the above mentioned lifetime. The rest remains constant thus indicating a different source for this ^{210}Po contamination. As pointed out before, the distance between the two peaks is in excellent agreement with the expected recoiling energy and indicate a similar thermalization efficiency for α-particles and recoils. Other weak peaks appear at values around 4016, 4196, 4688, 4780, 5304, 5420, 5490, 5686, 6003, 6288, 6779, 7687 and 8785 keV and indicate contaminations from the uranium and thorium chains *directly facing the detector.* There are only indications of peaks corresponding to full α transition energies due to internal contaminations other than that due to ^{210}Po. On the basis of an α–α time coincidence analysis and assuming secular equilibrium we can set 90% c. l. upper limits around one pg/g to the *internal* contamination both of ^{232}Th and of ^{238}U.

The line at 5407 keV is efficiently used to stabilize our measurements and correct for temperature drifts of the detector. As a consequence the resolution of background α and γ lines of the final spectrum are similar and compatible with the noise figure, as in the short calibration runs. In order to construct a mathematical relation between the deposited energy and the corresponding pulse amplitude, a simple phenomenological model was developed. The temperature variation is deduced from the change in the resistance of the thermistor using the known thermistor characteristic curve. This variation is then related to the corresponding deposited energy, assuming a temperature power law for the heat capacity. The exponent in this law is a free parameter, determined by the actual pulse amplitudes corresponding to the recognized background peaks.

We would like to point out that when γ lines are used for calibration the apparent energy of the α lines is found to be higher than expected. This seems to indicate a higher thermalization efficiency (by about 3%) for these particles.

In the region below 2400 keV (Fig. 2) the spectrum shows lines at 144, 186, 240, 295, 352, 511, 583, 609, 911, 964, 1001, 1120, 1238, 1764, 2118 and 2204 keV due to contaminations of ^{232}Th and ^{238}U. The lines at 1063, 1172 and 1331, and 1460 keV are due to ^{207}Bi,

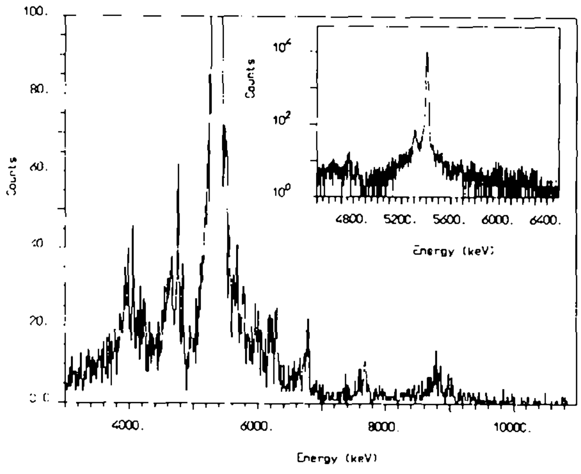

Fig. 3. The spectrum in the "α region". The full energy and satellite peaks of ^{210}Po are shown in logarithmic scale in the inset.

^{60}Co, and ^{40}K. In addition there are lines at 90 and 248 keV and excesses on the lines around 147 and 295 keV which could be tentatively attributed to internal transitions of ^{121m}Te, ^{123m}Te, ^{125m} and Te^{127m}Te. These nuclei could be due to cosmogenic activation of the crystal when outside the tunnel. The corresponding counting rates decrease in fact in reasonable agreement with the expected lifetimes.

In the region of neutrinoless DBD the spectrum (Fig. 2b) shows the two lines at 2447 and 2615 keV due to ^{214}Bi and ^{208}Tl, clearly confirming the stability of the experiment. The background counting rate between these peaks is $(1.3 \pm 0.1) \times 10^{-4}$ keV^{-1} h^{-1}. It is better by an order of magnitude, per unit mass, than in our preceding experiment. Even if it exceeds by about one order of magnitude that of the best experiments with Ge diodes we consider it very satisfactory. A dilution refrigerator is in fact much more difficult to shield than a germanium detector and materials of moderate radioactive contamination are difficult to be eliminated. Part of the background in the region of neutrinoless DBD can in particular be attributed to the spring loaded tips used to keep the crystal in position. A new fastening method to eliminate or reduce these springs is being developed.

No statistically significant peak appears in the region of neutrinoless DBD. We just observe an enhancement of 8.5 ± 4.5 events at an energy of 2521 ± 5 keV. On the basis of the maximum likelihood method we can then set lower limits of 1.8×10^{22} and 2.8×10^{22} yr for the lifetime of neutrinoless DBD of ^{130}Te at the 90% and 68% confidence level, respectively.

5. Conclusions

Our present limit excludes a relevant contribution of the neutrinoless channel in DBD of ^{130}Te, even if the large lifetime obtained in the geochemical experiment by Bernatovitz et al. [8] is assumed. If the average lifetime recommended by Manuel [7] is taken this neutrinoless contribution is less then 4.4% (2.8%) at the 90% (68%) confidence level.

On the basis of the recent theoretical predictions for neutrinoless DBD of ^{130}Te [2] we can set upper limits on the "average" neutrino mass of 3–6 and 2–4 eV at the 90% and 68% confidence level, respectively, in absence of right handed currents. The constraints on the right–right and right–left parameters λ and η can be obtained from the recent calculations by Suhonen et al. [37]. These limits are $\lambda < 8(5) \times 10^{-6}$ and $\eta < 2.2(1.4) \times 10^{-8}$ at 90% (68%) c.l., respectively.

An array made of four crystals of the same mass as the one used in the present experiment is beginning to operate in a second dilution refrigerator also installed in the Gran Sasso laboratory. Our future plans contemplate an array of 50 crystals of which a few will be enriched in ^{128}Te and ^{130}Te. With these set-ups we hope to increase our sensitivity of at least an order of magnitude.

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