A Calorimetric Search on Double Beta Decay of ^{130}Te

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Abstract

We report on the final results of a series of experiments on double beta decay of ^{130}Te carried out with an array of twenty cryogenic detectors. The set-up is made with crystals of TeO_2 with a total mass of 6.8 kg, the largest operating one for a cryogenic experiment. Four crystals are made with isotopically enriched materials: two in ^{128}Te and two others in ^{130}Te . The remaining ones are made with natural tellurium, which contains 31.7 % and 33.8 % ^{128}Te and ^{130}Te, respectively. The array was run under a heavy shield in the Gran Sasso Underground Laboratory at a depth of about 3500 m.w.e. By recording the pulses of each detector in anticoincidence with the others a lower limit of 2.1×10^{23} years has been obtained at the 90 % C.L. on the lifetime for neutrinoless double beta decay of ^{130}Te .

In terms of effective neutrino mass this leads to the most restrictive limit in direct experiments, after those obtained with Ge diodes. Limits on other lepton violating decays of ^{130}Te and on the neutrinoless double beta decay of ^{128}Te to the ground state of ^{128}Xe are also reported and discussed. An indication is presented for the two neutrino double beta decay of ^{130}Te . Some consequences of the present results in the interpretation of geochemical experiments are discussed.

Key words: Double beta decay, neutrino mass
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1 Introduction

Double beta decay (DBD), in its two negatron channel, consists in a rare transition from the nucleus (A,Z) to its isobar (A,Z+2) with the emission of two electrons. It can be searched for when the transition from (A,Z) to (A,Z+1) is energetically forbidden or at least strongly hindered by a large change of the spin-parity state. This process can occur into various channels:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\overline{\nu}_e \quad (1)$$

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + (N)\chi \;\; [N = 1, 2, ...] \quad (2)$$

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- \quad (3)$$

where χ is a massless Goldstone boson named Majoron. All three double beta processes can also occur to excited states of the daughter nucleus with a consequent lower "effective" transition energy. The lepton conserving process of two neutrino DBD, which is allowed by the Standard Model, has been revealed in 10 nuclei for the transition to the ground state and in one case also for the transition to an excited level of the daughter nucleus [1,2,3,4,5]. Both processes (2) and (3) violate the lepton number conservation and are forbidden by the Standard Model. The third, normally called "neutrinoless DBD" is experimentally very appealing, since it could be revealed by a peak corresponding to the total transition energy, since the nuclear recoiling energy is negligible. No evidence has been claimed so far for the leptonic violating channels (2) and (3), with the exception of an alleged evidence for neutrinoless DBD reported by Klapdor-Kleingrothaus et al. [6,7] but confuted by other authors [8,9].
Experiments for neutrinoless DBD represent a powerful tool to search for a finite "effective" neutrino mass and/or for the presence of right handed currents in the weak interaction amplitude. A non-zero $\langle m_\nu \rangle$ has been suggested [5,10,11,12,13,14,15,16,17] by the recent evidence of neutrino oscillations [18,19,20,21].
An indirect approach to search for DBD consists in radiochemical experiments [22] where the material containing the parent nucleus is stored underground for a long period and later searched for the decay of the radioactive daughter nucleus. Geochemical experiments [23,24,25,26,27] consist in the search for an abnormal abundance of the (A,Z+2) isotope extracted from a geological old rock containing a substantial amount of the nucleus (A,Z). These

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experiments are very sensitive, due to the long "exposure time", but, like the radiochemical ones, indicate only the presence of the daughter nucleus and cannot therefore discriminate between lepton conserving and non conserving processes or between decays to the ground or excited states of the daughter nucleus. Some indication for DBD [27] of ^{96}Zr and definite evidence for DBD of ^{82}Se, ^{128}Te and ^{130}Te have been reported [1,2,3,4,5,23,24,25,26].
Direct experiments are based on two different methods. In the source≠detector approach a double beta active material is inserted, normally in form of thin sheets, in a suitable detector. In the source=detector or "calorimetric" experiments [28] the detector itself is made by a material containing the double beta active nucleus. The use of cryogenic detectors to search for DBD has been suggested in 1984 [29]. These detectors [30,31] are based on the peculiar property of the heat capacity of diamagnetic and dielectric crystals which, at low temperature, is proportional to the cube of the ratio between the operating and Debye temperatures. As a consequence in a cryogenic set-up this capacity can become so small that even the tiny energy released by a particle in form of heat can be revealed by the temperature increase of the absorber by means of a suitable thermal sensor. Unlike conventional detectors, the cryogenic ones offer a wide choice of DBD candidates, the only requirement being that the candidate nucleus be part of a compound which can be grown in the form of a crystal with reasonable thermal and mechanical properties. ^{130}Te looks an excellent candidate to search for DBD due to its high transition energy (2528.8 ± 1.3 keV) [32], and large isotopic abundance (33.8 %)[33] which allows to perform a sensitive experiment with natural tellurium. In addition, the expected signal at 2528.8 keV is in an energy region between the peak and the Compton edge of the ^{208}Tl γ-rays at 2615 keV, which generally dominates the background in this high energy region.
Results on neutrinoless double beta decay of ^{130}Te have been already obtained with one [34], four [35] and eight [36] detectors made by 340 g crystals of TeO_2. The first operation and the preliminary results of an array of 20 crystals of natural TeO_2 of 340 g each, operated in coincidence and anticoincidence, has been presented previously [37]. We report here new results on two neutrino and neutrinoless DBD, based on substantial improvements of the detector and larger statistics.

2 Experimental details

The array consists in a tower with five planes of 4 detectors each, operating in a dilution refrigerator in the Gran Sasso Underground Laboratory [38]. The twenty absorbers are crystals of TeO_2 of 3x3x6 cm^3 volume with a total active mass of about 6.8 kg, the largest in any cryogenic experiment. Sixteen of these crystals are made of natural telluride. Two contain tellurium isotopi-

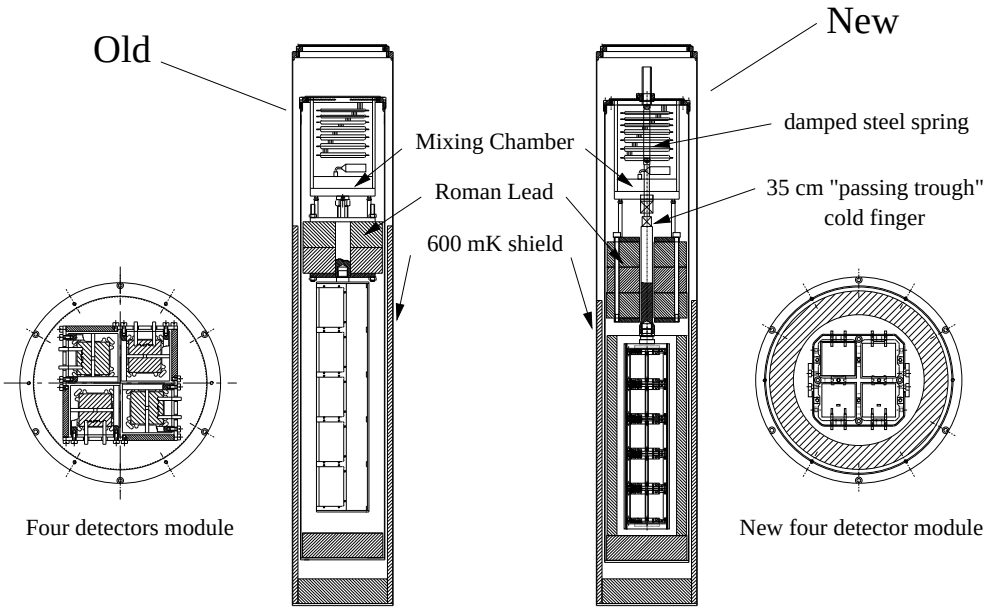

Fig. 1. Scheme of the array of twenty detectors.

cally enriched at 82.3 % in ^{128}Te and other two at 75.0 % in ^{130}Te . By mass spectrometer measurements we found that these enrichments are lower than the original ones (94.7 % and 92.8 %, respectively). This is due to the process of crystallization which is more complex when isotopically enriched powder is used, and requires seeds of natural telluride. The temperature sensors are Neutron Transmutation Doped (NTD) Ge thermistors thermally coupled to each crystal. They were specifically prepared in order to present similar thermal performance. A resistor of 100 - 200 kΩ, realized with a heavily doped meander implanted on a 1 mm^3 silicon chip, was attached to each absorber and acted as a heater to calibrate and stabilize the gain of the bolometer [39]. The tower is connected via an OFHC copper cold finger to the mixing chamber of a dilution refrigerator specially constructed with previously tested low radioactivity materials. The entire set-up is shielded with two layers of lead of 10 cm minimum thickness each. The outer one is made of common low radioactivity lead, the inner of special lead with a contamination of 16 $\pm$ 4 Bq/kg in ^{210}Pb . The electrolytic copper of the refrigerator thermal shields provides an additional shield of 2 cm minimum thickness.
The new results reported here refer to runs carried out with two different configurations (Fig. 1). In the former one the intrinsic radioactive contamination of the dilution unit materials (e.g. from silver and stainless steel) is shielded by a layer of 10 cm Roman lead (^{210}Pb activity $<$ 4 mBq/kg [40]), framed inside the cryostat immediately above the tower of the array. The refrigerator is surrounded by a Plexiglas anti-radon box fluxed with clean N_2 from a liquid nitrogen evaporator, and by a Faraday cage to eliminate electromagnetic interference. In the latter configuration the following improvements have been implemented:

a. all crystals have been thoroughly lapped with previously tested low radioactivity powder to reduce the surface contamination introduced by the original production process in China. All these operations and the final mounting of the tower were carried out in a clean box.

b. a more compact assembling of the crystals has been adopted. This has allowed us to add an internal lateral shield of Roman lead of 2 cm minimum thickness and to increase by 5 cm the thickness of the lead shield between the mixing chamber and the detector.

c. a spring to which the tower is hanged has been added to reduce vibrations.

The front-end electronics of each detector is located at room temperature. It consists of a differential voltage sensitive preamplifier followed by a second stage and an antialiasing filter [41,42,43]. The differential configuration has been adopted in order to minimize signal cross talk and microphonic noise coming from the connecting wires. Precautions have been taken to suppress any possible effect coming from any room temperature drift [41] and main supply instability [44]. A pair of load resistors serves to bias each bolometer in a symmetric way. They are located at room temperature, close to the preamplifier, and consist of metal films (Micro-Ohm) with a value of 30 GΩ each. Their manufacturing process and large value have been chosen in order to maintain as low as possible their thermal and low frequency noise contribution [45]. All the necessary settings for the front-end and the biasing system are programmed remotely via computer, in order to allow the optimization of the overall dynamic performance separately for each detector [42].
All other details, which are common to both set-ups have been reported previously [37]. In both cases the array was cooled down to temperatures around 8 mK with a temperature spread of $\sim$1 mK among the different detectors. The detectors were calibrated by a combined radioactive source of ^{238}U and ^{232}Th. Their FWHM energy resolutions at the 2615 keV ^{208}Tl line range from 5 to 15 keV.

3 Experimental results

The two set-ups have been operated for effective running times of $\sim$31,508 and $\sim$5,690 hours·kg, respectively. Sum spectra have been obtained both with no anticoincidence cut and by operating each detector in anticoincidence with all the others. In all these spectra the main lines due to the natural activity of the ^{232}Th and ^{238}U chains, of ^{40}K and the lines at 1173 and at 1332 keV due to cosmogenic ^{60}Co are present.
No peak appears in the region of neutrinoless DBD of ^{130}Te, where the rates are, respectively, of 0.59 $\pm$ 0.06 and 0.33 $\pm$ 0.11 counts keV^{-1} kg^{-1} year^{-1} for the former and latter run, when operated in anticoincidence. No peak also appears at the energies corresponding to neutrinoless DBD of ^{130}Te to excited

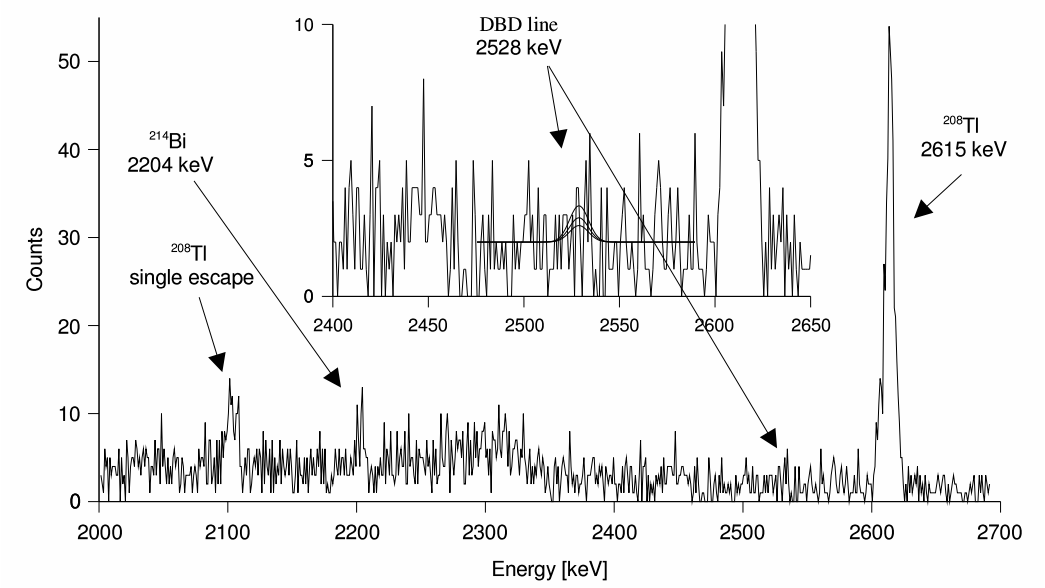

Fig. 2. Total spectrum (in anticoincidence) in the region of neutrinoless DBD obtained with the twenty crystal array. The solid curves represent the best fit (lowest curve) and the 68 % and 90 % C.L. excluded signals.

levels of ^{130}Xe, and at the energy of 867 keV corresponding to neutrinoless DBD of ^{128}Te.

The sum of the spectra obtained in anticoincidence in the two runs in the region above 2000 keV is shown in Fig. 2. It corresponds to ∼3.56 kg x year of TeO_2 and to ∼0.98 kg x year of ^{130}Te . The clear peaks corresponding to the lines at 2104 keV (single escape of the 2615 keV ^{208}Tl line), at 2204 keV (^{214}Bi) and at 2615 keV (^{208}Tl), confirm the reproducibility of the array during both runs.
We would like to note that in the spectrum of the second run both the peaks and the continuum were decreased by a factor of about two with respect to the first run. However, according to the results obtained from the background analysis and supported by the Monte Carlo simulation of the detector, these similar reduction factors are due to two different effects. While the peaks were due to sources outside the detector and were consequentely reduced by the increased shield of lead, the continuum was mainly reduced by the lapping and cleaning of the crystals and copper frame. This confirms that the origin of the background at the energy corresponding to neutrinoless DBD is mainly due to surface contamination.

Fit parameters and 90 % C.L. limits for the various decay processes were evaluated with a maximum likelihood procedure. Assuming a Poisson statistics for the binned data the fit procedure was formulated in terms of the likelihood

chisquare (χ^2_L) [46]:

$$\chi^2_L = 2\sum_i (y_i - n_i + n_i\, ln(n_i/y_i)) \quad (4)$$

where n_i is the number of events in the i-th spectrum bin and y_i the number of events predicted by the fit model. Fit parameters were estimated by minimizing χ^2_L, while limits were obtained, after proper renormalization, just considering the χ^2_L distribution in the physical region [47]. A global fit procedure based on the minimization of $\chi^2_T = \sum_i \chi^2_i$ was adopted to combine different measurements. Similar results were obtained following the approach proposed by G.J. Feldman and R.D. Cousins [48], suggested by the Particle data Group [49].

Table 1
Half lifetime limits (90 % C.L.) on lepton violating and conserving channels. E_0 is the energy at which $T_{1/2}$ was obtained while *a.c.* means anticoincidence between different detectors.

Isotope	Transition	Used Spectra	Cuts	E_0 (keV)	Efficiency (%)	$T_{1/2}$ (years)
^{130}Te	$0\nu : 0^+ \to 0^+$	All spectra	a.c.	2528.8	84.5	$> 2.1 \times 10^{23}$
^{130}Te	$0\nu : 0^{+*} \to 0^+$	All spectra	none	1992.8	7.9	$> 3.1 \times 10^{22}$
^{130}Te	$0\nu : 0^{+*} \to 2^+$	All spectra	none	1992.8	37.5	$> 1.4 \times 10^{23}$
^{130}Te	$2\nu : 0^+ \to 0^+$	^{130}Te crystals	a.c.			$> 3.8 \times 10^{20}$
^{130}Te	$1\chi : 0^+ \to 0^+$	^{130}Te crystals	a.c.			$> 2.2 \times 10^{21}$
^{130}Te	$2\chi : 0^+ \to 0^+$	^{130}Te crystals	a.c.			$> 0.9 \times 10^{21}$
^{128}Te	$0\nu : 0^+ \to 0^+$	All spectra	a.c.	867.2	97.9	$> 1.1 \times 10^{23}$

Efficiencies and limits for the various decay channels were estimated as follows:

a. The spectra used to evaluate neutrinoless DBD to the ground level were obtained by considering only events which are, as expected, contained in a single detector. By rejecting all multiple events we have achieved a reduction of the background in the neutrinoless DBD region of ∼25 %.

b. A neutrinoless DBD to a 0^{+*} intermediate state at 1072 keV has been suggested in ref. [50]. It would be followed by the decay of this state to the 536 keV 2^+ level, followed by the emission of a second γ-ray. The limit for this process can be evaluated in various ways. We found that the more restrictive limit could be obtained from the spectrum without anticoincidence, assuming that the same crystal absorbs the two electrons and the first γ-ray, while the 536 keV one escapes from it. Efficiency and limit have been evaluated accordingly.

c. Efficiency and rate for the neutrinoless $0^+ \rightarrow 2^+$ DBD to the 536 keV state have been also evaluated from the spectrum without anticoincidence and assuming the escape of the 536 keV γ-ray.

d. The constraints for two neutrino and majoron decays have been estimated from the spectrum obtained with each $^{130}TeO_2$ crystal in anticoincidence with the other crystals of the array. The corresponding limits have been conservatively obtained by evaluating the maximum areas for which the expected spectra do not exceed the background spectra and their fluctuations at any energy. The detection efficiency for these processes is near to one.

4 Lepton non conserving double beta decay

The constraints on the effective neutrino mass $\langle m_\nu \rangle$, on the right handed current parameters $\langle \lambda \rangle$ and $\langle \eta \rangle$ and on the coupling majoron parameter $\langle g_{\chi\nu} \rangle$ suffer from uncertainties in the calculation of the nuclear matrix elements [51,52,53,54,55,56,57,58,59]. The limits on the various channels of neutrinoless DBD of ^{130}Te are reported in Table 2 on the basis of various QRPA calculations, since the shell model does not seem appropriate for heavy nuclei [51]. Taking into account theoretical uncertainties we obtain from our data constraints in the ranges (1.1-2.6) eV; $(1.6 - 2.4) \times 10^{-6}$ and $(0.9 - 5.3) \times 10^{-8}$ for the values of effective neutrino mass, and the two right handed parameters λ and η respectively. Our limit on $\langle m_\nu \rangle$ appears to be the most restrictive one among those obtained with direct methods after those on ^{76}Ge (0.35-1.4 eV).

Table 2
Limits on the lepton non-conserving parameters from this experiment. For each parameter, limits are abtained assuming vanishing the others.

Ref.	$\langle m_\nu \rangle$	$\langle \lambda \rangle \times 10^{-6}$	$\langle \eta \rangle \times 10^{-8}$	$\langle g_{\chi\nu} \rangle \times 10^{-5}$
Engel et al. (1988)[53]	1.8			28
Engel et al. (1989)[54]	1.1			17
Muto et al. (1989)[55]	1.5	2.1	1.4	24
Suhonen et al. (1991)[56]	2.0	2.1	5.3	31
Tomoda et al. (1991)[57]	1.6	2.4	1.6	25
Faessler et al. (1998)[51]	2.1			33
Barbero et al. (1999)[52]	1.3	1.6	0.9	
Klapdor-Kleingrothaus and Stoica(2001)[58]	2.2-2.3			
Faessler and Simkovic (2001)[59]	2.6	2.4	1.8	

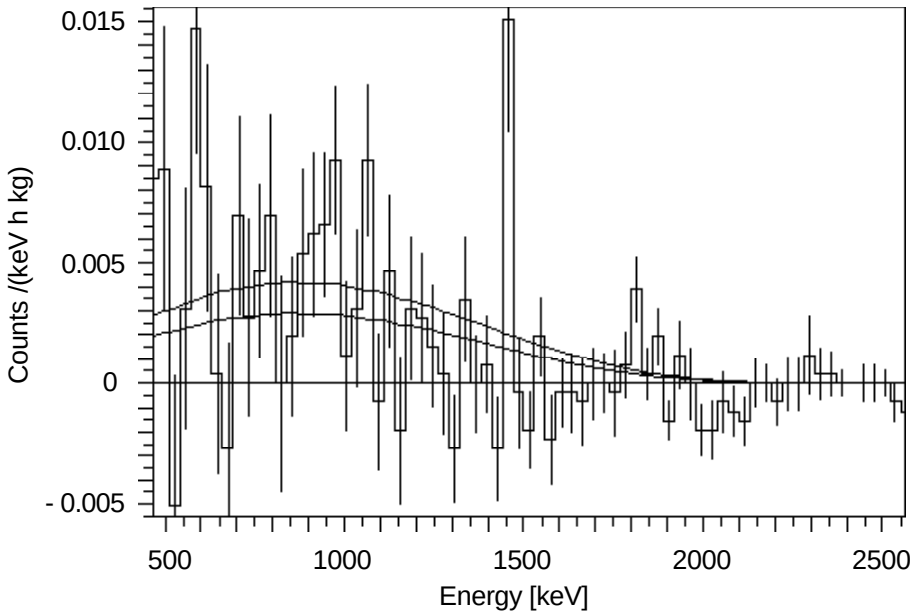

Fig. 3. Total difference spectrum between ^{130}Te and ^{128}Te detectors (no background subtraction). The solid curves represent the best fit (lowest curve) and the 90 % C.L. excluded signal (Tab. 1)

Our exclusive limit on the half lifetime for neutrinoless DBD of ^{128}Te is the best in direct experiments, but less constraining than those extracted (for the same nucleus) from the inclusive limits of geochemical experiments [23,24,25,26].

5 Lepton conserving double beta decay

The 90 % C.L. limit for two neutrino DBD of ^{130}Te reported in Table 1 already excludes a relevant loss of the daughter isotope in geochemical experiments, which has been considered by O.K. Manuel [23]. We have also attempted to obtain an evaluation of the rate for this lepton conserving process by analyzing the difference between the sum of the two spectra of the crystals isotopically enriched in ^{130}Te and the sum of those of the crystals enriched in ^{128}Te . (Fig. 3). These differences are positive in the region of two neutrino DBD with an excess of 269 ± 60 counts corresponding to $T_{1/2} = (6.1 \pm 1.4\, stat.) \times 10^{20}$ years. However a precise evaluation of the half life is not straightforward because the background differs among the four enriched crystals. In particular different rates are observed for the 1460 keV gamma line of ^{40}K and for the alpha lines in the 4-6 MeV energy region. With the aid of a Monte Carlo simulation of the possible background contributions we were able to restrict the possible sources responsible of these lines. The 1460 keV gamma peak appears to be due to an accidental ^{40}K contamination localized on the bottom surface of the detector copper holder, while the alpha lines are clearly due to ^{238}U and ^{232}Th surface contaminations of the crystals. A similar - although lower - surface contam-

ination is observed also for all the natural crystals. Taking into account the different rates observed in the lines of our isotopically enriched detectors we extrapolated the contribution to the ^{130}Te - ^{128}Te spectra produced by such contaminations in the two neutrino DBD region. The maximum expected difference due to ^{238}U and ^{232}Th contaminations is negative and corresponds to 380 conts, which should therefore be added to the actually found signal. On the contrary the corresponding maximum expected difference due to background from ^{40}K (86 counts) is positive and should therefore be subtracted. Slightly different values are obtained by varying the contaminations location. In all the cases however negative values are obtained for the ^{238}U and ^{232}Th contribution (responsible of the differences in the alpha counting rates) and positive for the corresponding ^{40}K ones. We conclude that the difference in the crystal background rates cannot account for the two neutrino DBD effect, but introduce a large systematics in the half life time evaluation. By assuming the above quoted background rates as the maximum possible contribution to our systematic error, our final result is $T_{1/2} = (6.1 \pm 1.4\, stat._{-3.5}^{+2.9}\, sys.) \times 10^{20}$ years. This value, while in agreement with most geochemically obtained results, looks somewhat higher than most of those predicted theoretically [3]. The already running NEMO 3 experiment [60], as well as the an improved search to be carried out with the larger CUORICINO array [61] being mounted in the Gran Sasso laboratory, will allow to reduce soon the present uncertainty.

6 Comparison with geochemical experiments

Geochemical experiments simply indicate the presence of the (A,Z+2) nucleus in the sample containing (A,Z). The quoted rates for ^{130}Te refer therefore to the sum of all possible transitions to the ground or excited levels, with or without the emission of neutrinos or majorons. Our indication for two neutrino DBD of ^{130}Te is in qualitative agreement with the inclusive rates indicated in most geochemical experiments.

On the other side our exclusive limits on individual neutrinoless DBD processes allow to constrain their contribution to the inclusive values found geochemically. In particular our limit on neutrinoless DBD of ^{130}Te excludes contributions of 0.3 to 1.3 % to the overall rate in the two extreme results of Manuel et al [23] and Bernatowicz et al. [25], respectively. Our limit on neutrinoless DBD to a hypothetical 0^+ excited state at 1072 keV [50] indicates that this process cannot be responsible for more than 2 and 9 % of the geochemically obtained rates in the two extreme results reported above. The corresponding maximal contributions of neutrinoless DBD to the 2^+ excited state of ^{130}Xe at 536 keV are 0.5 and 2 %, respectively. By applying the same procedure to our limit on DBD mediated by a majoron we achieve upper limits of 33 and 87 %.

7 Conclusions

No evidence is found in this experiment for neutrinoless DBD of ^{130}Te with a 90 % C.L. lower limit of 2.1×10^{23} years. This corresponds to an upper limit on the effective neutrino mass $\langle m_\nu \rangle$ ranging from 1.1 to 2.6 eV, on the basis of the various evaluations of the nuclear matrix elements. This, as well as the limits on the values of the contributions of right handed currents and on the possible majoron coupling, are the most constraining ones in direct experiments after those obtained with Ge diodes.
We have an indication for two neutrino double beta decay of ^{130}Te to the ground state of ^{130}Xe which roughly confirms the positive evidence found in geochemical experiments. Our experiment also shows that the neutrinoless channels do not account for relevant contributions to the overall DBD rate of ^{130}Te measured in geochemical experiments.
The peculiarly large isotopic abundance of ^{130}Te allows the use of natural telluride in large scale searches for neutrinoless DBD. An experiment, named CUORE (for Cryogenic Underground Observatory for Rare Events) made by 1000 crystals of TeO_2 with a total mass of almost 800 kg is being studied [61] and a smaller array, named CUORICINO, totalling about 40 kg of active TeO_2 , is being constructed [62].

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