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Section A

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Present status of MI-BETA cryogenic experiment and preliminary results for CUORICINO

S. Pirro[a,*], A. Alessandrello[a], C. Brofferio[a], C. Bucci[b], O. Cremonesi[a], E. Fiorini[a], A. Giuliani[a], A. Nucciotti[a], M. Pavan[a], G. Pessina[a], C. Pobes[a,1], E. Previtali[a], M. Vanzini[a], L. Zanotti[a]

[a] *Dipartimento di Fisica dell'Università di Milano-Bicocca e Sezione di Milano dell'INFN, Via Celoria 16, I-20213 Milan, Italy*
[b] *INFN - Laboratori Nazionali del Gran Sasso, I-67100 Assergi (Aq), Italy*

Abstract

Present results on neutrinoless double beta decay of ^{130}Te obtained with an array of 20 cryogenic detectors are presented. The setup consists of 20 crystals of tellurium oxide of 340 g each, corresponding to the largest presently operating cryogenic mass. Combining the results of the few runs obtained with the same array, corresponding to 1.5 kg yr, a limit on neutrinoless double beta decay half-life of 9.5×10^{22} yr (90% CL) has been obtained. On the basis of the results obtained with the MI-BETA experiment, we propose a construction of a 42 kg array of 56 TeO_2 bolometers (CUORICINO project) to extend the sensitivity of the present experiment, and as a first test for CUORE. Thanks to an innovative technique of vibration reduction and despite the high mass (750 g instead of the 340 g of the presently running detectors) we reached an energy resolution of 3.9 keV FWHM at 2615 keV decreasing to 1.4 keV at low energies. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Double beta decay; TeO_2; Cryogenic detector

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1. Introduction

Double beta decay is a rare radioactive transition from an even nucleus (A, Z) to its isobar $(A, Z+2)$, with the simultaneous emission of two electrons. The two-neutrino double beta decay mode, where two antineutrinos are emitted together with the two electrons, is expected to occur in the Standard Model as a second-order effect of the well-known beta decay Hamiltonian, and it has been observed, or at least indicated, for 10 nuclei [1–4]; besides, if lepton number is violated, the two electrons could be emitted without any other particle; this would lead to a new neutrino physics, implying a finite mass and a Majorana nature for the neutrino.

The advantages of using large mass, high resolution detectors to search for neutrinoless double beta decay (0νDBD) have been largely discussed. In this experimental approach the detector contains, or is made of, the isotope candidate to DBD and the signature of the decay will be the appearance of a monochromatic line in the background spectrum, corresponding to the transition energy of the decay.

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[*] Corresponding author. Fax: + 39-0862-437570.
E-mail address: stefano.pirro@lngs.infn.it (S. Pirro).

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The application of this technique using conventional (ionization or scintillation) detectors has been made possible only for ^{76}Ge and ^{116}Cd DBD experiments: the limit on 0νDBD half life of ^{76}Ge obtained with germanium diodes is the highest ever reported [5].

Using thermal detectors, on the contrary, a search on a wide choice of other 0νDBD isotopes is possible.

We believe that the study of ^{130}Te is one of the most promising approaches for new generation DBD experiments. In fact, considering the reasonably high transition energy (2.528 MeV) and the nuclear matrix elements, ^{130}Te DBD rate is predicted to be about four/five times faster than for ^{76}Ge [6], and is one of the fastest among the most interesting candidates. In large mass DBD experiments the availability of the isotope nuclide is a critical point. The natural isotopic abundance of ^{130}Te is 34%, much higher than those of the other interesting DBD candidates. Therefore, a significant ^{130}Te experiment can be performed even without isotopic enrichment, which is often economically prohibitive in large quantities.

2. Experimental details

The array (see Fig. 1) consists of 20 modular detectors framed in a tower with five floors of four detectors, operating in a dilution refrigerator in the Gran Sasso Underground Laboratory. The single module absorber consists of a crystal of natural TeO_2 of $3 \times 3 \times 6$ cm^3. The total active mass is about 6.8 kg, corresponding to the largest presently operating cryogenic mass. The tower frame is made of previously tested low radioactivity Oxygen Free High Conductivity (OFHC) copper, soldered with an electron beam after accurate polishing in order to avoid radioactive contaminations. The crystals are fastened to this structure by means of PTFE supports. The temperature sensors are neutron transmutation doped Ge thermistors of $3 \times 1.5 \times 0.4$ mm^3, specifically prepared in order to present similar thermal characteristics, and thermally coupled to each crystal with six ~ 0.6 mm diameter epoxy glue spots. A resistor of 100–200 kΩ, realized with a heavily doped meander on a 1 mm^3 silicon chip, was attached to each absorber and acted as a heater to calibrate and stabilize the gain of bolometer [7].

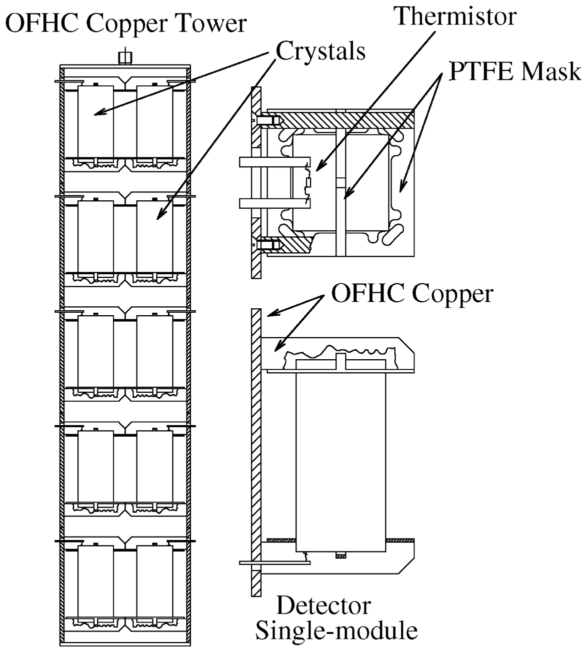

Fig. 1. Schematic view of the 20-crystal tower and detector single module.

The tower is connected via an OFHC copper cold finger to the mixing chamber of an Oxford 1000 dilution refrigerator specifically constructed with previously tested low radioactivity materials. The entire cryostat is shielded with two layers of lead each with a minimum thickness of 10 cm. The outer one is made of common low radioactivity lead, the inner of special lead with a contamination of 16 ± 4 Bq/kg in ^{210}Pb. The details of the experimental setup and the front-end readout can be found elsewhere [8].

3. Detector performances

The array was cooled down to temperatures around 8 mK. A spread in the detector base temperature around 1 mK was observed, which we consider reasonable if the non-perfect reproducibility of the detector modules is taken into account.

To optimize the detector energy resolution the mixing chamber had to be *slightly heated* to about 11 mK. At the optimum bias point the operating temperature of each detector ranges from 11.5 to 13.5 mK. The corresponding heat capacity of the crystal absorber is about 1.1×10^{-9} J/K. A list of the most relevant detector characteristics is given in Table 1.

At low energies the effective energy resolution practically approaches the base-line width, while at high energies (~ 2 MeV) it becomes worse by a factor of 2–3, due to not yet completely understood systematic effects.

The 20 detectors were calibrated by a combined source of ^{232}Th and ^{238}U. The 20-channel 70 h calibration sum spectrum, showing the excellent reproducibility of the array, is presented in Fig. 2.

The FWHM energy resolution of the 20 crystals sum spectrum ranges from 3.1 keV for the 609 keV γ-line of ^{214}Bi to 5.5 keV for the 1764 keV γ-line due to the same nuclide. Near the region of 0νDBD decay line, the energy resolution is given by the 2.615 MeV γ-line of ^{208}Tl whose FWHM is 8 keV. A small worsening in the energy resolution is observed, during the long time of the background measurements, on the small natural radioactive contaminations peaks (mainly ^{40}K and ^{208}Tl) present in the setup. These effects are mainly due to the unavoidable thermal instabilities of the cryogenic facilities during the time of the measurements; thanks to the heater stabilization method, however, this worsening can be reduced to only ~ 10%.

Since March 1999 we replaced four natural crystals with four isotopically enriched crystals (two 93% of ^{130}Te and two 94% of ^{128}Te) in the array in order to search for the 2νDBD decay mode with the method of background subtraction. The thermal

Table 1
Thermal characteristics and performances of the 20 detectors. The last four rows are with respect to the enriched crystals

DET no.	*R* (MΩ)	*T* (mK)	μV/MeV	Decay (ms)	FWHM at 2615 (keV)	FWHM O.F (keV)
1	133	12.3	330	250	7.4	2.3
2	80	11.8	200	220	5.7	3.3
3	130	11.9	300	355	16.2	8.6
4	133	12.4	285	135	6.9	2.4
5	95	12.9	190	180	8.4	3.7
6	148	11.7	230	235	5	3.1
7	89	12.4	210	140	10.5	2.7
8	117	12.1	350	160	6.9	6.7
9	187	11.5	420	150	5.7	3
10	140	12.8	390	345	4.8	3.8
11	296	10.8	385	120	9.1	2.2
12	86	12.1	320	235	8.2	1.8
13	67	13.1	160	125	7.9	2.8
14	61	12.7	210	215	6.4	2.2
15	55	13	130	230	8.9	2.4
16	81	12.7	200	205	5.8	2
17	108	12.4	310	160	8.5	1.9
18	152	13.5	240	265	9	3
19	56	13.6	200	210	5.5	2.2
20	98	12.8	225	130	5.6	2.3
Mean	115	12.4	265	200	7.6	3.1
128-1	109	12.1	60	152	16	6.5
128-2	135	13.7	185	60	8	5.5
130-1	69	12.8	70	78	15	6.5
130-2	67	13.1	160	82	8	6

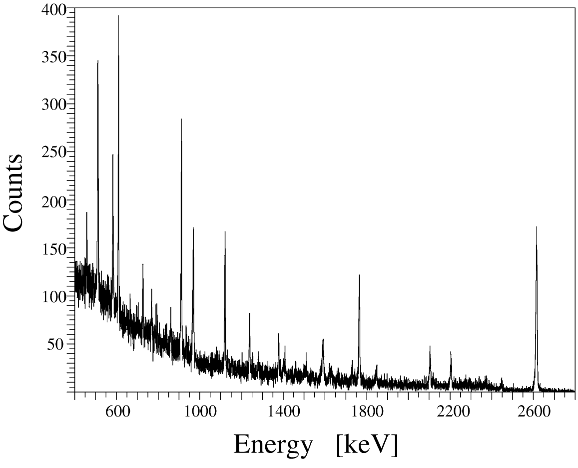

Fig. 2. Sum spectrum of the 20 TeO_2 detectors exposed to ^{232}Th and ^{238}U sources.

properties we found for the enriched crystals are very different with respect to the natural ones (see Table 1).

The thermal response we have found is worse by a factor of 2–4 with respect to the mean value of natural crystals; moreover, the decay time of the pulse shows a different behavior: instead of a single component, the decay development of the thermal pulse is compatible with two decay time constants: a fast component (~ 40–60 ms) resulting in ~ 70% of the total signal, and a slow component (~ 300 ms) to which corresponds ~ 30% of the total thermal signal.

A possible explanation for this behavior could be the presence of some impurities (mainly Si) in the enriched powder from which the crystals were grown. Despite the worse thermal response, however, the energy resolution is, in the worse case, lower only by a factor of 2 with respect to the natural crystal.

4. Physics results

A limit on neutrinoless DBD half-life of 9.5×10^{22} yr (90% CL), corresponding to effective Majorana neutrino mass limit ranging from 2.3 to 4.7 eV [6] was obtained with all the data collected with the 20 crystal array (1.5 kg yr July 1999). The background spectra in the 0νDBD decay region is shown in Fig. 3.

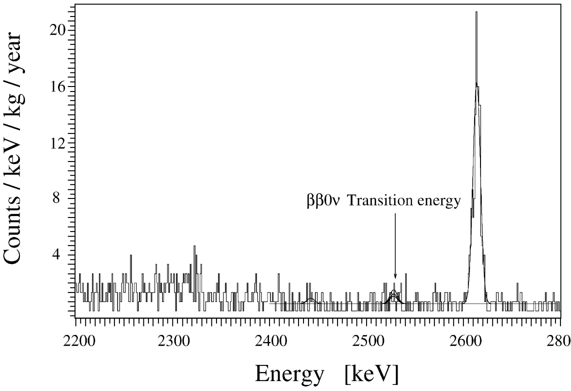

Fig. 3. Experimental background in the region around the 0νDBD transition energy, measured with the 20 detector array (1.5 kg yr).

Combining the results of the 20 crystal array with all the previous measurements carried out with 340 g TeO_2 bolometers at LNGS (2.14 kg yr in total) the limit on neutrinoless DBD half-life becomes 1×10^{23} yr (90% CL).

The background level in the 0νDBD transition energy region is about 0.5 counts/(keV kg yr), an order of magnitude better than that achieved in our preliminary, one-module, 10 000 h DBD experiment [9–11], thanks to the reduction of radioactive contaminations in the materials surrounding the detector and to an improvement of the radioactive shields. The residual background is due, probably, to two components which give a similar contribution: energy-degraded alpha particles coming from the surfaces of materials facing directly the detectors and external Compton-degraded high energy photons (mainly from ^{208}Tl) due to some not yet identified contamination in the setup. Tests are in progress in order to improve the understanding of this background sources.

5. Preliminary results for CUORICINO

On the basis of the results obtained with the presently running TeO_2 MI-BETA experiment, we propose a large, high granularity, closely packed array of bolometric detectors, named "CUORE" (which stands for Cryogenic Underground Observatory for Rare Events). The elementary CUORE [12] detector is a single TeO_2 crystal with a cubic shape ($5 \times 5 \times 5$ cm^3) and a mass of 750 g. It is about 2.5 times more massive than the previous ones, and the largest cryogenic detector presently operating underground. In a preliminary structure CUORE consists of seventeen 90 cm high towers hanging parallel to each other from a copper plate (kept at about 10 mK) and included within a cylinder of 75 cm diameter. The single tower contains 15 layers, each of which turns out to be the smallest independent detector unit with four 750 g TeO_2 crystals.

As a preliminary test a single CUORE tower (CUORICINO) will be cooled down in the refrigerator presently housing the 20 element array. The CUORICINO Project (Cuoricino means "Small Cuore") is officially approved and funded by the International Scientific Committee of the Gran Sasso Laboratories.

The first test 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. In order to account for the larger absorber size and to further reduce the electron–phonon decoupling we have adopted a thermistor considerably larger ($3 \times 3 \times 1$ mm^3) than those used in the MI-Beta experiment. It is thermally coupled to the crystal with 12 glue spots of ~ 0.6 mm diameter. The working temperature is ~ 9 mK. In order to reduce the vibration and thermal noise induced on the bolometer, we developed a new kind of suspension resulting in a mechanical decoupling of the crystal with respect to the cryostat [13].

To further improve the energy resolution by decreasing microphonics and electronic intrinsic noise of the amplifier, the bolometer was connected to a pair of cooled JFETs kept at a temperature of ~ 120 K inside the cryostat. The two 10 GΩ load resistors were also kept at the same temperature. JFETs and load resistors were installed in a suitable box between the 600 mK plate and the 1 K Pot plate.

The calibration spectrum obtained in 47 h of effective running time with a combined source of ^{232}Th and ^{238}U shows an impressive improvement in the resolution at all energies with respect to the results of Mi-Beta. The FWHM resolution of the baseline is 1.4 keV. The energy resolution obtained ranges from 1.5 keV for the 352 keV γ-line of ^{214}Pb to 2.8 keV for the 1764 keV γ-line of ^{214}Bi; for the 2615 ^{208}Tl γ-line the resolution is 3.9 ± 0.7 keV.

These resolutions 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 was placed outside the shield of our bolometer, with a consequent poorer statistics and larger background.

An excellent result was obtained with α-particles [13,14]. The average energy resolution of 4.2 keV FWHM on the ^{210}Po α-line is the best ever obtained with any type of detector.

6. Conclusions

The good performance of our array of 20 cryogenic detectors of TeO_2 in few runs corresponding to ~ 84 d of background measurements (1.57 kg yr) allows to set at 90% CL a lower limit of 9.5×10^{22} yr for the lifetime of neutrinoless DBD of ^{130}Te. The corresponding limits on the effective Majorana neutrino mass range from 2.3 to 4.7 eV.

Considering the construction of CUORICINO, that will start data taking in 2001, a preliminary test run performed on a 750 g TeO_2 crystal gave excellent results. The mean energy resolution obtained is better by a factor of two with respect to the mean of the presently running experiment. The energy threshold achieved is ~ 5 keV, aiming for other very interesting applications like search of WIMPs and Solar Axions, undergoing coherent Bragg conversion into photons by Primakoff effect.

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