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First results on neutrinoless double beta decay of ^{130}Te with the calorimetric CUORICINO experiment

C. Arnaboldi [a], D.R. Artusa [b], F.T. Avignone III [b], M. Balata [c], I. Bandac [b], M. Barucci [d], J.W. Beeman [e], C. Brofferio [a], C. Bucci [c], S. Capelli [a], F. Capozzi [a], L. Carbone [a], S. Cebrian [f], O. Cremonesi [a], R.J. Creswick [b], A. de Waard [i], H.A. Farach [b], A. Fascilla [h], E. Fiorini [a,*], G. Frossati [i], A. Giuliani [h], P. Gorla [a,f,2], E.E. Haller [e,g], R.J. McDonald [e], A. Morales [f], E.B. Norman [e], A. Nucciotti [a], E. Olivieri [d], E. Palmieri [j], E. Pasca [d], M. Pavan [a], M. Pedretti [h], G. Pessina [a], S. Pirro [c], C. Pobes [c,1], E. Previtali [a], M. Pyle [c], L. Risegari [d], C. Rosenfeld [b], S. Sangiorgio [h], M. Sisti [a], A.R. Smith [e], L. Torres [a,f,2], G. Ventura [d]

[a] *Dipartimento di Fisica dell'Università di Milano-Bicocca e Sezione di Milano dell'INFN, I-20126 Milano, Italy*
[b] *Department of Physics and Astronomy, University of South Carolina, Columbia, SC 29208, USA*
[c] *Laboratori Nazionali del Gran Sasso, I-67010, Assergi (L'Aquila), Italy*
[d] *Dipartimento di Fisica dell'Università di Firenze e Sezione di Firenze dell'INFN, I-50125 Firenze, Italy*
[e] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[f] *Laboratorio de Fisica Nuclear y Alta Energias, Universidad de Zaragoza, 50009 Zaragoza, Spain*
[g] *Department of Material Science and Engineering, University of California, Berkeley, CA 94720, USA*
[h] *Dipartimento di Scienze Chimiche, Fisiche e Matematiche dell'Università dell'Insubria e Sezione di Milano dell'INFN, I-22100 Como, Italy*
[i] *Kamerling Onnes Laboratory, Leiden University, 2300 RAQ, Leiden, The Netherlands*
[j] *Laboratori Nazionali di Legnaro, I-35020 Legnaro (Padova), Italy*

Abstract

The first results are reported on the limit for neutrinoless double decay of ^{130}Te obtained with the new bolometric experiment CUORICINO. The set-up consists of 44 cubic crystals of natural TeO$_2$, 5 cm on the side and 18 crystals of $3 \times 3 \times 6$ cm^3. Four of these latter crystals are made with isotopically enriched materials: two in ^{128}Te and two others in ^{130}Te. With a sensitive mass of ~ 40 kg, our array is by far the most massive running cryogenic detector to search for rare events. The array is operated at a temperature of ~ 10 mK in a dilution refrigerator under a heavy shield in the Gran Sasso Underground Laboratory at a depth of about 3500 m.w.e. The counting rate in the region of neutrinoless double beta decay is ~ 0.2 counts keV^{-1} kg^{-1} y^{-1}, among the lowest in this type of experiment. No evidence for neutrinoless double beta decay is found with the present statistics obtained in about three months with a live time of 72%. The corresponding lower limit for the lifetime of this process is of 5.5×10^{23} years at 90% C.L. The corresponding limit for the effective neutrino mass ranges between 0.37 to 1.9 eV depending on the theoretically calculated nuclear matrix elements used. This constraint is the most restrictive one except those obtained with Ge diodes, and is comparable to them.

1. Introduction

Strong interest has been recently revived in neutrinoless double beta decay (DBD) by the discovery of neutrino oscillations in solar [1,2], atmospheric [3], and reactor [4] experiments. This discovery indicates a non-zero value for the difference between two neutrino mass eigenvalues. It becomes therefore imperative to search for a finite value for the effective electron neutrino mass [5–7]. In astrophysics, the recent results of the full sky microwave maps by WMAP together with the 2dF galaxy redshift survey [8] constrain to less than ~ 0.7 eV the sum of the masses of neutrinos of the three flavors. Direct experiments on single beta decay presently constrain the absolute value of this mass to less than 2.2 eV, while a bound of ~ 0.2 eV is expected in the KATRIN experiment [9]. A more restrictive limit for the effective mass of Majorana neutrinos can undoubtly come from neutrinoless double beta decay (DBD). In its two negatron channel DBD consists of the direct emission of two electrons from a nucleus (A, Z) decaying to the corresponding isobar $(A, Z + 2)$. This process can be searched for when the single beta 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. The process of two neutrino DBD is accompanied by the emission of two electron anti-neutrinos and therefore conserves lepton number. It is allowed by the standard model of electroweak interactions, and it has been found in ten nuclei [10–13]. On the contrary conservation of the lepton number is violated in the majoron decay, where the massless Goldstone boson accompanies the emission of the two electrons, and in the so called *neutrinoless* DBD, where only the two electrons are emit-

ted. In this case these two particles would share the total transition energy and a peak would appear in the sum energy spectrum of the two electrons. In addition the available phase space is much larger with respect to the two neutrino one, rendering neutrinoless DBD a very powerful way to search for lepton number non-conservation. The expected value for the effective neutrino mass, $\langle m_\nu \rangle$, or its upper limit is proportional to the square root of the rate, which makes searches for neutrinoless DBD quite difficult. On the other hand this rate is proportional to the square of the nuclear matrix element, whose evaluation is at least presently, quite uncertain. Since the uncertainty in the value of the nuclear matrix element reflects itself directly in that of $\langle m_\nu \rangle$, searches for neutrinoless DBD should be carried out on several candidate nuclei. There is another reason for this statement; should a peak appear at the expected region of neutrinoless DBD, one cannot exclude a priori that it could be due to a line from a *so far unknown* radioactive contamination. Only the evidence for peaks at the different energy expected for a different DBD candidate nucleus would definitely prove the existence of neutrinoless DBD. No evidence was claimed so far for the neutrinoless channel in any nucleus, with the exception of an alleged evidence for neutrinoless DBD of ^{76}Ge reported by a subset of the Heidelberg–Moscow Collaboration [14,15], but confronted by other authors [5,16,17], and even by a different subset of the same collaboration [18].

DBD can be searched for, indirectly, in radiochemical [19] or geochemical experiments [20–24], based on the search for the $(A, Z + 2)$ product nuclei. These experiments are very sensitive, but 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.

Direct experiments are based on two different approaches. In the source $\neq$ detector ones thin sheets of a double beta active material are inserted in a suitable detector. In the source $=$ detector or "calorimetric" experiments [25] the detector itself is made of a material containing the double beta active nucleus.

* Corresponding author. Piazza della Scienza 3, I-20126 Milano, Italy.

E-mail address: ettore.fiorini@mib.infn.it (E. Fiorini).

[1] CEE fellow in the Network on Cryogenic Detectors, under contract FMRXCT980167, presently at the Laboratorio De Fisica Nuclear y Altas Energias, University of Zaragoza, Spain.

[2] CEE fellow in the Network on Cryodetectors, under Contract HPRN-CT-2002-00322.

The use of cryogenic detectors to search for DBD was suggested in 1984 [26]. These bolometers are made [27–29] with diamagnetic and dielectric crystals, and therefore at low temperature their heat capacity 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 the form of heat generates a measurable temperature increase of the absorber. Cryogenic detectors 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. The isotope ^{130}Te is an excellent candidate to search for DBD due to its high transition energy (2528.8 ± 1.3 keV) [30], and large isotopic abundance (33.8%) [31] which allows a sensitive experiment to be performed with natural tellurium. In addition, the expected signal at 2528.8 keV happens to be in an energy region between the peak and the Compton edge of the ^{208}Tl γ-rays at 2615 keV, which generally dominates the γ background in this high energy region. Of the various compounds of this element, TeO_2 appears to be the most promising one due to good mechanical and thermal properties.

A series of experiments with various arrays of 340 gram crystals of natural TeO_2 have been carried out in the Laboratori Nazionali del Gran Sasso. The results of an experiment carried out with an array of 16 crystals of natural Te and four enriched crystals of which two in ^{128}Te and two in ^{130}Te, with a total mass of ~ 6.8 kg has been recently published [32]. We report here the first operation and the preliminary results on neutrinoless DBD obtained with the new set-up, CUORICINO, with a total mass of ~ 40 kg of TeO_2.

2. Experimental details

The CUORICINO array consists of a tower with 13 planes containing 62 crystals of TeO_2 operating in Hall A of the Gran Sasso Underground Laboratory [33] in the same dilution refrigerator previously used in our experiment with 20 crystals [32].

As shown in Fig. 1, the structure is as follows: the upper 10 planes and the lowest one consist of 4 natural crystals of $5 \times 5 \times 5$ cm^3, while the 11th and 12th planes have nine, $3 \times 3 \times 6$ cm^3 crystals. In the $3 \times 3 \times 6$ cm^3 planes the central crystal is fully surrounded by the nearest neighbors.

The small size crystals are also made with natural tellurium except for four. Two of them are enriched in ^{128}Te and two in ^{130}Te, with isotopic abundance of 82.3 and 75%, respectively. All crystals were grown with pre-tested low radioactivity material by the Shanghai Institute of Ceramics and shipped to Italy by sea in order to minimize the activation due to cosmic rays. They have then been lapped with specially selected low contamination abrasives to reduce the radioactive contamination on surface, introduced by the original production process in China. All these operations and the final mounting of the tower were carried out in a nitrogen atmosphere glove box in a clean room. The mechanical structure of the array was made exclusively with OFHC Copper and Teflon, also previously tested for absence of measurable radioactive contaminations.

Thermal pulses are recorded by means of Neutron Transmutation Doped (NTD) Ge thermistors thermally coupled to each crystal and specifically prepared to present similar thermal performance. The gain of the bolometer is calibrated and stabilized by means of a resistor of 50–100 kΩ, attached to each absorber and acting as a heater [35]. The tower is mechanically decoupled from the cryostat in order to avoid vibrations from the overall facility to reduce noise in the detectors. It is therefore connected through a 25 mm copper bar to a steel spring fixed to the 50 mK plate of the refrigerator. It is therefore connected through a 25 cm copper bar to a steel spring fixed to the 50 mK plate of the same dilution refrigerator previously used in the experiment with the 20 detector array [32]. 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 ± 4 Bq/kg in ^{210}Pb. The electrolytic copper of the refrigerator thermal shields provides an additional shield of 2 cm minimum thickness. An external 10 cm layer of borated polyethylene has been installed to reduce the background due to environmental neutrons. In order to shield against the intrinsic radioactive contamination of the dilution unit materials (e.g., from silver and stainless steel) an internal layer of 10 cm Roman lead
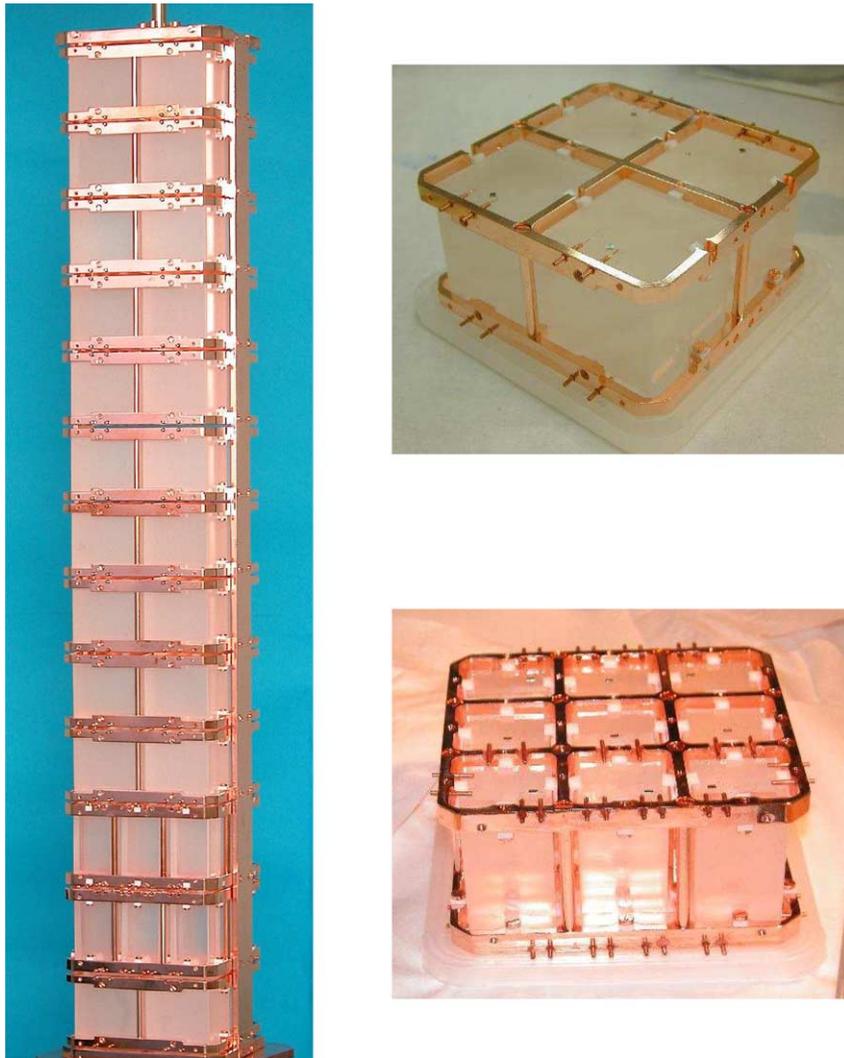
Fig. 1. The tower of CUORICINO and the four and nine crystal modules.

(^{210}Pb activity < 4 mBq/kg [34]) was framed inside the cryostat immediately above the tower of the array. The lateral activity due mainly to the thermal shields of the dilution refrigerator is reduced by a lateral internal shield of Roman lead of 1.2 cm minimum thickness. We should point out that to use the same cryostat with the much larger CUORICINO array, the inner thermal shields had to be changed. As a consequence the lateral layer of Roman lead had to be substantially reduced with respect to the configuration of the previous set-up with 20 crystals. The corresponding worsening of the γ-ray background suppression was al-

most counterbalanced by the better quality of the new cryostat thermal shields. In fact the rate of the 2615 line from ^{208}Tl has not substantially changed. We can therefore extrapolate that no additional contribution due to ^{232}Th contaminations of the cryostat elements is expected in the neutrinoless DBD region. The refrigerator is surrounded by a Plexiglas anti-radon box flushed with clean N_2 from a liquid nitrogen evaporator, and by a Faraday cage to eliminate electromagnetic interference.

The front-end electronics of all $3 \times 3 \times 6$ cm^3 detectors and of 20 of the 44 detectors of $5 \times 5 \times 5$ cm^3 are

located at room temperature. They consists of a differential voltage sensitive preamplifier followed by a second stage and an anti-aliasing filter [35–37]. The differential configuration has been adopted to minimize signal cross talk and microphonic noise coming from the connecting wires. Precautions have been taken to suppress any possible effect coming from room temperature drift [35] and main power supply instability [38]. A pair of load resistors serves to bias each bolometer in a symmetric way [39]. All the necessary settings for the front-end and the biasing system are programmed remotely via computer, to allow the optimization of the overall dynamic performance separately for each detector [36]. The so-called *cold electronics* has been applied to 24 of the $5 \times 5 \times 5$ cm^3 detectors. In this case the preamplifier is located near the detector in a box kept at ~ 100 K to reduce the noise due to microphonics, which is particularly dangerous in the low-energy region of the spectrum, relevant for searches for interactions of WIMPS.

The array was cooled down to temperatures around 8 mK with a temperature spread of ~ 1 mK among the different detectors. A routine calibration was performed using two wires of thoriated tungsten inserted inside the external lead shield in immediate contact with the OVC of the dilution refrigerator. This calibration, which normally lasts one-two days is performed at the beginning and end of each run, which usually lasts two weeks. In all the runs considered in the present Letter the average difference between the starting and ending calibrations was less than the experimental error in the peaks position evaluation (fraction of keV). All runs not satisfying this requirement were discarded. An indirect check of the detector response stability and reproducibility during the whole measurement period was obtained also from the analysis of the background sum spectrum. In fact the positions of the environmental radioactivity γ lines are in agreement with the corresponding ones observed in the calibration, without any sizeable worsening of the energy resolution.

3. CUORICINO performance

CUORICINO was cooled down at the beginning of 2003. Unfortunately during this operation electrical connections to 12 of the 44 detectors of $5 \times 5 \times 5$ cm^3

and to one of the crystals of $3 \times 3 \times 6$ cm^3 were lost. This was mainly due to the disconnection of a few of the thermalizers which allow the transition in various steps of the electric signals from the detectors to room temperature. The technical problem responsible for this disconnection has been identified to be located in the thermalization stages and new thermalizers have been fabricated and tested at low temperatures. Since, however, the performance of the remaining detectors was very good, and their total mass was ~ 30 kg, we decided to postpone the warming up of the array and the entire rewiring for a few months while collecting data.

The performance of the electrically connected detectors was found to be quite good: the average FWHM resolution during the calibration runs was of ~ 7 keV and ~ 9 keV, in the region of neutrinoless DBD for the $5 \times 5 \times 5$ cm^3 and the $3 \times 3 \times 6$ cm^3 crystals, respectively. The improved resolution of the new large size crystals with respect to that of the smaller ones is due to their better quality and thermal coupling. The sum calibration spectra of the large and small size crystals are shown in Fig. 2.

Double beta decay measurements started on April 2003 and were interrupted after three months due to the disconnection of the cooling water supply of the Laboratory as consequence of the environmental problems associated with the Laboratory itself. During this period CUORICINO operated with a duty factor of 72%, which is considered very good for a large cryogenic experiment. After the interruption, and a second short run, an independent cooling system has been recently implemented and CUORICINO is starting running again.

4. Results

The results reported here refer to the first run totalling an effective exposure of ~ 2.9 kg y^{-1} and ~ 0.26 kg y^{-1} for the large and small crystals, respectively. The corresponding spectra in Fig. 3, show the γ-ray line due to ^{40}K, and those due to the ^{238}U and ^{232}Th chains. Also visible are the lines of ^{121}Te, ^{121m}Te, ^{123m}Te, ^{125m}Te and ^{127m}Te due to Te activation and those of ^{57}Co ^{58}Co, ^{60}Co, and ^{54}Mn most likely due to activation of the copper frame.
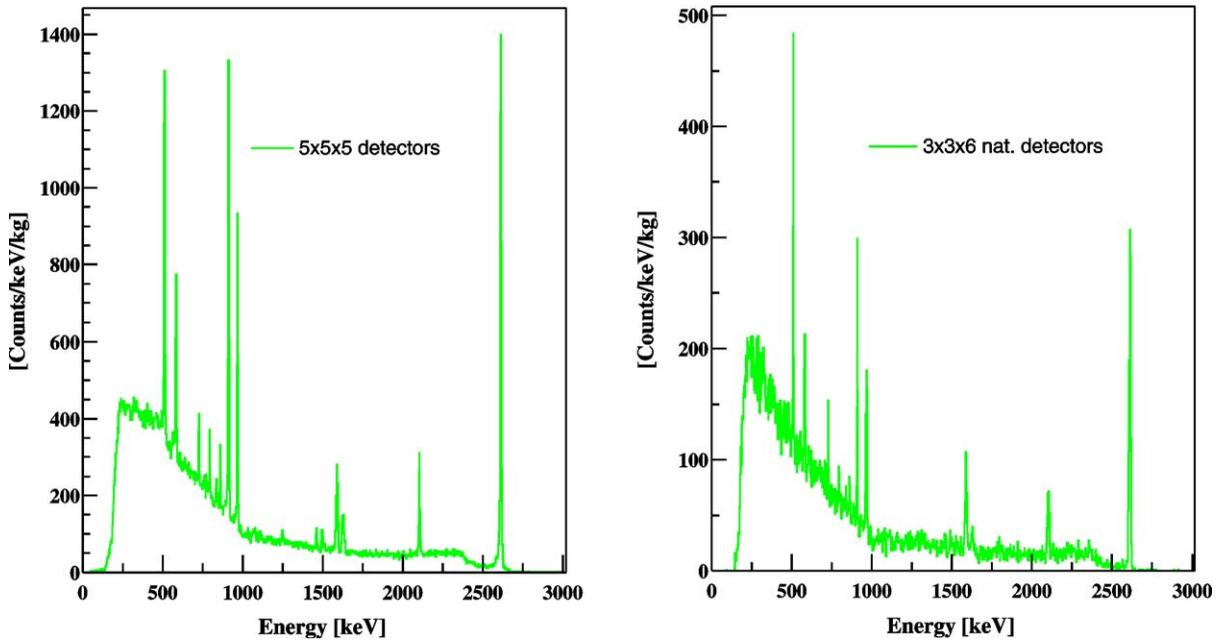
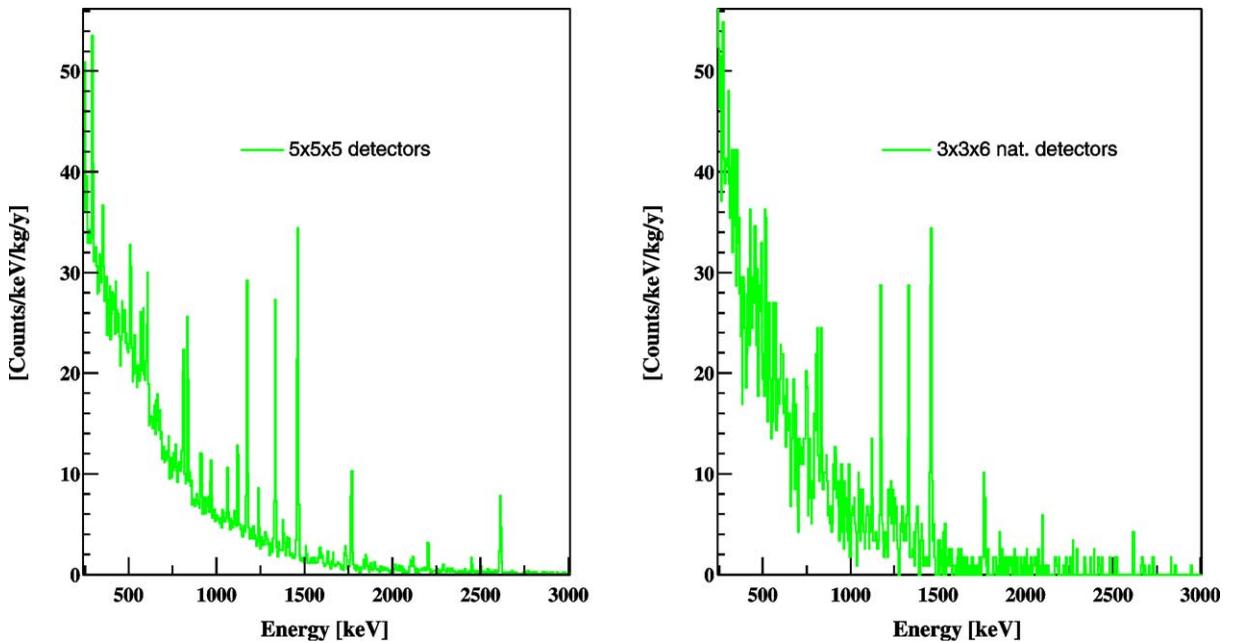Fig. 2. Sum calibration spectra of the $5 \times 5 \times 5$ cm^3 and $3 \times 3 \times 6$ cm^3 crystals.

Fig. 3. Sum *background* spectra of the $5 \times 5 \times 5$ cm^3 and $3 \times 3 \times 6$ cm^3 crystals.

The background counting rates in the region of neutrinoless DBD are 0.20 ± 0.03 and 0.2 ± 0.1 for the $5 \times 5 \times 5$ cm^3 and $3 \times 3 \times 6$ cm^3 natural crystals, respectively. These values are among the best ever obtained in this energy region and similar to those reached in the experiments with Ge diodes [10–13].
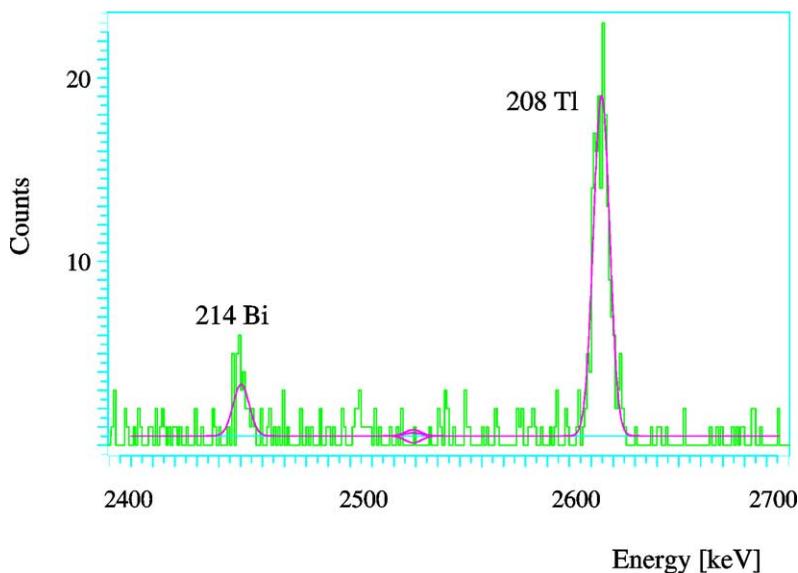
Fig. 4. Sum of the spectra of the $5 \times 5 \times 5$ cm^3 and $3 \times 3 \times 6$ cm^3 crystals in the region of neutrinoless double beta decay.

We would like to point out that the enriched crystals were introduced in the CUORICINO setup to investigate the two neutrino DBD. Even if the present statistics is still inadequate to that aim, it indicates a considerable improvement in the background in low-energy region with respect to what found in our previous experiment [32]. This first run of CUORICINO was optimized to investigate the high-energy region relevant for neutrinoless DBD. We found, however, that even in the low-energy region, which could be relevant for WIMPs searches, the background was reduced by about a factor of two with respect with the previous experiment [32]. This item will be further investigate in the future runs of CUORICINO. The sum *background* spectrum of the $5 \times 5 \times 5$ cm^3 and $3 \times 3 \times 6$ cm^3 crystals is shown in Fig. 4. No peak appears in the region of neutrinoless DBD of ^{130}Te. A maximum likelihood procedure used to establish the maximum number of $\beta\beta$ (0ν) events compatible to the measured background [40,41] implies an upper limit of 5.5×10^{23} years for neutrinoless DBD of ^{130}Te at 90% C.L. [40–43]. Similar results are obtained using the unified approach proposed by G.J. Feldman and R.D. Cousins [42,43].

The limits that can be extracted from our result on the effective neutrino mass are reported in Table 1 for the various theoretical calculations, apart from

Table 1
Lower limits on $\langle m_\nu \rangle$ according to different evaluation methods (QRPA: Quasi Random Phase Approximation and OEM: Operator Expansion Method)

	Authors/Ref.	Method	$\langle m_\nu \rangle$ (eV)
QRPA	Staudt et al., 1992 [46]	pairing (Paris)	0.37–0.4
		pairing (Bonn)	0.4–0.44
	Pantis et al., 1996 [47]	no p–n pairing	1.2
		p–n pairing	1.9
	Vogel, 1986 [48]		1.1
	Civitarese, 1987 [49]		0.97
	Tomoda, 1991 [50]		0.97
	Barbero et al., 1999 [51]		0.78
	Simkovich, 1999 [52]	pn-RQRPA	1.6
	Suhonen et al., 1992 [53]		1.5
	Muto et al., 1989 [54]		0.93
	Stoica et al., 2001 [55]	large basis	1.4
		short basis	1.3
	Faessler et al., 1998 [44]		1.3
	Engel et al., 1989 [56]	seniority	0.66
	Aunola et al., 1998 [57]	WS	0.91
		AWS	0.97
OEM	Hirsh et al., 1995 [58]		1.2

those based on the shell model which have not been successful for heavy nuclei [44]. We have also not considered the recent paper by Rodin et al. [45], whose calculations for neutrinoless DBD are based on the experimental values for the corresponding two

neutrino channel. In fact there is not yet an universally accepeted value for the decay of ^{130}Te. The half-life they used, 2.7×10^{21} years, due to Bernatowicz et al. [22], is the highest among the geochemical ones [20, 21,23,24], while a recent indication [32] yields a value of the order or below 10^{21} years. A definite answer should come soon from the NEMO III experiment [59] and also by an extended analysis of our results on two neutrino DBD of ^{130}Te from CUORICINO.

Taking into account theoretical uncertainties we obtain from our data constraints in the ranges (0.37–1.9) eV for the value of effective Majorana mass of the electron neutrino. Our limit on $\langle m_\nu \rangle$ appears to be the most restrictive one among those obtained with direct methods after those from ^{76}Ge.

5. Conclusions

No evidence is found in this first run of CUORICINO (lasting only three months) for neutrinoless DBD of ^{130}Te with a 90% C.L. lower limit of 5.5×10^{23} years. This corresponds to an upper limit for the effective mass of the electron neutrino, $\langle m_\nu \rangle$, ranging from 0.37 to 1.9 eV, on the basis of various evaluations of the nuclear matrix elements. Our range of limits already partly covers the corresponding span of the experiments on neutrinoless DBD of ^{76}Ge.

CUORICINO is presently running and we soon hope to reach a more stringent constraint on the effective mass of the electron neutrino with some improvements of the set-up, including the repair of the disconnected channels. CUORICINO is a real experiment, but also a first step towards CUORE (for Cryogenic Underground Observatory for Rare Events).

CUORE will consist of 1000 crystals of TeO$_2$ with a total mass of almost 800 kg. Taking advantage of the large isotopic abundance of ^{130}Te it could reach the sensitivity on the effective neutrino mass of a few tens of meV, indicated by the recent results of Solar, Atmospheric and Reactor neutrino experiments [60,61].

Acknowledgements

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