New Limit on the Neutrinoless $\beta\beta$ Decay of ^{130}Te

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We report the present results of CUORICINO, a search for neutrinoless double-beta ($0\nu\beta\beta$) decay of ^{130}Te. The detector is an array of 62 TeO_2 bolometers with a total active mass of 40.7 kg. The array is cooled by a dilution refrigerator shielded from environmental radioactivity and energetic neutrons, operated at $\sim$8 mK in the Gran Sasso Underground Laboratory. No evidence for ($0\nu\beta\beta$) decay was found and a new lower limit, $T_{1/2}^{0\nu} \geq 1.8 \times 10^{24}$ yr (90% C.L.) is set, corresponding to $\langle m_\nu \rangle \leq 0.2$ to 1.1 eV, depending on the theoretical nuclear matrix elements used in the analysis.

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Great interest was stimulated recently in neutrinoless double-beta decay ($0\nu\beta\beta$ decay) by the observation of neutrino oscillations [1–6], proving that the differences of the squares of neutrino mass eigenvalues is different from zero. This indicates that the mass m_ν of at least one neutrino is finite, but does not allow the determination of its absolute value.

The sum of the masses of the neutrinos of the three flavors is constrained to values from 0.7 to 1.7 eV from the Wilkinson microwave anisotropy probe full sky microwave map together with the survey of the 2dF galaxy redshift [7–11]. A claim for a nonzero value of 0.64 eV has also been proposed [12]. These values are more constraining than upper limits of 2.2 eV for m_ν obtained so far in experiments on single-beta decay, but they are strongly model dependent and therefore less robust than laboratory measurements. The sensitivity of $\sim$0.2 eV is expected in the KATRIN experiment [13]. If neutrinos are Majorana particles more stringent constraints, or a positive value for the effective neutrino mass, can be obtained by $0\nu\beta\beta$ decay. In this lepton number violating process, a nucleus (A, Z) decays into $(A, Z + 2)$ with the emission of two electrons and no neutrinos, resulting in a peak in the sum energy spectrum of the two electrons. The decay rate of this process is theoretically proportional to the square of the effective neutrino mass $|\langle m_\nu \rangle|$, which can be expressed in terms of the elements of the neutrino mixing matrix as follows:

$$|\langle m_\nu \rangle \equiv ||U_{e1}^L|^2 m_1 + |U_{e2}^L|^2 m_2 e^{i\phi_2} + |U_{e3}^L|^2 m_3 e^{i\phi_3}|, \quad (1)$$

where $e^{i\phi_2}$ and $e^{i\phi_3}$ are the Majorana CP phases (± 1 for CP conservation), $m_{1,2,3}$ are the Majorana neutrino mass eigenvalues. The coefficients U_{ej}^L of the Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix were determined by a recent global analysis of all oscillation experiments [14–23], and yield on average

$$|\langle m_\nu \rangle| = |(0.70 \pm 0.030)m_1 + (0.30 \pm 0.030)m_2 e^{i\phi_2} + (<0.05)m_3 e^{i\phi_3}|. \quad (2)$$

Neutrino oscillation experiments only yield the differences of the neutrino mass eigenvalues squared, and imply two possible hierarchies: the normal $m_1 \approx m_2 \ll m_3$, and the inverted hierarchy $m_1 \ll m_2 \approx m_3$. With this convention, U_{e3}^L and U_{e1}^L are exchanged in the inverted hierarchy case. The mass parameter measured in solar oscillation experiments, δ_{solar}, is $m_2^2 - m_1^2$ in the normal hierarchy case and $m_3^2 - m_2^2$ in the inverted case. That measured in atmospheric neutrino experiments, δ_{atm}, is then approximately $m_3^2 - m_1^2$ in both cases. If we neglect U_{e3}^L, and also note that experimentally, $\delta_{\mathrm{solar}} \ll \delta_{\mathrm{atm}}$, a useful approximate expression for $|\langle m_\nu \rangle|$ results in the case of the in-

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verted hierarchy

$$|\langle m_\nu \rangle| = \sqrt{m_1^2 + \delta_{\rm atm}}|0.70e^{i\phi_2} + 0.30e^{i\phi_3}|. \qquad (3)$$

If one uses the current experimental value, $\delta_{\rm atm} = 2 \times 10^{-3}$ eV^2, Eq. (3) implies that $|\langle m_\nu \rangle|$ could have a minimum value as large as 0.055 eV, which implies a minimum sensitivity acceptable for next generation $0\nu\beta\beta$ decay experiments.

The rate for this process is proportional to the square of the nuclear matrix elements whose calculations are still quite uncertain. As a consequence it is imperative to search for $0\nu\beta\beta$ decay in different nuclei. This is because a peak attributed to this process could in principle be mimicked by a radioactive background line. Only the discovery of peaks at the energies expected for $0\nu\beta\beta$ decay, in two or more candidate nuclei, would definitely prove its existence. No positive evidence has been reported so far [24–27], with the exception of the claimed discovery of the decay of ^{76}Ge reported by a subset of the Heidelberg-Moscow collaboration [28]. This claim has drawn criticism [14,29,30], while other members of the Heidleberg-Moscow Collaboration refute the claim [31]. However, a new analysis favoring the previous claim has recently been published [32,33].

Here we report new results on the $0\nu\beta\beta$ decay of ^{130}Te from the CUORICINO experiment operating in the Gran Sasso Underground Laboratory at a depth of about 3500 mwe [34]. This search, like the previous ones performed in the same laboratory, is carried out with the cryogenic technique first suggested 20 years ago for searches for rare events [35]. The cryogenic detectors of the type used in CUORICINO [36,37] are diamagnetic and dielectric crystals kept at low temperature, where their heat capacity is proportional to the cube of the temperature. As a consequence, their heat capacity can become so small that even the tiny energy delivered to this ''absorber'' by particle interactions, can be detected and measured by a suitable thermal sensor. Since the only requirement for these absorbers is that they have appropriate thermal and mechanical properties, cryogenic detectors offer a wide choice of candidate nuclei. ^{130}Te is an excellent candidate due to its high transition energy (2528.8 ± 1.3 keV) [38], and especially to the large natural isotopic abundance (33.8%) [39] making the need for enrichment less important. A preliminary report on the first part of this experiment was published earlier [40].

CUORICINO (Fig. 1) is a tower of 13 planes containing 62 crystals of TeO_2; 44 of them are cubes of 5 cm on a side while, the dimensions of the others are $3 \times 3 \times 6$ cm^3. All crystals are made with natural paratellurite, apart from two $3 \times 3 \times 6$ cm^3 crystals, enriched in ^{128}Te and two others of the same size enriched in ^{130}Te, with isotopic abundances of 82.3% and 75%, respectively. The total mass of TeO_2 in CUORICINO is 40.7 kg (11 kg of ^{130}Te). More details on the preparation of the crystals

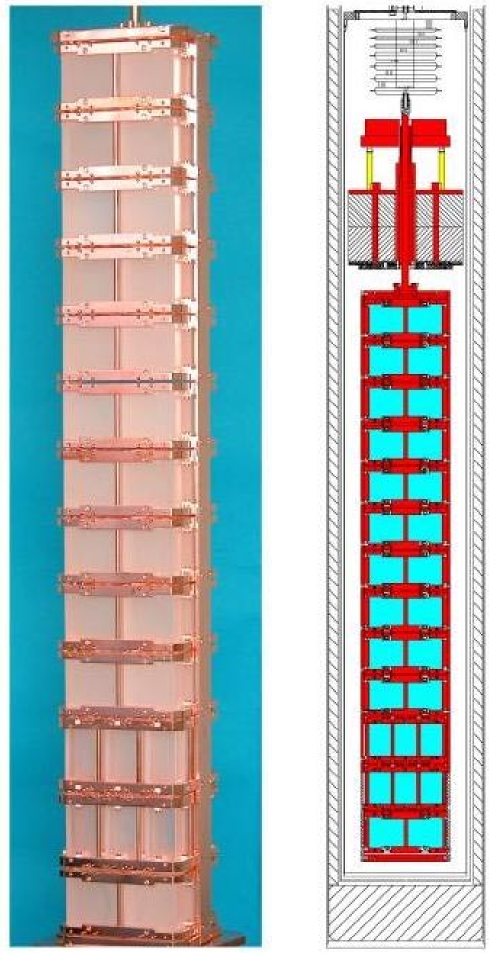

FIG. 1 (color online). Scheme of CUORICINO.

and on the mechanical structure of the array is reported elsewhere [40–44].

In order to shield against the radioactive contaminants in the materials of the refrigerator, a 10 cm layer of ancient lead from Roman ships, with ^{210}Pb activity of <4 mBq kg^{-1} [41], is inserted inside the cryostat immediately above the CUORICINO tower. A 1.2 cm lateral layer of the same lead surrounds the array to reduce the background from the thermal shields. The cryostat is externally shielded by two layers of lead of 10 cm minimal thickness. While the outer is made by common lead, the inner one has a ^{210}Pb activity of (16 ± 4) Bq kg^{-1}. There is an additional layer of 2 cm of electrolytic copper of the thermal shields. The background from environmental neutrons is reduced by a layer of borated polyethylene of 10 cm minimum thickness. The refrigerator operates inside a Plexiglass antiradon box flushed with clean N_2, and inside a Faraday cage to reduce electromagnetic interference.

Thermal pulses are recorded by neutron transmutation doped Ge thermistors thermally coupled to each crystal. Baseline stabilization is performed with voltage pulses across heater resistors attached to each bolometer. The voltage pulses are generated by high stability pulse generators, designed and developed for this purpose [42]. These stabilizing signals are tagged by the acquisition system. The detector baseline is stabilized with a dedicated circuit with a precision of better than about 0.5 keV/day on the average [43] between the successive refilling of liquid helium of the main reservoir. The energy resolution for the complete data set was computed from the FWHM of the 2615 keV background γ-ray line from the thorium chain. The results are 8 keV for the 44 $5 \times 5 \times 5$ cm^3 crystals, and 12 keV for the 18 $3 \times 3 \times 3$ cm^3 crystals. Therefore no counts from the nearby peak at 2505 keV, from the sum of the ^{60}Co γ rays, can reach the region of $0\nu\beta\beta$ decay at 2529 keV.

The front-end electronics for all the $3 \times 3 \times 6$ cm^3 and for 20 of the $5 \times 5 \times 5$ cm^3 detectors are maintained at room temperature. In the so-called *cold electronics*, applied to the remaining 24 crystals, the preamplifier is located in a box at $\sim$100 K near the detector to reduce the noise due to microphonics [44]. The data acquisition system, and readout electronics are discussed in [40,44].

CUORICINO is operated at $\sim$8 mK with a spread of $\sim$1 mK. A routine energy calibration is performed before and after each subrun, of about two weeks, with two thoriated tungsten wires inserted in contact with the refrigerator. All data, with an average difference between the initial and final calibration larger than experimental error in the evaluation of the peak position, were discarded. Only 0.19 kg yr of data were rejected, representing about 6% of the total data set of 3.09 kg yr (^{130}Te).

During the first cooldown, 12 of the $5 \times 5 \times 5$ cm^3 and one of the $3 \times 3 \times 6$ cm^3 crystals were lost, due to the disconnections at the level of the thermalization stages which allow the transmission of the signals from the detectors to room temperature [40]. The problem has now been solved and the detector was cooled down with loss of contacts of only two bolometers. The data presented here is that from this first run plus new data obtained in about 3 months with a second run, where the contacts of only two bolometers were lost.

The 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 the $0\nu\beta\beta$ decay energy is shown in Fig. 2. One can clearly see the peaks at 2447 and 2615 keV from the decays of ^{214}Bi and ^{208}Tl, plus a small peak at 2505 keV due to the sum of the two γ lines of ^{60}Co. The background at the energy of $0\nu\beta\beta$ decay is 0.18 ± 0.01 counts/ kg^{-1} keV^{-1} yr^{-1}.

The total exposure was 3.09 kg yr (^{130}Te), equivalent to N(^{130}Te)$t = 1.43 \times 10^{25}$ yr. Multiplying by ln2, and the efficiency, 0.85, and dividing by 4.8, the 90% C.L. upper bound on the number of candidate events in a peak centered at 2529 keV, leads to $T_{1/2}^{0\nu}(^{130}\mathrm{Te}) \geq 1.8 \times 10^{24}$ yr. The background and the bound, 4.8, were extracted using a maximum likelihood analysis [45,46], fitting the peaks and

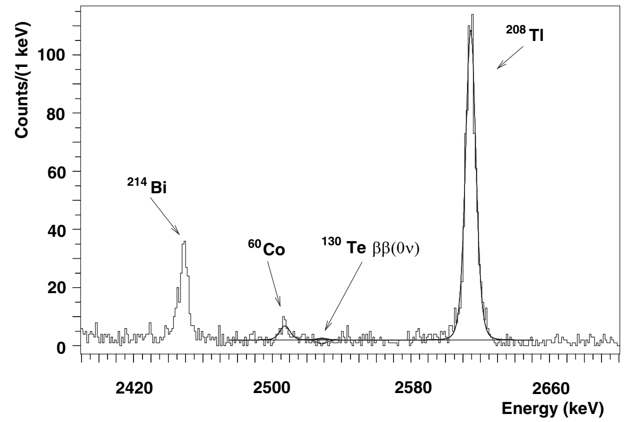

FIG. 2. Anticoincidence spectrum of the sum of the two electron energies in the region of neutrinoless $0\nu\beta\beta$ decay.

continuum in the spectrum in the region of the spectrum from 2475 to 2665 keV. Including or excluding the peak at 2615 keV changes the results by $\sim$10%.

The bounds on $\langle m_\nu \rangle$, obtained using various quasiparticle random phase approximations (QRPA), are given in Table I. We assumed that the model space is too large for reliable shell model calculations. We have not included the recent results of Rodin *et al.*, [60], based on novel use of the $2\nu\beta\beta$ decay rate to extract the particle-particle interaction parameter g_{pp}, because of issues raised by Suhonen [61], and because there is no direct measurement of $2\nu\beta\beta$ decay of ^{130}Te.

The range of bounds in Table I, 0.2–1.1 eV, partially covers the range of values 0.1–0.9 eV corresponding to the evidence claimed by Klapdor-Kleingrothaus *et al.* [33].

TABLE I. Effective Majorana mass of the electron neutrino, $\langle m_\nu \rangle$, corresponding to $T_{1/2}^{0\nu}(^{130}\mathrm{Te}) = 1.8 \times 10^{24}$ yr derived from various nuclear (QRPA) models.

Authors/Reference	Method	$\langle m_\nu \rangle$ (eV)
[47] Staudt *et al.*, 1992	pairing (Paris)	0.21–0.22
	pairing (Bonn)	0.22–0.24
[48] Pantis *et al.*, 1996	no *p*-*n* pairing	0.66
	p-*n* pairing	1.05
[49] Vogel, 1986		0.61
[50] Civitarese, 1987		0.54
[51] Tomoda, 1991		0.54
[52] Barbero *et al.*, 1999		0.43
[53] Simkovich, 1999	*pn*-RQRPA	0.88
[54] Suhonen *et al.*, 1992		0.83
[55] Muto *et al.*, 1989		0.51
[56] Stoica *et al.*, 2001	large basis	0.77
	short basis	0.72
[57] Faessler *et al.*, 1998		0.72
[58] Engel *et al.*, 1989	seniority	0.37
[59] Aunola *et al.*, 1998	Woods Saxon (WS)	0.50
	Adjusted WS	0.54

CUORICINO is a first step towards the realization of CUORE (Cryogenic Underground Observatory for Rare Events). It would be an array made by 19 towers, each similar to CUORICINO, with 988 cubic crystals of TeO_2, 5 cm on a side, and a total active mass of about 741 kg. The expected sensitivity for CUORE is $2.93 \times 10^{26}\sqrt{t}$ yr, where t is the live running time of the experiment in years. CUORE has been approved by the Gran Sasso Scientific Committee and by the Instituto Nazionale di Fisica Nucleare (INFN).

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