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The CUORICINO ^{130}Te $\beta\beta$-Decay Experiment and a New Limit on $T_{1/2}^{0\nu}(\beta\beta)$*

C. Arnaboldi, D. R. Artusa[1)], F. T. Avignone III[1)**], M. Balata[2)], I. Bandac[1)], M. Barucci[3)], J. Beeman[4)], C. Brofferio, C. Bucci[2)], S. Capelli, L. Carbone, S. Cebrian[5)], O. Cremonesi, R. J. Creswick[1)], A. de Waard[6)], H. A. Farach[1)], A. Fascilla[7)], E. Fiorini, G. Frossati[6)], A. Giuliani[7)], P. Gorla[5)], E. E. Haller[4),8)], I. G. Irastorza[5)], R. J. McDonald[4)], A. Morales[5)], E. B. Norman[4)], A. Nucciotti, E. Olivieri[3)], V. Palmieri[9)], E. Pasca[3)], M. Pavan, M. Pedretti[7)], G. Pessina, S. Pirro, E. Previtali, C. Pobes[5)], M. Pyle[2),4)], L. Risegari[3)], C. Rosenfeld[1)], M. Sisti, A. R. Smith[4)], L. Torres, and G. Ventura[3)]
(The CUORICINO Collaboration)

Dipartimento di Fisica dell'Università di Milano, Bicocca e Sezione di Milano dell'INFN, Italy

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Abstract—The CUORICINO $\beta\beta$-decay detector is an array of 62 TeO_2 bolometers; 44 are $5 \times 5 \times 5$-cm crystals made with natural tellurium (33.8% ^{130}Te). There are 18, $3 \times 3 \times 6$-cm crystals, 14 of which are made of natural tellurium, 2 are isotopically enriched to 75% in ^{130}Te, and 2 are enriched to 82.3% in ^{128}Te. The total mass of ^{130}Te is ~ 11 kg. The background rate is 0.23 ± 0.04 counts/keV/kg/yr in the energy interval 2480 to 2600 keV. During the cooling process, some of the wires became disconnected and only 32 of the large and 16 of the smaller crystals could be read out. The data presented here come from 29 of the $5 \times 5 \times 5$-cm crystals containing 6.2 kg of ^{130}Te. The new limit on the half-life is $T_{1/2}^{0\nu} \geq 5 \times 10^{23}$ yr, corresponding to an effective Majorana mass of the electron neutrino $\langle m_\nu \rangle$ between 0.42 and 2.05 eV, depending on the nuclear model used to analyze the data. © *2004 MAIK "Nauka/Interperiodica"*.

1. THEORETICAL MOTIVATION OF NEUTRINOLESS DOUBLE-BETA EXPERIMENTS

Neutrinoless double-beta decay is an old subject [1]. What is new is the fact that positive observation of neutrino oscillations in atmospheric neutrinos [2] and in solar neutrinos [3] gives new motivation for more sensitive searches. In fact, recently published constraints on the mixing angles of the neutrino-mixing matrix [2, 3] make a strong case that if neutrinos are Majorana particles, there are many scenarios in which next generation $\beta\beta$-decay experiments should be able to observe the phenomenon and measure the effective Majorana mass of the electron neutrino, $|\langle m_\nu \rangle|$, which would provide a measure of the neutrino mass scale, m. One fact is clear: neutrino oscillation experiments can only provide data on the mass differences of the neutrino mass eigenstates. The absolute scale can only be obtained from direct mass measurements, ^{3}H end point measurements for example [4], or in the case of Majorana neutrinos, more sensitively by neutrinoless $\beta\beta$ decay. The time for large, next generation $\beta\beta$-decay experiments has arrived, because if the mass scale is below ~ 0.25 eV, $\beta\beta$ decay may be the only hope for measuring it.

The most sensitive experiments carried out so far have probed the decay $^{76}\mathrm{Ge} \to \mathrm{Se} + 2\beta^-$ with specially built Ge detectors fabricated from germanium

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1)Department of Physics and Astronomy, University of South Carolina, Columbia, USA.
2)Laboratori Nazionali del Gran Sasso dell'INFN, Assergi (L'Aquila), Italy.
3)Dipartimento di Fisica dell'Università di Firenze e Sezione di Firenze dell'INFN, Italy.
4)Lawrence Berkeley National Laboratory, California, USA.
5)Laboratorio de Física Nuclear y Altas Energías, Universidad de Zaragoza, Spain.
6)Kamerling Onnes Laboratory, Leiden University, The Netherlands.
7)Dipartimento di Scienze Chimiche, Fisiche e Matematiche dell'Università dell'Insubria, e Sezione di Milano dell'INFN, Como, Italy.
8)Department of Material Science and Engineering, University of California, Berkeley, USA.
9)Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy.
**e-mail: gudkov@asg.sc.edu

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isotopically enriched from 7.8 to 86% in ^{76}Ge. The Heidelberg–Moscow Experiment [5] and the International Germanium Experiment (IGEX) [6] have placed lower bounds on the half-life for this process of 1.9×10^{25} yr (90% C.L.) and 1.6×10^{25} yr (90% C.L.), respectively.

2. NEUTRINOLESS DOUBLE-BETA DECAY

The decay rate for the process involving the exchange of a Majorana neutrino can be expressed as follows:

$$(\tau_{1/2}^{0\nu})^{-1} = G^{0\nu}(E_0, Z)|\langle m_\nu \rangle|^2 |M_{\rm F}^{0\nu} - (g_A/g_V)^2 M_{\rm GT}^{0\nu}|^2. \tag{1}$$

Here, $G^{0\nu}$ is the two-body phase-space factor including coupling constants, $M_{\rm F}^{0\nu}$ and $M_{\rm GT}^{0\nu}$ are the Fermi and Gamow–Teller nuclear matrix elements, respectively, and g_A and g_V are the axial-vector and vector relative weak coupling constants, respectively. The quantity $|\langle m_\nu \rangle|$ is the effective Majorana electron neutrino mass given by:

$$|\langle m_\nu \rangle| = ||U_{e1}^L|^2 m_1 + |U_{e2}^L|^2 m_2 e^{i\phi_2} + |U_{e3}^L|^2 m_3 e^{i\phi_3}|, \tag{2}$$

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 mass eigenvalues, and $U_{e1,2,3}^L$ are elements of the first row of the unitary transformation between neutrino mass and flavor eigenstates for left-handed neutrinos.

In this notation, $U_{e1}^L = \cos\theta_3 \cos\theta_2 \equiv c_3 c_2$, $U_{e2}^L = \sin\theta_3 \cos\theta_2 \equiv s_3 c_2$, and $U_{e3}^L = \sin\theta_2 \equiv s_2$. In other notation $\theta_2 = \theta_{13}$ which is very small and $s_2^2 \leq 0.026$. Here we use the notation of Chau and Keung [7]. In the notation of the Particle Data Book: $c_3 = \cos\theta_{12}$, $c_2 = \cos\theta_{13}$, and $c_1 = \cos\theta_{23}$, etc.

The neutrino oscillation data yield values and errors for the mixing angles θ_1, θ_2, and θ_3, and two neutrino mass patterns or hierarchies [8–10]. We use the convention of [9], normal hierarchy $m_1 \leq m_2 \ll m_3$ and $m_1 \ll m_2 \leq m_3$ in the inverted hierarchy. In general, in the normal hierarchy case, for example, we have:

$$|\langle m_\nu \rangle| = |c_3^2 c_2^2 m_1 + s_3^2 c_2^2 e^{i\phi_2} m_2 + s_2^2 e^{i\phi_3} m_3|. \tag{3}$$

With the values and errors (3σ) from the literature, this becomes:

$$|\langle m_\nu \rangle| = |(0.75^{+0.07}_{-0.12}) m_1 + (0.25^{+0.12}_{-0.07}) e^{i\phi_2} m_2 + (< 0.026) e^{i\phi_3} m_3|. \tag{4}$$

3. NEUTRINO MASS PATTERNS

The measured values of δm_s^2 (solar) and $\delta m_{\rm AT}^2$ (atmospheric) motivate the pattern of masses in the two possible hierarchy schemes mentioned above. From the mass hierarchy relations we can write $m_2 = \sqrt{\delta m_s^2 + m_1^2}$ and $m_3 = \sqrt{\delta m_{\rm AT}^2 + m_1^2}$ in the case of normal hierarchy and $m_2 = \sqrt{\delta m_{\rm AT}^2 - \delta m_s^2 + m_1^2}$ and $m_3 = \sqrt{\delta m_{\rm AT}^2 + m_1^2}$ in the case of inverted hierarchy. From these, we can write Eq. (3), for normal and inverted hierarchy, respectively, in terms of the mixing angles, δm_s^2, $\delta m_{\rm AT}^2$, and CP phases as follows [9, 10]:

$$|\langle m_\nu \rangle| = |c_2^2 c_3^2 m_1 + c_2^2 s_3^2 e^{i\phi_2} \sqrt{\delta m_s^2 + m_1^2} + s_2^2 e^{i\phi_3} \sqrt{\delta m_{\rm AT}^2 + m_1^2}|, \tag{5}$$

$$|\langle m_\nu \rangle| = |s_2^2 m_1 + c_2^2 c_3^2 e^{i\phi_2} \sqrt{\delta m_{\rm AT}^2 - \delta m_s^2 + m_1^2} + c_2^2 s_2^2 e^{i\phi_3} \sqrt{\delta m_{\rm AT}^2 + m_1^2}|. \tag{6}$$

Numerical values are given in Table 1. These values (Table 1) set the requirements for the sensitivities that a $0\nu\beta\beta$ experiment must reach.

Below we discuss the CUORICINO/CUORE technique designed to reach the levels of interest and give the first results from CUORICINO.

4. DETECTOR PRINCIPLES

CUORICINO is an array of 44 TeO_2 crystals, $5 \times 5 \times 5$ cm with an average mass of 790 g, and 18 TeO_2 crystals, $3 \times 3 \times 6$ cm with an average mass of 330 g. Two of the small crystals are isotopically enriched to 75% in ^{130}Te, and two are isotopically enriched to 82.3% in ^{128}Te. Unfortunately, during the cooling down process, some of the signal wires disconnected, so that only 32 of the large crystals and 16 of the small ones could be read. This gives a total of 30.56 kg of TeO_2 that are functioning effectively as bolometers that can be read out. The data analyzed were from 29 of the 32 readable $5 \times 5 \times 5$-cm crystals.

Tellurium oxide is a dielectric and diamagnetic material. According to the Debye law, the heat capacity of a single crystal at low temperature is proportional to the ratio $(T/T_\Theta)^3$, where T_Θ is the Debye temperature of TeO_2. Thus, providing that the temperature is extremely low, a small energy release in the crystal results in a measurable temperature rise.

Table 1. Central values of the numerical predictions of $|\langle m_\nu \rangle|$ for both hierarchies and CP phase relations (all mass values are given in eV)

Normal hierarchy				Inverted hierarchy			
$e^{i\phi_2} = -1$		$e^{i\phi_2} = +1$		$e^{i\phi_2} = -e^{i\phi_3}$		$e^{i\phi_2} = +e^{i\phi_3}$	
m_1	$\|\langle m_\nu \rangle\|$	m_1	$\|\langle m_\nu \rangle\|$	m_1	$\|\langle m_\nu \rangle\|$	m_1	$\|\langle m_\nu \rangle\|$
0.02	9.30	0.02	20.4	0.00	26.0	0.00	55.9
0.04	19.1	0.04	40.3	0.02	27.7	0.02	59.0
0.06	28.9	0.06	60.0	0.05	35.3	0.05	74.5
0.08	38.7	0.08	80.0	0.075	44.7	0.075	90.3
0.10	48.5	0.10	100	0.10	55.2	0.10	114
0.20	96.5	0.20	200	0.20	100	0.20	208
0.40	194	0.40	400	0.40	194.5	0.40	404

This temperature change can be recorded with thermal sensors and, in particular, using Neutron Transmutation Doped (NTD) germanium thermistors. These devices were developed and produced at the Lawrence Berkeley National Laboratory (LBNL) and UC Berkeley Department of Material Science [11]. They have been made uniquely uniform in their response and sensitivity by neutron exposure control with neutron absorbing foils accompanying the germanium in the reactor [12].

The TeO_2 crystals are produced by the Shanghai Quinhua Material Company (SQM) in Shanghai, China, which will produce the 750-g TeO_2 crystals for CUORE [13]. A single CUORICINO detector consists of a $5 \times 5 \times 5$-cm single crystal of TeO_2 that acts both as a detector and a source. The detectors are supported by a copper frame. The frame and the dilution refrigerator mixing chamber to which it is thermally connected form the heat sink, while the PTFE (Polytetrafluoroethylene or TEFLON®) standoffs provide the thermal impedance, which delays the cooling of the bolometers. The bolometers operate at ~ 10 mK.

A single Large CUORICINO bolometer is a $5 \times 5 \times 5$-cm single crystal of TeO_2 grown with ultrapure TeO_2 powders and lapped on the surfaces. Crystals of TeO_2 have a tetragonal structure and are grown along the [001] axis. The two axes normal to this axis are crystallographically equivalent, a fact relevant to their use in the search for solar axions [14]. The surface hardness is not the same for all the sides, which complicates the crystal polishing. We have shown that repeated thermal cycling does not damage the crystals, as in the case of crystals of other tellurium compounds or of metallic tellurium. The Debye temperature of the TeO_2 crystals was specially measured for the CUORE project as 232 K [15]. This differs from the previous value of 272 K in the literature [16]. The specific heat of the TeO_2 crystals was found to follow the Debye law down to 60 mK; the heat capacity of the 790-g crystals is 2.3×10^{-9} J/K extrapolated down to 10 mK.

The NTD thermistors are attached by epoxy to the crystal and are operated in the Variable Range Hopping (VRH) conduction regime with a Coulomb gap [17–19]. The most important parameter characterizing the thermal response is the sensitivity A defined as follows:

$$A = \left| \frac{d \log R}{d \log T} \right| = \gamma \left(\frac{T_0}{T} \right)^{\gamma}. \quad (7)$$

For the CUORICINO NTD thermistors this parameter ranges between 7 and 10. The resistance behavior follows the relation

$$R = R_0 \exp(T_0/T)^{\gamma}; \quad \gamma = 1/2. \quad (8)$$

The VRH regime occurs in Ge when it is "doped" close to the metal-to-insulator transition, which is $\sim 6 \times 10^{16}$ atom/cm^3. This is achieved by thermal neutron radiation in a nuclear reactor, resulting in (n, γ) reactions on ^{70,72,73,74,76}Ge, followed by β^- decay or electron capture. To the first order, this produces (for a natural Ge sample) the following stable isotopes: ^{71}Ga (18%), ^{73}Ge (8.3%), ^{74}Ge (36%), ^{75}As (12%), and ^{77}Se (0.8%). Beta minus and electron capture lead to n and p dopants, respectively. The sensitivity parameter A depends on the neutron irradiation dose. Therefore, each thermistor must be characterized at operating temperatures, similar to that described for Si thermistors by Alessandrello *et al.* [20].

It is very important to optimize the neutron irradiation exposure and to make the exposures as uniform as possible. It is not possible to evaluate the

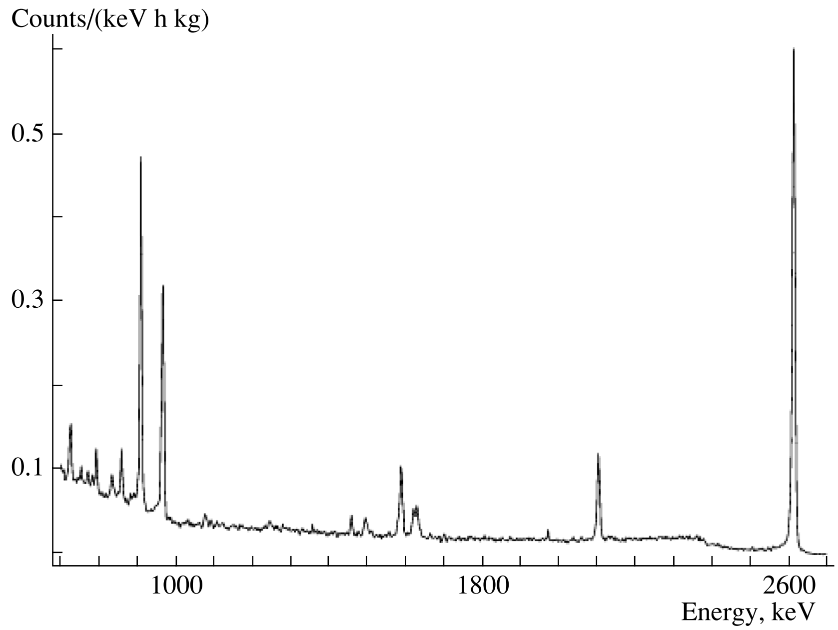

Fig. 1. The sum of calibration spectra of the $5 \times 5 \times 5$-cm detectors taken with a ^{232}Th source.

thermistor material directly from the reactor because of the long half-life of ^{71}Ge (11.43 d). A delay of several months is required to see if the Ge needs more exposure. To circumvent this difficulty, the Ge material is accompanied by foils of metal with long-lived (n,γ) radioactive daughter nuclides. Accordingly, the neutron exposure of the Ge can be determined accurately, and uniformity of exposure is achieved. This technique was developed recently by the LBNL group of the CUORE Collaboration [12]. Following the neutron exposure and radioactive decay period, the NTD germanium is first heat treated to repair the crystal structure then cut into $3 \times 3 \times 1$ mm strips. The thermistors are glued to the TeO_2 crystal by nine spots of Araldit rapid Ciba Geigy epoxy of 0.4 to 0.7 mm in diameter deposited on the crystal surface by an array of pins. The height of each spot is 50 μm. This procedure was found to be reliable and reproducible in the MI–DBD experiment [21]. The heat conductance of the epoxy spots was measured in Milan and the phenomenological relation was found to be $\sim 2.6 \times 10^{-4}\,(T[\mathrm{K}])^3$ watts per degree kelvin per spot.

The stabilization of the response of the bolometers is crucial because of the unavoidable small variations in the temperature of the heat bath that change the detector gain (and consequently deteriorate the energy resolution). This problem is successfully addressed by means of a Joule heater glued onto each crystal. The heater is used to inject a uniform energy into the crystal, the thermal gain is monitored and corrected off-line. The heaters are Si chips with a heavily doped meander structure with a constant resistance between 50 to 100 kΩ. They are manufactured by the ITC–IRST company in Trento, Italy.

The electrical connections are made with two 50-μm diameter gold wires that are ball bonded to metallized surfaces on the thermistor. The gold wires are crimped into a copper tube, which is inserted into a larger one forming the electrical connection, thus avoiding low-temperature solder which contains ^{210}Pb and traces of other radioisotopes. The larger copper tube, $\sim$ 14 mm long and 2 mm in diameter, is glued to the copper frame that supports the crystals. This tube is thermally connected to the frame but electrically insulated.

5. EXPERIMENTAL RESULTS

The detector was run for approximately 865 h with a total of 11 kg of ^{130}Te; however, the data discussed here are from 22.9 kg of TeO_2 collected only with 29 large crystals ($\sim$6.2 kg of ^{130}Te). Accounting for the phase-space factors, computed nuclear matrix elements, and relative isotope abundances, this is as effective in sensitivity to the effective Majorana mass of the electron neutrino as approximately 25 kg of Ge isotopically enriched to 86% ^{76}Ge. A calibration spectrum using a source of ^{232}Th is shown in Fig. 1. It is a sum spectrum of all of the readable $5 \times 5 \times 5$-cm TeO_2 crystals. The mean resolution is FWHM $\simeq$ 7 at 2615 keV. The calibrations are made with a tungsten wire containing ^{232}Th outside the refrigerator but inside the 20 cm thick lead shield.

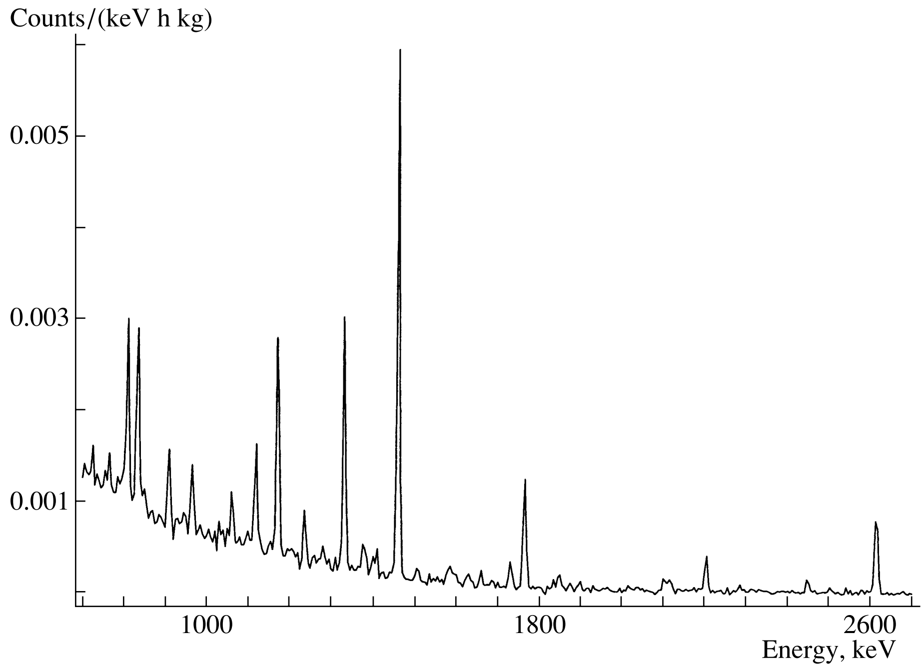

Fig. 2. The sum of background spectra of 29 $5 \times 5 \times 5$-cm detectors taken over the course of the experiment.

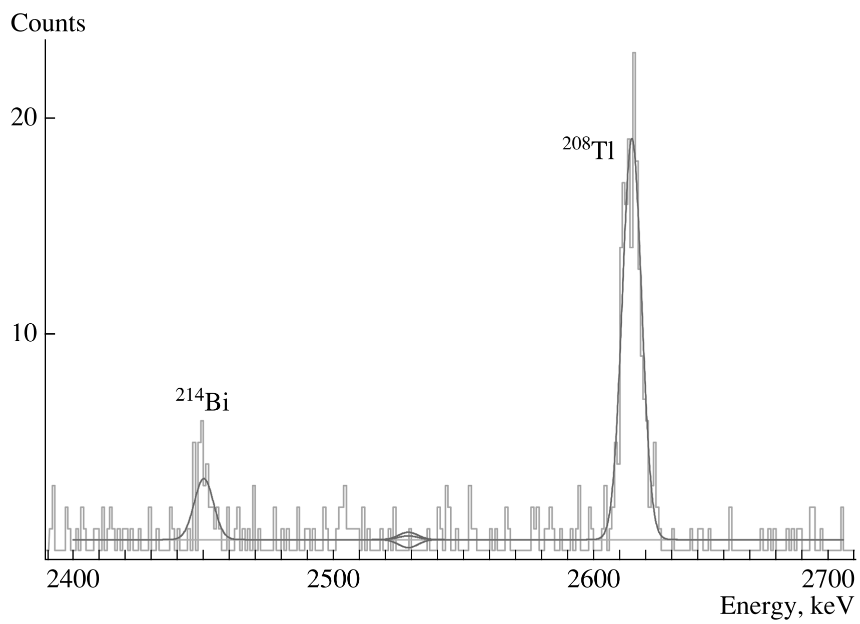

Fig. 3. The portion of the sum spectrum of Fig. 2 in the region of neutrinoless $\beta\beta$ decay.

The spectrum from 19.800 kg × h of live time of 29 of the operating $5 \times 5 \times 5$-cm bolometers is shown in Figs. 2, 3. The data were analyzed as discussed below and the effective Majorana mass of the electron neutrino $\langle m_\nu \rangle$ was evaluated using 15 different nuclear matrix elements [21–36].

The data were analyzed in the usual way using the following expression:

$$T_{1/2}^{0\nu} \geq \frac{(\ln 2) N t \epsilon}{n(\max)}, \tag{9}$$

where $N = 2.93 \times 10^{25}$ is the total number of ^{130}Te atoms, t is the live counting time in years, ϵ is the detection efficiency, and $n(\max)$ is the maximum number of events in the spectrum that can be attributed to $0\nu\beta\beta$ decay (to a confidence level of 90%). The counting efficiency ϵ was evaluated by a Monte Carlo computation to be 86.3%. The value of $n(\max) = 3.48$ was obtained from the spectrum by a maximum likelihood analysis. Accordingly,

$$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) > 5.0 \times 10^{23}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.}). \qquad (10)$$

The effective Majorana neutrino mass $|\langle m_\nu\rangle|$ is directly derivable from the measured half-life of the decay as follows:

$$|\langle m_\nu\rangle| = m_e \frac{1}{\sqrt{F_N T^{0\nu}_{1/2}}}\ [\mathrm{eV}], \qquad (11)$$

where $F_N = G^{0\nu}|M^{0\nu}_{\mathrm{F}} - (g_A/g_V)^2 M^{0\nu}_{\mathrm{GT}}|^2$. This quantity is derived from nuclear structure calculations and is model dependent as seen from Table 2. The values of F_N from 15 different calculations are given in Table 2. The result of these analyses is that the upper bound on $|\langle m_\nu\rangle|$ is between 0.42 and 2.05 eV. It can be shown that with the current background rate of 0.20 ± 0.03 counts/keV/kg/yr and the current average energy resolution, the full CUORICINO array can achieve $T^{0\nu}_{1/2} > 3.5 \times 10^{24}$ yr (68% C.L.), corresponding to an upper bound on $|\langle m_\nu\rangle|$ between 0.27 and 0.78 eV. This is similar to the current ^{76}Ge experimental bounds. The values of $F_N(^{130}\mathrm{Te})$ reported in the literature are from very disparate models; however, we have chosen to analyze our data using only the more conventional QRPA models presented in Table 2. The result ranges from $\langle m_\nu\rangle < 0.70{-}2.06$ eV, depending on the model, to (90% C.L.). If we use the recent theoretical treatment of [36] this half-life corresponds to $\langle m_\nu\rangle = 2.3 \pm 0.2$ eV.

Table 2. Values of the nuclear structure factor $F_N = G^{0\nu}|M^{0\nu}_{\mathrm{F}} - (g_A/g_v)^2 M^{0\nu}_{\mathrm{GT}}|^2$ and the respective values of $|\langle m_\nu\rangle|$ for $T^{0\nu}_{1/2} = 5 \times 10^{23}$ yr (with $n{-}p$ pairing)*

$F_N(^{130}\mathrm{Te})$, yr^{-1}	$\lvert\langle m_\nu\rangle\rvert$, eV	Ref.	$F_N(^{130}\mathrm{Te})$, yr^{-1}	$\lvert\langle m_\nu\rangle\rvert$, eV	Ref.
1.88×10^{-13}	1.67	[22]	4.84×10^{-13}	1.04	[29]
2.37×10^{-13}	1.48	[23]	5.00×10^{-13}	1.02	[30]
2.43×10^{-13}	1.47	[24]	5.06×10^{-13}	1.02	[31]
2.78×10^{-13}	1.37	[25]	5.33×10^{-13}	1.00	[32]
3.04×10^{-13}	1.31	[26]	5.61×10^{-13}	0.97	[33]
1.24×10^{-13}	2.05*	[26]	7.83×10^{-13}	0.82	[34]
3.96×10^{-13}	1.15	[27]	2.90×10^{-12}	0.42	[35]
4.35×10^{-13}	1.10	[28]			

6. PROSPECTS FOR CUORE

CUORE is a proposed assembly of 25 towers like CUORICINO but with 40 750-g TeO_2 bolometers each. The total mass, 750 kg of TeO_2, would contain 203 kg of ^{130}Te. What do the present results from CUORICINO imply for the success of CUORE?

The early CUORICINO data have already shown us what and where the sources of background are and how to reduce them. We conclude that a reduction in the background by a factor of 20 is quite straightforward. This would allow the full CUORE array to achieve a 5-yr sensitivity of 1.0×10^{26} yr, corresponding to an effective mass between 0.02 and 0.06 eV. Another order of magnitude reduction will present a real challenge, but it is possible. In that case, a 5-yr sensitivity in the effective mass would be as small as 0.015 eV. In the least optimistic scenario above and in the case of inverted hierarchy of the neutrino mass spectrum a null experiment would rule out the Majorana character of neutrinos, whereas a definite observation would confirm that neutrinos are Majorana particles. Only double-beta experiments can achieve this goal. In the more optimistic case, the experiment would be sensitive to a Majorana mass of the lightest neutrino mass eigenvalue of between 0.015 and 0.04 eV in the case of normal hierarchy and again nearly zero in the case of inverted hierarchy. The technology is now proven, and, with adequate funding, there are no show-stoppers. The proposal is to build the CUORE experiment in the Laboratori Nazionale del Gran Sasso (LNGS) in Assergi, Italy, the present site of CUORICINO. CUORE is by far the most cost effective next generation $\beta\beta$-decay experiment proposed that can reach the desired levels of sensitivity.

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