CUORICINO AND CUORE: AN UPDATE

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ABSTRACT

After a short introduction on Double Beta Decay (DBD), an update of CUORICINO results is given, together with a discussion on the background and the consequent discovery potential. The CUORE project is then presented and the ultimate sensitivity to Majorana neutrino effective mass is discussed, on the basis of the experience and information gathered with the realization and running of the past Mi-DBD and present CUORICINO experiments.

1. Introduction

Neutrinoless Double Beta Decay (0ν-DBD) is a rare nuclear process¹ where 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. Unlike the standard electroweak process, where two antineutrinos are emitted together with the two electrons, in this decay the neutrino does not appear explicitly but it is hidden

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as a virtual particle connecting the two electroweak vertices. This is possible if and only if at least one neutrino eigenstate has a non-zero mass and if neutrino is a self-conjugated particle. The observation and measurement of the $0\nu$-DBD lifetime can therefore prove the “Majorana” character of the neutrino, while obtaining informations on the neutrino mass hierarchy and absolute scale, and on the Majorana CP phases.

The connection between the lifetime $\tau$ of $0\nu$-DBD and neutrino mass is expressed quantitatively (assuming the dominance of the so-called mass mechanism) by the formula

$$\frac{1}{\tau} = G_{0\nu}|M^{0\nu}|^2 \left(\frac{\langle m_\nu \rangle}{m_e}\right)^2,$$

where $G_{0\nu}$ is a phase-space factor growing steeply with the Q-value of the decay, $|M^{0\nu}|$ (the “nuclear matrix element”, NME) includes all the nuclear physics of the process, and $\langle m_\nu \rangle$ is a linear combination of the three neutrino mass eigenvalues $m_i$:

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

where $e^{i\phi_2}$ and $e^{i\phi_3}$ are the Majorana CP phases ($\pm 1$ for CP conservation) and $U_{e\nu}$ are the neutrino mixing matrix elements related to the electron neutrino, and represent therefore the bridge between flavour oscillations, that have been recently unambiguously observed, and $0\nu$-DBD.

From the oscillation experiments, that give information on the neutrino mixing matrix elements $U_{\alpha j}$, and on the mass eigenvalue differences squared $\delta m_{ij}^2 = m_i^2 - m_j^2$, it is possible to predict the range of values for the effective mass of the Majorana electron neutrino $\langle m_\nu \rangle$ that should be expected in the different mass hierarchy scenarios\(^2\). The present data show that this range could be within the reach of next generation double-beta decay experiments, at least if the inverted or quasi-degenerate hierarchies should be proven to be the correct ones, thus increasing the expectations for a discovery in this field in the near future.

The bolometric approach for the experimental study of $0\nu$-DBD consists in developing a device which is at the same time source and detector of the phenomenon, with high energy resolution and low radioactive background. In bolometers, the energy deposited in the detector by a nuclear event is measured by recording the temperature increase of the detector as a whole. In order to make this temperature increase appreciable and to reduce all the intrinsic noise sources, the detector must be operated at very low temperatures, of the order of 10 mK for large masses. Since the only characteristic required to the detector material is to have a low specific heat at low temperatures, many compounds can be taken into consideration. The choice has fallen on natural TeO\(_2\) (tellurite) that has reasonable mechanical and thermal properties together with a very large (27% in mass) content of the $\beta\beta$-candidate \(^{130}\)Te, which makes the request of enrichment not compulsory, as it is for other interesting isotopes. Moreover, the transition energy ($Q_{\beta\beta} = 2528.8 \pm 1.3$ keV) is located in the valley between the peak and the Compton edge of the 2615 keV $\gamma$-line of \(^{208}\)Tl, at
the very end of the $\gamma$ natural background spectrum, so that it is easier to look for
the signal. In comparison to other $\beta\beta$-emitters, phase-space and NME look quite
favourable.

The typical bolometer developed to search for $0\nu$-DBD consists of a single tellu-
rite crystal, with a mass of the order of hundreds of grams, thermally coupled to a
Neutron Transmutation Doped Ge thermistor which operates as a temperature-to-
voltage transducer. The crystal is weakly coupled through PTFE clamps to a heat
sink kept at $\sim 5$ mK by a high power dilution refrigerator. Technical details can be
found elsewhere.$^{3}$

2. CUORICINO

Proposed as an intermediate step to demonstrate the feasibility of CUORE (Cryo-
genic Underground Observatory for Rare Events, see Sec.3), CUORICINO consists of
an array of 44 5-cm-side cubic crystals and of 18 $3 \times 3 \times 6$ cm$^3$ crystals of TeO$_2$, with
a total active mass of about 40.7 kg ($5.2 \times 10^{25}$ nuclei of $^{130}$Te). The larger crystals
are arranged in 11 four-detector independent modules, while the 18 smaller crystals
are arranged in two $3 \times 3$ matrices. The four-detector modules and the two matrices
are stacked one onto the other, so as to form a tower-like structure (Fig. 1a) that fills
almost completely the whole experimental volume of the refrigerator that was used
previously for the Mi-DBD$^4$ experiment and that now houses CUORICINO. All the
crystals are made of natural tellurite except for 4 of the small size ones. Two of these
are isotopically enriched to 75% in $^{130}$Te while the remaining two are isotopically
enriched to 82.3% in $^{128}$Te.

Figure 1: (a) CUORICINO tower and (b) background spectrum in the DBD region

In the past years our efforts have been addressed both to the improvement of
the detector performances (microphonic noise reduction, \(^5\) conversion gain stability, \(^6\) energy resolution, \(^7\) etc.) by operating four-detector test modules in a smaller refrigerator, and to the reduction of the background. As far as the latter point is concerned, special care was taken in polishing crystal surfaces with ultra-pure powders and in etching chemically the copper and PTFE elements surrounding the detectors. There is in fact a strong indication \(^8\) that the main source of the background is due to energy-degraded alpha particles originated in surface contamination (in bolometers there is no dead layer, therefore they are fully sensitive to surface contaminants).

**CUORICINO** was cooled at the beginning of year 2003. Unfortunately, due to an annoying problem with the soldering of the read-out wires at low temperature, only **75%** of the detectors were really connected to the outside world. However, the total **130**Te mass of the working detectors was 7.7 kg; large enough to allow to start a meaningful experiment. In few months 3.75 kg·y of TeO\(_2\) data were collected and analyzed, \(^9\) before warming up in fall 2003 to repair the readout. All but 2 channels were successfully recovered and **CUORICINO** is now running again, collecting data from 83 moles of **130**Te and with a duty-cycle around **70%**. Data here reported refer to a total statistics of 10.85 kg·y of TeO\(_2\), while an almost equal amount of data has been collected already and waits to be processed. Fig. 1 reports the sum energy spectrum of the big crystals in the region of the 0\(^{\nu}\)-DBD, obtained operating all the detectors in anticoincidence. 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 \(\gamma\)-lines of \(^{60}\)Co. These lines are not visible in the spectra of the single detectors: they become evident only by summing them all up, and are a good check of the calibration and stability of the detectors during all the data taking. The energy resolution was computed from the FWHM of the 2615 keV background gamma ray line in the sum spectrum and is found to be 7.8 keV for the big crystals and 12.3 keV for the small ones (we sum them separately). The background in the region of interest is **0.18 \pm 0.01** counts/keV·kg·y. No peak appears at the **130**Te double beta decay transition energy (2528.8 keV), and therefore an upper limit on the half-life of **1.8 \times 10^{24}** years at **90%** C.L. can be extracted using a Maximum Likelihood method. The corresponding upper bound on the Majorana effective mass ranges from 0.2 to 1.1 eV, depending on the nuclear model used to interpret the data. Using the Staudt et al. \(^10\) evaluation, which is often chosen to make comparisons among different isotopes, the limit is 0.53 eV. This constraint is already comparable to those obtained with Ge diodes, and could become 0.26 eV in 3 years of data taking.

Last year, after a first claim in 2001, a report of evidence of the 0\(^{\nu}\)-DBD of **76**Ge with a half-life of **1.19 \times 10^{25}** y at **4.2\(\sigma\)** C.L. was published. \(^11\) This result has been heavily debated and the scientific community is now waiting for an experimental confirmation or confutation of the claim to end the discussion. With **CUORICINO** a \(2\sigma\) level signal, or even more depending on the NME calculations, could be seen in 3 y. For instance the half-life that should be expected according to \(^10\) for the 0\(^{\nu}\)-DBD
of $^{130}$Te, assuming the claimed best value for the half-life of $^{76}$Ge, can be calculated to be $2.5 \times 10^{24}$ y. Then 34 counts in an energy window 13 keV wide (1.5 FWHM) around the Q-value are expected in 3 years (notice that this evaluation does not depend on the Majorana neutrino mass, being based only on lifetime ratios), with a corresponding $1 \sigma$ background fluctuation of 16 counts. A confirmation of the $^{76}$Ge claim is therefore within the reach of the experiment, but a disproof is impossible because of the statistical errors in the Ge claimed half-life and of the uncertainties on NME calculations.

3. CUORE

Our present knowledge on the neutrino properties together with theoretical considerations indicate that $\langle m_\nu \rangle$ should lie in the range between 0.3 eV and 1 meV, \(^2\), depending on the mass hierarchy. This reinforce the importance of designing and building experiments that can explore this mass range, and CUORE is one of them. The real challenge consists in the construction of a large mass (of the order of 1 ton) counting facility with extremely low background. Main goal of the CUORE collaboration is to reach, in the energy region of interest, a background level lower than 0.01 (possibly 0.001) counts/keV·kg·y obtaining hence a sensitivity on the effective Majorana mass of neutrino lower than 50 meV (15 meV, in the more optimistic case).

![Figure 2: (a) CUORE detector and (b) the comparison between CUORICINO background spectrum and Montecarlo simulation of the surface contaminations (see text)](image)

Like CUORICINO, CUORE will be based on an elementary module of 4 crystals. In the final design of the detector, groups of 13 modules are stacked together to form a tower. The CUORE array will consist of 19 of these towers in a cylindrical structure (see Fig. 2a), with a total active mass of 741 kg. Each tower will be very similar to the tower tested in CUORICINO, both from the mechanical and from the thermal
point of view, and substantially independent of the nearby towers. The close packing and the high granularity will help in background identification and rejection. The array will be operated underground at a temperature of 10-15 mK. The experiment has been already approved by the Scientific Committee of Gran Sasso Lab and the special dilution refrigerator that is intended to house the detector has been funded. More details on CUORE design can be found elsewhere.\footnote{12}

As far as background is concerned, CUORICINO shows that a dominant contribution to the background level could come from radioactive surface contaminations of the TeO$_2$ crystals and Cu holder. The improvements obtained in CUORICINO with respect to Mi-DBD experiment\footnote{4} is a consequence of the surface treatment of the TeO$_2$ crystals and of the mounting structure (copper and PTFE). A Monte Carlo code has been developed in order to simulate decay processes occurring in the bulk and on the surfaces of the various parts of the experimental setup, in order to disentangle the sources responsible of measured background by comparing the simulated data with the experimental ones\footnote{8}. The agreement between data above 3 MeV and Monte Carlo simulation of surface contaminations of crystals and Cu frames is excellent (see Fig. 2b), provided you take into account the presence of a tiny bulk contamination of $^{210}$Po and $^{190}$Pt in the crystals. To explain also the gamma region, sources of background far away from the detectors must be taken into account. This should be a minor problem for CUORE: the lead shield designed for CUORE will be optimized in order to practically cancel the background coming from outside. This optimization was not possible in CUORICINO because it had to be housed in a pre-existing cryostat. More details on the background origin and location are expected from the systematic study of CUORICINO background.

Figure 3: (a) $\alpha$ peaks reduction after crystal etching and (b) Surface-sensitive bolometer: different risetimes in the Ge auxiliary bolometer for different origins of the event. In the inset: scatter plot of the TeO$_2$ vs Ge bolometer response

Meanwhile, an intensive activity aiming at the reduction of surface contaminations has been started, with already stimulating results on crystal surface contaminations, that have been reduced of a factor $\sim$5 (see Fig. 3a)\footnote{8}. The possibility to develop
surface sensitive bolometers in order to actively discriminate events originated near the crystals surface is also under study, with encouraging results. The basic idea consists in the realization of active shields in the form of thin, large-area, ultrapure Ge or Si bolometers, by which the TeO$_2$ crystal is surrounded. The Ge or Si auxiliary bolometers are attached at the main crystal, providing almost complete coverage. In this way, a composite bolometer is realized with multiple read-out, capable to distinguish the origin of the event. A degraded alpha coming from outside or from the Ge itself generates a much higher and faster thermal pulse in the shield bolometer than the corresponding pulse generated by the same energy released directly in the main TeO$_2$ crystal. Discrimination is then easily realized through a scatter plot, as can be seen in Fig. 3b.

4. Conclusions

CUORE is designed to reach a sensitivity capable of probing most of the expected range for the effective neutrino mass, at least in the frame of inverted or quasi-degenerate neutrino mass hierarchies$^2)$. The observation and measurement of the neutrinoless double-beta decay half-life could determine the scale of the neutrino mass, which is fixed by the lightest neutrino mass eigenvalue. Of course a large systematics could arise by the difficult computation of NME$^1)$, but the qualitative physics results that would arise from an observation of neutrinoless double-beta decay are so profound that the $0\nu$-DBD search is fundamentally important even if the resulting $\langle m_\nu \rangle$ would be rather uncertain in value. Moreover, by making $0\nu$-DBD measurements in several nuclei the uncertainty arising from the NME could eventually be reduced enough to give the expected quantitative informations on neutrino characteristics.

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6. References

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