Double beta decay: calorimeters

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Abstract.

Calorimeters or, with a more specific definition, low temperature detectors, have been used by now for more than 15 years in Double Beta Decay (DBD) searches, with excellent results: they compete with Ge diodes for the rank of detectors with the highest sensitivity to the effective neutrino mass, which is defined as a linear combination of the neutrino mass eigenvalues. After a brief introduction to the argument, with some notes on DBD and on bolometers, an update on the now closed experiment CUORICINO and on its successor, CUORE, is given. The fundamental role of background is then revealed and commented, introducing in this way the importance of the specific experiment now under construction, CUORE-0, that will precede CUORE to help optimizing the struggle against surface background. The possible future of this technique is then commented, quoting important R&D studies that are going on, for active shielding bolometers and for scintillating bolometers coupled with light detecting bolometers.

1. Introduction

As it has been reported already in many other papers in these Proceedings, one of the fundamental questions yet unsolved on neutrinos properties is their nature and mass. Neutrinoless Double Beta Decay (0ν–DBD) is one of the easiest way to get information concerning the mass hierarchy and absolute scale, provided the neutrino is a Majorana particle. This explains the big interest that has grown recently around the subject and the high number of experiments proposed or under construction worldwide [1].

Experimental search for DBD based on the direct detection of the two emitted electrons can distinguish the 2ν standard channel from the 0ν channel, since the spectrum of the electron sum energy is expected to be a continuum in the former case and a sharp peak at the transition Q-value in the latter. Possible approaches can be divided into two main classes: the Active Source (AS) experiments, in which detector and source coincide, and the Passive Source (PS) experiments, where the detecting elements monitor a properly prepared sample containing the emitting nuclei. Practically all the known techniques in elementary particle detection have been employed by the experimentalists: solid-state detectors, complex tracking systems, scintillators and calorimeters (in the sense of low temperature phonon-mediated detectors). We will refer in this paper only to the last family of devices listed above, since the other techniques are already reported elsewhere in these Proceedings.

1.1. 0ν–DBD: the elements of the game

The connection between the lifetime τ of 0ν–DBD, which is the parameter extracted from the experimental data, and neutrino mass is expressed quantitatively (assuming the dominance of the so-called mass mechanism) by the formula

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

where $G_{0\nu}$ is the 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:

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

where $e^{i\phi_2}$ and $e^{i\phi_3}$ are the Majorana CP phases (± 1 for CP conservation) and U_{ei} are the neutrino mixing matrix elements related to the electron neutrino, and represent therefore the bridge between flavour oscillations, already observed, and 0ν–DBD.

In order to evaluate the sensitivity of a given AS-type experiment (as bolometers are), to the 0ν half-life of the investigated nucleus, the following *factor of merit* can be defined

$$F_{0\nu} = \ln 2 \frac{n\,\eta\,\epsilon\,N_A}{A} \sqrt{\frac{MT}{B\Delta E}} \;\; (68\%\text{C.L.}) \tag{3}$$

corresponding to the maximum half-life detectable against 1 σ background fluctuation. The relevant parameters are n, number of active atoms per source molecule, η, isotopic abundance, ϵ, detector efficiency, N_A, Avogadro number, A, molecular mass of the source, M, detector mass, T, measurement time, ΔE, energy resolution, and B, background per unit mass, time and energy. Note that for zero-background experiments $F_{0\nu}$ scales linearly with T.

The simultaneous use of equations (1) and (3) allows to define the sensitivity to $\langle \mathrm{m}_\nu \rangle$. Once the isotope and the technique are chosen, the only parameters on which experimentalists can really play (B, M and T) are related to the $\langle \mathrm{m}_\nu \rangle$ with a fourth root law, therefore big efforts are required to improve even a little bit. And since time will never improve fast enough, experimentalists know very well that they will have to struggle with bigger and bigger masses and trying to reduce orders of magnitude the background.

1.2. Bolometers as true calorimeters

The bolometric approach for the experimental study of 0ν–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.

In fact there are more than one proposal for DBD search with bolometers. It is, for instance, the preferred technique proposed for a 0ν–DBD experiment on ^{124}Sn by the INO Collaboration (see Appendix E in the INO Project Report, 2006), while the Kiev group and collaborators assert already that to improve really the $CaMoO_4$ experiment to the ton scale they will have to switch to low temperature detectors. As we will see, studies of feasibility of a 0ν–DBD experiment with scintillating bolometers are going on since several years at the Gran Sasso National Laboratories, under the acronym BOLUX.

Anyhow, the best representatives of the use of bolometers for 0ν–DBD are the TeO_2 detectors, developed in Italy since many years [2]. TeO_2 (tellurite) has been chosen as absorber because it 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 ($\mathrm{Q}_{\beta\beta} = 2530.30 \pm 1.99$ keV) is located in the valley between the peak and the Compton edge of the 2615 keV γ-line of ^{208}Tl, at the very end of the γ 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 reasonably favourable. TeO_2 detectors have been used in the Mi-DBD [3] experiment at the end of the '90s, then in the CUORICINO detector [4], that has been taking data until this summer, and will now, in a couple of years, be the base for the CUORE adventure [5]. It is therefore worthwhile to spend some time for an update on these two projects, one just ended and the other on its way towards startup.

2. CUORICINO

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 (5.2×10^{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 3×3 matrices. The four-detector modules and the two matrices are stacked one onto the other, so as to form a tower-like structure that fills almost completely the whole experimental volume of the refrigerator. 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.

The total statistics analysed up to now (corresponding to data collected until August 2007) is 15.53 kg·y of ^{130}Te.

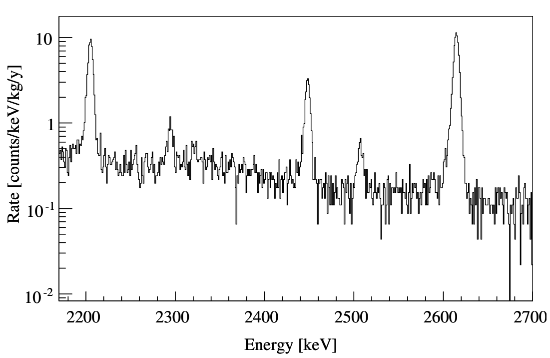

Figure 1. Sum energy anticoincidence spectrum of the big crystals in the region of the 0ν–DBD.

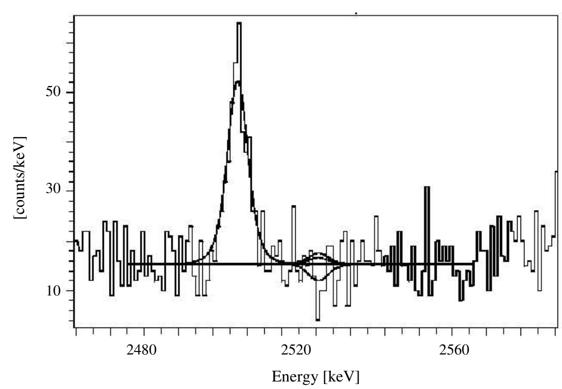

Figure 2. The ML best fit of the expected 0ν–DBD peak (neg.) and those excluded at 68% and 90% CL.

Figure 1 reports the sum energy spectrum of the big crystals in the region of the 0ν–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 γ-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 (they are summed separately). The background in the region of interest is 0.18 ± 0.01 counts/keV·kg·y. No peak appears at the ^{130}Te double beta decay transition energy and therefore an upper limit on the half-life of 3.1×10^{24} years at 90% C.L. can be extracted using a Maximum Likelihood method (see figure 2). The corresponding upper bound on the Majorana effective mass ranges from 0.2

to 0.7 eV, depending on the nuclear model used to interpret the data. Details on the detector and on data collected are reported in [4].

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 [6], depending on the mass hierarchy. This reinforce the importance of designing and building experiments that can explore this mass range, and CUORE [5] 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).

CUORE detector is composed of 19 towers, obtained stacking together 13 floors of 4 crystals $5 \times 5 \times 5$ cm^3 each, with a total active mass of 741 kg ($\sim 10^{27}$ nuclei of ^{130}Te). Each tower will be substantially independent of the nearby towers. The close packing and the high granularity will help in background identification and rejection. It should be assembled in 2010 and start taking data in 2011. While the energy resolution can improve at most a factor 2 with respect to CUORICINO, mass is in fact increased by a factor 20. This makes all together only a factor 2.5 of improvement in the sensitivity on the effective neutrino mass. Therefore a big as possible improvement on background is fundamental to make CUORE really appealing. The Collaboration has therefore invested many efforts on this item.

4. Understanding backgrounds

A common point to all the direct searches on DBD is the struggle against background, which can be originated by cosmic rays (underground operation is mandatory), environmental radioactivity and residual radioactive contamination in the detector and materials surrounding it.

In the 0ν–DBD searches, natural radioactivity is more or less important depeding on the energy at which the peak is expected, making those nuclides for which the Q-value is higher than 2.6 MeV more favourable. As for the background caused by the 2ν decay, which must be taken carefully into account since it is unavoidable and indistinguishable, good energy resolution and high 2ν half-life are preferable. On the other hand, a preliminary check of the materials used for detector construction allows in principle a relevant reduction of most natural/artificial contaminants as well as a reduced exposure to cosmic rays (through underground storage of materials) allows to get rid of the cosmogenic ones. Unfortunately reaching with standard techniques a screening capability on materials at the level of the order of μBq/kg for any contaminant and for any material is not straightforward: in a large fraction of cases conventional techniques are not enough to reach the desired sensitivity. Therefore, often the check is performed with the use of the detector itself as a device to measure its own radioactivity.

In this sense the study of CUORICINO background has been very useful and it has shown that a dominant contribution to the background level could come from radioactive surface contaminations of the TeO_2 crystals and Cu holders. The improvement obtained in CUORICINO with respect to Mi-DBD experiment is a consequence of the surface treatment of the TeO_2 crystals and of the mounting structure (copper and PTFE). To really understand background, an analysis method supported by a Monte Carlo code was developed and the most probable sources contributing to the measured background were identified [7]. The most worrisome background source comes out to be the surface contamination, also because, once material screening has been applied and all parts have been cleaned to remove as much as possible surface radioactivity, then packaging, shipping and storage become very delicate steps to be accomplished before the detector construction, to avoid as much as possible recontamination. The CUORE collaboration is trying to apply a "zero contact" philosophy. This means no exposure to air or Rn contaminated gas and minimized (in space and time) exposure or contact with other materials after cleaning and before assembly. But specific studies to understand the ways in which exposure to Rn-rich air re-contaminates materials are important to help in defining the correct approach. The results obtained by now on the subject are very preliminary, but go in the direction to show that the sticking factor (ratio between the number of Rn atoms that stick on surface and the number of Rn atoms that have reached the surface) is very small (of the order of 10^{-10}), and the diffusion inside the crystals is bigger than in Cu and can reach depths of the order of 1 μm. Both sticking and diffusion effects have been for the moment studied for Rn, and are different for the daughter nuclei. Studies in this sense are still going on. Meanwhile important tests on the best procedure to clean Cu are on their way, and will be finally checked with a first CUORE tower, named CUORE-0, assembled on purpose with 2 groups of differently cleaned Cu frames.

5. CUORE-0: the demonstrator

CUORE-0 is a single CUORE tower, to be installed and operated in the old CUORICINO dilution refrigerator, placed in the hall A of the LNGS. CUORE-0 motivations are manifold. It is a real test of the CUORE assembly chain and procedure (a completely different way with respect to Cuoricino and CUORE-R&D detectors). It will be a high statistics test of crucial components of the estimated CUORE background, being able to measure 0.01 c/(keV kg y) in the 3-4 MeV window with 20 % precision in only one month. This result will give room to possible well-oriented improvements to the CUORE structure before its mounting. Unfortunately, the background in the region of neutrinoless Double Beta Decay will not be better than 0.06 c/(keV kg y), since this is an unavoidable contribution from the ^{232}Th contamination in the superinsulation of the Cuoricino cryostat. Nevertheless, this (factor 3) improvement makes CUORE-0 a competitive DBD experiment. After a few months of CUORE-0 data taking, the combined CUORE-0 / Cuoricino results will lead to a more stringent limit on ^{130}Te half life than what would have been obtained with continuous Cuoricino operation. After that, the CUORE-0 half-life sensitivity will increase by a factor $\sqrt{3}$ faster than what would be obtainable with Cuoricino alone.

6. The (far) future: BOLUX

The use of bolometers in DBD searches is a "'neverending story"': CUORE must not be considered as the ultimate potential of a mature technique that has already given all its best. For instance, since background is the limiting factor in many cases, and particularly in 0ν–DBD, there are studies, with very promising results, on the use of bolometers as active discriminators between surface and volume events [8], to get rid of most of the spurious events that are expected, for instance, in CUORE.

On the other hand, scintillating crystals containing interesting DBD emitters have already been successfully tested as light-heat detectors. Contemporary read-out of scintillation light (a signal highly sensitive to the ionizing properties of the interacting particle) and thermal signal (a signal practically insensitive to the type of particle) has been realized for the first time in the 90s expressively with the purpose of rejecting the alpha background in CaF2 crystals [9] [10]. The light detector was a Si photodiode and showed some difficulties to work at the 10 mK temperature required for the scintillating bolometer. This technique has been there after refined, substituing the Si diode with another thin bolometer and is today used in dark-matter detection experiments [11] while its possible application for 0ν–DBD detection has been explored in the last years [12], testing different kind of crystals. The successful results obtained for different composites (containing a DBD active isotope) and the high rejection capability for alpha background have opened new possibilities for the 0ν–DBD searches with bolometers. One of the best candidate (up to now) for this application is $CdWO_4$, that contains the DBD isotope candidate ^{116}Cd, with a Q-value of 2805 keV [13]. In 1066 hours of background data collection,

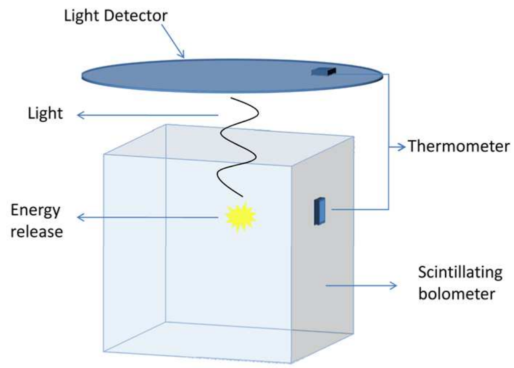

Figure 3. A typical BOLUX detector structure: a scintillating bolometer together with a light detector bolometer

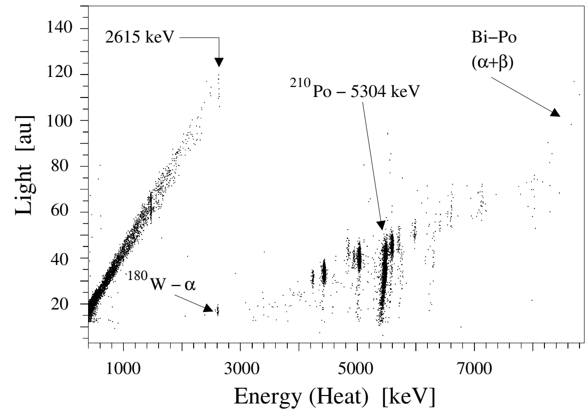

Figure 4. Scatter plot of Heat vs Light of a 426g $CdWO_4$ bolometer. Live time = 1066 h

with a crystal of 426 g and a light detector bolometer made of a pure 35mm diam. Ge disk (see figure 3), a very neat scatter plot has been obtained (figure 4), where the β–γ events are clearly separated from α, with no β-like event left above the ^{208}Tl gamma line (at 2615 keV). This shows the potentiality of the BOLUX technique, that has reached already in this R&D test a background limit compatible with not more than 1.2×10^{-4} counts/keV/kg/y in the 0ν–DBD region, a factor 1000 times better than in CUORICINO, which is a good starting point from where to begin thinking at the far future of DBD searches with bolometers.

7. Conclusions

The calorimetric detectors (bolometers) used in DBD searches have improved very much in this last fifteen years, since their first appearance on the stage. Today they are for sure one of the more accredited technologies for this and many other rare event searches, and are among the selected detectors for the second generation 0ν–DBD experiments. But they have yet not put to use all their potentialities: background identification, through bolometer active shieldings or through complex heat-light low temperature detectors, has still to be optimized and could easily become the base on which a third generation of detectors for 0ν–DBD could be developed, with the scope of reaching the direct hierarchy region of neutrino masses.

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