Calorimetry at 10mK

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Abstract.
The search for neutrinoless double beta decay requires extreme technologies since the process searched is nearly impossibly rare. Calorimetric technique is one of the best promising line of attack to the problem expecially when the materials are operated at ultra-low temperatures as bolometers. This allows, at least in principle, the use of a large variety of different isotopes and a control of the main parameter dominating the game: the background index. In this paper we will discuss the CUORE calorimeter and the industrial processes with associated QC/QA for the production of radiopure TeO_2 crystals and mention other type of materials that could suit even better the goal of this fundamental yet extremey difficult measurement.

1. Introduction

In the field of fundamental particle physics the neutrino has become more and more important in the last few years, since the discovery of its mass. In particular, the ultimate nature of the neutrino (if it is a Dirac or a Majorana particle) plays a crucial role not only in neutrino physics, but in the overall framework of fundamental particle interactions and in cosmology.

One shall notice that the ambiguity inherent to the measurement of squared mass differences in the oscillation process leaves two possibilities for the hierarchical mass arrangements of neutrinos. There could also be a common baseline. The measured values of the neutrino mass differences are indeed tiny. Many orders of magnitude smaller than the mass of the lightest of charged leptons, the electron. Long ago E. Majorana formulated an elegant and minimal description [1] of the neutrino field. The question is whether Nature makes use of this simplicity. The only way to disentangle its ultimate nature is to search for the so-called Neutrinoless Double Beta Decay ($0\nu2\beta$) [2]. The DBD are extremely rare processes. In the two neutrino decay mode their half- lives range from $T_{1/2} \simeq 10^{18}y$ to $10^{25}y$. The rate for this process will go as

$$1/\tau = G(Q,Z)|M_{nucl}|^2 m_{\beta\beta}^2$$

where G is the easily calculable phase space factor and M is the challenging nuclear matrix element that is known [3] with still large uncertainties. The experimental investigation of these phenomena requires a large amount of DBD emitter, in low-background detectors with the capability for selecting reliably the signal from the background. The sensitivity of an experiment will go as

$$S^{0\nu} \propto a(\frac{MT}{b\Delta E})^{1/2}\epsilon$$

Isotopic abundance (a) and efficiency (ϵ) will end up in a linear gain, while mass (M) and time (T) only as the square root. Also background level (b) and energy resolution (ΔE) behaves as a square root. In the case of the neutrinoless decay searches, the detectors should have a sharp energy resolution, or good tracking of particles, or other discriminating mechanisms. The choice of the emitters should be made also according to its two-neutrino half-life (which could limit the ultimate sensitivity of the neutrinoless decay), according also to its nuclear factor-of-merit and according to the experimental sensitivity that the detector can achieve. One of the best technology for studying this extremely challenging problem is the bolometric one.

2. Bolometric technique

Bolometers are low-temperature-operated particle detectors which provide better energy resolution, lower energy thresholds and broader material choice than conventional devices. They can be thought as perfect calorimeters, able to thermalize fully the energy released by a particle. The best features of bolometric detectors are:

- They can contain the candidate nuclei with a favorable mass ratio and be massive
- They exhibit good energy resolution. This parameter is crucial since the signal is a peak in the energy spectrum of the detector positioned exactly at the Q-value of the reaction. This peak must be discriminated over the background and therefore has to be narrow.
- They can be built in a way to be characterized by low intrinsic background.

Up to now, the choice for bolometers as $0\nu2\beta$ detectors has fallen on natural TeO_2 that has very good mechanical and thermal properties together with a very large (27% in mass) content of the candidate ^{130}Te. The success of CUORICINO [4] and the excellent prospects for CUORE [5] are based on this approach. Bolometer-based $0\nu2\beta$ searches require however extremely low levels of background. Even if you reduce drastically the one arising from radioactive contaminants in the bolometers themselves, you still have the problem of the surrounding materials. Surface contamination is of particular concern. In fact, α particles arising from radioactive contaminations located on the surfaces of the detector or of passive elements facing them can lose part of their energy in a few microns and deposit in the detector an energy close to that of the signal, thus mimicking a signal event. A realistic possibility to improve substantially the background rejection capability is to join the bolometric technique proposed for the CUORE experiment with the bolometric light detection technique used in cryogenic dark matter experiments. The bolometric technique allows an extremely good energy resolution while its combination with the scintillation detection offers an ultimate tool for background rejection. Preliminary tests on several double-beta-decay detectors have clearly demonstrated the excellent background rejection capabilities that arise from the simultaneous, independent, double readout (heat + scintillation). One of the great advantages of the bolometric technique is that most of the candidate elements for DBD searches can form chemical compounds suited to be grown as crystals.

3. The TeO_2 show case

In principle, almost any crystal containing DBD candidates could be used in cryogenic experiments. Tellurite crystals have the advantage of very good thermal and mechanical properties. Furthermore, the high natural abundance of ^{130}Te (33.8%) in practice eliminates the need for the extremely costly enrichment processes. TeO_2 crystal is particularly convenient for the use in a cryogenic particle detector because of its thermodynamic char- acteristics. TeO_2 is a dielectric and diamagnetic crystal with a specific heat at low temperature following the Debye law ($\sim$ $(T/T_D)3$). The crystal absorber (1000 modules, cubic, 125cm^3, 790gr each) forms the core of a cryogenic bolometer: the CUORE experiment, preceded by its demonstrator Cuoricino. The energy deposited by a particle is measured through the temperature increase of the crystal. The numerology says that an energy deposit of 1 MeV will produce a temperature

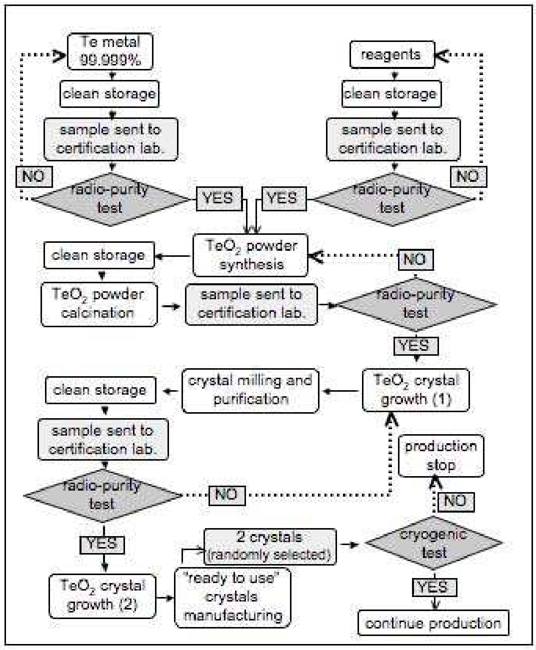

Figure 1. Sketch of the protocol for the production of the TeO_2 crystals of the CUORE experiment at SICCAS.

increase of 100 μK. A high level of crystal perfection is requested for high sensitivity bolometers because the presence of bulk defects like bubbles and metallic inclusions or veil sandcracks may drastically reduce the signal intensity and the energy resolution of such detectors. Mechanical perfection is however only a part of the story. In Double Beta Decay calorimetric experiments events can be identified by their energy spectrum. In practice the sensitivity of the experiment is limited by the presence of environmental radioactivity and radioactive contaminants in the detector. Therefore,it is critical for the detector to be be free of any contaminant that can mimicthe signal. The contamination may come from long-lived, naturally occurring isotopes, such as ^{238}U, ^{232}Th, ^{40}K and their daughters and from cosmogenic activation of the detector after production. To minimize the influence of long-lived nuclei, great care must be devoted to the selection of all material sand ancillaries used forthe preparation of the crystals. A sketch of the production protocol [6] used at SICCAS for the production of the TeO_2 crystals of the CUORE experiment is shown in Fig. 1.

The performances of the final product can be seen looking at the energy resolution (Fig. 2) in the final bolometric test that is used, on a sample basis, to evaluate the quality of the on-going production at SICCAS.

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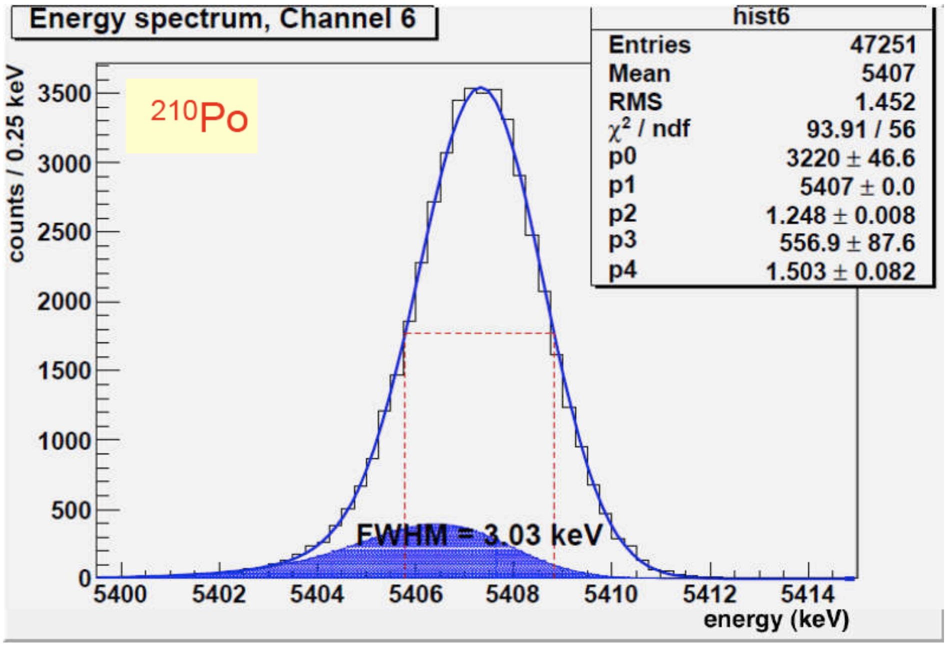

Figure 2. Energy spectrum in a TeO_2 crystal of the CUORE experiment at the ^{210}Po α line.

4. Scintillating bolometers

Although TeO_2 crystals are extremely good bolometers there are two problems that cannot be avoided when making a DBD search with them. The first is that the transition energy, the so-called Q-value is below the last important photon line coming from the U, Th chains, the ^{208}Tl. The second and most important is that the shape of the bolometric response does not allow any discrimination of α particle signals with respect to β/γ ones. The problem is best elucitated in Fig. 3.

Scintillating bolometers to the search for $0\nu2\beta$ bring in an enormous added value, by allowing the use of high Q-value candidates first, and second by providing a substantial α/β discrimination power. When the energy absorber in a bolometer is an efficient scintillator at low temperatures, a small but significant fraction of the deposited energy (up to a few %) is converted into scintillation photons, while the remaining dominant part is detected as usual in the form of heat. The simultaneous detection of the scintillation light is a very powerful tool to identify the nature of the interacting particle. In particular, α particles can be discriminated (see Fig. 3) with respect to beta and gamma interaction because of the different quenching factor (QF).

A scintillating bolometer for $0\nu2\beta$ is no new concept in the field and was proposed more than one decade ago for ^{48}Ca with CaF_2 crystals [7]. Nature has kindly provided us with a few isotope candidates presenting a transition energy higher than 2615 keV and forming chemical compounds suitable for the growth of large scintillating crystals, which proved to work as highly performing bolometers as well. The most suited are based on Cd, Mo and Se with the drawback of a need for an isotopic enrichment that brings their natural abundances (less than 10%) to a much higher

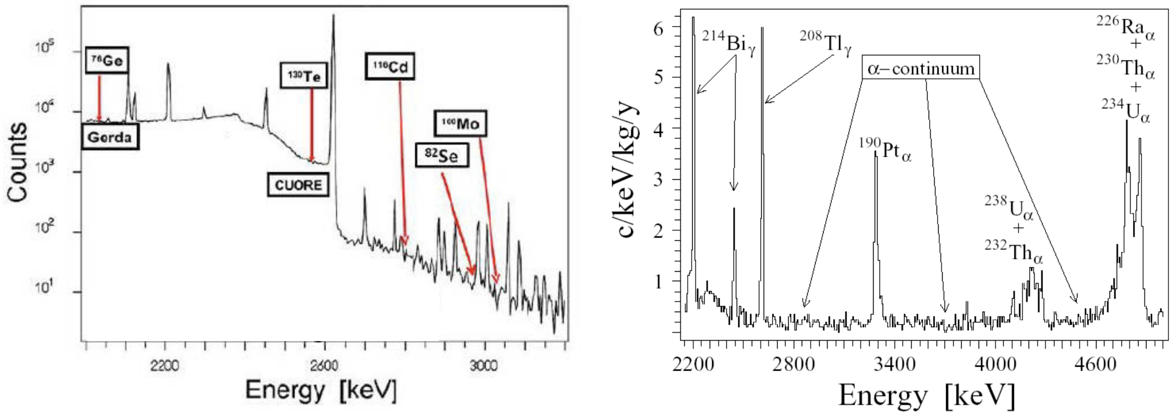

Figure 3. Left: Radiative nuclear transitions. It clearly shows that above the ^{208}Tl this contribution to the DBD background becomes negligible. Right: Cuoricino background in the DBD region and above. It clearly shows the dominance of degraded α's.

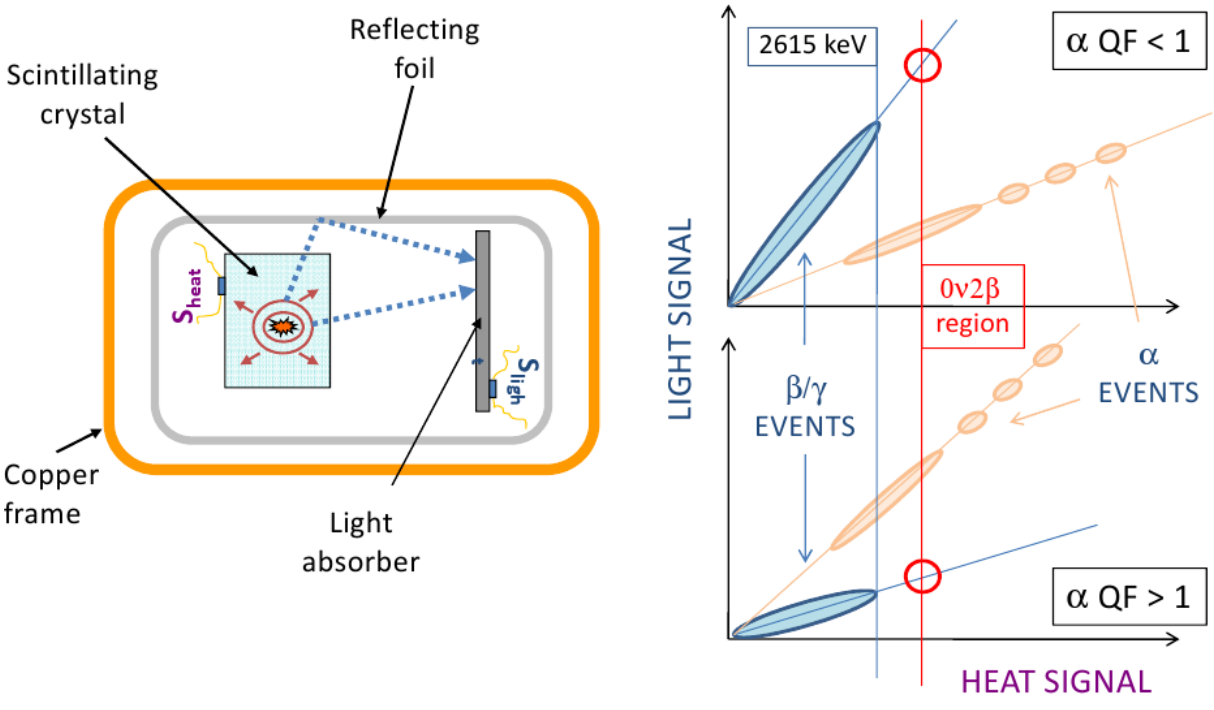

Figure 4. Left: schematic structure of a double read-out scintillating bolometer. All the basic elements of the detector are shown. Right: schematic scatter plots of light signals vs. heat signals corresponding to events occurring in the scintillating bolometer. Cases with QF larger or smaller than 1 are illustrated. In both circumstances α events can be efficiently rejected and the $0\nu2\beta$ signal region is background free.

value. This means in practice that although results [8] obtained by using $CdWO_4$ have basically proven (see Fig. 5) the power of this approach the final choice for a practical experiment cannot make use of this crystal. Cd presents some drawback like the residual, unavoidable presence of ^{109}Cd and ^{113}Cd that could be too much of a nuisance even after enrichment. Mo does not offer at this point any convincing cristalline compound and it is an element heavily contaminated by the presence of U, Th. When applying different materials to this scheme and considering all the relevant elements (scientific, technical, economical), the final balance is in favour of ^{82}Se (ZnSe crystals) although ^{116}Cd still deserves attention.

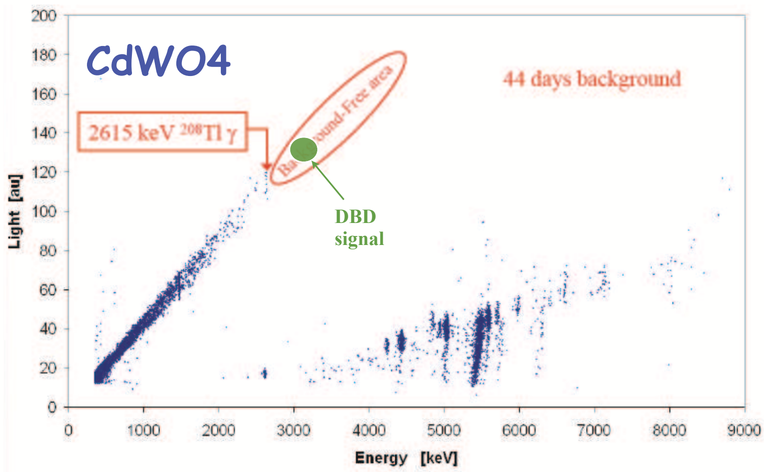

Figure 5. Results from a run on a $CdWO_4$ crystal with double (heat and light) readout

5. LUCIFER: a prototype of a double read out cold calorimeter

One of the most striking features of ZnSe is the abnormal QF, higher than 1 unlike all the other studied compounds. Although not really welcome, this unexpected property does not degrade substantially the discrimination power [9] of this material compared to the others and makes it compatible with the requirement of a high sensitivity experiment. An additional very useful feature is the possibility to perform α/β discrimination on the basis of the temporal structure of the signals, both in the heat and light channel (see Fig. 6).

The detector configuration proposed for LUCIFER resembles closely the one selected and extensively tested for CUORE, with an additional light detector, designed according to the recipes developed during the scintillating-bolometer R&D and consisting of an auxiliary bolometer, opaque to the light emitted by the ZnSe crystals (see Fig. 7). A preliminary version of the LUCIFER structure consists of an array of 48 crystals, divided in 12 elementary modules with 4 crystals each arranged in a tower, which would fit exactly the experimental volume of the Cuoricino cryostat. This structure assumes that a single light detector, quite large in order to monitor four scintillating crystals simultaneously, is sensitive enough to perform efficiently the α/β discrimination. The total detector mass would be 25 kg, with about 14 kg of enriched material assuming an enrichment level of 97% A preliminary evaluation of the LUCIFER sensitivity can be made on the basis of the structure discussed above and on the background expectations after α/β rejection. Assuming 5 year live time, an energy window of 20 keV and a specific background coefficient of 10^{-3} counts/keV/kg/y, less than a few background counts are expected in the region of interest (the transition energy for ^{8}2Se is 2995 keV). The most

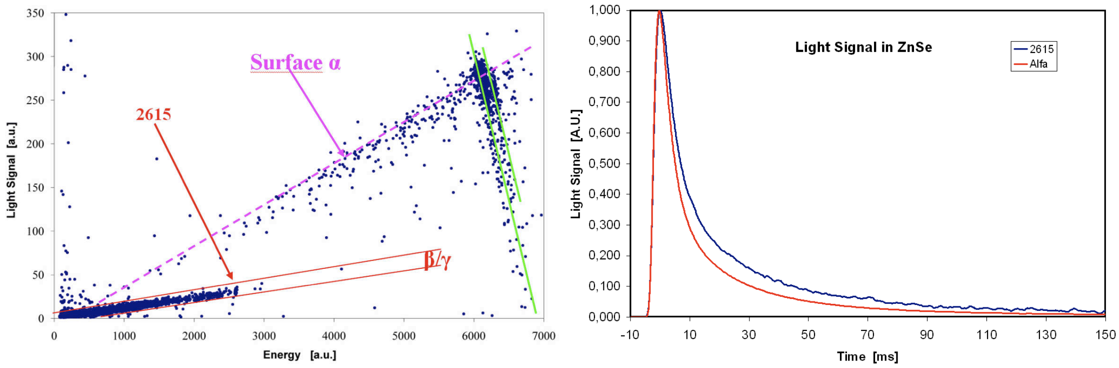

Figure 6. Results from a run on a ZnSe crystal with double (heat and light) readout exposed to radiactive sources. Left: scatter plot Light vs. Heat. Right: Decay time of the scintillation light for α's and ^{208}Tl line.

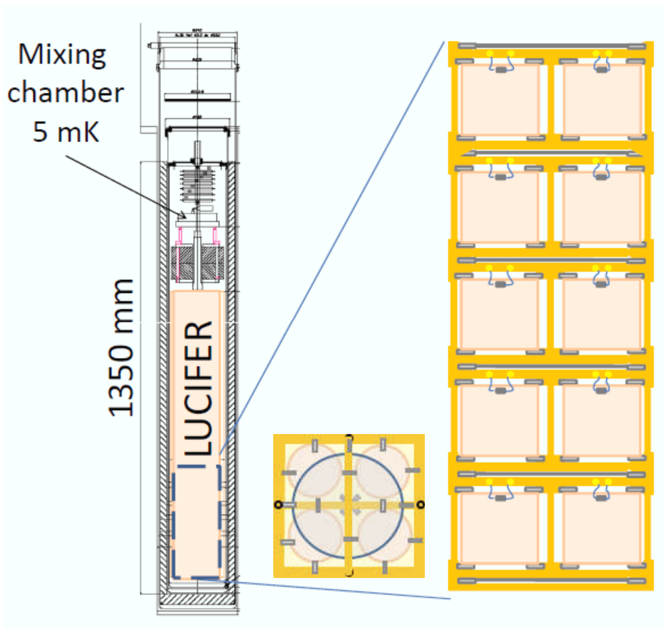

Figure 7. Schematics of Lucifer detector. Left: Cuoricino cryostat with Lucifer inserted. Center: Top view of 2×2 crystal plane with Ge light detector on top. Right: Side view of the detector array

important goal for LUCIFER is to be a demonstrator of the scintillating bolometer technology, with a significant mass and a full test of all the critical elements of this approach:

- large scale enrichment
- efficient chemical purification meeting radioactive requirements
- large size crystals grown with high efficiency in using the precious (100$/gr) material
- background rejection invesigated in many modules simultaneously operated.

It has the ambition to indicate the way to the experiment for the search of $0\nu2\beta$ able to span over the whole inverted hierarchy region.

6. Acknowledgments

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