

## Bolometric light detectors for Neutrinoless Double Beta Decay search

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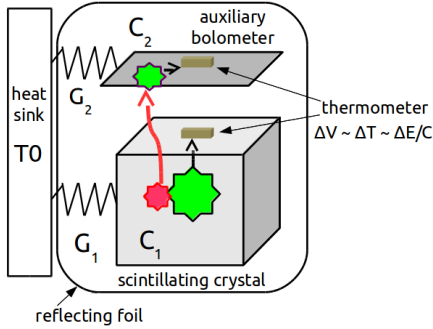
Bolometric light detectors provide an efficient method to collect light signals at small thresholds in cryogenic experiments and are being exploited in present and next-generation experiments for the search of Dark Matter and Neutrinoless Double Beta Decay. In this paper, we discuss the performance of sample light detecting bolometers made up of a ultra-pure Ge slab read by a high impedance thermistor, which were assembled and tested at very low temperatures, below 30 mK; we report about signal amplitude, signal to noise ratio, energy resolution and reproducibility. The purpose of this investigation is to develop hybrid detectors to search for Neutrinoless Double Beta Decay.

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## 1. Introduction and goals



**Figure 1:** Schematics of a typical scintillating bolometer setup: light detectors are thin-absorber-bolometers, placed in front of the scintillating crystal.

This can be accomplished using scintillating bolometers (figure 1), where the photons produced in the main scintillating crystal absorber are collected by a light detector, consisting of another auxiliary bolometer, in the form of a thin slab opaque to the emitted light.

The main purpose of our work is to probe and optimize the light sensor performances, such as sensitivity, energy resolution and reproducibility, in view of the assembly of a next-generation large mass 0νDBD experiment.

## 2. Experimental methods

Light detectors concerned in this work are made up of an ultrapure Ge absorber, held in a copper frame by PTFE pieces; the temperature sensor is a Ge Neutron Transmutation Doped thermistor (NTD) [6], glued on the absorber's surface with spots of Araldite epoxy glue. Electric and thermal connections are provided by 25 μm golden wires. The detectors are cooled down to very low temperatures, in a range from 15 to 30 mK, by means of a dilution refrigerator. Calibration is performed by means of a <sup>55</sup>Fe source, placed in front of the Ge absorber, emitting X-rays peaking at 5.9 and 6.4 keV. In some tests, the Ge absorbers are placed in front of a scintillating crystal, sometimes irradiated with external sources, so as to probe the α/β discrimination capability of the whole scintillating bolometer setup and its energy resolution. We considered in our tests ZnSe and ZnMoO<sub>4</sub> scintillating crystals, whose emission spectrum peaks at around 645 nm and 625 nm respectively.

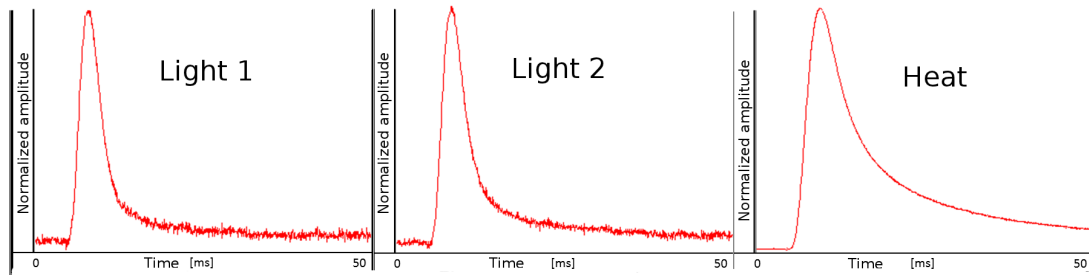
Having to perform serial R&D tests, easy-assembling, reproducibility and adaptability to different detector setups have to be fulfilled: a first, non-negligible aim of this work was the search for an optimal design for the light detector itself. Different types of setups were tested, changing absorber dimension and thickness, PTFE arrangement, NTD type and size.

The first light detector prototypes were assembled in the cryogenic laboratory of Insubria University, Italy, and consisted of bare square shaped Ge slabs, 15 mm side and 0.5 mm thickness,

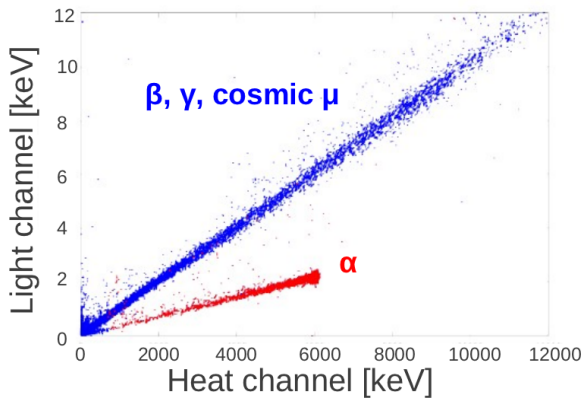
equipped with  $3 \times 1 \times 0.6 \text{ mm}^3$  NTDs. The absorbers are held transversally by slit PTFE pieces and wires connections are incorporated into the whole detector frame, making it impossible to isolate the light detector without dismounting it completely. A devoted holder was then conceived, in order to be integrated into different setups without compromising the original thermal couplings: Ge absorbers are kept in place by means of PTFE pincers, screwed on an independent copper frame which also hosts pads for wire connections. This kind of setup was adapted to large absorbers as well, 5 cm diameter and around  $250 \mu\text{m}$  thick, equipped with  $3 \times 2.2 \times 0.6 \text{ mm}^3$  NTDs (figure 4).

### 3. Results

#### 3.1 Coupling to scintillating crystals



**Figure 2:** Example of a coincidence event on the 5 g ZnSe bolometer: registered pulses on the heat channel and the two light detectors facing the scintillating crystal. Signal amplitudes are normalized.



**Figure 3:** Light yield detected by Ge light detectors as a function of phonon energy deposited in the 5 g ZnMoO<sub>4</sub> scintillating crystal [7]. The run was performed aboveground: high energy portion of the  $\beta$  band arises from cosmic muons.

(figure 3): light channel signal amplitudes as a function of heat channel amplitudes. Two bands are discernible,  $\beta$ -like events yielding a different amount of light with respect to  $\alpha$ s: the *quenching factor*, the ratio of  $\alpha$  to  $\beta$  light yield at a fixed deposited energy in the scintillating absorber, is around 5 for ZnSe and around 0.2 for ZnMoO<sub>4</sub>. In the energy region of interest, relative  $\beta$  events

Small light detectors ( $15 \times 15 \text{ mm}^2$  Ge absorbers), coupled to small ZnSe ( $\sim 5 \text{ g}$ ) and ZnMoO<sub>4</sub> ( $\sim 5 \text{ g}$  and  $\sim 24 \text{ g}$ ) crystals, were operated aboveground (University of Insubria - Como and CSNSM - Orsay): our primary goal was to assess light detector performances in a typical luminescent bolometer configuration, in particular  $\alpha$  versus  $\beta$  discrimination power.

The thermal signal on the main scintillating absorber is of the order of 50 ms, while light detectors generally yield faster signals, due to their smaller heat capacity (figure 2). Coincidence events on the main scintillating crystal (usually referred to as *heat channel*) and the auxiliary Ge bolometer (*light channel*) are displayed in the so called *scatter plot*

light yields range from a few keVs for  $\text{ZnMoO}_4$  to tens of keVs for  $\text{ZnSe}$ , for 1 MeV deposited energy.

In all these tests, a good separation between  $\beta$  and  $\alpha$  events was achieved: the two bands can be clearly discriminated in the scatter plot of the coincidences on the main scintillating crystal and the auxiliary bolometer.

### 3.2 Reproducibility of large detectors

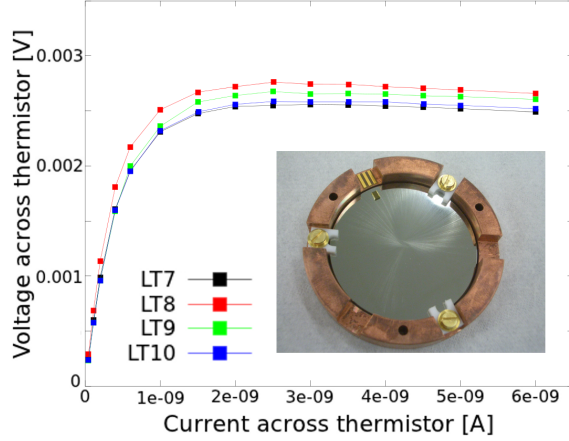
A tower of four identical large light detectors was assembled and tested at CSNSM: absorbers are 5 diameter Ge disks,  $\sim 250 \mu\text{m}$  thick. This size is likely to be adopted in the construction of a future 0 $\nu$ DBD experiment, so the run provided a first, important investigation of detectors whose configuration is very close to the final one.

Static characterization showed homogeneous behaviour of the four detectors, symptomatic of similar thermal couplings (figure 4).

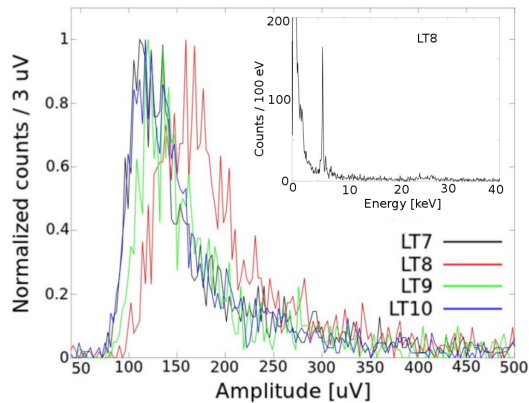
The dynamic sensitivities (figure 5), extrapolated from  $^{55}\text{Fe}$  and cosmic muon coincidences calibrations, are all compatible as well: detectors signal amplitude is around  $1 \mu\text{V}$  for 1 keV deposited energy in the Ge crystal, at 19 mK nominal base temperature, while baseline fluctuations vary from 133 eV to 1830 eV due to channel-dependent microphonic noise (figure 6). The worst detector is however still compatible with minimum requirements for its employment in a next-generation 0 $\nu$ DBD experiment: in the energy region of interest for  $^{100}\text{Mo}$  and  $^{82}\text{Se}$ , around 3 MeV, the collected light is expected to range from a few keV/MeV to tens of keV/MeV, for  $\text{ZnMoO}_4$  and  $\text{ZnSe}$  respectively (see section 3.1). At 17 mK heat sink temperature, one detector showed a baseline noise of 88 eV FWHM, the best limit ever measured so far for detectors of this type. A summary of the performed measurements is reported in table 1.

Detector	$T_b$ [mK]	Sensitivity [ $\mu\text{V}/\text{keV}$ ]	Baseline noise FWHM [eV]
LT7	19	0.79	148
LT8	19	1.02	133
	17	1.83	88
LT9	19	0.80	184
	17	1.53	249
LT10	19	0.78	1830

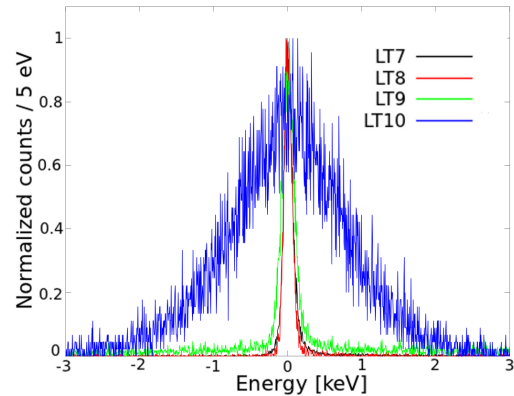
**Table 1:** Sensitivities and baseline noise of the four large detectors tested in Orsay.



**Figure 4:** Static characterization of the four large light detectors: voltage across thermistor as a function of polarization current. In the photo, detector setup: 5 cm diameter ultrapure Ge absorber,  $3 \times 2.2 \times 0.6 \text{ mm}^3$  NTD thermistor.

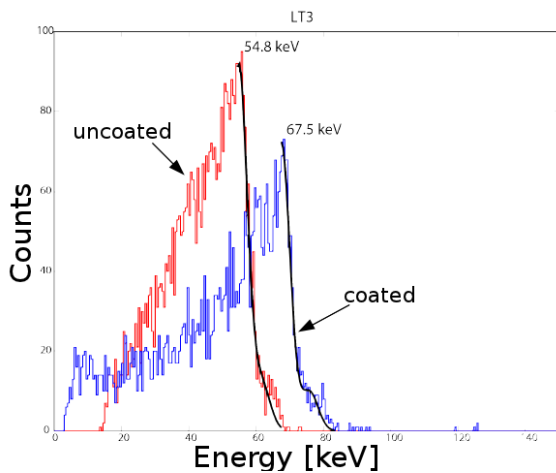


**Figure 5:** Spectra of muon coincidences in  $\mu\text{V}$ : detector responses are comparable. In the inset, a spectrum collected with LT8 shows the  $^{55}\text{Fe}$  5.9 keV line.



**Figure 6:** Baseline fluctuation spectra in keV, largely spread due to channel-dependent microphony. The worst FWHM value is however still acceptable in the 0vDBD scope.

### 3.3 Coating effect



**Figure 7:** Spectra collected in the two runs with Ge light detectors: without sputtering and coated by  $\text{SiO}_2$ . Results are reproducible and show a gain of the order of 20% when the surface exposed to the light source is  $\text{SiO}_2$  coated.

depositing a liquid uranium solution on a thin ZnSe slab: the expected light spectrum pattern has an end point at the characteristic energy of the source, smearing at lower energies. Two runs were performed, changing the Ge side exposed to the source. The detector responses were compared by referring to heaters pulses and calibrated using minimum ionizing cosmic rays. A gain of the order of 20% in light collection efficiency was assessed for  $\text{SiO}_2$  coated sides (figure 7), in reasonable agreement with expectations.

A dedicated setup was constructed in Como cryogenic laboratory in order to study the effect of the deposition of a thin layer of  $\text{SiO}_2$  by radio frequency (RF) sputtering on the surface of Ge wafers:  $\text{SiO}_2$  has a refraction index value intermediate with respect to Ge's and vacuum's, which, according to the index matching anti-reflective method, should increase the absorption efficiency of the coated material with a gain of the order of 22% with  $\text{SiO}_2$  in amorphous form.

Four nominally identical light detectors were assembled, the Ge absorber being coated with an approximately 70 nm thick  $\text{SiO}_2$  layer only on one side. Each detector was equipped with a heating device [8], directly glued on Ge, in order to periodically dissipate a fixed energy signal into the absorber. Light sources were fabricated by

## 4. Conclusions

Small Ge devices, 15 mm side, were successfully tested as light detectors for scintillating bolometers. The deposition of a thin SiO<sub>2</sub> layer enhances light collection efficiency of about 20%, as a study carried on in Como laboratory showed up. We optimized light detectors design in order for it to suit serial tests and different setups for scintillating bolometers studies. Four nominally identical large Ge devices, 5 cm diameter, were tested and their good performances were assessed. Static patterns and sensitivities are homogeneous and baseline noise values, though spread due to microphonics, are all within acceptable limits for the detectors to be successfully employed in future 0νDBD experiments: these detectors will be used in the LUCIFER [9] program and on large ZnMoO<sub>4</sub> crystals.

Next step will be the investigation of 5-cm-diameter Ge detectors coupled to a large scintillating crystal: a 313 g ZnMoO<sub>4</sub> bolometer was assembled in CSNSM, Orsay (France) and it will be cooled down at Laboratoire Souterrain de Modane.

## Acknowledgments

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