Cryogenic light detectors with enhanced performance for rare events physics

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Abstract

We tested a new way of coupling bolometric light detectors to scintillating crystal bolometers. This simple and extremely neat coupling is obtained by resting the light detector on the crystal surface, held in position only by gravity. This apparently straightforward mounting results in three important improvements: i) it decreases the amount of non active materials needed to assemble the detector; ii) it substantially increases the light collection efficiency by minimizing the light losses induced by the mounting structure iii) it enhances the thermal signal induced in the light detector thanks to the extremely weak thermal link to the thermal bath. We measured that the heat exchange between the crystal absorber and the light detector is negligible, provided that the pressure force is of the order of few grams.

We tested this new technique with thermistor-based sensors on a large TeO$_2$ bolometer, demonstrating that the light collection efficiency on the tiny Cherenkov light emission is magnified by more than 50% with respect to all the previous measurements, obtained with different cryogenic sensors and different types of mountings. We obtained a baseline energy resolution on the light detector of 20 eV RMS, that, together with increased light collection, enabled us to obtain the best $\alpha$/$\beta$ discrimination ever obtained in massive TeO$_2$. At the same time we achieved rise and decay times of 0.8 and 1.6 ms, respectively. Thanks to these excellent performances, this bolometric light detector fully matches all the requirements for CUPID (CUORE Upgrade with Particle IDentification), the 1-ton scintillating bolometer follow up of CUORE, both in the case of TeO$_2$ and $^{100}$Mo-based crystal options.

Keywords: Double Beta Decay, Dark Matter, Scintillating bolometers, Cherenkov radiation, Particle identification methods, Cryogenic Detectors

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1. Introduction

The use of Low Temperature Detectors (LTDs) is nowadays widely diffused being their superior performances as X-ray and $\gamma$-ray detectors well established [1]. LTDs are also deeply used in the field of fundamental physics, especially for Double Beta Decay (DBD) and Dark Matter (DM) searches [2]. In these surveys the possibility to have an hybrid detector, in which an energy release can be measured through different mechanisms, is of primary importance in order to disentangle the nature of interacting particle and, consequently, the background induced by natural radioactivity. With thermal detectors this can be achieved using scintillating or luminescent crystals: the simultaneous and\textsuperscript{independent} readout of the heat and the (escaping) light produced by the interaction reveals the nature of the interacting particles thanks to the different scintillation yields of $n$, $\alpha$ and $\gamma/\beta$ particles. This technique is presently used for DM searches [3, 4, 5], DBD searches [6, 7, 8] and it can be also implemented for rare nuclear decays [9, 10, 11]. At milli-Kelvin temperatures, the light detectors are usually bolometers themselves: a dark thin crystal absorbs the photons, producing heat (phonons) that is measured by a suitable thermometer. The main difference among the different class of Bolometric Light Detectors (BLDs) is represented by the thermometer, e.g. Transition Edge Sensors (TES) [12], Neutron Transmutation Doped (NTD) thermistors [13] or Micro Magnetic Calorimeters (MMC) [14].

The work presented here was performed within the CUPID framework [15, 16], the future follow up of CUORE [17] that represents nowadays the largest world-wide bolometric experiment. The aim was to develop NTD-based BLDs with improved performances in terms of sensitivity, time response and simplified packaging for large arrays. Indeed, the possibility to use the tiny Cherenkov light emission of TeO$_2$ [18] to disentangle the $\alpha$ induced background requires a BLD with a RMS baseline resolution of the order of 25 eV to guarantee a $3\sigma$ discrimination capability [19] between $\alpha$ and $\beta/\gamma$ interactions, while in case of $^{100}$Mo-based compounds also a fast time response of the BLD ($\leq 1$ ms) is required to suppress the 2$\nu$ DBD induced...
background [20].

Our work was therefore focused towards two aspects: i) improving the performances of the NTD thermometer and ii) increasing the light collection. While the first aspect is strictly related to a specific technique, the second one is worth of some additional remarks. The working principle of a BLD is the same, irrespective of the sensor: a thin crystal wafer (usually Si or Ge) absorbs the emitted photons that converts then into heat; differently from the conventional approach, we have to avoid the optical coupling between crystal and BLD made with optical grease or similar: in such case, the unavoidable heat flow through the optical coupling and the increase of the heat capacity of the system, would reduce the reciprocal independency of the two detectors, washing out the possibility of particle discrimination induced by the different scintillation yields.

Therefore the thermal contact between the luminescent crystal and BLD has to be avoided, especially in the case of extremely low scintillation yields: this is true for most of the Mo-based compounds [7] and, even more important in case of Cherenkov signals. A 2615 keV γ-ray energy release in a TeO$_2$ absorbs a light signal in the BLD of the order of ~100 eV [13]. For this reason the BLD is always facing -without any contact- the scintillating crystal.

In the following it is shown that if the BLD is simply resting on the crystal surface, held in position only by gravity, the thermal coupling between the BLD and the crystal is almost negligible and the leakage of the heat (signal) vanishes: the BLD will thermalize to the heat sink by means of only its thermistor gold wires.

This fact can be explained considering the acoustic mismatch theory in the diffused mismatch model where the heat carriers (phonons) in insulating materials are scattered at the interfaces [21][22]. Within this approach the thermal resistance between two dielectric crystals is strongly dependent on the surface state, on the different phonon characteristics in the two materials (density and Debye temperature) and on the applied force. This latter simply because when two solids are pressed together, due to surface irregularities, the actual contact area can be much smaller than the nominal one; only rising the applied force between the materials the "real" contact surface can increase, and a plastic or permanent deformation occurs. The deformation changes the area and therefore the thermal conductance of the contact is direct proportional to the applied force [23][24].

Although such simple stand will clearly not produce a so-called optical matching, the light collection will be definitively larger due to geometrical factors [1]. Moreover, this will avoid to use a dedicated frame to hold the BLD in place, with the important benefit of decreasing the presence of dead materials/surfaces close to the detector, thus reducing possible radioactive contamination, a fundamental aspect while dealing with rare event searches.

2. Bolometric Light Detectors

Our BLDs are constituted by electronic grade undoped Ge wafers, coupled with Ge NTD thermistors. We started to develop these detectors coupled with several scintillating DBD crystals [25] and we deeply characterized their operation and performances [26] to finally arrive to LUCIFER [27], now renamed to CUPID-0 [28]. Each BLD of CUPID-0 (totalling 26 detectors) was made by a double side polished electronic grade undoped Ge wafer (44.5 mm diameter, 0.15 mm thick). The NTD thermistor, with dimension of (2.85 × 2 × 0.5) mm$^3$, is glued through six small glue dots (~0.5 mm diameter, 0.05 mm height) made with Araldit® Rapid glue. The performances of six of these detectors were evaluated in a dedicated test run [29]. Their main performances are summarized in Tab. 1.

In order to further optimize our BLDs, we decided in this work to adopt the same strategy described in the pioneering work of Coron et.al. [30]: i) a decrease of the heat capacity (size) of the thermistor, ii) an increase of the thermal conductance between thermistor and Ge wafer, iii) a decrease of the thermal conductance to the thermal bath.

With respect to the thermistor size, we use a NTD with dimension of (2.85 × 1 × 0.4) mm$^3$, therefore roughly 2.5 times smaller with respect to the CUPID-0 ones. Moreover we decide to replace the six glue dots with a uniform layer, thus increasing the thermal conductance between NTD and Ge wafer.

For the sake of completeness it has to be noted that in our experience the use of glue dots instead of a more effective thin layer is preferred when coupling different materials (e.g. TeO$_2$ crystals and Ge thermistors) to reduce the mechanical stresses induced by the different expansion coefficients of the materials. In such cases, working with larger size thermistors we sometimes observed cracks on the crystal surface after a cooling cycle. In our new BLDs, however, being Ge glued on Ge$^2$ and using thermistors with a small contact area, we decided to use a glue layer.

With respect to the mounting (i.e. the conductance to the thermal bath), there are many ways to hold the BLD in place: we adopt two [26] or three [28] small PTFE clamps that squeeze an edge of the Ge, keeping it fixed in a Cu standalone holder. PTFE is a common material also used by other groups working with NTD sensors [31] and with MMC detectors [14]. In fact there is a large variety of choices in the materials and in the way these detectors are held, as demonstrated by the CRESST group: bronze clamps, Silicon or CaWO$_4$-based sticks [32].

The one used in [30], however, is probably the most complex from a construction point of view, using several ultra thin super-conductive wires to suspend the Ge wafer from the copper with a negligible thermal link and a complex structure to maximize the heat flow from the wafer to the NTD.

In this work, we decided to avoid any kind of holding structure and we laid the BLD directly on the crystal, kept in position only by its weight (~1.1 g). By this choice the main thermal

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1 In case the BLD is held in its own structure then, depending on the different solutions, there are always few mm of distance from the crystal, that increase the amount of photons that can escape (and being absorbed) towards the holding structure rather than the BLD.

2 In fact, even if we glue Ge on Ge, the glued surfaces belongs (incidentally) to orthogonal crystalline planes, originating therefore some unavoidable mechanical stress.
link between BLD and thermal bath is represented by the thin gold electrical wires (1 × 15 mm length, 25 μm diameter) of the NTD thermistor, since, as mentioned above, the expected thermal conductance to the crystal is negligible.

For this test we placed our new BLD on a (50.5 × 50.5 × 50.5) mm$^3$ TeO$_2$ crystal. The aim was to test the new setup with a light signal of the order of few tens of eV, fully exploiting this new design. The Ge wafer belongs to the batch used for CUPID-0. The side resting on the TeO$_2$ is deposited with a 70 nm SiO anti-reflecting coating [33].

### 3. Experimental details

The TeO$_2$ crystal was mounted in the same way as described in [18][34] with the only exception that both TeO$_2$ and BLD were not equipped with a Si Heater normally glued on the bolometer to inject pulsed thermal signals for gain stabilization.

The TeO$_2$ crystal is held by four S-shaped PTFE supports mounted on Cu columns. These PTFE supports ensure that the crystal is clamped tighter with the cooling down of the set-up (PTFE thermal contraction is one of the highest among different materials), to minimize heat-noise generated by frictions induced by the mechanical/acoustical vibrations of the cryogenic facility. The four PTFE supports, at the same time, prevent (possible) accidental displacements of the BLD that is simply resting on the TeO$_2$ crystal -without any kind of constraints- during the cryostat movements. In order to maximize the light collection, the crystal is completely surrounded by a plastic reflecting sheet (3M Vikuiti™), in the same way as in [18][34]. The entire setup was enclosed in a Cu box and thermally coupled to the mixing chamber of the CUPID R&D cryostat, a wet $^3$He/$^4$He dilution refrigerator installed deep underground in the Hall C of the Laboratori Nazionali del Gran Sasso, Italy.

To avoid vibrations reaching the detectors, the box is mechanically decoupled from the cryostat by a two stages pendulum system [35]. The thermistors of the detectors are biased with a constant voltage through large (27±27 or 2±2 GΩ) load resistors [36], resulting in a constant current operation. The resistance variations, generated by a temperature rise induced by an interacting particle, are converted into voltage pulses read across the resistive sensor. The heat and light voltages are then amplified using a Front-End electronics located just outside the cryostat [32]. The signals are then filtered by an anti-aliasing 6-pole Bessel-filter (with a cut-off frequency of 16 Hz for the TeO$_2$ crystal and 550 Hz for the BLD) and finally fed into a NI PXI-6284 18-bits ADC.

The sampling rate of the ADC was 1 kHz for the TeO$_2$ crystal and 8 kHz for the BLD. The two independent triggers are software generated: when a trigger fires, the corresponding waveform is recorded. Moreover, when the trigger of the TeO$_2$ crystal fires, the corresponding waveform of the BLD is always recorded, irrespective of its trigger. A detailed description of the DAQ system can be found in [38]. The amplitude and the shape of the voltage pulses are then determined via off-line analysis. The pulse amplitude of the thermal signals is estimated by the Optimum Filtering (OF) technique [39][40], that maximizes the signal-to-noise ratio in a way that improves the energy resolution and lowers the threshold of the detector. The amplitude of the light signal, however, is evaluated from the filtered waveform at a fixed time delay with respect to the TeO$_2$ bolometer, as described in detail in [31].

The amplitude of the acquired TeO$_2$ heat signals is energy-calibrated using several $\gamma$-ray peaks from a $^{228}$Th source. The BLD, on the contrary, is calibrated thanks to the 5.9 keV and 6.5 keV lines produced by a $^{55}$Fe X-ray sources permanently faced to the detector.

### 4. Data analysis and results

#### 4.1. BLD performances

The crystals were tested at a cryostat base temperature of ~11 mK. In order to obtain a fast response, we operated the BLD in the so-called over-biased configuration: the biasing current of the circuit is set much larger than the one that ensures the highest absolute thermal response [13]. This choice ensures a small working resistance, thus minimizing the effect of the low pass filtering induced by the overall capacity ($\sim$200 pF) of the readout wires, connecting the detector to the Front End.

In Fig. 1 we show the $^{55}$Fe calibration spectrum obtained with the BLD. The baseline energy resolution, or energy sensitivity of the BLD is given by the width of the distribution of the pulse height of randomly acquired baselines (noise), after the application of OF. It is rather usual for these detectors [13][42] that the energy resolution evaluated on the monochromatic energy depositions is much worse with respect to the baseline resolution, irrespective of the type of sensor: this probably depends upon position effects which do not play any role in the case of light detection, since the light signal cannot be spatially localized as an ionizing X-ray. The noise and signal power spectra of the BLD are presented in Fig. 2.

The bump that can be observed in Fig. 2 at ~400 Hz arise from the resonance, that enhances the thermal noise generated within the thermistor, that takes place when the impedance of the parasitic capacitance of the link becomes smaller than that of the thermistor, which is a fed-backed device [35]. The bump is found at the border of the bandwidth of the signal and is rejected from the optimum filter algorithm.

The rise and decay times, evaluated on the $^{55}$Fe X-rays are shown in Fig. 3. The intrinsic rise time of the detector is expected smaller with respect to the one measured and shown in

### Table 1: Mean performances of six CUPID-0-like light detectors [29]: resistance of the NTD Ge thermistor in working conditions $R_{\text{work}}$, absolute voltage drop (in $\mu$V) produced by an energy release of 1 keV, RMS baseline resolution after the OF, $\tau_r$ and $\tau_d$ are the rise and decay times, computed as the time difference between the 90% and 10% of the leading edge and as the time difference between the 50% and 90% of the trailing edge, respectively. The Bessel cut-off frequency is 200 Hz (see last remarks of Sec. 4.1).

| $R_{\text{work}}$ [MΩ] | Response [μV/keV] | Baseline RMS [eV] | $\tau_r$ [ms] | $\tau_d$ [ms] |
|------------------------|-------------------|------------------|-------------|-------------|
| 0.87                   | 1.36              | 54               | 1.77        | 5.06        |
foil to smear the source deposition was covered with a $6 \mu$m $^{238}$U source, facing the TeO$_2$ crystal. This source was permanently exposed to a mix of calibration sources, both derived from Cherenkov e/γ light, produced by a 2615 keV γ-emission that increases towards lower energies. This feature can only be ascribed to an energy loss in the Mylar that emits few scintillation photons. To avoid this effect we usually face the aluminized surface of the Mylar to the crystal so to reflect the (very few) photons that could be produced in plastics like Mylar. This time however, we miss this step and we checked -afterwards- that the aluminized surface was facing the source instead of the crystal.

The obtained result in Fig. 4 is excellent: the amount of Cherenkov light, produced by a 2615 keV γ, that is collected with this new set-up is $(151 \pm 4)$ eV, $50 \%$ larger with respect to all our previous measurements with massive crystals [19], and larger by more than a factor two with respect to a similar measurement recently performed with a NTD-based light detector [31]. The light distribution of the 74 events belonging to the internal $^{210}$Po α at 5407 keV (5304 keV α + 103 keV nucleus recoil) shows a mean value of $(5.8 \pm 3.3)$ eV, still compatible with zero (see Sec. 5) as it should be if the light only arise from Cherenkov effect. More important the width of the light distribution of α is $\sigma_\gamma=(22.7 \pm 2.7)$ eV, fully compatible with the RMS noise of the BLD of Tab. 2. The width of the light signal induced by the 2615 keV γ instead, shows a width $\sigma_\gamma/\beta=(31.5 \pm 4.3)$ eV larger with respect to the noise and induced by the photostatistics and by light collection.

In order to evaluate the Discrimination Power (DP) that can be obtained between the α and β/γ distributions at 2528 keV (the Q$_{\beta\gamma}$-value of the DBD of $^{130}$Te) we use the same formula and arguments used in [18, 31]: the DP can be quantified as the difference between the average values of the two distributions at 2528 keV.
tions normalized to the square root of the quadratic sum of their widths:

$$DP = \frac{[\mu_{\gamma/\beta} - \mu_{\alpha}]}{\sqrt{\sigma_{\gamma/\beta}^2 + \sigma_{\alpha}^2}}. \tag{1}$$

Re-scaling the light signal from 2615 to 2528 keV, we obtain DP=3.6, having the only (robust) assumption that an α particle at 2528 keV will show a light signal equal or smaller with respect to the same particle at 5304 keV ($^{210}$Po). This DP is the best ever achieved with large mass TeO$_2$ crystals (M > 7 g) and without the need of additional Neganov-Luke amplification [31, 44, 45], more sophisticated TES sensors [46] or both [47].

5. Thermal conductance

As stated in Sec. 1, the actual goal of this work was to experimentally demonstrate that the BLD can rest on the scintillating or luminescent crystal, sharing a negligible heat conductance with it. The results in the previous Section can be exploited to compare the weights: 1.1 g in the case of the wafer resting onto the TeO$_2$ crystal, 34 g in this last setup. Their ratio, assuming no light emission, then we have simply given by the ratio 5.8 eV/5407 keV ∼ 10$^{-6}$.

An extremely low heat conductance was instead determined in static conditions: we measured the base resistance of the BLD as 223.5 MΩ (corresponding to 11.8 mK), being the TeO$_2$ thermistor unbiased (i.e. no power dissipated on it). We then gave the maximum (allowed by our biasing set-up) bias to the TeO$_2$ thermistor, corresponding to 4.8 nA: the TeO$_2$ thermistor changed its resistance from 626 MΩ (bias → 0) to 1.71 MΩ, being the power dissipated on it (and therefore on the TeO$_2$) 40 pW. The base resistance of the BLD decreased to 222.8 MΩ, that corresponds to a temperature increase of only ∆T ≈ 4.3 μK. The same operation was performed with the BLD in working condition, i.e. bias current of 3.7 nA and a resistance of 1.47 MΩ (corresponding to ∼23 mK). No variation of the baseline of the BLD was registered.

A further investigation of the thermal conductance between Ge-BLD and TeO$_2$ was performed exploiting a small TeO$_2$ crystal of (20 × 20 × 14) mm$^3$, with a mass of 34 g. We used a standard BLD (same thickness and height of the previous), with the Ge wafer held by PTFE clamps in a standalone Cu mounting [13]. This time, however, it was the 34 g crystal (through the (20 × 20) mm$^2$ surface) resting onto the Ge wafer. The TeO$_2$ crystal was surrounded with the same reflecting foil and equipped with a NTD thermistor. We performed the same measurement described in Sec. 4.2 with the same overall setup. This time the mean signal registered in the BLD in coincidence with a 5304 keV $^{210}$Po decay occurring in the TeO$_2$ was measured as (317 ± 29) eV, definitively not compatible with the result of Sec. 4.2. The mean light signal registered in coincidence with the 2615 keV γ-line of $^{208}$Tl was, instead (336 ± 5) eV. The α-induced signal in the BLD, therefore, has to be ascribed to an effective heat (phonon) cross talk from TeO$_2$ to BLD. We can make a very rough estimation of the size of this heat cross talk using the results of the measurement of Sec. 4.2 if we assume the heat conductance to be linearly proportional to the pressure force between the two mediums, then we have simply to compare the weights: 1.1 g in the case of the wafer resting onto the TeO$_2$ crystal, 34 g in this last setup. Their ratio, i.e. 31, should be, in first approximation, the ratio between the thermal conductance in the two setups: ascribing the α signal of Sec. 4.2 exclusively to heat cross talk, then we would expect a cross talk heat signal of (180 ± 90) eV, that is compatible with
the one (317 eV) observed this time. On the other hand, under the same assumption, we can evaluate the 2615-keV induced Cherenkov light signal of this crystal as the difference between the observed signal and the re-scaled heat cross talk evaluated from the $\alpha$. In this way we get that the Cherenkov light emission in this 34 g crystal is $(185 \pm 15)$ eV.

6. Conclusions

We demonstrated the possibility to run BLDs simply resting on the surface of the corresponding scintillating crystal. With this new mounting method the light collection can increase up to 50% with respect to standard setups. We do not observe appreciable heat flow between scintillating crystal and BLD. We also improved the time response of our thermistor-based light detectors, reaching a rise time of 0.8 ms and demonstrating that 0.5 ms is achievable. We reached a baseline resolution of 20 eV RMS, more than 2 times better with respect to our previous CUPID-0-like detectors. Thanks to these developments, we definitively demonstrated that standard thermistor-based BLDs can be used for CUPID both to read out the tiny Cherenkov light of TeO$_2$ as well as read out Mo-based scintillating crystals, in which the time response is fundamental to get rid of the background induced by the pile-up of the 2$\nu$-DBD mode.

We do believe that this simplified technique could be applied to any kind of BLD, irrespective of the sensor type: in first approximation the thermal conductance between crystal and BLD does not depend upon the energy of the phonons, so that also in case of TES and/or MMC the possible heat cross-talk should be negligible.

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