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An innovative bolometric Cherenkov-light detector for a double beta decay search

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ABSTRACT

We present here an innovative cryogenic light detector capable to measure a few tens of eV signal thanks to the amplification assisted by the Neganov–Luke effect. The thermal signal boost in the presence of an electric field allows us to improve the signal-to-noise ratio reaching a baseline noise of around 20 eV. This device – coupled to an enriched ^{130}TeO$_2$ bolometer (435 g) – registered 160 eV Cherenkov light signal induced by 2615 keV^{208}Tl with a signal to noise ratio about 6:1. Since α particles emitted in decays of natural radionuclides do not produce the Cherenkov radiation, we were able to achieve an efficient α/γ separation in the region of interest for neutrinoless double beta decay of^{130}Te (Q-value is 2527 keV). Specifically, a rejection factor of 99.9% for α particles was obtained with a 98.3% acceptance of β/γ events. The achieved α rejection efficiency is required to reduce the dominant α background in the follow-up of the CUORE experiment (CUPID), a ton-scale bolometric search with particle identification.

1. Introduction

Neutrinoless double beta ($0\nu2\beta$) decay [1] is a hypothetical nuclear transition which requires neutrino to be a Majorana particle ($\nu \equiv \bar{\nu}$). The existence of this process would imply new physics beyond the Standard Model demonstrating the violation of the lepton-number-conservation law. Also this discovery would allow the measurement of the still unknown absolute mass scale of neutrino.

CUORE (Cryogenic Underground Observatory for Rare Events), a ton-scale experiment based on 988 TeO$_2$ bolometers (cryogenic detectors) of 0.75 kg mass each, is searching for the $0\nu2\beta$ decay of ^{130}Te isotope [2], which should manifest itself as a 2527-keV peak at the total energy of the two electrons emitted. According to simulations [3], CUORE is not a zero-background experiment. The main contribution to the background consists of α particles with degraded energy emitted by the surfaces close to the crystals. A clever solution to suppress this kind of background is the detection of Cherenkov light to discriminate β/γ

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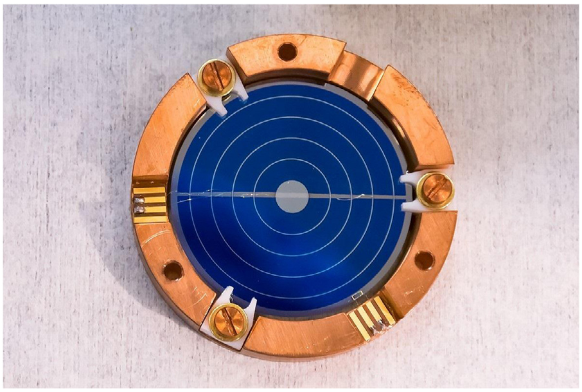

Fig. 1. Neganov–Luke-effect-assisted light detector.

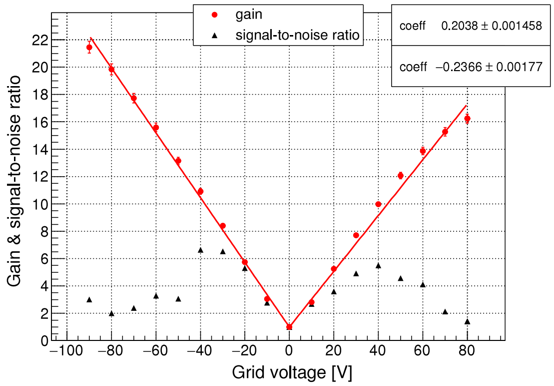

Fig. 2. Gain (in red) and signal-to-noise ratio (in black) as a function of the voltage bias applied on the grids together with a fit.

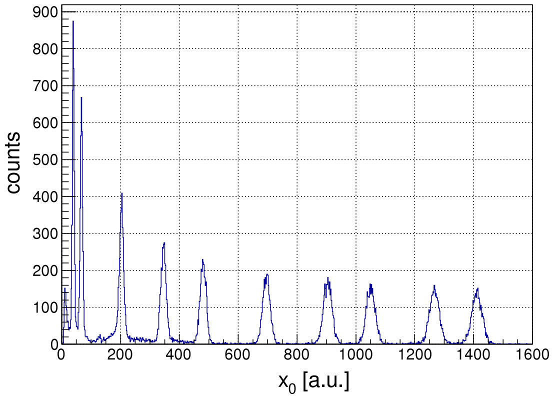

Fig. 3. Distribution of the LED-induced-photon energies acquired by the light detector. The peaks width depends on the number of photons collected.

particles from αs [4]. As a matter of fact, only electrons in the region of interest have enough energy to pass the Cherenkov-light-production threshold (50 keV for electrons and 400 MeV for αs). The Cherenkov light collected from a CUORE-size crystal is around 100 eV for a 2527-keV-energy deposition, which is comparable to the baseline noise of a standard-performance light detector with semiconductor–thermistor technology [5]. The development of a light detector technology able to reveal this tiny signal is strongly needed in CUPID (CUORE Upgrade with Particle IDentification) [6,7].

2. Neganov–Luke-effect-assisted light detectors

The standard performance of a light detector can be enhanced by exploiting the Neganov–Luke effect [8,9]. The electron–hole pairs produced by an energy deposition E_0 are drifted inside the semiconductor crystal in presence of an electric field set by an external applied voltage V. The total energy budget is:

$$E = E_0 + q\frac{E_0}{\epsilon}V = E_0\left(1 + \frac{q \cdot V}{\epsilon}\right) = E_0 \cdot G, \qquad (1)$$

where q is the electron charge, ϵ is the energy needed to create an electron–hole pair[1] and G is the gain. The light detector linearity is preserved also in the Neganov–Luke regime since the thermal gain is proportional to the number of electron–hole pairs produced.

A batch of Neganov–Luke-assisted light detectors was constructed at CSNSM (Orsay, France), whose typical fabrication procedure is as follows. The absorber – constituted by an electronic grade germanium wafer with a size of Ø44 × 0.17 mm – is bombarded with argon ions in order to remove the germanium oxide improving the adherence of its following depositions. Then a 500-Å-hydrogenated-amorphous-germanium layer is deposited. 1000-Å-thick aluminium electrodes – used to apply the electric field in the semiconductor – are evaporated to form a grid of concentric rings. Finally, a 700-Å-SiO layer is deposited on the surface to improve the light collection [10]. A neutron-transmutation-doped germanium (NTD-Ge) thermal sensor is then glued with Araldite glue on the wafer. The absorber is mounted inside a copper holder with PTFE clamps. The NTD-Ge is bonded with 25-μm-diameter gold wires to Kapton pads placed on the copper holder, while the bonding of the electrodes is done with 25-μm-diameter aluminium wires in such a way that the voltage is applied between nearby electrodes. Fig. 1 shows a photograph of a Neganov–Luke-assisted light detector.

3. Detector characterization

A batch of Neganov–Luke light detectors was tested in a pulse-tube cryostat [11] at CSNSM. During the measurement the devices underwent a typical characterization to estimate their gain and signal-to-noise ratio (SNR), performed with LED light. To this end, the cryostat is equipped with two optical fibres that transmit the light of a LED – working at room temperature – to the detectors cooled down at temperatures of the order of 15 mK. In the present work we used a 820-nm-wavelength LED, driven by a waveform generator.

The Neganov–Luke gain has been evaluated for all the light detectors measuring the amplitude variation of the same LED pulse as a function of the bias applied on the grids. This measurement showed a reproducible performance for these devices. Fig. 2 shows the gain and the SNR obtained at different bias for one of these detectors. This characterization is important to choose the best working point with maximal SNR.

We have performed an absolute photon-statistics calibration of one light detector using the LED. For this purpose we acquired a large number of LED pulses at different energies. The measured amplitudes (x_0) are proportional to the number of photons collected (N):

$$x_0 = a \cdot N. \qquad (2)$$

Fig. 3 shows the histograms of acquired-LED-event amplitudes with the evident enlargement of the width of the Gaussians as the number of photons increase. We can assume that the width is constituted by a constant component (σ_0) – whose main contribution is the baseline noise fluctuation – and the second term (σ_{ph}) which depends on the photon statistics:

$$\sigma^2 = \sigma_0^2 + \sigma_{ph}^2. \qquad (3)$$

Since photons follow a Poissonian distribution we can rewrite the width as follow:

$$\sigma^2 = \sigma_0^2 + (a\sqrt{N})^2 = \sigma_0^2 + a \cdot x_0. \qquad (4)$$

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[1] E_0/ϵ is the number of electron–hole pairs created.

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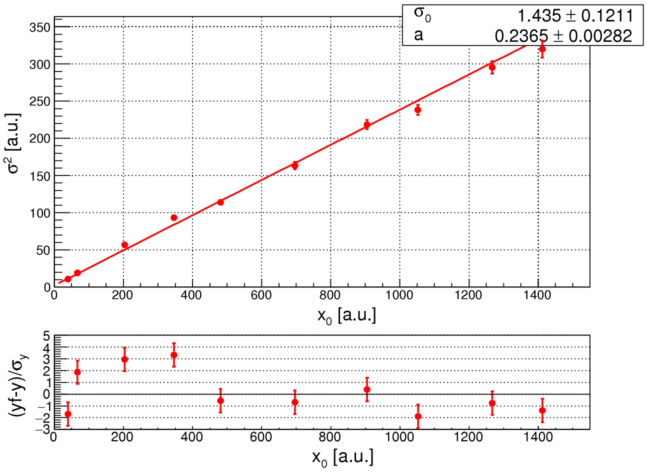

Fig. 4. Squared widths of the peaks reported in Fig. 3 as a function of their energy and on the bottom their residuals with 1σ uncertainty.

Table 1
Light detector performance obtained in the measurement at the LNGS.

Grids bias [V]	Baseline RMS [eV]	Sensitivity [μV/keV]	Gain
0	87	1.3	1
55	25	11.6	9

Fig. 4 shows the distribution of σ^2 as a function of the amplitudes acquired. We calibrated the detector by using the experimental results of the fit and the energy of the LED photons. The detector showed a sensitivity of 22 μV/keV at 50-V-applied bias. The expected gain at 50 V is 13, so the deduced sensitivity of the detector with grounded grids is 1.7 μV/keV.

4. TeO_2 cherenkov light tagging by Neganov–Luke light detector

A Neganov–Luke-assisted light detector has been coupled to an enriched $^{130}TeO_2$ crystal (435 g) and measured at LNGS (Laboratori Nazionali del Gran Sasso, Italy), as described in [12]. The detectors have been operated at 13 mK in the CUPID R&D cryostat. The TeO_2 crystal was kept by PTFE clamps in a copper support and it was surrounded by a reflecting foil to increase the light collection.

The light detector performance obtained in this measurement are summarized in Table 1. The calibration of the light detector has been performed with a ^{55}Fe source (5.9 and 6.5 keV X-rays). The Cherenkov light energy – emitted by ^{208}Tl quanta (2615 keV) – was measured with grounded grids during the calibration. This light released 160 eV in the detector, but the noise did not allow the separation between the β/γ events and the αs. Data have been acquired with 55-V-grids bias to maximize the SNR. In this configuration we obtained an acceptance of 98.3% of β/γ events rejecting the 99.9% of α events. The achieved separation between β/γ and α fulfils the requirement of CUPID experiment on α rejection efficiency [6].

5. Conclusions and acknowledgements

A batch of Neganov–Luke-effect-assisted light detectors has been developed and studied at CSNSM. They have been characterized in an aboveground cryostat in terms of gain and SNR ratio showing similar performance. The photon-statistics calibration on one light detector – performed with 50 V applied on the grids – proved that this kind of light detector can reach a sensitivity of 22 μV/keV for 820-nV-wavelength LED. One of these detectors has been measured at LNGS demonstrating its capability to distinguish β/γ events from the α background thanks to the Cherenkov light emitted by an enriched $^{130}TeO_2$ crystal of 435 g. This technology provides an acceptance level as good as 98.3% of β/γ events with only one per mille α-induced background contribution.

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References

[1] R. Henning, Current status of neutrinoless double-beta decay searches, Rev. Phy. 1 (2016) 29–35.
[2] C. Arnaboldi, et al., CUORE: A cryogenic underground observatory for rare events, Nucl. Instr. and Meth. A 518 (2004) 775–798.
[3] C. Alduino, et al., The projected background for the CUORE experiment, Eur. Phys. J. C 77 (2017) 543.
[4] T. Tabarelli de Fatis, Cerenkov emission as a positive tag of double beta decays in bolometric experiments, Eur. Phys. J. C 65 (2010) 359–361.
[5] D. Artusa, et al., First array of enriched $Zn^{82}Se$ bolometers to search for double beta decay, Eur. Phys. J. C 76 (2016) 364.
[6] G.Wang, et al., CUPID: CUORE (Cryogenic Underground Observatory for Rare Events) Upgrade with Particle IDentification, arXiv Preprint arXiv:1504.03599.
[7] G. Wang, et al., R&D towards CUPID (CUORE upgrade with particle identification), arXiv Preprint arXiv:1504.03612.
[8] B. Neganov, V. Trofimov, USSR patent no 1037771, Otkrytia I Izobreteniya 146 (1985) 215.
[9] P. Luke, Voltage-assisted calorimetric ionization detector, J. Appl. Phys. 64 (1988) 6858–6860.
[10] M. Mancuso, et al., An experimental study of antireflective coatings in Ge light detectors for scintillating bolometers, EPJ Web of Conf. 65 (2014) 04003.
[11] M. Mancuso, et al., An aboveground pulse-tube-based bolometric test facility for the validation of the LUMINEU $ZnMoO_4$ crystals, J. Low Temp. Phys. 176 (2014) 571–577.
[12] D. Artusa, et al., Enriched TeO_2 bolometers with active particle discrimination: Towards the CUPID experiment, Phys. Lett. B 767 (2017) 321–329.

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