Neganov-Luke amplified cryogenic light detectors for the background discrimination in neutrinoless double beta decay search with TeO$_2$ bolometers

M. Willers,$^{a,1}$ F. v. Feilitzsch,$^a$ A. Gütlein,$^{a,2}$ A. Münster,$^a$ J.-C. Lanfranchi,$^a$
L. Oberauer,$^a$ W. Potzel,$^a$ S. Roth,$^a$ S. Schöner,$^a$ M. v. Sivers,$^{a,3}$ S. Wawoczny,$^a$
A. Zöller$^a$ and A. Giuliani$^b$

$^a$Physik-Department E15 & Excellence Cluster Universe, Technische Universität München,
D-85748 Garching, Germany
$^b$Centre de Sciences Nucléaires et de Sciences de la Matière,
91405 Orsay Campus, France

E-mail: mwillers@ph.tum.de

ABSTRACT: We demonstrate that Neganov-Luke amplified cryogenic light detectors with Transition Edge Sensor read-out can be applied for the background suppression in cryogenic experiments searching for the neutrinoless double beta decay of $^{130}$Te with TeO$_2$ based bolometers. Electron and gamma induced events can be discriminated from $\alpha$ events by detecting the Cherenkov light produced by the $\beta$ particles emitted in the decay. We use the Cherenkov light produced by events in the full energy peak of $^{208}$Tl and by events from a $^{147}$Sm source to show that at the Q-value of the neutrinoless double beta decay of $^{130}$Te ($Q_{\beta\beta} = 2.53$ MeV), a separation of $e^-/\gamma$ events from $\alpha$ events can be achieved on an event-by-event basis with practically no reduction in signal acceptance.

KEYWORDS: Cryogenic detectors; Particle identification methods; Double-beta decay detectors; Cherenkov and transition radiation

ArXiv ePrint: 1407.6516

1Corresponding author.
2Present address: Institut für Höchenergiephysik der Österreichischen Akademie der Wissenschaften, A-1050 Wien, Austria.
3Present address: LHEP, Albert Einstein Center, University of Bern, 3012 Bern, Switzerland.
1 Introduction

The observation of the neutrinoless double beta ($0\nu\beta\beta$) decay would establish violation of lepton number conservation and the Majorana character of neutrinos. Experiments searching for the $0\nu\beta\beta$ decay are therefore considered as one of the most important experimental efforts in neutrino physics and the next generation of experiments strive to reach a sensitivity for the effective neutrino Majorana mass of $\sim 10$ meV. The key to the success of next-generation $0\nu\beta\beta$ experiments is the efficient suppression of background events while retaining a high signal acceptance. In the source-equal-to-detector approach, novel experimental concepts encompass the detection of two signals, one coming from the main detector containing the $0\nu\beta\beta$ isotope and the other one from an auxiliary device, e.g., the charge signal in germanium detectors in anti-coincidence with a liquid argon scintillation veto [1] or the simultaneous measurement of a heat signal and the emitted scintillation light with cryogenic detectors [2, 3]. The latter technique is currently being used by the direct dark matter search experiment CRESST-II (Cryogenic Rare Event Search with Superconducting Thermometers) [4, 5] to distinguish different kinds of interacting particles in CaWO$_4$ crystals by their respective light yield using two low-temperature detectors.

This technique can also be applied to experiments using non-scintillating tellurium dioxide (TeO$_2$) crystals in the search for the $0\nu\beta\beta$ decay of $^{130}$Te ($Q_{\beta\beta} = 2.53$ MeV) as proposed in [6]. The $\alpha$ background in such an experiment could be discriminated from $0\nu\beta\beta$ signal events by detecting the Cherenkov light produced by the two electrons emitted in this process. In TeO$_2$, the threshold for the production of Cherenkov light is $\sim 50$ keV for electrons and $\sim 400$ MeV for $\alpha$ particles. Thus, for $\alpha$ particles no light is being generated in the energy range of interest at $Q_{\beta\beta}$. Though the emitted $\beta$ particles are above this threshold, the amount of light being produced is very small. In the spectral range relevant for the measurement presented in this work, a total energy of only $\mathcal{O}(400 \text{eV})$ is carried by the Cherenkov photons. Previous measurements with cryogenic light

---

\footnote{We consider a spectral range from $\lambda \approx 390$ nm, where the reflectivity of the reflective foil surrounding the detector module is cut-off [7], to $\lambda \approx 1000$ nm, where the absorption of the silicon absorber exhibits a cut-off [8] (see experimental setup).}
detectors consisting of germanium absorbers, read out with neutron transmutation doped germanium thermistors (NTDs) [9, 10], successfully showed that the detection of Cherenkov radiation from TeO$_2$ crystals is possible in principle. However, in [9, 10], the sensitivity of the cryogenic light detectors was not sufficient to provide an effective event-by-event suppression which requires a high suppression efficiency of $\alpha$ induced events and a large signal acceptance simultaneously.

In this work we present the results of a measurement performed with a cryogenic light detector with transition edge sensor (TES) read-out, amplified by the Neganov-Luke (NL) effect [11, 12]. Such devices are currently being developed in the framework of the direct dark matter search experiments CRESST-II [5] and EURECA (European Underground Rare Event Calorimeter Array) [13] to investigate experimental techniques capable of further increasing the sensitivity of cryogenic light detectors at low energies. By employing the NL effect, the heat signal of particle interactions in a semiconductor absorber operated at cryogenic temperatures (\(~\Omega\)(mK)) can be amplified by drifting the created electrons and holes in an electric field applied to the absorber [12]. For optical photons, the resulting theoretical thermal gain is given by

$$G = 1 + \frac{e \cdot V_{NL}}{E_{ph} \cdot \eta}$$  \hspace{1cm} (1.1)

where $e$ is the electron charge, $V_{NL}$ the applied NL voltage, $E_{ph}$ the photon energy and $\eta$, the corresponding quantum efficiency for electron-hole pair production in the absorber material [14]. In the spectral range relevant for the measurements presented in the present work, $\eta$ is close to unity [15]. By taking advantage of the NL effect, the threshold of a cryogenic light detector as well as the detector resolution at energies below $1-2\text{keV}$ can be improved significantly [16].

2 Experimental setup

A detector module consisting of a NL light detector and a TeO$_2$ bolometer was operated in a dilution refrigerator in the shallow underground laboratory (overburden \(~\sim\) 15 m.w.e.) at the Physik-Department of the Technische Universität München, Germany. A schematic drawing of the detector module is shown in figure 1. Both detectors are mounted inside a copper housing, the inner surface of which is covered with a reflective foil (VM2002) to increase the light collection efficiency. A $20 \times 20 \times 10\text{mm}^3$ TeO$_2$ crystal with a mass of \(~\sim\) 23 g is mounted inside the housing using Teflon.
(PTFE) clamps. All sides of the crystal are roughened to reduce the amount of light trapped inside the crystal [17]. Since all sides are roughened, the IrAu transition edge sensor (TES) [18] is deposited onto a silicon carrier substrate (5 × 3 × 0.5 mm³) and then glued to the crystal. The NL light detector is a 20 × 20 × 0.5 mm³ high purity silicon light absorber with 4 aluminum electrode strips (18 × 0.2 mm² each, 6 mm separation between strips), deposited onto the side facing the crystal. In order to maintain electrical insulation between the TES and the silicon absorber, a silicon TES carrier is glued to the absorber. For the measurements presented in this work, a NL voltage of $V_{\text{NL}} = 70$ V is applied between electrodes adjacent to each other. The TeO$_2$ crystal is irradiated with $\alpha$ particles from a $^{147}$Sm ($E_\alpha = 2.3$ MeV) source consisting of a sheet of natural samarium (10 × 10 × 1 mm³). Since the $\alpha$ particles are emitted throughout the source, a flat energy spectrum of degraded $\alpha$ particles is observed (expected rate $\mathcal{O}(0.1 \text{ Hz})$).

3 Calibration of the light detector

Prior to each measurement, the light detector is calibrated using a novel calibration scheme based on photon counting statistics [19]. Short light pulses ($\sim 250$ ns) of varying intensity are generated by a light-emitting diode (LED) operated at room temperature and are guided onto the NL detector using an optical fiber (see figure 1). Since the development of these detectors is performed within the framework of direct dark matter search with CaWO$_4$ crystals, an LED matching the scintillation spectrum of these crystals is used ($\lambda_{\text{LED}} \approx 430$ nm, corresponding to a photon energy of $E_{\text{ph}} = 2.9$ eV). Figure 2 shows the detector resolution $\sigma_{\text{tot}}$ as a function of the signal amplitude for different LED intensities used for the calibration of the light detector when operated without applied NL voltage ($V_{\text{NL}} = 0$ V).

![Figure 2](image_url)

**Figure 2.** Signal amplitude and detector resolution $\sigma_{\text{tot}}$ of the light detector for the different LED intensities recorded during the LED calibration measurement performed without applied NL voltage ($V_{\text{NL}} = 0$ V). The additional x-axis on the top shows the corresponding energy scale of the light detector and the additional y-axis on the right shows the energy resolution in units of eV.

Following [19], the energy resolution $\sigma_{\text{tot}}$ of the light detector, when operated without an applied NL voltage, can be described by the following equation

$$
\sigma_{\text{tot}}(x) = \sqrt{\sigma_0^2 + \sigma_{\text{ph}}^2} = \sqrt{\sigma_0^2 + a^2 \cdot N_{\text{ph}}} = \sqrt{\sigma_0^2 + a \cdot x} \quad (3.1)
$$
where $\sigma_0$ refers to all energy-independent contributions to the detector resolution. $\sigma_{ph}$ describes the contribution due to photon counting statistics (i.e., $\sigma_{ph} = a \cdot \sqrt{N_{ph}}$) and $a$ is a conversion factor between the number of detected photons $N_{ph}$ and the corresponding signal amplitude $x$ in mV (i.e., $x = a \cdot N_{ph}$). Contributions of higher order to the energy resolution can be neglected. By fitting the function given in eq. (3.1) to the data points shown in figure 2, the factor $a$ and the energy-independent term $\sigma_0$ are determined. From the conversion factor $a$, the energy detected in the light detector when operated without NL voltage can be deduced as $E = N_{ph} \cdot E_{ph} = S_{0V} \cdot x$ where $S_{0V} = E_{ph}/a$. For the calibration measurement shown in figure 2, a conversion factor of $a = (0.298 \pm 0.006)$ mV is obtained, leading to an energy conversion factor $S_{0V} = (9.73 \pm 0.20)$ eV/mV. The energy-independent term was determined to be $\sigma_0 = (4.97 \pm 0.05)$ mV, corresponding to $(48.5 \pm 1.1)$ eV. The energy resolution (eq. (3.1)) can be written in units of eV as $\sigma_{tot}(E) = \sqrt{\sigma_0^2 + E_{ph} \cdot E}$ where $E$ is the energy detected in the cryogenic light detector.

With applied NL voltage, the observed gain is $G_{ob} = 10.8 \pm 0.1$ and an improvement in the signal-to-noise (S/N) ratio of $6.2 \pm 0.1$ is achieved. The difference between the gain and the improvement of the S/N ratio is due to additional electronic noise introduced by applying the NL-voltage. The theoretical gain predicted by eq. (1.1) is $\sim 25$ and the discrepancy to the observed value can be attributed to a reduced drift length of the charge carriers, caused by trapping in impurities and defects at the absorber surface [19]. The energy conversion factor for measurements performed with applied NL voltage can be deduced from the calibration performed without applied NL voltage as $S_{NL} = S_{0V}/G_{ob}$ [16, 20]. When operated with an applied NL voltage, an extended function which takes higher-order terms into account is used to describe the detector resolution [16, 20]:

$$\sigma_{tot} = \sqrt{\sigma_{NL}^2 + E_{ph} \cdot E + a_{cc} \cdot E + b_{rc} \cdot E^2}$$

The term $\sigma_{NL}$ describes the energy-independent contributions to the resolution when operated with applied NL voltage. The parameters $a_{cc}$ and $b_{rc}$ are physically motivated parameters [16] which take into account incomplete charge collection and charge recombination processes, respectively. These additional parameters increase the uncertainty of the detected energy and are device-specific and depend on the applied voltage. With applied NL voltage, the energy-independent term was found to be $\sigma_{NL} = (7.8 \pm 0.2)$ eV. The energy resolution of the light detector operated without and with applied NL voltage is shown in figure 3. In the energy range relevant for the detection of Cherenkov light emitted by TeO$_2$ (gray-shaded area in figure 3, 0 – 400 eV), the resolution with applied NL voltage is significantly improved while above $\sim 1.4$ keV, the resolution is deteriorated. When investigating Cherenkov light emitted from a TeO$_2$ crystal, the actual light detector resolution can differ from the resolution determined by the LED calibration since the mean wavelength and the spectral shape of the detected photons are expected to be different from the wavelength and spectral shape of the LED used. For this special case, the detector resolution still has to be studied in further detail. However, an exact knowledge of the energy dependence of the light detector resolution as well as an absolute energy calibration is not required to determine the suppression efficiency of $\alpha$ from $e^-/\gamma$ events in the measured spectra.
Figure 3. Data points recorded during the LED calibration ($\lambda_{LED} \approx 430\text{nm}$) with $V_{NL} = 0V$ (solid blue line) and $V_{NL} = 70V$ (dotted red line). In the energy range relevant for this work (gray-shaded area, $0 - 400\text{eV}$) the resolution with applied NL voltage is significantly improved. The error bars represent the $2\sigma$ errors.

4 Results

Two measurements with a $^{228}\text{Th}$ $\gamma$-source (rate $\sim 5\text{Hz}$), placed outside the cryostat, were performed in order to determine the discrimination efficiency between $\alpha$ and $e^-/\gamma$-induced events. A measurement ($\sim 16h$) without applied NL voltage and a measurement ($\sim 42h$) with applied NL voltage were performed. Figure 4 shows the energy spectrum of the TeO$_2$ crystal obtained during the 42h measurement. Prominent $\gamma$-lines emitted by the $^{228}\text{Th}$ calibration source as well as the single- and double-escape peak (SEP and DEP) of the 2.614 MeV line of $^{208}\text{Tl}$ are indicated. The plot furthermore shows the energy range of the $\alpha$ particles emitted by the $^{147}\text{Sm}$ source and the $\mu$-induced events, visible above an energy of $\sim 3\text{MeV}$. Figure 5 top and bottom display the results of the measurements without and with applied NL voltage, respectively.

Figure 4. Energy spectrum of the TeO$_2$ crystal obtained during the 42h measurement. The energies of prominent $\gamma$ lines emitted by the $^{228}\text{Th}$ calibration source and the single- and double-escape peak (SEP and DEP) of the 2.614 MeV line of $^{208}\text{Tl}$ are indicated.

The energy calibration of the light detector is based on the results of the LED calibration [16, 19, 20], the calibration of the TeO$_2$ detector is performed using $\gamma$-peaks from the $^{228}\text{Th}$ source.
Figure 5. Two-dimensional histogram of the measurements performed without (top) and with applied NL voltage (bottom). In the measurements, events induced by the $^{228}$Th source (inclined band), by the $^{147}$Sm $\alpha$-source (horizontal band, only visible with applied NL voltage) and muon-induced events (inclined band above $\sim$ 2.6 MeV) are visible.

In both spectra shown in figure 5, $e^{-}/\gamma$ events (inclined band) and $\alpha$ events (horizontal band) are present. However, the population of $\alpha$-induced events can only be distinguished from $e^{-}/\gamma$ events when the NL voltage is applied to the detector. Both measurements also include events induced by atmospheric muons which can be identified at energies $>$ 2.6 MeV. At the full energy peak of $^{208}$Tl (2.614 MeV), an energy resolution of $\Delta E_{FWHM} = 67$ keV is achieved in the phonon detector. The observed resolution is worse by a factor of $\sim$ 10 than the resolution achievable with CRESST-type cryogenic detectors with TES read-out ($\Delta E_{FWHM} = 6.7$ keV at 2.31 MeV) [21]. This is probably caused by an acoustic mismatch between the silicon TES carrier and the TeO$_2$ crystal or due to a poor glue-interface between the crystal and the carrier. Since only one TeO$_2$ crystal was available for the measurements performed in the present work, no further tests concerning the energy resolution could be performed.

As reported in [19], NL light detectors, when operated with an applied NL voltage, can exhibit a reduction of the observed gain with time due to an accumulation of charge carriers in the vicinity of the aluminum electrodes. This causes an electric field with reverse polarity with respect to the applied voltage and therefore reduces the effective NL voltage. In the measurement presented here, a reduction of the gain by $\sim$ 10% during the 42 h measurement, determined from the reduction of the signal amplitude of events within the full width at half maximum of the 2.614 MeV $\gamma$ line with time, is observed.

A simulation performed with Geant4 [22] shows that the total amount of Cherenkov light produced for the two electrons emitted in the $0\nu\beta\beta$ decay is practically identical to the amount of
light produced for $\gamma$ events in the full energy peak (FEP) of $^{208}\text{Tl}$ [20]. Therefore, we determine the signal in the light detector expected at $Q_{\beta\beta}(^{130}\text{Te})$ using events from the FEP of $^{208}\text{Tl}$. The signal in the light detector for $\alpha$-induced events is obtained in a reference region between 2.0 and 2.3 MeV and is assumed to be also valid at $Q_{\beta\beta}$. This has also been supported by independent measurements which show that no Cherenkov light is being produced for $\alpha$-induced events in TeO$_2$ [10]. A histogram showing the individual light-energy distributions is depicted in figure 6. We assume that all contributions can be described by normal distributions. For the measurement without applied NL voltage, the light-energy distribution of both reference regions is fitted using a single normal distribution (figure 6 top), while for the measurement with applied NL voltage, the light-energy distribution of the $\alpha$ reference region is fitted with two normal distributions (figure 6 bottom), accounting for $\alpha$ as well as $e^-/\gamma$ events. The individual fits are characterized by the mean $x_0$ and the variance $\sigma$ of the distribution. The results of the individual fits are given in table 1 and directly show the improved energy resolution of the light detector when operated with applied NL voltage. Due to a small reduction of the gain throughout the measurement (mentioned above), the mean light energy in the FEP of $e^-/\gamma$ events is slightly reduced in the measurement performed with NL voltage compared to the measurement without applied voltage.

In the measurement without applied NL voltage, the different contributions to the $\alpha$ reference region cannot be disentangled and no discrimination of $\alpha$-induced events is possible. However, in the measurement performed with applied NL voltage, the individual distributions in the $\alpha$ reference region can be clearly identified (dotted black lines in bottom panel of figure 6). The contribution of

Figure 6. Logarithmic histogram of the light energy for $\gamma$ events from the full energy peak (FEP) of $^{208}\text{Tl}$ (red) and $\alpha$ & $\gamma$ events obtained from a reference region between 2.0 and 2.3 MeV (black) for the measurement without applied NL voltage (top) and with applied NL voltage (bottom). The plots also show the normal distributions fitted to the individual histograms. The vertical (dashed, blue) line indicates the signal acceptance of 99.8% in the full energy peak when operated with applied NL voltage.
Table 1. Values obtained for the mean $x_0$ and the standard deviation $\sigma$ of individual normal fits shown in figure 4.

| $E$ [keV] | $x_0$ [eV] | $\sigma$ [eV] |
|-----------|------------|--------------|
| $V_{NL} = 0V$ | | |
| $\alpha + e^-/\gamma$ | 2000 – 2300 | 64.6 ± 0.7 | 48.8 ± 0.6 |
| $e^-/\gamma$ (FEP) | 2581 – 2647 | 81.2 ± 0.9 | 44.0 ± 0.9 |
| $V_{NL} = 70V$ | | |
| $\alpha$ | 2000 – 2300 | 2.9 ± 0.3 | 7.1 ± 0.3 |
| $e^-/\gamma$ | 2000 – 2300 | 65.6 ± 0.2 | 20.4 ± 0.2 |
| $e^-/\gamma$ (FEP) | 2581 – 2647 | 77.5 ± 0.3 | 19.5 ± 0.2 |

The $\alpha$ events can be clearly separated from the $e^-/\gamma$ events in the full energy peak.\(^2\) We determine the efficiency of the $\alpha$-suppression by requiring a high signal acceptance in the full energy peak, i.e., a threshold in the light detector is chosen in such a way that 99.8% of all events in the FEP are accepted, which leads to a threshold of 19.0 eV (blue line in figure 6). From the distribution of the $\alpha$ events in the $\alpha$ reference region it follows that the amount of $\alpha$ events above this threshold is $\sim 1\%$. These results show that, for energies close to $Q_{\beta\beta}(^{130}\text{Te})$, $e^-/\gamma$ events can be discriminated from $\alpha$-induced background events on an event-by-event basis. For comparison with ref. [9], we calculate a separation between the distributions of $\alpha$- and $\gamma$-induced events at energies close to $Q_{\beta\beta}(^{130}\text{Te})$ of $x_0, e^-/\gamma - x_0, \alpha = 10.5 \sigma_\alpha$ (see table 1), demonstrating the excellent separation which allows for the first time to perform an event-by-event separation of the individual distributions. Furthermore, the light collection efficiency in the detector module can be calculated as the ratio between the expected signal ($\sim 400$ eV) and the observed signal ($\sim 80$ eV) and is $\sim 20\%$. By increasing the coverage of the detector module with the light reflecting foil, the light collection efficiency can be increased further, leading to an increased separation between the distributions.

The sensitivities predicted for next-generation experiments searching for the neutrinoless double beta decay of $^{130}\text{Te}$ with TeO\(_2\) based cryogenic bolometers crucially depend on the background level in the region of interest (ROI) around $Q_{\beta\beta}$ [23]. A significant reduction of the background level is the key to overcoming this limiting factor of the sensitivity. The CUORE-0 (Cryogenic Underground Observatory for Rare Events) experiment [24], employing TeO\(_2\) based cryogenic detectors, reports background levels of 0.019 cts/keV/kg/yr in the flat $\alpha$ continuum region between 2.7 MeV and 3.4 MeV. This value allows to anticipate a background level for CUORE [25] of the order of 0.01 cts/keV/kg/yr. The results presented here show that a further $\alpha$ background reduction of about two orders of magnitude is achievable using the phonon-light technique with NL amplified cryogenic light detectors. Therefore, the contribution of the $\alpha$ background in the ROI around $Q_{\beta\beta}$ in next-generation TeO\(_2\) experiments implementing this technology is compatible

---

\(^2\)With applied NL voltage, the mean light energy $x_0$ of the $\alpha$ events is $\sim 2.9$ eV (see table 1). This systematic, energy-independent offset is present when the light detector is operated with applied NL voltage and is caused by a small cross-talk between both detectors. The width of the distribution of $\alpha$-induced events is compatible with the noise present in the light detector, indicating that, in fact, no light is being detected.
with a background index of $10^{-4}$ cts/keV/kg/yr, which corresponds to a total $\alpha$ background close to zero at the ton$\times$year exposure scale, given the excellent energy resolution already achieved by TeO$_2$ bolometers [24].

The background suppression technique described in the present work can provide an important contribution to future experiments by providing the ability to actively discriminate $\alpha$ induced background from $e^-/\gamma$ events with a high efficiency, while at the same time, retaining a high signal acceptance. However, an important aspect, which has to be considered by the individual experiments when incorporating such light detectors in future-generation searches, is a possible introduction of additional backgrounds into the experiment, especially due to the additional wiring required to operate the detectors. Another aspect to be taken into account is related to the crystal size. Due to practical reasons, the crystals used in bolometric arrays searching for $0\nu\beta\beta$ have masses in the $500\text{ g} - 1000\text{ g}$ range and it is therefore important to show in future tests that the suppression factor achieved in this work can also be reached with such larger crystals. Recent measurements have shown that a background suppression as demonstrated in the present work can also be achieved in larger TeO$_2$ crystals (mass $\sim 280\text{ g}$) [26]. For future systematic studies of the background suppression efficiency, the light collection efficiency in the detector module and the dependence on the optical properties of TeO$_2$ crystals (e.g. the absorption and scattering lengths) and crystal shape have to be studied in further detail. Simulations performed in [20] show that the detectable amount of Cherenkov radiation produced in a TeO$_2$ crystal could be increased by a factor of $\sim 2$ by using a reflector foil with a higher reflectivity in the UV compared to the presently used VM2002 foil. Furthermore, recent work [16, 20] indicates that light detectors based on NL technology can be improved even further, in particular with respect to a reduction of the thermal gain with time and the achievable thermal gain and, therefore, to S/N ratio.

5 Conclusion

We demonstrate for the first time, that an event-by-event discrimination between $e^-/\gamma$ and $\alpha$-induced events at $Q_{\beta\beta}(^{130}\text{Te})$ in TeO$_2$ based bolometers is possible using NL light detectors. We reach an $\alpha$-suppression of 99% while accepting 99.8% of $e^-/\gamma$ events at the full energy peak of $^{208}\text{Tl}$. The achieved suppression factor could be further improved by an increased light collection efficiency of the detector module (due to the presence of the Sm source and to accommodate electrical and mechanical feed-throughs, the detector housing was not completely covered with the reflective foil [20]) and by further enhancing the performance of the NL light detector, in particular concerning the achieved gain and the electronic noise introduced by the application of the NL voltage.

Acknowledgments

We gratefully acknowledge the support of the DFG cluster of excellence “Origin and Structure of the Universe”, the “Helmholtz Alliance for Astroparticle Phyiscs”, and the “Maier-Leibnitz-Laboratorium”, Garching.
References

[1] M. Heisel et al., LArGe R&D for active background suppression in Gerda, *J. Phys.: Conf. Ser.* **375** (2012) 042009.

[2] J.W. Beeman et al., Current Status and Future Perspectives of the LUCIFER Experiment, *Adv. High En. Phys.* **2013** (2013) 237973.

[3] L. Bergé et al., Purification of molybdenum, growth and characterization of medium volume ZnMoO$_4$ crystals for the LUMINEU program, *2014 JINST 9 P06004*.

[4] G. Angloher et al., Commissioning run of the CRESST-II dark matter search, *Astropart. Phys.* **31** (2009) 270.

[5] G. Angloher et al., Results from 730 kg days of the CRESST-II Dark Matter Search, *Eur. Phys. J. C* **72** (2012) 1971 [arXiv:1109.0702].

[6] T. Tabarelli de Fatis, Cerenkov emission as a positive tag of double beta decays in bolometric experiments, *Eur. Phys. J. C* **65** (2010) 359.

[7] M. Janeczek, Reflectivity Spectra for Commonly Used Reflectors, *IEEE Trans. Nucl. Sci.* **59** (2012) 3.

[8] M.A. Green, Self-consistent optical parameters of intrinsic silicon at 300 K including temperature coefficients, *Sol. Energ. Mat. Sol. Cells* **92** (2008) 1305.

[9] J.W. Beeman et al., Discrimination of $\alpha$ and $\beta / \gamma$ interactions in a TeO$_2$ bolometer, *Astropart. Phys.* **35** (2012) 558 [arXiv:1106.6286].

[10] N. Casali et al., TeO$_2$ bolometers with Cerenkov signal tagging: towards next-generation neutrinoless double beta decay experiments, *Eur. Phys. J. C* **75** (2015) 12 [arXiv:1403.5528].

[11] B. Neganov and V. Trofimov, USSR Patent No 1037771, Otkryt. Izobret. **146** (1985) 215.

[12] P.N. Luke, Voltage-assisted calorimetric ionization detector, *J. Appl. Phys.* **64** (1988) 6858.

[13] G. Angloher et al., EURECA Conceptual Design Report, *Phys. Dark Univ.* **3** (2014) 41.

[14] M. Stark et al., Application of the Neganov-Luke effect to low-threshold light detectors, *Nucl. Instrum. Meth. A* **545** (2005) 738.

[15] V.S. Vavilov, On photo-ionization by fast electrons in germanium and silicon, *Phys. Chem. Solids* **8** (1959) 223.

[16] S. Roth, The Potential of Neganov-Luke Amplified Cryogenic Light Detectors and the Scintillation-Light Quenching Mechanism in CaWO$_4$ Single Crystals in the Context of the Dark Matter Search Experiment CRESST-II, Ph.D. Thesis, Technische Universität München, Germany (2013), http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss-20130930-1172019-0-2.

[17] F.A. Danevich et al., Optimization of light collection from crystal scintillators for cryogenic experiments, *Nucl. Instrum. Meth. A* **744** (2014) 41 [arXiv:1402.2241].

[18] U. Nagel et al., Proximity effect in iridium-gold bilayers, *J. Appl. Phys.* **76** (1994) 4262.

[19] C. Isaila et al., Low-Temperature Light Detectors: Neganov-Luke Amplification and Calibration, *Phys. Lett. B* **716** (2012) 160 [arXiv:1106.0167].

[20] M. Willers, Background Suppression in TeO2 Bolometers with Neganov-Luke Amplified Cryogenic Light Detectors, Ph.D. Thesis, Technische Universität München, Germany (2015), http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss-20150127-1236050-0-7.
[21] C. Cozzini et al., Detection of the natural alpha decay of tungsten, Phys. Rev. C 70 (2004) 064606 [nucl-ex/0408006].

[22] GEANT4 collaboration, S. Agostinelli et al., GEANT4: A simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250.

[23] F. Alessandria et al., Sensitivity of CUORE to Neutrinoless Double-Beta Decay, arXiv:1109.0494.

[24] CUORE collaboration, D.R. Artusa et al., Initial performance of the CUORE-0 experiment, Eur. Phys. J. C 74 (2014) 2956 [arXiv:1402.0922].

[25] CUORE collaboration, C. Arnaboldi et al., CUORE: a cryogenic underground observatory for rare events, Nucl. Instrum. Meth. A 518 (2004) 775 [hep-ex/0212053].

[26] K. Schäffner et al., Particle Discrimination in TeO$_2$ Bolometers using Light Detectors read out by Transition Edge Sensors, arXiv:1411.2562.