

BINGO: background reduction techniques for $0\nu2\beta$ bolometric experiments

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Abstract. BINGO is a project dedicated to explore new methods for background reduction in experiments searching for $0\nu2\beta$ decay. It is based on bolometers, one of the most promising techniques to search for $0\nu2\beta$. CUORE and CUPID-Mo/0 are the main bolometric experiments that have illustrated the most relevant limiting factors on sensitivity the bolometers are facing. Surface α s are the main source of background in CUORE, and this contribution has been mitigated in CUPID-Mo/0 using dual heat-light channels, i.e., a main absorber embedding the 2β decay isotope facing a light detector. In this case, surface α rejection is achieved thanks to the lower α light output compared to β/γ . However, there are still other background components that limit the sensitivity of the experiments, such as pile-ups due to random coincidences of physical events, external γ background and β surface radioactivity. BINGO's proposed technology aims at reducing the background index down to 10^{-5} counts/(keV kg yr) in the region of interest, thus boosting the sensitivity on the effective Majorana neutrino mass. This can be achieved by: (i) having a revolutionary detector assembly with a reduction in the passive materials facing the detector; (ii) increasing the light detector sensitivity thanks to Neganov-Luke amplification; (iii) using an active shield, based on BGO scintillators with bolometric light detector readout to surround the experimental volume. The main text describes the listed approaches in detail, as well as the recent results of prototype tests.

1 Introduction

Neutrinoless double-beta decay ($0\nu2\beta$) is a hypothetical lepton-number violating process that was proposed by W. H. Furry in 1939 [1]. It can occur when an even-even nucleus (A, Z) decays into its isobar ($A, Z+2$) with the emission of two electrons. Searching for this decay is currently the only way to prove experimentally that neutrinos are Majorana particles ($\nu = \bar{\nu}$). The signature of $0\nu2\beta$ decay is a monochromatic peak at the Q -value ($Q_{\beta\beta}$) of the transition corresponding to the energy sum of the two emitted electrons. There are many experiments digging their way to discover this decay, however, there are many challenges on the way that needs to be overcome to boost their sensitivity. One of the most limiting factors to search for this decay are the backgrounds from various components. In fact, we expect very few events in the region of interest (ROI) coming from this decay because of the very long half-life (the best current limits are $> 10^{24-26}$ yr, depending on the 2β isotope [2]), which can be easily buried in the background. BINGO (Bi-Isotope $0\nu2\beta$ Next Generation Observatory), an ERC funded project, focuses on introducing new methods to mitigate the backgrounds. It aims to set the ground for large-scale next generation bolometric experiments to be capable of exploring the inverted hierarchy region and a part of the normal region thanks to the very low expected background index of about 10^{-5} counts/(keV kg yr). The three main background components that will be fought against are: pile-ups (espe-

cially those due to random coincidences of events from the relatively fast $2\nu2\beta$ decay of ^{100}Mo), external γ radioactivity and near surface radioactivity. BINGO will study two 2β decay isotopes: ^{100}Mo ($Q_{\beta\beta} = 3034$ keV) and ^{130}Te ($Q_{\beta\beta} = 2527$ keV), they will be embedded respectively in Li_2MoO_4 and TeO_2 crystals, which will be operated as bolometric detectors. The project will bring original improvements to the well-established technology of the dual heat-light readout, demonstrated by CUPID-Mo [3, 4] and CUPID-0 [5]: (i) a revolutionary detector assembly that will reduce the total surface radioactivity contribution by at least one order of magnitude; (ii) the light-detector sensitivity will be increased by one order of magnitude thanks to Neganov-Luke amplification that can help achieve pile-ups rejection; (iii) for the first time in an array of macrobolometers, an internal active shield will be used, based on BGO scintillators with scintillation light readout, that will suppress the external γ background and surface contamination from crystals facing it using coincidence cuts. This paper will describe the foreseen BINGO demonstrator “mini-BINGO” that will be operated in a pulse-tube cryostat at Modane Underground Laboratory (LSM), in addition to some of the prototype tests results.

2 Mini-BINGO demonstrator

The mini-BINGO demonstrator will be composed of two towers: one tower will consist of 12 Li_2MoO_4 crystals ($45 \times 45 \times 45$ cm³) and the other of 12 TeO_2 crystals ($50 \times 50 \times 50$ cm³). The tower is arranged in 6 floors,

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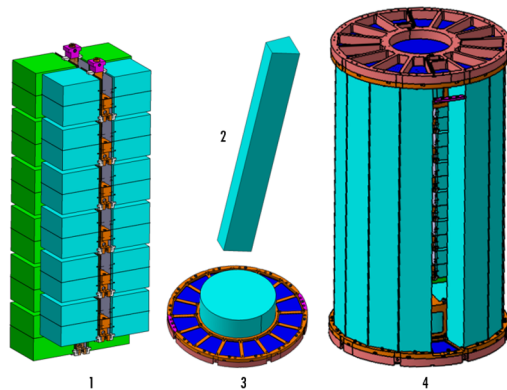


Figure 1. All the components of mini-BINGO. (1) The Li_2MoO_4 and TeO_2 towers coupled to LDs. (2 & 3) The active veto, consisting of 16 BGO bars on the lateral and 2 BGO cylinders on top and bottom. Each scintillator will be coupled to a NL LD. (4) The full mini-BINGO design, the $0\nu 2\beta$ detectors (towers) surrounded by the active veto (one BGO scintillator is not shown for the internal set-up structure visibility).

each floor will host two crystals, each crystal will be coupled to a Ge light detector with the same dimensions as the crystal face. The light detectors (LD) will be based on the Neganov-Luke (NL) effect in order to improve their performance [6, 7]. In addition, the towers will be surrounded by an active veto which will consist of BGO scintillators coupled to NL LDs to register the scintillation signal after particle interaction. Fig. 1 summarizes the design.

2.1 Assembly design

The design that BINGO proposes for the detector's assembly is based on three concepts: less passive material in the detectors array volume, open structure to exploit coincidence cuts and easiness of assembly. Each module consists of a copper piece that acts as the main support for the module. Three PTFE pieces are fixed on each side of the copper piece to keep the LDs and the crystals. A 0.35 mm slot is made in all PTFE pieces to sandwich the 0.3 mm LDs (Fig. 2). Against the same PTFE pieces the crystal is fixed. A nylon wire with a diameter of 0.45 mm presses the crystal to the copper holder, its ends are locked with a screw to the copper support. Like this, the crystals and the LDs are fixed from moving. The tension exerted by the nylon wire on the crystals is calibrated to 4 kg per wire side using a torque screwdriver. All the single modules are connected together using a rope to get the full tower. The detectors are equipped with a Ge-NTD (neutron transmutation doped) thermistors to register the temperature variation after particles interaction. The Ge-NTD ($3 \times 3 \times 1 \text{ cm}^3$ on crystals and $3 \times 1 \times 1 \text{ cm}^3$ on LDs) is glued to the crystals using Araldite® rapid epoxy glue. The Ge-NTDs have gold pads which are bonded to kapton with also gold pads that are placed on the copper piece to have the electrical and thermal contact.

This compact design allows us to have a reduction by more than one order of magnitude in passive materi-

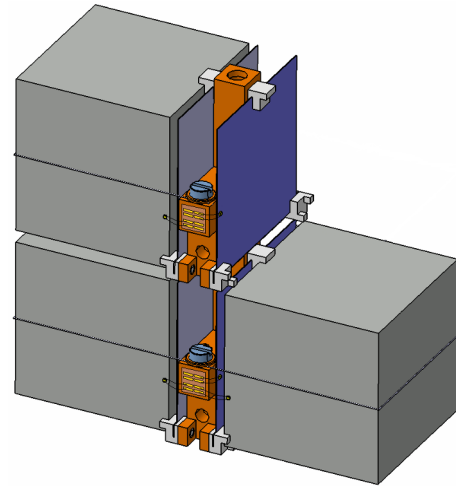


Figure 2. A scheme showing two detectors module. Each module consists of two crystals and two LDs that are fixed using a nylon wire.

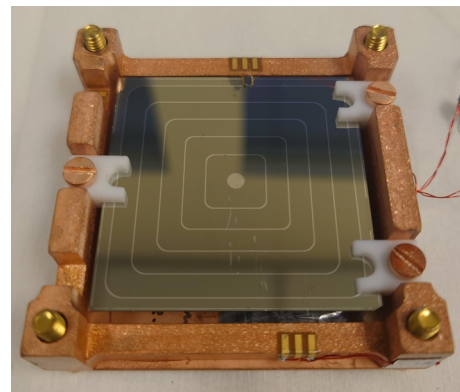


Figure 3. A NL square LD with concentric rounded corners square electrodes.

als surrounding the 2β decay detectors compared to the standard way of keeping bolometers [3–5]. Furthermore, this design allows us to have surface background rejection through anti-coincidence between crystals. Another feature for this design is exploiting the LDs to shield the crystals from the main copper pieces, the only passive material along with the nylon wire. The latter composes only a tiny fraction of passive material surface, around 2 cm^2 .

2.2 Neganov-Luke light detectors

The second technological innovation in BINGO is the development of a bolometric light detector enhanced by the Neganov-Luke effect. It will consist of a thin Ge wafer (0.3 mm) with Al electrodes deposited on it. Biasing the electrodes will result in an electric field in the wafer which will drift the electron-hole pairs produced by the absorbed light. The work done by the field on the charge carriers contributes with an additional heat (it is a manifestation of the Joule effect), magnifying the signal-to-noise ratio in the thermal signal by a significant factor (10-20

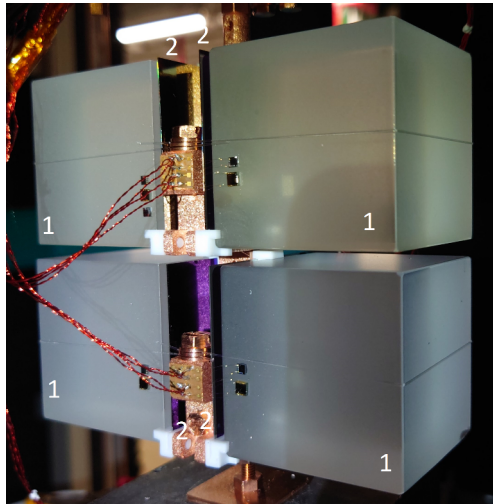


Figure 4. Two modules of the nylon wire assembly hosting four Li_2MoO_4 (1) each coupled to a standard LD (2) tested at LSC.

in gain depending on the maximum applied bias possible, i.e. the strength of electric field). The target of BINGO is to be able to detect the light signal corresponding to a $0\nu 2\beta$ event, which amounts to ~ 3 keV in the case of the scintillation signal in Li_2MoO_4 and to only ~ 100 eV in the case of the prevalent Cherenkov signal in TeO_2 . An α particle releasing the same energy as a $0\nu 2\beta$ event would produce only $\sim 15\%$ of scintillation light in Li_2MoO_4 [3] and no Cherenkov light at all in TeO_2 [8], allowing for its safe rejection by the comparison of the heat and light signals. BINGO light detectors aim at a baseline width of only ~ 3 eV RMS. This low value is essential to achieve the desired α rejection in the challenging TeO_2 case, but it is also crucial for Li_2MoO_4 , where a high signal-to-noise ratio in the light signal is required to reject the background induced by the random coincidences of the $2\nu 2\beta$ events, which is very challenging in the ^{100}Mo case because of the relatively fast $2\nu 2\beta$ process ($T_{1/2} = 7 \times 10^{18}$ yr). Fig. 3 shows an example of a NL LD with concentric electrodes.

2.3 Active veto

For the first time in a large array of macro-bolometers, an almost-hermetic active inner shield will be developed, surrounding completely the BINGO detectors. The first function of this shield is to reduce the contribution coming from external γ radioactivity, especially from the 2615 keV line of ^{208}Tl , but also some low-intensity characteristic γ 's of ^{214}Bi (belonging to the ^{238}U chain and related to ^{226}Ra and radon progeny) above 2615 keV. The second function is to reject surface radioactivity in the external crystals of the arrays, which face directly the active shield. It is very important that this shield is sensitive to surface events, otherwise these peripheral elements will not take advantage of a complete β surface rejection. We remark that this shield will operate also as a very efficient muon veto. The active shield will consist of BGO scintillator bars on the lateral and also two BGO cylinders on top and bottom. Each scintillator will be coupled to NL LD to

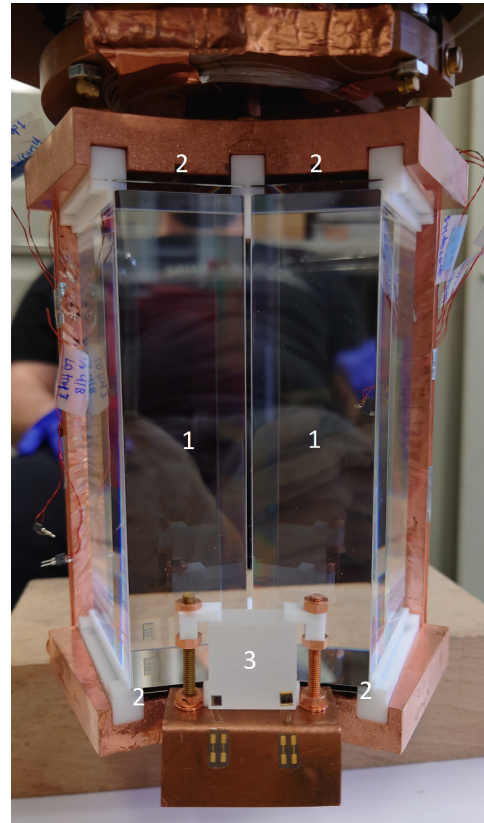


Figure 5. A section of the active veto, composed of two trapezoidal BGO bars (1), each bar is coupled to two standard Ge LDs (2). The BGOs are facing TeO_2 crystal (3) that has a U source deposited on its surface to mimic surface contamination.

register the light signal after particle interaction. It is important for the scintillator to have a low energy threshold (around 50 keV) to reject the 2615 keV γ that is specially dangerous in the case of TeO_2 ($Q_{\beta\beta} = 2527$ keV). 50 keV energy threshold in the scintillator translates to < 1 keV energy threshold in the LD, depending on the light yield (LY) which is given in keV/MeV, meaning the energy in keV detected in the LD for a 1 MeV energy deposition in the scintillator. Of course, such an energy threshold in the LD needs to be improved, and this can be realised thanks to the NL LD which will lead to an amplification of the signal to achieve few keV energy threshold (depends on LY and gain induced by the NL effect).

3 Prototype tests results

Emerging to mini-BINGO requires some prototype tests validation on all mini-BINGO ingredients: starting with the nylon wire assembly, the BGO active veto and the NL LDs. The first prototype tests on the nylon wire assembly was performed on two small $2 \times 2 \times 2 \text{ cm}^3$ Li_2MoO_4 crystals each coupled to a $2 \times 2 \text{ cm}^2$ standard LD. The performances allowed us to validate the first prototype test of the design, the baseline resolutions FWHM of the crystals were on average around 0.9 keV [9]. Then we moved to test mini-BINGO size crystals and LDs (Fig. 4). The assembly was tested first above-ground at the IJCLab (results

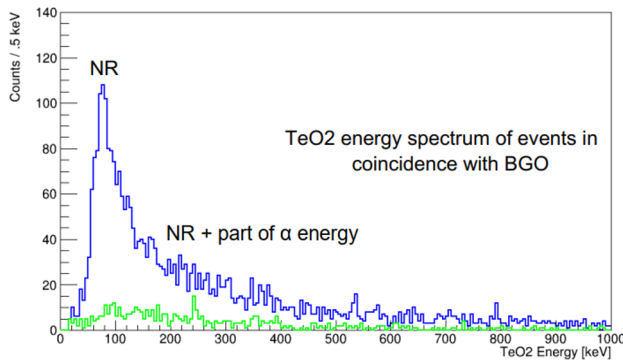


Figure 6. Blue: The energy spectrum of TeO_2 events in coincidence with BGO. The peak at low energy (~ 80 keV) represents the nuclear recoil energy and the tail to the right represents the nuclear recoil plus part of the α energy deposited in TeO_2 before escaping to BGO. Green: The accidental coincidences between TeO_2 and BGO.

can be found in paper [10]) before moving to Canfranc underground laboratory (LSC) in the CROSS pulse-tube cryostat. At LSC, we have measured baseline resolutions 1.9–5.9 keV FWHM for the four crystals with an average of 3.3 keV. The LDs baseline resolutions RMS were ranging between 70–111 eV. These values are achieved without exploiting the NL effect in which we expect more than 10 times better baseline resolution. The assembly with the nylon wires undergone two thermal cycles during the run ranging from room temperature to mK stages, which validates that the nylon wire preserves its properties and doesn't stretch out.

In addition, we performed a study to study a small section of the BGO active veto, in particular the anti-coincidence between a crystal with surface contamination and the LD reading the light signal from the BGO. For this purpose, we have assembled in a copper holder a section of the active veto consisting of two BGO scintillators (height 12 cm) with a trapezoidal cross-section (Fig. 5). The crystals are in direct contact with the PTFE piece, that sandwich also the trapezoidal shaped LD, making the required thermal decoupling from the copper holder and protecting the LDs from vibrations. Facing the BGOs, a TeO_2 crystal is placed with a solution of U α source deposited on the surface facing the BGOs. The source has two main α lines at ~ 4.2 and ~ 4.7 MeV from the ^{238}U and ^{234}U decays, respectively, and is used to mimic surface radioactivity. An α decay will result in two scenarios: (i) the α escapes the TeO_2 surface and deposits all of its energy in BGO and the recoil nucleus is completely absorbed in TeO_2 ; (ii) the α deposits a part of its energy in TeO_2 before escaping to BGO and the recoil nucleus is absorbed in TeO_2 also. In both cases, when the α interacts in BGO, a scintillation light will be emitted and detected by the LDs. The nuclear recoil energy is around 80 keV, so the TeO_2 energy spectrum will show a peak at this energy with a tail extending to the higher energy region representing the degraded energy of the α escaping to BGO. Fig. 6 shows the energy spectrum of TeO_2 events in coincidence with BGO.

The second important study of the active veto is to have a rough estimation of the efficiency at the energy

threshold of the LD, keeping in mind that we are not exploiting the NL effect, yet in this set-up. The LY was estimated to be around 7 keV/MeV, so for a 50 keV energy threshold in BGO and an expected gain of at least 10 when having a NL LD, the energy threshold in the LD is foreseen to be around 3–4 keV. To estimate the efficiency at this value, fake pulse with such an energy were injected into the streaming data. After the data processing, the efficiency at 3 keV was found to be $>92\%$. The result is quite encouraging knowing also that we can improve even better by having a NL LD giving a higher gain in amplification.

Currently the group is doing some R&D on NL LD to study various electrode geometries and their method of deposition (evaporation and lithography) to achieve the best performance.

4 Conclusions

In this paper we have summarized the BINGO project innovative ideas. The proposals will allow next-next generation bolometric experiments to boost their sensitivity on $0\nu 2\beta$ decay by working on reducing the background from various components to achieve a background index of the order of 10^{-5} counts/(keV kg yr). The first demonstrator of mini-BINGO that will take place at LSM is currently under development. Various prototype tests have been carried out successfully, and some studies are still ongoing, especially for the NL LD. In addition, performing screening on different samples of BGO for γ -ray spectroscopy is needed to reduce the scintillation material radioactivity, particularly on ^{207}Bi contamination that can affect the active veto purpose, if it is present at high values.

5 Acknowledgments

The BINGO project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No 865844). The INR NASU group was supported in part by the National Academy of Sciences of Ukraine in the framework of the project "Development of bolometric experiments for the search for double beta decay".

References

- [1] W.H. Furry, Phys. Rev. **56**, 118 (1939)
- [2] M. Agostini et al., arXiv:2202.01787 (2022)
- [3] E. Armengaud et al., Eur. Phys. J. C **80**, 4 (2020)
- [4] C. Augier et al., Eur. Phys. J. C **82**, 1033 (2022)
- [5] O. Azzolini et al., Phys. Rev. Lett. **129**, 111801 (2022)
- [6] B. Neganov and V. Trofimov, Otkrytia i izobretenia **146**, 215 (1985)
- [7] P. N. Luke, J. Appl. Phys. **64**, 6858 (1988).
- [8] L. Bergé et al., Phys. Rev. C **97**, 032501(R) (2018)
- [9] A. Armatol et al., arXiv:2204.14161 (2021)
- [10] A. Armatol, arXiv:2301.06946 (2023)