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MONTE CARLO SIMULATIONS FOR THE MINI-BINGO DEMONSTRATOR

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The BINGO (Bi-Isotopic 0ν2β Next Generation Observatory) is an innovative assembly of bolometric spectrometers to search for neutrinoless double beta decay with background rejection of down to 10^{-5} counts/(keV · kg · year) in the region of interest. We present the experimental approach and the outcome of Monte Carlo (MC) simulation of the detector and its comparison with the first results of the underground measurements.

INTRODUCTION

The neutrinoless double-beta decay, if observed, would provide profound insights into the nature of neutrinos and the fundamental symmetries of particle physics. In the standard two-neutrino double-beta decay (2ν2β), a nucleus (*A*, *Z*) decays into (*A*, *Z*+2) with the emission of two electrons and two antineutrinos:

$$(A, Z) \rightarrow (A, Z{+}2) + 2e^- + 2\bar{\nu}_e.$$

In contrast, the hypothetical neutrinoless mode of the double beta decay is accompanied by the emission of only two electrons, with no neutrinos in the final state:

$$(A, Z) \rightarrow (A, Z{+}2) + 2e^-.$$

The absence of neutrinos implies that the neutrino is its own antiparticle, a Majorana fermion, and indicates a non-conservation of lepton number which changes by two units. In the case of light neutrino exchange mechanism, the decay rate for 0ν2β is inversely proportional to the half-life ($T_{1/2}$) and can be expressed as [1]:

$$[T_{\frac{1}{2}}(0_i \rightarrow 0_f)]^{-1} = G^{(0\nu)}\left|M_{FGT}^{(0\nu)}\right|^2 \frac{\langle m_\nu\rangle^2}{m_e^2}, \quad (1)$$

where: $G^{(0\nu)}$ is the phase space factor dependent on the decay energy (*Q*) and atomic number (*Z*), $M_{FGT}^{(0\nu)}$ is the nuclear matrix element (NME) representing the nuclear structure aspects of the decay, $\langle m_\nu\rangle$ is the effective Majorana neutrino mass, defined as $\langle m_\nu\rangle = \sum m_i\lambda_i|U_{ei}|^2$, summing over the neutrino mass eigenstates m_i weighted by the square of the electron neutrino mixing matrix elements $|U_{ei}|$ and CP phase λ_i, m_e is the electron mass.

The effective Majorana mass $\langle m_\nu\rangle$ encapsulates the contribution of different neutrino masses and their mixing to the decay process. A measured decay rate would provide a direct estimate of $\langle m_\nu\rangle$, offering insights into the absolute neutrino mass scale and hierarchy. Accurate determination of the NME is crucial, as it directly influences the extraction of $\langle m_\nu\rangle$ from experimental data. The BINGO experiment aims to achieve an unprecedented sensitivity to the half-life of 0ν2β decay, thereby probing $\langle m_\nu\rangle$ down to the meV scale, which would significantly advance our understanding of neutrino properties and their role in the universe.

The BINGO is an ambitious project designed to advance the search for neutrinoless double-beta decay (0ν2β) [2], a process whose observation would confirm the Majorana nature of neutrinos and demonstrate lepton number violation, significantly advance our understanding of fundamental symmetries in particle physics. Based on the previous bolometric experiments, BINGO aims to achieve better sensitivity by developing innovative technologies that significantly reduce background in the region of interest.

One of the features of BINGO is its bi-isotope configuration, using both ^{100}Mo and ^{130}Te embedded in Li_2MoO_4 (LMO) and TeO_2 crystals, respectively. This strategy leverages the favorable properties of both isotopes, enhancing observation efficiency for the 0ν2β decay [3].

The project focuses on achieving an exceptionally low background index, targeting approximately 10^{-5} counts/(keV · kg · yr), which is crucial for the detection of such rare events. To this end, BINGO is developing an innovative detector assembly designed to minimize passive materials near detectors, thereby reducing potential sources of background radiation.

Additionally, the implementation of an active cryogenic veto system using $Bi_4Ge_3O_{12}$ scintillators (BGO) aims to detect and reject background events originating from gamma radiation. Germanium bolometric photosensors serve as the active veto and the signal readout. All the sensitive volumes, including the veto scintillators, operate at the temperature of ~10 mK. The number of non-sensitive details (copper supports, wires etc.) inside the veto inner cavity is minimal.

DETECTOR CONFIGURATION

The technical realization of BINGO involves several innovations to enhance the sensitivity and accuracy of 0ν2β detection. Central to this is the development of an innovative detector assembly that minimizes the use of passive materials facing the detectors, thereby reducing potential background sources. This assembly employs a single copper support structure with polytetrafluoroethylene (PTFE) components to support the Li_2MoO_4 and TeO_2 crystals, as depicted in Fig. 1. The crystals are coupled with germanium (Ge) light/heat detectors, forming a compact and efficient detection module. Ge sensors should also suppress the background flux from copper holders by rejecting the energy deposition coincidence.

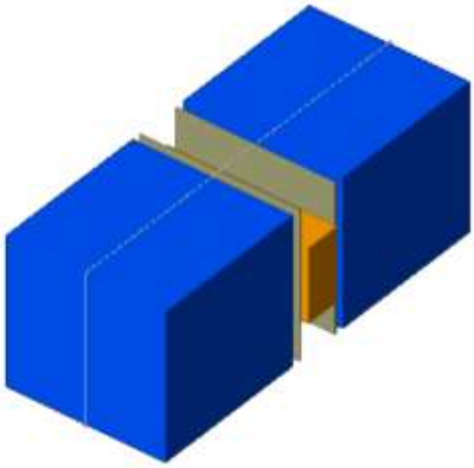

Fig. 1. Two LMO scintillators coupled to Ge photo-sensors, secured with nylon wire on the part of the copper support tower (simplified visualization for simulation purposes)

To further suppress background, BINGO incorporates an active cryogenic veto system composed of BGO scintillating crystals arranged around the detector modules. This configuration enables the identification and rejection of external and residual internal gamma radiation events, enhancing the overall signal-to-noise ratio. The entire setup is housed within a cryogenic infrastructure that maintains the detectors at millikelvin temperatures, essential for the optimal performance of bolometric detectors. The cryostat is designed to provide excellent thermal stability while minimizing vibrational disturbances, ensuring the precise measurement of energy depositions resulting from potential 0ν2β events.

In summary, the technical design of BINGO integrates advanced materials and innovative engineering solutions to create a highly sensitive and low-background environment for the investigation of neutrinoless double-beta decay, potentially unlocking new insights into the fundamental nature of neutrinos.

CURRENT STATUS OF EXPERIMENT

Current stage of the experiment is a demonstrator which consists of the assembly of two LMO bolometers with Ge photosensors, without BGO veto and external lead shields. The latest measurements were performed at the Modane Underground Laboratory (LSM). Along with experimental measurement, we conduct the Monte-Carlo simulations to evaluate the optimal conditions for the next measurements.

In the current run of measurements, a dominant source of the background in the detectors is assumed to be the external gamma radiation since the lead shielding is not placed around the cryostat. For the simulations we considered the approximation of the external gamma-ray background flux at the LSM (Fig. 2).

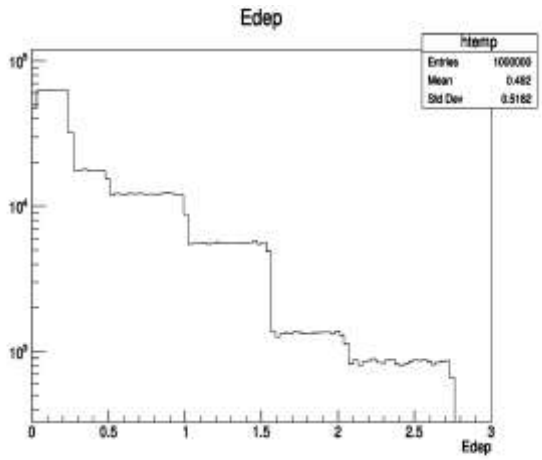

Fig. 2. The model of the background gamma spectrum at LSM. The steps in the spectra represent the measured gamma fluxes in the corresponding energy ranges [see Ref. 4, Table 2]. Such a quite rough approximation is enough for the reproduction of the event rate in the Ge photosensors

The start positions of the simulated external gamma radiation are uniformly distributed on a spherical surface around the cryostat. The momenta of gammas were generated half isotropically to face a direction to the internals of the sphere (Fig. 3) to match the conditions of the measured gamma flux in the laboratory using germanium spectrometer [4].

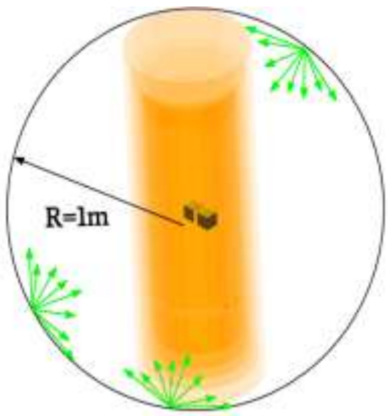

Fig. 3. Visualization of the MC simulation of current mini-BINGO geometry set-up exposed by external background gamma flux

According to this, the equivalent time of measurement can be calculated using the following equation:

$$Time[s] = \frac{Number\ of\ generated\ events}{Flux\left[\frac{1}{cm^2 s}\right] \cdot Surface\ [cm^2]}. \qquad (2)$$

The number of events when photons hit the LMO scintillator or Ge photosensor divided by the equivalent time of measurement (Formula 2) is the total event rate in the corresponding detector.

Simulated total event rate in a Ge photo-sensor is 1.00±0.22 events/s which is pretty close to the measured rate of 0.600±0.003 events/s.

CONCLUSIONS

BINGO is the next logical step in the adaptation of bolometric spectrometry of 0ν2β decay candidate isotopes embedded into crystals. The investigated decay mode is expected very rare and needs the lowest achievable background rate in the region of interest.

The concept of BINGO includes the latest technology and new ideas for background rejection. The demonstrator should be conventionally developed and tested and each further step should be accompanied by a MC simulation.

The recent set-up contains two LMO detectors coupled to Ge sensors inside the cryostat. The simulation of total event rate in the LMO crystals and the Ge sensors is in a reasonable agreement with the results of measurement, that makes the model useful to prepare a further stages of the R&D.

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