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First Energy Calibration of SuperNEMO's Calorimeter using its Tracko-Calo Technology

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The discovery of neutrinoless double beta decay ($0\nu\beta\beta$) would be an important step in the understanding of the nature of the neutrino. SuperNEMO is an experiment designed to search for $0\nu\beta\beta$, whose demonstrator module is located in Modane Underground Laboratory in France (LSM, 4800 m.w.e). It uses a unique technique combining a tracker and a segmented, scintillator-based calorimeter that allows to unambiguously identify the two final-state electrons and measure their time of flight and energy. It aims to achieve an ultra-low background level of $< 10^{-4}$ events/(keV.kg.yr) and its topological reconstruction allows us to probe double-beta decay mechanisms.

The main energy calibration method uses conversion electrons from ^{207}Bi sources that can be automatically deployed in the centre of the detector. A tracking algorithm based on the Legendre transform is being developed to reconstruct tracks. By combining tracker and calorimeter information, detailed studies of the energy response can be performed to evaluate effects such as non-uniformity and non-linearity of the scintillator, and energy losses in the tracker. Some preliminary measurements using the first data from the Demonstrator will be presented.

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1. SuperNEMO - a full topological design to understand double-beta decay

SuperNEMO was designed to search for neutrinoless double-beta decay and is optimized to search for other exotic modes of double beta decay (DBD) and study the Standard Model DBD mechanism. Its unique design separates the decay source from the detector: a wire chamber to reconstruct particle tracks, plus a segmented calorimeter to measure individual particle energies. This topological reconstruction allows for great background rejection, and for testing theoretical predictions about the mechanism.

The SuperNEMO Demonstrator is currently installed at the LSM, France. Its calorimeter is made up of 712 optical modules (OMs), each consisting of a scintillator block coupled to a photomultiplier tube (PMT). These are calibrated using internal-conversion electrons emitted by 42 ^{207}Bi sources that can be automatically deployed inside the detector. To correctly reconstruct electron energies from the PMT response, one must consider several factors, including energy lost in the tracker, and the position and angle at which they intercept an OM.

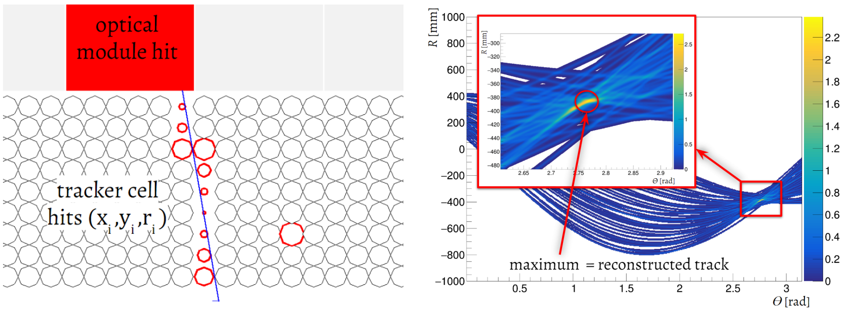
2. Particle Track Reconstruction

The Demonstrator's tracker comprises 2034 drift cells operating in Geiger mode. As a charged particle traverses a cell, it ionizes the gas within. Free electrons produced during ionization are accelerated towards the central anode wire, initiating an avalanche effect. The duration of the avalanche development (drift time) is measured and used to calculate the radial distance r_i between the particle's trajectory and the anode wire position (x_i, y_i). Positive gas ions (plasma) generated during the ionization are attracted by cathodes at both ends of the cell and the time difference between their arrivals at the ends is proportional to the vertical position z_i of the tracker hit.

Each tracker hit is represented by a horizontally aligned circle centred at the anode wire position (x_i, y_i) with radius r_i and vertical position z_i. When viewed from above, these circles should be tangent to the reconstructed trajectory (Figure 1a). Without magnetic field applied, it is expected that all particles follow a straight linear path (in three dimensions). Vertical reconstruction is straightforward using the least squares method. The primary challenge lies in the horizontal plane. A method based on the Legendre transform is utilised [1]. This transform describes each circular tracker hit with a new function representing all possible tangent lines to the original function (described by direction θ and a distance to the origin R). The track candidates can be identified in so-called sinograms (Figure 1b). Detailed description of the algorithm can be found in [2].

3. Electron Energy Loss Correction

OMs will be calibrated using electrons emitted by ^{207}Bi calibration sources. Before reaching an OM, each electron has to pass through the tracker where it loses part of its energy (ΔE). This effect can significantly influence the energy spectrum observed by OMs and also the quality of the calibration. ΔE depends on the length of the track (d) and the kinetic energy of the electron. The tracker allows us to precisely determine the value of d while the calorimeter gives us information about an electron's energy in the moment when it reaches an OM (E_f). The goal of the presented work is to develop a model which would allow us to estimate ΔE from these two observables. We



(a) Reconstruction of real data **(b)** Legendre images of tracker hits

Figure 1: Reconstructing a particle track

base our model on the Landau distribution. It describes energy losses of mono-energetic particles passing through a layer of constant thickness. The most probable value of the Landau distribution is described by equation 1 [3].

$$\Delta_p = \xi \left[\ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right] \tag{1}$$

Besides common physical constants and a numerical constant $j = 0.2$ it depends on $\beta = \frac{v}{c}$ (relativistic factor), mean excitation energy I, relativistic mass of the particle m and a combination of atomic numbers and atomic masses of the gas $\langle Z/A \rangle$ which is included in ξ. Subsequently, we can construct distribution $\rho\left(\Delta E, d, E_f\right)$ representing probability of the electron to lose energy ΔE. In Figure 2 we can see a comparison between the energy loss distribution obtained from simulated data and the function ρ fitted on these data.

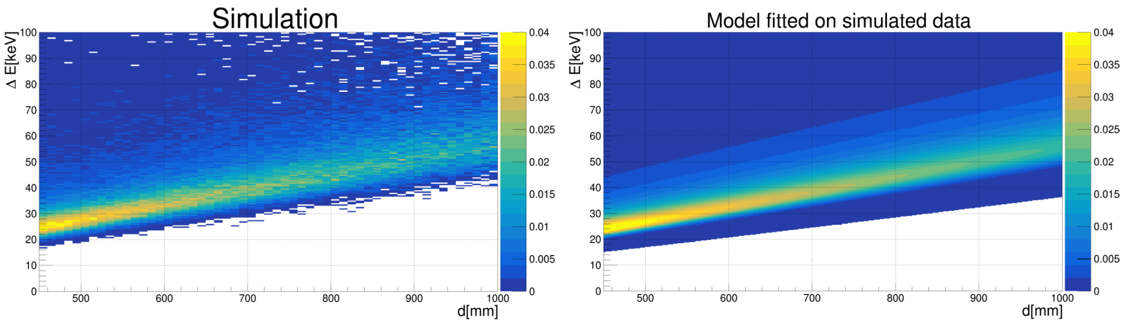


Figure 2: A comparison of the distribution of energy losses of electrons obtained from a simulation of the calibration measurement and theoretical model fitted on the data (not normalised).

4. Scintillator Response Non-uniformity

If an electron deposits its energy in the middle or in the sides of the front face of the scintillator, the quantity of scintillation light detected by the photomultiplier will be different, inducing a non-uniformity on the energy reconstruction. A detailed simulation of emission, propagation, and absorption of optical photons in the scintillator has been conducted using GEANT4 [4]. This work predicts a non-uniformity in the light collection across the front face of the scintillator with up to 10% variation, as shown in figure 3 a).

To measure this effect on real data, the impact point of the electron on the scintillator's front face is needed. For this preliminary study, two areas of the front face of the scintillator were considered: all electrons interacting at less than 5 cm from the centre (centre area) and all electrons interacting at more than 10 cm from the centre (side area). The light response to internal conversion electrons from ^{207}Bi with energies of (976, 1048 and 1060 keV) is measured.

The mean energy distribution measured by each studied optical module as a function of the impact area (red centre, blue sides) in the data (solid line) and in the simulation (dotted line) is shown in figure 3 b). The total event count is not significant, corresponding to the data and simulation sample sizes; only the central value, width, and shape of each distribution are important. This figure shows that there is an important difference in the mean response between the two areas, which, if uncorrected, would correspond to an energy difference of up to 16 keV in the data. The same result is found in simulation, validating the accuracy of the non-uniformity prediction. Further studies are to be conducted for a better quantification of this effect. These will be used to provide a more accurate energy calibration of the calorimeter.

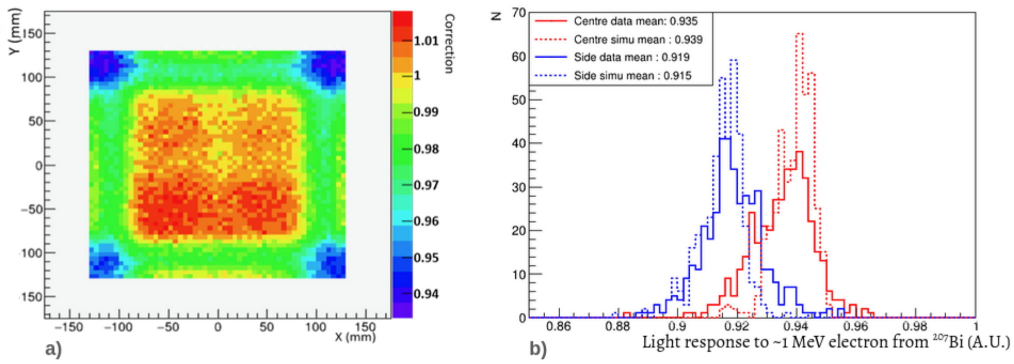


Figure 3: a) Simulation of the front face of a scintillator block, showing the difference in light collection as a function of the impact point of the incident electron [4]. b) Difference in the scintillator response to ^{207}Bi electrons (976, 1048 and 1060 keV) impacting in different regions.

5. Conclusion

The SuperNEMO Demonstrator is now taking background and calibration data. Sophisticated tracking and calibration algorithms are being developed and tested with this first data. The Demonstrator will start taking double-beta decay data after shielding installation in 2024.

References

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