PROCEEDINGS OF SCIENCE

Status of the SuperNEMO Experiment and sensitivity estimates to $0\nu\beta\beta$ and beyond

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The SuperNEMO Experiment has entered its physics data-taking phase as of April 2025, becoming the only operational double beta decay detector capable of full topological event reconstruction via the tracker-calorimeter design. This topology-driven approach provides powerful discrimination of signal and background, and is uniquely suited to explore a wide range of BSM scenarios. The detector, located at the Laboratoire Souterrain de Modane (LSM) in France, uses 6.11 kg of enriched ^{82}Se as its double beta decay source.

We present the first simulation-based sensitivity estimates using the newly developed tracking algorithm and an updated analysis framework, targeting both the $0\nu\beta\beta$ mode and other exotic decays such as Majoron-emitting decays and the right-handed currents. The extended analysis takes advantage of SuperNEMO's capability to measure not only the total electron energy but also single-electron energies and angular correlations. These results represent an important step toward quantifying SuperNEMO's sensitivity to a broad range of double beta decay processes.

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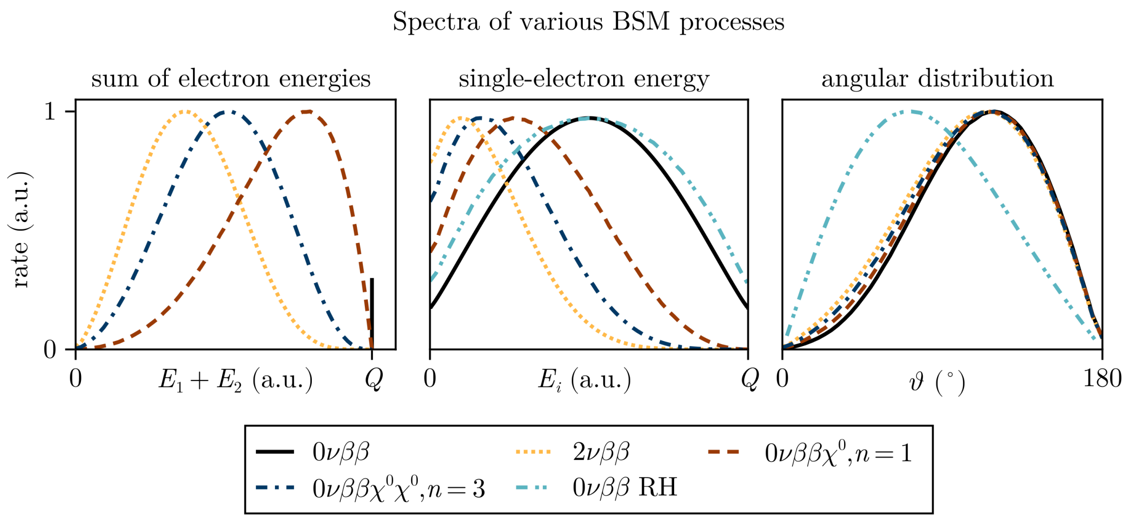

Figure 1: Spectra of various BSM processes in different channels.

1. Introduction

Searches for neutrinoless double beta decay ($0\nu\beta\beta$) mainly focus on the light Majorana neutrino exchange, studied via the summed electron energy spectrum at the Q-value. However, this approach leaves other possible mechanisms mainly unexplored. Exotic decays, such as those involving right-handed currents [1], emission of majorons [2], or sterile neutrinos [3], affect single-electron energy spectra and angular correlations in various manners, requiring complementary observables [4]. Figure 1 illustrates examples of such BSM processes across different channels.

The SuperNEMO Demonstrator is uniquely suited for these studies thanks to its tracker–calorimeter design, which reconstructs individual electron energies and angular distributions. This allows simultaneous access to multiple observables, enabling searches beyond the standard $0\nu\beta\beta$ paradigm. In this contribution, we outline how these observables can be exploited to constrain exotic mechanisms, present sensitivity estimates using newly developed multidimensional analysis techniques, and summarize the current status of data-taking in SuperNEMO.

2. The SuperNEMO Demonstrator

The SuperNEMO Demonstrator follows a tracker–calorimeter design, based on its predecessor NEMO-3, optimized for reconstructing the full topology of double beta decay events. A source foil, placed in the center of the detector, contains 6.11 kg of ^{82}Se in the form of thin metallic strips [5]. On each side of the foil, the tracker is made up of two sections of 9×113 drift cells operated in Geiger mode [6]. The tracker provides information about the electron trajectories as they traverse the active volume. Surrounding the tracker are six calorimeter walls with a total of 712 optical modules (plastic scintillators coupled to PMTs), providing an energy resolution of about 8% FWHM at 1 MeV and a timing resolution of ~ 200 ps [7], which enables precise time-of-flight measurements.

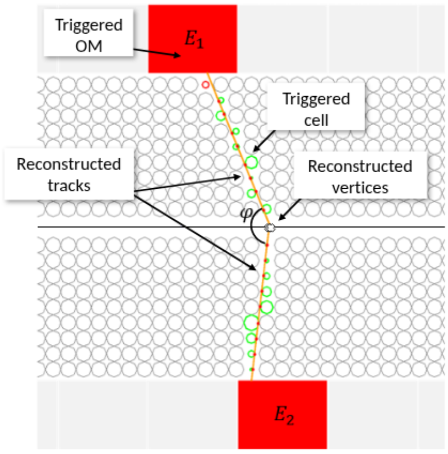

Figure 2: Depiction of a double beta decay event in SuperNEMO.

This configuration offers excellent background rejection and allows simultaneous measurement of multiple event variables: individual electron energies, timing, track length, vertex position, and more. These observables can be combined in multidimensional analyses to disentangle signal and background contributions. A typical double beta decay candidate event consists of two distinct tracks emerging from a common vertex on the source foil and terminating in two calorimeter hits, as illustrated in Fig. 2.

The detector is located in the Laboratoire Souterrain de Modane (LSM), benefitting from significant rock overburden (4800 m.w.e.) for cosmic-ray suppression. Additional shielding is installed in layers: an anti-radon tent surrounding the detector flushed with radon-free air (target activity 150 μBq/m^3), 18 cm of iron shielding against external γ radiation, and polyethylene shielding against neutrons.

The detector entered its full data-taking phase on April 10th and has since been operating steadily with an average duty cycle of 92%. At present, the assessment of background levels is ongoing.

In the following section we present the expected background composition for the target exposure of 17.5 kg·yr, which forms the basis of the sensitivity projections for the Demonstrator.

3. SuperNEMO Expected Background

The background model of the SuperNEMO Demonstrator is divided into four main categories. The dominant component is the irreducible $2\nu\beta\beta$ background from the standard decay mode. Additional sources arise from radon gas inside the tracker, internal contamination of the source foil (mainly ^{214}Bi and ^{208}Tl, with ^{234m}Pa and ^{40}K relevant at lower energies), and external radiation due to ambient neutrons and γ rays.

Figure 3 shows the simulated spectrum for an exposure of 17.5 kg·yr. The wide region of interest for $0\nu\beta\beta$ extends from 2700 keV to 3100 keV, where the total background index is expected to reach $\sim 2 \times 10^{-4}$ cts/(keV·yr·kg). The largest contributions in this window originate from $2\nu\beta\beta$

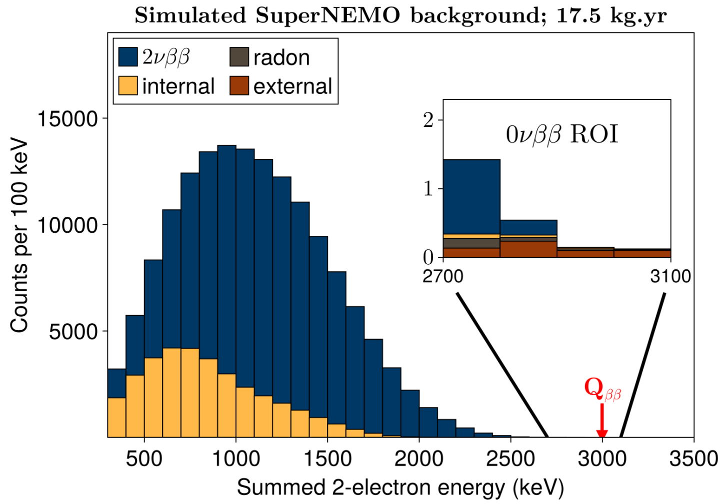

Figure 3: Expected background model of the SuperNEMO Demonstrator for an exposure of 17.5 kg·yr.

tail events and neutrons. Over the full duration of the data-taking campaign, we expect about 1.5×10^5 reconstructed $2\nu\beta\beta$ events, which can be used for detailed studies of the spectral shape.

4. Sensitivity to Beyond Standard Model Physics

A multidimensional analysis technique has been developed to take full advantage of SuperNEMO's unique design. Instead of relying on a single observable, the signal-to-background ratio is optimized simultaneously across multiple measurable variables, collectively denoted as θ_i, and tailored for each BSM process. The optimization is expressed as:

$$T_{1/2}^{\mathrm{ROI}} = T_{1/2}(\theta_1^l, \theta_1^u, \theta_2^l, \theta_2^u, \ldots) \propto \frac{\varepsilon(\theta_1^l, \theta_1^u, \theta_2^l, \theta_2^u, \ldots)}{\sqrt{b(\theta_1^l, \theta_1^u, \theta_2^l, \theta_2^u, \ldots)}}, \tag{1}$$

where ε denotes the signal efficiency and b the expected background for a given region of interest (ROI), constrained by lower (l) and upper (u) bounds on the measurable θ_i. The goal of the optimization is to maximize the sensitivity. This N-dimensional optimization yields an improved set of selection cuts and can increase sensitivity by up to 16% relative to standard one-dimensional analyses.

The resulting sensitivities to various BSM modes are shown in Fig. 4. With sufficient exposure, SuperNEMO can reach world-best limits on $0\nu\beta\beta$ for the isotope ^{82}Se, achieve leading results for majoron-emitting modes within 1–2 years, and provide the first constraints on $2\nu\beta\beta$ decays with right-handed currents.

5. Conclusion

The SuperNEMO Demonstrator represents a significant step forward in the experimental studies of double beta decay. Its unique tracker–calorimeter design enables simultaneous access to single-

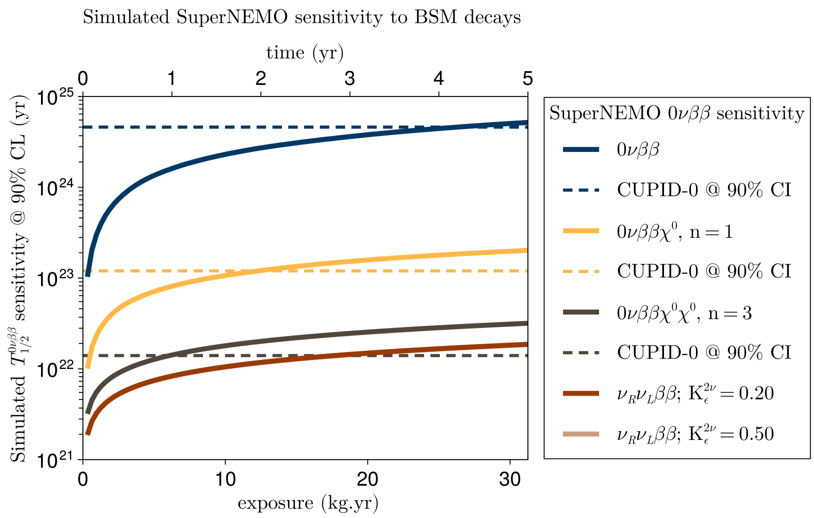

Figure 4: Projected sensitivities to various BSM processes as a function of exposure and time.

electron spectra, summed energies, and angular correlations, opening a broad program of searches for exotic mechanisms of BSM decays.

Our background model indicates that with a target exposure of 17.5 kg·yr, the experiment will boast an almost background-less status for searches of $0\nu\beta\beta$. At the same time, the multidimensional optimization method developed for signal selection promises up to a 16% improvement in sensitivity compared to traditional analyses.

With these capabilities, SuperNEMO will not only set competitive limits on $0\nu\beta\beta$ in ^{82}Se but also explore new parameter space for exotic decay modes, such as majoron emission and right-handed current contributions. The Demonstrator opens new avenues for a deeper understanding of neutrino properties and the search for new physics beyond the Standard Model.

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