PROCEEDINGS OF SCIENCE

The SuperNEMO Demonstrator: a unique technology for high-precision measurements of $\beta\beta$-decay

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The SuperNEMO Demonstrator is a unique instrument for studying various modes of double beta decay. Its distinctiveness lies in the use of a tracking detector, which enables significant background suppression not only in the region of interest (ROI) for neutrinoless double beta decay ($0\nu\beta\beta$), but also within the continuum of two-neutrino double beta decay. The detector provides access to single-electron energies as well as to the angular correlation between the two electrons emitted in the decay. SuperNEMO aims to achieve a competitive background index of 2×10^{-4} counts·keV^{-1}·kg^{-1}·yr^{-1} in the $0\nu\beta\beta$ ROI, corresponding to a background-free sensitivity for an exposure of 17.5 kg·yr. This article briefly discusses several chosen decay modes accessible to the SuperNEMO Demonstrator.

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1. SuperNEMO Demonstrator

The SuperNEMO Demonstrator is designed to search for the ultra-rare process called neutrinoless double beta decay ($0\nu\beta\beta$). The detector comprises five principal components: a source foil, a tracking detector, a segmented calorimeter, calibration systems (^{207}Bi and light injection), and shielding. A diagram of the detector can be found in figure 1.

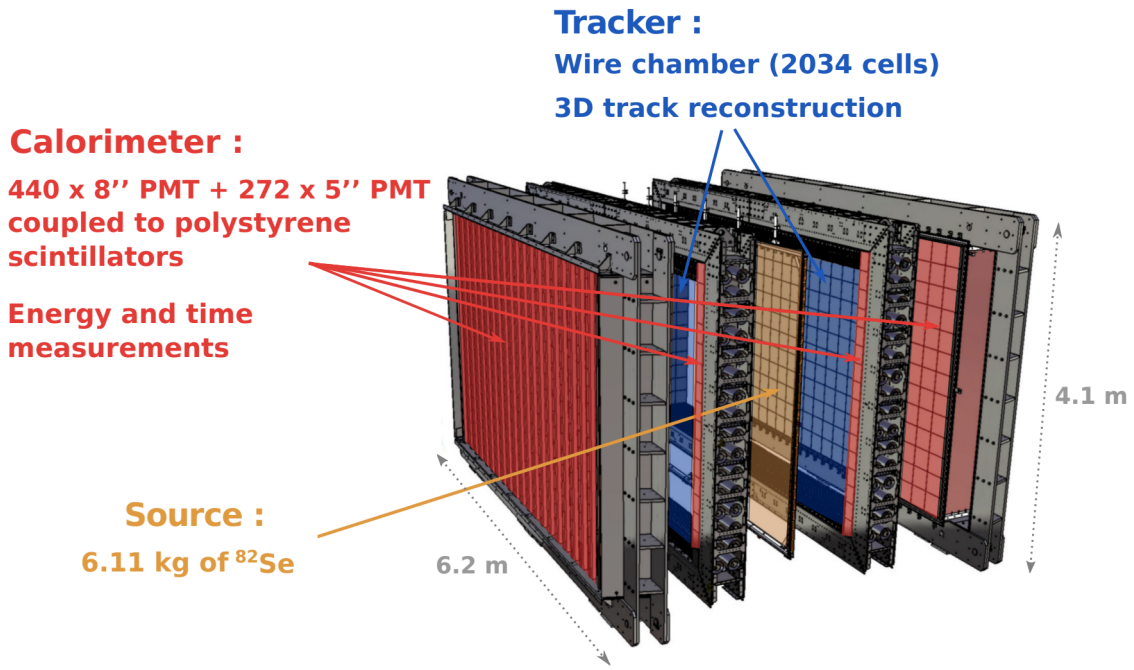


Figure 1: Schematic depiction of the SuperNEMO Demonstrator. The schema does not show X-wall and G-veto scintillators. The ^{207}Bi calibration system is placed between the source foils inside the detector. The layers of the shielding surrounding the detector are also not shown. The picture was adapted from [1].

1.1 Source foils

The SuperNEMO Demonstrator searches for $0\nu\beta\beta$ in ^{82}Se. Its high $Q_{\beta\beta}$ value of 2997.9 ± 0.3 keV [2] provides a clear advantage (over the choice of other isotopes), lying above the main backgrounds from natural radioactivity, including the 2615 keV γ line from ^{208}Tl. The detector employs 34 source foils (see figure 2) containing a total of 6.11 kg of ^{82}Se. As natural selenium includes only about 8.7% of ^{82}Se, enrichment was necessary to maximize the isotope mass. After the enrichment, foils contain 96% - 99.9% of ^{82}Se. Details of the enrichment and foil production are given in [3, 4].

1.2 Tracking detector

In SuperNEMO, the source foil is sandwiched between two halves of the tracking detector. The tracker is a multiwire drift chamber composed of 2,034 drift cells. Each cell consists of a central anode maintained at 1.6 kV, surrounded by 12 field-shaping wires arranged in a square formation, shared with neighboring cells. Each half of the tracker contains a grid of 9 × 113 cells.

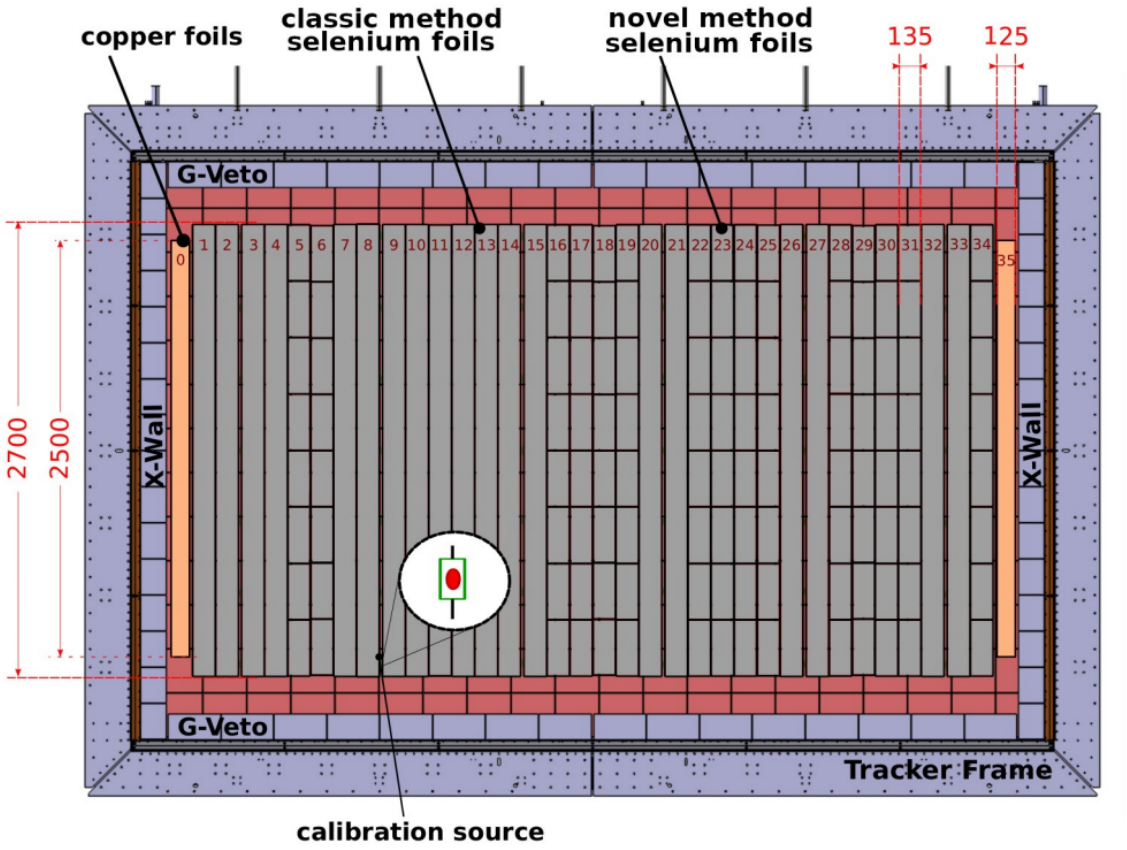


Figure 2: Schema depicting inner section of the SuperNEMO Demonstrator. Except for 34 strips of ^{82}Se source foils (numbered 1-34) and 2 copper foils (numbers 0 and 35) one can see 6 narrow gaps between foils pairs 2/3, 8/9, 14/15, 20/21, 26/27 and 32/33 which are there to fit 6 columns of ^{207}Bi sources. One can also notice X-wall and G-veto OMs omitted in figure 1. The picture was taken from [4].

The tracking gas is composed of 95% helium, chosen for its low atomic number, which minimizes electron energy loss within the chamber. The gas also contains 4% ethanol and 1% argon: ethanol stabilizes detector operation by suppressing UV photons and localizing the measurement signal by confining the Townsend avalanche to a single cell, while argon was selected for its very low ionization potential.

SuperNEMO is the only double-beta-decay experiment capable of reconstructing particle trajectories and full event topologies. This tracking capability provides excellent background rejection and allows for the measurement of single-electron energy spectra as well as the angular distribution between the two emitted electrons.

1.3 Segmented calorimeter

The outer layer of SuperNEMO's sensitive volume is fully covered by plastic scintillators on all six sides of the detector. Each side is segmented into optical modules (OMs), each consisting of a plastic scintillator coupled to a photomultiplier tube (PMT). In total, the detector is equipped with 712 OMs. The largest walls, parallel to the source foil, are referred to as the main walls (M-walls)

and comprise 520 OMs (see figure 1). Most of the M-wall OMs are based on polystyrene and contain 0.05% POPOP (1,4-bis(5-phenyloxazol-2-yl)benzene) and 0.6% / 1.5% pTP (p-Terphenyl), which act as wavelength shifters to enhance light collection efficiency. The concentrations of POPOP and pTP were optimized to achieve the best possible energy resolution [5, 6]. Tests conducted during the construction phase demonstrated an energy resolution of approximately 8% at 1 MeV for the OMs in the M-walls produced using the aforementioned combination of polystyrene and wavelength shifters [1].

The vertical sides perpendicular to the source foil are called X-walls, while the top and bottom sides are referred to as the gamma-veto (also called G-veto) - see figure 2. The OMs in the X-walls and G-veto were reused from SuperNEMO's predecessor, NEMO-3 [1]. These modules have energy resolutions of approximately 12% (X-walls) and 16% (G-veto). While the X-walls can detect electrons, their resolution is poorer. The primary purpose of the G-veto is to provide an active background veto. Both X-walls and G-veto are unlikely to have a high flux of electrons from the foil, therefore, stringent resolution requirements are not imposed on these sides.

In addition to energy measurements, the OMs serve as event triggers. With time resolutions on the order of a few hundred picoseconds, they also enable time-of-flight measurements. This further enhances the detector´s capability to suppress backgrounds.

1.4 Calibration systems

The energy calibration of the SuperNEMO Demonstrator is performed using 42 ^{207}Bi sources [7], with activities ranging from 120 to 145 Bq (as of 1 July 2018). ^{207}Bi emits mono-energetic electrons, with two dominant lines at 482 keV and 976 keV. To maintain the detector's gas-tight integrity, the collaboration developed an automated deployment system that can be operated remotely, without requiring access to the detector's interior. When deployed, the ^{207}Bi sources are arranged in a grid, with each of six columns (see figure 2) containing seven sources. The deployment of the sources is controlled by six stepper motors located above the columns. In addition to energy calibration, the ^{207}Bi sources are also used to calibrate the time resolution and to test the precision of vertex reconstruction. SuperNEMO Demonstrator also contains a light injection (LI) system based on ultra-violet (385 nm) LEDs and optical fibers (connecting LEDs with OMs). LI system serves for a regular survey of the PMT stability. Five additional reference OMs are placed outside the Demonstrator and are permanently equipped with electron (^{207}Bi) and alpha (^{241}Am) sources in order to provide reference for the OMs installed inside of the Demonstrator.

1.5 Shielding and background mitigation

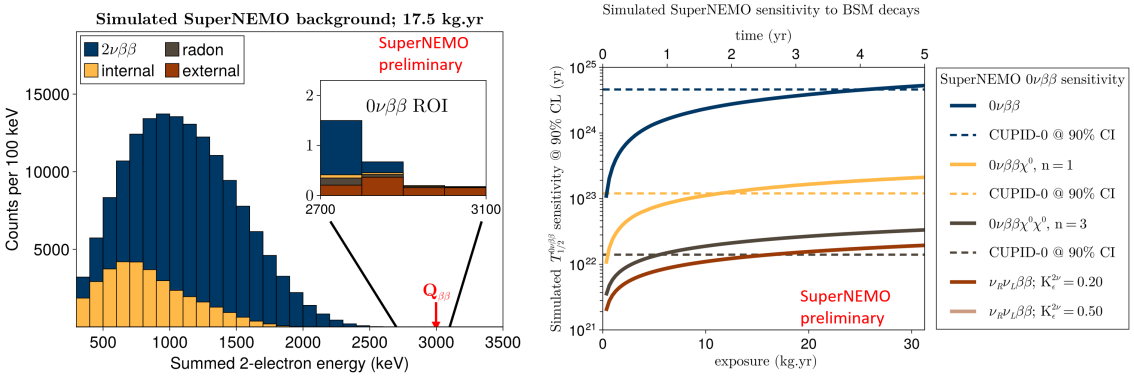
The SuperNEMO Demonstrator employs several strategies to shield against background radiation. First, the detector is located in the Modane Underground Laboratory (LSM) in France. With an overburden of 4,800 m.w.e., LSM is the deepest underground laboratory in Europe, resulting in only about one muon per million reaching the laboratory. Second, the collaboration constructed a three-layer shielding system comprising an anti-radon tent, iron shielding, and polyethylene shielding. The detector volume is enclosed within a tent designed to maintain air with a suppressed radon concentration [8]. The tent operates as part of a closed loop, where air is continuously extracted, passed through a radon-removal system, and then reintroduced into the tent. Surrounding

the anti-radon tent, the detector is shielded on all sides by 18 cm of iron, which suppresses gamma radiation, followed by an outer layer of 24 cm thick polyethylene to reduce neutron backgrounds.

In addition to these passive shielding measures, the collaboration carefully selected radiopure materials for detector construction. Finally, the SuperNEMO tracker provides powerful background suppression capabilities, enabling background-free operation within the region of interest for $0\nu\beta\beta$ decay.

2. Status of the detector

The SuperNEMO Demonstrator completed its commissioning phase in March 2025 and has been collecting physics data since April 2025. The collaboration has demonstrated the capability to operate the detector continuously over extended periods. The initial data were recorded without the radon suppression facility, which was subsequently commissioned in October 2025. The detector is now operating continuously with the full experimental setup in place.



(a) SuperNEMO´s preliminary background model. **(b)** Sensitivities of the SuperNEMO to selected processes.

Figure 3: Images showing preliminary simulation results. The zoom-in to $0\nu\beta\beta$ ROI in plot a) shows that the possibility to reach less than one count during the measurement campaign is realistic in the $0\nu\beta\beta$ ROI (2800 - 3100 keV). Plot b) shows the SuperNEMO's sensitivity to various new-physics processes, with a comparison to the current world's best limits for ^{82}Se as a function of measurement time / collected exposure. The compared processes are discussed in the text. Plots are courtesy of Maroš Petro and taken from [9].

2.1 Ongoing analysis

Current analysis efforts are focused on improving the understanding of background sources and refining the detector simulation model. Following numerous upgrades, the background model shown in figure 3a) indicates that SuperNEMO should achieve a background index of approximately 2×10^{-4} counts$\cdot$ keV$^{-1}\cdot$ kg$^{-1}\cdot$ yr^{-1} within the $0\nu\beta\beta$ region of interest [9]. With an expected exposure of 17.5 kg $\cdot$ yr, SuperNEMO is projected to operate in a background-free regime - that is, with less than one expected background event over the full data-taking period in the $0\nu\beta\beta$ ROI.

A preliminary analysis of data collected between April and October 2025 estimated the radon background level to be approximately 50 mBq / m^3. The collaboration aims to reduce this to 0.15 mBq / m^3 following the commissioning of the radon suppression facility. The elevated levels observed in the initial dataset are attributed to the absence of this system during early data taking.

The detector's tracking capability and its access to the angular distribution between emitted electrons allow the SuperNEMO Demonstrator to study not only the standard neutrinoless double beta decay ($0\nu\beta\beta$) via the neutrino mass mechanism, but also exotic modes such as $0\nu\beta\beta\chi_0(\chi_0)$ ($0\nu\beta\beta$ with emission of one or two Majorons) and the two-neutrino double beta decay with the emission of one right-handed neutrino ($\nu_R\nu_L\beta\beta$) described in [10]. Figure 3b) shows a comparison of the expected sensitivities with the current world's best limits from [11, 12]. The $\nu_R\nu_L\beta\beta$ mode has never been experimentally searched for, so SuperNEMO will either make the first observation or set the first limit on this process. The SuperNEMO Demonstrator is capable of studying other exotic double beta decay physics which includes sterile neutrinos [13], the capture of the electron in electron shells of daughter nucleus [14], the decay to excited states [15] and more.

3. Conclusions

The SuperNEMO Demonstrator is a unique detector in the field of double beta decay. Its tracking capability enables significant background suppression and provides access to the full event topology. The experiment's rich physics program offers valuable opportunities for detailed studies of the processes underlying double beta decay. The detector has been operating since 2025 and will be able to achieve its physics potential with a runtime of 2-3 years.

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