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Status of the SuperNEMO Demonstrator and Analysis of First Data

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SuperNEMO is searching for the hypothesised lepton-number-violating neutrinoless double-beta decay $0\nu\beta\beta$ process. Our unique NEMO-3-style tracker-calorimeter detector tracks individual particle trajectories and energies. This enables powerful background rejection and detailed studies of Standard Model $2\nu\beta\beta$ decay. By studying electron and photon energies and relative trajectories, SuperNEMO will investigate nuclear processes hidden to other technologies, such as decays to excited nuclear states, and will constrain the axial coupling constant, g_A. By precisely measuring $2\nu\beta\beta$ observables we will seek beyond-the-Standard-Model effects like exotic $0\nu\beta\beta$ modes, Lorentz-violating decays and bosonic neutrino processes.

The SuperNEMO Demonstrator at LSM, France has a 6.1 kg ^{82}Se $\beta\beta$ source, and is taking background data vital to isolate future signals. It is calibrated with a ^{207}Bi source deployment system. Multi-layer shielding, now in construction, will allow $\beta\beta$ data-taking in 2024.

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The nature of the neutrino is one of the hot topics in neutrino physics. In fact, the discovery of the neutrino's mass raises the question of the mechanism behind it. Various theories have been put forward on this subject, and they are based on Dirac or Majorana mechanisms. One consequence of the existence of a Majorana mass mechanism would be to confirm the Majorana nature of the neutrino. This would mean that the neutrino is its own antiparticle, which would open the door to new physics beyond the Standard Model. The Majorana nature of the neutrino would also make neutrinoless double beta decay ($0\nu\beta\beta$) possible.

$0\nu\beta\beta$ decay would be two simultaneous beta decays, in which two neutrons in a nucleus decay into two protons while emitting no neutrinos and two electrons. If the neutrino is a Majorana particle, we can imagine mechanisms where an antineutrino is emitted at the first vertex of the decay and absorbed as a neutrino in the second. An observation of this decay would be then a proof of the Majorana nature of the neutrino. There are different models to explain such reactions, such as light left-handed or right-handed neutrino exchange, majoron emission, and more. There is also a standard double beta decay ($2\nu\beta\beta$), which would consists of two simultaneous beta decays with the emission of two antineutrinos and two electrons. $2\nu\beta\beta$ is allowed by the Standard Model, and has been observed for several isotopes with half-lives of around 10^{19} y. In its simplest form, $0\nu\beta\beta$ two electrons summed energy would form a peak at the end of the continuous summed energy spectrum of the $2\nu\beta\beta$. In alternative mechanisms, the signature of $0\nu\beta\beta$ decay could be a distortion of electron's energy spectra (summed or individual), as well as in their angular distribution.

SuperNEMO is the only experiment able to differentiate these mechanisms due to its unique ability to reconstruct events' topology [4]. This topological reconstruction permits us to obtain the needed information such as the electron's angular distribution and their individual and summed energies. In addition to being necessary to study $0\nu\beta\beta$ mechanisms, the reconstruction of the kinematics of the decay is a powerful tool to study $2\nu\beta\beta$ decay. This decay is an unavoidable background for the detection of $0\nu\beta\beta$, but it's also interesting to study it on its own right (see ICHEP 2024 poster Searching for exotic modes of $2\nu\beta\beta$ with the SuperNEMO Experiment).

Thanks to the topological event reconstruction, exotic $2\nu\beta\beta$ can be searched with SuperNEMO, such as a decay with right-handed neutrino which would have a specific electron angular distribution. Studying the individual and summed electron spectra could also lead to observation of $2\nu\beta\beta$ decays with a sterile neutrino. SuperNEMO also aims to understand the $2\nu\beta\beta$ mechanism and the intermediate states that it goes through. Two models are studied, the HSD and SSD models. NEMO-3, the predecessor of SuperNEMO, showed a preference for the SSD model at 3σ in the ^{82}Se decay [3], and this measure will be redone with SuperNEMO to reach a precision of 5σ. This result, and the single-electron spectrum, will also help to understand the nuclear physics of the decay, and more specifically the quenching of the axial coupling constant g_A.

To measure the kinematics of the $\beta\beta$ decay, SuperNEMO use a unique tracker-calorimeter approach, as shown in figure 1. A $\beta\beta$ source foil, placed in the middle of the detector, is surrounded by a tracker which will follow the trajectories of the two electrons produced in the decay. These electrons will then reach a calorimeter that encloses the tracker, and their individual energies will be measured.

The source foil [1] of the SuperNEMO demonstrator is composed of 34 foils of ^{82}Se, enriched to 90-99 %, which represent 6.11 kg of ^{82}Se. In future iterations of a SuperNEMO-like detector, this could be replaced by any solid $\beta\beta$ isotope. ^{82}Se was chosen for its high decay energy ($Q_{\beta\beta}$

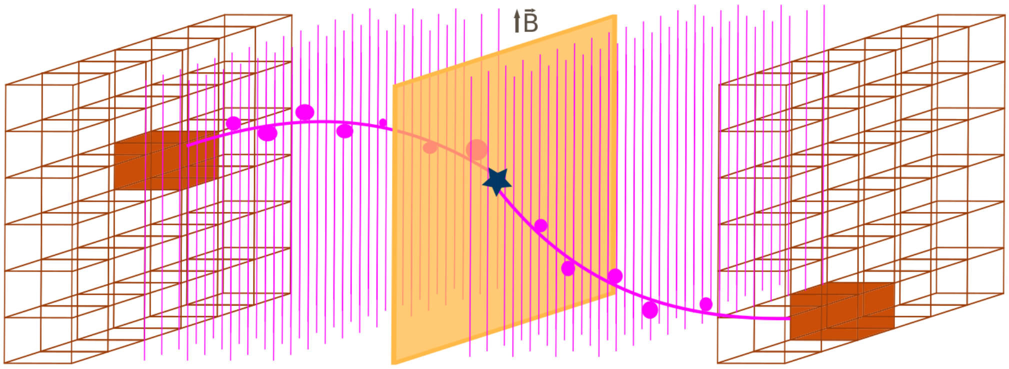

Figure 1: Diagram of the NEMO technique. The source foil is shown in yellow in the centre of the drawing, the pink lines represent the tracker and the orange structure the calorimeter. A $\beta\beta$ event is shown, with its emission vertex represented by a black star. The two emitted electrons' trajectories are described by the pink curves and their energy deposits in the calorimeter are highlighted.

= 2.998 MeV) above the energies of common background process, meaning that they are less of a problem for $0\nu\beta\beta$ measurements. It was also chosen for the long half-life of the $2\nu\beta\beta$ decay ($T_{1/2}$ = 8.69×10^{19} y), its relatively high natural abundance (8.73%). A photograph of the source foils is shown in the left of figure 2.

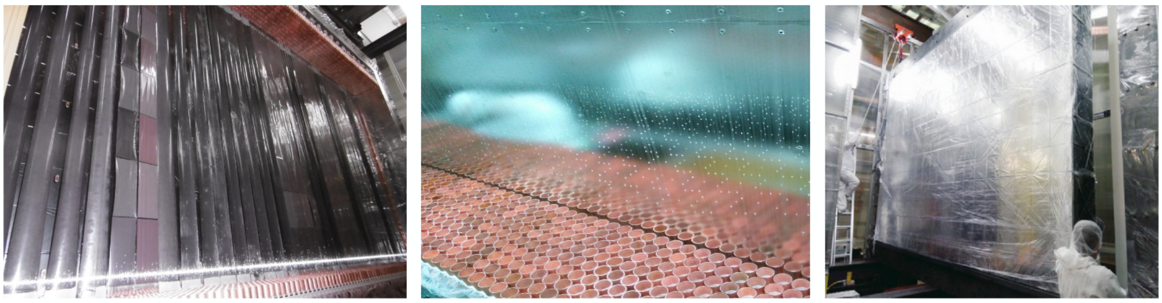

Figure 2: Left, photograph of the 34 ^{82}Se source foils. Middle, photograph of the tracker. Right, photograph of the calorimeter.

The tracker is a wire chamber composed of 2034 cells in Geiger mode. It surrounds the source foils and its role is to follow the trajectory of charged particles, such as the two electrons of the $\beta\beta$ decay. When a charged particle crosses the tracker, the gas inside it will be ionized. A first fast anodic signal will give the radial position of the particle and a second slower cathodic signal will give the vertical position, resulting in a 3D track reconstruction. 99% of the cells are currently working. A photography of the tracker is shown in the middle of figure 2.

The calorimeter's [2] role is then to measure the individual energy of particles. It is composed of 712 optical modules, each consisting of a scintillator block coupled to a photomultiplier tube. A photograph of the calorimeter is shown in the right of figure 2.

Tracker and calorimeter information combine to give sophisticated particle identification that can be used for background-rejection. A photon will deposit its energy on the calorimeter without leaving tracks in the tracker. Conversely, an alpha particle will leave a short track in the tracker, but won't be able to reach the calorimeter to deposit its energy. An electron will leave tracks and deposit its energy in the calorimeter. A crossing electron can be distinguished from a two-electron event by its time of flight. By applying a magnetic field to curve tracks, it becomes possible to differentiate electrons from positrons. This makes it possible to isolate golden $\beta\beta$ events, consisting of two tracks coming from the same vertex on the source foil that deposit their energy in two different optical modules of the calorimeter. An illustration of event reconstruction is shown in figure 3

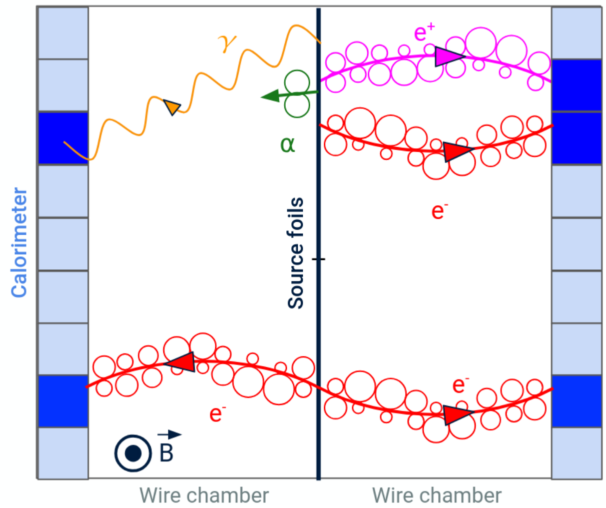

Figure 3: Top view of the SuperNEMO demonstrator. The source foils are in black in the middle, surrounded by the tracker, and the calorimeter is shown in the border. A γ track is shown in yellow, an α track in green and a positron and electron respectively in pink and red at the top. In the bottom of the figure, a golden $\beta\beta$ event is shown, with two electron tracks coming from the same vertex and interacting with the calorimeter after crossing the tracker.

As with all searches for extremely rare processes, SuperNEMO must be an ultra-low background experiment. To this end, the demonstrator is located in the Laboratoire Souterrain de Modane (LSM) in France, under 4800 m.w.e. The muon flux coming from cosmic radiation is reduced to 4 μ/day/m^2.

One of the biggest backgrounds for the SuperNEMO demonstrator at LSM comes from ^{222}Rn. ^{222}Rn is a descendant of ^{238}U present in the lab's rock walls. ^{222}Rn is a gas with a half-life of $\sim$4 days, which can easily propagate and emanate in the detector. The issue come from its descendent, ^{214}Bi, which undergoes β decay at 3.27 MeV. If this decay happens in the tracker, near the source foil, it could mimic a $\beta\beta$ decay by interacting with the source foils and leading to the emission of two electrons. It can be particularly problematic if there is ^{222}Rn in the tracker gas, which is composed of helium, ethanol and argon, as it could lead to β decay near the source foils.

SuperNEMO's goal is to have less than 150 μBq.m^{-3} originating from ^{222}Rn inside the tracker. The first measurement showed an activity of 10-15 mBq.m^{-3}. This first measurement was done by searching β-like events, followed by a delayed α coming from ^{218}Po decay, the daughter nucleus of ^{222}Rn (see ICHEP 2024 poster Study of Radon background in the SuperNEMO detector).

To decrease this activity, the following methods will be used. First, the gas of the tracker will be purified using active charcoal. The flux needed to renew the tracker gas can also help decrease the ^{222}Rn level, as the higher the flux, the lower the lingering ^{222}Rn level. A helium recycling system is currently being installed to allow reusing the tracker gas by removing the ethanol so it can be radon-reduced. This will permit better control over the gas flux, in regard to the global helium shortage. An anti-Rn tent has also been installed around the detector. This tent will be filled with radon-reduced air to avoid radon diffusion from outside the detector, and a photograph of it is shown in the left of figure 4. This should make it possible to achieve our ^{222}Rn background goal.

Figure 4: Left: photograph of the anti-Rn tent, middle: photograph of the incomplete iron shielding, right: drawing of the neutron shielding.

Another important background for SuperNEMO comes from ambient photons. For the $0\nu\beta\beta$ decay, the main contributor to the ambient γ background is the decay of ^{208}Tl, which is part of the ^{232}Th decay chain, naturally present on the lab's rock walls. ^{208}Tl emits a 2.6 MeV photon, which can then interact with the source foils of the detector and mimic a $\beta\beta$ event. It is therefore very important to protect the experiment from this background.

To this end, iron shielding is currently being installed all around the detector. This shielding is composed of 18 cm-thick iron panels. The iron was bought in China, and tested to ensure radiopurity. Its installation should be finished by August 2024. The middle of figure 4 shows a photograph of the incomplete iron shielding. This shielding should reduce the gamma background by a factor of 500 to reach a background of less than 0.1 events.keV^{-1}kg^{-1}.y^{-1}.

The last background SuperNEMO must take into account is generated by neutrons. Neutrons originate from the lab's rock walls by spontaneous fission or α/n reactions. These neutrons can then interact with the detector and produce photons in the energy range of the $\beta\beta$ decay. These gamma photons can then interact with the source foils and mimic $\beta\beta$ events. Neutrons have an especially high chance to interact with the iron of the gamma shielding. To mitigate this background, neutron shielding will be installed. It will consist of a mix of polyethylene plates and water tanks. Neutrons will be thermalised in this shielding before they can reach the iron shielding. The neutron shielding should be finished by November 2024. A drawing of the neutron shielding is shown in figure 4, on the right.

In conclusion, the final shielding and helium recycling construction will be completed in October. The $\beta\beta$ data taking will then be able to start, until the year 2027. This demonstrator will serve as a proof of concept for tracking detector for $0\nu\beta\beta$ research. This technology will be vital in the event of Majorana neutrino discovery to understand mechanisms behind $0\nu\beta\beta$.

Articles about the commissioning of the calorimeter and the making of the source foils, simulations and PMT poisoning are being finalised. Articles about the tracker and the calibration system are currently being worked on, and future articles about radon, external gamma measurement, trigger and general background are planned.

References

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