PROCEEDINGS OF SCIENCE

Status of SuperNEMO, and analysis of our first data

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SuperNEMO is searching for the hypothesized lepton-number-violating process, neutrinoless double-beta decay ($0\nu\beta\beta$). Extending NEMO-3's world-leading design, our isotope-agnostic tracker-calorimeter architecture has the unique ability to track trajectories and energies of individual particles. This is a vital background-rejection tool, and enables detailed studies of the Standard Model double-beta decay process ($2\nu\beta\beta$) that produces two electrons, invisible neutrinos and, for some nuclear transitions, photons. By studying the electrons' and photons' energies and the angles between their trajectories at the emission point, SuperNEMO will be able to investigate nuclear processes indistinguishable to other technologies. For example, we can study decays to excited nuclear states, and provide constraints on the axial coupling constant, g_A. Precise measurement of the observables of $2\nu\beta\beta$ decays allows searches for 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 is now taking data with the full tracker and calorimeter from a 6.3kg ^{82}Se double-beta source. We are currently calibrating the detector with an automatic ^{207}Bi source deployment system, as well as taking the vital background data required to isolate our future signal samples. A multi-layer shielding system, now under construction, will allow us to start collecting double-beta-decay data later this year.

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Neutrinoless double-beta decay ($0\nu\beta\beta$) is a hypothesized nuclear decay that has never been observed. In this process, two neutrons in a nucleus would decay to protons, producing two electrons and no additional particles. There are several proposed mechanisms via which the decay could take place; all of them rely on a neutrino being a Majorana particle, and for this reason an observation of $0\nu\beta\beta$ would act as a 'smoking gun' indication that neutrino mass was generated via the Majorana mechanism. The decay would only be possible in nuclei susceptible to the Standard Model double-beta decay process ($2\nu\beta\beta$), which generates two electron antineutrinos in addition to the two decay electrons. As these invisible neutrinos carry away some of the decay energy, the summed energy spectrum for the two $2\nu\beta\beta$ electrons will range from zero to the total energy $Q_{\beta\beta}$ of the decay, typically around 2-4 MeV, depending on decay isotope; neutrinoless double-beta decay would be characterized by a summed two-electron energy of exactly $Q_{\beta\beta}$. For this reason, most $0\nu\beta\beta$ searches concentrate on measuring this summed energy with high precision, often taking advantage of a detector made of a $\beta\beta$-decaying isotope. SuperNEMO, however, uses a unique tracker-calorimeter technique that allows the individual particles to be identified and tracked, enabling excellent background rejection and giving access to additional information about $\beta\beta$ decays, including the nuclear decay process that can help us constrain parameters such as the axial coupling constant g_A, decays to excited states and searches for exotic decay mechanisms. These effects can be studied through analysis of the $2\nu\beta\beta$ topology, making SuperNEMO a powerful tool for a deeper understanding of $\beta\beta$ decay, even in the absence of $0\nu\beta\beta$ discovery. Separation of the $\beta\beta$ source from the detection mechanism also renders the design largely isotope-agnostic. If $0\nu\beta\beta$ is discovered, the capabilities and flexibility of a SuperNEMO-like technology will be key to understanding the mechanism through which the decay takes place.

Figure 1 explains the NEMO technique. A solid $\beta\beta$-decaying isotope is formed into thin foils, which are suspended vertically in the middle of the detector [1]. Electrons produced by decays in the foil pass through a high-granularity tracker, consisting of a grid of Geiger cells. This allows us to track the height and distance from the center of each cell through which it passes, building a 3-dimensional reconstruction of the track. Applying a magnetic field allows charge discrimination, giving sophisticated particle identification capabilities. Finally, each electron's energy is individually measured in our segmented calorimeter, which consists of a wall of optical modules, each formed of a photomultiplier tube coupled to a scintillating block [2].

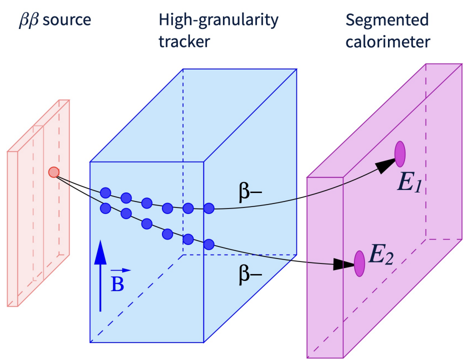

Figure 1: The NEMO technique

The SuperNEMO collaboration consists of around 100 collaborators from nine countries, with an experiment based at the Modane Underground Lab (LSM) in France. The NEMO-3 experiment, which ran from 2003-2011, used the NEMO technique to study seven $\beta\beta$ isotopes, achieving world's-best $2\nu\beta\beta$ half-life measurements and $0\nu\beta\beta$ limits in four of them. Using the individual electron-energy distributions and particle tracking, it also searched for exotic physics including $0\nu4\beta$ decays in ^{150}Nd [3]; searches for exotic decay modes and Lorentz-violating decays [4]; and

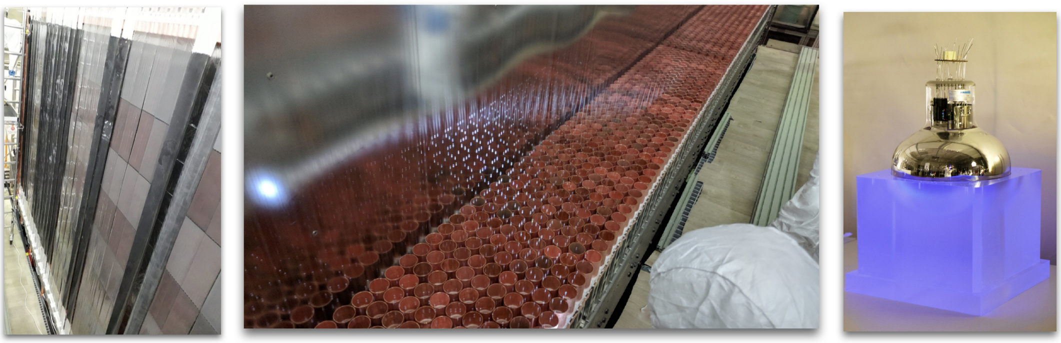

Figure 2: Components of the SuperNEMO detector. *Left:* ^{82}Se $\beta\beta$-decay source foils. Any solid isotope can be used. *Center:* SuperNEMO's array of 2034 Geiger cells provides 3-d particle tracking. *Right:* One of the calorimeter's 712 optical modules.

time-periodicity in the axial coupling constant [5]. This topological reconstruction also enabled a flagship measurement of the $2\nu\beta\beta$ half-life for ^{100}Mo where, with 5×10^5 signal events, we were able to determine with 5σ significance that the decay was single-state dominated (proceeded through the ground state of the intermediate nucleus, ^{100}Tc) rather than higher-state dominated, as previously assumed [4]. In 2023, with a boosted decision-tree algorithm trained on the energies and angles between electrons and photons, NEMO-3 made the world's first observation of ^{150}Nd $2\nu\beta\beta$ decay to the excited states to the 0_1^+ excited state of ^{150}Sm, and set new limits on the rare decay to the 2_1^+ state, and $0\nu\beta\beta$ decays to excited states, in the $ee\gamma$ and $ee\gamma\gamma$ channels [6].

The SuperNEMO Demonstrator, designed as a testbed for future large-scale NEMO detectors, is currently running at LSM. SuperNEMO updates the NEMO-3 design with a new, scalable geometry and improved components. The $\beta\beta$ source foils consist of 96-99% ^{82}Se, prepared using several different geometries and techniques [1] to determine the optimum design. The 2034-Geiger-cell tracker is filled with a carefully-controlled mix of helium, argon and ethanol. The calorimeter consists of 712 optical modules with improved optical coupling and resolution [2]. A magnetic coil (not yet activated) surrounds the detector. Improved radiopurity measures mean the projected background in the $0\nu\beta\beta$ region of interest is below 10^{-4} events per keV·kg·yr. This is partly due to our topological reconstruction and particle ID that enables us to reject the primary $0\nu\beta\beta$ backgrounds, β decays of the radon daughters ^{214}Bi and ^{208}Tl, where characteristic photons (seen as isolated deposits in optical modules) and alpha particles (short, delayed tracks) accompany the electrons (long tracks associated with an energy deposit) produced. To further reduce backgrounds, an anti-radon tent has been installed around the detector, which will be filled with radon-reduced air. Shielding is now being installed outside this tent; this will consist of 18 cm-thick iron plates, sufficient to reduce photon flux from 3.0 to 0.016 photon-induced events in the $0\nu\beta\beta$ ROI; surrounded by 243 50 cm-thick water-filled polyethylene tanks which, in conjunction with 20 cm-thick polyethylene plates, will provide neutron shielding.

The SuperNEMO Demonstrator has begun running continuously, with 99% of channels live, and taking background and calibration data. A preliminary measurement of the radon level in the tracker, based on identification of the characteristic 'BiPo' $\beta-\alpha$ decay chain of ^{214}Bi and its daughter

^{214}Po, has successfully reproduced the ^{214}Po half-life, and indicates an activity of 6 ± 2mBq/m^3. Already lower than NEMO-3 phase 1 and comparable to phase 2, this should improve significantly with higher gas-flow rates and anti-radon-tent operation; we aim to be below 0.15mBq/m^3.

An automatic system is able to deploy 42 ^{207}Bi electron sources between the $\beta\beta$ source foils. This is enabling us to calibrate our calorimeter, to test track reconstruction algorithms, and to investigate the effect of track lengths on energy reconstruction. In addition, we are using light-injection data to calibrate the detector's timing, as well as tuning thresholds, voltages and tracker gas composition to optimize performance.

When the shielding is complete, SuperNEMO's precision topological measurements of the $2\nu\beta\beta$ spectrum will enable exciting new analysis in the Demonstrator's 2.5-year run. Improving on NEMO-3's first indication of a preference for SSD decays in ^{82}Se, it should make a world's first 5σ SSD/HSD determination, and move beyond this to place constraints on the quenching of the axial coupling constant g_A. The $2\nu\beta\beta$ process is highly-sensitive to this vital, but poorly-understood, component of all neutrino-nucleus processes, particular via the individual electrons' energy spectra. Precision angular and energy measurements will also make SuperNEMO uniquely sensitive to new physics including Lorentz-invariance violation, exotic $0\nu\beta\beta$ mechanisms, scalar currents and right-handed neutrinos, through observation of the $2\nu\beta\beta$ spectrum [7].

The SuperNEMO Demonstrator will be able to make world-leading searches for these effects; even more importantly, it will serve as a first proof-of-concept step towards possible future iterations of the NEMO technique which, in the event of $0\nu\beta\beta$ discovery, will have a unique role in deciphering the mechanism behind this keenly-sought process.

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