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SuperNEMO Demonstrator A double-beta-decay experiment Status & Objectives

Christine Marquet, for the SuperNEMO collaboration – June 2025







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Standard-model double-beta decay $(2v\beta\beta)$



Standard Model process

- Lepton number conserved
- Doubly weak = long half-life
- Observed in several isotopes; $T_{\frac{1}{2}} \sim 10^{20}$ years











Neutrinoless double-beta decay ($0v\beta\beta$)



Lepton number violation

- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed $T_{\frac{1}{2}} > 10^{24}$ 10^{26} years

A **discovery** proves: neutrinos have **Majorana** nature ... and lepton number



... and lepton number is **not** a fundamental symmetry



Neutrinoless double-beta decay ($0v\beta\beta$)



Need for more observables: Unique approach from SuperNEMO









What makes SuperNEMO unique?

Need for more observables: Unique approach from SuperNEMO

SuperNEMO tracks the individual particles



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 $\beta\beta$ source foil Particle tracker Segmented calorimeter E_1 B- E_{2} Ď



What makes SuperNEMO unique?

Need for more observables: Unique approach from SuperNEMO



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What makes SuperNEMO unique?

Need for more observables: Unique approach from SuperNEMO













What makes SuperNEMO unique?

Need for more observables: **Unique** approach from **SuperNEMO**

- Individual energy
- > Angular correlation
- **Event identification:**
 - Golden-event signature
 - Excellent background rejection
 - Background measurement (dedicated channels)
- (Almost) isotope agnostic

Key to probing and understanding $\partial v \beta \beta$ mechanism if it's discovered











What makes SuperNEMO unique?

ALL EXPERIMENTS







Total energy

Event identification (simulation)

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Angular correlation



SuperNEMO demonstrator status



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Start of ββ **data acquisition: April 10th 2025**

Demonstrator main purposes:

Technology demonstration

Scaled-up version of SuperNEMO Demonstrator is the only way to determine $\partial v\beta\beta$ mechanism in the event of discovery (APPEC 2019)

Physics results

- $\partial v\beta\beta$ search in multiple modes
- $2\nu\beta\beta$ & nuclear physics
- Measurements for exotic & BSM $2v\beta\beta$ decays





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The SuperNEMO demonstrator: A technology demonstrator module









Successor of NEMO-3



NEMO-3: 2003-2011 at LSM

- NEMO-3 had 20 world's-best *0vββ* and *2vββ* results (PDG 2018)
- SuperNEMO improves NEMO-3 design to demonstrate a solution scalable to next-generation sensitivities







SuperNEMO as a technology demonstrator



Source-foil

- Mechanics
- Radiopurity

²⁰⁷Bi calibration sources



Goal: 2 µBq/kg ²⁰⁸TI; 10 µBq/kg ²¹⁴Bi

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6.11 kg of ⁸²Se

- high $Q\beta\beta$ value ~3 MeV
- long half-life~ 8.7 10¹⁹ y (CUPID-0)

34 foils, 96-99% enriched, 250μm

Proof of concept with different:

- geometries
- powder-production
- purification techniques









SuperNEMO as a technology demonstrator



- Source-foil radiopurity
- Tracker operation



- 2034 Geiger cells (14970 wires): 3D track reconstruction

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 Improved tracker geometry: taller and more transparent than NEMO-3 • Gas-mixture optimisation ~ 95% He, 4% ethanol (quencher: UV absorber), 1% argon (ionisation booster)

98.4% of cells operational







SuperNEMO as a technology demonstrator



- Source-foil radiopurity
- Tracker: Operation
 Radon purity
- Material selection
- Tracker sealing
- Gas purification
- Anti-radon tent
- LSM anti-radon facility



Anti-radon tent to be filled with Rn-free air (from LSM factory)

SuperNEMO target: **150µBq / m³** Measured 10-15 mBq/m³ **without** anti-radon strategies

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Tracker gas cleaned by radon trap

Materials screening, diffusion & emanation tests









SuperNEMO as a technology demonstrator



- Source-foil radiopurity
- Tracker: Operation
 - Radon purity
 - He recycling
- Motivated by:
- High helium prices
- Environmental concerns (finite helium supply)
- Scalability to large systems

- Tracker gas: 95% He, 1% Ar, 4% ethanol
- Consumption 5 20 I/min (0.3 1.2 m³/hour)



Custom-built ethanol removal

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Recycling requires: • Ethanol removal (radon trap cannot tolerate ethanol) • Recycled helium **storage** Remixing system with mass spectrometer control





Recycled-helium storage

Mass spectrometer





SuperNEMO as a technology demonstrator



- Source-foil radiopurity
- Tracker: Operation
 - Radon purity
 - He recycling
- Calorimeter performance
- Time & energy resolution
- > Linearity
- > Stability



97.4% of calorimeter operational

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712 Optical Modules

440 8" PMTs 272 5" PMTs

coupled to **Polystyrene scintillators**

• Time resolution: 615 ps for gammas

On target for goal of 250 ps for 1 MeV electrons

Energy calibration and resolution

Measurements ongoing Target 8% FWHM @ 1 MeV Non-linearity energy corrections implemented

> Nucl.Inst.Meth. A 868 98-108 (2017) arXiv:2412.18021, JINST submitted arXiv:2501.13755 JINST accepted







SuperNEMO as a technology demonstrator



- Source-foil radiopurity
- Tracker: Operation
 - Radon purity
 - He recycling
- Calorimeter performance
- Calibration accuracy
- Absolute calibration
- Relative calibration

Absolute weekly calibration

- 42 x ²⁰⁷Bi calibration sources at ~ 150 Bq
- Automated system

Relative daily calibration

- 712 Fibers to flash all the optical modules •

Goal: 1% accuracy

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10 LED light monitored by 5 dedicated optical modules (continuously calibrated with sources)









SuperNEMO as a technology demonstrator



- Source-foil radiopurity
- Tracker: Operation
 - Radon purity
 - He recycling
- Calorimeter performance
- Calibration accuracy
- External background level

$e^{+,}e^{-}$ from (n, γ)



~25 G



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Successive shieldings to protect from:

Ambiant Rn



Anti-Radon tent Filled with Rn-free air

Ambiant gamma



Iron shielding 18 cm thick

Ambiant neutron



PE shielding 24 cm thick

Goal: ~ 1 event in 3 years in $0v\beta\beta$ ROI





First $\beta\beta$ event!

10 April 2025 18:42:44 E_{e1}+E_{e2} ~ 1.56 MeV





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Top view







Demonstrator Data

Now in full data taking mode...



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Demonstrator is running!

... live data taking







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SuperNEMO Demonstrator Physics Goals > 0νββ search > 2νββ studies









0vββ with light neutrino exchange & V-A current

V-A current

Model assumed by most experiments







Bayesian and multi-variable analysis in progress







$0v\beta\beta$ with light neutrino exchange & V+A current

V+A current



- favours small angle between electrons
- favours energy asymmetry



SuperNEMO demonstrator - Expected sensitivity (90% CL)

- Background index in ROI: **2 10**⁻⁴ event kev⁻¹kg⁻¹
- Frequentist approach



Based only on **total energy** (multi variable analysis under study)

World's best limits reached in < 1year (⁸²Se) or 2-4 years (all isotopes)







$0v\beta\beta$ with Majoron emission

 $Q_{\beta\beta}$

Majoron e. Emission of one or more **Majorons** (Goldstone bosons χ^0) 1.25 **Ονββχ⁰χ**⁰ **Ονββχ**⁰ 0νββ 2382 0.75 0.5 0.25 -

Sum of electron energies



0

SuperNEMO demonstrator - Expected sensitivity (90% CL)

Frequentist approach

SuperNEMO expects to surpass ⁸²Se world's best limit







$0v\beta\beta$ and $2v\beta\beta$ to excited states



Example: from preliminary study SN can surpass world's best limit for $2v\beta\beta$ to 2^+2 state $T^{1/2} > 1.9 \ 10^{22} \ y \ 90\% \ C.L.$ for 17.5 kg.y exposure (Best world: 1.3 $10^{22} \ y$)

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SuperNEMO sees each individual electron and photon: dedicated channels with very low background









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$2\nu\beta\beta$ studies

~100.000 $2v\beta\beta$ events observed for 17.5 kg.y



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Analysis of **high-statistics data** to search for tiny **distortions** in total energy, single-particle energy, and angular correlation distributions. Looking for:

- Light right-handed neutrinos
- Massive sterile neutrinos
- Bosonic neutrino (Pauli exclusion violation)
- Lorentz violation
- Nuclear effects (gA, NME)
- . . .



 $2\nu\beta\beta$: constraining g_A quenching



 $[T_{1/2}^{0\nu}]^{-1} \propto (g_A^{\text{eff}})^4 G^{0\nu} |M^{0\nu}|^2$ Unknown $g_A^{\text{eff}} > g_A$ because our lack of understanding of |NME|

$2\nu\beta\beta$: constraining g_A quenching



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$2v\beta\beta$: constraining g_A quenching







SuperNEMO demonstrator: High $\beta\beta 2\nu$ statistics with low background + unique individual energy spectrum Should be very competitive for constraining g_{Δ}^{eff} and NME calculation

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SuperNEMO demonstrator is now running!

Goals:

- Demonstrate its unique capability for probing double beta events and investigating beyond Standard Model (BSM) mechanisms
- Determine optimisation drivers for scaling up to the next-generation experiment
- **>** World-leading sensitivity in ⁸²Se 0vββ processes
- High-precision results in 2vββ studies (including BSM process) and nuclear calculations

... 20 institutions ~100 collaborators

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... and LSM support

