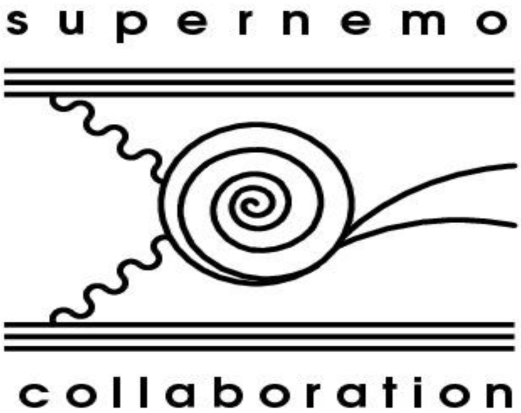
# Investigation of the 2β-decay processes of $^{82}$Se with the SuperNEMO detector



## JINR Participation
## 2022-2024

Form No. 24

# Проект SuperNEMO

## Исследования процессов 2β–распада $^{82}$Se с помощью детектора SuperNEMO (Участие ОИЯИ)

## Продление проекта на период 2022-2024 гг

# Project SuperNEMO

## Investigations of the 2β–decay processes of $^{82}$Se with the SuperNEMO detector (JINR participitation)

## Project extension for the period 2022-2024

## SuperNEMO COLLABORATION

**Theme 03 – 2 - 1100 - 2010/2021**

**(Неускорительная нейтринная физика и астрофизика, проект SuperNEMO)**

**(Non-accelerating neutrino physics and astrophysics, project SuperNEMO)**

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NAMES OF PROJECT LEADERS O.I. Kochetov

NAME OF PROJECT DEPUTY LEADERS V.I. Tretyak

DATE OF SUBMISSION OF PROPOSAL OF PROJECT TO SOD _________

DATE OF THE LABORATORY STC _5/11/2020_ DOCUMENT NUMBER _________

STARTING DATE OF PROJECT _January 2022

(FOR EXTENSION OF PROJECT — DATE OF ITS FIRST APPROVAL) _26/01/2012_

Форма № 24

# Исследования процессов 2β – распада $^{82}$Se с помощью детектора SuperNEMO
(Участие ОИЯИ)
Продление проекта на период 2022-2024 гг

# Investigations of the of 2β–decay processes of $^{82}$Se with the SuperNEMO detector
(JINR Participation)
Project extension for the period 2022-2024

SuperNEMO КОЛЛАБОРАЦИЯ

supernemo
collaboration

Шифр темы: 03 – 2 – 1100 – 2010/2021

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ДАТА ПРЕДСТАВЛЕНИЯ ПРОЕКТА В НОО _________

ДАТА НТС ЛАБОРАТОРИИ __5.11.2020_ НОМЕР ДОКУМЕНТА _________

ДАТА НАЧАЛА ПРОЕКТА __Январь 2022_

(ДЛЯ ПРОДЛЕНИЙ — ДАТА ПЕРВОГО УТВЕРЖДЕНИЯ ПРОЕКТА) 26.01.2012_

Form No. 25

# PROJECT ENDORSEMENT LIST

## PROJECT SuperNEMO

## Investigations of the 2β–decay processes of $^{82}$Se with the SuperNEMO detector

SuperNEMO COLLABORATION

THEME 03 – 2 – 1100 – 2010/2021

NAME OF PROJECT LEADER O.I. Kochetov

| | | |
|---|---|---|
| APPROVED BY JINR DIRECTOR | ------------------ | ---------- |
| | | |
| ENDORSED BY | | |
| JINR VICE-DIRECTOR | ------------------ | ---------- |
| CHIEF SCIENTIFIC SECRETARY | ------------------ | ---------- |
| CHIEF ENGINEER | ------------------ | ---------- |
| HEAD OF SCIENCE ORGANIZATION DEPARTMENT | ------------------ | ---------- |
| LABORATORY DIRECTOR | ------------------ | ---------- |
| LABORATORY CHIEF ENGINEER | ------------------ | ---------- |
| PROJECT LEADER | ------------------ | 19.11.2020<br>---------- |
| PROJECT DEPUTY LEADERS | ------------------ | 19.11.2020<br>---------- |
| | | |
| ENDORSED | | |
| RESPECTIVE PAC | ------------------ | ---------- |

Форма № 25

# ЛИСТ СОГЛАСОВАНИЙ ПРОЕКТА

Исследования процессов 2β – распада $^{82}$Se с помощью детектора SuperNEMO
(Участие ОИЯИ)
Продление проекта на период 2022-2024

Investigations of the 2β-decay processes of $^{82}$Se with the SuperNEMO detector
(JINR Participation)
Project extension for the period 2022-2024

SuperNEMO

Шифр темы: 03 – 2 – 1100 – 2010/2021

РУКОВОДИТЕЛЬ ПРОЕКТА: Кочетов О.И.

УТВЕРЖДЕН ДИРЕКТОРОМ ОИЯИ ------------------ ----------

СОГЛАСОВАНО

ВИЦЕ-ДИРЕКТОР ОИЯИ ------------------ ----------

ГЛАВНЫЙ УЧЕНЫЙ СЕКРЕТАРЬ ------------------ ----------

ГЛАВНЫЙ ИНЖЕНЕР ------------------ ----------

НАЧАЛЬНИК НОО ------------------ ----------

ДИРЕКТОР ЛАБОРАТОРИИ ------------------ ----------

ГЛАВНЫЙ ИНЖЕНЕР ЛАБОРАТОРИИ ------------------ ----------

РУКОВОДИТЕЛЬ ПРОЕКТА ------------------ 19.11.2020 ----------

ЗАМ. РУКОВОДИТЕЛЯ ПРОЕКТА ------------------ 19.11.2020 ----------

ОДОБРЕН

ПКК ПО НАПРАВЛЕНИЮ ------------------ ----------

Form No. 26

## Schedule proposal and resources required for the implementation of the SuperNEMO Project

| List of parts and devices; Resources; Financial sources | | | Cost of parts (K US$), resources needs | Allocation of resources and money | | |
|---|---|---|---|---|---|---|
| | | | | 1st year | 2nd year | 3rd year |
| Main parts and equipment | 1. Materials for Demonstrator iron shielding (radioactively pure iron) | | 200 | 200 | 0 | 0 |
| | 2. Spectroscopic electronics for test stands of PS&PMTs | | 20 | 20 | 0 | 0 |
| | 3. Borated polystyrene for neutron shielding of the Demonstrator | | 30 | 30 | 0 | 0 |
| | 4. Materials&Equipment for Demonstrator maintenance under JINR responsibility (2 Radon detectors, two HPGe spectrometer,) and carrying out calibrations, including creation of calibration sources. Radiochemical equipment. | | 60 | 20 | 20 | 20 |
| | **Total** | | **310** | **270** | **20** | **20** |
| Resources | Norm-hours | JINR workshop | 0 | 0 | 0 | 0 |
| | | DLNP workshop | 600 | 300 | 150 | 150 |
| Financial sources | JINR budget | Budget spending | 310 | 270 | 20 | 20 |
| | Off-budget sources | Grants;<br>Other sources<br>(these funds are not currently guaranteed) | *30* | *10* | *10* | *10* |

PROJECT LEADER O.I. Kochetov

Форма № 26

## Предлагаемый план-график и необходимые ресурсы для осуществления проекта SuperNEMO

| Наименование узлов и систем установки, ресурсов, источников финансирования | | | Стоимость узлов (тыс.$) установки. Потребности в ресурсах | Предложения Лабораторий по распределению финансирования и ресурсов | | |
|---|---|---|---|---|---|---|
| | | | | 1 год | 2 год | 3 год |
| Основные узлы и оборудование | 1. Материалы для пассивной защиты Демонстратора (радиоактивно чистое железо) | | 200 | 200 | 0 | 0 |
| | 2. Электроника для пластмассовых сцинтилляторов и ФЭУ | | 20 | 20 | 0 | 0 |
| | 3. Борированный полистирол для создания нейтронной защиты Демонстратора | | 30 | 30 | 0 | 0 |
| | 4. Материалы и оборудование для поддержания работоспособности детекторов, находящихся под нашем управлением в Демонстраторе SuperNEMO ( 2 радоновых детектора, два HPGe спектрометра) и проведения калибровок, включая создание калибровочных источников. Радиохимическое оборудование. | | 60 | 20 | 20 | 20 |
| | **Итого** | | **310** | **270** | **20** | **20** |
| Необходимые ресурсы | Нормо-часы | ОП ОИЯИ | 0 | 0 | 0 | 0 |
| | | ООЭП ЛЯП | 600 | 300 | 150 | 150 |
| Источники финансирования | Бюджет | Затраты из бюджета | **310** | **270** | **20** | **20** |
| | Внебюджетные средства | *Средства по грантам. Другие источники финансирования (получение данных средства в настоящее время не гарантировано)* | *30* | *10* | *10* | *10* |

РУКОВОДИТЕЛЬ ПРОЕКТА О.И. Кочетов

Form No. 29

## Estimated expenditures for the SuperNEMO project

| # | Designation for outlays | Total cost | 1 year | 2 year | 3 year |
|---|---|---|---|---|---|
| | Direct expenses for the project | | | | |
| 1. | Networking | 6.0 KUS$ | 2.0 | 2.0 | 2.0 |
| 2. | DLNP workshop | 600 norm-hour | 300 | 150 | 150 |
| 3. | JINR workshop | 0 | 0 | 0 | 0 |
| 4. | Materials | 290.0 KUS$ | 250.0 | 20.0 | 20.0 |
| 5. | Equipment | 20.0 KUS$ | 20.0 | 0.0 | 0.0 |
| 6. | Collaboration fee | 60.0 KUS$ | 20.0 | 20.0 | 20.0 |
| 7. | Travel expenses | 60.0 KUS$ | 30.0 | 15.0 | 15.0 |
| | **Total** | **436.0 KUS$** | **322.0 KUS$** | **57.0 KUS$** | **57.0 KUS$** |

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST

Форма № 29

# Смета затрат по проекту SuperNEMO

| №№ пп | Наименование статей затрат | Полная стоимость | 1 год | 2 год | 3 год |
|---|---|---|---|---|---|
| | Прямые затраты на Проект | | | | |
| 1. | Компьютерная связь | 6.0K US$ | 2.0 | 2.0 | 2.0 |
| 2. | ООЭП ЛЯП | 600 норма ч. | 300 | 150 | 150 |
| 3. | ОП ОИЯИ | 0 норма ч. | 0 | 0 | 0 |
| 4. | Материалы | 290.0K US$ | 250.0 | 20.0 | 20.0 |
| 5. | Оборудование | 20.0K US$ | 20.0 | 0.0 | 0.0 |
| 6. | Взнос в коллаборацию | 60.0K US$ | 20.0 | 20.0 | 20.0 |
| 7. | Командировочные расходы | 60.0K US$ | 30.0 | 15.0 | 15.0 |

**Итого по прямым расходам 436.0 KUS$ 322.0 KUS$ 57.0 KUS$ 57.0 KUS$**

РУКОВОДИТЕЛЬ ПРОЕКТА

ДИРЕКТОР ЛАБОРАТОРИИ

ВЕДУЩИЙ ИНЖЕНЕР-ЭКОНОМИСТ ЛАБОРАТОРИИ

# Content

## Abstract

The SuperNEMO project is aimed is searching for neutrinoless double beta decay (0vββ), which would be an indication of new fundamental physics beyond the Standard Model such as the absolute neutrino mass scale, the nature of neutrino (either Dirac or Majorana), and neutrino hierarchy. Observation of 0vββ would also help to resolve the topical puzzles of fundamental physics: CP violation, Leptogenesys, GUTs, right-handed currents, majoron emission, R-parity violating supersymmetry modes, and other non-standard scenarios. The main advantage of the SuperNEMO project is a unique potentially zero background tracking-calorimetric technique, which allows the reconstruction of the event topology and of the full kinematics of detected particles, including individual energies and emission angles. This allows to test different 0vββ-decay mechanisms in the case of discovery. In 2022, final work was carried out to equip the detector. Spectrometer's elements were assembled: gas system, magnet, electronics, anti-radon system. The cables were connected to the majority of the spectrometer channels (fully the calorimeter and, partially, the tracker). Physical data taking of a portion of a detector were carried out, the collected data were used to debug software and data processing algorithms. A passive shielding design was developed (iron + boron polyethylene, BP). BP-shielding delivered to the laboratory, the manufacture of iron shielding was delayed due to twice higher price asked by the manufacturer and the need to find additional funding resources. Unfortunately, due to problems with the tracker camera (discussed in detail in the report), the physical launch of the Demonstrator was delayed until mid-2021. Over the next 2.5 years, the detector will take data from the Se-82 source (6.3 kg).The main objective of the Demonstrator is to achieve the claimed parameters of the Module, primarily on the background level and energy resolution of the calorimeter. Successful completion of the first phase of SuperNEMO should be validation of the proposed experimental technique, demonstration of the possibility of its scaling to a full experiment with 100 kg of source (20 modules). Along with a demonstration of the technique, it is planned to obtain a physical 0vββ-result (for standard mass mechanism) at the level of 6 x 10 ^ 24 years over 2.5 years of measurement for 6.3 kg of the Se-82.

## Introduction

This project is devoted to the preparation of a new generation SuperNEMO experiment for the investigation of 2νββ and search for 0νββ decay processes with 100 kg of enriched $^{82}$Se, with expected sensitivity of $T(0\nu)_{1/2} > 10^{26}$ yr (<mν> < 40 - 110 meV). SuperNEMO uses the tracker-calorimetric detection technique successfully proven in the NEMO-3 experiment. At the first stage, the SuperNEMO Demonstrator was created, which should demonstrate the performance of the advanced, in comparison with NEMO-3, tracker-calorimetric technique, the ability to achieve the required background in SuperNEMO and, correspondingly, the sensitivity in mass production of low-background photomultipliers, and plastic scintillators. The SuperNEMO Demonstrator (first SuperNEMO module) should reach the sensitivity to the half-life $T(0\nu)_{1/2} > 6 \times 10^{24}$ years after 2.5 years of measurement.

Double beta decay is the simultaneous beta decay of two neutrons in a nucleus. The reaction can be calculated in the standard model as a second order process: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ . The two neutrino double beta decay (2vββ) has been observed in eleven nuclei, where single beta decay is energetically forbidden or strongly suppressed by the angular momentum conservation and very long half-lives, between $7 \times 10^{18}$ yr and $2 \times 10^{24}$ yr have been measured [1,2]. Several models extending the standard model predict that a neutrinoless double beta decay (0νββ) should also exists: $(A,Z) \rightarrow (A,Z+2) + 2e^-$. It's observation would imply that lepton number is violated by two units and that neutrinos have a Majorana mass component. The standard mechanism for 0vββ assumes that the process is mediated by light and massive Majorana neutrinos and that other mechanisms potentially leading to neutrinoless double beta decay are negligible [3]. With a light Majorana neutrino exchange, it would be possible to derive an effective neutrino mass using nuclear matrix element (NME) and phase space factor calculations. For recent reviews on the subject, see Ref. [4], [5]. The inverse of the lifetime for 2νββ processes can be expressed in terms of an exactly calculable phase-space factor $G^{2v}(E_0, Z)$ and the Nuclear Matrix Element $|M_{2v}|$:

$$T(2\nu)^{-1} = |M_{2v}|^2\, G_{2v}(E_0, Z),$$

where $E_0$ is available reaction energy, $E_0 = Q_{\beta\beta} + 2m_e$. The calculation NME is affected by theoretical uncertainties.

The lifetime for 0νββ processed can be expressed in terms of the phase-space factor $G_{0\nu}$ $(E_0, Z)$, and the Nuclear Matrix Element $|M_{0v}|$:

$$T(0\nu)^{-1} = \langle m_\nu \rangle^2\, |M_{0v}|^2\, G_{0v}(E_0, Z)$$

This equation states by itself why searching for 0vββ processes is a touch job. The inverse of the lifetime of the mode (thus the number of observable events) is suppressed quadratically with the small parameter $\langle m_\nu \rangle$, while the normal 2νββ mode stays constant. The main fundamental interest to the search for 0νββ-decay is the determination of the nature of neutrino. This process is the only sensible and reliable probe now. The answer to the question whether neutrinos are their own antiparticles (Majorana neutrinos) or not (Dirac neutrinos) is of central importance, not only to our understanding of neutrinos, but also to our understanding of the Universe (e.g. solution of matter-antimatter puzzle).

## Double beta-decay experiments

Many experimental searches for neutrinoless double beta decay have been performed in the past, going back for at least half a century, with increasing sensitivities. Two main approaches have been followed. Indirect methods based on the measurements of anomalous concentrations of the daughter nuclei in selected samples after very long exposures (i.e. radiochemical methods). Direct methods, on the other hand, try to measure in real time the two electrons emitted in ββ-decay. The detectors can be homogeneous, when the ββ-source is the detector medium (calorimetry approach) and in-homogeneous when external ββ sources are inserted in the detector (tracko-calo or TPC approach). The two neutrino double beta decay (2vββ) has been observed in eleven nuclei, and very high half-lives, between 7 x $10^{18}$ yr and 2 x $10^{24}$ yr have been measured.

In the following sections, the status of the art on 0vββ searches will be presented with special emphasis on large scale running experiments. Currently the lower limits on the half-life of this process exceed $10^{25}$ - $10^{26}$ yr.

**<u>Double Beta Decay in $^{136}$Xe</u>** Two large experiments have searched for 0vββ in $^{136}$Xe: EXO-200 is using Xenon in a homogeneous medium (both as 0vββ source and as detector), while in KanLAND-Zen it has been dissolved as a passive ββ source located in the center of a liquid scintillator detector.

**EXO.** The Enriched Xenon Observatory [6] is an experiment in operation at the Waste Isolation Pilot Plant (WIPP), at a depth 1600 m water equivalent near Carlsbad in New Mexico (USA). The experimental setup is built around a large liquid Xenon Time Projection Chamber filled with about 200 kg of liquid Xenon enriched to about 80.6 % in the Xe-136 isotope. The experiment exploits the readout of both scintillation and ionization signals produced by charged particles. The experiment started data taking in May 2011.

The latest EXO-200 results from a search for neutrinoless double-beta decay with total exposure of 177.6 kg.yr are presented at [9]. A lower limit on the half-life $T_{1/2}(0v) > 1.8 \times 10^{25}$ yr (90% C.L.) is established, that correspond to the upper limit on the Majorana neutrino mass $<m_{\beta\beta}> < (147 - 398)$ meV. A future evolution of EXO [10] is moving in the direction of a ton scale experiment, with an active mass of few tons of $^{136}$Xe and improved energy resolution and background suppression.

**KamLAND-Zen**. The KamLAND-Zen experiment is based on a modification of the existing KamLAND [11] detector. KamLAND is located at a depth of about 2700 m water equivalent at the Kamioka underground neutrino observatory near Toyama in Japan. The experiment has been equipped with 13 tons of Xe-loaded liquid scintillator (Xe-LS) contained inside a 3.08 m diameter spherical inner balloon. With an exposure of 504 kg-yr of 136 Xe a lower limit on the 0vββ-decay half-life was recently obtained [13] $T_{1/2}(0v) > 1.1 \times 10^{26}$ yr (90 % C.L.) The corresponding upper limit on the effective Majorana neutrino mass is in the range 61 – 165 meV. Several detector improvements are foreseen in the years to come and an increase in the mass of $^{136}$Xe (up to 1 ton) is expected [14].

**Double Beta Decay in Ge-76.** Germanium became a warhorse of 0vββ decay searches once it was realized that Ge-76 is both ββ source and excellent material for high-resolution semiconductor detectors. Milestone experiments were the Heidelberg-Moscow [15] (HdM) and the IGEX [16] used 11 kg and 8 kg of isotopically enriched Ge-76(86%) HPGe. Part of the HdM collaboration claimed evidence for 0ββ-decay at $T(0v)_{1/2} = 1.19\text{-}2.20 \times 10^{25}$ yr [18,19] (discussed at [4]). Two larger scale experiments, GERDA [20] in Europe and MAJORANA [21] in USA, are extend further this approach.

**GERDA** experiment operates germanium diodes made of isotopically modified material, enriched to about 86 % in $^{76}$Ge. The germanium detectors are suspended in strings into the stainless steel cryostat with 64 $m^3$ of liquid argon, used both as a coolant and shield. The cryostat is submerged into large tank with water worked as passive shield and active muon veto media. The experiment started taking data in 2011. Latest 2019 results with exposure 82.4 kg x yr, give a sensitivity $T_{1/2}(0v) > 5.8 \times 10^{25}$ yr and a limit for the half-life of $^{76}$Ge $T_{1/2}(0v) > 0.9 \times 10^{26}$ yr (90% C.L.), that corresponds to $<m_{\beta\beta}> < 70 - 160$ meV [24]. The experiment is supposed to collect an exposure of about 100 kg x yr and improve the 0vββ sensitivity to $T_{1/2}(0v) > 1.35 \times 10^{26}$ yr.

**MAJORANA** collaboration in USA is using standard HPGe technology (copper coolant) focusing on selection and production (copper) of ultra radio-pure materials. The MAJORANA demonstrator [26] (MJD, 44.1 kg (29.7 kg enriched)) proves the technology and background suppression in the Sanford Underground Research Facility (SUFR 1500 m.w.e.,South Dakota, USA). The first result [27] is $T_{1/2}(0v) > 2.7 \times 10^{25}$ yr (90% CL) based on 26.0 kg yr exposure.

**LEGEND** combines the strengths of GERDA and the MAJORANA DEMONSTRATOR moving towards a ton-scale $^{76}$Ge based experiment. [28]. At first stage 200 kg of enriched HPGe will be measured in the GERDA cryostat. At the second stage the LEGEND plans to measure a 1-ton of enriched Ge at zero background during 10 years exposure in order to reach $T_{1/2}(0v) \sim 10^{28}$ yr sensitivity level fully covering the inverted hierarchy region. Under favorable funding LEGEND-200 could start measurements by 2021.

**Double Beta Decay in Te-130.** Tellurium-130 is another good ββ-candidate ($Q_{\beta\beta} = 2527$ keV) due to high natural abundance (33.8 %) and it can be used without enrichment in the bolometric detectors (in the form of $TeO_2$ crystals).

**CUORE** is large array of $TeO_2$ bolometers (~1000 crystals, 206 kg of $^{130}$Te) located at LNGS [29]. The technology has been successfully validated with the Cuoricino prototype [30]. The first installed CUORE tower, CUORE0 is working as a stand-alone experiment to study the background rates $(1.38 \pm 0.07) \times 10^{-2}$ and sensitivities $1.7 \times 10^{25}$ yr for CUORE. Last combined limit (Cuoricino + CUORE0) is $T_{1/2}(0v) > 3.2 \times 10^{25}$ yr (90% C.L.) for 67.65

kg x yr exposure with corresponding limit on the effective Majorana neutrino mass $<m_{\beta\beta}> <$ 75-350 meV.

**SNO+** plans to dissolve 0.3% of natural tellurium (natTe) in the 780 tons of liquid scintillator (phase 1, 800 kg of $^{130}$Te) of the SNO detector (SNOLAB, Sudbury, Canada) [33]. Phase 1 should start this year in order to reach 55-133 meV sensitivity for neutrino mass. Possibility to dissolve 3% of natTe is also probing now.

### Double Beta Decay in Se-82

**CUPID-0** A convincing observation of neutrino-less double beta decay (0vDBD) relies on the possibility of operating high-energy resolution detectors in background-free conditions. Scintillating cryogenic calorimeters are one of the most promising tools to fulfill the requirements for a next-generation experiment. Several steps have been taken to demonstrate the maturity of this technique, starting from the successful experience of CUPID-0. The CUPID-0 experiment collected 10 kg year of exposure, running 26 ZnSe crystals during 2 years of continuous detector operation. The complete rejection of the dominant alpha background was demonstrated, measuring the lowest counting rate in the region of interest for this technique. Furthermore, the most stringent limit on the $^{82}$Se 0vDBD was established. In this contribution, the final results of CUPID-0 Phase I.

$T(2v\beta\beta)_{1/2}$ = [8.60 ± 0.03(stat.) ± 0.17/.10 (syst.)] x $10^{19}$ yr

$T(0v\beta\beta)_{1/2} > 6.0 \times 10^{24}$ yr (90 % C.L.), $<m_v> < 0.250 \pm 0.590$ eV

**NEMO-3** is in the process of publishing final results of ββ-studies for a set of isotopes.

**Mo-100** $T(2v\beta\beta)_{1/2}$ = [6.81 ± 0.01 (stat.) ± 0.38/0.40 (syst.)] x $10^{18}$ yr.
$T(0v\beta\beta)_{1/2} > 1.1 \times 10^{24}$ yr (90 % C.L.), $<m_v> <$0.310-620 eV

**Ca-48:** $T(2v\beta\beta)_{1/2}$ = [4.4 ± 0.5(stat.) ± 0.4 (syst.)] x $10^{19}$ yr.
$T(0v\beta\beta)_{1/2} > 1.3 \times 10^{22}$ yr (90% C.L.), $\langle m_v \rangle \leq$ 1.4–2.5 eV

**Cd-116:** $T(2v\beta\beta)_{1/2}$ = [2.74±0.04(stat.) ± 0.18(syst.)]×$10^{19}$ yr.
$T(0v\beta\beta)_{1/2} > 1.0 \times 10^{23}$ yr (90% C.L.), $\langle m_v \rangle \leq$ 1.4–2.5 eV

**Nd-150:** $T(2v\beta\beta)_{1/2}$ = [9.34 ± 0.22(stat) ± 0.62(syst)x$10^{18}$ yr
$T(0v\beta\beta)_{1/2} > 2.0 \times 10^{22}$ yr (90 % C.L.), $<m_v> <$ 1.6 – 5.3 eV.
$T(0v4\beta)_{1/2} > 1.1 \times 10^{21}$ yr (90 % C.L.)

The two-electron energy sum, single electron energy spectra and distribution of the angle between the electron (NEMO-3, Mo-100) are presented with an unprecedented statistics of 7x$10^5$ events and signal-to-ratio of ~80. Clear evidence for the Single State Dominance model is found for this nuclear transition. Limits on Majoron emitting 0vββ-decay modes with spectral indices of n=2,3,7, as well as constraints on Lorentz invariance violation and on the bosonic neutrino contribution to the 2vββ-decay mode are obtained. The tracker-calorimeter technique uniquely allows NEMO-3 to search for 0v quadrupole-beta decay. We report the results of a first experimental search for lepton number violation by four units in the neutrinoless quadruple-β-decay (0v4β) of $^{150}$Nd using a total exposure of 0.19 kg x y recorded with the NEMO-3 detector at the Modane Underground Laboratory (LSM, France). We found no evidence of this decay and set lower limits on the half-life $T(0v4\beta)_{1/2} > 1.1 \times 10^{21}$ y at the 90% CL, depending on the model used for the kinematic distributions of the emitted electrons.

**Conclusion.** Neutrinoless double beta decay is an exciting physics topic and double beta decay searches keep on playing a unique role in neutrino physics: probing the lepton number conservation, they can shed light on the Dirac/Majorana nature of neutrinos and determine the absolute neutrino mass scale. Several experiments will be running in the next few years and they will provide important results on 0vββ. In case of a positive signal, an observation with several methods and isotopes is crucial for convincing evidence. The positive results would confirm Majorana nature of neutrino followed an inverted hierarchy mass scheme with directly measured mass scale. Even a missing observation of 0vββ on all the isotopes under investigation would play an important role and the results would have to be combined with those coming from future neutrino oscillation experiments (reactors and long baseline). It can exclude inverted hierarchy and thus confirm normal hierarchy of neutrino mass.

Concerning the direct hierarchy mass scheme, at present none of the experiments seems to have any reasonable chance of going below the inverted hierarchy scheme. Therefore, new strategies and revolutionary techniques must be developed to push further the experimental sensitivity **~ $10^{28}$ yr and < $m_\nu$> ~ few meV.**

**Best present limit on < $m_\nu$>**

| **Nucleus** | **T1/2, y, 90% C.L.** | **<mν>, eV, QRPA + others** | **Experiment** |
|---|---|---|---|
| Ge-76 | > $1.8 \times 10^{26}$ | < 0.07 – 0.16 | GERDA – I + II |
| Ge-76 | > $1.9 \times 10^{25}$ | < 0.24 - 0.52 | Majorana |
| Xe-136 | > $1.1 \times 10^{26}$ | < 0.061 - 0.165 | KamLAND-Zen I + II |
| Xe-136 | > $1.8 \times 10^{25}$ | <0.147 – 0.398 | EXO-200 I + II |
| Te-130 | > $3.2 \times 10^{25}$ | < 0.075 – 0.350 | CUORE |
| Mo-100 | > $1.1 \times 10^{24}$ | < 0.310 – 0.620 | NEMO-3 |
| Se-82 | > $5.0 \times 10^{24}$ | < 0.311 – 0.638 | CUPID-0 |

**Best present limits on <$g_{ee}$>** (n = 1)

| **Nucleus** | **T1/2, y, 90% C.L.** | **< $g_{ee}$>, eV, QRPA + others** | **Experiment** |
|---|---|---|---|
| $^{76}$G | >$4.2 \times 10^{23}$ | $(2.1\text{-}6.2) \times 10^{-5}$ | GERDA – I + II |
| $^{100}$Mo | > $4.4 \times 10^{22}$ | $(4.2\text{-}11.6) \times 10^{-5}$ | NEMO-3 |
| $^{82}$Se | > $1.1 \times 10^{26}$ | $(1.6\text{-}3.0) \times 10^{-5}$ | NEMO-3 |
| $^{136}$Xe | > $2.6 \times 10^{24}$ | $(0.4\text{-}1.0) \times 10^{-5}$ | KamLAND-Zen I + II |

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# The SuperNEMO Demonstrator

## Introduction

The SuperNEMO Demonstrator is located in the Modane underground laboratory (LSM, France) and investigates double beta decay processes of $^{82}$Se. Its detection technique, based on tracking and calorimeter measurements, allows the reconstruction of the full kinematics of detected particles, including individual energies and emission angle, like its predecessor NEMO-3 [1] resulting in a strong reduction of the background. This technique allows, in principle, to disentangle different 0vββ-decay mechanisms [2]. The goal of the Demonstrator is to validate the technique and to reach a sensitivity on the 0vββ-decay half-life of about $T(0v)_{1/2} > 6 \times 10^{24}$ yr with “zero background“ in the region interest.

The goal for any double beta decay experiment is to unambiguously detect the characteristic 0vββ energy spectrum, among the continuous 2vββ spectrum and other radioactive backgrounds. This signal can either emerge as an excess of events located at the $Q_{\beta\beta}$, as predicted by most of the hypothesized mechanisms (mass mechanism, Right-handed currents, etc…) or as a continuous energy spectrum, resulting from emission of a new undetectable particle, the Majoron.

## Demonstrator's design

The SuperNEMO detector has modular structure with one (6 x 4 x 2 $m^3$) planar module hosted 7 kg of $^{82}$Se in the form of 36 thin foils of 40-60 mg/$cm^2$ thickness placed in the middle (see Fig.1) [3].

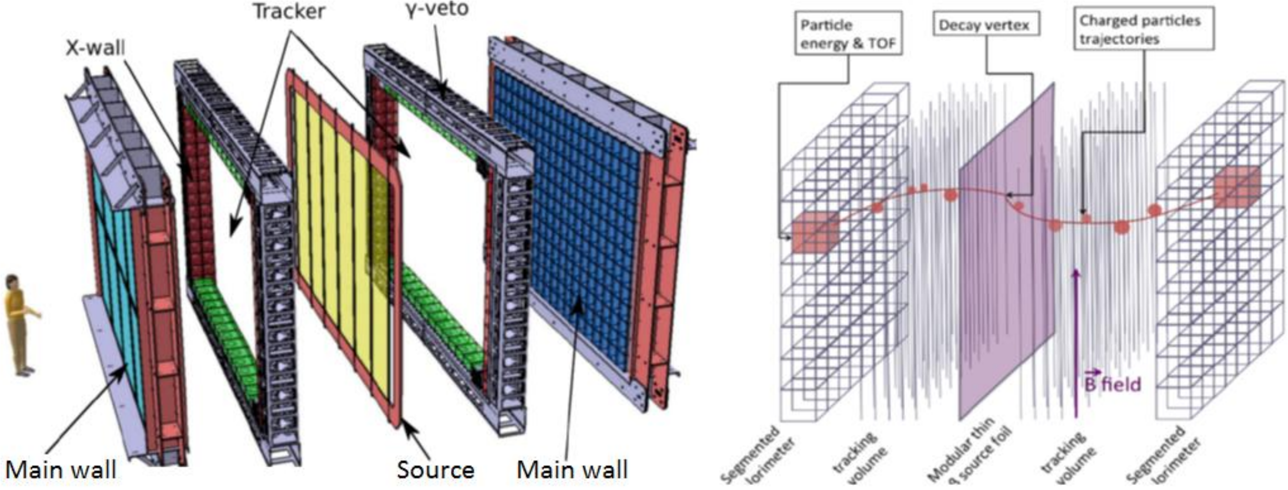

**Figure 1:** *Left*: Pictorial view of the SuperNEMO Demonstrator. On each side of the source frame a tracker and a calorimeter module are installed. *Right:* Detection principle of SuperNEMO: trajectories of charged particles emitted from the source foils are measured in the tracker while their energy is deposited into one or more calorimeter modules.

The source material is composed of $^{82}$Se (Q=2.99 MeV) powder mixed with PVA glue arranged on a Mylar support foil. On both sides and parallel to the source foil plane a tracker and a calorimeter are installed. In addition other two calorimeter planes (gamma veto) are installed perpendicular to the source foils plane. The tracker is a wire chamber operating in Geiger mode with 2034 cells (40 mm diameter, 2.7 m long) and filled with a gas mixture of He (95%), ethanol (4%) and Ar (1%). The construction and assembly of Geiger cells have been performed in ultraclean conditions. The fraction of dead channels after robotic industrial fabrication was measured to be less than 1 %. The two calorimeter walls are placed parallel to the tracker to precisely measure the energy deposited by the emitted particle. Each calorimeter module (Demonstrator) is composed of 520 Optical Modules (OMs) made of plastic scintillator (Polystyrene) coupled to 8” R5912 and 5” R6594 low background Photo Multipliers Tubes (PMTs) with Q.E. 30%.

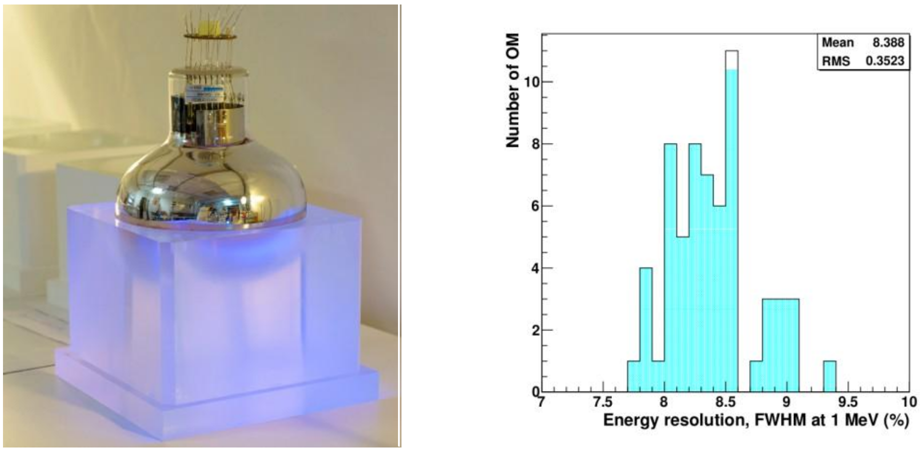

**Figure 2**. *Left*: one calorimeter Optical Module (OM), PS block equipped with a 8” PMT. *Right*: distribution of the energy resolution (FWHM) for the calorimeter Optical Modules with an average resolution of ~ 8 % FWHM for electrons 1 МэВ, respectively.

Thanks to successful R&D effort based on dedicated optical simulations and experimental tests of numerous prototypes, the energy resolution of the optical modules is in average ~ 8.0 % (full width at half maximum) [4] and the time resolution is about 400 ps at 1 MeV (see Fig. 2). Trajectories of the electrons emitted from the source foils are measured by the tracker while their curvature can be inferred thanks to a coil producing a 25 G magnetic field (see Fig. 1). The energy deposited and the ‘time of flight” of the particles are measured by the calorimeter optical modules. Calorimeter energy calibration is performed with $^{207}$Bi source emitting internal conversion electrons at energies 482 keV, 976 keV, and 1770 keV and time calibration with $^{60}$Co.

**Figure 3:** *Left:* a view of the installation procedure of Optical Modules in the calorimeter wall. *Right:* Side view of the two calorimeter walls and the two tracking chambers already installed at Modane.

Calibration sources are inserted in between the source foils by a dedicated automated system, which descends/rises the sources during calibration runs. The calibration procedure provides 1% accuracy of energy measurement. At present the

SuperNEMO Demonstrator is currently under integration at the Laboratoire Souterrain de Modane. Both sides of the tracker and calorimeter have been installed (see Fig. 3) and the detector is already in its final commissioning phase. The source foils and calibration system were installed end of 2021. Data collection will start at the end of 2021.

## Particle identification and kinematics reconstruction

Due to its tracking capabilities, SuperNEMO is currently the only experiment able to detect the two individual electrons emitted during a double beta decay. SuperNEMO is also capable of discriminating β particles from $e^+$, γ and α particles. This gives access to different topologies of events which can be used to accurately measure the different background contributions: 1e1α(Nγ) channel for $^{214}$Bi or 1e2γ channel for $^{208}$Tl for instance. This also allows SuperNEMO to look for the double beta decays to the exited states of the daughter nuclei, which signature is one or several γ particles emitted along with the two electrons. In addition, the full kinematics reconstruction means that SuperNEMO is the only experiment which, assuming the 0νββ observation, would be able to identify the underlying mechanism (the energy spectrum and the angular correlation of the two electrons depend on the mechanism). Furthermore, the use of these kinematic variables in a multivariate analysis can improve the detector sensitivity.

## Background origins

As mentioned earlier, the background for the 0νββ search is any processes which can produce two electrons with the energy sum close to the $Q_{\beta\beta}$ value. The main backgrounds are consequently:

- Some high energy 2ν2β-decay events which energy can be overestimated due to the detector’s limited energy resolution.
- A contamination of $^{208}$Tl and $^{214}$Bi in the source.
- Radon in a tracker gas that is generating $^{214}$Bi on inner surfaces of detector (mainly source foil and wires).

These β/γ emitters can mimick (imitate) ββ events through a beta decay, accompanied by deposited on inner surface a Compton or Moller scattering or an internal conversion.

## Multivariate analysis

The most sensitive variable for the 0νββ search is two electrons energy sum. However, SuperNEMO can take advantage of other topological information using a multivariate analysis to better discriminate signal events from background events and thus increase the sensitivity of the experiment. The energy-based variables (individual electrons energy and energy asymmetry) would also be helpful discriminating variables but they are highly correlated to the energy sum and as such, their discrimination power is limited. Some other variables which can be help discriminate signal from background are the distance between the two reconstructed vertices or the internal probability which is a quantity inferred from the Time-Of-Flight measurement.

The radiopurity targets for the demonstrator are the following: A($^{208}$Tl) = 2 μBq/kg, A($^{214}$Bi) = 10 μBq/kg and A(Radon) = 150 μBq/m$^3$. Considering a simplified background model composed of 2νββ, a source contamination in $^{208}$Tl and $^{214}$Bi, and some Radon in the tracker, Boosted Decisions Trees from ROOT’s TMVA have been trained on Monte-Carlo simulations in order to improve the sensitivity for the search of 0νββ assuming the mass mechanism.

At higher background levels, the improvement brought by the multivariate analysis increases, and it is especially, true for Radon, because Radon events mimicking ββ events originate from the tracker wires closest to the source, therefore their topological variables are more distinguishable than that of backgrounds originating from the source. This study

[10] shows that the use of the topological information provided by SuperNEMO in multivariate analysis guarantees a 10% sensitivity increase, assuming the radiopurity targets are reached, and more if the contaminations are higher.

## Radiopurity requirements and sensitivity

In order to reach the target sensitivity, the SuperNEMO Demonstrator has established various requirements in terms of radiopurity of its components. In particular the source foils internal contamination must not exceed 2 and 10 mBq/kg for $^{208}$Tl and $^{214}$Bi, respectively. The gas in the tracking chamber must satisfy Radon ($^{222}$Rn) levels below 150 mBq/kg and the radiopurity of component materials in the vicinity of source foils must be at the levels of few mBq/kg. A dedicated high sensitivity detector called BiPo-3 with a total sensitive area of 3.6 $m^2$ [5] has been built by the SuperNEMO collaboration in 2012 to measure the internal contamination of source foils at the levels of few mBq/kg for $^{208}$Tl and $^{214}$Bi (from the Thorium and Uranium series, respectively). BiPo-3 is operational since 2013 and is located in the Canfranc Underground laboratory (Spain). It is divided in two modules, each of them hosting 20 pairs of thin polystyrene scintillators coupled to 5” low background PMTs. The $^{208}$Tl contamination can be inferred by detecting the $^{212}$BiPo cascade, i.e. an electron from the β-decay of $^{212}$Bi and a delayed a (of 8.8 MeV energy) from the decay of $^{212}$Po (with half-life of 300 ns). Measurements for a subgroup of source foils indicate a contamination in $^{208}$Tl between 10 and 30 mBq/kg at 90% C.L.
Big efforts have been made to minimize the $^{222}$Rn contamination in a SuperNEMO gas achieving levels ~ 0.15 mBq/$m^3$. Indeed, Radon can emanate from detector materials with $^{226}$Ra impurities, can diffuse from outside materials or can be injected through the input gas in the tracker. Material selection has been performed to identify the most tight materials with the minimum Rn diffusion coefficient; thanks to this, the use of nylon between the tracker and the calorimeter has been validated [6]. Different groups of the collaboration have built several radiopure stainless steel emanation chambers in order to measure Radon emanation from a set of materials in contact with the tracker gas. A large chamber (with a 0.7 $m^3$ volume) with a 3 mBq sensitivity is able to measure large volume samples or films with surfaces up to 80 $m^3$ [7]. Small setups with sensitivity of 0.2 mBq and few liters volume have been used for smaller samples. A Radon Concentration Line (RnCL) has also been developed to measure the final activity of the tracker. The system is composed of an electrostatic Radon detector coupled to a carbon trap cooled to -50$^o$C. Nitrogen is flushed inside each quarter of the tracker and then it is directed to the RnCL to estimate the Radon emanation from the tracker internal materials. Performed measurements resulted in few mBq of Radon activity [8]. Considering a gas flushing rate of 2 $m^3$/h, Radon levels of 0.15 mBq/$m^3$ in the tracker will be achieved. Finally all the detector materials have also been screened by low background gamma spectrometry with High Purity Germanium detectors (HPGe). Measured activity levels for $^{40}$K, $^{238}$U, $^{214}$Bi and $^{208}$Tl range from few 0.1 mBq/kg to few 100 mBq/kg [9]. The sensitivity on the half-life of neutrinoless double beta decay is estimated by considering the target levels of background contaminations (Tl, Bi and Radon) and the 2νββ-decay of $^{82}$Se with a 8% (FWHM) energy resolution. With about 0.1 events expected in the region of interest, (between 2.8 and 3.2 MeV) and an exposure of 17.5 kg x yr, the sensitivity on the half-life is $T(0v)_{1/2} = 5.9 \times 10^{24}$ yr, which translates in a range of the effective neutrino mass between 0.20 and 0.55 eV [10].

## Plans in 2022-2024

**Schedule.** Installation of the Demonstrator in LSM is planned to be finished at **the end of 2022.**

**2022** - completion of assembly and launch of the Demonstrator without neutron shielding. The calibration of the Demonstrator, the launch of data accumulation in a configuration without neutron shielding.
**The first half of 2022** - the creation of neutron shielding of the Demonstrator.
**The end of 2022** – start and calibration of data accumulation in the full configuration of the Demonstrator.
**2022-2024** - data accumulation, data analysis. Determination of background. Fight with background if required and possible. Publication of results for the Demonstrator.
**2022-2024** - R&D on: the centrifuge method of $^{96}$Zr enrichment, improvement of the purification technique of $^{82}$Se (100 kg) and mass production of plastic scintillators.

**Physics goals and planned publications.**
(1) Study of backgrounds. We plan to publish two or three articles. One for internal and external backgrounds (perhaps the very first publication with Demonstrator data). One is specifically about Radon. This will be very important for other experiments too, including searches for dark matter. And, perhaps, one article will cover the extrapolation of backgrounds on the sensitivity of the full SuperNEMO setup.
(2) One article will describe the SuperNEMO Demonstrator in NIM or JINST.
(3) There should be at least 3 articles on $^{82}$Se. We already observe in NEMO-3 an indication that ββ-decay of $^{82}$Se goes through ground state of intermediate nucleus (so called Single State Dominance (SSD) hypothesis for ββ-decay mechanism) in contradiction with theoretical expectations. With a higher statistics and lower background this effect should be very well visible in the Demonstrator. This may be one of the most important physical results of the Demonstrator. And of course, we will publish an article on 2νββ – 0νββ-decay $^{82}$Se and separately on ββ-decay to excited states of $^{82}$Kr.
(4) The study of "exotic" models: bosonic neutrinos, violation of the Lorentz invariance, the variation of the Fermi constant, and so on. This is possible due to registration of full pattern of ββ-decay (single electron energies and angle between their impulses) event in our method.
(5) Measurement of the conversion constants of radioactive isotopes. We already see with NEMO-3 that there are uncertainties in the tables, for example, for Pa-234m. For low-background experiments, the existing uncertainties become a problem. We are practically the only ones who can measure this with our system of radioactive calibration sources.

## JINR contribution

1. Production in association with the Prague TU of 720 blocks of plastic scintillators for the complete program of the Demonstrator calorimeter.
2. Production of plastic scintillators for the VETO system. VETO scintillator sizes 308 x 310 x 150 mm, PMTs 5” R6594 HAMAMATSU, 400 euro/block x 60 =24 keuro
3. 100 photomultipliers, 8" R5912-03, ultra low-background, high quantum efficiency (QE=30%) produced by HAMAMATSU are purchased - 100 keuro.
4. 7 crates for calorimeter electronics - 39.5 keuro
5. 1.5 kg of enriched $^{82}$Se was purchased by JINR as sources of the double beta decay.
6. To purify the materials from radioactive contamination, a clean room has been created at JINR, a method was developed and a facility for radiochemical purification of $^{82}$Se was created. It was used to purify 3.5 kg of $^{82}$Se to the level required in the experiment.
7. Signal and high-voltage cables have been produced for the track detector of the Demonstrator.
8. JINR iron shielding – 200 keuro
9. Running expenses of SuperNEMO experiment at LSM. JINR contribution to the infrastructure of the LSM – 20 keuro/yr.

10.To check the radioactive contamination of materials for the Demonstrator, two ultra-low-background HPGe-detectors (600 cm3) were purchased. Using this detector, measurements of the double beta decay to excited isotope states were carried out also.
11. In parallel with R & D and the development of the Demonstrator software by a team from JINR, a work was carried out on the data analysis of the completed NEMO-3 experiment. New results on the double beta decay of isotopes: $^{48}$Ca, $^{82}$Se, $^{96}$Zr,$^{100}$Mo, $^{116}$Cd, $^{130}$Te, and $^{150}$Nd (NEMO-3) have been obtained and articles on these results have been prepared and published.
12. The software team from JINR took an active part in modeling of the Demonstrator, in the development of programs for the acquisition and processing of data, and in the creation of databases.

## Conclusions and future perspective

The SuperNEMO Demonstrator is currently in the last stage of its installation phase, which will be completed in the first months of 2022. After 2.5 yr of data taking, the sensitivity goal of the detector will be reached ($T(0v)_{1/2} > 5.9 \times 10^{24}$ yr (90% C.L.) - $<mv> <$ 0.20 – 0.55 eV for 17.5 kg x y exposure) if the required background levels of internal and external contaminations will be achieved.

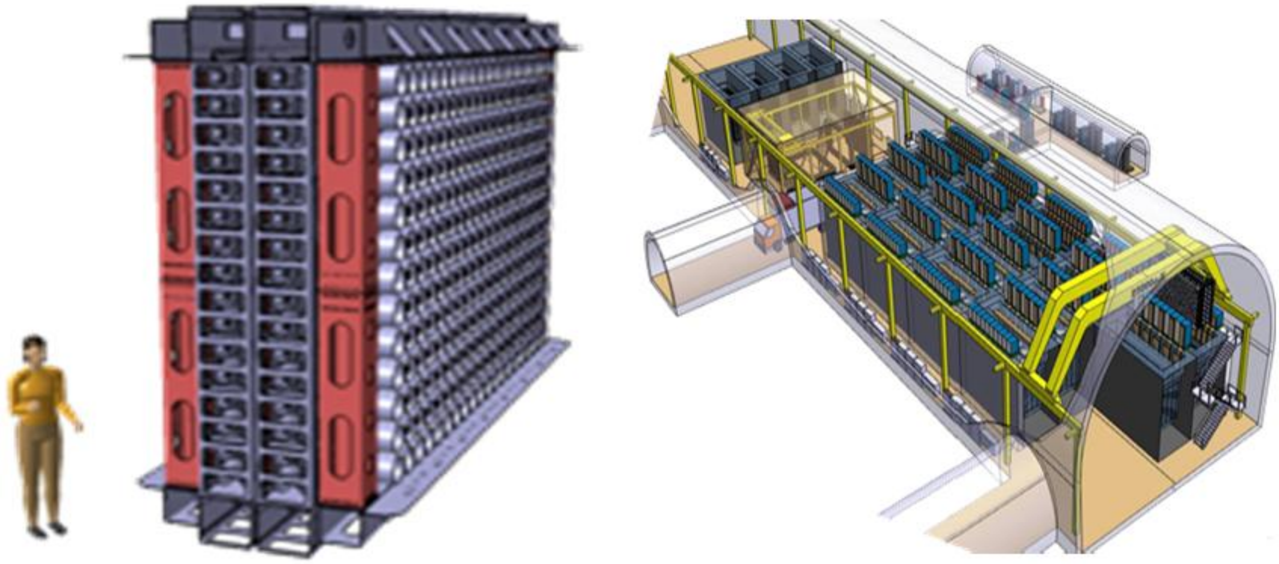

**Figure 4:** *Left:* Sensitivity projection of the SuperNEMO Demonstrator. *Right*: complete full SuperNEMO detector in the underground laboratory.

To enhance the sensitivity and partially explore the inverted region of the effective Majorana neutrino mass (between 40 and 110 meV), one need to measure 0vββ half-life at the level of $T(0v)_{1/2} > 10^{26}$ yr. With 20 detector modules based on the design of the demonstrator and hosting each 5 kg of $^{82}$Se, SuperNEMO will be able to fulfill this requirement after an exposure of 500 kg x yr (see Fig. 4).

## Recent publication of the SuperNEMO 2017- 2020

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## Reports of Dubna group at international conferences in 2019

Yu.A. Shitov “The Final Results of the NEMO-3 Experiment and Status of the SuperNEMO Project”, Nucleus-2019, Dubna, 1-5 July 2019.

V.I. Tretyak “Investigation of Mo-100 two-neutrino double beta decay in NEMO-3”, MEDEX-2019, Prague, 27-31 May 2019.

## Human resources

Most of the participants in the SuperNEMO experiment took part in the NEMO-3 experiment and R&D program of the SuperNEMO project. We have world level experience in the following directions: radiochemistry (radiochemical purification of isotopes and production of radioactive mono-isotopes), electro-magnetic mass separation of isotopes, Energy and time calibration, plastic scintillators and semiconductor detectors, software (simulation, data analysis, databases).

| N | Person | Status | Subjects | FTE |
|---|---|---|---|---|
| 1 | O.I Kochetov | Project Leader | calorimeter, data analysis, databases | 1.0 |
| 2 | Yu.A.Shitov | Participant | software, data analysis, databases | 0.1 |
| 3 | V.B.Brudanin | Participant | calorimeter, data analysis | 0.1 |
| 4 | 3. A.A. Smolnikov | Participant | calorimeter, data analysis, simulation | 0.3 |
| 5 | 4. A.A. Klimenko | Participant | software, data analysis | 0.3 |
| 6 | 5. V.I. Tretyak | Deputy Leader | software, data analysis, simulation | 1.0 |
| 7 | 7. D.V. Karaivanov | Participant | radiochemistry, $^{82}$Se-purification, sources | 0.4 |
| 8 | 8. A.V. Rahimov | Participant | radiochemistry, $^{82}$Se purification, sources | 0.6 |
| 9 | 9. D.V. Filosofov | Participant | radiochemistry, $^{82}$Se purification, sources | 0.3 |
| 10 | 10. N.A. Mirzaev | Participant | radiochemistry, $^{82}$Se purification, sources | 0.4 |
| 11 | 12. A.V. Salamatin | Participant | electronics, cables | 0.4 |
| 12 | 13. V.V. Timkin | Participant | calorimeter, VETO system and cables | 1.0 |
| 13 | 14. I.B. Nemchenok | Participant | PS production, calorimeter and VETO system | 0.2 |
| 14 | 15. I.I. Kamnev | Participant | PS production, calorimeter and VETO system | 0.3 |
| 15 | 16. O.I. Vagina | Participant | PS production, calorimeter and VETO system | 0.3 |
| **In total** | | | | **6.7** |

# SWOT analysis

**Advantages** of SuperNEMO experiment in comparison with existing advanced experiments:

1. It is possible to study simultaneously the double beta decay of several isotopes in the form of foil sources. The source and the detector are separated.
2. The only experiment in the world in which you really see the full signature of double beta decay (vertex, tracks and energies of two electrons). The complete kinematics of the double beta decay process is reconstructed due to simultaneous measurement of electron tracks (their angular distribution) and their energies in the PS blocks of the calorimeter. This is important in order to establish the mechanism of neutrinoless double beta decay.
3. Excellent background identification and rejection due to detection of gamma-, positron-, electron and alpha-particles.
4. Identification of e- and e+ with a superimposed magnetic field of 25 Gs.
5. Time of flight technique for suppression an external background.
6. Radon suppression by anti-radon factory.
7. SuperNEMO modular design (20 independent modules) allows you to increase the number of modules as they are ready

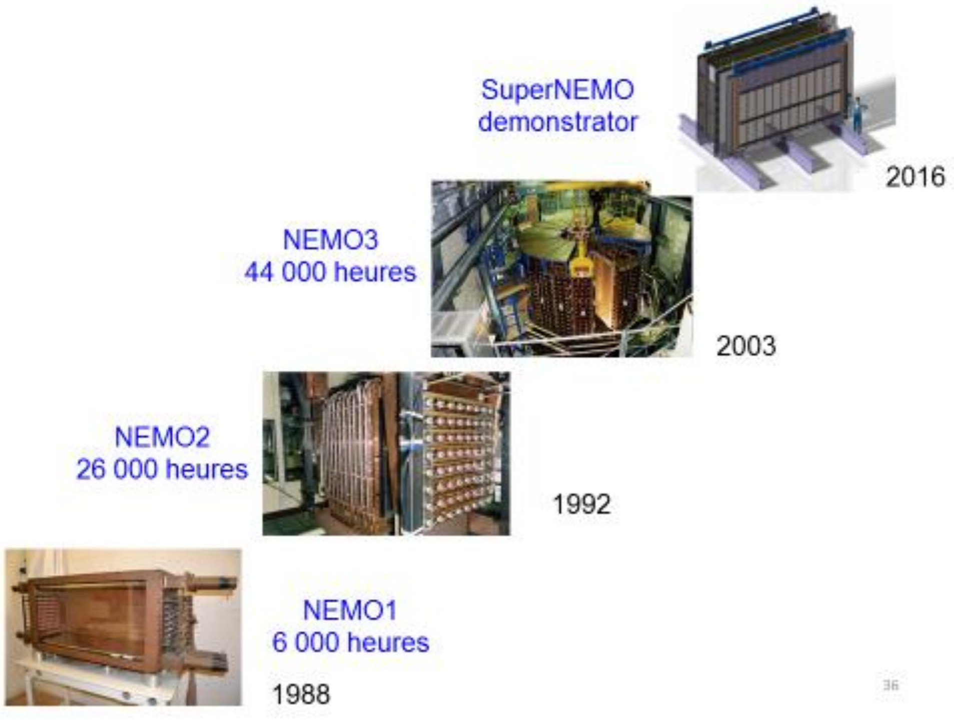
As a result, almost zero background is expected in the area of interest in the search for 0vββ-decay.

The full data set of the NEMO-3 tracko-calo experiment has been used to measure the half-life of the two-neutrino double beta decay of $^{100}$Mo to the ground state of $^{100}$Ru, $T(2v\beta\beta)_{1/2}$ = [6.81 ± 0.01 (stat.) ± 0.38/0.40 (syst.)] x $10^{18}$ yr. The two-electron energy sum, single electron energy spectra and distribution of the angle between the electrons are presented with an unprecedented statistics of 5 x $10^5$ events and a signal-to-background ratio of ~ 80. Clear evidence for the Single State Dominance model is found for this nuclear transition. Limits on Majoron emitting 0vββ-decay modes with spectral indices of n = 2, 3, 7, as well as constraints on Lorentz invariance violation and on the bosonic neutrino contribution to the 0vββ-decay mode are obtained. SuperNEMO experiment will achieve much better results in these parameters

**Disadvantages** are the following:

1. Low efficiency of recording the process of 0vββ-decay - 25%.
2. Low energy resolution of the calorimeter, FWHM = 8% for 1 MeV electrons (contribution from 2vββ decay). As a result of a fatal background of the continuous spectrum of 2vββ-decay

**Collaboration photo**



**History of the NEMO/SuperNEMO projects**