Investigations of the 2β-decay processes of Se-82 with the SuperNEMO detector

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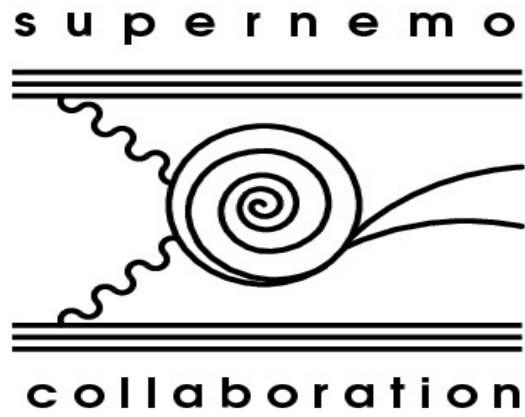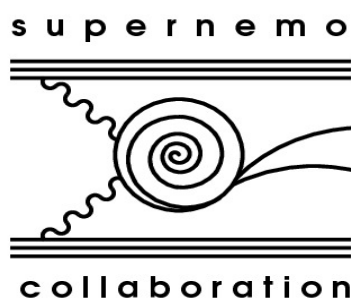
JINR Participation
2019-2021

Исследования процессов 2β – распада ^{82}Se с помощью детектора SuperNEMO
(Участие ОИЯИ)
Продление проекта на период 2019-2021 гг

Investigations of the of 2β–decay processes of ^{82}Se with the SuperNEMO detector
(JINR Participation)
Project extension for the period 2019-2021

SuperNEMO КОЛЛАБОРАЦИЯ

s u p e r n e m o

c o l l a b o r a t i o n

Шифр темы: 03 – 2 – 1100 – 2010/2018

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ДАТА НТС ЛАБОРАТОРИИ _____ НОМЕР ДОКУМЕНТА _____

ДАТА НАЧАЛА ПРОЕКТА _____

(ДЛЯ ПРОДЛЕНИЙ — ДАТА ПЕРВОГО УТВЕРЖДЕНИЯ ПРОЕКТА)_____

Проект SuperNEMO

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

Продление проекта на период 2019-2021 гг

Project SuperNEMO

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

Project extension for the period 2019-2021

SuperNEMO COLLABORATION

Theme 03 – 2 - 1100 - 2010/2018

(Неускорительная нейтринная физика и астрофизика, проект SuperNEMO)

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(Участие ОИЯИ)
Продление проекта на период 2019-2021

Investigations of the 2β-decay of ^{82}Se with the SuperNEMO detector
(JINR Participation)
Project extension for the period 2019-2021

SuperNEMO

Шифр темы: 03 – 2 – 1100 – 2010/2018

РУКОВОДИТЕЛЬ ПРОЕКТА: Кочетов О.И.

УТВЕРЖДЕН ДИРЕКТОРОМ ОИЯИ	ПОДПИСЬ	ДАТА

СОГЛАСОВАНО

ВИЦЕ-ДИРЕКТОР ОИЯИ	ПОДПИСЬ	ДАТА
ГЛАВНЫЙ УЧЕНЫЙ СЕКРЕТАРЬ	ПОДПИСЬ	ДАТА
ГЛАВНЫЙ ИНЖЕНЕР	ПОДПИСЬ	ДАТА
НАЧАЛЬНИК НОО	ПОДПИСЬ	ДАТА
ДИРЕКТОР ЛАБОРАТОРИИ	ПОДПИСЬ	ДАТА
ГЛАВНЫЙ ИНЖЕНЕР ЛАБОРАТОРИИ	ПОДПИСЬ	ДАТА
РУКОВОДИТЕЛЬ ПРОЕКТА	ПОДПИСЬ	ДАТА
ЗАМ. РУКОВОДИТЕЛЯ ПРОЕКТА	ПОДПИСЬ	ДАТА

ОДОБРЕН

ПКК ПО НАПРАВЛЕНИЮ	ПОДПИСЬ	ДАТА

PROJECT ENDORSEMENT LIST

PROJECT SuperNEMO

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

SuperNEMO COLLABORATION

THEME 03 – 2 – 1100 – 2010/2018

NAME OF PROJECT LEADER O.I. Kochetov

APPROVED BY JINR DIRECTOR	SIGNATURE	DATE

ENDORSED BY

JINR VICE-DIRECTOR	SIGNATURE	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	DATE
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LABORATORY DIRECTOR	SIGNATURE	DATE
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ENDORSED

RESPECTIVE PAC	SIGNATURE	DATE

Content

Abstract

The SuperNEMO Demonstrator, which is the first module of the SuperNEMO experiment, is located in Modane underground laboratory (France) and search for neutrinoless double beta decay ($0\nu\beta\beta$) of ^{82}Se in order to unveil the nature of the neutrino. Its detection technique, based on tracking and calorimetry, allows the reconstruction of the full kinematics of detected particles, including individual energies and emission angle, resulting in a strong reduction of the background and the possibility to disentangle different $0\nu\beta\beta$-decay mechanisms and processes such as the double beta decays to the excited states of the daughter nuclei. Indeed, fully reconstructing the event kinematics gives access to a variety of event topologies which can be used to measure the different background contributions. Using these informations in a multivariate analysis can improve the background discrimination power and further increase the detector sensitivity. The goal of the Demonstrator is to validate the technique and to reach a sensitivity of the $0\nu\beta\beta$-decay half-life of about $T(0\nu)_{1/2} > 5.9 \times 10^{24}$ yr with "zero background" in the region interest. The first physics data are expected to be taken at the beginning of 2018. Most of the JINR members of the NEMO/SuperNEMO collaboration have 20+ year experience in the project, participating in a successful NEMO-2 and NEMO-3 experiments studied $2\beta\beta$ processes in a set of nucleus: ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd, and in the R&D program of the SuperNEMO project. The requested financing for the project is 245 k$.

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 Se-82, and expected sensitivity of $T(0\nu)_{1/2} > 10^{26}$ yr (<mv> < 40 - 110 meV). SuperNEMO uses the tracker-calorimetric detection technique successfully proven in the NEMO-3 experiment. In 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 module should reach the sensitivity to the half-life $T(0\nu)_{1/2} > 5.9 \times 10^{24}$ 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 of particle physics as a second order process: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$. The two neutrino double beta decay (2νββ) has been observed in eleven nuclei, where single beta decay is energetically forbidden, and very high half-lives, between 7×10^{18} yr and 2×10^{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 0νββ 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 predictions. 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 $G^{2\nu}(E_0, Z)$ and the Nuclear Matrix Element $|M^{2\nu}|$:

$$T(2\nu)^{-1} = |M^{2\nu}| \, G^{2\nu}(E_0, Z)$$

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 $|M^{0\nu}|$:

$$T(0\nu)^{-1} = <m_\nu>^2 \, |M^{0\nu}| \, G^{0\nu}(E_0, Z)$$

This equation states by itself why searching for 0νββ 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 $<m_\nu>^2$, 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 performed in the past, going back for at least half a century, with increasing sensitivities. Two main approaches have 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 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).

In the following sections, the status of the art on 0νββ searches will be presented with special emphasis on large scale running experiments.

Double Beta Decay in ^{136}Xe Two large experiments have searched for 0νββ in ^{136}Xe: EXO-200 are using Xenon in an homogeneous medium (both as 0νββ 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 TAUP 2017 conference [9]. A lower limit on the half-life $T_{1/2}(0\nu) > 1.8 \times 10^{25}$ yr (90% C.L.) is established, that correspond to the upper limit on the Majorana neutrino mass $<m_{\beta\beta}> < (147 - 398)$ meV. An 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. The experiment started in October 2011.

With an exposure of 504 kg-yr of 136 Xe a lower limit on the 0νββ-decay half-life was recently obtained [13] : $T_{1/2}(0\nu) > 1.1 \times 10^{26}$ yr (90 % C.L.) The corresponding upper limit on the effective Majorana neutrino mass is in the range 60 – 161 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 0νββ decay searches once it was realized that Ge-76 is both 2ββ 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 $T(0\nu)_{1/2} = 1.19\text{-}2.2 \times 10^{25}$ 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 2017 results with exposure 46.7 kg x yr, give a sensitivity $T_{1/2}(0\nu) > 5.8$ x 10^25 yr and a limit for the half-life of ^{76}Ge $T_{1/2}(0\nu) > 8.0$ x 10^25 yr (90% C.L.), that corresponds to $<m_{\beta\beta}> < 120 - 270$ meV [24]. the experiment is supposed to collect an exposure of about 100 kg x yr and improve the $0\nu\beta\beta$ sensitivity to $T_{1/2}(0\nu) > 1.35$ x 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 $T_{1/2}(0\nu) > 1.9$ x 10^25 yr (90% CL) based on 10 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 year exposure in order to reach $T_{1/2}(0\nu) \sim 10^{28}$ yr sensitivity level fully covering the inverted hierarchy region). Under favorable funding LEGEND-200 could start measurements by 2020.

Double Beta Decay in Te-130. Tellurium-130 is another good $\beta\beta$-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 and sensitivities expected for CUORE. Last combined limit (Cuoricino + CUORE0) is $T_{1/2}(0\nu) > 6.6$ x 10^24 yr (90% C.L.) for 67.65 kg x yr exposure with corresponding limit on the effective Majorana neutrino mass $<m_{\beta\beta}> < 210-590$ 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.

NEMO-3 is in the process of publishing final results of $\beta\beta$-studies for a set of isotopes.

Ca-48: $T(2\nu\beta\beta)_{1/2} = [6.4 \pm 0.7/0.6$ (stat.) $\pm 1.2/0.9$ (syst.)] x 10^19 yr.

Cd-116: $T(0\nu\beta\beta)_{1/2} \geq 1.0 \times 10^{23}$ yr (90% C.L.), $\langle m_\nu \rangle \leq 1.4-2.5$ eV
$T(2\nu\beta\beta)_{1/2} = [2.74\pm0.04(stat.)\pm0.18(syst.)]\times10^{19}$ y.

Nd-150: $T(0\nu\beta\beta)_{1/2} > 2.0$ x 10^22 yr (90 % C.L.), $<m_\nu> < 1.6 - 5.3$ eV.

The tracker-calorimeter technique uniquely allows NEMO-3 to search for 0ν 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 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). We found no evidence of this decay and set lower limits on the half-life $T(0\nu4\beta)_{1/2} > 1.1$ x 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 indirectly measure the absolute neutrino mass scale. Several experiments will be running in the next few years and they will provide important results on $0\nu\beta\beta$. In case of a positive signal, an observation with several isotopes is crucial for convincing evidence. The positive results would confirm Maorana nature of neutrino followed an inverted hierarchy mass scheme with directly measured mass scale. Even a missing observation of $0\nu\beta\beta$ 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).

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.

Best present limit on $< m_\nu >$

Nucleus	T1/2, y, 90% C.L.	$<m\nu>$, eV, QRPA + others	Experiment
Ge-76	> 8.0 x 10^25	$< 0.120 - 0.270$	GERDA – I + II
Ge-76	> 1.9 x 10^25	$< 0.240 - 0.520$	Majorana
Xe-136	> 1.1 x 10^26	$< 0.061 - 0.165$	KamLAND-Zen I + II
Xe-136	> 1.8 x 10^25	$<0.147 – 0.398$	EXO-200 I + II
Te-130	> 6.6 x 10^24	$< 0.210 – 0.590$	CUORE
Mo-100	> 1.1 x 10^24	$< 0.310 – 0.620$	NEMO-3

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

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

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The SuperNEMO Demonstrator

Introduction

The SuperNEMO Demonstrator is located in the Modane underground laboratory (France) and investigate 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 0νββ-decay mechanisms [2]. The goal of the Demonstrator is to validate the technique and to reach a sensitivity on the 0νββ-decay half-life of about $T(0\nu)_{1/2} > 5.9$ x 10^24 yr with "zero background" in the region interest. The goal for any double beta decay experiment is to unambiguously detect the characteristic 0νββ energy spectrum, among the continuous 2νββ spectrum and other radioactive backgrounds. This signal can either translate into 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].
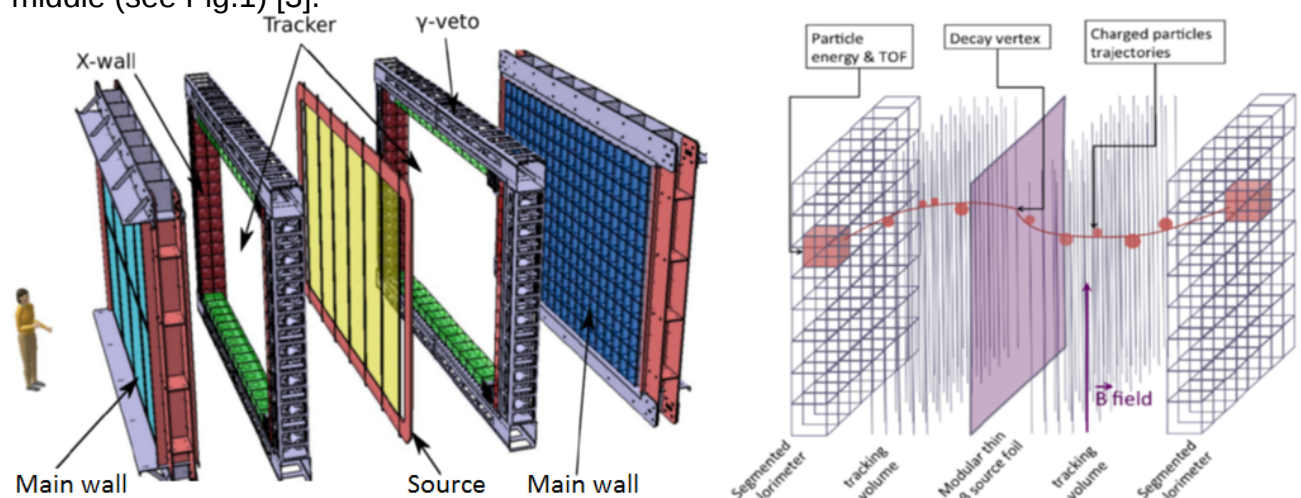

Figure 1: *Left*: Pictorial view of the SuperNEMO Demonstrator. On each side of the source frame a tracker and a calorimeter module are installed. *Right:* Detection principle of SuperNEMO: trajectories of charged particles emitted from the source foils are measured in the tracker while their energy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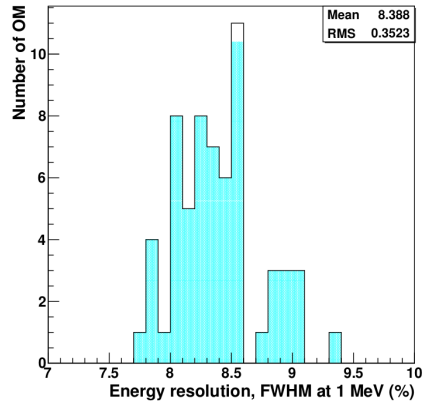

Figure 2. *Left*: one calorimeter Optical Module (OM), PS block equipped with a 8" PMT. *Right*: distribution of the energy resolution (FWHM) for the calorimeter Optical Modules with an average resolution of ~ 8 % FWHM for electrons 1 МэВ, respectively.

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 calibration is performed with [207]Bi source emitting internal conversion electrons at energies 482 keV, 976 keV, and 1770 keV.
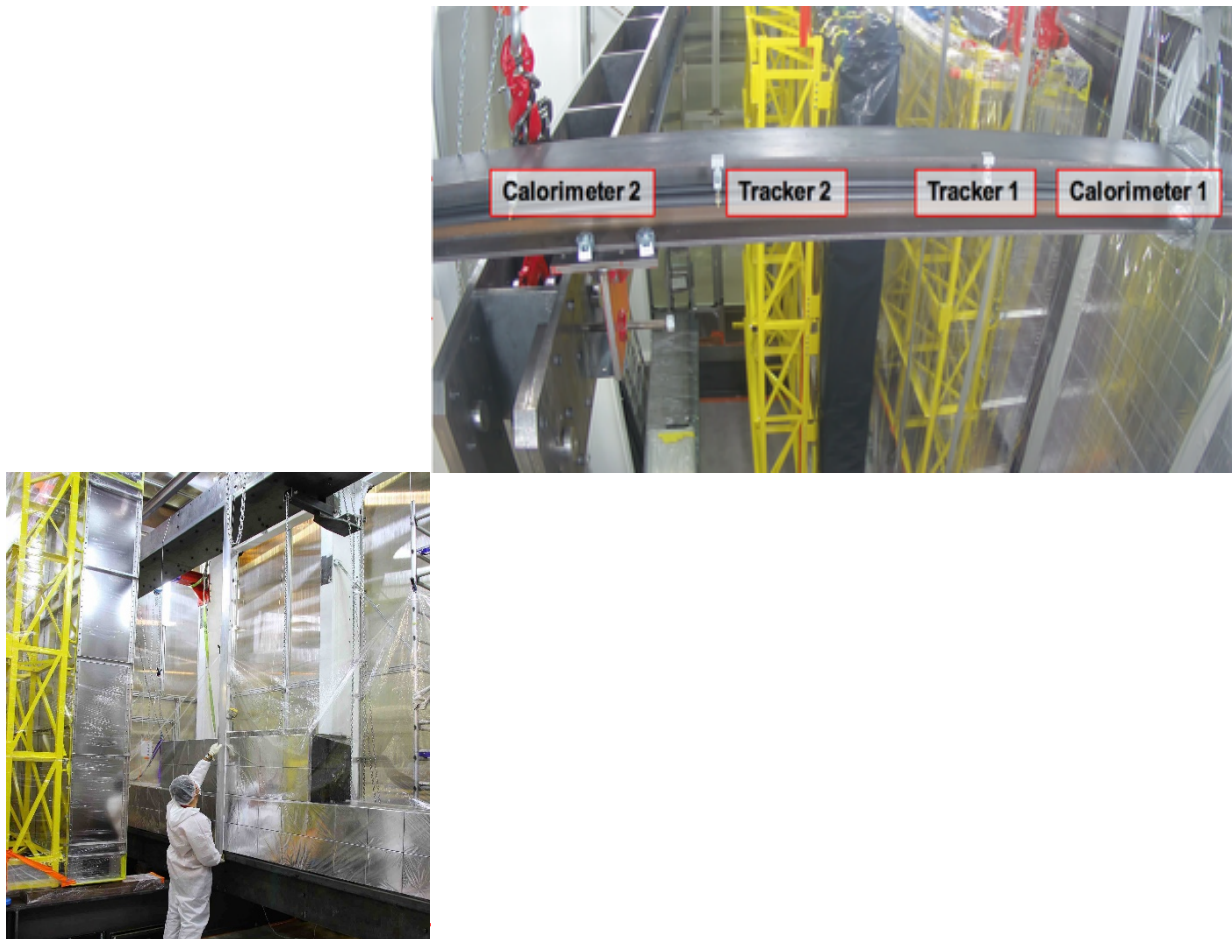
Figure 3: *Left:* a view of the installation procedure of Optical Modules in the calorimeter wall. *Right:* Side view of the two calorimeter walls and the two tracking chambers already installed at Modane.

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 main calorimeter have been installed (see Fig. 3) and the detector is already in its final commissioning phase. The rest source foils and calibration system will be installed in the spring of 2018. Data taking will begin in the summer of 2018.

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 γ or 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 deposited on inner surfaces of detector (mainly source foil and wires).

These β/γ emitters can mimic ββ events through a beta decay, accompanied by a Compton or Moller scattering or an internal conversion.

Multivariate analysis

The most sensitive variable for the 0νββ search is two electrons 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 informations 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 b 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). Preliminary 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°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 $T(0\nu)_{1/2} = 5.9 \times 10^{24}$ yr, which translates in a range of the effective neutrino mass between 0.20 and 0.55 eV [10].

Plans in 2018-2021

Schedule. Installation of the Demonstrator in LSM is planned to be finished in the spring of 2017.
Spring-summer of 2018 – start of the Demonstrator of SuperNEMO without shielding.
Summer of 2018 – full-scale calibration of the Demonstrator and start of a data taking (2.5 years).

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 in favour of SSD for [82]Se, that contradicts to previous 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 0νββ-decay and separately on ββ-decay to excited states.
(4) The study of "exotic" models: bosonic neutrinos, violation of the Lorentz invariance, the variation of the Fermi constant, and so on.

(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 Se-82 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 Se-82 was created. It was used to purify 3.5 kg of Se-82 to the level required in the experiment.

7. Signal and high-voltage cables have been produced for the track detector of the DEMONSTRATOR.

8.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.

12. 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: Ca-48, Se-82, Zr-96, Mo-100, Cd-116, Te-130, Nd-150 have been obtained and articles on these results have been prepared and published.

13. 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 2018. After 2.5 yr of data taking, the sensitivity goal of the detector will be reached ($T(0\nu)_{1/2} > 5.9$ x 10^{24} yr (90% C.L.) - $<m\nu>$ < 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.
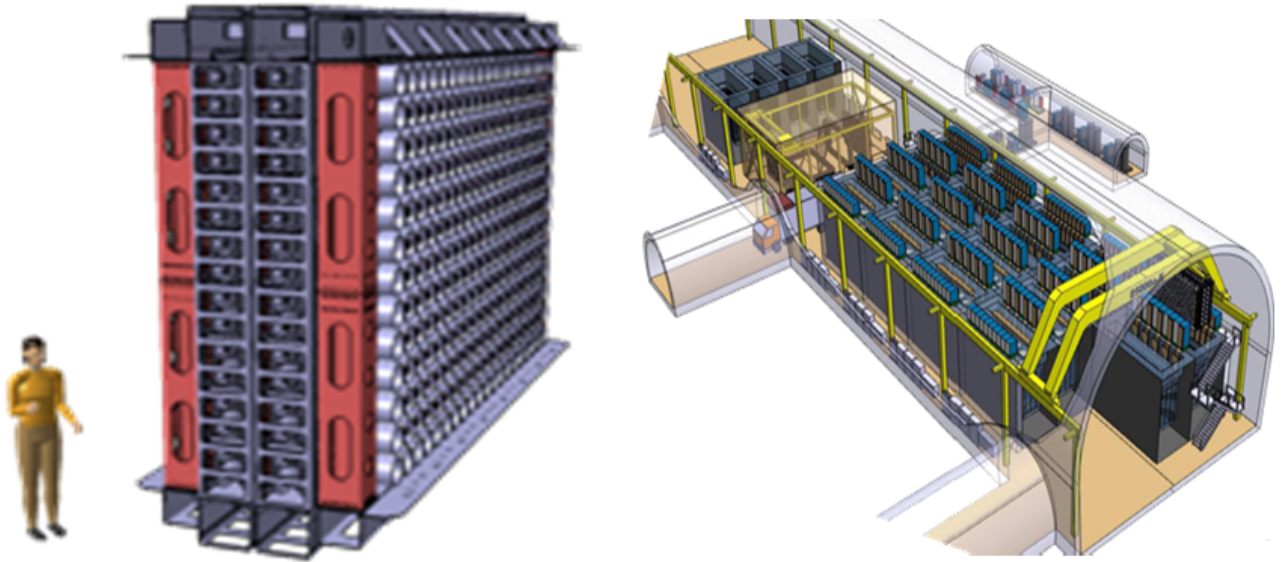
Figure 4: *Left:* Sensitivity projection of the SuperNEMO Demonstrator. *Right*: complete SuperNEMO detector in the underground laboratory.

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 0νββ half-life at the level of $T(0\nu)_{1/2} > 10^{26}$ 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).

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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, scintillation and semiconductor detectors, software (simulation, data analysis, databases).

N	Person	Status	Subjects	FTE
1	O.I Kochetov	Project Leader	calorimeter	0.9
2	Yu.A.Shitov	Deputy Leader	software, data analysis	0.5
3	V.B.Brudanin	Participant	calorimeter	
4	V.G.Egorov	Participant	calorimeter, data analysis	
5	3. A.A. Smolnikov	Participant	calorimeter, data analysis	0.3
6	4. A.A. Klimenko	Participant	software, data analysis	0.35
7	5. V.I. Tretyak	Participant	software, data analysis	0.9
8	7. D.V. Karaivanov	Participant	radiochemistry, Se-82 purification, sources	0.35
9	8. A.V. Rahimov	Participant	radiochemistry, Se-82 purification, sources	0.35
10	9. D.V. Filosofov	Participant	radiochemistry, Se-82 purification, sources	0.3
11	10. N.A. Mirzaev	Participant	radiochemistry, Se-82 purification, sources	0.4
12	11. Yu.V. Yushkevich	Participant	electromagnetic mass separation, calibration	0.25
13	12. A.V. Salamatin	Participant	electronics,cables	0.3
14	13. V.V. Timkin	Participant	calorimeter, VETO system and cables	0.9
15	14. I.B. Nemchenok	Participant	PS production, calorimeter and VETO system	0.2
16	15. I.I. Kamnev	Participant	PS production, calorimeter and VETO system	0.3
17	16. O.I. Vagina	Participant	PS production, calorimeter and VETO system	0.3
In total				**5.2**

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- 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.

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

Disadvantages are the following:

1. Low efficiency of recording the process of $0\nu\beta\beta$-decay - 25%.
2. Low energy resolution of the calorimeter, FWHM = 8% for 1 MeV electrons (contribution from $2\nu\beta\beta$ decay).

Collaboration photo
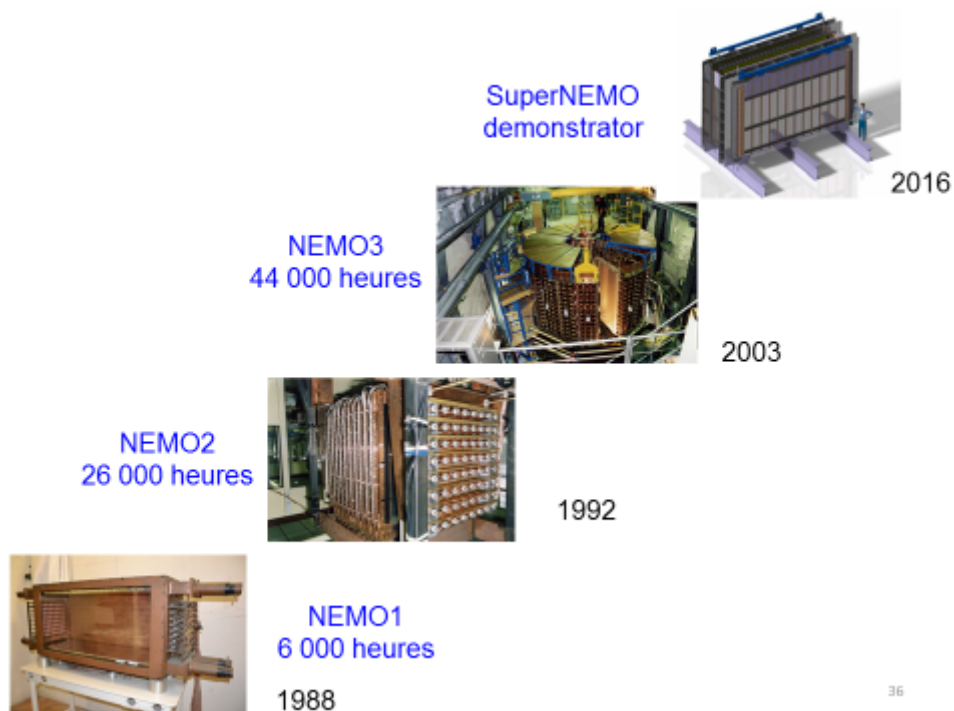
History of the NEMO/SuperNEMO projects

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 a calorimeter (styrene, aluminum, P-terphenyl, POPOP)	24	8	8	8
	2. Spectroscopic electronics for test stands of PS&PMTs	10	10	0	0
	3. Borated polystyrene for neutron shielding of the Demonstrator	40	30	10	0
	4. Materials&equipment for Demonstrator maintenance under JINR responsibility (2 Radon detectors, HPGe spectrometer,) and carrying out calibrations, including creation of calibration sources. Radiochemical equipment.	45	15	15	15
	Total	**119**	**63**	**33**	**23**
Resources	Norm-hours	JINR workshop	0	0	0	0
		DLNP workshop	1800	600	600	600
Financial sources	JINR budget	Budget spending	119	63	33	23
	Off-budget sources	Grants; Other sources (these funds are not currently guaranteed)	*30*	*10*	*10*	*10*

PROJECT LEADER   O.I. Kochetov

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 калориметра (стирол, алюминий, p-терфенил, POPOP	24	8	8	8
		2. Спектроскопическая электроника для стендов-тестирования пластмассовых сцинтилляторов и ФЭУ	10	10	0	0
		3. Борированный полистирол для создания нейтронной защиты Демонстратора	40	30	10	0
		4. Материалы и оборудование для поддержания работоспособности детекторов, находящихся под нашем управлением в Демонстраторе SuperNEMO (2 радоновых детектора, HPGe спектрометр) и проведения калибровок, включая создание калибровочных источников. Радиохимическое оборудование.	45	15	15	15
		Итого	**119**	**63**	**33**	**23**
Необходимые ресурсы	Нормо-часы	ОП ОИЯИ	0	0	0	0
		ООЭП ЛЯП	1800	600	600	600
	Бюджет	Затраты из бюджета	**119**	**63**	**33**	**23**

Источники финансирования	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

Estimated expenditures for the SuperNEMO project

#	Designation for outlays	Total cost	1 year	2 year	3 year
	Direct expenses for the project				
1.	Networking	6.0K US$	2.0	2.0	2.0
2.	DLNP workshop	1500 norm-h	500	500	500
3.	JINR workshop	0	0	0	0
4.	Materials	64.0K US$	38.0	18.0	8.0
5.	Equipment	55.0K US$	25.0	15.0	15.0
6.	Collaboration fee	60.0K US$	20.0	20.0	20.0
7.	Travel expenses	60.0K US$	30.0	15.0	15.0

Total   **245.0K US$**   **115.0K US$ 70.0K US$ 60.0K US$**

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST

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	1800 норм ч.	600	600	600
3.	ОП ОИЯИ	0 норма ч.	0	0	0
4.	Материалы	64.0K US$	38.0	18.0	8.0
5.	Оборудование	55.0K US$	25.0	15.0	15.0
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   **245.0K US$**   **115.0K US$**   **70.0K US$**   **60.0K US$**

РУКОВОДИТЕЛЬ ПРОЕКТА

ДИРЕКТОР ЛАБОРАТОРИИ

ВЕДУЩИЙ ИНЖЕНЕР-ЭКОНОМИСТ ЛАБОРАТОРИИ