Annex 4.

Project (LRIP subproject) report form

PROJECT REPORT

1. General information on the project / LRIP subproject

1.1. Scientific field

Nuclear Physics

1.2. Title of the project / LRIP subproject

LEGEND, TGV+Obelix+Idefix, SuperNEMO, MONUMENT, EDELEWEISS

1.4. Theme / LRIP code

Theme 03-2-1100-2010/2024

1.5. Actual duration of the project/ LRIP subproject

2020-2023

1.6. Project / LRIP subproject Leader(s)

Gusev K., Rukhadze N., Kochetov O., Zinatulina D., Rozov S.

2. Scientific report

2.1. Annotation

The **LEGEND** project as well as the predecessor GERDA experiment searching for neutrinoless double beta decay – the only known practical way to probe the Majorana nature of neutrinos. In 0νββ decay the lepton number is not conserved so its discovery would prove the existence of New Physics beyond the Standard Model. The LEGEND experiment is using the same approach as was successfully exploited in GERDA – bare Ge detectors enriched in ^{76}Ge are directly immersed in liquid argon that works as a cooling medium and simultaneously as an additional passive and active shield against external radioactivity. It allowed to reach in GERDA the unprecedented background index and set a world best lower half-life limit of $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr (90% C.L.) at the median sensitivity of 1.8×10^{26} yr [Phys. Rev. Lett. 125, 252502]. This result proves the success of used approach and opens the bright future for the LEGEND experiment.

Up to now, more attention in investigation of double beta decay has been given to $\beta^-\beta^-$-decay, but there are other channels of double beta decay - EC/EC, β^+/EC and $\beta^+\beta^+$decays. Recently, interest in other double-beta processes has significantly increased, in particular, in EC/EC capture. In contrast to other experiments on searching for 2*ν*EC/EC decay, experiment **TGV** is focused on the direct detection of 2*ν*EC/EC decay of ^{106}Cd by registration of coincidences of two Palladium (Pd) X–rays (energy ~ 21 keV) emitting in this rare decay. ^{106}Cd is one of the most promising candidates to search for 2*ν*EC/EC decay (Fig.1). Theoretical predictions of half-lives for this process are ranged between 1.1×10^{20} and 2.5×10^{22} y. ^{106}Cd is also a real candidate for searching for resonance neutrino-less EC/EC decay to excited states of daughter nuclei – ^{106}Pd. The TGV experiment lasted for several years. As a result of this investigation the best experimental limit on 2*ν*EC/EC decay of ^{106}Cd - $T_{1/2} \geq 4.2 \times 10^{20}$ y (90% CL) [Rukhadze N I et al 2012 *J. Phys.: Conf. Ser.* **375** 042020] was obtained in the previous phase II of experiment. In principle phase II of the experiment showed some indication on the possible 2*ν*EC/EC decay of ^{106}Cd. But statistics of KX(Pd)-KX(Pd) coincidence events in this phase was not enough to declare the detection of this process. Experimental possibilities of phase II was also limited by the presence of radioactive contamination of ^{241}Am on several investigated foils of ^{106}Cd. Therefore, the mass of investigated isotope in experiment TGV was highly increased - from ~5.787×10^{22} atoms of

^{106}Cd (~13.6 g of ^{106}Cd with enrichment of 75%).in phase II to ~1.3 × 10^{23} atoms of ^{106}Cd (~23.2 g of ^{106}Cd with enrichment of 99.57%) in current phase III.

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 0νββ-decay mechanisms in the case of discovery.

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 all the spectrometer channels (fully the calorimeter and the tracker). Physical data taking has been started in the configuration without passive shielding. The 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, the physical launch of the Demonstrator was delayed until end of 2022. 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 0νββ-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.

Direct search for Dark Matter (DM) is the fundamental scientific problem addressed by the **EDELWEISS**. It searches for DM using an array of cryogenic germanium bolometers with phonon and ionization channels, it thus able to identify events induced by nuclear recoils. In the present time there is an increasing gain of interest for the search of low-mass WIMPs and other DM particles (axions, etc) arising on the one hand from no observation yet of SUSY at the LHC and on the other hand from new theoretical approaches favouring lighter candidates. During the current phase un unprecedented charge resolution of 0.53 electron-hole pairs (RMS) has been achieved using the Neganov-Trofimov-Luke (NTL) internal amplification. With this the experiment set the first Ge-based constraints on sub-MeV/c^2 DM particles interacting with electrons, as well as on dark photons down to 1 eV/c^2 [Phys. Rev. Lett. 125, 141301]. These results demonstrate the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale electron signals. The collaboration efforts were recently directed to CDR of new phase of the experiment that will have dry dilution cryostat of new generation installed at LSM underground laboratory. Thus, the old setup that has been used by the EDELWEISS from 2005 is now start to be decommissioned.

2.2. A detailed scientific report

In 2022, the analysis of the GERDA experimental data was continued, resulting in new publications. During the past year, the **LEGEND** Collaboration with the decisive participation of JINR specialists carried out a step-by-step commissioning of the LEGEND-200 experiment at the Gran Sasso National Laboratory (Italy). In summer, the first 60 kg of ^{76}Ge enriched detectors were installed. In addition to the direct assembling of detector strings, our specialists fabricated high-purity nylon mini-shrouds used to reduce the radioactive background of the experiment and for the first time performed the installation of the complete liquid argon instrumentation, developed and created by a common team of scientists from JINR and the Technical University of Munich. In the fall, the DLNP staff returned to Gran Sasso to continue the detectors installation. The preparatory work needed for the full-scale launch of the experiment was carried out. The active argon instrumentation system and all currently available ^{76}Ge detectors were re-installed. Now 101 germanium detectors are assembled in LEGEND and data taking is being started. The enriched Ge-76 isotope mass exceeded 100 kg for the first time. Now it is ~140 kg.

In 2023, when the remaining detectors are made, they will be added to the setup to reach the final ^{76}Ge mass of 200 kg. Then, after 5 years of data taking, the LEGEND-200 aims to reach the desired neutrinoless double beta decay sensitivity of 10^{27} years.

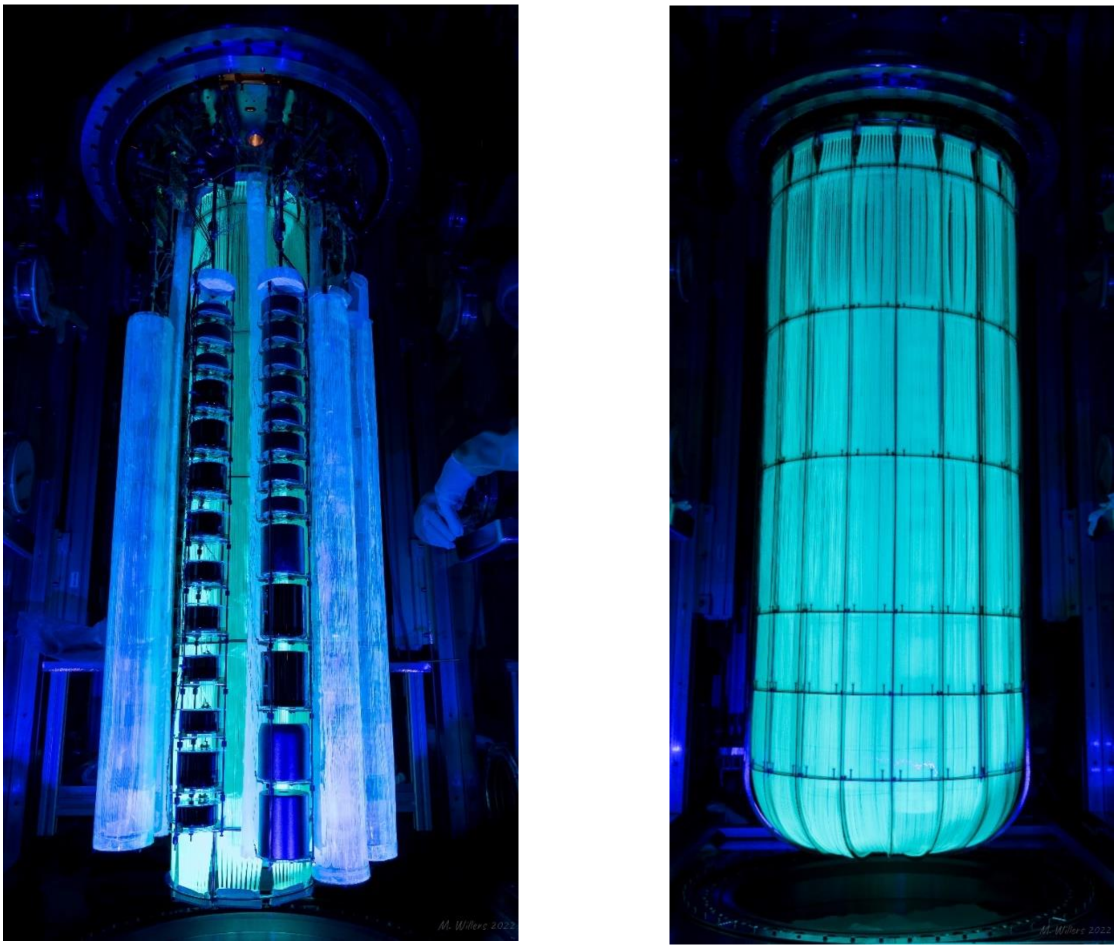

Fig. 1: ***On the left****: Inner part of the argon instrumentation and germanium detector strings (not all nylon mini-shrouds are on);* ***on the right****: LEGEND-200 before immersion in liquid argon (outer part of the veto is visible).*

Current phase III of the experiment **TGV** was started at the Modane underground laboratory (LSM) at the end of February 2014 with 32-detector spectrometer TGV-2 and 16 samples of ^{106}Cd with a total mass of ~23.2 g (~1.3×10^{23} atoms of ^{106}Cd). The level of background in current phase III of experiment was much lower (especially in a low energy region) than it was in previous phase II due to the lower level of radioactive contamination in investigated samples. Investigated samples were made by rolling in a form of metallic foils and had a diameter of 52 mm, and a thickness of ~70(10) μm The detector part of the spectrometer is composed of 32 HPGe planar type detectors each with sensitive volume of 20.4 cm^2 × 0.6 cm. 16 foils of ^{106}Cd foils used in current investigation (phase III) were inserted between the entrance windows of detectors. The distance from foils to detectors is about 1.5 mm. The 16 pairs of detectors with cadmium foils were mounted one over another in a common cryostat tower. The total sensitive volume of 32 TGV detectors is about 400 cm^3 and the total mass of them is about 3 kg of Ge. The energy resolution of the detectors measured at 1332 keV γ-line of ^{60}Co were ranged from 3.0 to 4.0 keV. The design of the detector part of TGV spectrometer delivers high detection efficiency for useful events (single and multiple coincidence) and strong suppression of external background. The detector part of the TGV spectrometer is surrounded by a passive shielding consisting of copper (≥20 cm), an airtight box against radon, lead (≥10 cm) and a neutron shielding made of borated polyethylene (16 cm). Location of the TGV spectrometer in the deep underground laboratory (4800 m w.e.) allows us to suppress cosmic rays (reduction factor of ~2×10^6) and fast neutrons (reduction factor of ~10^3). Additional suppression of background in the low energy region (<50 keV) may be achieved by filtering the electronic and microphone noise by digitizing the detector response with different shaping times (2 and 8 μs). Search for 2νEC/EC decay of ^{106}Cd to the ground 0^+ state of ^{106}Pd is based on the analysis of double coincidences between two characteristic KX-rays of Pd detected in neighboring detectors. This analysis of KX-KX coincidences showed an increased numbers of measured events in the region of ~21 keV (KXPd), which might be searching events from the 2νEC/EC decay of ^{106}Cd. But the statistics is still not enough to make the declaration about the experimental observation of 2νEC/EC decay of ^{106}Cd in experiment TGV. Calculation of other branches of double beta decay of ^{106}Cd (Fig.1) were based on the analysis of various types of KX-γ, γ-γ, and KX-γ-γ coincidences. New experimental results (at 90% C.l.) obtained on the present stage of phase III of the TGV experiment are presented in Table 1 in comparison with results of previous phase II of TGV.

Table 1. *Limits on double beta decay of ^{106}Cd (90% CL) obtained in the TGV experiment.*

Decay mode	Final level of ^{106}Pd	$T_{1/2}$, y Phase II (2012)[1]	$T_{1/2}$, y Phase III (T=42500h)[2]	$T_{1/2}$, y Phase III (T=47860h)[3]
2ν*EC/EC*	0^+g.s.	4.2×10^{20}	7.2×10^{20}	1.2×10^{21}
	2^+,511.9 keV	1.2×10^{20}	8.9×10^{20}	1.2×10^{21}
	0^+_1,1134 keV	1.0×10^{20}	7.2×10^{20}	9.6×10^{20}
$2\nu\beta^+/EC$	0^+g.s.	1.1×10^{20}	6.6×10^{20}	8.4×10^{20}
	2^+,511.9 keV	1.1×10^{20}	7.9×10^{20}	1.0×10^{21}
	0^+_1,1134 keV	1.6×10^{20}	9.0×10^{20}	1.2×10^{21}
$2\nu\beta^+\beta^+$	0^+g.s.	1.4×10^{20}	3.9×10^{20}	4.9×10^{20}
	2^+,511.9 keV	1.7×10^{20}	4.7×10^{20}	6.0×10^{20}

$T_{1/2}$theor. (2ν*EC/EC*) ~ $10^{20} - 10^{22}$ y

[1] N.I.Rukhadze et al., *Journal of Physics: Conference Series 375 (2012) 042020*
[2] N.I.Rukhadze et al., *Journal of Physics: Conference Series 2156 (2022) 012134*
[3] N.I.Rukhadze on behalf of TGV collaboration, LXXII International conference Nucleus-2022, Moscow, 2022

During the last three years the **SuperNEMO** Demonstrator Module project has been focused on the integration of the different components of the detector at the Laboratoire Souterrain de Modane (LSM). We have made major progress. The creation, assembly and installation of all the main internal elements of the module: calorimeter, tracker, VETO system, ^{82}Se foils and calibration system was completed, after which the Demonstrator module was closed. The detector is fully installed and commissioned. That allowed to start data taking in configuration without passive shielding.
The achievement of this goal was made possible by solving a set of tasks.

- The two calorimeter walls and two half-trackers were assembled, the Se-82 source foils were installed, the calibration source deployment system was integrated and commissioned, and the SuperNEMO Demonstrator Module was closed.
- The detector was fully cabled including all of the calorimeter cabling, the internal tracker cabling and the fibre-optic cables for the light-injection system.
- The calorimeter was fully commissioned, with the timing and energy calibration for each optical module.
- A major mechanical intervention restored the tracking detector to its nominal geometry, fixing a problem with loose wires that were causing short circuits. The tracker was mechanically stabilized and the fraction of dead tracker channels is 1-2%, which is fully acceptable.
- Gas tightness operations were performed. We obtain the required over-pressure during the gas-sealing operations.
- The re-commissioning of the gas-supply system and the radon suppression system is finished.

• All tracker HV system powering delivered and tested.

Fig. 2. *SuperNEMO Demosntrator (first module), mounted under the clean tent in the main hall of the LSM laboratory (Modane, France)*

Fig. 3. *Left: SuperNEMO Demonstrator gas system mounted in LSM. Right: Coil pre-mounting.*

• The operations for the magnetic coil installation were also completed.
• The full tracker was commissioned.
• Finally the data taking with the full detector (calorimeter+tracker) has been started. We routinely take radioactive source and usual data acquisition runs with the whole detector. The trigger and data-acquisition procedures are ready for long-term data taking operations.

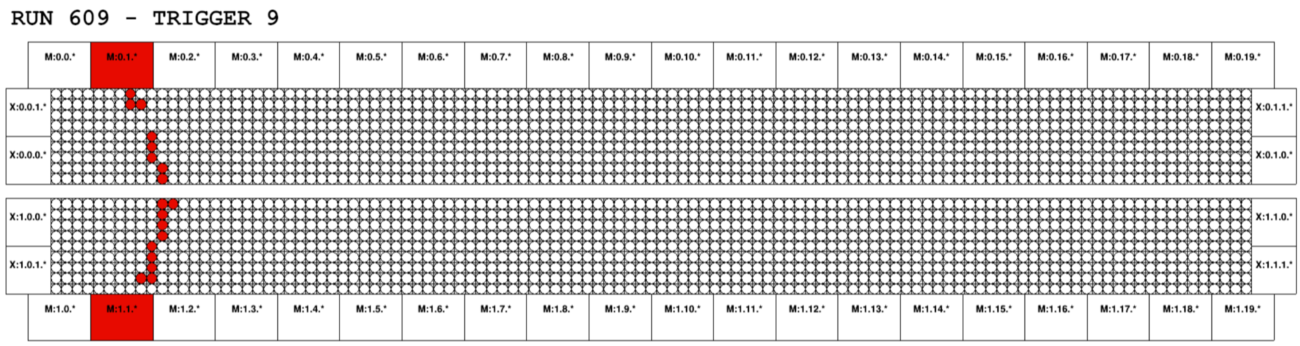

Fig. 4. *Event display of the first event candidate to the double beta decay of ^{82}Se registered in SuperNEMO Demonstrator using both the track detector and the calorimeter.*

Detailed plans exist for the remaining integration steps, including the installation of the anti-radon tent and the passive shielding. A detailed design for the SuperNEMO shielding has been developed.

Alongside the hardware work, a huge amount of work has been undertaken on the software and simulations and, in addition, collaboration members have continued to work on the analysis of NEMO-3 datasets. Physics analysis of the SuperNEMO data is being performed, including first radon level study with BiPo events, analysis of runs with signal from light injection system, analysis of ^{207}Bi runs. We have a well-defined physics programme using the first 2.5-year SuperNEMO Demonstrator Module dataset:

- Search for neutrinoless double-beta decay in ^{82}Se where, thanks to the unique tracker-calorimeter technique, we should be able to set new competitive physics bounds on lepton number violation including decays to excited states.

- Detailed studies of $2\nu\beta\beta$ decay of ^{82}Se will be used to constrain nuclear models of double-beta decay, especially in the context of the critical question of the quenching of the effective axial vector coupling g_A (entering in the fourth power in both the $2\nu\beta\beta$ and $0\nu\beta\beta$ decay rates). Recent theoretical studies have demonstrated the possibility of constraining the effective g_A from the shape of the individual energy of the $2\nu\beta\beta$ electrons and possibly their angular correlation, uniquely measured by the NEMO technique. In this perspective, a new study of $2\nu\beta\beta$ decay of ^{82}Se и ^{96}Zr using Demonstrator SuperNEMO data has started and will be continued with SuperNEMO data, ^{82}Se being particularly favored for this study.

- Demonstrate how the tracker-calorimeter approach could be expanded for a larger scale experiment, notably in the case of a positive indication of a $0\nu\beta\beta$ decay signal in the coming years.

MONUMENT – Muon Ordinary capture for the Nuclear Matrix elemENTs of 2β decays.

The first two quarters of 2022, together with German (Technical University of Munich, TUM) and Swiss colleagues (Paul Scherrer Institute, PSI), were devoted to preparing for the second stage of the MONUMENT project.

Based on JINR, the muon trigger system with a target was modernized and tests were carried out at TUM (Fig. 5). Together with colleagues from TUM and UZH (University of Zurich) during 2022, data analysis of the 2021 campaign was continued. The obtained results are presented in Table 2 and are being prepared for publication. In September-October 2022, ordinary muon capture (OMC) was measured in the enriched 100Mo isotope at the meson factory at PSI. The measurement of this isotope is associated with the study of the role of neutrinos in the formation of supernovae and the synthesis of heavy isotopes. The status and results of the project were presented at the international conference -- Physics of fundamental Symmetries and Interactions - PSI'2022 (October 16-21, 2022, PSI, Switzerland). At the moment, the analysis of the data obtained with the ^{100}Mo target has begun. The next stage of measurements is planned for September 2023 with isotopically enriched ^{48}Ti, ^{96}Mo, ^{56}Fe, and ^{24}Mg targets.

Table 2. *Muon lifetime in the enriched ^{136}Ba and ^{76}Se.*

Isotope (% of the enrichment)	$\tau \pm \Delta\tau_{stat} \pm \Delta\tau_{sys}$ (ns)
^{136}Ba (95.67%)	85.09 ± 0.64 ± 0.61
^{76}Se (99.7%)	136.30 ± 0.07 ± 0.76

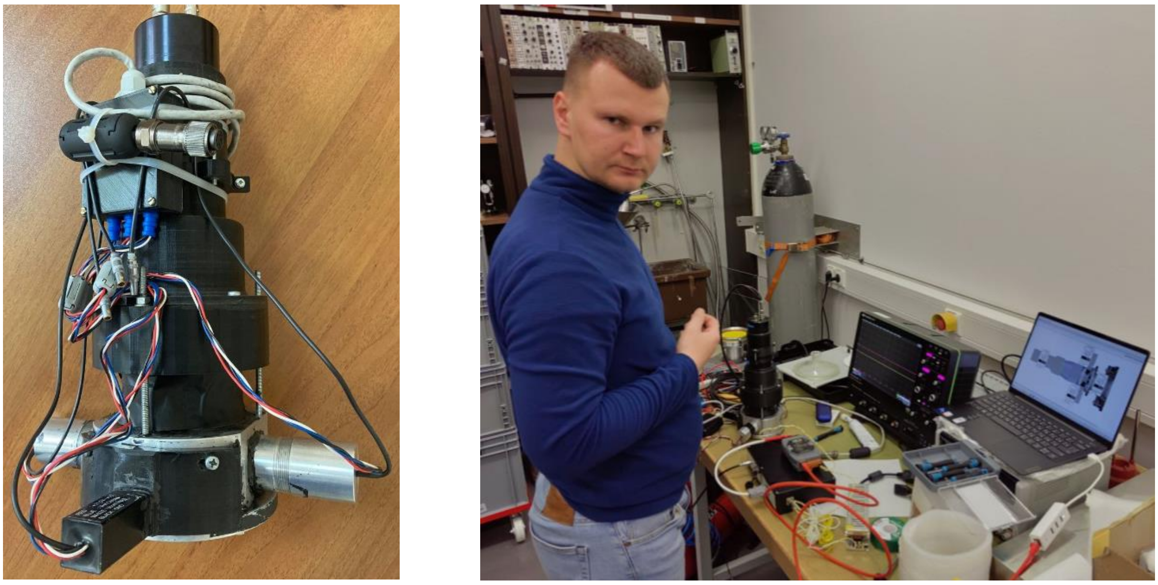

Fig. 5: *Muon trigger system and its testing at TUM.*

The **EDELWEISS** experiment originally designed for the search of WIMPs of $O(100\ \mathrm{GeV/c^2})$ has undergone a redirection of its strategy to optimization of used detectors for low-mass (light) WIMP searches. The region of "light WIMPs" could be further investigated in the EDELWEISS experiment thanks to advantage of energy resolution below 20 eV reachable with new HPGe bolometers.

The EDELWEISS scientific programs started as experiment directed to search for WIMP DM using natural HPGe detectors. The EDELWEISS detectors are cryogenic (work temperature is about 20 mK) Ge bolometers with simultaneous measurement of phonon and ionization signals. The comparison of the two signals provides a highly efficient event-by-event discrimination between nuclear recoils (induced by WIMP and also by neutron scattering) and electrons. For the past 25 years EDELWEISS is the leading experiment for direct Dark Matter search with Germanium detectors.

In the present time there is an increasing gain of interest for the search of low-mass WIMPs (with mass below 10 GeV/c^2). Many scenarios have been proposed where the evolution of the "dark" and "visible" sectors in the early Universe are such that the relic DM number density is naturally close to the baryon density. The current measurements of the corresponding mass densities then imply that $m_W \sim 5$ GeV/c^2, which is thus definitely become the desired subject of experimental search. EDELWEISS cryogenic bolometers with excellent energy resolutions is then a natural choice for investigation of low mass WIMP region.

Reducing detection thresholds is a common objective shared by all DM experiments as the theoretical recoil energy spectrum falls typically with an exponential behavior. It is compulsory for low-mass WIMP searches as the spectrum is increasingly softer as the WIMP mass gets lower. The Neganov-Trofimov-Luke boost is used in the EDELWEIS detectors to lower thresholds by amplifying the signal through the application of high voltage biases on collecting electrodes.

EDELWEISS recent experimental results were mainly associated with the development of unique low-threshold detector bolometers that allow detecting nuclear recoils from extremely low energies of ~20 eV. Such parameters were achieved thanks to: 1) internal signal amplification with using the Trofimov-Neganov-Luke effect; 2) the use high electron mobility transistors (HEMT); 3) a special suspension system for detectors in the holders, which reduces the influence of cryostat vibrations associated with operating cryocoolers.

Eleven different Ge new detectors with different designs were used at the LSM underground laboratory. It has to be noted that the same time rest of the EDELWEISS cryostat was used for joint physics run with CUPID-Mo $0\nu2\beta$ search (a number of physics results, including new best limits $0\nu2\beta$ decay and best results for Mo-100 double beta decay to excited stated were published). We compare detector physics in 32 g, 200 g and 800g detectors. Compare performance of NTD and NbSi-TES heat sensors. The TES technology is new for the EDELWEISS. It shows a promising result (Fig. 6). We were able to obtain near single-electron sensitivity on 33 and 200 g detectors. An unprecedented charge resolution of 0.53 electron-hole pairs (RMS) has been achieved using the NTL internal amplification. We set the first Ge-based constraints on sub-MeV/c^2 DM particles (Fig. 7) interacting with electrons, as well as on dark photons down to 1 eV/c^2. These are competitive with other searches and demonstrate the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale electron signals.

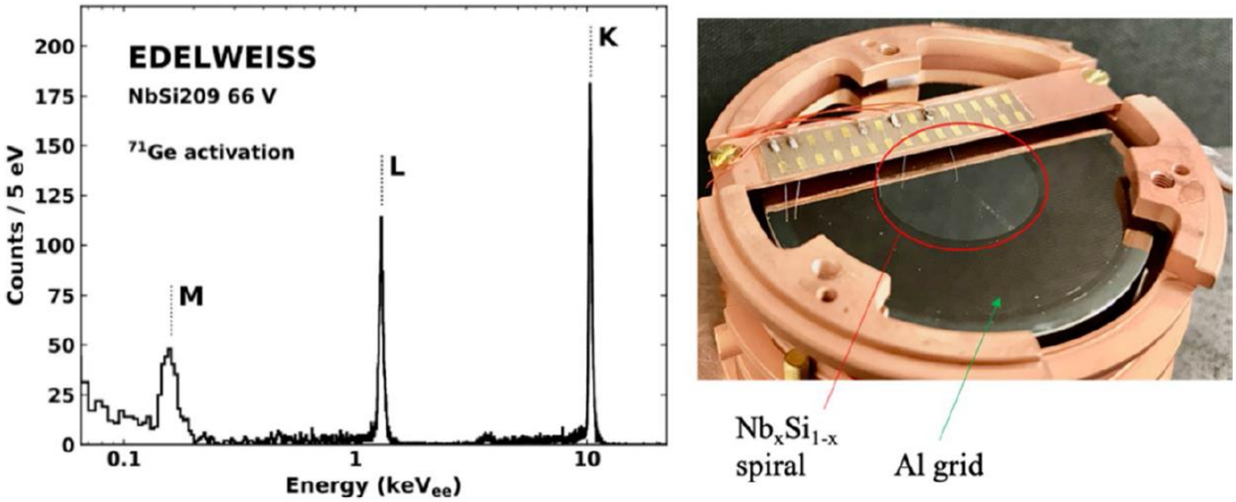

Fig. 6: *Left: calibration of a 200 g Nb_xSi_{1-x} Ge bolometer using ^{71}Ge activation by neutrons. The Ge crystal was biased at 66 V for NTL amplification. Right: the top surface of the detector is covered by a TES layer and a 2% coverage Al grid. The bottom Ge surface is fully covered by an Al grid.*

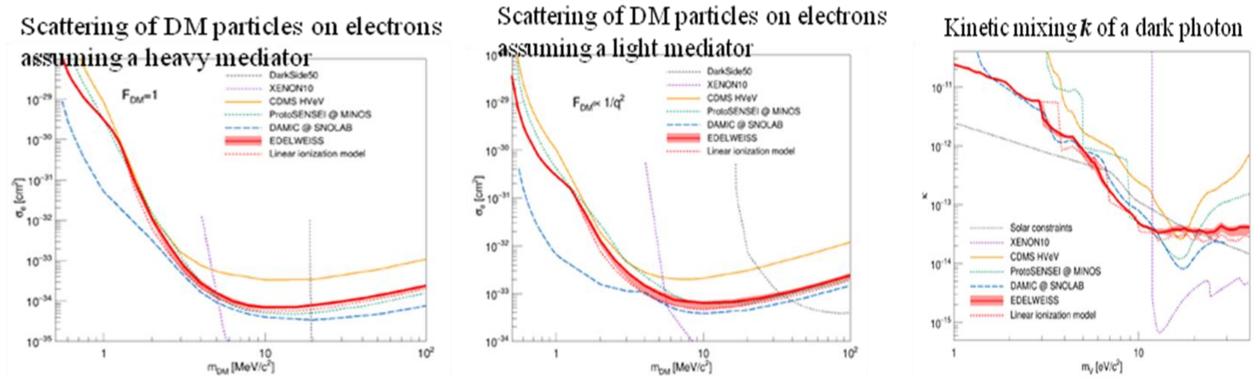

Fig. 7: *90% C.L. upper limit on the cross section for the scattering of DM particles on electrons, assuming a heavy (left panel) or light (middle panel) mediator. Right: 90% C.L. upper limit on the kinetic mixing of a dark photon. The EDELWEISS results are shown as the red line. The shaded red band and dotted red line represent alternative charge distribution models. Also shown are constraints from other direct detection experiments and solar constraints (see [Phys. Rev. Lett. 125, 141301] for references).*

2.3. A complete list of publications (electronic annex, for journal publications with journal impact factor).

1) Agostini, M et al. "Pulse shape analysis in Gerda Phase II.
" *European Physical Journal C* 82.4, 2022, ISSN 1434-6044,
https://doi.org/10.1140/epjc/s10052-022-10163-w
2) Armengaud, E et al. "Search for sub-GeV dark matter via the Migdal effect with an EDELWEISS germanium detector with NbSi transition-edge sensors."
Physical Review D 106.6, 2022, ISSN 2470-0010,
https://doi.org/10.1103/PhysRevD.106.062004

3) Agostini, M et al. "Search for exotic physics in double-β decays with GERDA Phase II." *Journal of Cosmology and Astroparticle Physics* 2022.12, 2022, ISSN 1475-7516, https://doi.org/10.1088/1475-7516/2022/12/012
4) Marnieros, S et al. "High Impedance TES Bolometers for EDELWEISS." *Journal of Low Temperature Physics*, 2022, ISSN 0022-2291, https://doi.org/10.1007/s10909-022-02899-2
5) Augier, C et al. "Final results on the 0 νββ decay half-life limit of ^{100} Mo from the CUPID-Mo experiment." *European Physical Journal C* 82.11, 2022, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-022-10942-5
6) Mirzayev, N.A et al. "High-purity ammonium acetate solution for low-background electronics." *Journal of Radioanalytical and Nuclear Chemistry* 331.12, 2022, pp. 5539-5545., ISSN 0236-5731, https://doi.org/10.1007/s10967-022-08608-3
7) Agostini, M et al. "Erratum: First Search for Bosonic Superweakly Interacting Massive Particles with Masses up to 1 MeV / c2 with GERDA (Physical Review Letters (2020) 125 (011801) DOI: 10.1103/PhysRevLett.125.011801)." *Physical Review Letters* 129.8, 2022, ISSN 0031-9007, https://doi.org/10.1103/PhysRevLett.129.089901
8) Rukhadze, N.I et al. *Journal of Physics: Conference Series* 2156.1, 2022, ISSN 1742-6588, https://doi.org/10.1088/1742-6596/2156/1/012134
9) Armengaud, E et al. "New Limit for Neutrinoless Double-Beta Decay of ^{100}Mo from the CUPID-Mo Experiment." *Physical Review Letters* 126.18, 2021, ISSN 0031-9007, https://doi.org/10.1103/PhysRevLett.126.181802
10) Huang, R et al. "Pulse shape discrimination in CUPID-Mo using principal component analysis." *Journal of Instrumentation* 16.3, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/03/P03032
11) Agostini, M et al. "Characterization of inverted coaxial ^{76}Ge detectors in GERDA for future double- β decay experiments." *European Physical Journal C* 81.6, 2021, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-021-09184-8
12) Agostini, M et al. "Calibration of the Gerda experiment." *European Physical Journal C* 81.8, 2021, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-021-09403-2
13) Sokolov, A et al. "Segmented HPGe Detector for Nuclear Reactions Research." *IEEE Transactions on Nuclear Science* 68.1, 2021, pp. 54-58., ISSN 0018-9499, https://doi.org/10.1109/TNS.2020.3037336
14) Ponomarev, D et al. "NaI(Tl+Li) scintillator as multirange energies neutron detector." *Journal of Instrumentation* 16.12, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/12/P12011
15) Arnold, R et al. "Search for periodic modulations of the rate of double- β decay of Mo 100 in the NEMO-3 detector." *Physical Review C* 104.6, 2021, ISSN 2469-9985, https://doi.org/10.1103/PhysRevC.104.L061601
16) Arnold, R et al. "Measurement of the distribution of ^{207}Bi depositions on calibration sources for SuperNEMO." *Journal of Instrumentation* 16.7, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/07/T07012
17) Agostini, M et al. "Final Results of GERDA on the Search for Neutrinoless Double- β Decay." *Physical Review Letters* 125.25, 2020, ISSN 0031-9007, https://doi.org/10.1103/PhysRevLett.125.252502
18) Arnaud, Q et al. "First Germanium-Based Constraints on Sub-MeV Dark Matter with the EDELWEISS Experiment." *Physical Review Letters* 125.14, 2020, ISSN 0031-9007, https://doi.org/10.1103/PhysRevLett.125.141301
19) Armengaud, E et al. "The CUPID-Mo experiment for neutrinoless double-beta decay: performance and prospects." *European Physical Journal C* 80.1, 2020, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-019-7578-6
20) Armengaud, E et al. "Precise measurement of 2 νββ decay of ¹⁰⁰ Mo with the CUPID-Mo detection technology." *European Physical Journal C* 80.7, 2020, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-020-8203-4

21) Agostini, M et al. "First Search for Bosonic Superweakly Interacting Massive Particles with Masses up to 1 MeV/c2 with GERDA." *Physical Review Letters* 125.1, 2020, ISSN 0031-9007, https://doi.org/10.1103/PhysRevLett.125.011801
22) Agostini, M et al. "Modeling of GERDA Phase II data." *Journal of High Energy Physics* 2020.3, 2020, ISSN 1126-6708, https://doi.org/10.1007/JHEP03(2020)139
23) Barabash, A.S et al. *Nuclear Physics A* 996, 2020, ISSN 0375-9474 , https://doi.org/10.1016/j.nuclphysa.2020.121697
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2.4. Status and stage (TDR, CDR, ongoing project) of the project (subproject)

LEGEND: LEGEND-200 is the ongoing experiment. LEGEND-1000 is on CDR stage.

The planned modernization of the **TGV** spectrometer may not provide a significant improvement in the energy resolution of the detectors and background suppression. If the enriched ^{130}Ba can be ordered, it will be possible to obtain the results of the planned study.

SuperNEMO: The SuperNEMO experiment is in the early stages of data collection. The SuperNEMO Demonstrator (the first SuperNEMO module) is commissioned in a configuration without passive shielding. It is installed in the low background underground laboratory LSM, France. Energy and time calibrations are carried out. In the near future, passive shielding and an anti-radon tent will be installed and full-scale measurements will begin.

The **MONUMENT** experiment is the ongoing experiment. Each year during the autumn we have an experimental campaign with the muon capture measurements at the meson factory at PSI. After the campaign, the system is upgraded and the data is continuously analyzed during the year.

EDELWEISS is in both execution and next phase CDR stage. The old setup is start to be decommissioned, new r&d and DM search will be executed in the BINGO cryostat, new EDELWEISS setup is under consideration.

2.5. Results of related activities

2.4.1. Research and education activities. List of defended dissertations.

TGV: Last PhD thesis (E.Rukhadze, IEAP, CTU Prague) in 2017.
SuperNEMO: Nemchenok I.B., DrS thesis in 2019
Rachimov A.V., PhD thesis in 2021
EDELWEISS: Evgeny Yakushev, DrS thesis in 2023.

2.4.2. JINR grants (scholarships) received.

JINR Annual Prize for 2020 in the field of Experimental Physics Research for the series of papers "Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA".