Form No 21

APPROVED BY
JINR VICE-DIRECTOR
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SCIENTIFIC AND TECHNICAL JUSTIFICATION FOR OPENING A NEW (EXTENSION) THEME

to be include in the

TOPICAL PLAN FOR JINR RESEARCH FOR 2022 – 2024

Theme code **03-2-1100-2010/2024** **Laboratory** **____DLNP __________**
Department **_Nuclear Spectroscopy and Radiochemistry___________**

Direction:_______ Nuclear Physics (03)_____________________________________

Theme title: Non-Accelerator Neutrino Physics and Astrophysics ___________

Theme leaders: _V. Brudanin, E. Yakushev_____________________

Abstract:

Search for and investigation of double-neutrino and neutrinoless modes of double beta-decay, clarification of the neutrino nature Majorana or Dirac, absolute neutrino mass scale and hierarchies. Search for the neutrino magnetic moment, neutrino-nucleus coherent scattering and Dark Matter. Investigation of galactic and extragalactic neutrino sources, diffusive neutrino cosmic background, search for exotic particles (monopoles). Application of the neutrino detector for a distant investigation of process inside of the reactor core of Kalinin Nuclear Power Plant. Search for sterile neutrinos. Spectroscopy of nuclei far from stability. Development of new methods for detection of charged and neutral particles.

Time interval and expected results: 2022-2024,

annotations for the theme and for scientific projects are attached.

Participating Countries, Institutes and International organizations: Azerbaijan, Bulgaria, Czech Republic, Finland, France, Germany, Kazakhstan, Poland, Russia, Slovakia, United Kingdom, Uzbekistan.

Time interval for the theme: 2022-2024

Total estimated cost of the theme per year k$, 16606.1

ENDORSED BY:

CHIEF SCIENTIFIC SECRETARY

______________/______________/

"_____"__________________2020

HEAD OF PLANNING AND FINANCE DEPARTMENT

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"_____"__________________2020

HEAD OF SCIENCE ORGANIZATION DEPARTMENT

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"_____"__________________2020

Resp. SCIENCE ORGANIZATION DEPARTMENT

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"_____"__________________2020

LABORATORY DIRECTOR

______________/ Bednyakov

"____" november 2020

LABORATORY SCIENTIFIC SECRETARY

______________/ Tikhova/ I.

"_____" november 2020

LABORATORY CHIEF ENGINEER-ECONOMIST

______________/Kuzmenkova/

"_____" november 2020

PROJECT LEADER

______________/ Yakushev /

" 18 " november 2020

This Form No. 21 is accompanied by a cost estimate for the theme

This Form No. 21 is accompanied by annotations for the theme and for the projects

Форма № 21

УТВЕРЖДАЮ

Вице-директор ОИЯИ

____

“_____“___________20 г.

НАУЧНО-ТЕХНИЧЕСКОЕ ОБОСНОВАНИЕ НА ОТКРЫТИЕ НОВОЙ (ПРОДЛЕНИЯ) ТЕМЫ

для включения

В ПРОБЛЕМНО-ТЕМАТИЧЕСКИЙ ПЛАН ОИЯИ НА 2022 – 2024 гг.

Шифр темы 03-2-1100-2010/2024 **Лаборатория ____ЛЯП__________**

Отдел ____НЭОЯСиРХ________

Направление:_______Ядерная физика (03)___________________________________

Наименование темы: Неускорительная нейтринная физика и астрофизика___________

Руководители темы: _Бруданин В.Б., Якушев Е.А.______________________

Краткая аннотация:

Поиск и изучение безнейтринной и двухнейтринной мод двойного бета-распада, выяснение природы нейтрино: майорановская или дираковская, определение абсолютных значений нейтринных масс и их иерархии, поиск магнитного момента электронного нейтрино, детектирование когерентного рассеяния реакторных антинейтрино на ядрах, поиск возможных проявлений темной материи в области низких и высоких энергий, изучение галактических и внегалактических нейтринных источников, диффузного нейтринного космологического фона и поиск экзотических частиц (магнитные монополи). Исследование внутриреакторных процессов на КАЭС. Поиск стерильных нейтрино. Спектроскопия ядер, удаленных от полосы бета-стабильности. Развитие новых методов регистрации заряженных и нейтральных частиц.

Этапы работы (указать год завершения) и ожидаемый результат по завершении темы:

2022-2024 гг, аннотации темы и проектов прилагаются.

Список участников и организаций: Азербайджан, Болгария, Германия, Казахстан, Польша, Россия, Словакия, Узбекистан, Чехия, Великобритания, Финляндия, Франция

Сроки выполнения работы: 2022-2024

Полная сметная стоимость темы в год, тыс. US$: 16606,1

СОГЛАСОВАНО:

Главный ученый секретарь

_____________/_____________/
“_____“__________________2020 г.

Директор лаборатории

_____________/_____________/
“____“ ноября 2020 г.

Начальник Планово-финансового отдела

_____________/_____________/
“_____“__________________2020 г.

Ученый секретарь лаборатории

_____________/ [illegible] И.В./
“_____“ ноября 2020 г.

Начальник научно-организационного отдела

_____________/_____________/
“_____“__________________2020 г.

Экономист лаборатории

_____________/ Кузьменкова/
“_____“ ноября 2020 г.

С.н.с. Научно-организационного отдела

_____________/_____________/
“_____“__________________2020 г.

Руководитель темы

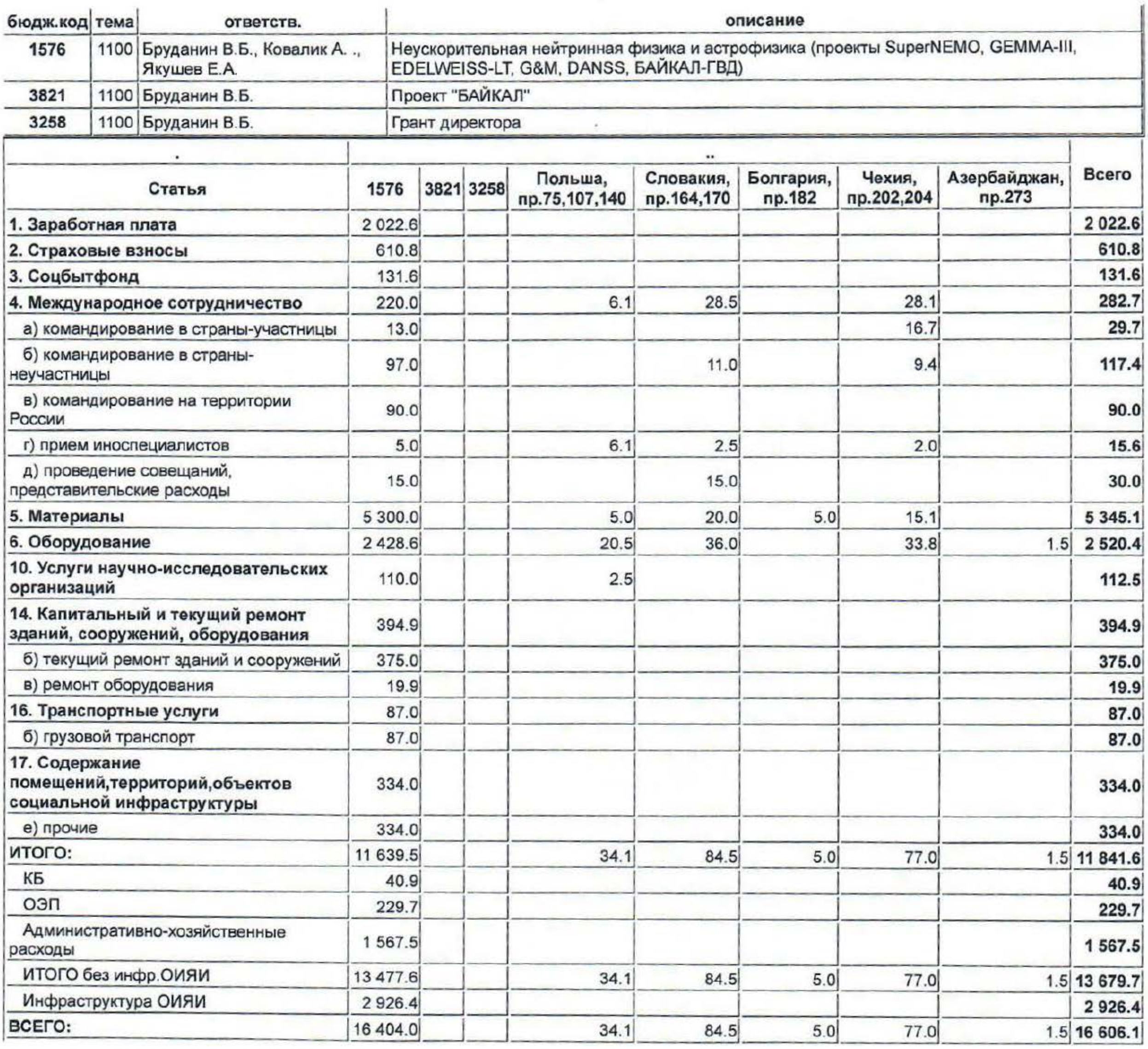
_____________/ Якушев/
“18“ ноября 2020 г.

К форме № 21 прилагается Смета затрат по теме

К форме № 21 прилагаются аннотации темы и проектов

СМЕТА ЗАТРАТ ПО ТЕМЕ

COST ESTIMATE FOR THE THEME 03-2-1100-2010/2024



бюдж.код	тема	ответств.	описание
1576	1100	Бруданин В.Б., Ковалик А. ., Якушев Е.А.	Неускорительная нейтринная физика и астрофизика (проекты SuperNEMO, GEMMA-III, EDELWEISS-LT, G&M, DANSS, БАЙКАЛ-ГВД)
3821	1100	Бруданин В.Б.	Проект "БАЙКАЛ"
3258	1100	Бруданин В.Б.	Грант директора

Статья	1576	3821	3258	Польша, пр.75,107,140	Словакия, пр.164,170	Болгария, пр.182	Чехия, пр.202,204	Азербайджан, пр.273	Всего
1. Заработная плата	2 022.6								**2 022.6**
2. Страховые взносы	610.8								**610.8**
3. Соцбытфонд	131.6								**131.6**
4. Международное сотрудничество	220.0			6.1	28.5		28.1		**282.7**
а) командирование в страны-участницы	13.0						16.7		**29.7**
б) командирование в страны-неучастницы	97.0				11.0		9.4		**117.4**
в) командирование на территории России	90.0								**90.0**
г) прием иноспециалистов	5.0			6.1	2.5		2.0		**15.6**
д) проведение совещаний, представительские расходы	15.0				15.0				**30.0**
5. Материалы	5 300.0			5.0	20.0	5.0	15.1		**5 345.1**
6. Оборудование	2 428.6			20.5	36.0		33.8	1.5	**2 520.4**
10. Услуги научно-исследовательских организаций	110.0			2.5					**112.5**
14. Капитальный и текущий ремонт зданий, сооружений, оборудования	394.9								**394.9**
б) текущий ремонт зданий и сооружений	375.0								**375.0**
в) ремонт оборудования	19.9								**19.9**
16. Транспортные услуги	87.0								**87.0**
б) грузовой транспорт	87.0								**87.0**
17. Содержание помещений,территорий,объектов социальной инфраструктуры	334.0								**334.0**
е) прочие	334.0								**334.0**
ИТОГО:	11 639.5			34.1	84.5	5.0	77.0	1.5	**11 841.6**
КБ	40.9								**40.9**
ОЭП	229.7								**229.7**
Административно-хозяйственные расходы	1 567.5								**1 567.5**
ИТОГО без инфр.ОИЯИ	13 477.6			34.1	84.5	5.0	77.0	1.5	**13 679.7**
Инфраструктура ОИЯИ	2 926.4								**2 926.4**
ВСЕГО:	16 404.0			34.1	84.5	5.0	77.0	1.5	**16 606.1**

THEME 03-2-1100 AND ITS PROLONGATION FOR 2022-2024

THEME TITLE: NON ACCELERATOR NEUTRINO PHYSICS AND ASTROPHYSICS

CURRENT THEME CODE: 03-2-1100-2010/2021

Leaders: V.B. Brudanin, E.A. Yakushev

Preamble:

The theme **"Non-accelerator neutrino physics and astrophysics"** at JINR is devoted to search and investigation of rear processes by means of nuclear physics methods. The base of the theme is Department of Nuclear Spectroscopy and Radiochemistry, DLNP. This department has a huge almost 50-years experience in high-precision nuclear spectroscopy using semiconductor, scintillator and other types of detectors in general and 30-years experience of rare processes studies in different underground environments. The department has the knowledge, personnel and capabilities to create world-class facilities, conduct measurements with them and obtain world-leading results. At present, the theme consists of seven main projects the implementation of which is related to common approaches and resources. In addition to the six scientific sectors involved in the theme, the following resources are available to carry out the scientific projects: the laboratory for the production and repair of semiconductor detectors; laboratory for creation and production of scintillation materials for detectors; radiochemical sector (creation of calibration radioactive sources, purification of materials designated for low-background measurements from their contamination by natural radioactivities, etc.), mechanical workshops, a group of computer support, a group of mass separators and others.

The problems targeted by scientific projects are: neutrino-less double beta decay (SuperNEMO, GERDA (Legend) and Monument projects), experiments with the reactor antineutrino: GEMMA (νGeN) – search for the neutrino magnetic moment and neutrino coherent scattering; DANSS – reactor diagnostics and investigation of the neutrino properties, direct search for the Dark Matter (EDELWEISS project) will be extended to search of New Physics with neutrino coherent scattering (joint EDELWEISS/Ricochet project), deep-water investigations with the neutrino telescope at Baikal lake (BAIKAL-GVD project).

Abstracts of each of these projects are given below. Each of the projects individually passes through the JINR approval (prolongation) procedures. BAIKAL-GVD project is approved for 2019-2023 yy, Monument project is approved for 2021-2023 yy. Approval of other projects for 2022-2024 years is in process.

ТЕМА 03-2-1100 И ЕЕ ПРОДЛЕНИЕ НА 2022-2024 ГОДЫ

НАЗВАНИЕ ТЕМЫ: НЕУСКОРИТЕЛЬНАЯ НЕЙТРИННАЯ ФИЗИКА И АСТРОФИЗИКА

ТЕКУЩИЙ ШИФР ТЕМЫ: 03-2-1100-2010/2021

РУКОВОДИТЕЛИ ТЕМЫ: В.Б. Бруданин, Е.А. Якушев

Преамбула:

Тема **“Неускорительная нейтринная физика и астрофизика”** в ОИЯИ посвящена поиску и исследованию редких процессов с использованием ядерно-физических методов. Тема проводится на базе Научно Экспериментального Отдела Ядерной Спектроскопии и Радиохимии ЛЯП. Этот отдел имеет огромный почти 50-летний опыт прецизионной ядерной спектроскопии с использованием полупроводниковых, сцинтилляционных и других типов детекторов и 30-летний опыт исследования редких процессов в различных подземных лабораториях. Отдел обладает знаниями, персоналом и возможностями для создания установок мирового класса, проведения измерений с ними и получения результатов на мировом уровне. В настоящее время тема состоит из семи основных проектов, реализация которых объединена общими имеющимися ресурсами и научными подходами. В дополнение к шести научным секторам имеются следующие ресурсы, позволяющие проводить реализуемые проекты: лаборатория по производству и ремонту полупроводниковых детекторов; создание и производство сцинтилляционных материалов для детекторов; радиохимический сектор (создание калибровочных радиоактивных источников, очистка материалов от естественной радиоактивности для низкофоновых измерений, и т.д.), механические мастерские, группа компьютерного обеспечения экспериментов, группа масс сепараторов и другие.

Научными задачами, исследуемыми в реализуемых в рамках темы проектах, являются: двойной безнейтринный бета-распад (проекты SuperNEMO, GERDA (Legend) и Monument); эксперименты с реакторными антинейтрино: GEMMA (νGeN) – поиск магнитного момента нейтрино и когерентного рассеяния нейтрино, DANSS – диагностика реакторов и исследование свойств нейтрино; прямой поиск темной материи (проект EDELWEISS) будет расширен на поиск новой физики при исследовании когерентного рассеяния реакторных нейтрино (объединенный проект EDELWEISS/Ricochet); исследования с глубоководным нейтринным телескопом на озере Байкал (проект BAIKAL-GVD). Аннотации каждого из этих проектов приведены ниже. Каждый из проектов индивидуально проходит через процедуры утверждения (продления) в ОИЯИ.

1) Project SuperNEMO (Investigations of the of 2β–decay processes of ^{82}Se with the SuperNEMO detector).

Project leader: O. Kochetov (kochet@jinr.ru)
Project deputy leader: V. Tretyak

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 (0νββ) 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. This unique information allows us to investigate the mechanisms of various modes of ββ decay, reconstruct and fundamentally suppress the background. The creation of the SuperNEMO Demonstrator is the result of 11-year R&D in a number of areas: the creation of optical modules of the calorimeter with record resolution characteristics, a tracker with automated assembly of cells and radon control, improved techniques for creating sources and calibration systems, methodical work on low-background measurements (construction of dedicated setups, the fight against radon, the selection of ultrapure materials).

The goal of the Demonstrator is to validate the technique, achieve the claimed background level, and to reach a sensitivity of the 0νββ- decay half-life of about $T(0\nu)_{1/2} > 5.9 \times 10^{24}$ yr with “zero background” in the region interest on 7 kg of Se-82 for 2.5 years of measurement. Start of the Demonstrator is planned for next year. In the case of a successful work of the Demonstrator, the opportunity will be open for a full-scale SuperNEMO project aimed to measure 100 kg of Se-82 at a sensitivity of $T(0\nu)_{1/2} > 10^{26}$ years for 5 years of measurement.

The demonstrator has been built with the decisive contribution of JINR to a number of systems: calorimeter, tracker, ββ sources. The JINR team has 25 years of experience of successful participation in NEMO-2 / NEMO-3 experiments studied ββ processes in a set of nucleus: ^{48}Ca, ^{82}Se, ^{96}Zr,^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd, and in the SuperNEMO R&D program.

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 $\beta\beta$-decay of ^{82}Se goes through ground state of intermediate nucleus (so called Single State Dominance (SSD) hypothesis for $\beta\beta$-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 $2\nu\beta\beta - 0\nu\beta\beta$--decay ^{82}Se and separately on $\beta\beta$-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 $\beta\beta$-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.

Publications:

[1] A.S. Barabash on behalf of the NEMO-3 and SuperNEMO collaborations, “Double beta decay experiments: present and future”, J. Phys.: Conf.Ser.1390 (2019) 012048.
DOI: 10.1088/1742-6596/1390/1/012048.

[2] R. Arnold et al., “Detailed studies of Mo-100 two-neutrino double beta decay in NEMO-3”, Eur. Phys. J. C (2019) 79:440.
DOI: 10.1140/epjc/s10052-019-6948-4

[3] Alimardon V.Rakhimov et al., “Development of methods for the preparation of radiopure Se-82 sources for the SuperNEMO neutrinoless double-beta decay experiment”, Radiochimica Acta, 2020; 108(2): 87-97. DOI: 10.1515/ract-2019-3129.

[4] R. Hodak et al., “Charactirization and Long-term Performance of the Radon Trapping Facility Operating at the Modane Underground Laboratory”, Journal of Physics G: Nuclear and Particle Physics 46 (2019)115105 (17pp).
DOI: 10.1088/1361-6471/ab368e.

[5] R. Arnold et al., NEMO-3 Collaboration, “Search for the double beta decay Se-82 to the excited states of Kr-82 with NEMO-3”, Nuclear Physics A v 996
(2020) 121701.
DOI: 10.1016/j.nucl.physa.2020.121701.

[6] Thibaud Le Noblet on behalf of the NEMO-3 and SuperNEMO collaborations, “Latest results from NEMO-3 and commissioning status of the SuperNEMO demonstrator”, J. Phys.: Conf.Ser. 1342 (2020) 012029.
DOI: 10.1088/1742-6596/1342/1/012029.

[7] A.S. Barabash et al., “Calorimeter development for the SuperNEMO double beta decay experiment, Nucl. Instrum. Meth. A 868 (2017) 98-108

[8] A.S. Barabash et al., “The BiPo-3 detector for the measurement of ultra low natural radio activities of thin materials”, JINST 12 (2017) no.06, P06002

[9] S. Calvez, on behalf of the SuperNEMO collaboration, “[illegible]-sensitivity with the SuperNEMO demonstrator, 52nd Rencontres de Moriond EW 2017, La Thuile, Italy, Mars 18-25, 2017

[10] R. Arnold et.al., “Measurement of the double beta-decay half-life and search for the neutrinoless double beta-decay of Cd-116 with the NEMO-3 detector”, Phys. Rev. D95 (2017) 012007-1 – 012007-12.

[11] R. Arnold et.al., “Measurement of the double beta-decay half-life of Nd-150 and a search for neutrinoless double beta-decay processes with the full exposure from the NEMO-3 detector”, Phys. Rev. D94 (2016) 072003.

[12] H. Gomes for the NEMO-3&SuperNEMO Collaborations, “Latest results of NEMO-3 experiment and present status of SuperNEMO”, Nuclear and Particle Physics Proceedings (2016) 1765-1770.

[13] P.Povinec on behalf of the SuperNEMO Collaboration, “SuperNEMO – a new generation of underground experiments for double beta-decay investigations”, The 14th Vienna Conference on Instrumentation 15-16 Feb., 2016.

[14] A.S. Barabash et. al.,”Calorimeter development for the SuperNEMO double beta-decay experiment”, NIM A868 (2017) 98-108.

[15] R. Arnold et al. from NEMO-3 Collaboration, “Search for neutrinoless quadrupole-b decay of the Nd-150 with the NEMO-3 detector” Phys. Rev. Lett. 119 (2017) 041801.

2) Project GERDA “LEGEND” (Searching for neutrinoless double beta decay of ^{76}Ge)

Project leader: K.Gusev (Konstantin.Gusev@jinr.ru)
Project deputy leaders: A. Lubashevskiy, N.Rumyantseva

The GERDA (Legend) collaboration searches for 0νββ decay of ^{76}Ge. The experimental facility is located at the Laboratori Nazionali del Gran Sasso of INFN in Italy. The experiment uses high purity germanium detectors enriched in ^{76}Ge, which are arranged in strings inside a cryostat filled with 64 m^3 of liquid argon (Fig. 2.1a). The liquid argon (LAr) acts both as cooling and shielding medium.

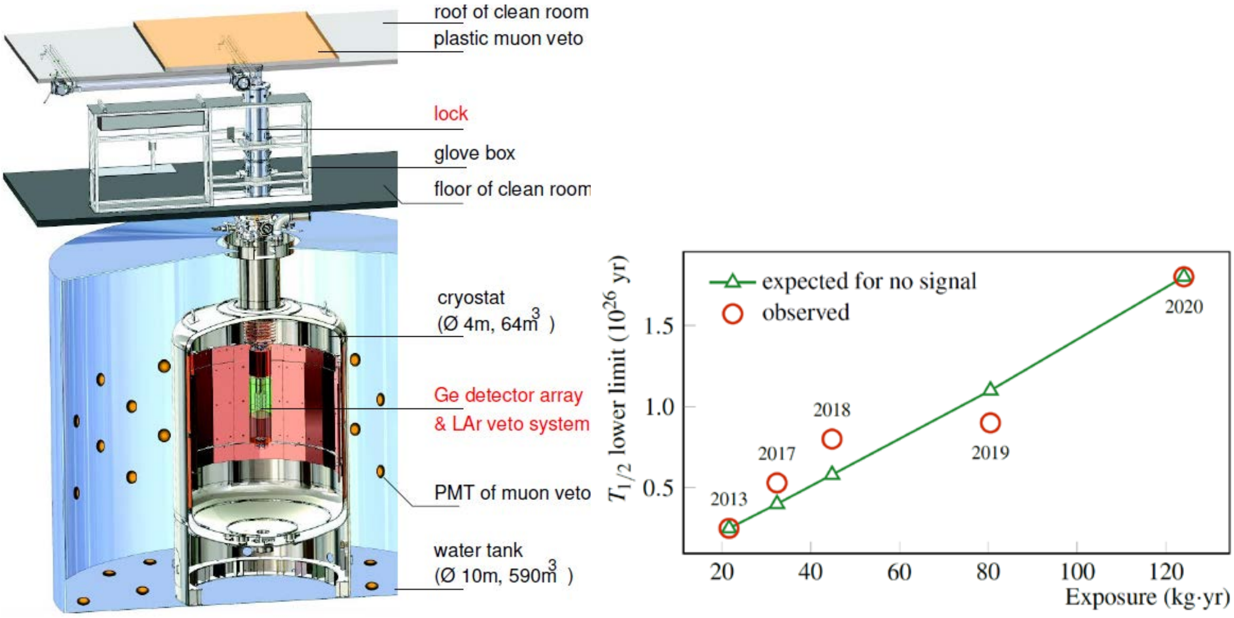


Fig. 2.1. a) Left: GERDA setup. The new Phase II components are marked in red; b) right: Increase of sensitivity with exposure measured in the GERDA experiment.

The Large Enriched Germanium Experiment for Neutrinoless double beta Decay (LEGEND) experiment is the successor of the GERDA experiment. The experiment will probe the 0νββ decay of ^{76}Ge with a sensitivity of $> 10^{28}$ years at 90% confidence level (C.L.). The 200-kg phase (LEGEND-200), currently under construction in the existing GERDA infrastructure at LNGS, is using the enriched detectors from the previous Majorana and GERDA experiments as well as new detectors for a total mass of up to 200 kg. The background projection of the LEGEND-200 is a factor of 5 below the measured levels of GERDA, reaching a level of $< 10^{-4}$ counts/(keV kg yr). A scaling toward a 1000-kg phase incorporating a further factor of 10 reduction in background beyond LEGEND-200 at a level of $< 10^{-5}$ counts/(keV kg yr) will provide discovery potential that encompasses the inverted hierarchy mass region for the light left-handed Majorana neutrino exchange mechanism. LEGEND-1000 will probe a large/relevant part of the parameter space even if the ordering is normal.

The LEGEND collaboration consists of 240 members from 47 institutions worldwide. JINR scientists are playing significant roles in all key parts of the project. So far JINR provided to the collaboration ~ 15 kg of enriched ^{76}Ge and this contribution is increasing on annual basis. Common JINR+TUM team is responsible for design and production of new liquid argon veto system for LEGEND-200 phase of the experiment and also for the R&D of such a system for LEGEND-1000. JINR is designing the glove box for the operations with bare germanium detectors as well as nylon mini-shrouds needed to mitigate the background form ^{42}Ar in LEGEND-200. Physicists from our institute are strongly involved in the analysis of LEGEND data and playing the central and leading roles in the core of LEGEND experiment – operations with bare germanium detectors.

Latest results:

The final results of the GERDA experiment were published in 2020. These results demonstrated the success of the GERDA project supported by JINR. The energy spectrum of full Phase II exposure is presented at Fig. 2.2. The achieved background index is more than factor of five lower in comparison with any non-^{76}Ge competitors.

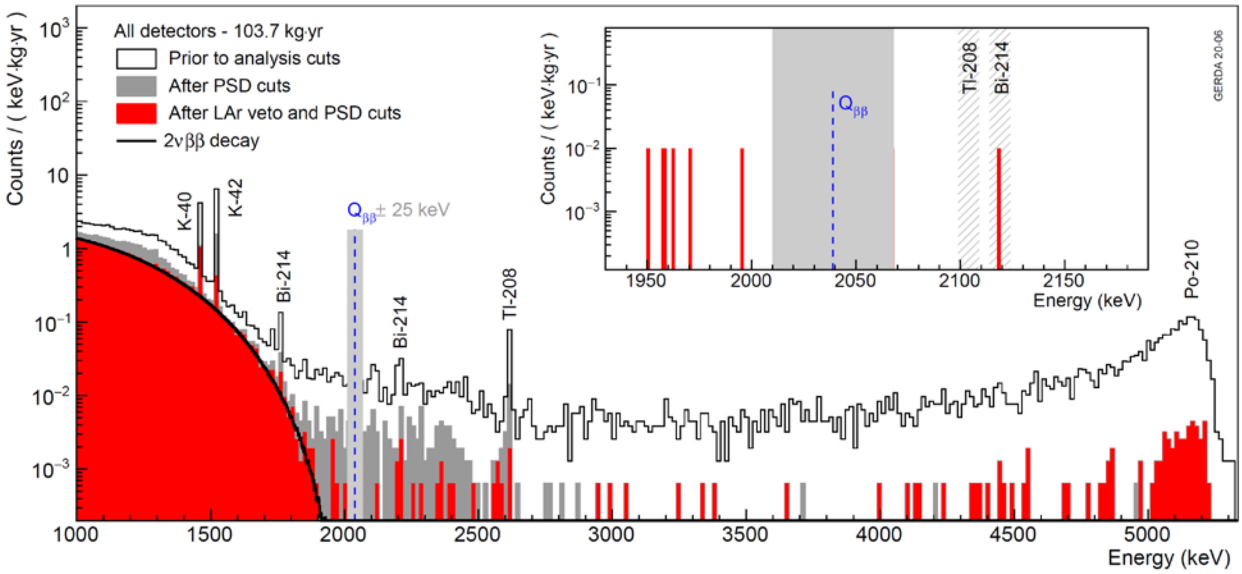


Fig. 2.2. Final energy spectra of GERDA Phase II. On the inset, the spectrum in the ROI is shown. The vertical grey line band shows the blinded region.

With a total exposure of 127.2 kg yr (103.7 kg yr in Phase II), no 0νββ signals were observed, GERDA derived a world best lower half-life limit of 1.8 × 10^{26} yr (90% C.L.). JINR scientists were playing significant roles in the GERDA experiment and plan to do the same or even take the lead in the key parts of the LEGEND project.

Plan of the Project implementation:

2021-2022: Modification of GERDA cryostat for LEGEND-200. Integration of the first strings with detectors and start data taking of the LEGEND experiment. Working on the conceptual design of LEGEND-1000.

2022-2023: Taking data in LEGEND-200. Finalizing the array by adding the rest of the enriched Ge detectors. Publication of the first results of LEGEND-200. Preparation of the LEGEND-1000 (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

2023-2024: Taking data in LEGEND-200. Adding the new detectors strings in the center of the LEGEND-200 array. Publication of improved results of LEGEND-200. Completion the design of LEGEND-1000. Continuation of preparation of the LEGEND-1000 (procurement of enriched ^{76}Ge, production and testing of new Ge detectors, R&D of low background materials and electronics).

Publications and talks:

1. «Upgrade for Phase II of the GERDA Experiment», Eur. Phys. J. C 78 (2018) 388.
2. «LArGe: active background suppression using argon scintillation for the Gerda 0νββ-experiment», Eur. Phys. J. C 75 (2015) 506.
3. «Mitigation of 42Ar/42K background for the GERDA Phase II experiment», Eur. Phys. J. C 78 (2018) 15.
4. «The GERDA experiment for the search of 0νββ decay in 76Ge», Eur. Phys. J. C 73 (2013) 2330.
5. «Results on Neutrinoless Double-β Decay of 76Ge from Phase I of the GERDA Experiment», Phys. Rev. Lett 111 (2013) 122503.
6. «Pulse shape discrimination for GERDA Phase I data», Eur. Phys. J. C 73 (2013) 2583.
7. «The background in the 0νββ experiment GERDA», Eur. Phys. J. C 74 (2014) 2764.
8. «Results on ββ decay with emission of two neutrinos or Majorons in 76Ge from GERDA Phase I», Eur. Phys. J. C 75 (2015) 416.
9. «2νββ decay of 76Ge into excited states with GERDA Phase I», J. Phys. G: Nucl. Part. Phys. 42 (2015) 115201.
10. «The performance of the Muon Veto of the GERDA experiment», EPJC 76 (2016) 298.
11. «Flux modulations seen by the muon veto of the GERDA experiment», Astroparticle Physics 84 (2016) 29.
12. «Limit on the radiative neutrinoless double electron capture of 36Ar from GERDA Phase I», Eur. Phys. J. C 76 (2016) 652.
13. «Limits on uranium and thorium bulk content in GERDA Phase I detectors», Astroparticle Physics 91 (2017) 15.
14. «Background-free search for neutrinoless double-β decay of 76Ge with GERDA», Nature 544 (2017) 47.
15. «The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND)», AIP Conference Proceedings 1894 (2017) 020027.
16. «Improved Limit on Neutrinoless Double-β Decay of 76Ge from GERDA Phase II», Phys. Rev. Lett. 120 (2018) 132503.
17. «Characterization of 30 76Ge enriched Broad Energy Ge detectors for GERDA Phase II», Eur. Phys. J. C. 79 11 (2019) 978.
18. «Probing Majorana neutrinos with double-β decay», Science 365 (2019) 1445.
19. «Modeling of GERDA Phase II data», Journal of High Energy Physics 03 (2020) 139.
20. «First Search for Bosonic Superweakly Interacting Massive Particles with Masses up to 1 MeV/c2 with GERDA», Phys. Rev. Lett. 125 (2020) 011801.
21. «Final Results of GERDA on the Search for Neutrinoless Double-β Decay», submitted to Physical Review Letters, arXiv: 2009.06079.
22. «Status of the GERDA experiment: on the way to Phase II», K.Gusev at TAUP 2015, Torino, Italy
23. «Status of preparations for the Phase II of the GERDA experiment aimed for the 0νββ decay search», A.Lubashevskiy at PATRAS 2015, Zaragoza, Spain.

24. «First results from Phase II of the GERDA experiment», K.Gusev at INPC 2016, Adelaide, Australia.
25. «Neutrinoless double beta decay: First results of GERDA Phase II and the status of other experiments», A.Lubashevskiy at PASCOS 2016, Quy Nhon, Vietnam.
26. «Double Beta Decay Experiments», K.Gusev at ICSSNP 2016, Dubna, Russia.
27. «Double beta decay experiments and neutrino mass investigation: Past, Present and Future», A.Smolnikov at QUARKS 2016, Pushkin, Russia.
28. «From Baksan to worldwide experiments searching for neutrinoless double beta decay», A.Smolnikov at ICSSNP 2017, Nalchik, Russia.
29. «Neutrinoless double beta decay search with the "background free" GERDA experiment», A.Lubashevskiy at ICSSNP 2017, Nalchik, Russia.
30. «GERDA: first background free search for neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.
31. «LEGEND: new opportunity to discover the neutrinoless double beta decay», K.Gusev at ICNFP 2017, Crete, Greece.
32. «Neutrinoless double beta decay: Experimental challenges», K.Gusev at NOW 2018, Brindisi, Italy.
33. «Fifty Years of Searching for Neutrinoless Double Beta Decay with Ge Detectors», A.Smolnikov at History of Neutrinos, Paris, France.
34. « New results of the search for neutrinoless double beta decay from GERDA Phase II», N.Rumyantseva at Nucleus 2018, Voronezh, Russia.
35. «GERDA searches for 0νββ and other ββ decay modes of 76Ge», A.Smolnikov at MEDEX 19, Prague, Czech Republic.
36. «Status of the search for neutrinoless double-beta decay with GERDA», A.Lubashevskiy at WIN 2019, Bari, Italy.
37. «Upgrade of the GERDA Phase II experiment», E.Shevchik at Nucleus 2019, Dubna, Russia.
38. «Latest results from the first background free search for neutrinoless double beta decay – GERDA Phase II», K.Gusev at INPC 2019, Glasgow, UK.
39. «Status of the GERDA Phase II experiment», N.Rumyantseva at ICNFP 2019, Crete, Greece.
40. «Results of the GERDA Phase II experiment», K.Gusev at ICHEP 2020, Prague (virtual conference).

3) Project νGEN (Investigation of neutrino properties with the low-background germanium spectrometer νGEN)

Project leader: V. Brudanin (brudanin@jinr.ru)
Project deputy leaders: A. Lubashevskiy, E. Yakushev

The νGEN project is aimed to investigate fundamental properties of neutrino at close vicinity of the reactor core of Kalinin Nuclear Power Plant (KNPP). The search for the coherent scattering of the neutrino from the reactor is performed within the project. This process has never been observed for the low-energy reactor neutrino. While observing, it opens a way to search of non-standard neutrino interaction and applied research, like reactor monitoring. The νGEN experimental setup is constructed under the reactor #3 of KNPP at a distance of about 10 m from the center of the reactor's core under an enormous antineutrino flux of more than $5\cdot10^{13}$ ν/cm^2/s. A special lifting mechanism allows moving the spectrometer away from the reactor core, suppressing main systematic errors caused by possible long-term instability and neutrino flux. Signals from neutrino scattering are detected with help of high purity low-threshold germanium detectors. New detectors in νGEN project with an ultimate resolution of about 80 eV (FWHM) with masses of more than 1 kg each are used to detect neutrino signals. It would allow exploring an energy region below 250 eV. A total mass of about 5.5 kg will be used for an upgrade of the experimental setup. Detectors at KNPP are surrounded by passive and active shielding reducing the external background in the region of interest. First coherent neutrino scattering from reactor would be observed in case of desired background level and energy resolution at KNPP are achieved. This setup would also open a way to investigate the coherent neutrino scattering with a much higher sensitivity to the non-standard neutrino interactions. The first phase of the project (GEMMA-I) sets up the world best upper limit for the Magnetic Moment of Neutrino (MMN) of $< 2.9\cdot10^{-11}\mu_B$ (90% CL). The experimental sensitivity with νGEN project will be improved to the level of ~ $(5\text{-}9)\cdot10^{-12}\,\mu_B$ after several years of data taking.

The experimental setup is located at about 10 m from the 3 GW$_{th}$ reactor core of KNPP. The available place for the measurement is located just under the reactor, which provides about 50 m w.e. shielding from cosmic rays. The scheme of the reactor is shown in Fig. 3.1, left.

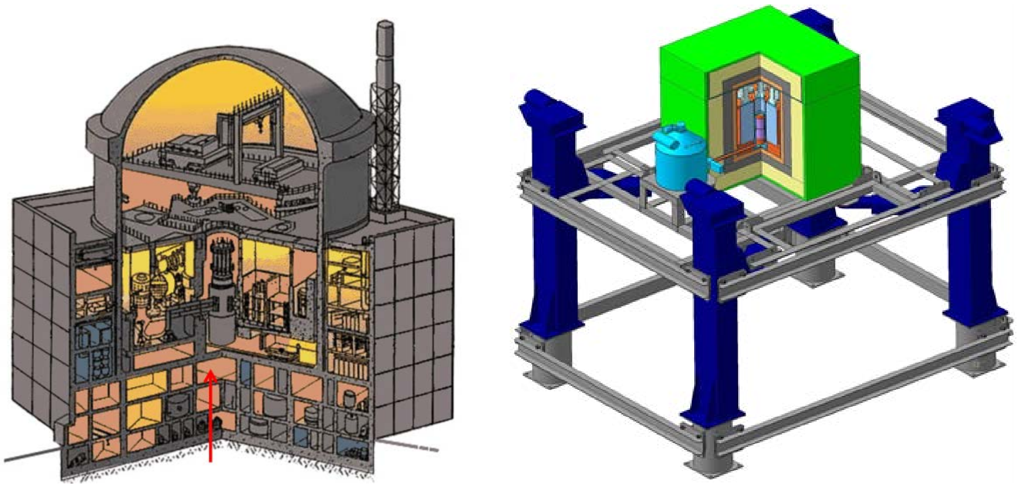


Fig. 3.1. Left: the scheme of the reactor unit #3 at KNPP. Arrow indicates the room where experimental setup is being constructed. Right: the scheme of the spectrometer placed on the lifting mechanism.

A special lifting mechanism allows to move the spectrometer away from the reactor core, suppressing main systematic errors caused by possible long-term instability and neutrino flux (Fig. 3.1, right). It gives us an opportunity to vary on-line the antineutrino flux significantly and reduce uncertainties of the background.

Installation of the first νGEN detector at KNPP started in the end of 2019. The scheme of the shielding is shown at Fig.3.2.

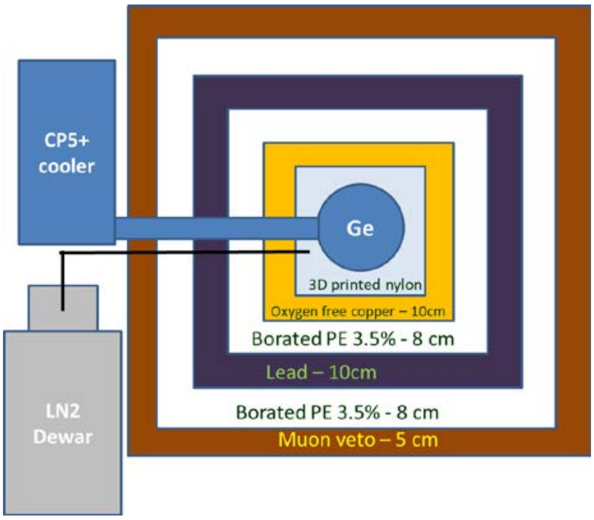


Fig. 3.2: Scheme of the shielding used at KNPP.

The inner part of the shielding is a specially produced 3D printed nylon, which displace air away from the detector, decreasing the amount of radon inside the shielding. Further layers are 10 cm of oxygen-free copper, 8 cm of 3.5% borated polyethylene, 10 cm of lead another 8 cm of 3.5% borated polyethylene and active muon veto. The energy spectrum obtained in a first measurement at KNPP is shown in Fig. 3.3. Further improvements of the background index is expected after decay of cosmogenic isotopes and further optimization of electronics and muon veto.

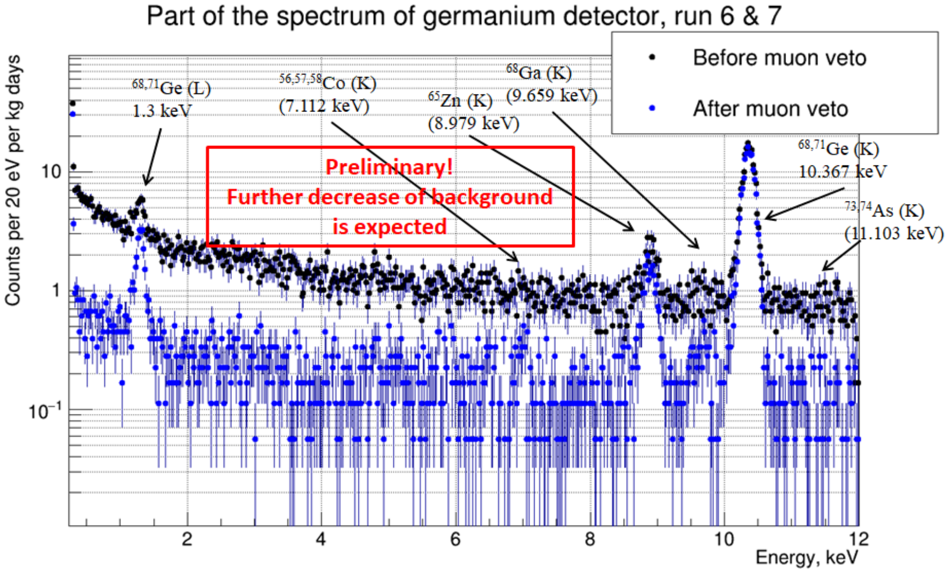


Fig. 3.3: Part of the experimental spectrum taken with the first detector at KNPP. Further decrease of the background is expected due to decay of cosmogenic isotopes and optimization of muon veto.

We are planning to continue implementation of this project and take measurements to search for the CEvNS and NMM with the current experimental setup. The next stoppage of the reactor is schedule in March 2020, so until this time we have data with reactor OFF. Therefore, this gives us possibility to compare spectra taken with the reactor ON and OFF. At the same time, we are planning to increase the sensitivity of the experiment by improving the background level, by lowering energy threshold and by increasing a total mass of the detectors. The sensitivity to magnetic moment of the neutrino is expected to be about (5-9)$\cdot 10^{-12}$ μB after several years of data taking.

Publications and talks

1. Beda A. G. et al. // Advances in High Energy Physics V.2012 (2012), Article ID 350150, 12 pages doi:10.1155/2012/350150
2. Alekseev I. et. al. // arXiv:1305.3350, 2013
3. A. Beda et al. GEMMA experiment: the results of neutrino magnetic moment search, Physics of Particles and Nuclei Letters, 2013, V.10, №2, pp.139-143
4. V. Belov et al., “The νGeN experiment at the Kalinin Nuclear Power Plant”, 2015 JINST 10 P12011.
5. D. Medvedev, The International Workshop on Non-Accelerator New Physics (NANPino-2013), Valday, Russia, 2013 2. D. Medvedev, Sixteenth Lomonosov Conference on Elementary Particle Physics, Moscow State University, Moscow, Russia, 2013 3. D. Medvedev, Wilhelm and Else Heraeus-Seminar Exploring the neutrino sky and fundamental particle physics on the Megaton scale, Bad Honnef, Germany, 2013 4. D. Medvedev, Wilhelm and Else Heraeus-Seminar Exploring the neutrino sky and fundamental particle physics on the Megaton scale (poster), Bad Honnef, Germany, 2013
6. V. Egorov, Symposium on JINR-SA collaboration, South Africa, 2012 6. D. Medvedev, JINR neutrino program, Dubna, Russia, 2013 7. D. Medvedev, The International Workshop on Prospects of Particle Physics: "Neutrino Physics and Astrophysics", JINR, INR, Valdai, Russia, 2014
7. D. Medvedev, AYSS 2016, Alushta, Russia, 2016
8. V.Belov, A.Kuznetsov, D. Medvedev, ISAAP, Milan, Italy, 2016
9. V.Belov, A.Kuznetsov, D. Medvedev, ISAAP, Arenzano, Italy, 2017 11. A. Lubashevskiy, ICSSNP 2017, Nalchik, Russia, 2017 12. D. Medvedev, ICSSNP 2017, Nalchik, Russia, 2017 10. A. Lubashevskiy, ISSP 2017, Erice, Italy, 2017

Thesis of the participants of the project

M. Shirchenko, “Investigation of the neutrino properties: helicity and magnetic moment”, 2019

4) Project DANSS (Detector of the reactor Anti-Neutrino based on Solid state plastic Scintillator)

Project leader: Yu. Shitov (shitov@jinr.ru)
Project deputy leader: V. Brudanin

Within the framework of this project, a relatively compact and safe neutrino spectrometer DANSS based on plastic scintillators (PS) with a sensitive volume of 1 m^3 has been developed and created, capable of operating near powerful industrial reactors. The spectrometer is mounted at the fourth power unit of the Kalinin NPP under the WWER1000 reactor (P^{THERM} = 3.1 GW), which provides protection from cosmic background at a level of ~ 50 m.w.e. A high degree of segmentation and the use of a combined active and passive protection provide excellent background suppression when registering ~ 5000 antineutrinos per day. The lifting platform allows to move the spectrometer vertically by 2 meters, providing a measurement 10-12 m range from the reactor core. The analysis of data collected in 2016-2020 have showed no significant sign of oscillations into sterile neutrinos, which made it possible to exclude the record-breaking region of the phase space of possible oscillations into sterile neutrinos (“3 + 1” model). In addition, the DANSS detector has demonstrated the capability of long-term precision monitoring of reactor power and sensitivity to nuclear fuel composition.

At the same time, in 2018 the NEUTRINO-4 experiment (PNPI, Gatchina) has claimed the observation of oscillations in sterile neutrinos with the parameters $\sin^2(2\theta_{14})$~0.25, Δm_{14}^2~7 eV^2 (arXiv:2005.05301), which are outside the DANSS sensitivity range in its current configuration. Independent verification of the NEUTRINO-4 result is an important fundamental problem at the present time. In order to reach the phase point of the effect, we have developed an upgraded **DANSS-2** spectrometer, which will be built in 2022. The main goal is to increase significantly the energy resolution of the spectrometer to 15% @ MeV from the current 34% @ MeV. A new detecting cells (strips made of better PS with more fibers for better light collection) and updated electronics will be used. At the same time, DANSS-2 will use the same passive and active shielding, mobile platform and the DAQ as DANSS, which will significantly reduce the cost of modernization.

Together with Czech colleagues, it is planned also to complete the development and creation of the $\mathbf{S^3}$ neutrino detector (S-cube) (only ~64L with improved detecting elements). Such a detector will register ~ 300-400 antineutrinos per day and, together with the DANSS-2, will help to study the systematics of the used measurement method as well as to solve applied tasks of reactor monitoring.

Latest results:

During four years of measurements (3 full reactor fuel campaigns), DANSS has registered almost 4M reactor antineutrinos, that is, ~1M antineutrinos per year or 5000 antineutrinos per day. The accumulated statistics and spectra of IBD-positrons (antineutrinos) measured with the DANSS spectrometer are shown in Fig. 4.1.

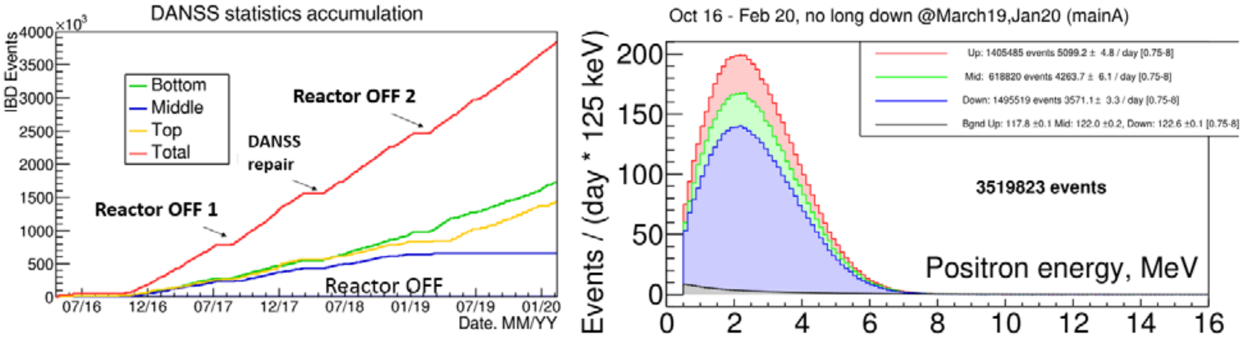


Fig. 4.1: Statistics of accumulated antineutrinos (left) and spectra of IBD-positrons in different positions of the detector minus all backgrounds (right).

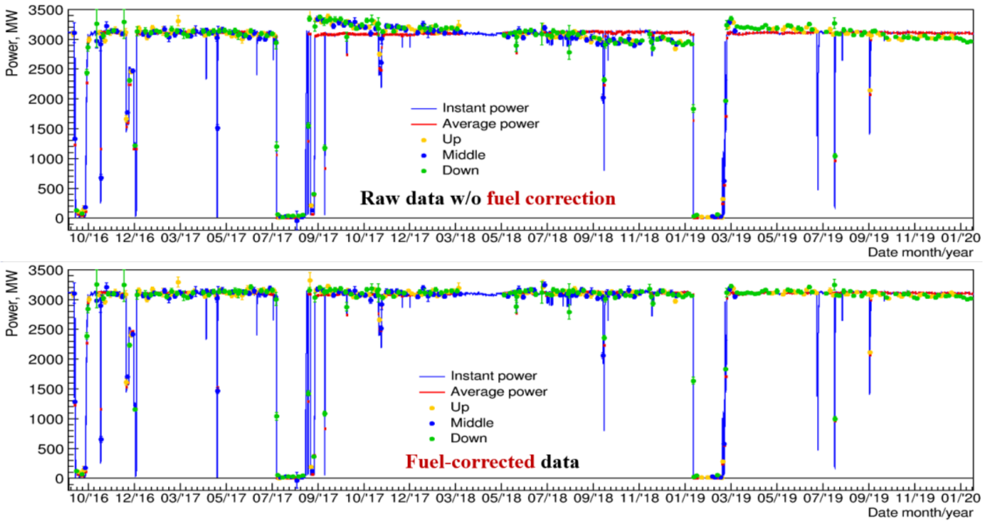
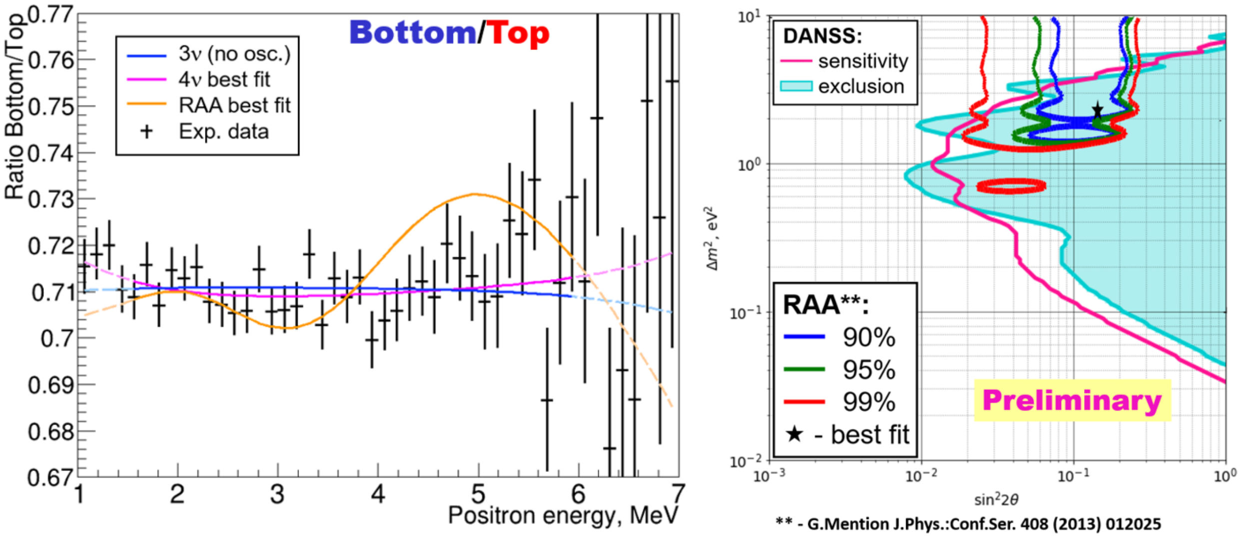


Fig. 4.2: Comparison of the reactor power (blue line) with the DANSS measurements (colored points of 3 positions) without (top) and with (bottom) fuel composition correction.

During four years 2016-2020, the DANSS spectrometer has been continuously monitoring the reactor power with an accuracy of 1.5% on 2-day statistics, and also demonstrates sensitivity to the composition of nuclear fuel - a decrease in the count rate over time due to a decrease in the U/Pu ratio (see. Fig. 4.2).

The main DANSS result at the current moment (3M IBD-events in the Down/Up positions) is shown in Fig. 4.3. The left figure shows the per bin ratio of the energy spectra of IBD-positrons measured by the DANSS spectrometer in the Down/Up positions. Visually and mathematically, the oscillatory pattern of sterile neutrinos is not observed on it. The best fit of the 3+1 model (purple curve) has a significance less than 1.5σ and does not differ significantly from the null hypothesis of no oscillation (blue curve). Figure 4.3 on the right shows an area of phase space in which oscillations have been excluded by the current analysis (cyan fill). This is the best result in the world to date among reactor experiments to search for sterile neutrinos.



** - G.Mention J.Phys.:Conf.Ser. 408 (2013) 012025

Fig. 4.3: The per bin ratio of the IBD-positron spectra measured at the Bottom/Top positions with a DANSS spectrometer (left). Region excluded by the current analysis is shown by cyan fill (right). The RAA best fit 3+1 model is shown by an orange curve on the left plot and by black star on the right plot.

The main work plan for 2022-2024 is the development, creation, commissioning, and launch of the upgraded DANSS-2 spectrometer, followed by data collection and analysis. In its current configuration, DANSS is not sensitive to the phase point of the positive signal declared by the NEUTRINO-4 experiment. The main reason is the low energy resolution, which smears the effect of oscillations. Therefore, the main goal and motivation for upgrading the spectrometer is to significantly improve the resolution to 15% @ MeV from the current 34% @ MeV. This will make it possible to reach the region of the NEUTRINO-4 signal, the verification of which is an important and urgent fundamental problem of neutrino physics, which was discussed earlier. In addition, the region of the verified phase space of possible oscillations into a sterile neutrino will significantly expand.

The schedule for the upgrade of the spectrometer is as follows.

1. Detailed design studies, tests and R&D of individual elements, final design approval of all elements, electronics development will be carried out during 2021 and will be completed by mid-2022.
2. In parallel, in 2021 and until mid-2022, 1,440 new detector elements will be manufactured. The process will be carried out in three stages:
    a) cooking plates from a plastic scintillator, checking and certifying them for a light output. This procedure will be carried out in JINR by the Dubna group. The planned production speed is 30-60 strips per week.
    b) cutting of grooves, gluing of fibers and applying a diffusion reflective coating on strips (matting) will be performed by a third-party commercial company in Vladimir under the supervision of representatives of the Dubna group, also responsible for the delivery of strips from Dubna to Vladimir.
    c) equipment of strips with SiPMs and final certification of their individual characteristics will be carried out at ITEP by our colleagues, who are also responsible for transporting strips from Vladimir to Moscow.

3. "Dry assembly" of the setup in a clean room at ITEP for testing and tuning its operation is provided for six months (second half of 2022). It will be carried out by the ITEP group with the possible involvement of members of the Dubna group, if necessary.
4. Final assembly and commissioning of the DANSS-2 at KNNP is planned for the first half of 2023. Note that the work on items 1-3 will be carried out in parallel with the operation of the DANSS spectrometer. Before starting point 4, it will take 1-2 months to disassemble the DANSS.
5. Physical start-up and data collection by the DANSS-2 spectrometer is scheduled for the summer of 2023. The minimum exposure to get valuable results is ~ 2.5 years

Publications

1. I.G. Alekseev et al., DANSSino: a pilot version of the DANSS neutrino detector, Phys.Part.Nucl.Lett. 11 (2014) 473-482, DOI: 10.1134/S1547477114040050, локальная копия: https://drive.google.com/file/d/1_srxh5AoC1YEDQMhPu6h1i_qSMbgCNDV/view?usp=sharing
2. I.G. Alekseev et al., DANSS: Detector of the reactor AntiNeutrino based on Solid Scintillator, JINST 11 (2016) no.11, P11011, DOI: 10.1088/1748-0221/11/11/P11011, локальная копия: https://drive.google.com/open?id=1bnYa3qgD99UYTWs-2A9e4ZfIgAcdB2T-
3. I.G. Alekseev et al., DANSS Neutrino Spectrometer: Detector Calibration, Response Stability, and Light Yield, Phys.Part.Nucl.Lett. 15 (2018) no.3, 272-283, DOI: 10.1134/S1547477118030020, локальная копия: https://drive.google.com/file/d/1R8V2QyAivktQewtl30XvKwBaz1iqluqp/view?usp=sharing
4. I.G. Alekseev et al., Search for sterile neutrinos at the DANSS experiment, Phys.Lett. B787 (2018) 56-63, DOI: 10.1016/j.physletb.2018.10.038, локальная копия: https://drive.google.com/open?id=1R8V2QyAivktQewtl30XvKwBaz1iqluqp
5. И.Г.Алексеев и др., Мониторирование мощности промышленного реактора по счету антинейтрино в детекторе DANSS, Ядерная физика, Том 82, номер 5, 2019, стр. 371-381, DOI: 10.1134/S0044002719050040, локальная копия: https://drive.google.com/open?id=1w65AOo2lz56HZpquT15OdPahkwPFAH7O; I.G. Alekseev et al., Industrial Reactor Power Monitoring Using Antineutrino Counts in the DANSS Detector, Phys.Atom.Nucl. 82 (2019) no.5, 415-424, DOI: 10.1134/S1063778819050041, локальная копия: https://drive.google.com/open?id=1yrby_PBNl40CPt5vtVXeEwwc2vWcRxls
6. D. Svirida et al., Searches for sterile neutrinos at the DANSS experiment, PoS NOW2018 (2019) 066, DOI: 10.22323/1.337.0066, локальная копия: https://drive.google.com/file/d/1Aa6gD7c6XQUiBaSZw6YDguhnuukreOM7/view?usp=sharing
7. N.A. Skrobova et al., Calibration of the DANSS Detector with Cosmic Rays, Bull.Lebedev Phys.Inst. 45 (2018) no.10, 325-328, DOI: 10.3103/S106833561810010X, локальная копия: https://drive.google.com/file/d/11kn8nAsL2-jJJ2igvsSFl6JYcNAzh7AO/view?usp=sharing
8. Mikhail Danilov et al., Recent results of the DANSS experiment, Nuovo Cim. C41 (2019) 162, DOI: 10.1393/ncc/i2018-18162-0, локальная копия: https://drive.google.com/file/d/1FacqryB8eakf5bPEVYfPAJvFM6IeLRUf/view?usp=sharing

9. I.G. Alekseev et al., Reactor antineutrino physics with DANSS experiment, PoS ICHEP2018 (2019) 060, DOI: 10.22323/1.340.0060, локальная копия: https://drive.google.com/file/d/1yYocwbOiJ1Fn-GactFYmGVGh0xRtNrgC/view?usp=sharing
10. I.G. Alekseev et al., Measurements of the Reactor Antineutrino with Solid State Scintillation Detector, Int.J.Mod.Phys.Conf.Ser. 46 (2018) 1860044, DOI: 10.1142/S2010194518600443, локальная копия: https://drive.google.com/file/d/1K5hTeO0tuALtz33FX7CU24xfYZy3kcyS/view?usp=sharing
11. D. Svirida et al., Electronics of the data acquisition system of the DANSS detector based on silicon photomultipliers, Phys.Part.Nucl. 49 (2018) no.1, 84-85, , локальная копия: ; Fiz.Elem.Chast.Atom.Yadra 49 (2018) no.1, DOI: 10.1134/S1063779618010367, локальная копия: https://drive.google.com/file/d/1zloVKEAFQ30qqj7NlxRIkgigFrVadJsU/view?usp=sharing
12. Machikhiliyan et al., Reconstruction and initial calibration of silicon photomultipliers response in the DANSS experiment, Phys.Part.Nucl. 49 (2018) no.1, 70-72, локальная копия: ; Fiz.Elem.Chast.Atom.Yadra 49 (2018) no.1, DOI: 10.1134/S1063779618010276, локальная копия: https://drive.google.com/file/d/1ErbCa_k1NScNdE1GHH-LtCPFX8mafaF9/view?usp=sharing
13. N. Pogorelov et al., Light output distribution in scintillator strips with wave length shifting fibers of DANSS spectrometer, J.Phys.Conf.Ser. 934 (2017) no.1, 012055, DOI: 10.1088/1742-6596/934/1/012055, локальная копия: https://drive.google.com/file/d/1hRjMTbg6T0-tYSATmO3p9insVGHZiRRK/view?usp=sharing
14. I.G. Alekseev et al., Detector of the reactor AntiNeutrino based on Solid-state plastic Scintillator (DANSS). Status and first results. J.Phys.Conf.Ser. 798 (2017) no.1, 012152, DOI: 10.1088/1742-6596/798/1/012152, локальная копия: https://drive.google.com/open?id=1kj136sf8zPkWxwzq5m9XDKrsng_u9Ngp
15. Zdenek Hons, Jakub Vlášek , Data Acquisition System for Segmented Reactor Antineutrino Detector, JINST 12 (2017) no.01, P01022, DOI: DOI: 10.1088/1748-0221/12/01/P01022, локальная копия: https://drive.google.com/file/d/1v10GXt2vwjRS8b2icWTrN5wPeBicUCYS/view?usp=sharing
16. M.Danilov et al., Sensitivity of the DANSS detector to short range neutrino oscillations, PoS EPS-HEP2013 (2013) 493, Nucl.Part.Phys.Proc. 273-275 (2016) 1055-1058, DOI: 10.22323/1.180.0493, 10.1016/j.nuclphysbps.2015.09.165, локальная копия: https://drive.google.com/file/d/1BOl_Rg27KifpdZsAj7LhF8T4s_XP6wkJ/view?usp=sharing
17. V. Belov et al., Registration of reactor neutrinos with the highly segmented plastic scintillator detector DANSSino, JINST 8 (2013) P05018, DOI: 10.1088/1748-0221/8/05/P05018, локальная копия: https://drive.google.com/file/d/1iJgfpOSACRXRwQmrB4boLfvSaKcIVxSt/view?usp=sharing
18. Mark Shirchenko, Nataliya Skrobova Searches for sterile neutrinos at the DANSS experiment // EPJ Web Conf. 219 (2019) 08002, DOI: 10.1051/epjconf/201921908002,

локальная копия: https://drive.google.com/open?id=127e9oPOOwTw3i04x-9sqqNyF9PlWla25

19. Nataliya Skrobova & DANSS Collaboration, Statistical data analysis in the DANSS experiment // J.Phys.Conf.Ser. 1390 (2019) no.1, 012056, DOI: 10.1088/1742-6596/1390/1/012056, локальная копия: https://drive.google.com/open?id=152RvK4sHqO8A6LV5YnrAzuITlBw6K13M
20. I. Alekseev & DANSS Collaboration, Reactor antineutrino measurements with DANSS experiment // J.Phys.Conf.Ser. 1390 (2019) no.1, 012050, DOI: 10.1088/1742-6596/1390/1/012050, локальная копия: https://drive.google.com/open?id=1f24MUGFP3xAmBJGSgKKnV-S3aqyD4FTa
21. Eduard Samigullin & DANSS Collaboration, Cosmic muons measurements in the DANSS experiment // J.Phys.Conf.Ser. 1390 (2019) no.1, 012072 DOI: 10.1088/1742-6596/1390/1/012072, локальная копия: https://drive.google.com/open?id=1D4psn1VgYle7PYNcVViH3GYR3Mh_w_Pw
22. M.Danilov & DANSS Collaboration, Recent results of the DANSS experiment // Proceedings of European Physical Society Conference on High Energy Physics, EPS-HEP2019, 10-17 July 2019, Ghent, Belgium Nov 22, 2019. 7 pp. arXiv:1911.10140, локальная копия: https://drive.google.com/open?id=1uNqZYXXzXGNI-Mc2W7aq7UuVxf1s14Vc
23. Yuriy Shitov & DANSS Collaboration, New results from the DANSS experiment // PoS LeptonPhoton2019 (2019) 056, DOI: 10.22323/1.367.0056, локальная копия: https://drive.google.com/open?id=1sKmr9lmf2Vw-p9LajspJKu2Mqmr6H6Rp
24. Yu. Shitov & DANSS Collaboration, Status of the DANSS project // Applied Antineutrino Physics 2018 Proceedings, p. 14-15. e-Print: arXiv:1911.06834 [hep-ex], локальная копия: https://drive.google.com/open?id=1VNpWSs3aM3thsCER4Rk807xY2HjHp3Ak
25. N.A. Skrobova & DANSS collaboration, Statistical Data Analysis in the DANSS Experiment Including Antineutrino Relative Count Rate Data as a Function of Distance, Bull.Lebedev Phys.Inst. 47 (2020) 9, 271-275, DOI https://doi.org/10.3103/S1068335620090067, локальная копия: https://drive.google.com/file/d/1kSHlME6yYBMeMMPEfTd8SEORm9MJY8r8/view?usp=sharing
26. N.A. Skrobova & DANSS collaboration, Estimation of the DANSS Experiment Sensitivity to Neutrino Oscillations, Bull.Lebedev Phys.Inst. 47 (2020) 4, 101-104, Kratk.Soobshch.Fiz. 47 (2020) 4, 3-8, DOI: https://doi.org/10.3103/S1068335620040077, локальная копия: https://drive.google.com/file/d/1TS_i_6W-YfVQDJcDf56GSw8FFghBA0G8/view?usp=sharing
27. Igor Alekseev & DANSS collaboration, Measurements of the reactor antineutrinos with the DANSS experiment, J.Phys.Conf.Ser. 1468 (2020) 1, 012156 • Contribution to: TAUP 2019, DOI: https://doi.org/10.1088/1742-6596/1468/1/012156, https://drive.google.com/file/d/1ZcAN6gExLcJex6kV0DVQ47U8pIgFEQRj/view?usp=sharing

Presentations:

1. International session-conference of the Nuclear Physics Section of the Physical Sciences Division of the Russian Academy of Sciences "Physics of fundamental interactions" dedicated to the 50th anniversary of the Baksan Neutrino Observatory International session-conference of the Nuclear Physics Section of the Physical Sciences Division of the Russian Academy of Sciences "Physics of fundamental interactions" dedicated to the 50th anniversary of the Baksan Neutrino Observatory. Igor Zhitnikov, Status of the DANSS experiment
2. Report of LXVIII International conference NUCLEUS 2018: Actual status of “DANSS” project
Report New Trends in High-Energy Physics 2018: Actual status of “DANSS” project
Vyacheslav Belov + 1 report by Fomin M.V.
3. International Workshop on Particle Physics at Neutron Sources 2018, DANSS, M. Shirchenko.
4. 6th Symposium on Neutrinos and Dark Matter in Nuclear Physics 2018.https: //indico.ibs.re.kr/event/212/, M. Shirchenko, DANSS
5. Yu. Shitov Status of the DANSS project / AAP 2018, 14th International Workshop on Applied Antineutrino Physics, 10-11 October 2018, Livermore, California, USA
https://neutrinos.llnl.gov/content/assets/docs/workshops/2018/AAP2018 -DANSS-Shitov.pdf
6. Yu. Shitov New results from the DANSS experiment / LP2019 XXIX International Symposium on Lepton Photon Interactions at High Energies, 5-10 August 2019, Toronto Canada, https://indico.cern.ch/event/688643/contributions/3429530/
7. Yu. Shitov Search for a light sterile neutrino at SBL reactor experiments / Seminar at University of Comenius, Bratislava, Slovakia, 14 November 2018. https://fmph.uniba.sk/detail-novinky/back_to_page/fakulta-matematiky-fyziky-a- informatiky-uk / article / translate-to-english-nuklearny-seminar-yuri-shitov-14112018 /
8. Yu. Shitov, The DANSS project: resent status / Colloquium Prague 19, 24-25 October 2019, J. Heyrovsky Institute of Physical Chemistry
https://indico.cern.ch/event/802062/timetable/#all.detailed
9. Yu. Shitov, Recent results from DANSS / NuPhys2019, Prospects in Neutrino Physics, 16-18 December 2019, London, UK, Invited oral talk is foreseen
https://indico.cern.ch/event/818781/timetable/#all.detailed
10. Yu.Shitov, Recent results from the DANSS experiment, Neutrino-2020, Chicago, online, June 22-July 2, 2020 https://indico.fnal.gov/event/43209/timetable/#20200622.detailed
11. Irina Machikhiliyan The DANSS neutrino spectrometer: the results of reactor antineutrino studies, Nucleus-2020, https://indico.cern.ch/event/839985/timetable/#all.detailed

5) Project EDELWEISS/RICOCHET (Joint project for Direct Dark Matter search and precision study of CEvNS with new cryogenic detectors)

Project leader: E. Yakushev (yakushev@jinr.ru)
Project deputy leader: S. Rozov

Introduction and general description of the project:

In direct searches for Dark Matter (DM) a technology developing by **EDELWEISS** experiment is arrays of Ge mono-crystal detectors operated at a temperature of few mK and equipped with electrodes and thermal sensors. Applying a small (few V/cm) external field, a simultaneous measurement of ionization and heat signals allows efficient identification of nuclear and electron recoils. New results demonstrated the high relevance of cryogenic Ge detectors for the search of DM interactions producing eV-scale signals. The region of "light WIMPs" will be further investigated in the EDELWEISS experiment thanks to advantage of energy resolution below 20 eV reachable with new array of HPGe bolometers. This stage is in the R&D phase, building of improved detectors, their holders and supports, improvement of the background and acquisition. The unlimited target of current R&D and measurements in the EDELWEISS experiment is achievement of sensitivity allowing detection of B-8 solar neutrinos through coherent elastic neutrino-nucleus scattering (CEvNS). The same technology and detectors will be applied for precision measurements of CEvNS in the region of full coherency in the **Ricochet** experiment (reactor neutrinos). Due to direct energy reconstruction (heat signal) the main uncertainty arising due to not well known quenching in germanium will be avoided. 1 kg of new cryogenic detectors (developing thanks to joint R&D of EDELWEISS and Ricochet teams) will be integrated in the Ricochet cryostat. The Ricochet is going to be deployed at ILL (Grenoble, France) site, on a distance at about 8 m from the 58 MW nuclear reactor, with first results expected to 2025. In addition to the main goal: precise (1% level) study of CEvNS the experiment will target NMM and other New physics phenomena. Possibility of further phases of the experiment at a Nuclear power plant (a 3.2 GW reactor) at Russia is under investigation.

The EDELWEISS/Ricochet are going to use jointly developed cryogenic detectors in two setups: in the LSM underground laboratory, and near the ILL nuclear research reactor. Measurements at LSM are going to provide data about an ideal background and DM search. It has to be mentioned that in own turn the Ricochet data are going to clarify the CEvNS' background for DM searches. The Ricochet will use new cryogenic setup, so-called dry ^{3}He-^{4}He dilution cryostat, that is not required any helium and nitrogen refills for many years. Such a test cryostat has been already used for the current R&D phase and demonstrated its applicability for planned research. There are plans to eventually replace current LSM underground setup with such new technology cryosystem, with an aim to reduce low level noises and radioactive backgrounds.

The cryogenic detectors

The EDELWEISS/Ricochet detectors are designed to provide the first percentage precision CEvNS measurement in the sub-100 eV energy region to search for new physics in the electroweak sector and to be competitive with low-mass DM searches in eV mass range. Therefore, they have to fulfill the following specifications:

- Energy thresholds in the *O*(10) eV range, as the discovery potential scales exponentially with lowering the energy threshold;

- Significant background rejection combined with a low-radioactivity environment, as the experiment's sensitivity scales linearly with the signal-to-noise ratio;
- Total target mass of about one kilogram to have significant sensitivity to new physics signatures in both cases (DM and CEνNS).
- Accommodation of several monolithic target materials, as most new physics signatures, such as Non-Standard Interactions, depend on the target's nuclear properties.

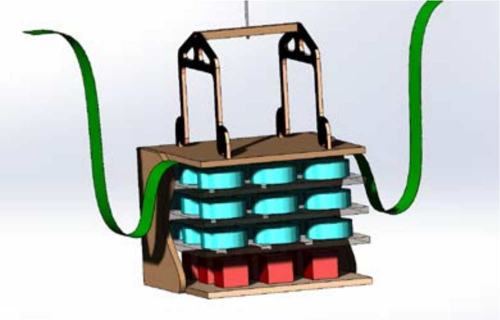


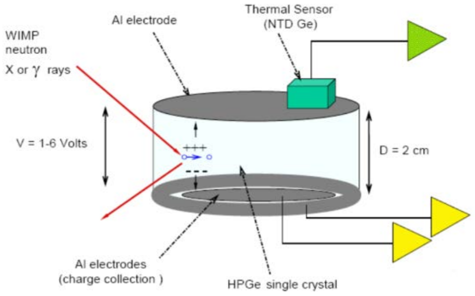
Fig. 5.1: Cryogenic detector assembly suspended below the inner shielding – CryoCube with its 27 Ge crystals (blue) and the Q-Array with its 9 Zn crystals (red) – suspended below the inner shielding.

Two detector technologies will be used: cryogenic Ge-semiconductors and Zn-superconducting metals, which are both well suited to provide electromagnetic background discrimination at the lowest energies. Figure 5.1 shows a simplified design of the Ricochet cryogenic detector assembly. It consists of a total array of 36 bolometers of about 30 g each, leading to a total payload of 1.3 kg, and divided among two sub-arrays: the CryoCube (27 Ge-crystals) and the Q-Array (9 Zn). The crystals from the two detector arrays will be packed together and encapsulated in radio-pure infrared-tight copper box suspended below the inner shielding with its dedicated cryogenic suspension system and cold front end electronics.

Ge semi-conductor

In semiconductor bolometers, the rejection between backgrounds and WIMP or CEνNS-signal events will be achieved thanks to the double measurement of the heat and ionization energies, which ratio depends on the nature of the interacting particle: γ- or β-induced electronic recoils (electromagnetic interactions), DM induced electronic recoils; CEνNS- , WIMPs-, or neutron-induced nuclear recoils (lattice interactions).

Scheme of detection principle of a heat and ionization detector



The goal is to reach ~10 eV (RMS) energy resolution in heat and ~20 eV (RMS) resolution in ionization to provide a rejection power of about 10^3 down to the energy threshold. To reach such background rejection to all sorts of electromagnetic backgrounds, two key features have to be met: i) Fully Inter-Digited (FID) electrodes, as first introduced by the EDELWEISS collaboration, thanks to which events happening near the surface can be tagged as such and be rejected while providing excellent charge collection for bulk events; ii) ~10 eV ionization energy resolution (RMS), which is few times better than the best resolution achieved so far in such massive cryogenic bolometers. This will be achieved thanks to dedicated low-noise HEMT-based preamplifiers combined with low-capacitance cabling and detectors.

The fabrication of the Ge detectors will be accomplished by the collaboration. High purity Ge crystals are available commercially. Charge collection electrodes are based on evaporated thin films of Aluminum that can be patterned to an optimized design using lithography and shadow mask techniques. The available fabrication facilities allow to cover both flat and lateral surfaces of the Ge crystal. An amorphous Ge:H layer is deposited prior to the Al film to improve the charge collection efficiency, especially for near surface events. In a second step, a heat sensor is implemented using NTD-Ge thermistors that are glued directly onto the Ge crystal. The detector is finally mounted into its copper holder.

EDELWEISS/Ricochet groups have successfully demonstrated a 55 eV energy threshold on a 33-g Ge bolometer operated from a surface lab early 2019 and with several detectors in underground laboratory in 2020, suggesting that the very low-energy threshold of 50 eV is secured. Nowadays, the main R&D focus is dedicated to demonstrating the rejection capabilities of the electromagnetic backgrounds down to the energy threshold. To that end, a first bolometer combining a heat sensor and four ionization electrodes (see Fig. 5.2 left panel) has been tested above ground test facility and exposed to an AmBe neutron source. Fig. 5.2 (right) shows the resulting event distribution on the ionization yield where two populations of events can clearly be identified: electronic recoils and nuclear recoils. An improvement by a factor of 10 on the ionization resolution, hence on the particle identification threshold, is expected due to transition from the FET-based to our upcoming HEMT-based preamplifiers. The collaboration is expects to have by mid-2022 the Ge-based CryoCube detector array, including its cold front-end electronics (HEMT-based preamplifiers) and cabling, which is fully funded by French side. During R&D phase the same detectors will be used underground to DM search.

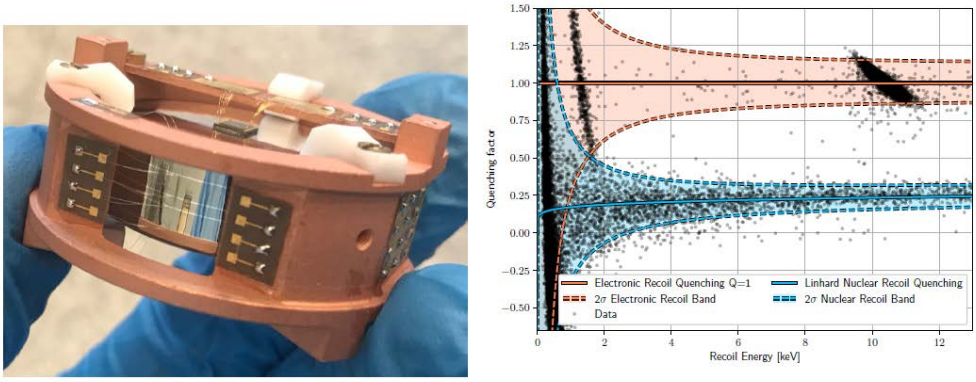


Fig 5.2: Photograph of a 10 mm height and 30 mm diameter Ge detector prototype with 4 electrodes, one NTD-Ge heat sensor mounted in its copper holder. Right: Neutron calibration of the detector represented on the quenching versus recoil energy. Two populations of events are: electronic recoils with Q ~ 1 (red band) and nuclear recoils with Q ~ 0.3 (blue band). Electronic captures from the K and L shells of the ^{73}Ge at 10.37 keV and 1.3 keV respectively are also visible and are used for calibration. Those two lines have been activated by an exposition of the detectors to a high activity neutron source.

Zinc Superconductors

The Ricochet experiment will also use metallic superconductor (Zn) absorbers for its bolometric array. These detectors are developing by the US Ricochet group which are not member of the

EDELWEISS, thus in beginning this technology will be used exclusively for Ricochet. The motivation for using new detectors is twofold: i) zinc detectors may offer the unique advantage of providing strong discrimination between events arising from most residual backgrounds and CEvNS-induced recoils, and ii) it opens the door to a completely new detection technique that could theoretically reach down to the Cooper pair binding energy. Recently, new 40-g zinc cubes have been produced by RMD, Inc (see Fig. 5.3 – left panel). Each detector is instrumented with two gold pads, one in direct contact with the zinc absorber, the other having a 50-100 nm ZnO layer in between the two metals. Such a configuration will allow one to simultaneously measure the phonon and the phonon+quasi-particle population from a given particle energy deposition. This will enable a better understanding of the potential background discrimination capabilities of metallic superconductors. We plan to use transition edge sensors (TES) for the readout of the phonon and quasi-particle signals from these superconducting bolometers. Initial prototype TES chips (with a transition temperature of 80 mK) have been developed by Argonne National Laboratory for this use (see Fig. 5.3 – right panel).

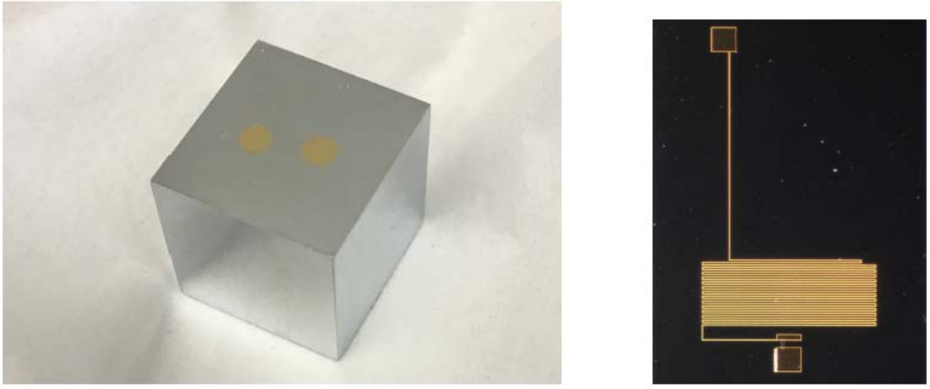


Fig 5.3: Left: Zinc cubic crystal developed by RMD, Inc. Two gold readout pads (left: direct Au-Zn contact, right: Au-ZnO-Zn contact) are present for phonon and quasi-particle readout. Right: Transition edge sensor "chip" with 80 mK T_c developed at Argonne National Laboratory.

The experimental setup

In this section design of **new Ricochet setup** will be addressed as the EDELWEISS one is well known and properly documented in the technical review of the experiment published in Journal of Instrumentation, 12, 08, P08010, 2017. Some improvements in detectors' holders, preamplifiers, data acquisition will be implemented as result of the joint EDELWEISS/Ricochet R&Ds. It corresponds to a general philosophy of the experiment: continuous improvement of the energy resolution and energy threshold, increasing of the detector mass, with simultaneous reduction of the background. Thanks to this approach during each of the previous stages of the EDELWEISS experimental program world leading results of DM search have been obtained.

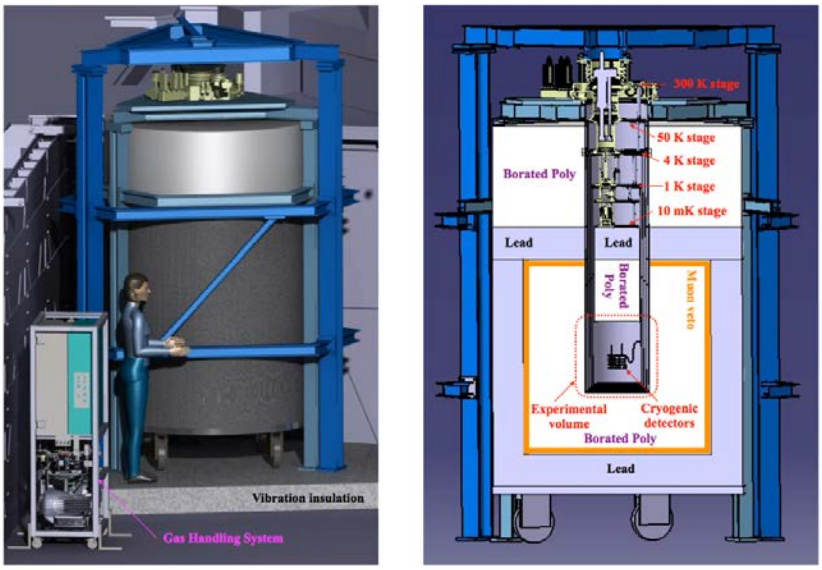


Fig 5.4: Left panel: Future Ricochet experimental setup, illustrating the cryostat held by a double-frame, its movable lead and polyethylene(PE) shields and its gas handling system (GHS). For clarity, the tubing from the GHS and the cryostat is not shown. Right panel: Open view of the Ricochet setup where the dilution refrigerator, the internal shields, the muon-veto, and the experimental volume hosting the detectors and the cold electronics are shown. The double frame has a mass of 1.5 tons, the lead 22 tons and the PE 3 tons, all previous masses are subject to changes depending of the final design.

Thanks to the high CEvNS cross section, Ricochet will be a compact neutrino experiment with a total detector payload of about one kilogram. Due to its use of cryogenic detectors running at ~10 mK and its need to mitigate the environmental backgrounds, the future Ricochet experiment will need the operation of a dry dilution refrigerator surrounded by both lead and polyethylene shields. Fig. 5.4 shows a preliminary drawing of the future Ricochet experiment with the following specifications and infrastructure requirements:

- The cryostat: is composed of a dilution unit with several stages (50K, 4K, 1K, 100mK, and 10mK) as shown on the right panel of Fig. 5.4. The detector will be suspended below the mixing chamber. To minimize the stray capacitance from the cabling, the cold front-end electronics will be thermally anchored at 1K but mounted in the near proximity of the detectors, within the experimental volume, thanks to a cold finger. Eventually, the warm electronics, containing the bias DACs, signal preamplifiers and digitizers will be mounted directly on the 300K flange. Based on the excellent noise performance achieved in the EDELWEISS-III experime, the digitized signals will be sent to the data acquisition system using optical fibers.
- The double frame: the cryostat will be held by two mechanically isolated frames. One for the dilution unit hosting the cryogenic detectors, and the other one for mechanical isolation of the pulse tube cold head, that generates high vibration levels, from the dilution fridge. This vibration mitigation strategy has been shown to reduce by about two orders of magnitude the vibration induced by the pulse tube cryocooler at the detector. The total height of the setup, including the additional floor is 3.4 m with a ground footprint corresponding to a 2.2 m diameter circle. These dimensions are however still subject to changes depending on the final design of the experiment.
- The gas handling system (GHS): it contains all the pumps, the ^{3}He/^{4}He tank, the Pulse Tube (PT) compressor, and the tubing required to operate the cryostat. The cooling of the two first stages of the cryostat is based on a PT cryocooler. The cooling of the two first stages (50K and 4K) is ensured by a Stirling thermal cycle oscillating from 9 to 18 bars at a frequency of ~1 Hz. A 10 mK base temperature is further obtained with an ^{3}He/^{4}He

dilution circuit in closed loop that is using a 2 bar compressor, a dry primary pump and a turbo pump. Vacuum in the cryostat is created thanks to an additional primary and a turbo pump. The GHS is 2 meters tall (total) with a ground footprint of 2 m^2.

- The shields: the cryostat will be encapsulated by different layers of passive materials to reduce the environmental backgrounds. Our preliminary shielding design counts a first layer of borated polyethylene (40 cm thick), a muon-veto (except inside the cryostat), then a lead layer (20 cm thick), and an additional 40 cm thick layer of polyethylene on top to further reduce the reactogenic neutrons. In total, including the frames, we anticipate a load of about 25 tons.
- A small (few-meters squares) semi-clean space should also be in close proximity of the Ricochet experiment in order to store the detectors in a dust-free environment prior to their integration in the cryostat.

Time schedule

It has to be mentioned that timely realization of the scientific program is only possible to 1) detectors already developed in joint R&D EDELWEISS/Ricochet, 2) detectors characterization in EDELWEISS, 3) available electronics and data acquisition system, 4) available infrastructure for low background measurements and for material selection, 5) available supplementary detectors for background measurements/monitoring, 6) the ILL site is well known thanks to the STEREO experiment, 7) calibration procedures for low energy region are well established. In general, the Ricochet will be impossible without the EDELWEISS. In the same time financial resources available for development of Ricochet detectors are the base for ultra-low mass DM search in EDELWEISS.

Time	**Task**
First year	Ricochet: complete building of all Ge detectors (1 kg), their tests, building and commissioning of the cryo-system, shields, supplementary systems. Start the Ricochet implementation at ILL site. EDELWEISS: using of new detectors in a special detection modes for reduction of heat-only events. Building and testing of new HPGe crystals with different termistors, holders, crystal treatments, delivery of the detectors to LSM, measurements.
Second year	Ricochet: Start of data taking. Background measurements, calibrations. Improved MC model based on real data. Implementation of Zn detectors. First results. EDELWEISS: results with accumulated data. Decision about further EDELWEISS detectors design. Selection of materials for improved EDELWEISS setup at LSM.
Third year	Ricochet: data taking, results. Finalizing characterization of NVNPP site for possible further Ricochet implementation. EDELWEISS: Upgrade of EDELWEISS setup at LSM with new cryo-system/shields.

Current phase experimental results:

In 2019-2020, new 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.

At the first stage a number of tests were performed at “on ground” laboratory with new dry dilution cryostat that become a prototype to now developing cryosystem of the Ricochet setup. The cryostat is a Hexadry-200 commercially available from Cryoconcept, which has been upgraded to reduce the vibration levels of the mixing chamber by mechanically decoupling the cold head of the pulse tube cryocooler from the dilution unit. The vibrations at the detector level were further mitigated with the use of a dedicated suspended tower. This was verified with the energy calibration by the use of a low-energy X-ray ^{55}Fe source.

From measurements with new detectors “on ground”, new DM search results were obtained and published in 2019. We searched for DM with masses between 45 MeV/c^2 and 10 GeV/c^2. The energy deposits were measured using a Ge-NTD thermal sensor with a 60 eV analysis threshold. This performance, combined with the nearly completely stationary behavior of the detector, led to the achievement of the first limit for the spin-independent interaction of sub-GeV WIMPs based on a germanium target. The experiment provides the most stringent, nuclear-recoil-based, above-ground limit on spin-independent interactions above 600 MeV/c^2. The search results were also interpreted in the context of SIMPs, taking into account the screening effect of the atmosphere and material surrounding the detector. The lower part of the excluded region for SIMPs represents the most stringent constraint for masses above 600 MeV/c^2. The dark matter search has also been extended to interactions via the Migdal effect, resulting in the exclusion for the first time of particles with masses between 45 and 150 MeV/c^2 with cross sections ranging from 10^{-29} to 10^{-26} cm^2.

At the second stage, 11 different Ge new detectors with different designs were used at the LSM underground laboratory. Run at <21 mK continued since January 2019 to June 2020. In the same time rest of the EDELWEISS cryostat was used for joint physics run with CUPID-Mo 0ν2β search. Data analysis is continued. We compare detector physics in 32g, 200 g and 800g detectors. Compare performance of NTD and NbSi-TES heat sensors (Fig. 5.5). 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 Neganov-Trofimov-Luke internal amplification. With preliminary data we 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. 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. Future context for the 2020-2021: EDELWEISS and Ricochet common R&D for detectors with even lower energy thresholds. The aim is to have 1 kg HPGe array with: 10 eV phonon resolution and 20 eVee ionization resolution.

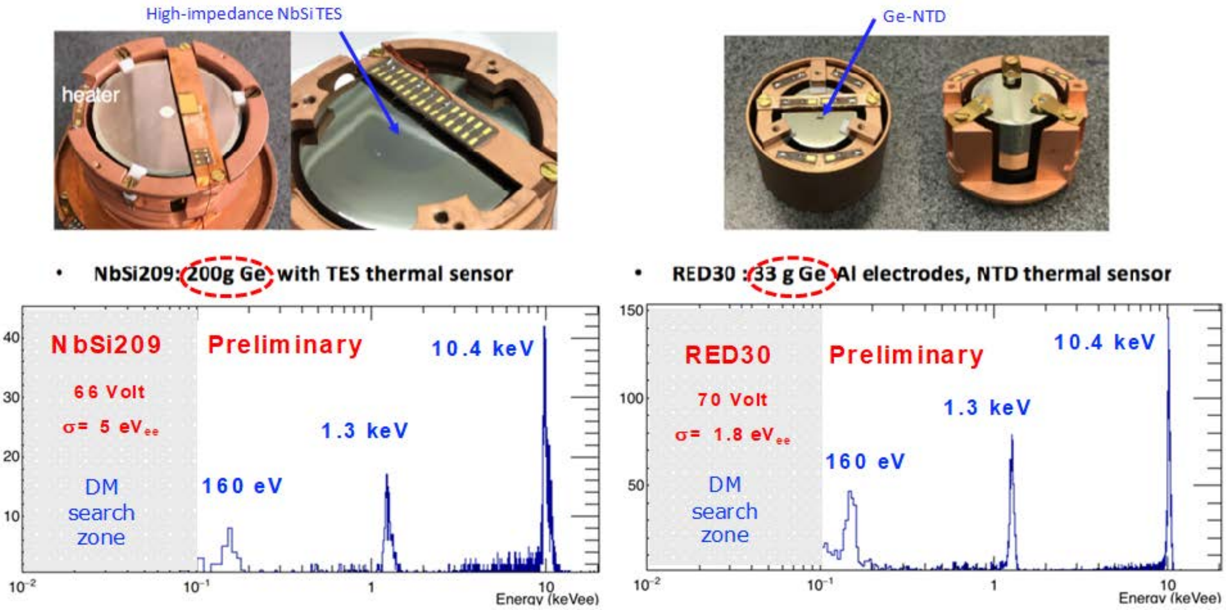


Fig. 5.5: View of two significantly different EDELWEISS detectors and their energy calibration spectra. Near zero energy thresholds were achieved for both cases.

The main result achieved during the current stage is connected to a number of intermediate "small" results that are not subject of this report. More details can be found in the EDELWEISS publications for last 5 years (2015-2020) listed below in the chronological order:

- NA Mirzayev et al, Low radioactive NH_4Cl flux, Journal of Instrumentation 15 (05), T05004, 2020
- Q Arnaud et al (EDELWEISS collaboration), First germanium-based constraints on sub-MeV Dark Matter with the EDELWEISS experiment, arXiv:2003.01046, 2020
- DV Ponomarev et al, Measuring Low Neutron Fluxes at the Modane Underground Laboratory Using Iodine-Containing Scintillators, Instruments and Experimental Techniques 62 (3), 309-311, 2019
- E Armengaud, et al (EDELWEISS collaboration), Searching for low-mass dark matter particles with a massive Ge bolometer operated above ground, Physical Review D 99 (8), 082003, 2019
- PS Fedotov, NN Fedyunina, DV Filosofov, EA Yakushev, G Warot, A novel combined countercurrent chromatography–inductively coupled plasma mass spectrometry method for the determination of ultra trace uranium and thorium in Roman lead, Talanta 192, 395-399, 2019
- E Armengaud, et al (EDELWEISS collaboration), Searches for electron interactions induced by new physics in the EDELWEISS-III germanium bolometers, Physical Review D 98 (8), 082004, 2018
- Q Arnaud, et al (EDELWEISS collaboration) Optimizing EDELWEISS detectors for low-mass WIMP searches, Physical Review D 97 (2), 022003, 2018
- E Armengaud, et al (EDELWEISS collaboration), Measurement of the cosmogenic activation of germanium detectors in EDELWEISS-III, Astroparticle Physics, 91, 2017, 51-64
- E Armengaud, et al (EDELWEISS collaboration) Performance of the EDELWEISS-III experiment for direct dark matter searches, Journal of Instrumentation, 12, 08, P08010, 2017, arXiv preprint arXiv:1706.01070

- L Hehn, et al (EDELWEISS collaboration) Improved EDELWEISS-III sensitivity for low-mass WIMPs using a profile likelihood approach, 2016, The European Physical Journal C 76 (10), 548
- E Armengaud, et al (EDELWEISS collaboration) Constraints on low-mass WIMPs from the EDELWEISS-III dark matter search, 2016, Journal of Cosmology and Astroparticle Physics 2016 (05), 019
- AV Rakhimov, et al, Neutron activation analysis of polyethylene from neutron shield of EDELWEISS experiment, Radiochimica Acta 103 (9), 673-678, 2015

During participation of JINR in the EDELWEISS program the most cited (more than 300 times) article is: E Armengaud et al. “Final results of the EDELWEISS-II WIMP search using a 4-kg array of cryogenic germanium detectors with interleaved electrodes”. Phys.Lett. B702 (2011), pp. 329–335. arXiv: 1103.4070 [astro-ph.CO]

6) **BAIKAL-GVD (Deep underwater muon and neutrino detector on Lake Baikal)**

Project leader: I. Belolaptikov (igor.belolaptikov@jinr.ru)

The construction of the Baikal-GVD neutrino telescope [1] is motivated by its discovery potential in astrophysics, cosmology and particle physics. Its primary goal is the detailed study the diffuse flux of high-energy cosmic neutrinos and the search for their sources. It will also search for dark matter candidates (WIMPs), for neutrinos from the decay of super heavy particles, for magnetic monopoles and other exotic particles. The high angular resolution of GVD for track-like or cascade-like events (~0.25-0.5° for muon tracks and ~2-3° for cascades, respectively) provides a high capability for identifying point-like cosmic-ray accelerators. It will also be a platform for environmental studies in Lake Baikal.

The concept of BAIKAL-GVD is based on a number of evident requirements to the design and architecture of the recording system of the array: the utmost use of the advantages of array deployment from the ice cover of Lake Baikal, the extendibility of the facility and provision of its effective operation even in the first stage of deployment, and the possibility of implementing different versions of arrangement and spatial distribution of light sensors within the same measuring system.

With all above requirements taken into account, the following conceptual design of BAIKAL-GVD has been developed. The Data Acquisition System of BAIKAL-GVD is formed from three basic building blocks: optical modules (OM), sections of OMs and clusters of strings. The OM consists of a photomultiplier tube with large hemispherical photocathode and attendant electronics, which are placed in pressure-resistant glass sphere.

The detector will utilize the deep water of Lake Baikal instrumented with OMs, which record the Cherenkov radiation from secondary particles produced in interactions of high-energy neutrinos inside or near the instrumented volume. The Infrastructure will consist of a network of autonomous subdetectors - so-called clusters – each of them with 288 OMs arranged at eight vertical strings attached to the lake floor. The coordinates of the optical modules are determined using an acoustic positioning system. Acoustic positioning system of the cluster comprises 32 acoustic modems (AM). The clusters are connected to shore via a network of cables for electrical power and high-bandwidth data communication. The large cubic-kilometer scale detection volume, combined with high angular and energy resolutions and moderate background conditions in fresh lake water allows for efficient study of cosmic neutrinos, muons from charged cosmic rays and exotic particles. It is also an attractive platform for environmental studies.

During the Design Study (2008–2010) and the Preparatory Phase (2011–2015), design, production and comprehensive in-situ tests of all elements and systems of the future detector have been performed. The Preparatory phase was concluded in 2015 with the deployment of a demonstration cluster "Dubna" comprising 192 OMs. The construction of the first phase of Baikal GVD (GVD-I) was started in 2016 by deployment of the first cluster in its baseline configuration (see fig.6.1).

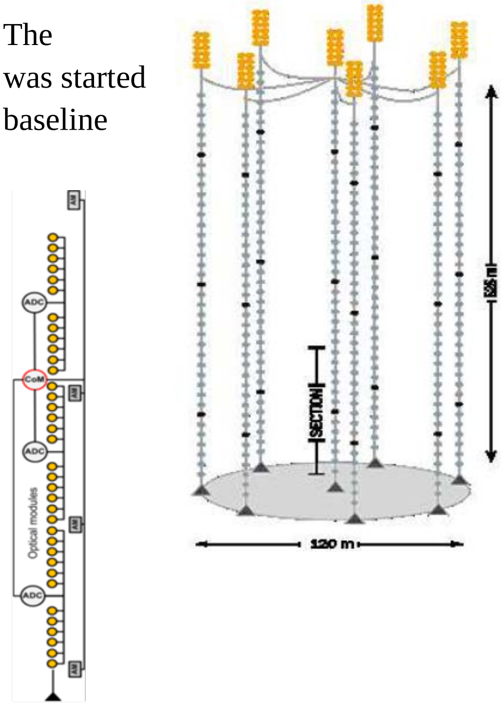


Fig. 6.1: Block diagram of the string and view of a cluster of Baikal-GVD.

An analysis of the data recorded by the “Dubna” cluster allowed collect first neutrino events, reconstruct the angular distribution of atmospheric muons and select very high-energy shower events that are candidates for extraterrestrial neutrino.

In next years 2017-2020 the telescope has been extended (see Table 1). The detector contains 5 laser calibration light sources allow control time synchronization both for each cluster and between clusters. Now, the array is developed up to 7 clusters positioned in 300 m to each other’s and has effective volume for high energy cascade events about 0.35 км^3. Fig. 6.2 (left) shows the present layout of the array. The figure (right) presents results of hydroacoustic scan of the detector site.

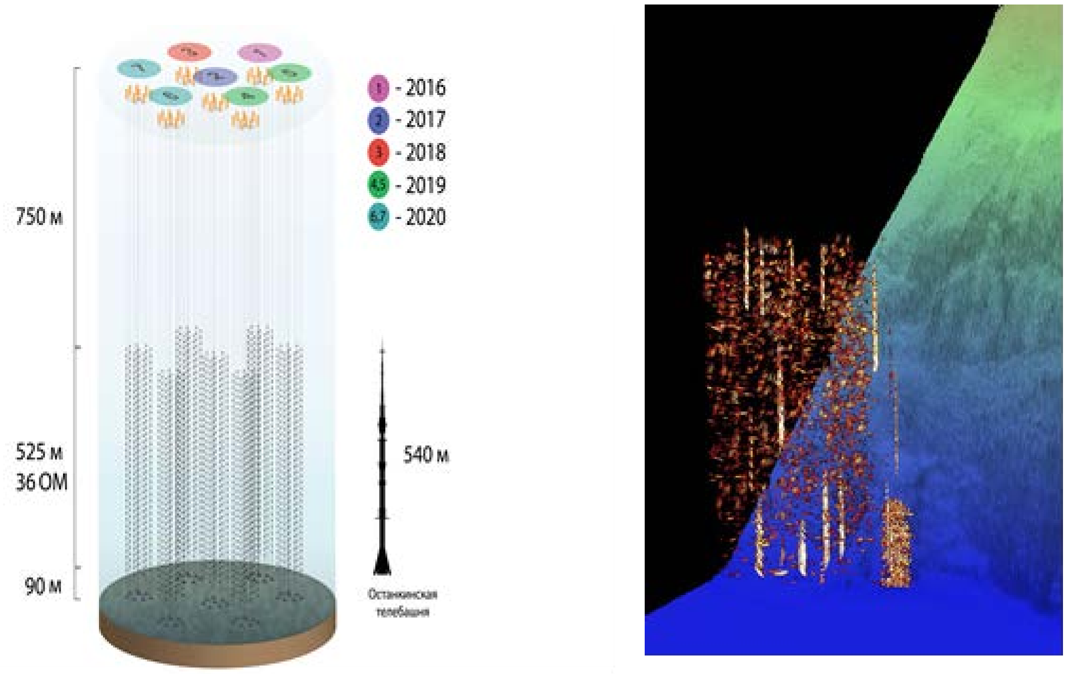


Fig. 6.2. Layout of the array Baikal-GVD 2020 (left). Right: results of hydroacoustic scan of the detector site. The GVD and NT-200 array can be seen.

Timeline for GVD Stage-1

2016	**2017**	**2018**	**2019**	**2020**
1 cluster	**2 clusters**	**3 clusters**	**5 clusters**	**7 clusters**

2021	2022	2023
8-9 clusters	10 clusters	12 clusters

A further extension of GVD Stage 2 to more 12 clusters will depend on the worldwide physics situation in the 2020s, on additional funding from new partners, and last but not least on the performance and physics output of the BAIKAL-GVD detector.

Contribution of JINR Members

JINR Members are playing significant roles in all key parts of the BAIKAL experiment:

- Assembly and test of OMs and strings
- Participation in winter deployment campaigns
- Access and security service.
- Data archive processing and analysis.
- Detector calibration and mass processing of data.
- Remote control and monitoring systems of detector
- Simulation software and MK production.

- On-line software
- Development of new methods of event selection and reconstruction.
- Data analysis with respect to high-energy neutrinos and neutrinos from dark matter annihilation.

References

[1] BAIKAL Collaboration. *BAIKAL - GVD*. Tech. rep. Gigaton Volume Detector in Lake Baikal(Scientific-Technical Report). 2011. URL:http://baikal.jinr.ru/~belolap/GVD/BAIKAL-GVD_En.pdf.

Baikal-GVD invited talks:

1. И. А. Белолаптиков, “Status of GVD”, MANTS meeting (ANTARES, Baikal, KM3NeT, IceCube), Amsterdam, Netherlands, 17 – 19 октября 2015, MANTS-2015: https://indico.cern.ch/event/395631/timetable/#20151017;
2. Ж.-А. М. Джилкибаев, “Baikal-GVD: results, status and plans”, VLVnT , Very Large Volume Neutrino Telescope, Rome, Italy, 14 – 16 сентября 2015. https://indico.cern.ch/event/378423/
3. О. В. Суворова, “Status of the Baikal-GVD project: firt cluster Dubna”, XVII Международная Ломоносовская конференция по физике элементарных частиц, Москва, Россия, 20 – 26 августа 2015. http://www.icas.ru/english/LomCon/17lomcon/17lomcon_programme.htm
4. Ж.-А. М. Джилкибаев, Б. А. Шойбонов, “The first construction phase of the Baikal-GVD neutrino telescope”, ICRC-2015 , The 34th International Cosmic Ray Conference, Hague, Netherlands, 30 июля – 6 августа 2015. http://icrc2015.nl/
5. В. М. Айнутдинов, “Байкальский нейтринный эксперимент”, Восьмые Черенковские чтения, Новые методы в экспериментальной ядерной физике и физике цастиц, Москва, Россия, 14 апреля 2015. http://x4u.lebedev.ru/che2015/program_ru-RU.html
6. А.И. Панфилов, “Многопараметрический мониторинг гидрофизических процессов в рамках Байкальского нейтринного проекта ”, XIV Международная научно-техническая конференция «СОВРЕМЕННЫЕ МЕТОДЫ И СРЕДСТВА ОКЕАНОЛОГИЧЕСКИХ ИССЛЕДОВАНИЙ», (МСОИ-2015) г. Москва, 19-21 мая 2015 г. , http://www.msoi.ocean.ru/sbornik-dokladov.html
7. О. В. Суворова, “Status of indirect Dark Matter search with neutrino telescopes”, The International Workshop on Prospects of Particle Physics: "Neutrino Physics and Astrophysics", Валдай, Россия, 21 – 29 февраля 2015. http://www.inr.ac.ru/~school/program.php
8. В. М. Айнутдинов, “Status/schedule GVD construction, results from 2015/16 cluster”, MANTS meeting (ANTARES, Baikal, KM3NeT, IceCube), Manz, Germany, 1 – 2 октября 2016, MANTS-2016: https://events.icecube.wisc.edu/sessionDisplay.pysessionId=1&confId=80#20161001
9. Ж.-А. М. Джилкибаев, “Current status of the Baikal-GVD”, APPEC (Astroparticle Physics European Consortium), The Three Messenger Conference, Listvyanka at Lake Baikal, Листвянка, Россия, 29 августа – 3 сентября 2016,

https://indico.desy.de/conferenceDisplay.py?confId=14253

10. О. В. Суворова, “Baikal-GVD and it's extension ”, 1st Neutrino Oscillation Tomography Workshop, 7-8 January 2016, Tokyo, Japan, https://indico.cern.ch/event/442108/

11. Б. А. Шойбонов, “The status of the Baikal neutrino experiment”, Международная сессия-конференция Секции ЯФ ОФН РАН «Физика фундаментальных взаимодействий», 12 – 15 апреля 2016, Дубна, Россия, http://icssnp.jinr.ru/

12. О. В. Суворова, “Baikal-GVD”, RICAP-2016 - 6th Roma International Conference on Astroparticle Physics, 21-24 June 2016, Villa Tuscolana, Italy, https://agenda.infn.it/conferenceDisplay.py?confId=10450

13. Г.В. Домогацкий, “Gigaton Volume Detector (GVD) in Lake Baikal: status of the project”, XVII International Workshop on Neutrino Telescope, 13-17 March 2017, Venezia, Palazzo Franchetti - Istituto Veneto di Scienze, Lettere ed Arti, https://pos.sissa.it/307/063/

14. В. М. Айнутдинов, “Baikal/GVD Status Report”, MANTS meeting (ANTARES, Baikal, KM3NeT, IceCube), Marseille, France, 1 – 2 октября 2017, MANTS-2017: https://events.icecube.wisc.edu/

15. В. М. Айнутдинов, “Status of the Baikal-GVD experiment - 2017”, 35th ICRC-2017, 12-20 июля 2017, Bexco, Busan, S.Korea, https://pos.sissa.it/301/1034/pdf.

16. Ж.-А. М. Джилкибаев, “Project Baikal-GVD, 8th International Workshop on Air Shower Detection at High Altitudes, Shanghai Astronomical Observatory (SHAO), Chinese Academy of Sciences, 10-13 December 2017, Shanghai, China.

17. Ж.-А. М. Джилкибаев, “Baikal-GVD: first results”, The 3rd workshop of Searching for the sources of Galactic cosmic rays, December 11-14, 2018, APC, Paris, France, http://www.apc.univaris7.fr/~semikoz/CosmicRays2018/conference.html

18. В. М. Айнутдинов, “Status GVD”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia, https://indico.jinr.ru/contributionDisplay.py?sessionId=20&contribId=65&confId=633

19. Ж.-А. М. Джилкибаев, “Baikal-GVD neutrino project”, The 5th SOUTH AFRICA - JINR SYMPOSIUM Advances and Challenges in Physics within JINR and South Africa, November 4 - 9, 2018, Somerset West, South Africa, http://www.jinr.ru/posts/5th-symposium-advances-and-challenges-in-physics-by-jinr-and-south-africa/

20. О. В. Суворова, “ Dark Matter: results of the Baikal neutrino experiment”, 2nd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes: Dark Ghosts, 13-14 November 2018, Brussels, Belgium, https://indico.iihe.ac.be/event/1199/

21. О. В. Суворова, “Baikal-GVD neutrino experiment”, The 9th international Workshop on Air Shower Detection at High Altitudes, WHASD2018, 17-18 September 2018, INR RAS, Moscow, Russia, http://wasdha2018.inr.ac.ru/

22. О. В. Суворова, “Baikal-GVD: first results and prospects”, The 7th Roma International Conference on AstroParticles Physics, RICAP2018, 4-8 August, 2018 Rome, Italy, https://agenda.infn.it/event/15062/timetable/?view=standard

23. В. М. Айнутдинов, “Baikal-GVD Status Report”, Расширенный Европейский симпозиум по космическим лучам и 35-я Всероссийская конференция по космическим лучам, 6-10 июля 2018, Барнаул, Россия,

https://ecrs18.asu.ru/event/1/contributions/

24. Ж.-А. М. Джилкибаев, “Baikal-GVD: status and prospects ”,The XXth International Seminar on High Energy Physics QUARKS-2018", QUARKS2018, 27 May - 2 June 2018, Valday, Russia; https://q2018.inr.ac.ru/event/1/timetable/#20180527.detailed

25. О.В.Суворова, “Baikal and GVD”, XVIII International Workshop on Neutrino Telescopes, NEUTEL2019, 18-22 March 2019, Venice, Italy, https://indico.cern.ch/event/768000/timetable/#20190318

26. F.Simkovic, “Neutrino Telescope in Lake Baikal: Present and Future”, 36th ICRC 2019, July 24 - August 1st, Madison, WI, USA.

27. О.В.Суворова, “BSM searches with Baikal”, 4th Uppsala workshop on Particle Physics with Neutrino Telescopes (PPNT2019), 7-9 October 2019, Uppsala, Sweeden, https://indico.uu.se/event/600/timetable/#20191007.detailed.

28. О.В.Суворова, “Status of Baikal-GVD and its multi-messenger program”, Cosmic Neutrinos and Multi-messenger Workshop “CosNuMM2019”, 27-30 November 2019, Shanghai, China, https://indico-tdli.sjtu.edu.cn/event/43/timetable/#20191130.

29. О.В.Суворова, “Baikal-GVD multi-messenger program”, Town Hall KM3Net meeting,17-19 December 2019, Marseille, France, https://indico.cern.ch/event/848390/timetable/#all.detailed.

30 Г.В. Домогацкий, “Глубоководный нейтринный телескоп – Baikal-GVD”, 36 Всероссийская конференция по космическим лучам, 28 сентября -2 октября 2020, НИИЯФ МГУ, online,
https://events.sinp.msu.ru/event/3/sessions/22/#20200930

Other talks 2015-2020:

1. А. Д. Аврорин, “Baikal-GVD: status and plan”, SAO-BNO, The International Workshop on Quark Phase Transition in Compact Objects and Multimessenger Astronomy: Neutrino Signals, Supernovae and Gamma-Ray Bursts, Нижний Архыз-Терскол, Россия, 7 – 14 октября 2015. http://www.sao.ru/hq/grb/conf_2015/index.html

2. В. М. Айнутдинов, “LED based calibration systems of the Baikal-GVD neutrino telescope”, VLVnT , Very Large Volume Neutrino Telescope, Rome, Italy, 14 – 16 сентября 2015. https://indico.cern.ch/event/378423/

3. О. В. Суворова, “Baikal-GVD: firt cluster Dubna”, European Physical Society, High Energy and Particle Physics conference, Vienna, Austria, 22 – 29 июля 2015. https://indico.cern.ch/event/356420/search

4. А. А. Кулешов, “Data acquisition system for the Baikal-GVD neutrino telescope”, The International Workshop on Prospects of Particle Physics: "Neutrino Physics and Astrophysics", Валдай, Россия, 14 – 16 февраля 2015. http://www.inr.ac.ru/~school/program.php

5. Ж.-А. М. Джилкибаев, “Cascades in GVD”, MANTS meeting (ANTARES, Baikal, KM3NeT, IceCube), Manz, Germany, 1 – 2 октября 2016, MANTS-2016:
https://events.icecube.wisc.edu/contributionDisplay.pysessionId=10&contribId=23&confId=80

6. Ж.-А. М. Джилкибаев, “Cascades in GVD”, MANTS meeting (ANTARES, Baikal, KM3NeT, IceCube), Marseille, France, 1 – 2 октября 2017, MANTS-2017:
https://events.icecube.wisc.edu/

7. Б.А. Шайбонов, “Calibration in Baikal-GVD”, MANTS meeting (ANTARES, Baikal, KM3NeT, IceCube), Marseille, France, 1 – 2 октября 2017, MANTS-2017: https://events.icecube.wisc.edu/

8. Г.Б. Сафронов, “Muon reconstruction in Baikal-GVD”, MANTS meeting (ANTARES, Baikal, KM3NeT, IceCube), Marseille, France, 1 – 2 октября 2017, MANTS-2017: https://events.icecube.wisc.edu/

9. Б. А. Шайбонов, “Data management and processing system for the Baikal-GVD telescope”, 35th ICRC-2017, 12-20 июля 2017, Bexco, Busan, S.Korea, https://pos.sissa.it/301/1046/pdf.

10. А. Д. Аврорин, “Data management and processing system for the Baikal-GVD telescope”, the regular JINR 26th Symposium on Nuclear Electronics and Computing - NEC'2017, 25 – 29 September, 2017, Montenegro (Budva), https://indico.jinr.ru/conferenceTimeTable.py?confId=151#20170926

11. Ж.-А. М. Джилкибаев, “GVD: results of cascade reconstruction”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=21&contribId=83&confId=633

12. Ж.-А. М. Джилкибаев, “GVD results and plans MM”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=25&contribId=104&confId=633

13. Г.Б. Сафронов, “GVD: results of track reconstruction”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=15&contribId=44&confId=633

14. А. Д. Аврорин, “Hydroacoustic Positioning System for the Baikal-GVD”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=15&contribId=44&confId=633

15. М. Д. Шелепов, “Time calibration in GVD”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=22&contribId=90&confId=633

16. М. Д. Шелепов, ““Исследование временных задержек измерительных каналов нейтринного телескопа Baikal-GVD”, VII Международная молодежная научная школа конференция «Современные проблемы физики и технологий», 16-21 апреля 2018, Национальный исследовательский ядерный университете, МИФИ, г. Москва, http://magistr.mephi.ru/school/

17. А. А. Дорошенко, “GVD optical module and other mechanics: experience and progress ”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=11&contribId=28&confId=633

18. Е.А. Храмов, “Data processing and quality monitoring of Baikal-GVD”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=26&contribId=107&confId=633

19. R.Dvornicky, “Optical activity in lake Baikal: GVD results”, Very Large Volume Neutrino Telescopes, VLVnT2018, 2 - 4 October 2018 Dubna, Russia; https://indico.jinr.ru/contributionDisplay.py?sessionId=23&contribId=96&confId=633

20. L.Fajt, “Neutrino Telescope Baikal-GVD ”, 2nd Workshop on TeV Particle Astrophysics, TeVPA 2018, 27-31 August 2018,Berlin, Germany; https://indico.desy.de/indico/event/18204/timetable/#20180827

21. О.В.Суворова, “Recent progress of the Baikal-GVD project”, (section), The European Physical Society Conference on High Energy Physics (EPS-HEP2019), 10-17 July 2019, Ghent, Belgium, https://indico.cern.ch/event/577856/timetable/#20190710.
22. R.Dvornicky, “The Baikal-GVD neutrino telescope: cascade events results”, 36th ICRC 2019, July 24 - August 1st, Madison, WI, USA.
23. L.Fajt, “The Baikal-GVD neutrino telescope: muon track events reconstruction”, 36th ICRC 2019, July 24 - August 1st, Madison, WI, USA.
24. Б.А.Шайбонов, “Status of Baikal-GVD”, "PAHEN 2019", September 25-27, Berlin, Germany.
https://www-zeuthen.desy.de/exps/2019_PAHEN/PAHEN_Timetable.pdf
25. Г.Б. Сафронов, “’Эксперимент Baikal-GVD”, 10-12 – March 2020, Международная сессия-конференция Секции ЯФ ОФН РАН «Физика фундаментальных взаимодействий», Novosibirsk, Russia; https://indico.inp.nsk.su/event/26/timetable/#all.detailed
26. Г.Б. Сафронов, “Status of Baikal-GVD: results of track reconstruction”, 40th International Conference on High Energy Physics, ICHEP2020, 28 July- 6 Aug 2020, online; https://indico.cern.ch/event/868940/contributions/3813595/
27. Д.Н. Заборов, “High-energy neutrino astronomy and the Baikal-GVD neutrino telescope”, The 5th International conference on particle physics and astrophysicsб ICPPA-2020, 5 - 9 October 2020 MEPHI, Russia, online; https://indico.particle.mephi.ru/event/35/

7) **MONUMENT (Muon Ordinary capture for the Nuclear Matrix elemENTs in ββ decays)**

Project leader: D. Zinatulina (zinatulina@jinr.ru)

The purpose of this project is carrying out experimental measurements of muon capture at several daughter candidates for 0νββ decay nuclei. Obtained results would be drastically important for checking the accuracy of theoretical calculations of nuclear matrix element (NME). Our group, together with colleagues, already applied for the beam time for measurements of ordinary muon capture (OMC) on several isotopes on a meson-factory of the Paul Scherrer Institute (PSI) in Switzerland. This application was reviewed and approved by the PSI User committee in January 2020. The beam time is officially granted in 2020 for a preliminary study of ^{136}Ba (daughter nucleus for ^{136}Xe) with a further measurement program for at least three years. This project continues and extends the previous OMC measurement program proposed and implemented under the guidance of JINR employees from 1998 to 2006. Our group has rich experience in the field of high-precision nuclear spectroscopy and its implementation for the study not only rare processes, but also muon capture.

Throughout the period from 2021 to 2023, it is planned to perform OMC measurements for ^{136}Ba isotopes, ^{76}Se and ^{96}Mo. The OMC on ^{136}Ba and ^{76}Se is of particular importance for the planned leading experimental searches for the 0νββ decay of ^{136}Xe – nEXO, KamLAND2-Zen, NEXT, DARWIN, and PandaX-III – and of ^{76}Ge – LEGEND. In addition, we are going to measure and obtain results for OMC in ^{32}S, ^{40}Ca, ^{56}Fe and ^{100}Mo isotopes. These results are important for the experimental verification of theoretical calculations and may also be useful for astrophysics. JINR will play a leading role in the experiment. With the exception of the experimental infrastructure at the accelerator complex, which will be provided by our collaborators, the rest of the project will be led by us. We plan to purchase isotopes for the enriched targets, buy several germanium detectors and the necessary electronic equipment. We also going to produce the targets and to construct an active muon filtration system for the experimental data.

Description of the measurements

Measurement principle

The idea of μ-capture experiments is based on a precise measurement of time and energy distributions of γ-rays following the ordinary muon capture (**OMC**). These distributions provide rich experimental information, which serves as a useful input to the calculations of nuclear matrix elements (**NME**) of double beta (**ββ**) decay. The total OMC rates of specific isotopes are extracted by analyzing the time distribution of delayed γ-rays. The measured intensities of the delayed γ-rays give partial OMC rates to the bound states. The yields of the short-lived isotopes are obtained using the beam-off and off-line measurements. The μX-rays data is an important by-product of the measurements. It helps to identify the type of atoms captured the muons and serves as a normalization for the total number of stopped muons.

Experimental method

The target arrangement sketched in Fig. 7.1 consists of an active muon veto-counter system: the C0 counter at the entrance of the target, two thin (0.5 mm) pass-through counters C1 and C2, and the actual target area, surrounded by the cup-like counter C3. The target is able to accommodate both solid and gaseous materials. The C3 counter together with the pass-through counters is used to define a mu-stop trigger as:

$$\mu_{stop} = \overline{C0} \wedge C1 \wedge C2 \wedge \overline{C3},$$

as well as to discriminate against high-energy electrons from muon decay. As it is made of low-Z material, the C3 counter does not affect heavily on the measurement of low energy (20 - 100 keV) gamma rays by the external germanium detectors.

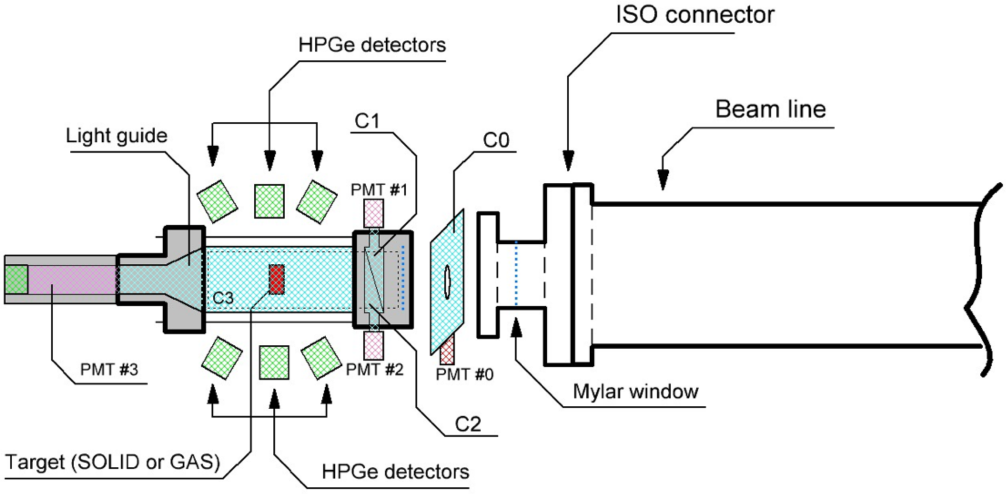


Fig. 7.1: Schematic layout of the μ-beam line and the target arrangement: the aperture defining veto-counter C0, the passing trigger counters C1 and C2, the target area, the veto counter C3 and the HPGe γ-detectors surrounding target.

The beam momentum and position is tuned to maximize the intensity of μX-rays from the target nucleus, while minimizing the background from the surrounding materials. Under optimal conditions, fraction of muons stopping at target nuclei is usually more than 95%. Typical μ-stop rates during the experiment are between 10^4 s^{-1} and 4×10^4 s^{-1}.

Detection system

The μX- and γ-rays following OMC will be detected with a set of HPGe detectors placed around the target at a distance of about 10 - 15 cm and integrated into the frame used in previous muX experiments. This already existing frame is supposed to be used in first phase of the project. For further measurements it is planned to create a new holder system, which will be designed by the JINR group.

Preliminary/proposed measurements

During the two weeks period in October 2019 we carried out, in collaboration with the muX experiment group, a test measurement that served several purposes. Firstly, it allowed us to check how well one can detect and identify the bound states produced by OMC using the existing setup and DAQ. Secondly, it gave us a chance to assess the steps needed to operate the HPGe detectors optimally. Finally, we made sure that the existing experimental configuration satisfies our requirements to collect enough statistics of good quality for all the relevant types of accumulated data: muonic X-rays, γ-rays following OMC, and γ-rays associated with the decay of short-lived isotopes. Detailed analysis of the collected data is ongoing, but it is already clear that the test was successful. The experimental setup is presented in Fig. 7.2.

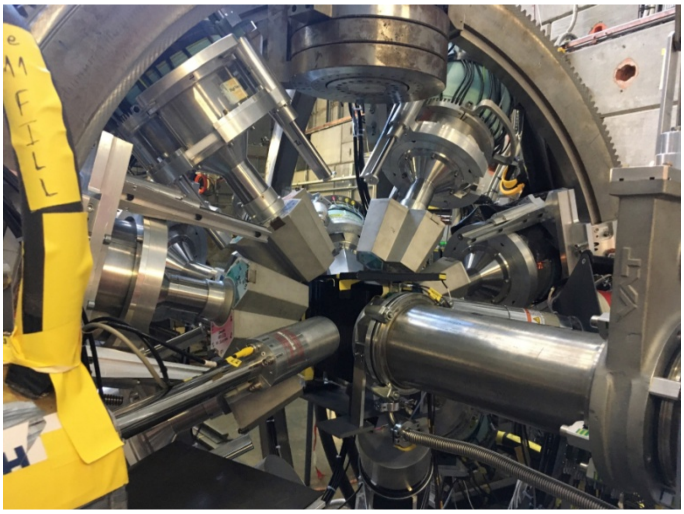


Figure 7.2: Experimental setup in 2019 measurements.

All data from the γ-detectors (on-line measurements) can be divided into two types: events correlated and uncorrelated in time with the incoming muons. If a signal from the γ-detector was not preceded by a stop of the muon in the target within the time window *W*, then the event is considered as Uncorrelated and is written to **U-spectrum**. Otherwise, the event goes to **C-spectrum**. A typical U-spectrum includes γ-lines of natural and technogenic radioactive isotopes (^{40}K, ^{60}Co,^{137}Cs, U- and Th-chain, etc). These lines are used to calibrate the detectors. The OMC products decay rapidly with the emission of γ-rays. The yields of the individual isotopes and isomers produced in OMC are extracted using their γ-rays intensities calculated from U-spectra. C-spectra of ^{24}Mg, ^{82}Kr, and ^{130}Xe were measured in the 2019 campaign at the πE1 beamline of PSI.

We obtain 3D (E,t)-spectra (see Fig.7.3) that allow us to extract maximum information about the OMC. The determination of relative intensities of the delayed lines with respect to the μX-rays allows the extraction of partial capture rates to the individual excited states of the daughter nucleus.

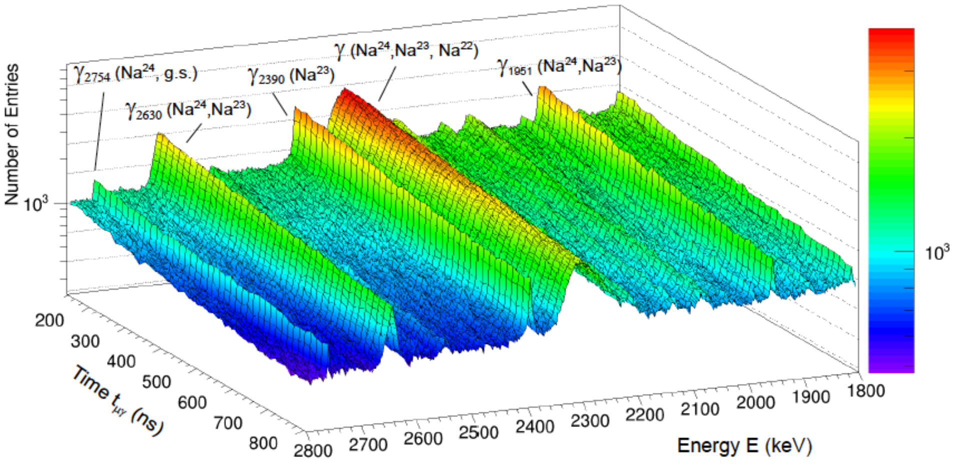


Fig. 7.3. Part of the (E,t) distribution events measured with the ^{24}Mg target.

Further investigations:

We propose to carry out a comprehensive three-year research program, which pursues the following scientific objectives:

1. The OMC measurements on ^{136}Ba, ^{76}Se, and ^{96}Mo. Results of these measurements will provide significant new input into theoretical models of calculations of nuclear matrix elements (NME) for double beta decay (DBD) of ^{136}Xe, ^{76}Ge, and ^{96}Zr, which are the sources nuclei (primarily ^{136}Xe and ^{76}Ge) in leading DBD-projects. This will improve the accuracy of NME-calculations, which is a fundamental task for this direction of research. Other important goal is solution of g_A-quenching puzzle, and the OMC data will be also helpful here. Partial OMC rates will be obtained in the first phase of the project. And the total OMC rates will be determined in the next phase.
2. The measurement of the OMC on ^{100}Mo is valuable for studies of properties of astrophysical neutrinos. This isotope is a one of the best candidates for measuring Supernova (**SN**) explosions (the MOON project), and the results of OMC measurements on ^{100}Mo will provide vital information for theoretical model calculations of SN-neutrino interaction on ^{100}Mo.
3. Measurement of the total and partial OMC rates on ^{40}Ca, ^{56}Fe and ^{32}S will provide essential experimental input in order to test nuclear shell model (SM) calculations. The NME of these relatively light nuclei are well calculated in theoretical models, so a comparison of experimental and theoretical data will help to improve and tune the theoretical models. The results of these studies will also be used in future to improve the NME-calculations of DBD.
4. The experimentally determined production rates of isotopes in the OMC will be compared with the theoretical assumption - proton and neutron emission model, which derives the OMC strength function and the associated giant resonance (GR) peaks.
5. The muonic X-rays spectra measured in OMC will continue to fill and update already existing Mesoroentgen electronic catalogue (muxrays.jinr.ru), which is the international database provided unique information for all projects (both fundamental and applied) used the OMC.
6. All results will be published in peer reviewed Russian and international journals, as well as be presented on the Russian and international conferences.