Annex 3.

Form of opening (renewal) for Project /
Sub-project of LRIP

APPROVED

JINR DIRECTOR

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PROJECT PROPOSAL FORM

Opening/renewal of a research project/subproject of the large research infrastructure project within the Topical plan of JINR

1. General information on the research project of the theme/subproject of the large research infrastructure project (hereinafter LRIP subproject)

1.1 Theme code / LRIP (for extended projects) - *the theme code includes the opening date, the closing date is not given, as it is determined by the completion dates of the projects in the topic.*

03-2-1100-2010/2024

1.2 Project/LRIP subproject code (for extended projects)

1.3 Laboratory

Dzhelepov Laboratory of Nuclear Problems

1.4 Scientific field

Nuclear Physics

1.5 Title of the project/LRIP subproject

Investigations of reactor neutrinos on a short baseline

1.6 Project/LRIP subproject leader(s)

Igor Zhitnikov

1.7 Project/LRIP subproject deputy leader(s) (scientific supervisor(s))

Mark Shirchenko, Alexey Lubashevskiy, Sergei Rozov

2 Scientific case and project organization

2.1 Annotation

The project presented here combines 3 experiments: DANSS, RICOCHET and νGeN. All experiments are devoted to the study of antineutrino fluxes from nuclear reactors at distances of less than 20 meters. Even though each of the experiments was developed for different goals, all works are united by a common area of research (reactor antineutrinos), in many respects overlapping and coinciding scientific problems, and ways to solve them. In addition, these studies are united by the general scientific staff, JINR infrastructure resources, or due to the specifics of the location (limited number of JINR personnel with access to DANSS and νGeN facilities at the Kalinin NPP), or due to some similarity in approaches (RICOCHET and νGeN - the use of semiconductor germanium detectors to search for coherent scattering of reactor antineutrinos on nuclei). The decision to combine these experiments into one project for more efficient coordination of resources is the next step in the development and organization of neutrino research within the theme "Non-accelerator neutrino physics and astrophysics". Below there are brief annotations for each of the experiments.

2.1.1. DANSS

DANSS is an antineutrino spectrometer based on plastic scintillators with a sensitive volume of 1 m^3, located at the fourth power unit of the Kalinin NPP. The lifting mechanism makes it possible to move the spectrometer 2 meters vertically in on-line mode, providing a measurement range of 11–13 m from the reactor. The high degree of detector segmentation and the use of combined active and passive shielding ensure background suppression up to several percent relative to ~5000 IBD events recorded per day (in the closest to the reactor position). The main objectives of the experiment are search for reactor antineutrino oscillations to a sterile state and long-term precision monitoring of the operation of a nuclear reactor by measuring the antineutrino flux. During 2023–24 it is planned to upgrade the experiment - DANSS-2. DANSS-2 will have improved energy resolution and increased volume, which will increase the sensitivity of the experiment to for oscillations into the sterile state.

2.1.2. νGeN

The νGeN experiment is aimed at studying the fundamental properties of neutrinos, in particular the search for neutrino magnetic moment (NMM), coherent elastic neutrino scattering (CEνNS), and other rare processes. The νGeN spectrometer was installed under the Kalinin nuclear power plant reactor core, allowing to operate a giant antineutrino flux of (3.6-4.4) × 10^{13} $\tilde{\nu}_e/\mathrm{cm}^2/\mathrm{s}$ with a good shielding against cosmic rays. Neutrino scatterings are detected with a special low-threshold, low-background germanium detector. With systems of active and passive shielding from background radiation a low level of background in the region of searching for rare events is achieved. Registration of the searched events allows the search for New Physics beyond the Standard Model, besides it can also have a practical usage, for example, in the development of new generation detectors for monitoring the operation of a nuclear reactor using the antineutrino flux.

2.1.3. RICOCHET

The RICOCHET is new generation of reactor neutrinos experiments. The RICOCHET detectors are designed to provide the first percentage precision Coherent Elastic Neutrino(ν)-Nucleus Scattering (CEνNS) measurement in the sub-100 eV energy region (i.e. under total coherency condition) to search for New physics in the electroweak sector. It is planned to be installed until the end of 2023 at Laue Langevin Institute (ILL) near the research nuclear reactor. The RICOCHET will host two cryogenic detector arrays: the CRYOCUBE (Ge target, based on EDELWEISS developed detector-bolometers) and the Q-ARRAY (Zn target). The CryoCube will be composed of 27 Ge crystals of 30 g each, instrumented with NTD-Ge thermal sensor as well as aluminum electrodes operated at 20 mK in order to measure both the ionization and the heat energies arising from a particle interaction. The main advantage of bolometers, compared to any other detection techniques, is that the deposited energy from a neutrino-nucleus interaction is left in the detector volume, therefore they act as true calorimeters with almost no quenching effects. In the present time this is the only way for measurement of CEνNS with 1% precision or better.

2.2 Scientific case (aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks)

The scientific cases for each of the experiments, united by a one main research project for investigations reactor (anti)neutrinos on a short baseline, are presented below.

2.2.1. The DANSS

Purpose, relevance, and scientific novelty

The search for oscillations into the light (Δm_{14}^2 ~ 0.1-10 eV) sterile neutrino is one of the current trends in fundamental neutrino physics. The existence of a sterile neutrino could explain several observed contradictory results, first of all, the reactor and gallium (anti)neutrino anomalies (RAA) and at the same time become a revolutionary discovery of New Physics. Reactor experiments on a short baseline (<30 m) have several competitive advantages in this area of research: a giant antineutrino flux from the most intense available artificial sources of (anti)neutrinos on Earth and a small distance from the radiation source where the oscillation pattern is not yet smeared. It should be noted that the DANSS spectrometer is one of the leading experiments of this type, making it possible to study the highest available antineutrino flux (∼ 5 × 1013 ν̃e/cm2/s) with one of the best signal-to-background ratio (S/B > 50).

Methods and approaches, methodologies

Antineutrinos are detected via the Inverse Beta Decay (IBD) reaction $(\bar{\nu}_e + p \rightarrow e^+ + n)$. The detector is made of a plastic scintillator coated with a thin Gd-containing layer for light reflection and neutron capture. Light is collected by three wavelength-shifting (WLS) fibers, one of which is connected to a Silicon PhotoMultiplier (SiPM, 2500 channels), and two are connected to a PhotoMulTiplier (50 channels). PMTs collect light from 100 elementary cells - strips (2x5x100 cm^3), combined into modules 20x20 cm^2 (Fig. 1, right). The strips are stacked in layers. Adjacent layers are located orthogonally to each other to fix the XY-coordinate of the particles that caused the operation of two adjacent layers. In such a mixed light collection system, signals from PMTs are used as a main trigger. SiPMs are used to determine the spatial patterns of events by single triggered strips. This scheme makes it possible to effectively suppress background events.

The spectrometer has a cubic form with a total volume of 1 m^3, surrounded by a combined passive protection (copper, lead, borated polyethylene) and active veto system for cosmic muons detection in the form of scintillation planes (Fig. 1, left). DANSS is located at 4th Kalinin NPP power unit. Dedicated lifting system is used to change the distance between the center of the detector and the reactor core from 10.9 to 12.9 m. It helps us to exclude the uncertainties in antineutrino flux thus providing model independent analysis of data**.**

At the moment, most of the leading experiments at this field do not observe a significant signal of neutrino oscillations (Figure 1, left). Cosmology and neutrino experiments on measuring q13 also have only limitations but due to the large baseline (L > 100 m) these reactor experiments are relevant in the region of ultra-low sterile neutrino masses [0.001-0.1] eV^2 and are not sensitive to the RAA region (Fig. 2, right).

In 2018, the first results of the NEUTRINO-4 experiment (PNPI, Gatchina) were published, confirming the existence of antineutrino oscillations to a sterile neutrino with parameters $\sin2(2\Theta_{14})$~0.2-0.3, Δm_{14}^2~6-7 eV^2 [arXiv:2005.05301]. Later the new results were also announced by BEST collaboration [arXiv:2109.11482]. The parameter space in this experiment is $\sin^2(2\theta_{14}) \approx 0.4$, $\Delta m_{14}^2 < 0.5\ \mathrm{eV}^2$. Since such results are of fundamental importance, their independent verification is a topical and important problem for neutrino physics at the present time.

Unfortunately, DANSS is not sensitive to the phase point of the claimed effect in NEUTRINO-4. To advance into the area of effect of NEUTRINO-4, an upgrade of the detector is required. The main goals of the modification are a significant increase in resolution to 12% @ MeV from the current 34% @ MeV and a 70% increase in the volume of the detector. For these purposes the next version of the spectrometer is being developed using new strips design (1440 pcs., 2 x 5 x 120 cm3, 8 fibers of 2 SiPM per fiber), plastic scintillator with improved optical properties and updated front-end electronics. 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. The upgrade is scheduled to be completed in 2 years.

DANSS-2 will have greater sensitivity to sterile oscillation search and will be able to reach the point of interest with few years of measurements. It will make a significant contribution to testing the hypothesis of the existence of a sterile neutrino in the region of phase space indicated by NEUTRINO-4 and BEST experiments.

JINR participation:

JINR plays a key role in the DANSS experiment:

- Production and testing of strips.
- Lifting mechanism creation and exploitation.
- Measurement methods development; DAQ development.
- Development and creation of a muon veto system.
- Detector assembly at the Kalinin Nuclear Power Plant.
- Provision of experimental data collection, permanent presence of personnel at KNPP.
- Study of background conditions and development of new methods for accounting and background suppression.
- Participation in data analysis.
- Publication of results.

Risks

Regarding the risks of this project, they include the fact that the experimental setup is located in the KNPP area and therefore potential difficulties due to the introduction of new rules and regulations at KNPP cannot be excluded. However, it is worth noting that over the years, the KNPP Directorate and staff have been very helpful and cooperative for our projects.

The main risks in the implementation of the upgrade to DANSS-2 related to the purchase of the necessary equipment (especially optical fibers and silicon photomultipliers), for which import-substituting analogues which are currently not found. The search and purchase of equipment and components for the next phase of the experiment continues.

2.2.2. The νGeN

The project νGeN is aimed to study the fundamental properties of neutrinos using reactor antineutrinos from the Kalinin Nuclear Power Plant (KNPP). The study of neutrino properties is an important task for particle physics, astrophysics, and cosmology. Despite the fact that the neutrino is one of the most abundant particles in the Universe, its detection is a difficult task due to the extremely weak interaction of this particle with matter. Therefore, to study its properties, a very strong neutrino source is needed, as well as special techniques to suppress background events. The νGeN experiment is aimed at searching for coherent neutrino scattering, neutrino magnetic moment, and other rare phenomena occurring in neutrino scattering. Coherent elastic neutrino-nucleus scattering (CEνNS) is a process predicted within the Standard Model. However, it has never yet been detected in the region of full coherence and for reactor antineutrinos. Detecting this process is an important test of the Standard Model. The current great interest to this process is also due to the fact that it can be used to search for non-standard neutrino interactions, sterile neutrinos, and other studies. However, due to the low cross-section and low energy release, the detection of this effect is a nontrivial task requiring the use of low-threshold detectors and various methods to suppress background events. The Neutrino Magnetic Moment (NMM) is a fundamental parameter, and its study can lead to physics beyond the Standard Model. The minimally extended Standard Model predicts a very small magnetic moment value for massive neutrinos ($\mu_\nu<10^{-19}\ \mu_B$), which cannot be measured in current experiments. However, a large number of extensions of the Standard Model predict that the value of the MMN can be at the level of $10^{-(10\div12)}\ \mu_B$ for Majorana neutrinos. The observation of a MMN value higher than $10^{-14}\ \mu_B$ would indicate the discovery of physics beyond the Standard Model and the Majorana nature of neutrinos. The GEMMA project has set the current best limit on the neutrino magnetic moment value at $< 2.9\cdot10^{-11}\ \mu_B$. The νGeN experiment plans to increase the sensitivity to the level of $(5\text{-}9)\cdot10^{-12}\ \mu_B$ after several years of measurements. The detection of reactor neutrino can also have possible applications, such as monitoring of reactor power and controlling nuclear weapons nonproliferation.

The νGeN experiment is located under KNPP No.3 Unit to study the above-mentioned processes. A distance from the center of the reactor core to the experimental setup is 11-12.2 m, allowing an enormous neutrino flux of $(3.6\text{-}4.4)\cdot 10^{13}$ neutrinos/($\text{cm}^2\cdot$sec). Moreover, the experimental area is located directly below the reactor, which gives good shielding from cosmic rays, at level of 50 m water equivalent. A scheme of the reactor is shown in Figure 3, left. In 2022 the installation of a special lifting mechanism was completed, allowing the entire experimental setup to move towards the reactor core (Figure 1, right). This allows to manually change the antineutrino flux and significantly reduces the systematic error associated with uncertainties in determining the background level. To reduce the number of background events in the region of interest, a special system of active and passive shielding from external radiation is used. The scheme of shielding is shown in Figure 4.

The inside part of the shielding is a special nylon made by a 3D printer, followed by a 10 cm layer of copper, 8 cm of borated polyethylene, 10 cm of lead, and 8 cm of borated polyethylene. On the outside is an active muon veto created of a 5 cm thick scintillator. To reduce microvibrations and noise events, the detector is mounted on a special anti-vibration platform. It allows to significantly improve the energy resolution of the detector and reduce the energy threshold. To ensure good resolution and to reduce background and noise events, a special data set system was created. The schematic diagram of the acquisition system together with a photo of the electronics is shown in Figure 5.

A specially designed low-threshold, low-background germanium detector is used to detect a signal from neutrinos. The detector is calibrated using a thorium source, cosmogenic peaks, and a pulse generator. The energy resolution under NPP conditions obtained with the pulse generator was 101.6(5) eV (FWHM). It has been demonstrated that the signal detection efficiency remains always above 80% for signals with energies greater than 250 eV. The effective threshold for event analysis is about 300 eV, which is a big improvement in comparison to the GEMMA experiment, where the effective threshold was 2.8 keV. Expanding the measurement region into the low energy range increases the sensitivity in the search for MMN, in addition it allows to search for coherent elastic neutrino scattering and other rare processes. A comparison of the experimental spectra obtained in GEMMA and νGeN experiments is shown at Figure 6.

As demonstrated in Figure 6, the resulting background level in the low-energy search region is much better than that obtained in the GEMMA experiment. Also, it was demonstrated that the total background level does not change in the different measurement modes when the reactor is on and when it is off, which indicates a good quality of performance of the experiment and stability of the data set.

The established νGeN facility has one of the world's best sensitivity to coherent scattering of reactor antineutrinos. A total data of 170 kg days with the reactor off and about 1000 kg day with the reactor running were collected through December 2022. The collected statistics are comparable to those of the GEMMA experiment (1133.4 kg days ON, 280.4 kg days OFF). Therefore, after careful analysis of the data, a significant improvement in neutrino magnetic-momentum sensitivity is expected, in comparison to the results obtained in the GEMMA experiment. Data acquisition is currently underway (from 2022 in the near-reactor position). A significant improvement in the sensitivity to the CEνNS detection is expected. Upgrades are also planned to further improve the sensitivity of the experimental setup. The upgrade plans include production of an internal active veto, to reduce the background level in the region of interest. Work is also planned to improve detector parameters and purchase a new detector with a lower measurement threshold.

As a result of the project, it is expected to detect for the first time the coherent antineutrino scattering from the reactor and to improve the sensitivity of the neutrino magnetic moment detection to $(5\text{-}9)\cdot 10^{-12}\ \mu_B$ after several years of measurements, which will greatly improve the current best limit.

JINR participation:

The νGeN experiment is performed mainly by JINR group. We have purchased the necessary equipment and made the experimental setup. We are carrying out measurements and analyzing of the data. Collaborators from other institutes assist in modeling and analysis of the experimental data.

Risks

Regarding the risks of this project, they include the fact that the experimental setup is located in the KNPP area and therefore potential difficulties due to the introduction of new rules and regulations at KNPP cannot be excluded. However, it is worth noting that over the years, the KNPP Directorate and staff have been very helpful and cooperative for this and other projects.

2.2.3. The RICOCHET

Purpose, relevance, and scientific novelty

The search for physics beyond the Standard Model with CEνNS requires to measure with the highest level of precision the lowest energy range of the induced nuclear recoils, as most new physics signatures induce energy spectral distortions in the sub-100 eV region. Another requirement is to perform the CEνNS measurements at the region of full coherency, i.e. below 10 MeV neutrino energy for Ge nuclear.

By providing the first percentage-level precision CEνNS measurement down to O(10) eV, thanks to next generation cryogenic bolometers with unprecedented low-energy threshold and background rejection capabilities, the RICOCHET collaboration proposes to go far beyond simply completing the Standard Model picture by testing various exotic physics scenarios. These include for instance the existence of sterile neutrinos and of new mediators, which could be related to the long-lasting Dark Matter (DM) problem, and the possibility of Non-Standard Interactions (NSI) that would dramatically affect our understanding of the electroweak sector.

Methods and approaches, methodologies

The RICOCHET is going to use cryogenic detectors jointly developed with another our project EDELWEISS near the ILL 58 MW nuclear research reactor. 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. The cryostat has been developed in cooperation between JINR, IP2I and produced by the CryoConcept company. The similar test cryostat has been already used for the R&D phase and demonstrated its applicability for planned research [Physical Review D 99 (8), 082003].

The cryogenic detectors

The Ricochet detectors are designed 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 reduction 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.

Accommodation of several monolithic target materials, as most new physics signatures, such as Non-Standard Interactions, depend on the target's nuclear properties

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 7 shows a simplified design of the Ricochet cryogenic detector assembly. 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 semiconductors

In semiconductor bolometers, the rejection between backgrounds and 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); CEνNS- or neutron-induced nuclear recoils (lattice interactions).

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 [JINST, 12, 08, P08010], 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.

RICOCHET team together with EDELWEISS groups have successfully demonstrated a 55 eV energy threshold on a 33-g Ge bolometer operated from a surface lab [Phys. Rev. D 99 (8), 082003] and with several detectors in underground laboratory [Phys. Rev. Lett. 125, 141301], suggesting that the very low-energy threshold of 50 eV is achieved. The detector implementation into the setup with commissioning phase at IP2I is ongoing.

Zinc Superconductors

The RICOCHET experiment will also use metallic superconductor (Zn) absorbers for its bolometric array. 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 CEνNS-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 [JHEP 1608, 057 (2016)]. 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. We will use transition edge sensors (TES) for the readout of the phonon and quasi-particle signals from these superconducting bolometers.

Thanks to the high CEνNS cross section, the 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 ~20 mK and its need to mitigate the environmental backgrounds, the experiment will need the operation of the dilution refrigerator surrounded by both lead and polyethylene shields. Figure 9 shows a drawing of the setup with the following specifications and infrastructure requirements:

- The cryostat: is composed of a dilution unit with several stages (50K, 4K, 1K, 100mK, and 10mK). 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. 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.
- 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 shields: the cryostat will be encapsulated by different layers of passive materials to reduce the environmental backgrounds.
- A small (few-meters squares) semi-clean space in a close proximity of the setup will be needed to store the detectors in a dust-free environment prior to their integration in the cryostat.

The RICOCHET experimental site

The experiment will be conducted at ILL (Grenoble, France) the H7 experimental site, where the STEREO neutrino experiment was previously operated. The H7 site starts at about 8 m from the ILL reactor core that provides a nominal nuclear power of ~57.8 MW, leading to a neutrino flux at the RICOCHET detectors of 1.4×10^{12} $cm^{-2}s^{-1}$. The reactor is operated in cycles of typically 50 days duration with reactor-off periods sufficiently long to measure reactor-independent backgrounds, such as internal radioactivity or cosmogenically induced backgrounds, with good statistics. The place is located below a water channel providing about 15 m water equivalent (m.w.e) against cosmic radiation. It is not fed by a neutron beam and is well-shielded against irradiation from the reactor and neighboring instruments. The site is well-characterized in terms of backgrounds, and the operation of the STEREO neutrino experiment has been successfully demonstrated [JINST 13, 07, P07009 (2018).].

Expected results

Figure 11 presents the expected signal and targeted background event rates as a function of the recoil (kinetic) energy expected for the experiment installed at 8 meters from the ILL reactor core. Considering developed and experimentally studied the experiment background model, compared against experimental data from an ensemble of detectors and sites, we found that the statistical significance of a CEνNS detection with RICOCHET, after only one reactor cycle, should be between 4.6 and 13.6 σ, depending on the effectiveness of the muon veto.

The following projected discovery reach and exclusion limits are computed using a profile likelihood analysis where we assumed 5% systematic uncertainties on all backgrounds, and a 70% detection efficiency mostly due to the deadtime loss from the muon-veto. After about 10 reactor cycles, i.e. 3 years onsite, we will reach the targeted ~1% precision measurement (not including signal systematics), that will lead to orders of magnitude improved sensitivities to various new physics scenarios compared to existing experiments.

JINR participation:

Dubna team participates and make commitments to the following parts of the RICOCHET project:

- New cryosystem for the Ricochet: development and running;
- Development of methods for low background measurements; New supplementary detectors.
- Muon veto systems: partly some plastic panels development and building;
- Data taking (this includes daily routine procedures, as well as regular and special calibration runs);
- Low background study and development of methods of neutron and radon detection;
- Selection and production of less radioactive materials;
- Detector simulations and data analysis; Publication of results.

Risks

The schedule of the project can be significantly affected due to factors connected to stability of running of all components of the experiment including cryosystem with dilution cryostat and its stability, electronics, acquisition system, subsystems. Though failure of different components of the setups is difficult to predict, the collaboration already accumulated more than 20 years of running of the cryogenic setups (EDELWEISS), with accumulated experience in fixing of arising problems including problems with the cryosystem in short time.

One of critical part of any low background experiment is avoiding of its contamination from outside. The trace activities on unacceptable level can be accumulated due to calibrations with not properly tested (on radioactive leak and integrity) radioactive sources, due to radon and other radioactive gases in atmosphere, due to dust and dirt. To avoid these problems a set of special procedures is in place during all stages of experiment starting from the detector production to calibration measurements.

Now, let us consider some of the scientific challenges: the main challenge for the Ricochet rare-event search experiments is to the CEvNS signals from recoils induced by natural radioactivity, cosmic rays and other sources. In other words, the most important problem is the background. Thus, the key to the success of the experiments is the possibility to identify with high efficiency the background events, which can mimic the signal. The RICOCHET experiment together with traditional methods of background reduction uses several special methods for discrimination of backgrounds (heat/ionization measurements, FID detectors for discrimination of surface events, PSD for reduction of the noise). For the RICOCHET experiment proper interpretation of results will be strongly depended on stability of the neutron background, especially for comparison of reactor ON/OFF runs. Analysis of the neutron background was addressed by the collaboration in [Eur. Phys. J. C (2023) 83:20].

As the RICOCHET experiment aim is 1% level precision measurements, the questions about possible systematic become extremely important.

2.3 Estimated completion date

2.3.3 DANSS

2023 year: methodological works and purchases for DANSS-2

2023-2024: The continuation data taking with DANSS, data analysis, preparation of publications

2023-2024: R&D and final construction of DANSS-2 at KNPP area. Start data taking.

Measurements are planned until 2028. The continuation of the experiment after 2028 will depend on the results obtained.

2.3.3 νGeN

2023-2024 measurements in the current configuration.

2024 plans to upgrade the setup, install a new internal veto, improve the lifting mechanism to work closer to the detector, and reconfigure the muon veto.

2024-2028 data set. The continuation of the experiment beyond 2028 will depend on the results.

2.3.3 RICOCHET

2024 year: commissioning of the setup at ILL site, start data taking with Ge bolometers, continue development of improved cryogenic detectors. Improved MC model based on real data.

The experiment needs minimum 10 reactor cycles to achieve the sensitivity level needed for 1% precision level. Thus, the measurements will be continued minimum 3 years (this depends on the ILL).

The developing Zn cryo array will be added to the setup at once ready (most probably not early than end of 2024).

During all time of the project we will continue to study the setup environmental background, perform intensive calibration program and R&D for further experiments.

All years: data analysis, preparation of publications.

2.4 Participating JINR laboratories

Dzhelepov Laboratory of Nuclear Problems

2.4.1 MICC resource requirements

Computing resources	**Distribution by year**				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB) - EOS - Tapes	400	550	700	850	1000
Tier 1 (CPU core hours)	300000	360000	420000	480000	540000
Tier 2 (CPU core hours)	30000	36000	42000	48000	54000
SC Govorun (CPU core hours) - CPU - GPU	-	-	-	-	-
Clouds (CPU cores)	-	-	-	-	-

2.5. Participating countries, scientific and educational organizations

2.5.1 DANSS

Organization	**Country**	**City**	**Participants**	**Type of agreement**
ITEP	Russian Federation	Москва	Alekseev I. Kobyakin A. Nesterov V. Perminov K. Rusinov V. Samigullin E. Svirida D. Skrobova N. Tarkovsky E.	Scientific collaboration agreement
LPI RAS	Russian Federation	Moscow	Danilov M. Konovalov A. Tulupov A.	Scientific collaboration agreement

2.5.2 νGeN

Organization	Country	City	Participants	Type of agreement
LPI RAS	Russian Federation	Moscow	Danilov M. Konovalov A.	Scientific collaboration agreement
IEAP	Czech Republic	Prague	K.Balej K.Smolek	Scientific collaboration agreement

2.5.3 RICOCHET

Organization	Country	City	Participants	Type of agreement
Univ Lyon, Universite Lyon 1, CNRS/IN2P3, IP2I-Lyon	France	Lyon (Villeurbanne)	Billard J. Juillard A. De Jesus M. Augier C. Gascon J. Cazes A. Sanglard V. Misiak D. Colas J. Filippini J.-B. Salagnac T. Martini N. Lattaud H. Guy E. Vagneron L. Guerin C. Ferriol S. Baulieu G. Chaize D. Ianigro J.-C. Mounier F.	Scientific collaboration agreement
Centre de Spectroscopie Nucleaire et de Spectroscopie de Masse, IN2P3-CNRS, Universite Paris XI	France	Orsay	Marnieros S. Giuliani A. Olivieri E. Oriol C. Poda D. Berge L. Broniatowski A. Dumoulin L. Chapellier M. de Marcillac P. Redon T.	Scientific collaboration agreement
Univ. Grenoble Alpes, CNRS	France	Grenoble	Monfardini A. Calvo M. Goupy J. Exshaw O.	Scientific collaboration agreement

			Minet J. Bres G. Bret J-.L. Mocellin J-.L. Chala M. Chemin G. Goy C. Heusch M. Real J.-S. Ricol J.-S. Lamblin J. Perbet E. Rarbi F. Scorza S. Stutz A. Vezzu F.	
Institut Laue-Langevin	France	Grenoble	Fuard S. Robert A. Soldner T.	Scientific collaboration agreement
Laboratory for Nuclear Science, Massachusetts Institute of Technology	USA	Cambridge	Formaggio J. A. Li M. Heine S.T. Mayer D.W. Harrington P. Stachurska J. Winslow L. Sibille V. Johnston J. P. Reyes F. C. Van De Pontseele W.	Scientific collaboration agreement
Department of Physics & Astronomy, Northwestern University	USA	Evanston	Figueroa-Feliciano E. Chen R. Schmidt B. Ovalle Mateo L. Novati V.	Scientific collaboration agreement
University of Massachusetts	USA	Amherst	Hertel S.A. Pinckney H.D. Patel P.K. Chaplinsky L.	Scientific collaboration agreement

2.6. Key partners *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

3. Manpower
3.1. Manpower needs in the first year of implementation

№№ n/a	Category of personnel	JINR staff, amount of FTE	JINR Associated Personnel, amount of FTE
1.	research scientists	11.45	-
2.	engineers	8.15	-
3.	specialists	0.4	-
4.	office workers	-	-
5.	Technicians	0.6	-
	Total:	**20.6**	**-**

3.2. Available manpower
3.2.1. JINR staff

№№ п/а	Category of employees	NAME	Division	Position	Amount of FTE
1.	research scientists	Belov V.	DLNP	Research scientist	0.5
		Bystryakov A.	DLNP	Junior scientist	1.0
		Vaganov Yu.	DLNP	Research scientist	0.1
		Vasilyev S.	DLNP	Senior scientist	0.5
		Vorobyeva M.	DLNP	Research scientist	0.1
		Gurov Yu.	DLNP	Head of the sector	0.1
		Gusev K.	DLNP	Senior scientist	0.2
		Zhitnikov I.	DLNP	Research scientist	0.8
		Inoyatov A.	DLNP	Head of the sector	0.4
		Kazartsev S.	DLNP	Junior scientist	0.5
		Karaivanov D.	DLNP	Senior scientist	0.2
		Lubashevskiy A.	DLNP	Head of the sector	0.9
		Medvedev D.	DLNP	Research scientist	1.0
		Mirzayev N.	DLNP	Junior scientist	0.1
		Morozov V.	DLNP	Chief scientist	0.2

		Ponomarev D.	DLNP	Junior scientist	0.5
		Rozov S.	DLNP	Deputy head of department	0.5
		Salamatin A.	DLNP	Senior scientist	0.3
		Salamatin D.	DLNP	Junior scientist	0.1
		Sandukovskiy V.	DLNP	Consultant at the directorate of the DLNP	0.25
		Suslov I.	DLNP	Junior scientist	0.5
		Temerbulatova N.	DLNP	Junior scientist	0.1
		Timkin V.	DLNP	Research scientist	0.4
		Filosofov D.	DLNP	Head of the sector	0.1
		Fomina M.	DLNP	Research scientist	0.2
		Khushvaktov Ju.	DLNP	Senior scientist	0.5
		Shirchenko M.	DLNP	Senior scientist	0.6
		Shitov Yu.	DLNP	Senior scientist	0.5
		Yakushev E.	DLNP	Head of department	0.2
		Nemchenok I.	DLNP	Head of the group	0.1
2.	engineers	Abd A.M.A.M.	DLNP	Engineer	0.1
		Aksenova Yu.	DLNP	Engineer	0.5
		Alekseev I.	DLNP	Senior engineer	0.3
		Vagina O.	DLNP	Engineer	0.2
		Volnykh V.	DLNP	Lead engineer	0.25
		Dovbnenko M.	DLNP	Senior engineer	1.0
		Dotsenko I.	DLNP	Senior engineer	0.1
		Evseev S.	DLNP	Engineer	0.2
		Kalinova B.	DLNP	Engineer	0.2
		Kamnev I.	DLNP	Engineer	0.2
		Katulin S.	DLNP	Senior engineer	0.1
		Katulina S.	DLNP	Senior engineer	0.2
		Kiyanov S.	DLNP	Senior	0.5

				engineer	
		Kuznetsov A.	DLNP	Engineer	1.0
		Pushkov D.	DLNP	Senior engineer	0.5
		Rozova I.	DLNP	Engineer	0.8
		Fateev S.	DLNP	Engineer	0.1
		Shakhov K.	DLNP	Engineer	0.8
		Shevchenko M.	DLNP	Engineer	0.3
		Shevchik E.	DLNP	Senior engineer	0.5
		Sherbakova I.	DLNP	Engineer	0.3
3.	specialists	Kulkova E.	DLNP	Document management specialist	0.1
		Lednicka T.	DLNP	Laboratory assistant	0.1
		Morozova T.	DLNP	Senior inspector	0.2
4.	technicians	Emelyanov A.	DLNP	Mechanic-repairman	0.2
		Zaikin A.	DLNP	Mechanic of experimental stands and setups	0.1
		Fariseeva	DLNP	Senior technician	0.3
	Total:				**20.6**

3.2.2. JINR associated personnel

No.	Category of personnel	Partner organization	Amount of FTE
1.	research scientists	-	-
2.	engineers	-	-
3.	specialists	-	-
4.	technicians	-	-
	Total:	**-**	**-**

4. Financing

4.1 Total estimated cost of the project/LRIP subproject

The total cost estimate of the project (for the whole period, excluding salary). The details are given in a separate table below.

2 900 000 USD

4.2 Extra funding sources

Expected funding from partners/customers – a total estimate.

Project (LRIP subproject) Leader __________/___________/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: _________
Date of decision of the laboratory's STC: _________ document number: _________

Year of the project (LRIP subproject) start: ________________

(for extended projects) – Project start year: _______

Proposed schedule and resource request for the Project / LRIP subproject

Expenditures, resources, funding sources			**Cost (thousands of US dollars)/ Resource requirements**	**Cost/Resources, distribution by years**				
				1^{st} year	2^{nd} year	3^{rd} year	4^{th} year	5^{th} year
		International cooperation	550	110	110	110	110	110
		Materials	550	110	110	110	110	110
		Equipment, Third-party company services (commissioning)	1500	300	300	300	300	300
		Commissioning work	100	20	20	20	20	20
		R&D contracts with other research organizations	-	-	-	-	-	-
		Software purchasing	50	10	10	10	10	10
		Design/construction	50	10	10	10	10	10
		Service costs (*planned in case of direct project affiliation)*	100	20	20	20	20	20
Resources required	**Standard hours**	Resources						
		– the amount of FTE,	20.6	20.6	20.6	20.6	20.6	20.6
		– accelerator/installation,	-	-	-	-	-	-
		– reactor,…	-	-	-	-	-	-
Sources of funding	**JINR Budget**	JINR budget *(budget items)*	2900	580	580	580	580	580
	Extra fudning (supplementary estimates)	Contributions by partners Funds under contracts with customers Other sources of funding	-	-	-	-	-	-

Project (LRIP subproject) Leader_________/________________/

Laboratory Economist _________/________________/

APPROVAL SHEET FOR PROJECT / LRIP SUBPROJECT

TITLE OF THE PROJECT/LRIP SUBPROJECT

SHORT DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/LRIP SUBPROJECT CODE

THEME / LRIP CODE

NAME OF THE PROJECT/ LRIP SUBPROJECT LEADER

AGREED

JINR VICE-DIRECTOR	SIGNATURE	NAME	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	NAME	DATE
CHIEF ENGINEER	SIGNATURE	NAME	DATE
LABORATORY DIRECTOR	SIGNATURE	NAME	DATE
CHIEF LABORATORY ENGINEER	SIGNATURE	NAME	DATE
LABORATORY SCIENTIFIC SECRETARY THEME / LRIP LEADER	SIGNATURE	NAME	DATE
PROJECT / LRIP SUBPROJECT LEADER	SIGNATURE	NAME	DATE
APPROVED BY THE PAC	SIGNATURE	NAME	DATE

Appendix 1

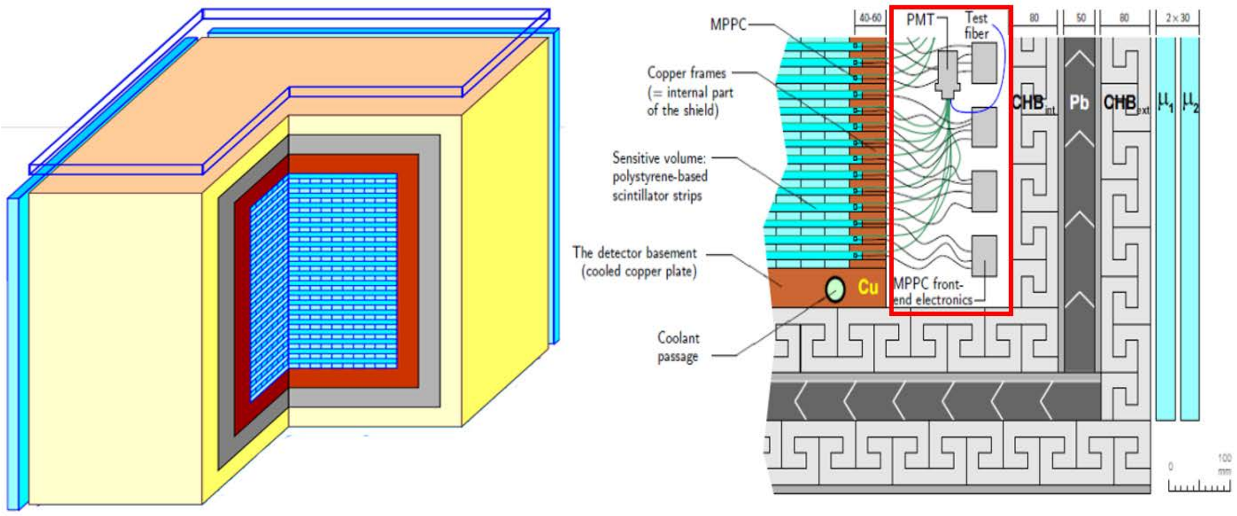

Figure 1. *DANSS spectrometer (left) and composition of the detector shielding (right).*

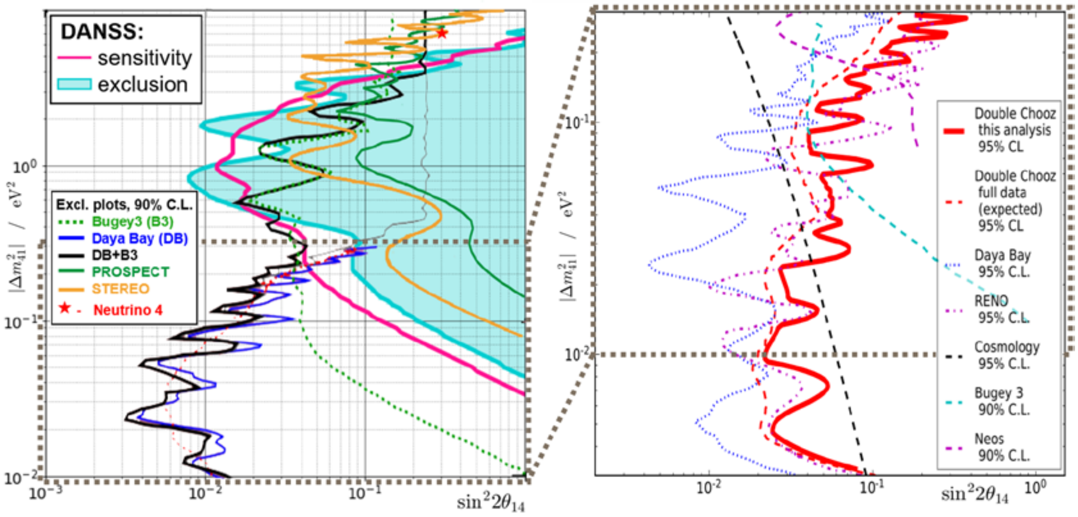

Figure 2. *Excluded regions of oscillations into sterile neutrinos in leading reactor experiments on a short baseline L <15 m (left); and the results (exclusion contours) of cosmology and neutrino oscillation experiments on a larger base L>100 m (right).*

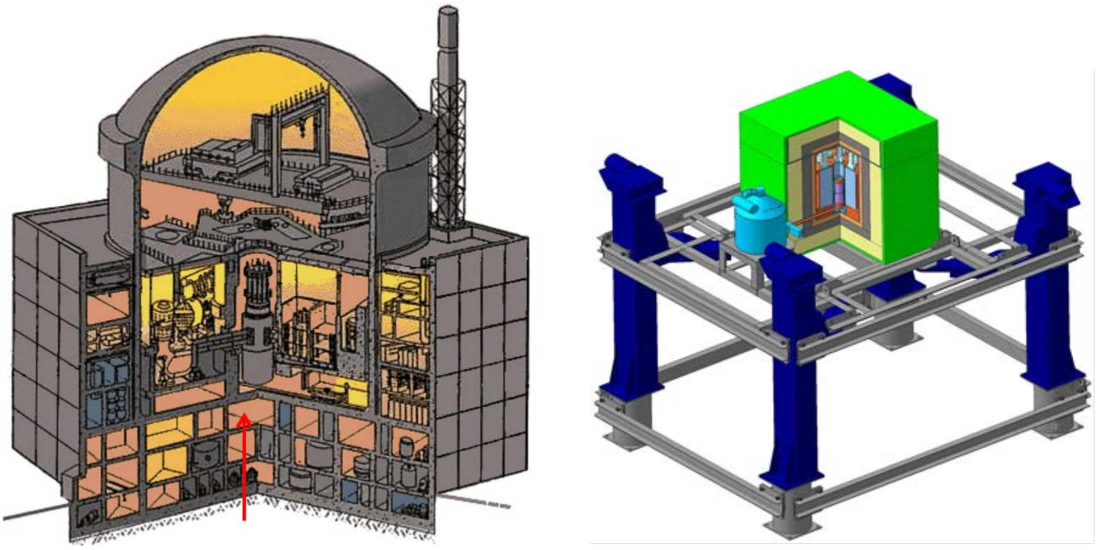

Figure 3. *Left: Scheme of the reactor unit No. 3 of the KNPP. The arrow indicates the room with the experimental setup.*
Right: Scheme of the spectrometer placed on the lifting mechanism.

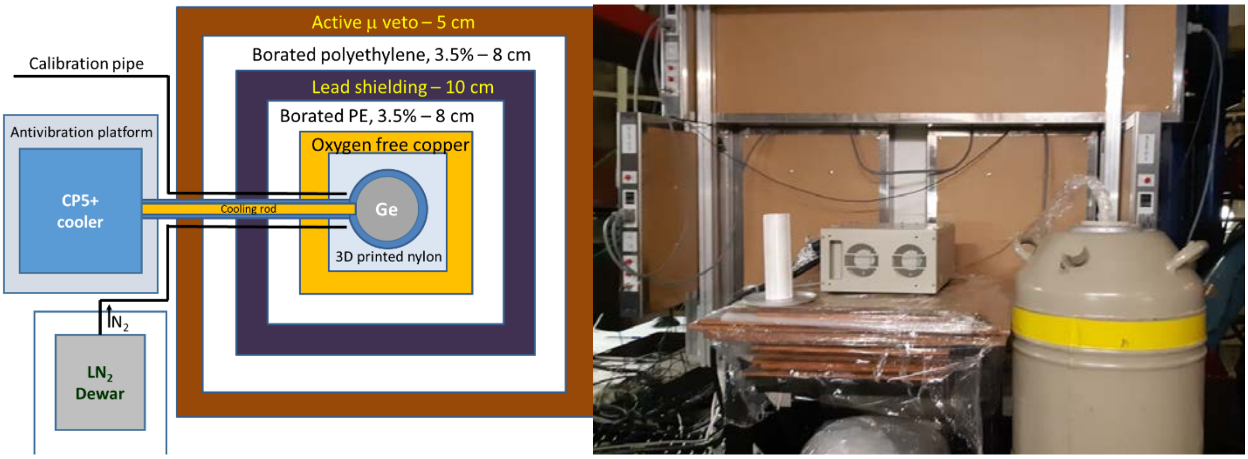

Figure 4. *Left: Scheme of the shielding used at KNPP. Right: photo of the experimental setup at KNPP.*

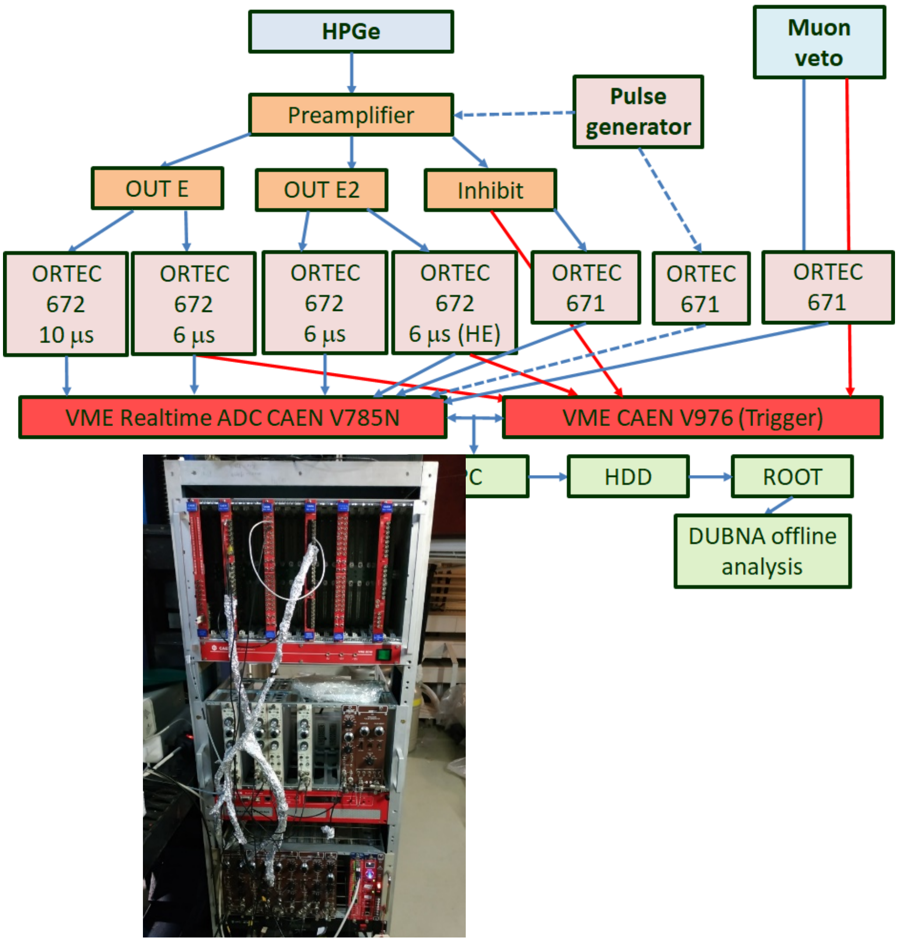

Figure 5. *Left: schematic diagram of the νGeN acquisition system. Right: photo of the electronics at KNPP.*

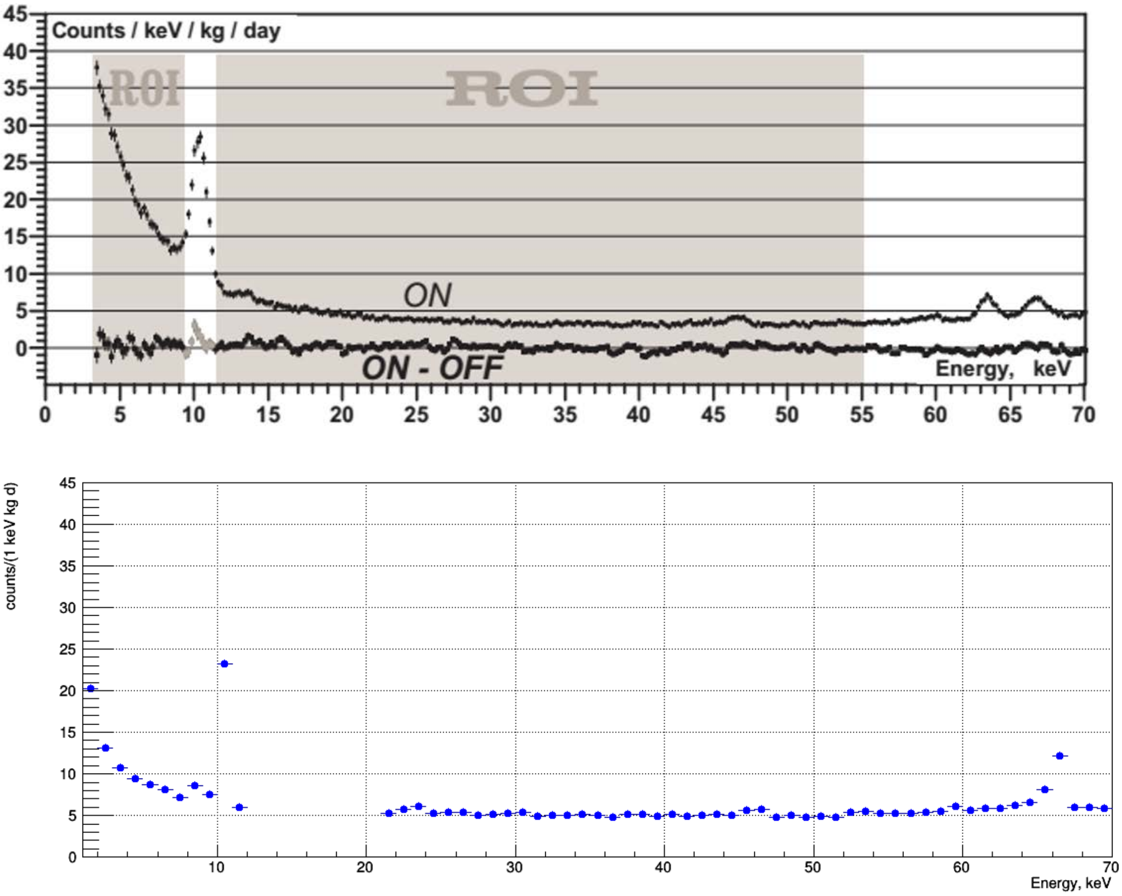

Figure 6. *Top: the experimental spectrum obtained in the GEMMA experiment. Bottom: the preliminary experimental spectrum obtained in the νGeN experiment (exposure time of 173.6 days, operating reactor).*

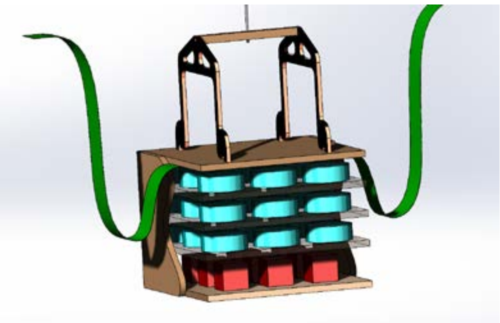

Figure 6. *Cryogenic detector assembly suspended below the inner shielding – CryoCube with its 27 Ge crystals (blue) and the Q-Array with its 9 Zn crystals (red) – suspended below the inner shielding.*

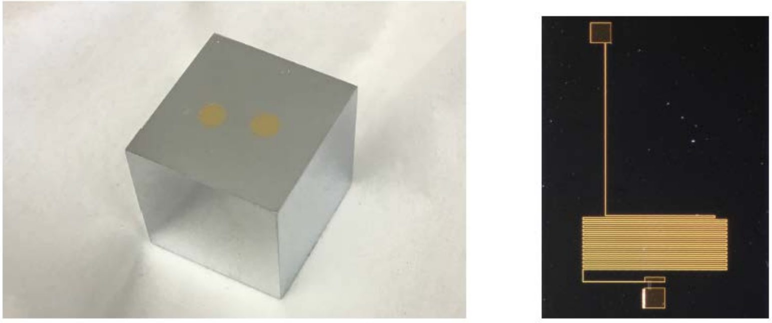

Figure 7. *Left: Zinc cubic crystal. Two gold readout pads (left: direct Au-Zn contact, right: Au-ZnO-Zn contact) are present for phonon and quasi-particle readout. Right: Transition edge sensor "chip" with 80 mK* T_c *developed at Argonne National Laboratory.*

The RICOCHET experimental setup

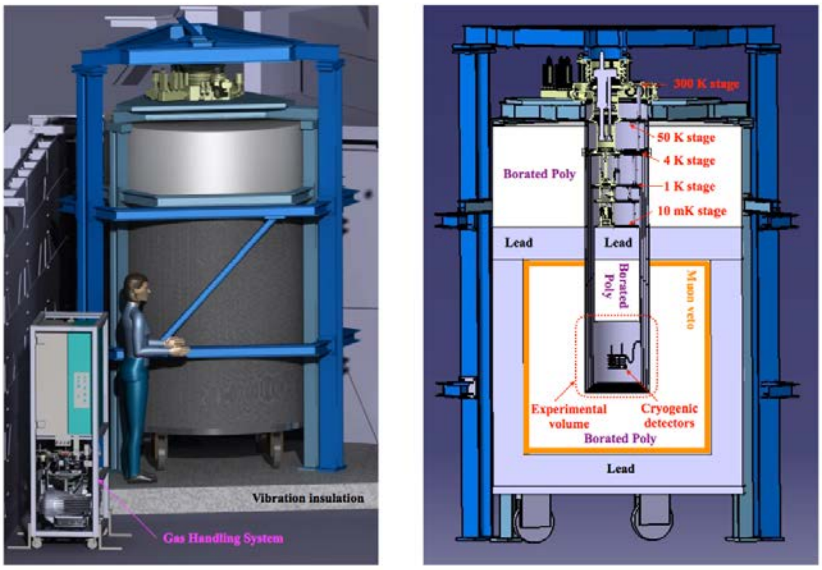

Figure 8. *Left panel: Future Ricochet experimental setup, illustrating the cryostat held by a double-frame, its movable lead and polyethylene(PE) shields and its gas handling system (GHS). For clarity, the tubing from the GHS and the cryostat is not shown. Right panel: Open view of the Ricochet setup where the dilution refrigerator, the internal shields, the muon-veto, and the experimental volume hosting the detectors and the cold electronics are shown.*

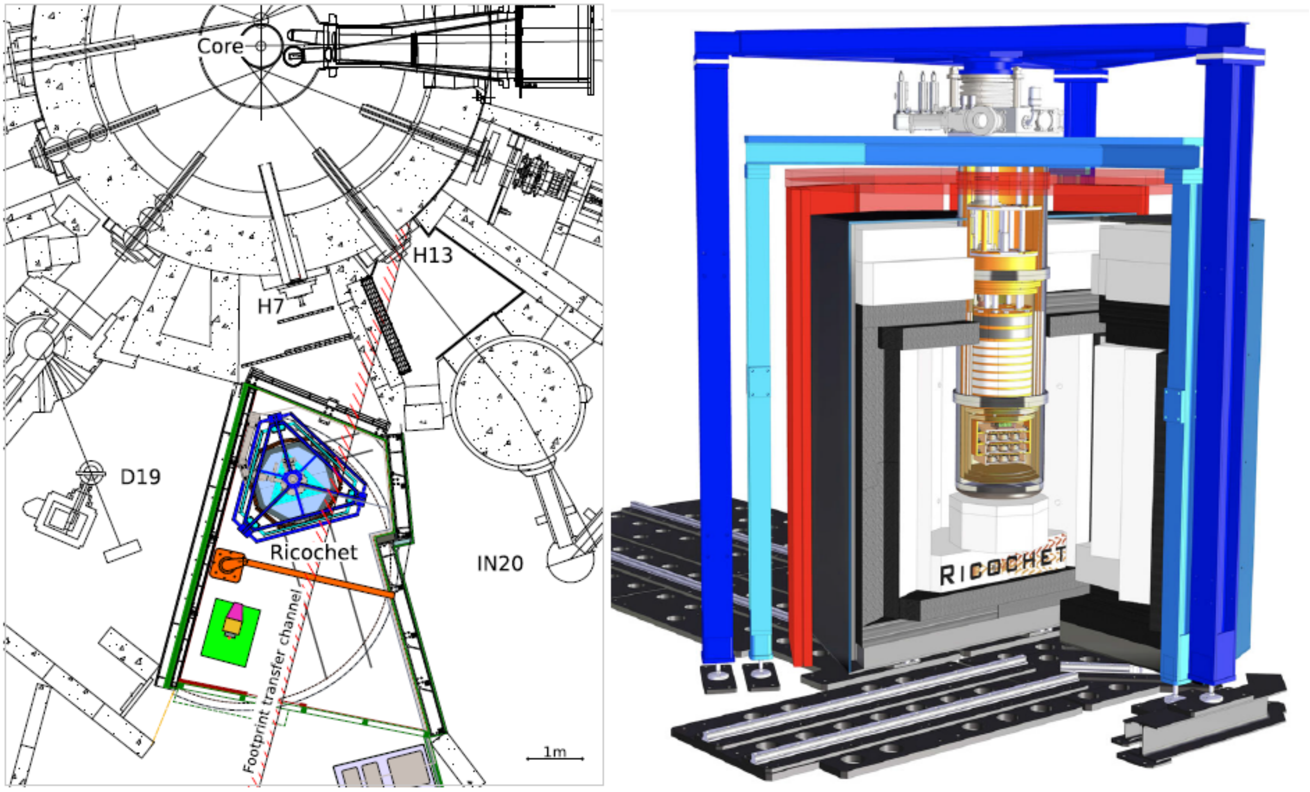

Figure 9. *The RICOCHET experiment scheme in the H7 site at the ILL. Shown are the cryostat, hosting the ultra sensitive cryogenic detectors, its holding structure made of two frames and its integrated shielding.*

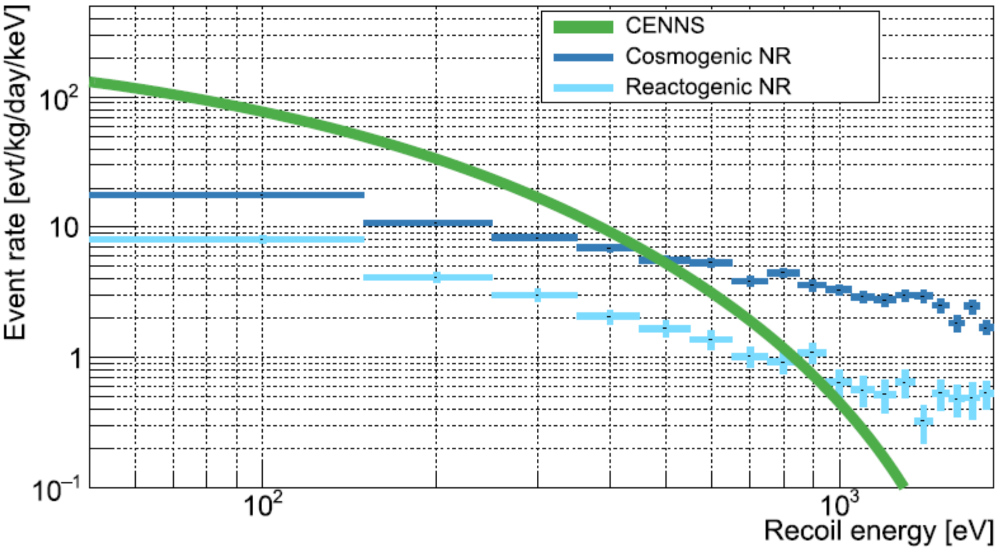

Figure 10. *Expected energy spectra for the future RICOCHET experiment at ILL, 8.8 m away from the core of the 58.3 MWth nuclear reactor. The CEνNS signal is given by the green distribution while the resulting nuclear recoil background from the cosmogenic and reactogenic components correspond respectively to the dark and light blue histograms.*

Appendix 2

PROJECT EXPERIMENTS REPORT 2021-2022

1. DANSS:

During the considering period (2021-22), the DANSS experiment continued to occupy a leading position in the field of short-baseline reactor antineutrino measurements. At the same time, the announced results of the NEUTRINO-4 experiments (PINP, Gatchina) with parameters $\sin^2(2\theta_{14})$~0.25, Δm_{14}^2~7 eV^2 (arXiv:2005.05301) and BEST – $\sin^2(2\theta_{14})\approx 0.4$, $\Delta m_{14}^2<0.5$ eV^2 only fueled interest in research of this kind. The question of confirmation/denial of the statements of these collaborations will underlie the next generation of experiments with nuclear reactors as a source of neutrinos.

That is why the DANSS collaboration undertook work to develop the design of the future DANSS-2 experiment, and also began testing the equipment and detector elements of this setup. The main goal is to significantly increase the resolution from the current 34% @ MeV to 15% @ MeV. In this case, the limits obtained using the spectrometer will be able to achieve the declared NEUTRINO-4 parameters. To do this, a new spectrometer will be assembled using new detector cells (strips) (plastic scintillators with dimensions 2 x 5 x 120 cm^3 and eight glued fibers and picking up an optical signal using two silicon photomultipliers). At the same time, the improved DANSS will use the same shielding and mobile platform, which will significantly reduce the cost of its modernization, planned to be carried out during 2023-2024.

As part of this work, the selection of new plastic scintillators specially made is being carried out, as well as the purchase of fiber optic fibers and silicon photomultipliers. Also the devoted efforts is also underway to improve the light yield, which in our case is the critical parameter limiting the energy resolution of the spectrometer. The data collection system will also be changed, as the current one is at the limit of its throughput capacity.

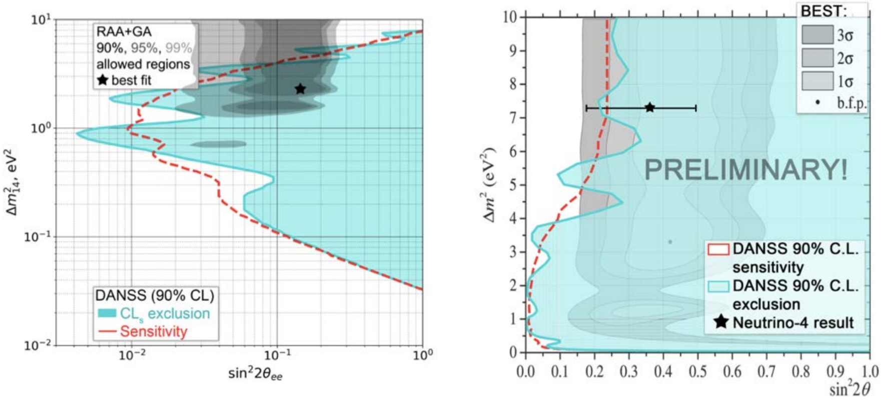

Fig. 1 Various options for analyzing data from the DANSS spectrometer. Model independent (left) and with absolute spectrum simulation (right).

At the same time, the analysis of data from the existing spectrometer continued. It should be noted that it connected not only with the consistent improvement of the constraints on the sterile neutrino parameters within the existing data analysis technique. In parallel with it, an analysis was carried out with a simulation of the antineutrino flux from the reactor. The results obtained using both methods are shown in Fig. 1.

The agreement between ours and the power plant personnel data on reactor power monitoring was also improved. The change is illustrated in Fig. 2. The improvement was achieved by introducing a correction for the composition of the fuel, considering its changes during the reactor campaign.

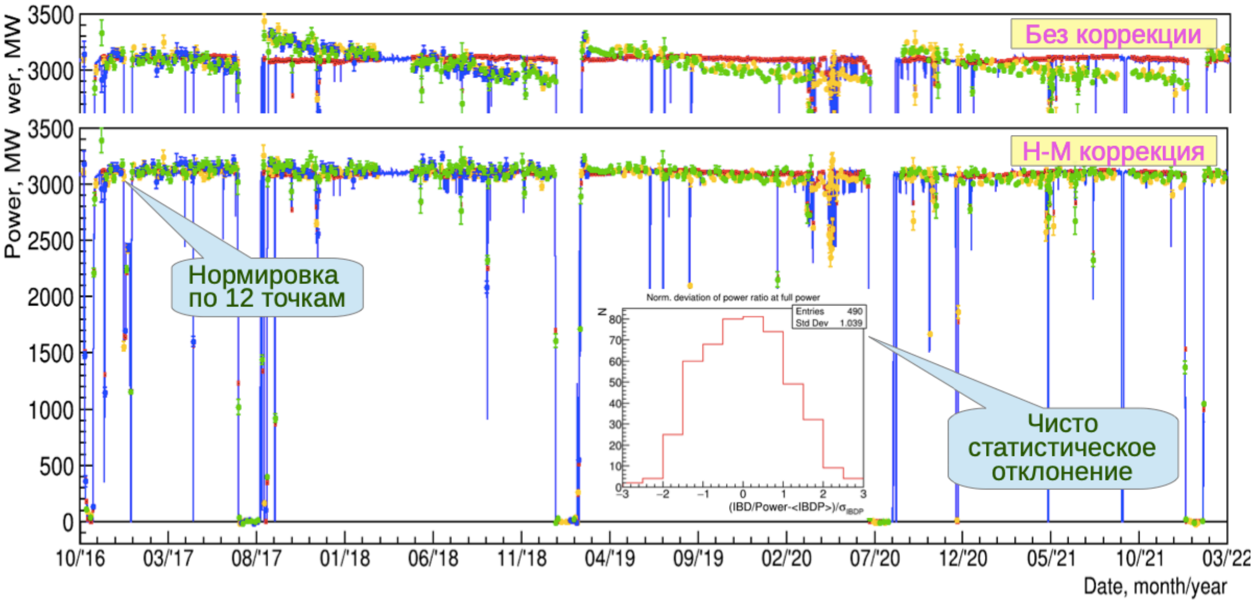

Fig. 2. Accounting for the fuel composition when determining the reactor power using the antineutrino flux.

A detailed analysis of the background conditions at the location of the DANSS facility was also performed. It included both the analysis of gamma and neutron backgrounds, including the background from fast neutrons, which is the most problematic, since the latter is able to mimic the signature of a neutrino event. Based on the results of the analysis, a review article is being prepared.

In 2023-24 Zhitnikov I.V. is going to defend a Ph.D. thesis based on the results of the experiment.

2. νGeN

The unique νGeN experimental setup was created to study the properties of neutrinos and search for rare events. A comparison of the first data collected with the reactor on and off (94.5 and 47.1 days, respectively) has not yet found significant differences in the spectra (see Fig. 1).

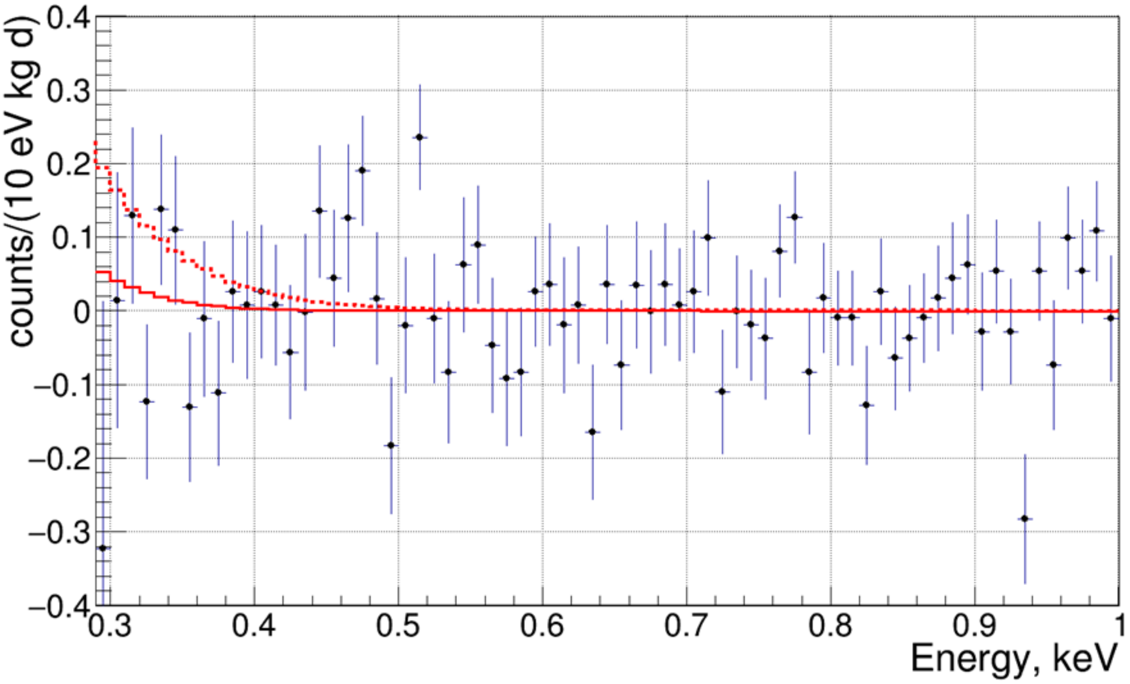

Fig.1. Residual spectrum (reactor on-off). The red lines are the predicted spectra from coherent neutrino scattering depending on the value of the quenching parameter k = 0.179, 0.26 (solid and dashed lines, respectively).

Analysis of the data revealed no evidence for the expected signal from coherent neutrino scattering. This allowed to set up an upper limit on the important parameter of ionization losses in Ge (quenching): $k < 0.26$ (90% CL).

In 2022 the installation of a lifting mechanism was completed, allowing measurements to be made closer to the reactor core than previously. The active veto system was completed. The power supply system was improved, the data set was optimized and the equipment was adjusted. The first results of measurements showed that low background levels, good energy resolution and stability in data acquisition were achieved. This allows us to expect an improvement of the world's best results for the search for MMN. By the end of 2022, over 1100 kg· days of data had been acquired. At present, the data obtained are being analyzed and publications are being prepared.

3. RICOCHET

The main experimental results that is the base for the RICOCHET is 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 under commissioning cryosystem of the RICOCHET setup. The cryostat is the main JINR yield to the experiment. It has been developed in cooperation with IP2I and produced by Cryoconcept. The cryosystem design reduces 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. The latter consists in a 25-cm-long elastic pendulum, attached to the 1 K stage by a Kevlar string and a stainless steel spring, holding the detector tower situated below the mixing chamber at 10 mK.

The detector tower is thermally anchored to an intermediate holding structure, via supple copper braids, which also hosts the connectors for the detector readout. This suspended tower design significantly reduces detector vibrations, with displacements in the order of a few nanometers (rms) in all three axes, leading to substantial gains in energy resolutions.

This was verified with the energy calibration by the use of a low-energy X-ray ^{55}Fe source irradiating the bottom side of the Ge crystal, opposite to the Ge-NTD heat sensor, inducing an interaction rate of ~0.3 Hz. The ^{55}Fe source produces two lines corresponding to the K_{α} and K_{β} lines of Mn at 5.90 and 6.49 keV, respectively. They are clearly visible on the left panel of Fig. 1, showing the calibrated energy as a function of time over the 137-hour acquisition period. The energy resolution of these peaks is 34 eV (rms).

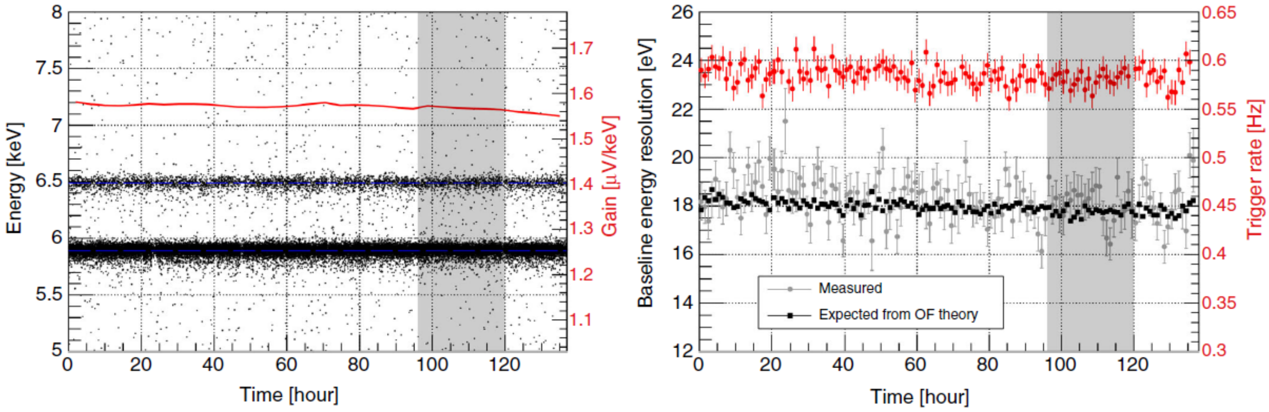

Fig. 1: *Left: Event energy distribution between 5 and 8 keV as a function of time. The horizontal bands at 5.90 and 6.49 keV correspond to the Kα and Kβ x-ray lines, respectively, of Mn emitted by the* ^{55}*Fe source. The data have been corrected for the measured time evolution of the detector gain as a function of time, shown as the red line, and corresponding to the right-hand axis.*

Right: Baseline heat energy resolution (RMS) in eV as a function of time.

The gray dots are the values derived from a fit to the energy distributions of the noise event selection, and the black squares are those derived from the ratio of the signal and noise PSDs. The corresponding trigger rates in hertz are shown as red dots. Each data point corresponds to one hour.

Another important recent achievement is onsite measurements of fast neutron flux, with original methods proposed by RICOCHET, published in [Eur. Phys. J. C (2023) 83:20]. For the RICOCHET experiment proper interpretation of results will be strongly depended on stability of the neutron background. With this experimental data we were able to make a conclusion that the statistical significance of a CEνNS detection with RICOCHET, after only one reactor cycle, should be between 4.6 and 13.6 σ, depending on the effectiveness of the muon veto.

RICOCHET in the starting of the implementation phase with ongoing final tests of the cryosystem and detectors at IP2I site, with starting ILL onside implementation later in 2023. Dmitry Ponomarev, PhD thesis is written, defense is expected in 2023.

Publications of experiments for 2021–2022:

1. Augier, C et al. "Fast neutron background characterization of the future Ricochet experiment at the ILL research nuclear reactor." *European Physical Journal C* 83.1, 2023, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-022-11150-x
2. Alekseev, I et al. "First results of the νgeN experiment on coherent elastic neutrino-nucleus scattering." *Physical Review D* 106.5, 2022, ISSN 2470-0010, https://doi.org/10.1103/PhysRevD.106.L051101
3. Suslov, I.A et al. "Development of a new tellurium loaded liquid scintillator based on linear alkylbenzene." *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1040, 2022, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2022.167131
4. Alekseev, I et al. "Observation of the temperature and barometric effects on the cosmic muon flux by the DANSS detector." *European Physical Journal C* 82.6, 2022, ISSN 1434-6044, https://doi.org/10.1140/epjc/s10052-022-10471-1
5. Alekseev, I et al. "Optimized scintillation strip design for the DANSS upgrade." *Journal of Instrumentation* 17.4, 2022, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/17/04/P04009
6. Sokolov, A et al. "Segmented HPGe Detector for Nuclear Reactions Research." *IEEE Transactions on Nuclear Science* 68.1, 2021, pp. 54-58., ISSN 0018-9499, https://doi.org/10.1109/TNS.2020.3037336
7. Ponomarev, D et al. "NaI(Tl+Li) scintillator as multirange energies neutron detector." *Journal of Instrumentation* 16.12, 2021, ISSN 1748-0221, https://doi.org/10.1088/1748-0221/16/12/P12011