Форма № 24

Детектор реакторных антинейтрино на основе пластмассового сцинтиллятора

(продление проекта)

DANSS

Шифр темы: **03-2-1100-2010/2024**

Лаборатория ядерных проблем (ЛЯП ОИЯИ), Дубна

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Дата представления проекта в НОО ____________________

Дата НТС Лаборатории ___12.11.2020___ Номер документа ____________________

Дата представления физобоснования на семинаре Лаборатории __5.10.2020___.

Дата первого утверждения проекта ____________________

Форма № 25

ЛИСТ СОГЛАСОВАНИЙ ПРОДЛЕНИЯ ПРОЕКТА

Детектор реакторных антинейтрино на основе пластмассового сцинтиллятора

DANSS

Шифр темы: **03-2-1100-2010/2024**

РУКОВОДИТЕЛЬ ПРОЕКТА: **Юрий Александрович ШИТОВ**

УТВЕРЖДЕН ДИРЕКТОРОМ ОИЯИ	ПОДПИСЬ	ДАТА
СОГЛАСОВАНО		
ВИЦЕ-ДИРЕКТОР ОИЯИ	ПОДПИСЬ	ДАТА
ГЛАВНЫЙ УЧЕНЫЙ СЕКРЕТАРЬ	ПОДПИСЬ	ДАТА
ГЛАВНЫЙ ИНЖЕНЕР	ПОДПИСЬ	ДАТА
НАЧАЛЬНИК НОО	ПОДПИСЬ	ДАТА
ДИРЕКТОР ЛАБОРАТОРИИ	ПОДПИСЬ	ДАТА
ГЛАВНЫЙ ИНЖЕНЕР ЛАБОРАТОРИИ	ПОДПИСЬ	ДАТА
РУКОВОДИТЕЛЬ ПРОЕКТА	ПОДПИСЬ	ДАТА
ЗАМ. РУКОВОДИТЕЛЯ ПРОЕКТА	ПОДПИСЬ	ДАТА
ОДОБРЕН		
ПКК ПО НАПРАВЛЕНИЮ	ПОДПИСЬ	ДАТА

Форма № 26

Предлагаемый план-график и необходимые ресурсы для продления проекта «Детектор реакторных антинейтрино на основе пластмассового сцинтиллятора DANSS»

Наименования затрат, ресурсов, источников финансирования			Стоим. ($ тыс.). Потреб-ности в ресурсах	Предложение ЛЯП по распределению финан-сирования и ресурсов		
				1 год	2 год	3 год
Затраты		Материалы для детектора DANSS-2 (стрипы, SiPM, фибры и т.п.)	520	180	160	180
Затраты		Расходные материалы (оптич. клей, разъемы, кабель, и т. п.)	30	10	10	10
Затраты		Материалы для **S3** (фибры, электроника, компьютеры)	30	10	10	10
Затраты		**Итого**	**580**	**200**	**180**	**200**
Необходим. ресурсы	Нормо-час	Ресурсы – конструкторского бюро лаборатории, – опытного производства лаборатории,	300 600	100 200	100 200	100 200
Источники финансирования	Бюджет. средства	Затраты из бюджета, в том числе инвалютные средства	**580**	**200**	**180**	**200**
Источники финансирования	Внебюдж. ср-ва	Вклады коллаборантов. Средства по грантам.	0 0	0 0	0 0	0 0

РУКОВОДИТЕЛЬ ПРОЕКТА

Форма № 29

Смета затрат по продлению проекта «Детектор реакторных антинейтрино на основе пластмассового сцинтиллятора DANSS»

NN пп	Наименование статей затрат	Полная стоимость	1 год	2 год	3 год
	Прямые расходы на Проект				
1.	Компьютерная связь	$ 6 тыс.	2	2	2
2.	Конструкторское бюро	300 нормо-час	100	100	100
3.	Опытное производство	600 нормо-час	200	200	200
4.	Материалы	$ 360 тыс.	140	100	120
5.	Оборудование	$ 220 тыс.	60	80	80
6.	Транспортировка оборудования	$ 25 тыс.	15	10	0
7.	Проведение рабочих совещаний	$ 15 тыс.	5	5	5
8.	Командировочные расходы, в т.ч.	$ 90 тыс.	30	30	30
	а) в страны нерублевой зоны		-	-	-
	б) в города стран рублевой зоны	$ 90 тыс.	30	30	30
	в) по протоколам		-	-	-
	Итого по прямым расходам:	$ 716 тыс.	252	227	237

РУКОВОДИТЕЛЬ ПРОЕКТА

ДИРЕКТОР ЛАБОРАТОРИИ

ВЕДУЩИЙ ИНЖЕНЕР-ЭКОНОМИСТ ЛАБОРАТОРИИ

Form No 24

Detector of the reactor antineutrino based on solid state plastic scintillator

(project prolongation)

DANSS

Code of theme: **03-2-1100-2010/2024**

Dzhelepov Laboratory of Nuclear Problems (DLNP JINR), Dubna

V. V. Belov, V. B. Brudanin, V. P. Volnykh, I.V. Zhitnikov, S.V. Kazartsev, S.P. Kiyanov, A.S. Kuznetsov, F. Mamedov, I.V. Machikhilyan, D.V. Medvedev, D.S. Pushkov, I.E. Rozova, A.V. Salamatin, D.V. Filosofov, M.V. Fomina, E.A. Shevchik, Yu.A. Shitov.

Institute of Theoretical and Experimental Physics (ITEP), Moscow

I. G. Alekseev, A. Ershova, A. S. Kobyakin, V. M. Nesterov, K. A. Perminov, V. Yu. Rusinov, E.I. Samigullin, D.N. Svirida, N.A. Skrobova, A.S. Starostin, E.I. Tarkovsky, A.E. Yakovleva.

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M.Špavorová, L.Fajt, R.Hodák, Z.Hons, P.Přidal, E.Rukhadze, I.Štekl.

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M.V.Danilov

Project leader from JINR Yu.A. Shitov (*shitov@jinr.ru*)

Project deputy leader from JINR V.B. Brudanin

Date of submission of proposal of project to SOD ____________________

Date of the Laboratory STC ___________12.11.2020_______ Document number ____________________

Date of the Project physical justification at the Laboratory seminar ___5.10.2020

Date of the first approval ____________________

Form No. 25

PROJECT ENDORSEMENT LIST

Detector of the reactor antineutrino based on solid state plastic scintillator
DANSS

CODE OF THEME **03-2-1100-2010/2021**

NAME OF PROJECT LEADER: **Yury SHITOV**

APPROVED BY JINR DIRECTOR	SIGNATURE	DATE
ENDORSED BY		
JINR VICE-DIRECTOR	SIGNATURE	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	DATE
CHIEF ENGINEER	SIGNATURE	DATE
HEAD OF SCIENCE ORGANIZATION DEPARTMENT	SIGNATURE	DATE
LABORATORY DIRECTOR	SIGNATURE	DATE
LABORATORY CHIEF ENGINEER	SIGNATURE	DATE
PROJECT LEADER	SIGNATURE	DATE
PROJECT DEPUTY LEADERS	SIGNATURE	DATE
ENDORSED		
RESPECTIVE PAC	SIGNATURE	DATE

Form No. 26

Schedule proposal and resources required for the prolongation of the Project

Detector of the reactor antineutrino based on solid state plastic scintillator

DANSS

Expenditures, resources, financing sources			Costs (k$) Resource Require-ments	Proposals of the Labora-tory on the distribution of finances and resources 1st yr	2nd yr	3rd yr
Expenditures		Materials and equipment for the DANSS-2 detector (strips, SiPM, fibers, etc.)	520	180	160	180
Expenditures		Consumables (optical glue, connectors, cable, etc.)	30	10	10	10
Expenditures		Materials and equipment for S^3 (fibers, electronics, computers)	30	10	10	10
Expenditures		**Total**	**580**	**200**	**180**	**200**
Required resources	Standard hour	Resources of – Laboratory design bureau – Laboratory experimental workshop	300 600	100 200	100 200	100 200
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	**580**	**200**	**180**	**200**
Financing sources	External resources	Contributions by collaborators. Grants.	0	0	0	0

PROJECT LEADER

Form No. 29

Estimated expenditures for the Project

Detector of the reactor antineutrino based on solid state plastic scintillator

DANSS

NN	Expenditure items	Units	Full cost	1st yr	2nd yr	3rd yr
	Direct expenses for the Project					
1.	Computer connection	k$	6	2	2	2
2.	Design bureau	std.h.	300	100	100	100
3.	Experimental Workshop	std.h.	600	200	200	200
4.	Materials	k$	360	140	100	120
5.	Equipment	k$	220	60	80	80
6.	Transportation of equipment	k$	25	15	10	0
7.	Collaboration meetings and workshops	k$	15	5	5	5
8.	Travel allowance, including:	$k	90	30	30	30
	a) non-rouble zone countries	-	-	-	-	-
	b) rouble zone countries	$k	90	30	30	30
	c) protocol-based	-		-	-	-
	Total direct expenses:	k$	716	252	227	237

PROJECT LEADER

LABORATORY DIRECTOR

LABORATORY CHIEF ENGINEER-ECONOMIST

Proposal for prolongation of the project

DANSS

Detector of the reactor AntiNeutrino based on Solid state plastic Scintillator

Theme: 03**-2-1100-2010/2024** (**non-accelerator neutrino physics and astrophysics**)

Dzhelepov Laboratory of Nuclear Problems (DLNP JINR), Dubna
V. V. Belov, V. B. Brudanin, V. P. Volnykh, I.V. Zhitnikov, S.V. Kazartsev, S.P. Kiyanov, A.S. Kuznetsov, F. Mamedov, I.V. Machikhilyan, D.V. Medvedev, D.S. Pushkov, I.E. Rozova, A.V. Salamatin, D.V. Filosofov, M.V. Fomina, E.A. Shevchik, Yu.A. Shitov.

Institute of Theoretical and Experimental Physics (ITEP), Moscow
I. G. Alekseev, A. Ershova, A. S. Kobyakin, V. M. Nesterov, K. A. Perminov, V. Yu. Rusinov, E.I. Samigullin, D.N. Svirida, N.A. Skrobova, A.S. Starostin, E.I. Tarkovsky, A.E. Yakovleva.

Institute of Experimental and Applied Physics, Czech Technical University in Prague (ÚTEF ČVUT), Prague
M.Špavorová, L.Fajt, R.Hodák, Z.Hons, P.Přidal, E.Rukhadze, I.Štekl.

P.N. Lebedev Physical Institute of the Russian Academy of Sciences (LPI RAS), Moscow
M.V.Danilov

Project leader from JINR Yu.A. Shitov (shitov@jinr.ru)
Project deputy leader from JINR V.B. Brudanin

Abstract

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 online, 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. Verification of the NEUTRINO-4 result is aт 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 during 2021-22. 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.

Introduction

The aim of the project, started in 2008, is to search for oscillations into sterile neutrinos in measurements of reactor antineutrinos. Most of the results in the field of neutrino physics are well described by the theory of a light three-component neutrino (PMNS-matrix). However, a number of discrepant experimental results – reactor and gallium anomalies, contradictory results of LSND and MiniBoone - can be explained by the existence of a light sterile neutrino with oscillation parameters $\sin^2(2\theta) \sim 0.1$, $\Delta m^2 \sim 2$ eV^2, determined from the global fit of these data. The discovery of sterile neutrinos, if this happens, will be a fundamental breakthrough and discovery of New Physics. Therefore, experimental tests of this hypothesis are carried out by various methods in different directions of physical research. The relevance of this topic is beyond doubt.

During the implementation of this project, we have developed, created and launched a unique neutrino spectrometer **DANSS** (DOI: 10.1088/1748-0221/11/01/P01011), which has a number of advantages over competitors. A high degree of segmentation ensures effective suppression and measurement of all backgrounds. The use of a solid plastic scintillator (PS) guarantees a safe application near the industrial reactor. The record high neutrino flux is 5×10^{13} $cm^{-2}s^{-1}$ at 10 m from the reactor core. The location under the reactor provides significant protection against cosmic background (~ 50 m.w.e.). The movable platform allows relative measurements of antineutrino spectra at 10-12 m from the reactor core, which are insensitive to a number of systematic errors.

During four years of measurements 2016-2020, DANSS has registered 4M reactor antineutrinos, did not see a significant oscillatory signal and, therefore, obtained the world's best exclusion area on the existence of sterile neutrinos among reactor experiments, demonstrated long-term monitoring of reactor power and sensitivity to the composition of nuclear fuel.

To fully implement the project goals, it is proposed to extend the project for the period 2022-2024 in order to solve the following tasks:

1. The DANSS will take data till the end of 2022. We will finalize the analysis of the data including all possible improvements and enhancements and publish the final results.

2. During 2021-2022 the modernized **DANSS-2** spectrometer will be created with improved energy resolution up 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 upgrade.

3. In 2023-2024. data will be taken by the DANSS-2 spectrometer, the analysis of which will allow expanding the region of the tested phase space of oscillations into a sterile neutrino and, most importantly, reaching the signal region in the NEUTRINO-4 experiment $\sin^2(2\theta_{14})$~0.25, $\Delta m_{14}{}^2$~7 eV^2. Verification of this signal is an important scientific problem in modern fundamental physics.

4. To complete the creation of a reduced and simplified neutrino detector $\mathbf{S^3}$ for additional monitoring of the reactor and verification of the measurement systematics and for solving applied tasks.

Project costs are estimated at $ 200,000 per year.

State-of-the-art of the science case proposed

The search for oscillations into the light (0.1-10 eV) sterile neutrino is one of the hottest trends in fundamental neutrino physics. The existence of a sterile neutrino could explain a number of contradictory results observed, first of all, reactor and gallium (anti)neutrino anomalies (RAA) [1] and at the same time become a revolutionary discovery of New Physics. Therefore, it is not surprising that RAA [1] caused a wide resonance in the scientific community (more than 1600 citations at the moment) and generated a lot of experimental activity in various areas of neutrino physics aimed at testing this hypothesis. Reactor experiments on a short baseline (<30 m) have a number of competitive advantages in this area of research, while the DANSS spectrometer, developed within the framework of this project, is one of the leaders.

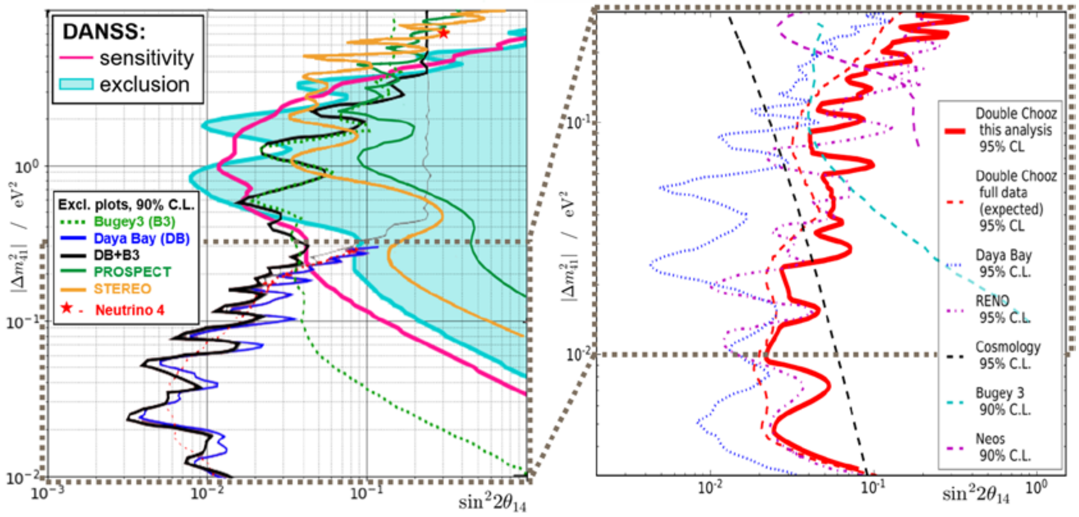

Figure 1. *Excluded regions of oscillations into sterile neutrinos in leading reactor experiments on a short baseline L<15 m (left); and the results (exclusion contours) of cosmology and neutrino oscillation experiments on a larger base L>100 m (right) [2].*

The current situation with the search for oscillations in sterile neutrinos is shown in Fig. 1. Most of the leading projects, namely PROSPECT [3], STEREO [4], NEOS [5], BUGEY-3 [6], and DANSS have not yet observed a significant signal of neutrino oscillations (Fig. 1 on the left). Cosmology and neutrino experiments to measure θ_{13} Daya Bay, RENO and Double Chooz also give out only limitations. But because of the large base 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 insensitive to the RAA area (Fig.2 on the right) [2].

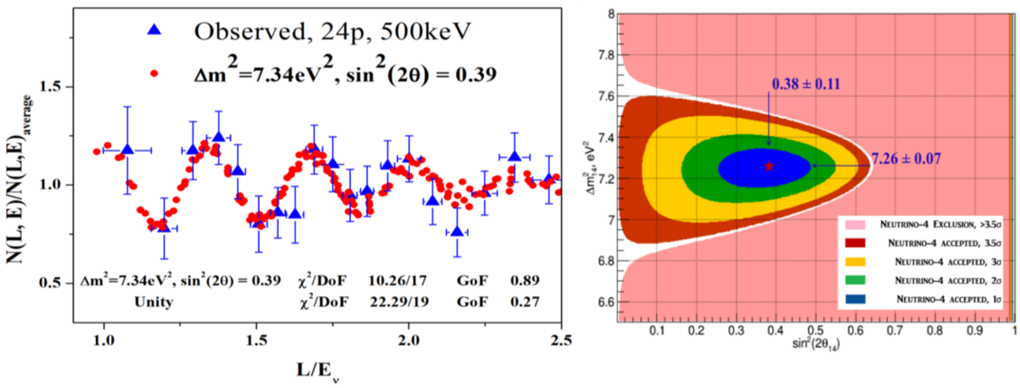

Figure 2. *The oscillation pattern observed in NEUTRINO-4 in the L/E coordinates (left) and the corresponding point in the phase space of oscillations into a sterile neutrino according to the 3 + 1 model (right) [7].*

The situation was intrigued by the NEUTRINO-4 experiment (PNPI, Gatchina, leader - A.P. Serebrov), which in 2018 announced the discovery of oscillations in sterile neutrino with parameters $\sin2(2\theta_{14})$~0.2-0.3, Δm_{14}^2~6-7 eV^2 (see Fig. 2) [7], which is discussed now [8-9]. Since this result is of fundamental importance, it is necessary to confirm it by other independent experiments.

Unfortunately, in its current configuration, DANSS is not sensitive to the phase point of the claimed signal in NEUTRINO-4. To move into the area of the NEUTRINO-4 effect, an upgrade of the DANSS spectrometer is required, the plan of which has already been prepared. The main goal is to significantly increase the resolution to 15% @ MeV from the current 34% @ MeV. For this, **a new spectrometer DANSS-2** will be assembled on new strips (2 x 5 x 120 cm3, 8 WLS-fibers) from the best plastic. At the same time, the updated DANSS-2 will use the same protection and mobile platform, which will significantly reduce the cost of its upgrade, which is planned to be carried out within two years.

The upgraded DANSS-2 will have more sensitivity and will be able to reach the point of interest. Possessing a different technique, other sources of systematic error, 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 experiment.

If we talk about competitors, the only PROSPECT project has the chances if they manage to solve the problem of stability of operation with a liquid scintillator loaded by ^{6}Li (this caused problems and forced the measurements to be stopped six months after the start of operation) and restart the detector. The STEREO project is being completed this year and has no prospects (unlike the PROSPECT😉) of significant improvement in the result due to the low reactor power combined with a large background. The SOLID detector has serious background problems from radioactive impurities of thorium and uranium in the inorganic neutron scintillator. The SOLID is completing its data taking in the end of this year and will unlikely to be able to obtain record results. The SOX [11] and CeLAND [12] projects, which proposed to measure powerful neutrino sources in large neutrino detectors BOREXINO and KAMLAND, respectively, have not been implemented and are practically closed for political reasons (protests by the “green” parties against dangerous high-intensity radioactive neutrino sources required for these experiments). This year the result of the BEST experiment is expected [13], which may provide new interesting information.

Thus, the present project, being the leader in terms of current results, will remain so in the next 5 years. In addition to the main task, it will continue to solve applied problems of reactor diagnostics that are important for the IAEA [14].

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14. M. Fallot, B. Littlejohn, P. Dimitriou IAEA Vienna, Austria Antineutrino spectra and their applications Summary of the Technical Meeting IAEA Headquarters, Vienna, Austria 23-26 April 2019. https://nds.iaea.org/publications/indc/indc-nds-0786.pdf

Description of the proposed research

The object of research is reactor antineutrinos. **The subject of research** is the search for oscillations of reactor antineutrinos into sterile neutrinos. **The hypothesis** of the existence of a fourth sterile neutrino in addition to the three known active ones arose as a scenario of solving a number of problems in neutrino physics related to discrepant experimental results. First of all, we are talking about the **reactor antineutrino anomaly RAA**, discovered in [1], in which it was found that the results of measurements of the electron antineutrino flux in 20 previous reactor experiments are on average 7 ± 2% less than the calculated values determined taking into account all our modern knowledge about the nature of the process (3σ effect). Further, the calibration measurements with the ^{51}Cr and ^{37}Ar antineutrino sources in the SAGE, GALLEX gallium experiments on the registration of solar neutrinos also showed a deficit in the experimental neutrino flux compared to theoretical expectations at the level of 14 ± 6% - a gallium antineutrino anomaly. The solution to the problem can have several options: an unknown systematic effect, incorrect calculations. But the most interesting for physicists, of course, is the scenario of the existence of the fourth sterile neutrino, which interacts with three active neutrinos of White Matter only through oscillations (hence the term "sterile"). In this version, some of the electron antineutrinos produced in the reactor are converted into sterile neutrinos on the fly that are not recorded in the detector, thereby determining the observed effects. Obviously, the discovery of a sterile neutrino (a particle of Dark Matter) if such takes place, will become a fundamental breakthrough and discovery of New Physics. Therefore, it is not surprising that the verification of this hypothesis has generated a storm of experimental activity in various directions.

The ongoing DANSS project occupies a leading position among reactor experiments searching for oscillations in sterile neutrinos on a short baseline (<30 m). Since the start in 2008, we have developed, created and launched a unique neutrino spectrometer DANSS [2], free from many of the disadvantages existed in other reactor experiments.

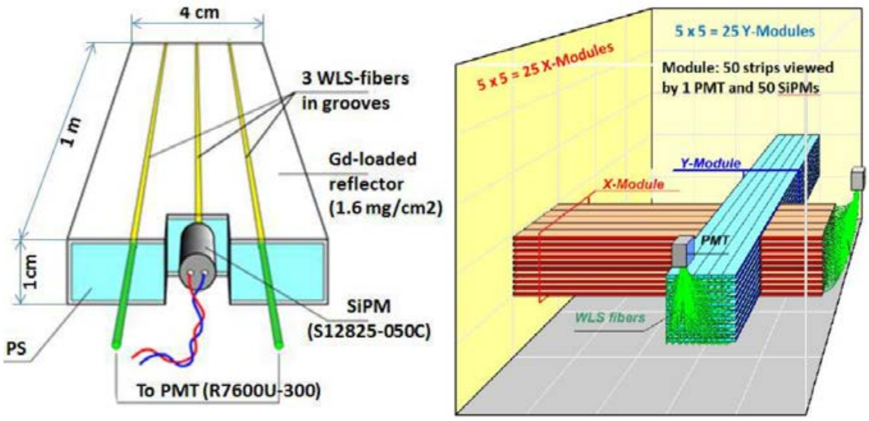

Figure 3. *The base cell (strip) of the DANSS detector (left) and the modular principle of light collection (right).*

The DANSS is based on **the technique** of measuring reactor antineutrinos using a plastic scintillator covered with a thin Gd-containing layer that acts as a reflector and a neutron trap (see Fig. 3, left). Note that this innovative method was first proposed by the DANSS collaboration, although the technology was not patented. Light is collected through three wavelength shifting (WLS) fibers, one of which is connected to a multipixel avalanche photodiode (SiPM, 2500 channels), and two are connected to a PMT (50 channels). The strips are stacked in layers, with adjacent layers being orthogonal to each other to fix the XY-coordinate of the particles that hits two adjacent layers. PMTs collect light from 100 strips (2 x 5 x 10), 20 x 20 cm^2 modules (see Fig. 3, right). In such a mixed light collection system, the signals from the PMT are used as event triggers and to determine the energy release, while the SiPM allow determining spatial patterns of events with an accuracy down to a single triggered strip.

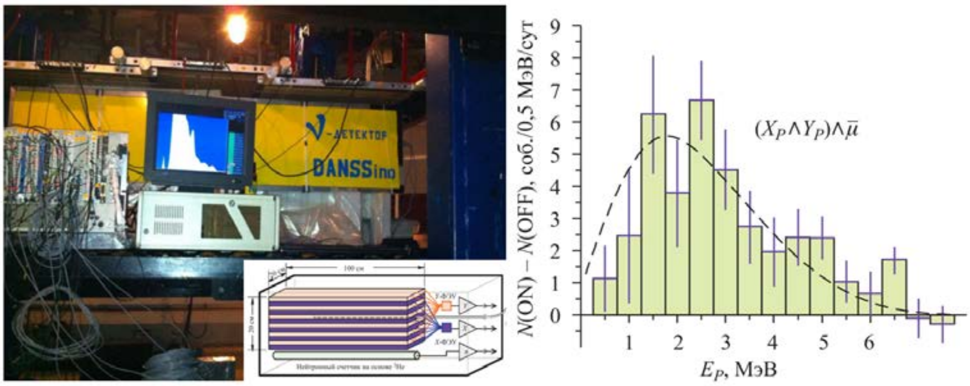

Figure 4. *The DANSSINO dataset at KNPP (left) and the difference (reactor ON - reactor OFF) spectrum of reactor antineutrinos obtained during measurements (right).*

Verification of the technique was carried out on the DANSSINO prototype. Despite its tiny size (the volume is only 40 liters with light collection for only two PMTs), being mounted 11 m from the 3.15 GW reactor (module No. 4 of the KNPP), in 2012 DANSSINO has measured the spectrum of reactor antineutrinos, registering 70 events per day at the signal to background ration S/B ~ 1 (see Fig. 4) [3].

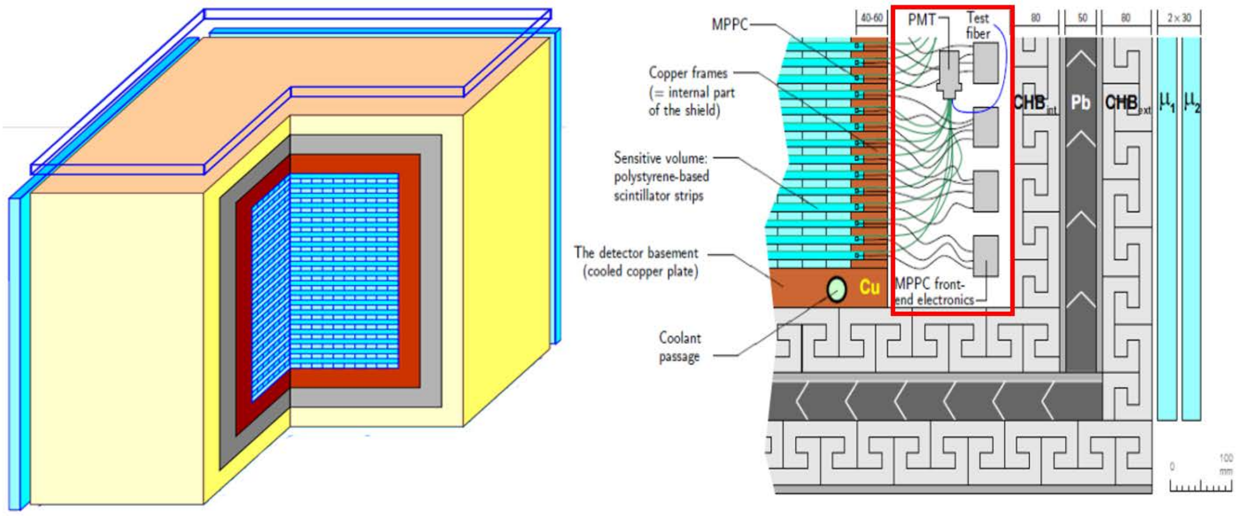

Figure 5. *DANSS spectrometer assembly (left) and structure of its shield (right).*

The full DANSS spectrometer is a 1 m^3 cube, surrounded by a combined passive shielding (copper, lead, and borated polyethylene), as well as active shielding against cosmic muons in the form of scintillation plates (Fig. 5).

DANSS is located under the 4th unit of KNPP on a mobile platform, thanks to which measurements are carried out in the upper (10.9 m to the reactor), middle (11.9 m) and lower (12.9 m) positions of the detector (Fig. 6). This is a record short distance to an industrial reactor, where scientific measurements are carried out all over the world.

The change of positions is made regularly with a passage of all three positions in a week (~2 days of exposure in each position) in order to discard systematic error due to the change in the composition of nuclear fuel (U/Pu ratio) during the fuel campaign of the reactor. Another important circumstance is the fact that the reactor itself and the adjacent large water basins for storing spent nuclear fuel provide good protection against cosmic radiation (approximately 50 m.w.e., 6-fold suppression of cosmic muons and complete suppression of primary neutrons from cosmic rays).

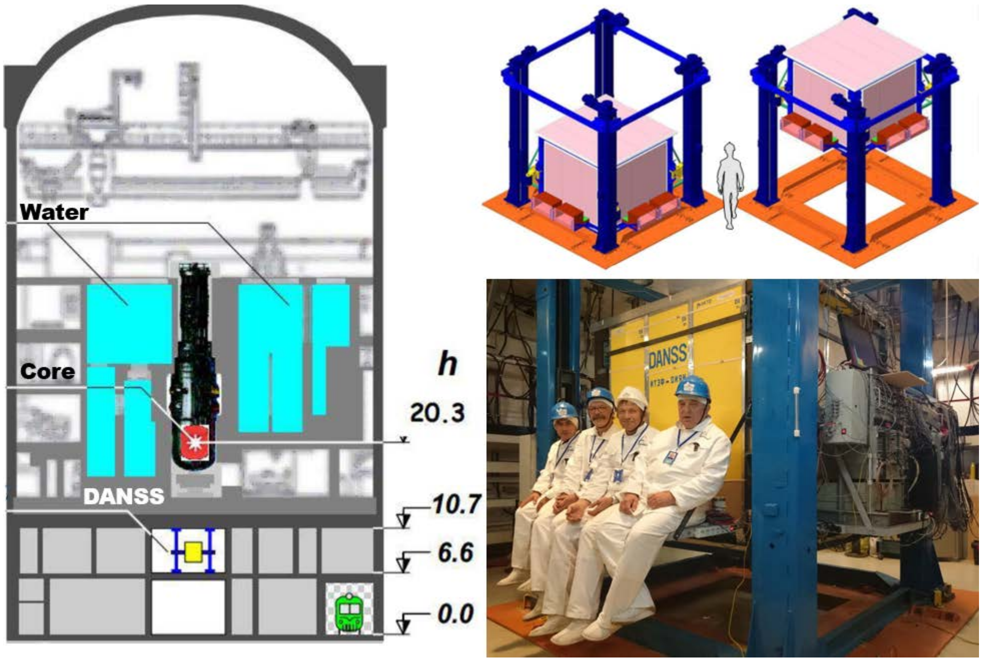

Figure 6. *The DANSS spectrometer under the 4th unit of the KNPP (left), its mobile platform (top right) and the DANSS team on board (bottom right).*

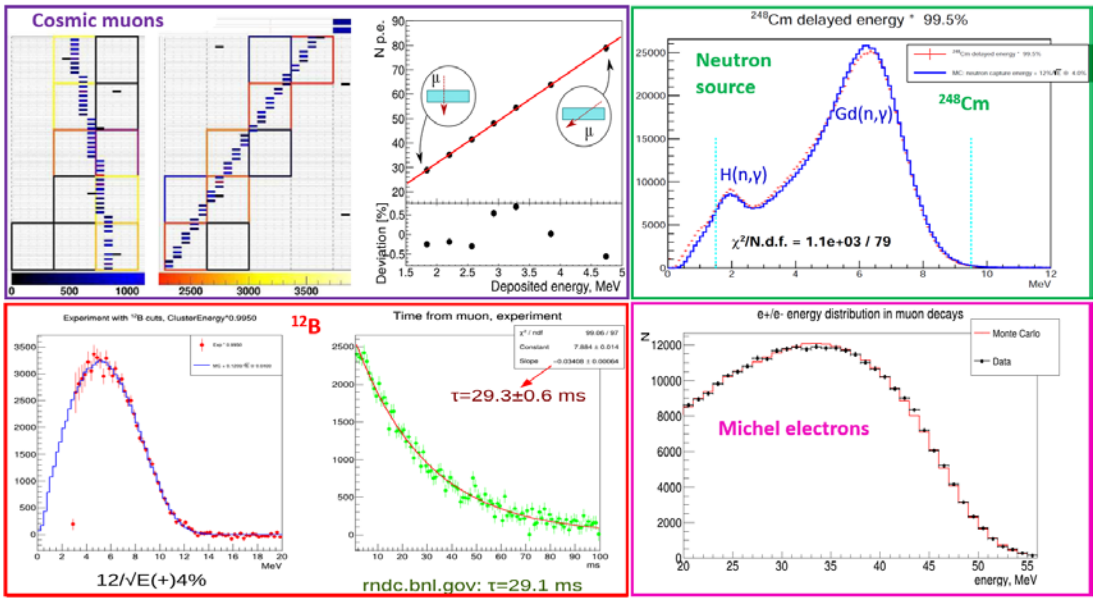

Figure 7. *Checking the linearity of the strip light yield on cosmic muons (top left), calibration on neutrons (top right), boron ^{12}B (bottom left) and Michel electrons form stopping cosmic muons (bottom right).*

The detecting reaction is inverse beta decay (IBD), due to the use of which and high segmentation of the detector, it is possible to effectively measure, filter and suppress all known background components: random coincidence background, background from cosmic muons and background from fast neutrons.

To calibrate the detector, cosmic muons, gamma (^{22}Na and ^{60}Co) and neutrons (^{248}Cm) sources, boron ^{12}B produced by cosmic muons and Michel electrons produced in the decays of stopping cosmic muons are used. Thus, the calibrations cover the wide

[1-50] MeV range, while the calibration accuracy, including all systematic errors, is ~1.7% (Fig. 7). 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. 8.

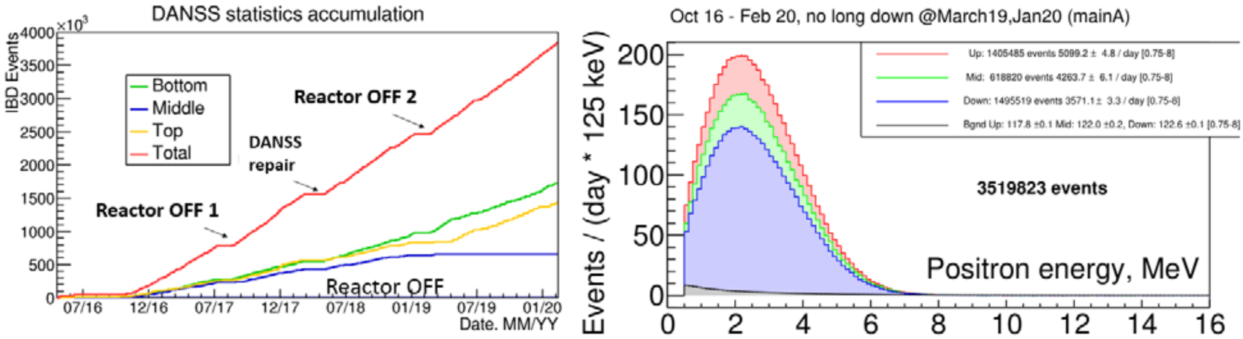

Figure 8. *Statistics of accumulated antineutrinos (left) and spectra of IBD-positrons in different positions of the detector minus all backgrounds (right).*

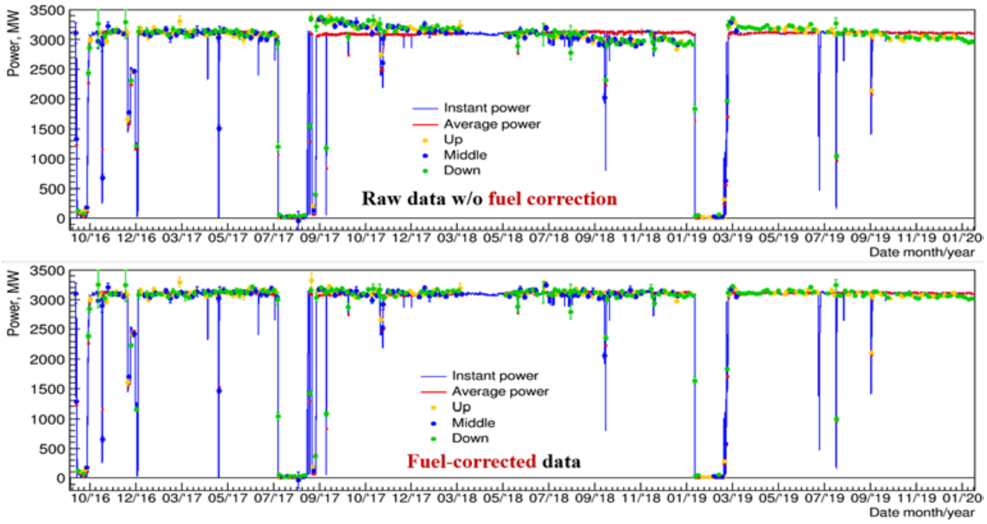

Figure 9. *Comparison of the reactor power (blue line) with the DANSS measurements (colored points of 3 positions) without (top) and with (bottom) fuel composition correction.*

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. 9).

The main DANSS result at the current moment (3M IBD-events in the Down/Up positions) is shown in Fig. 10. 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). For example, the graph shows the expected shape of this spectrum in the presence of oscillations corresponding to the best point RAA ($\sin^2(2\theta_{14})=0.05$, $\Delta m^2_{14}=2$ eV^2, orange curve) [1]. The presence of such oscillations is excluded at a significance level of more than 5σ. Figure 10 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, as can be seen from Fig. 1, which also shows the results of competitors.

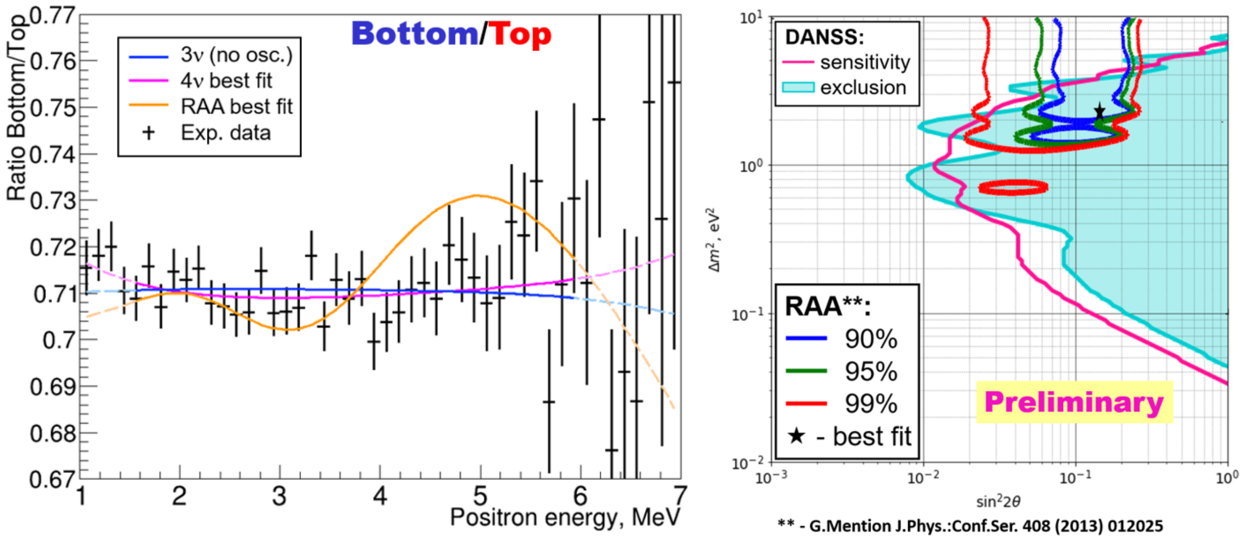

Figure 10. *The per bin ratio of the IBD-positron spectra measured at the Bottom/Top positions with a DANSS spectrometer (left). Region excluded by the current analysis is shown by cyan fill (right). The RAA best fit 3+1 model is shown by an orange curve on the left plot and by black star on the right plot.*

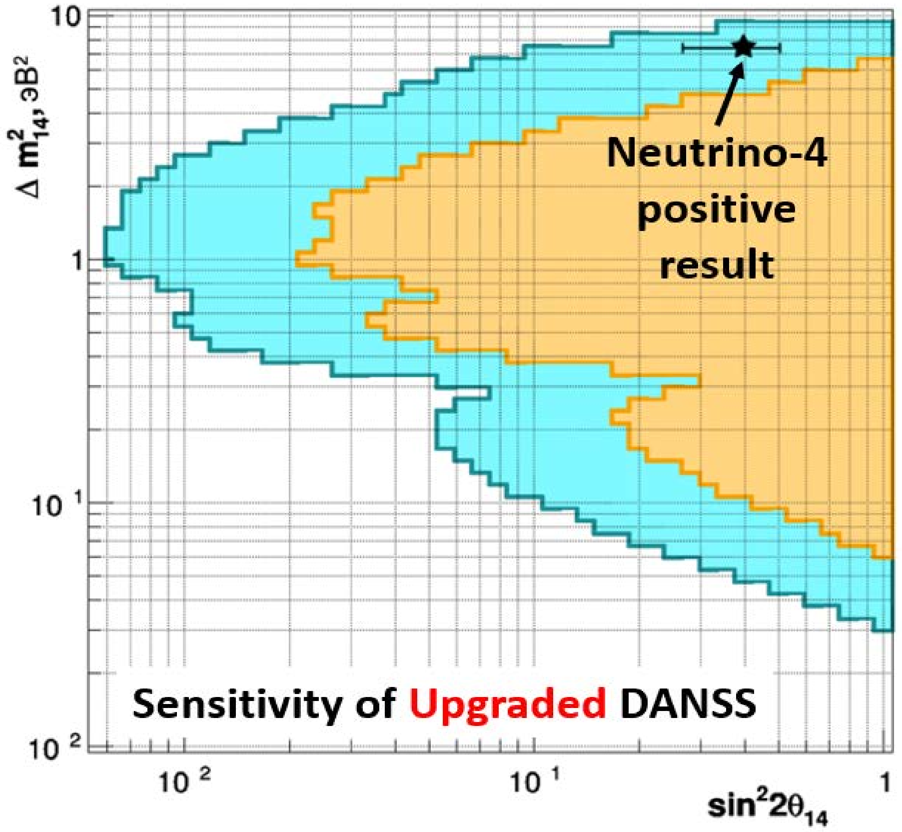

Figure 11. *Evaluation of the sensitivity of the upgraded DANSS-2 (cyan fill extension over orange fill set by the DANSS) based on the simulation results.*

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.

Unfortunately, in its current configuration, DANSS is not sensitive to the phase point of the positive signal declared by the NEUTRINO-4 experiment (see Fig. 2 and work [4]). 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 (see Fig. 11).

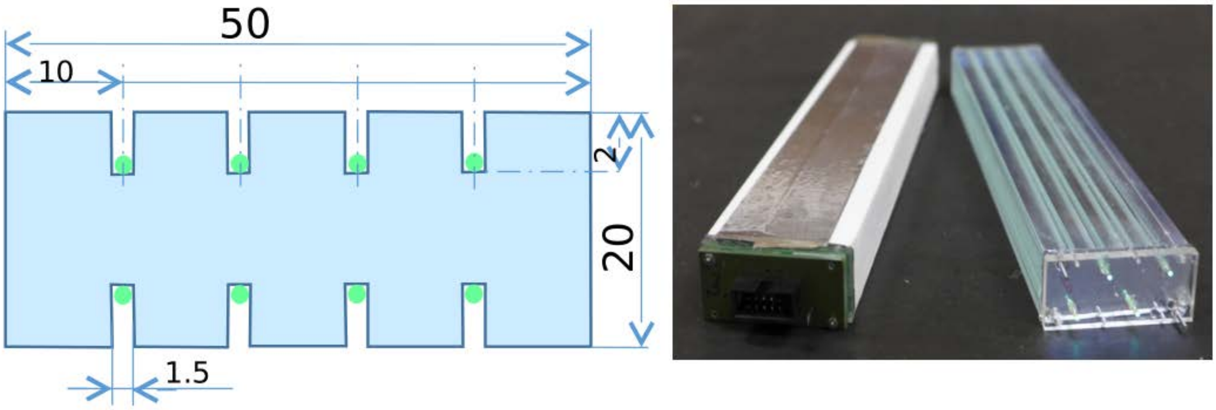

Figure 12. *Profile design of the DANSS-2 detecting element (left) and its prototypes (L = 1.2 m) used in test measurements (right).*

To achieve a good resolution, we need a **new detection element (NDE)**, the design of which is shown in Fig. 12. Compared with the old detecting element (ODE, see Fig. 3, left) it has a number of advantages:

- NDE will be made of high quality polymerized plastic scintillator. ODEs were made by extrusion and had low transparency.
- Light collection from LDE will be carried out using eight wavelength shifting fibers, read by eight SiPMs, 4 on each side.
- The NDE will be twice as thick as the NDE, which will make it possible to better measure (without dead layers) the low-energy IBD-positrons.

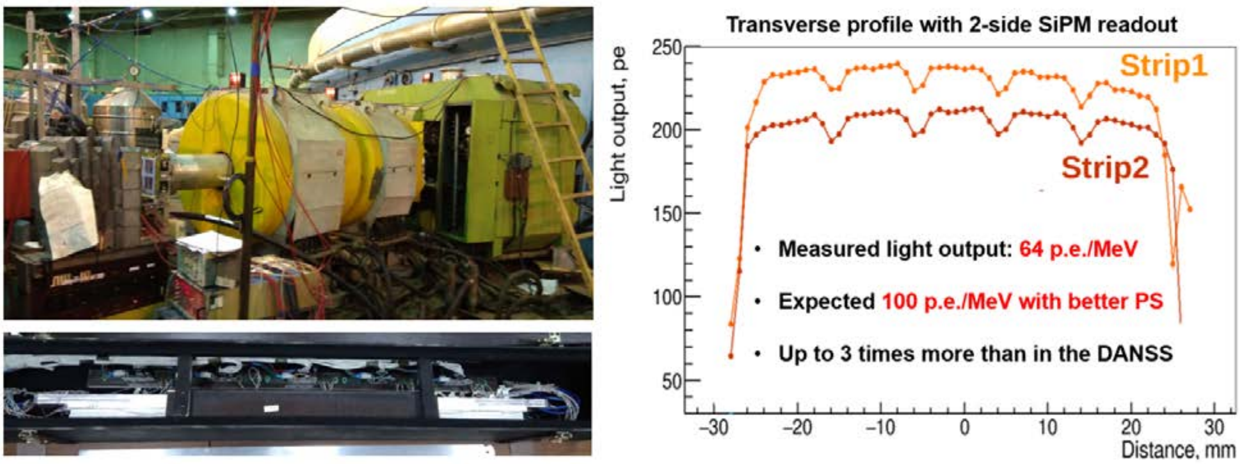

Figure 13. *Pion beam at PNPI, Gatchina (top left), NDE prototypes (bottom left) and test results of the light output profile from NDE (right).*

To check the characteristics of the NDE, two prototypes were made, the test of which on a pion beam of PNPI (Gatchina) showed a three times better light yield compared to the ODE (see Fig. 13) and a spatial resolution ± 15 cm along the strip length. At the same time, old plastic scintillators (PS) were used for prototypes, new strips for DANSS-2 will be produced with definitely better characteristics (see Fig. 14 below).

A principal decision for upgrade is to keep the same: a) passive shield; b) active shield; c) mobile platform; d) DAQ. This will reduce costs and time of upgrade. But the central part of the detector will be totally replaced. The new core of the DANSS-2 spectrometer will be assembled from 60 layers of 24 NDE (2x5x120 cm^3, Fig. 12) with orthogonal layer packing, as in DANSS (see Fig. 3, right). Light collection will be done only by SiPMs, which works well in DANSS. Remove of PMTs will allow using the vacated space (red box in Fig. 5 on the right) for NDE elongated by 20 cm. As a result, the volume of the detector will increase 1.7 times, and the counting rate will increase 2 times.

Polyethylene film with **gadolinium oxide (neutron capturer)** will be placed between the strips. Simulations have shown that an optimal film (200 μm, 25% of gadolinium oxide) will provide 90% of neutron captures on gadolinium. At the same time, the mass of the dead layers will be significantly reduced (6 times, 2% of the mass of gadolinium in DANSS-2 compared to 12% in DANSS), the detector will become more homogeneous and sealed.

Table 1. *Contributions to energy resolution from different factors: DANSS vs. DANSS-2.*

Source	Contribution to energy resolution			
	DANSS		DANSS-2	
	Value, %/√E	Remark	Value, %/√E	Remark
Statistics, including cross talk and first dinodes	18,3	30 p.e./MeV	11,1	80 p.e./MeV
Longitudinal coordinate information	10,8	Only for 2-layer and neutron hits	3,3	For all strips by time in 2-side readout
Annihilation gammas	9,8		5,0	Less by knowing both coordinates for all hits
Transverse profile	7,8		2,3	
Dead layer of Gd cover	17,0	12% of the mass of strips	7,0	2% of the mass of strips
Unknown materials in dead layers	17,0		5,0	Less due to significantly better detector uniformity
Final resolution (sum of squares)	**34,4**		**15,4**	

New NDE mounts, frontend electronics (preamplifiers and commutation boards) with drastically reduced power consumption (up to 50 W from the current 350 W) will be used. Finally, a new copper mounting frame will be designed with cooling systems down to 15° to reduce noise and SiPM x-talks.

Detectors. New SiPM S13360-1350PE with significantly lower noise and x-talks will be used. The output from four SiPMs on one side of the strip will be combined into one channel to keep the same number of channels in the DAQ, while individual SiPM on/off and voltage regulation control will be provided for tunings and calibrations. Double-sided light collection from NDE will make it possible to determine the coordinates of hits along the strip length with an accuracy of ~ ± 15 cm.

DAQ. No common trigger logic will be used. All signals above 3 pixels (~ 40 keV) in sums from two sides and at least 1 pixel on each side will be recorded. For the expected noise level (40/2 kHz for single/multi pixel hits, taking into account the cooling down to 15^o) and a standard firmware time resolution of 50 ns we will get 8 Hz noise signals per strip and ~ 3 MB/s of raw data for the entire DANSS-2 compared to ~7 MB/s in DANSS. The assembly of events will take place offline, using 125 MHz time stamps. Bench tests of this approach were carried out by our colleagues from ITEP and have confirmed the efficiency of the method proposed.

The contributions of various factors to the energy resolution of the DANSS and DANSS-2 spectrometers are summarized and compared in Table 1.

The working 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 NDE 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

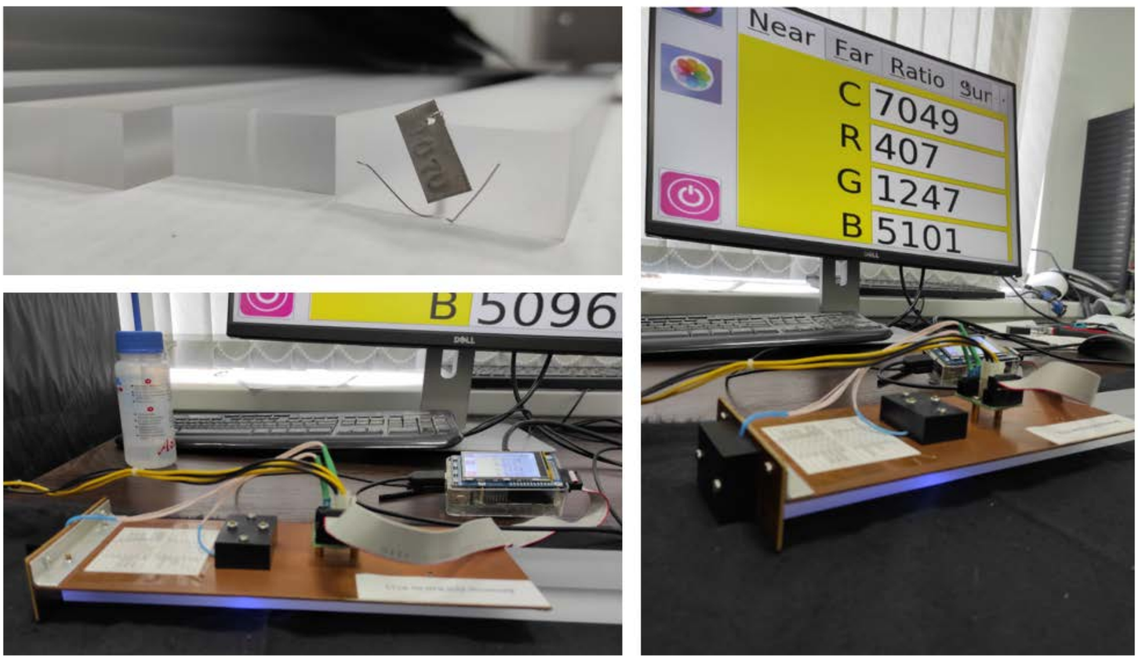

Figure 14. *New strips (top left) and a test bench for certification (light output measurement) of strips (the rest in different focuses).*

Estimates of time intervals were made conservatively, therefore, with a successful coincidence of circumstances, it is possible to accelerate the upgrade process up to six months, and the physical launch of DANSS-2 is possible at the beginning of 2023.

In October 2020, we received the first trial batch of new strips, the test stand was organized in the laboratory to check the light output and certification of the strips (see Fig. 14). By the end of the year, it is planned to fine-tune the procedures for certification and shipment of strips according to the schedule of the process described above. Next year, regular (30-60 strips per week) production, testing and shipping of strips will begin.

Other plans. In addition to the main task of spectrometer upgrade, a set of other activities will be carried out within the framework of the project.

The maintenance of the DANSS spectrometer. The detector continues to collect data, presumably until the end of 2022, and the support of its operation is entirely the responsibility of the JINR group.

Data analysis continues with the efforts of all participating groups. We continue to study in detail the systematic errors of the spectrometer - the neutron background, refinement of calculations on the composition of nuclear fuel, improvement of the methodology for calculating the sensitivity and exclusion regions, improvement of calibrations, refinement of simulations. Among the new ideas, we note the plans for using **machine learning** methods in processing experimental data. We are talking about using neural networks to determine IBD-signals. Both signals from antineutrinos - a positron (fast) and a neutron (delayed) - have characteristic patterns in the spectrometer, which can be efficiently isolated by filtering out the background using new Big Data processing technologies. The main ultimate goal here is the publication by the end of 2022 of the final results obtained by DANSS in relation to oscillations in sterile neutrinos, taking into account the accumulated knowledge about the installation and experiment.

Finalization of the S^3 spectrometer. The **S^3** detectors are of interest to our Czech colleagues (Institute of Technical and Experimental Physics of the Czech Technical University in Prague, ČVUT, ÚTEF) with the assistance of the JINR group. Taking into account the conducted R&D, the S^3 concept for today appears as follows (see Fig. 15).

The detector will be assembled from 80 polystyrene-based scintillator plates having a size of 40 × 20 × 1 cm^3 and produced by NUVIA (formerly ENVINET) using the "between glasses" technology, assembled into a cube 40 × 40 × 40 cm^3 (Fig. 5) ... A gadolinium-containing film based on Tyvek, manufactured by the same company (similar to the upgraded DANSS-2) will be placed between layers.

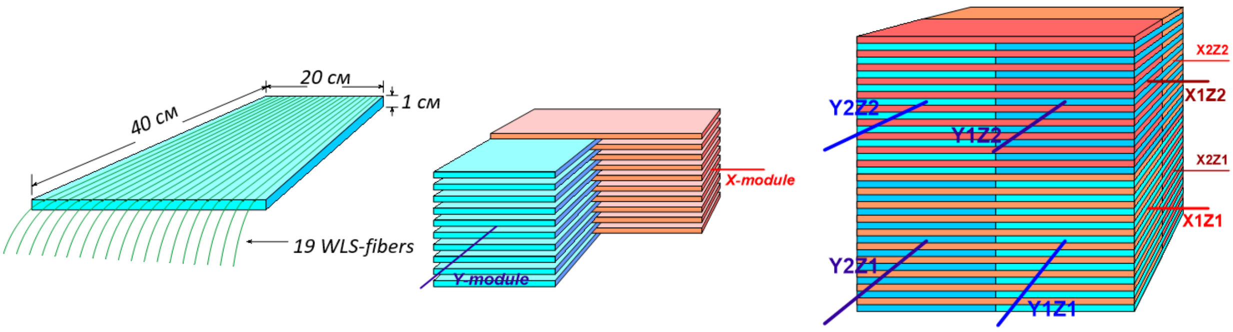

Figure 15. *Concept of the S^3 spectrometer with a volume of 64 liters.*

Every 10 plates are combined into an X- or Y-module - the experience of the DANSS clearly shows the usefulness of such a layered structure for background suppression. The light signal is collected using WLS-fibers glued into the grooves with a step of 1 cm. Light collection will be organized on both sides on the SiPM similar to the DANSS-2 technique. The light output is expected to be around 75-80 p.e. @ MeV. When the S^3 detector is installed in the same room as the A336 (at the Kalinin NPP), the detector will register 300-400 neutrino events per day, which is quite enough for diagnostic tasks.

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4. A.P. Serebrov et al. Preparation of the Neutrino-4 experiment on search for sterile neutrino and the obtained results of measurements. e-Print: 2005.05301 [hep-ex].

Public scientific activity

Publications and presentations. The results of the DANSS project are presented in numerous publications (the full list is available at the link https://docs.google.com/document/d/1lhhx4SM67YcPC70vEBbjrAPLN2djnjAVpy-KeFiHEnQ/edit?usp=sharing), and in the form of reports at conferences of various levels. Below is a **list of recent reports** made by members of the JINR group (the full list of reports is available at https://docs.google.com/document/d/1jEklwWMMAnzdhjF_gG1yVE2JmDv-M3KmHQJ7N1S83GM/edit?usp=sharing).

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

Ph.D. Two DANSS project participants successfully defended their dissertations in 2019. Daniya Zinatulina (http://ftp.jinr.ru/dissertation/Zinatulina_autoref.pdf) and Mark Shirchenko (http://159.93.39.20/dissertation/Shirchenko_autoref.pdf). They are currently leading their own MONUMENT project, which is now carrying on under the same theme as current project. Currently, I. Zhitnikov, M. Fomina, V. Belov and S. Kazartsev are working on dissertations; defenses are planned in 2022-2024.

Estimation of human resources

DLNP JINR staff: continuation of work with the **DANSS** detector (duty at the facility, data processing and analysis, current repair); development, creation, start-up and operation of the **DANSS-2** detector at the KNPP (R&D, installation, electronics, analysis), completion of the **S^3** detector.

Table 3. *List of project participants of the JINR group and their tasks.*

JINR member			DANSS		DANSS-2		
			Types of work on neutrino spectrometers				
Surname, Name	*Position*	*FTE portion*	*Service of the spectrometer*	*Data analysis, simulation*	*R & D*	*Installation*	*Data analysis, simulation*
Brudanin V.B.	leading researcher	0.1	Coordination of all works				
Shitov Yu.A.	head of sector	0.5	Management of all works				
Belov V.V.	junior researcher	0.3	+	+	+	+	+
Volnyh V.P.	leading engineer	0.1		+			+
Zhitnikov I.V.	researcher	0.5	+	+	+	+	+
Kazartsev S.V.	junior researcher	0.2	+		+	+	+
Kiyanov S.P	senjor engineer	0.2	+		+	+	
Kuznetsov A.S.	engineer	0.9	+		+	+	+
Mamedov F.	senior researcher	0.5		+	+	+	+
Machihilyan I.V.	senjor engineer	0.5		+			+
Medvedev D.V.	researcher	0.3	+			+	
Pushkov D.S.	senjor engineer	0.3	+			+	
Rozov I.E.	engineer	0.4			+	+	
Salamatin A.V.	senior researcher	0.1		+	+	+	
Filosofov D.V.	head of sector	0.1			+	+	
Fomina M.V.	junior researcher	0.4		+	+	+	+
Shevchik EA	senjor engineer	0.2	+		+	+	+
Total FTE		**5.6**					

The ITEP and LPI RAS participants (Moscow) : I. G. Alekseev, A. Ershova, A. S. Kobyakin, V. M. Nesterov, K. A. Perminov, V. Yu. Rusinov, E.I. Samigullin, D.N. Svirida, N.A. Skrobova, A.S. Starostin, E.I. Tarkovsky, A.E. Yakovleva - participation in the maintenance and analysis of data from the DANSS detector, as well as the development, creation, launch and analysis of data from the upgraded DANSS-2 spectrometer.

The ÚTEF ČVUT participants (Prague): M.Špavorová, L. Fajt, R. Hodák, Z. Hons, P. Přidal, E. Rukhadze, I. Štekl – development, creation, launch, maintenance and analysis of S^3 detector data.

Estimation of budgets

Form No. 26

Schedule proposal and resources required for the prolongation of the Project

Detector of the reactor antineutrino based on solid state plastic scintillator DANSS

Expenditures, resources, financing sources			Costs (k$) Resource Require-ments	Proposals of the Labora-tory on the distribution of finances and resources		
				1st yr	2nd yr	3rd yr
Expenditures		Materials for the DANSS-2 detector (strips, SiPM, fibers, etc.)	520	180	160	180
		Consumables (optical glue, connectors, cable, etc.)	30	10	10	10
		Materials for S^3 (fibers, electronics, computers)	30	10	10	10
		Total	**580**	**200**	**180**	**200**
Required resources	Standard hour	Resources of – Laboratory design bureau – Laboratory experimental workshop	300 600	100 200	100 200	100 200
Financing sources	Budgetary resources	Budget expenditures including foreign-currency resources.	**580**	**200**	**180**	**200**
	External resources	Contributions by collaborators. Grants.	0	0	0	0

PROJECT LEADER

SWOT

Strengths of the project:

- Based on a solid plastic scintillator with a gadolinium neutron absorber, the DANSS spectrometers, the future DANSS-2 and S^3 have no restrictions on placement near industrial reactors. The use of plastic scintillators to create detectors operating on the surface and with the possibility of mobile movement (placed on the chassis of a truck) is a modern trend in the creation of detectors for monitoring reactors (projects **CHANDLER**, **CORMORAD**, **PANDA**);
- Being installed 10 meters under the WWER-1000 reactor, the detector is irradiated with a record high neutrino flux - 5×10^{13} $cm^{-2}s^{-1}$ (in such good conditions, L. Mikhaelyan's group at the Rivne NPP managed to work in the late 80s, however, with a less powerful WWER-440 reactor);
- Covered from above by a large mass of hydrogen-containing substance (~ 50 m of water equivalent), it is not affected by the hadronic component of the cosmic background (something similar was only in the conditions of the now liquidated underground military reactor in Krasnoyarsk);
- A high degree of segmentation facilitates the identification of neutrino events, suppression and accurate determination and suppression of all background channels. Segmentation is now a mandatory element in almost all projects in our direction;
- Regular (3 times a week) movements of the spectrometer eliminate most of the systematic errors in oscillation studies. In our project it was first proposed to make the movable detector, the same approach is now used in Neutrino4 and is proposed in some other projects.

Weaknesses include:

- Low energy resolution due to several factors - poor transparency of scintillation strips made by extrusion, high attenuation in WLS fibers, the presence of dead layers of variable thickness between the scintillator layers, inhomogeneity of photocathodes of compact PMTs. Fortunately, all these disadvantages are planned to be overcome in the DANSS-2 and S^3 detectors;
- The complex internal structure does not allow accurate calculation of the absolute efficiency of the detector. Again, the redesigned DANSS-2 and S^3 will have a more uniform structure and less dead layers;
- The scintillator based on polystyrene contains one and a half times less hydrogen atoms (~ 7.7% wt.) Than the widely used liquid scintillator based on LAB (~ 11.5% wt), which directly affects the detection efficiency of antineutrino.

For these reasons, the DANSS detector is not a precision instrument for measuring the precise shape of a reactor antineutrino spectrum. However, it should be emphasized that the new detectors DANSS-2 and S^3 will have greater capabilities in this regard due to significantly improved energy resolution, less dead materials inside and better homogeneity.