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EXPERIMENT FOR SEARCH FOR STERILE NEUTRINO AT SM-3 REACTOR

A. P. Serebrov[1,*], *V. G. Ivochkin*[1], *R. M. Samoylov*[1], *A. K. Fomin*[1], *V. G. Zinoviev*[1], *P. V. Neustroev*[1], *V. L. Golovtsov*[1], *N. V. Gruzinsky*[1], *V. A. Solovey*[1], *A. V. Cherniy*[1], *O. M. Zherebtsov*[1], *V. P. Martemyanov*[2], *V. G. Zinoev*[2], *V. G. Tarasenkov*[2], *V. I. Aleshin*[2], *A. L. Petelin*[3], *S. V. Pavlov*[3], *A. L. Izhutov*[3], *S. A. Sazontov*[3], *D. K. Ryazanov*[3], *M. O. Gromov*[3], *V. V. Afanasiev*[3], *L. N. Matrosov*[1], *M. Yu. Matrosova*[1]

[1] Petersburg Nuclear Physics Institute, Gatchina, Russia

[2] National Research Centre "Kurchatov Institute", Moscow

[3] State Scientific Centre — Research Institute of Atomic Reactors, Dimitrovgrad-10, Russia

In connection with the question of possible existence of sterile neutrino, the laboratory on the basis of SM-3 reactor was created to search for oscillations of reactor antineutrino. A prototype of a neutrino detector with scintillator volume of 400 l can be moved at the distance of 6–11 m from the reactor core. The measurements of background conditions have been made. It is shown that the main experimental problem is associated with cosmic radiation background. Test measurements of dependence of a reactor antineutrino flux on the distance from a reactor core have been made. The prospects of search for oscillations of reactor antineutrino at short distances are discussed.

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INTRODUCTION

At present there is a widely spread discussion of possible existence of a sterile neutrino having much less cross section of interaction with matter than, for example, reactor electron antineutrino. It is assumed that owing to reactor antineutrino transition to sterile condition, oscillation effect at a short reactor distance and deficiency of a reactor antineutrino beam at a long range are likely to be

*E-mail: serebrov@pnpi.spb.ru

observed [1, 2]. Moreover, sterile neutrino can be regarded as a candidate for the Dark Matter.

We have studied the possibility of carrying out new experiments at research reactors in Russia. These are research reactors that are required for performing such experiments as they possess a compact reactor core center and can be situated at a sufficiently small distance from possible location of a neutrino detector. Unfortunately, the research reactor beam hall has a fairly large background of neutron and gamma quanta, which makes it difficult to perform low-background experiments. Due to some peculiar characteristics of its construction, SM-3 reactor provides the most favorable conditions for conducting an experiment on search for neutron oscillations at short distances.

1. SM-3 REACTOR

Initially, 100-MW SM-3 reactor was designed for carrying out both beam and loop experiments. Five beam halls were built, separated from each other with big concrete walls as wide as ~ 1 m (Fig. 1). This enabled to carry out experiments on neutron beams, without changing background conditions at neigh-

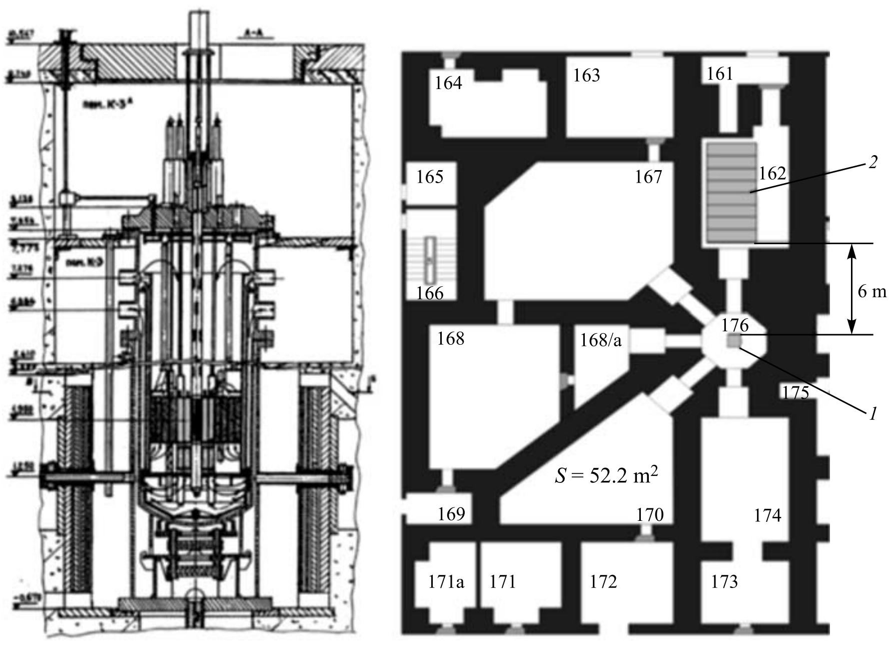

Fig. 1. Detector location at SM-3 reactor: *1* — reactor core; *2* — antineutrino detector

boring installations. Later on, the main experimental program was focused on the tasks concerned with irradiation in the reactor core center. For 25 years a sufficiently high fluence had been accumulated on materials of the reactor cover, which necessitated its replacement. Setting a new reactor cover into an old reactor tank was the simplest decision to be taken. Such a decision, however, resulted in raising a reactor core center by 67 cm higher than the previous position.

Horizontal beam channels were sacrificed for the sake of priority of loop experiments. Neutron flux in the location place of the former beam channels was decreased by four orders of value. Respectively, it caused decrease in neutron background in the former beam halls, which became about $4\cdot10^{-3}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ (on thermal neutrons). It is approximately by 4–5 orders of value lower than a typical neutron background in the beam hall of a research reactor. Lately in making preparations for an experiment on search for transitions of reactor antineutrino to sterile state by SM-3 reactor, upgrading of slide valve of the former neutron beam has been completed. As a result, the background of fast neutrons has dropped to the level of a few units by $10^{-3}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$, i.e., practically, to the level of neutron background on the Earth surface caused by cosmic radiation. These conditions are most preferable for a neutron experiment to be performed. Other advantages of SM-3 reactor are a compact reactor core center $(35\times42\times42\ \mathrm{cm})$ with high reactor power being equal to 100 MW, as well as sufficiently short distance (5 m) from the center of a reactor core to the walls of an experimental hall. Besides, of special significance is the fact that an antineutrino beam can be measured within a sufficiently wide range from 6 to 13 m. Up to $1.8\cdot10^3$ neutrino events are expected to occur per day at the reactor power of 100 MW, at the distance of 6 m from a reactor core, in the volume of 1 m^3.

2. PASSIVE SHIELDING OF A NEUTRINO DETECTOR AT SM-3 REACTOR

Layout of passive shielding from the outside and inside is given in Fig. 2. It is created from elements based on steel plates 1×2 m, 10 mm thick, to which six sheets of lead as thick as 10 mm are attached. The cabin volume is $2\times2\times8$ m. From the inside the cabin is covered with plates of borated polyethylene 16 cm thick. The total weight of passive shielding is 60 t, the volume of borated polyethylene is 10 m^3. Inside the passive shielding there is a platform with the antineutrino detector which can be moved with a step motor along the rails within the range of 6 to 12 m from the reactor core center. A neutrino channel can be entered by means of a ladder through the roof with the removed upper unit, as shown in Fig. 2. Loading of the detector into a neutron channel is carried out from the main hall through a trap door in the building ceiling. In this case an overhead crane of the main hall is used.

Fig. 2. General view of passive shielding: from the outside and inside. The range of detector dislocation is 6–12 m from the reactor core center

3. A NEUTRINO DETECTOR MODEL

With a view of preparation for the experiment Neutrino-4 by SM-3 reactor [3–6] we did an experimental research with a detector model Neutrino-4 at WWR-reactor. An experimental task was to register reactor antineutrino in the conditions of high background of cosmic radiation on the surface of the Earth as well as in the conditions of neutron and gamma background in an experimental hall of a research reactor. This experiment was to investigate principal possibility of performing such an experiment by SM-3 reactor. The experiment demonstrated that of main difficulty is the background of cosmic radiation producing correlated events which are difficult to distinguish from those of reactor antineutrino recordings. Neutron and gamma background in an experimental hall can be suppressed by 4–5 orders of value with passive shielding made of lead, borated polyethylene, and concrete. It is to be noted that the most optimal sequence of placing protection layers is as follows: concrete is to be located outside, followed by lead, and then borated polyethylene inside. An internal layer of borated polyethylene is absolutely necessary, as it provides protection from neutrons emitted on lead by muons. Moreover, this process is likely to give rise to correlated events. After testing the detector model was transported to SM-3 reactor.

The detector model scheme Neutrino-4 is shown in Fig. 3. The detector volume $0.9 \times 0.9 \times 0.5$ m is filled with liquid scintillator with addition of Gd. The detector makes use of 16 photoelectron multipliers PMT-49b located on the upper surface of the detector. The scintillation type detector is based on using the reaction $\tilde{\nu}_e + p \to e^+ + n$. At the first moment, the detector registers positron, whose energy is determined by antineutrino energy, and also registers two annihilation gamma quanta with energy 511 keV each. At the second moment, neutrons emerging in reaction are absorbed by Gd to form a cascade of gamma quanta with total energy of about 8 MeV. The detector keeps records of two subsequent signals from positron and neutron — the so-called correlated events.

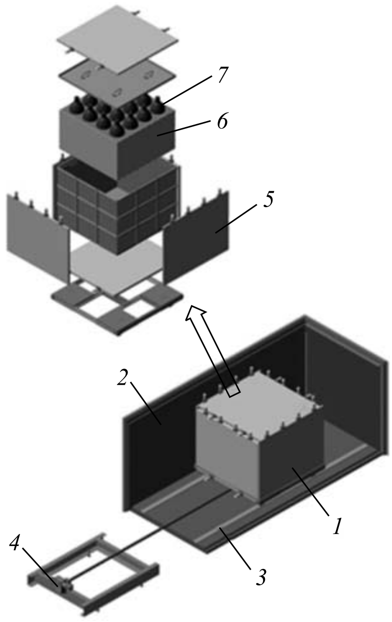

Fig. 3. Detector layout: *1* — detector of reactor antineutrino; *2* — passive shielding made of lead (6 cm) and borated polyethylene (16 cm); *3* — rails; *4* — device for detector displacement; *5* — plates of active shielding; *6* — liquid scintillator; *7* — PMT

The antineutrino spectrum is restored from that of positron, since in the first approximation the relationship between positron energy and that of antineutrino is linear: $E_{\tilde{\nu}} = E_{e^+} + 1.8$ MeV. Scintillator material is made up of mineral oil with added Gd 1 g/l. Light output of scintillator BC-525 is 10^4 photons for 1 MeV. The detector is surrounded by six scintillation plates as big as $0.9 \times 0.9 \times 0.03$ m, with photoelectron devices being anticoincidence shielding from cosmic muons. After conducting test experiments at WWR-M reactor, research on a neutron detector model was carried out at SM-3 reactor, where by that time a neutron laboratory and passive shielding of the detector had been prepared.

4. INVESTIGATION OF COSMIC BACKGROUND

The neutrino detector model involved can be used for cosmic ray registration and gamma quanta from radioactive contaminations. Figure 4 presents the neutrino detector model spectrum, which can be conventionally divided into four parts.

The first part of it up to 2 MeV is relevant to radioactive contamination background, the second one from 2 to 10 MeV covers the registration neutron

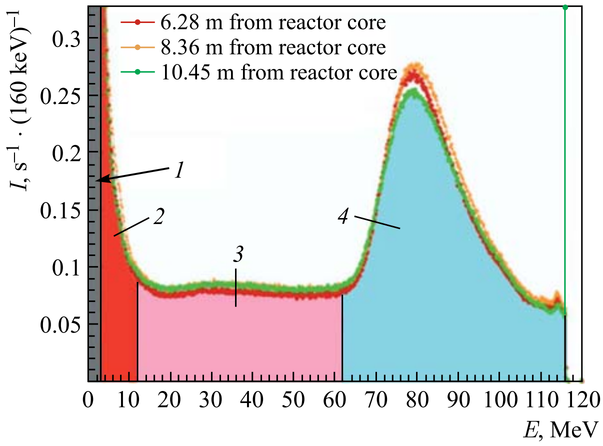

Fig. 4. Detector energy spectrum at different distances from reactor core and conventional division of spectrum into zones: *1* — radioactive contamination background; *2* — neutrons; *3* — cosmic radiation soft component; *4* — muons

area, since it corresponds to gamma-quanta energy at neutron capture by Gd. The range from 10 to 60 MeV is relevant to cosmic radiation soft component produced by muon decay and muon capture in substance. And finally, the range from 60–120 MeV is related to muon component passing through the detector. Here are also shown small alterations of spectrum shape for different detector positions.

In the course of long-term measurements temporary variations of cosmic radiation intensity were found. They are caused by fluctuations of atmospheric pressure and temperature drift during season changes. It is a well-known barometric and temperature effect of cosmic rays [7–9]. Muons are formed in the upper layers of the atmosphere. Higher pressure gives rise to a larger amount of substance over the detector and to intensity attenuation of cosmic rays. Figure 5 shows anticorrelation effect between atmospheric pressure and total intensity of rigid and soft components of cosmic radiation, i.e., within energy range from 10 to 120 MeV. This effect is barometric.

Behavior of rigid and soft components is distinguished by presence of additional long-term drift, with the drift sign being opposite for rigid and soft components. It is the so-called temperature effect which is interpreted in the following way. At temperature rise of the lower atmospheric layers, their expansion results in raising the height of the layer forming muon fluxes. Because of increase on the way to the Earth the share of the decayed muons increases. Thus, rigid component intensity (muons) decreases and soft component intensity (decay products: electrons, positrons, gamma quanta) rises.

As a result of studying background conditions for performing an experiment on search for neutrino oscillations at short distances, it became clear that back-

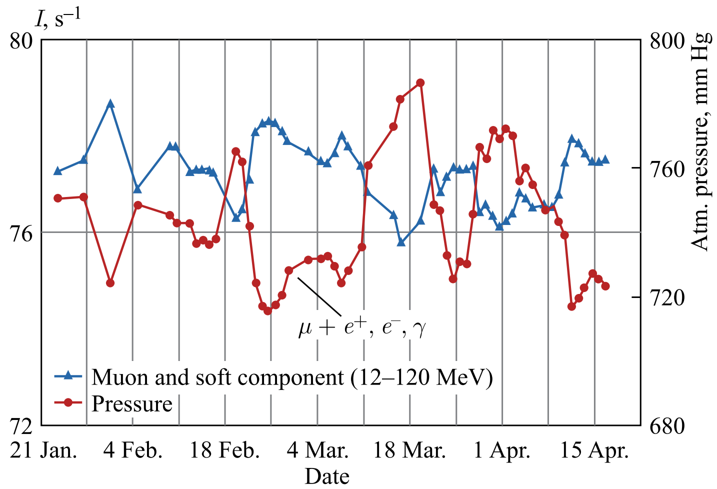

Fig. 5. Barometric effect of cosmic rays: the left axis shows summary detector count rate in the areas 3 and 4, the right axis shows atmospheric pressure, horizontal axis gives the measurement time since 21 January – 15 April 2014

ground conditions were extremely unfavorable. Cosmic background depends on the distance from the reactor core center because of distribution of concrete structure of the building. Moreover, cosmic background is changing with time due to atmospheric pressure and temperature fluctuations in lower atmosphere layers. However, the following ways of overcoming these problems can be suggested. Firstly, one can implement monitoring of cosmic ray intensity regarding a higher energy part of the detector spectrum starting with 10 MeV. Applying monitoring data, one can introduce corrections for a cosmic ray background. Secondly, measurements of the distance dependence should be made by means of scanning the distance in the moving mode from one point to another every 45–60 min. Thus, the total range is measured for 4–5 h, which is less than the time of atmospheric pressure variation. It enables to average considerably the time variation effect of cosmic rays.

5. TESTING MEASUREMENT OF ANTINEUTRINO FLUX FROM SM-3 REACTOR AND ITS DISTANCE DEPENDENCE

5.1. Energy and Time Spectra of Correlated Events. As was noted earlier, in measuring antineutrino flux from the reactor the technique of correlated coincidences is employed for distinguishing the registration process of antineutrino — $\tilde{\nu}_e + p \to e^+ + n$. Figure 6 gives the spectrum of delayed coincidences. The background of random coincidences is subtracted. One can see two exponents

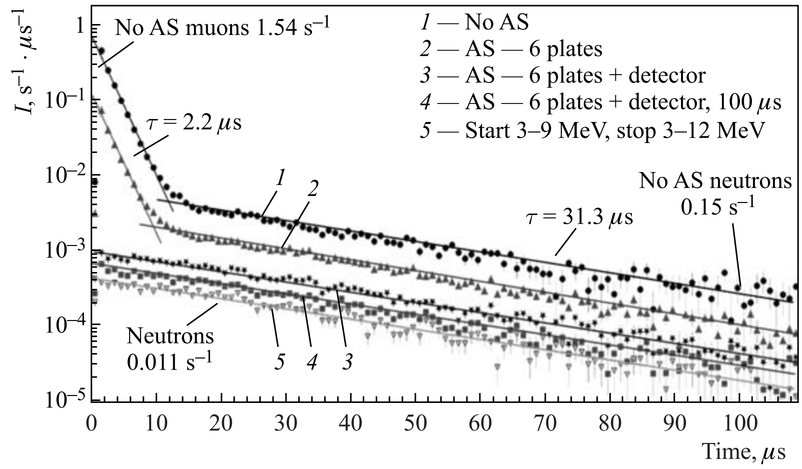

Fig. 6. Time spectra at different configurations of the active shielding: *1* — no active shielding; *2* — plates of the active shielding are on; *3* — the same + ban from the detector at signals higher than 12 MeV; *4* — the same + ban on 100 μs after the detector signal, at energy higher than 12 MeV, or after the signal in the active shielding; *5* — the same + limit on start and stop signals in ranges 3–9 MeV and 3–12 MeV, respectively

(straight lines in logarithmic scale), which correspond to a muon decay and a neutron capture by Gd. Without employing an active shielding, the integral under the first exponent corresponds to the muon stop rate 1.54 μs, and the exponent (2.2 μs) corresponds to a muon lifetime. The integral under the second exponent is relevant to the neutron capture rate in the detector 0.15 s^{-1}, and the exponent (31.3 μs) corresponds to neutron lifetime in the scintillator at 0.1% Gd concentration.

The number of muon stops per second corresponds to estimation on the muon flux and scintillator mass calculation, while the number of captured neutrons per second corresponds to the calculated rate of neutron formation in the detector itself, caused by a muon flux passing through it. It points out that, in general, one succeeded in solving the task under consideration by means of the passive shielding in combination with lead placed outside with 16 cm of borated polyethylene inside. Indeed, addition of 10 cm borated polyethylene upon the detector cover did not alter the neutron capture rate in the detector. Use of a ban from active shielding and the detector, which gives evidence for muon passing, allows one to suppress the capture rate by the detector to level of $1.8 \cdot 10^{-2}$ s^{-1}. Figure 6 presents the first version of the active shielding. Detailed studies of the active shielding are quoted in the next section.

The most essential experimental problem is the possibility of distinguishing correlated events against background of accidental coincidences. Figure 7

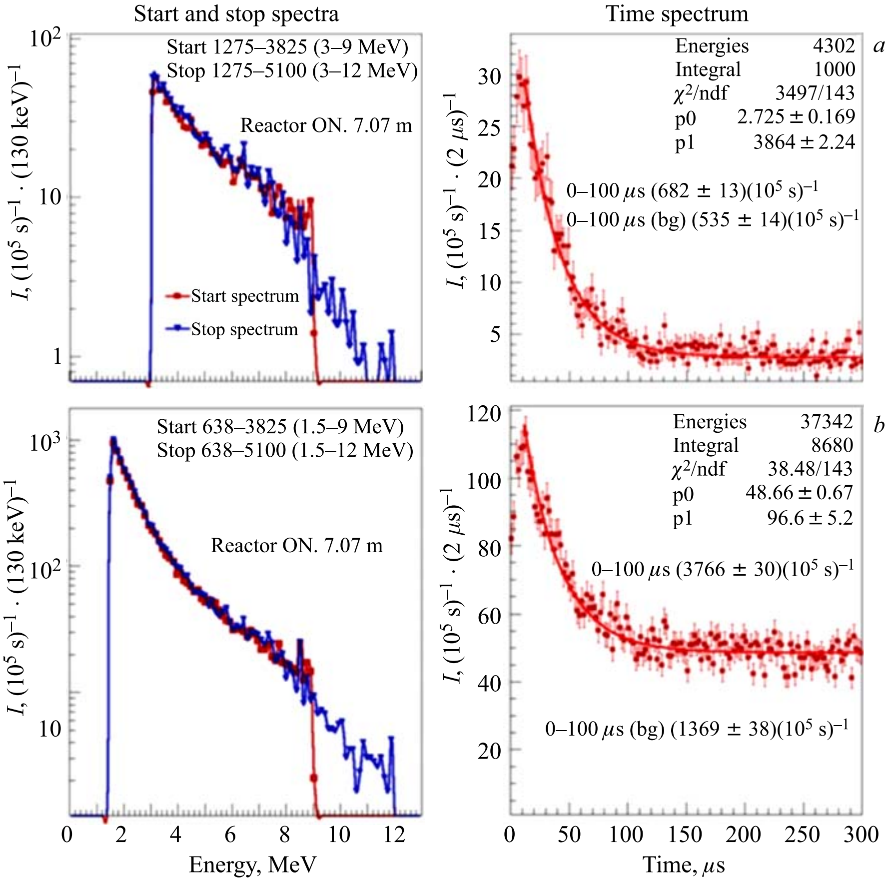

Fig. 7. Energy spectra of direct and delayed signals and time spectra: *a*) threshold of start and stop signals 3–9 MeV and 3–12 MeV, respectively; *b*) threshold of start and stop signals 1.5–9 MeV and 1.5–12 MeV, respectively

presents examples of correlation signal measurements. Measurements were made for 300 μs, the last 100 μs used for measuring background of accidental coincidences. At lower threshold of start and stop signals of 3 MeV, contribution of accidental coincidences is very small (Fig. 7, *a*). In decreasing the lower threshold the number of accidental coincidences increases, however, the number of correlated events grows (Fig. 7, *b*). Nevertheless, accuracy of correlated signal is not growing. Radioactive contamination background remains high enough. Unfortunately, its reduction does not seem to be possible for the time being. However, it should be noted, that a much more essential problem appears to be concerned with correlated background related to cosmic radiation, i.e., muons and fast neutrons.

Expected count rate of neutrino events is calculated with the following ratio: $n_\nu = (W_{\text{eff}}/E_f)\left(4\pi R^2\right)^{-1} N_p \sigma_f \varepsilon$, where W_{eff} — reactor thermal power, E_f — energy release per fission, including direct and delayed processes, $R = 7.07$ m — distance from the reactor core to the detector center, N_p — the number of protons in the detector, σ_f — efficient neutrino cross section per fission. The data from works [10, 11] were used for calculations. The number of expected neutrino events at reactor power 90 MeV at the distance of 7.07 m is $0.67 \cdot 10^{-2}$ s$^{-1} \times \varepsilon$, where ε is the detector efficiency on registration of occurring neutrino events according to reaction $\tilde{\nu}_e + p \to e^+ + n$.

Experimental number of registered neutrino events is determined as a difference at the reactor on and off. Figure 8, a gives the ratio of registered neutrino

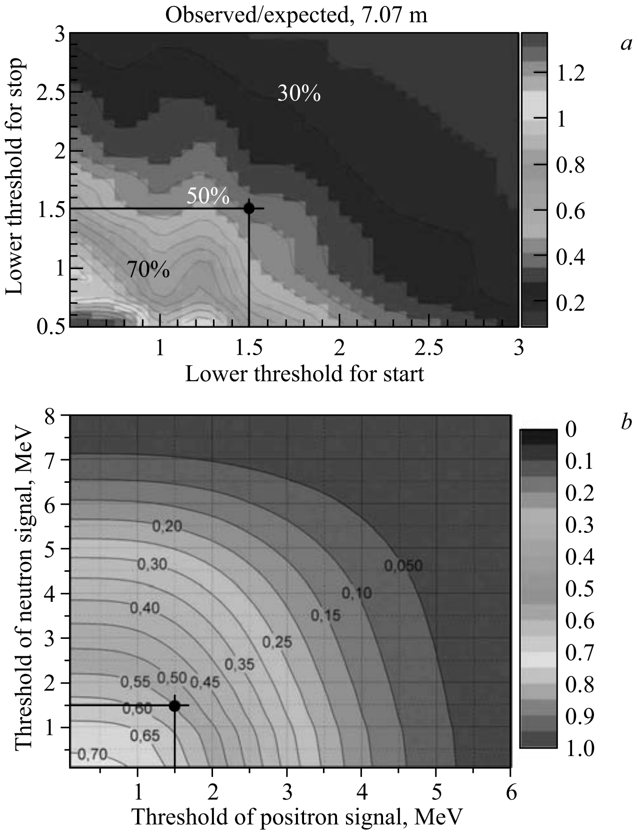

Fig. 8. a) Experimental efficiency on registration of antineutrino events depending on lower thresholds of registration of start and stop signals; b) registration efficiency of antineutrino events from Monte Carlo calculations depending on lower registration thresholds of start and stop signals

events to the total number of neutrino events depending on thresholds of start and stop signals for the detector position 7.07 m. For comparison, Fig. 8, b presents Monte Carlo calculation. At the lower 1.5 MeV threshold of start and stop signals registration efficiency of the reactor antineutrino is about 50%, which does not disagree with Monte Carlo calculation and an experimental estimation of neutron registration efficiency in an experiment with Cf source. Undoubtedly, estimation accuracy is rather approximate, i.e., on $\pm 15\%$ level.

5.2. Active Shielding of the Detector. The next stage of research was concerned with the active shielding of the detector. The first part of measurements was made with the first version of the active shielding, with scintillator plates 3 cm thick. Its application resulted in reducing the number of muon stops by 7 times to the level of 0.27 μs, with the number of neutron captures being reduced by 2 times to the level of 0.078 s^{-1} (Fig. 6). The next stage of suppressing correlated neutron events was to limit the energy of start signals from the detector to the level of 12 MeV. After that the count rate of neutron events dropped to $2.7 \cdot 10^{-2}$ s^{-1}. It turned out that it is reasonable to lock the detector for another 100 μs after the signal emergence in the detector at energy over 12 MeV or after the signal in the active shielding. This decreased count rate of correlated neutron captures in the detector to the level of $1.8 \cdot 10^{-2}$ s^{-1}. Finally, restriction of start and stop signals to the ranges 3–9 MeV and 3–12 MeV, respectively, decreased the neutron capture rate to the level of $1.1 \cdot 10^{-2}$ s^{-1}, with the number of expected neutrino events noticeably dropping.

The second version of the active shielding was made of plates 12 cm thick. In this case one succeeded in obtaining the effect-background ratio equal to 0.23 rather than 0.12 for the point nearest to the reactor (Fig. 9). As earlier this ratio 0.23 remains unsatisfactory to measure within a few percent accuracy dependence $1/R^2$, i.e., for search for neutrino oscillation. It is necessary to obtain the ratio equal to unit for the farthest point from the reactor. We assume the remaining background of correlated events to be mainly related to fast neutrons of cosmic background. Fast neutron produces a start signal via a recoil proton and gives a stop signal at absorbing the same neutron. Now we are undertaking investigation on separating signals according to an impulse shape, as a signal shape in recording a recoil proton or a positron must be different. We do hope to improve the signal-background ratio by increasing the detector efficiency due to enlarging the detector volume. The full scale detector volume is expected to be increased by 4 times.

To conclude, investigations with the external active shielding were carried on (external one with respect to the passive shielding). On the roof of the passive shielding over the detector the active shielding (umbrella) was installed made of scintillator plates 12 cm thick and the total area 2×3 m. Taking into account the fact that the detector area is 0.9×0.9 m, such an umbrella must capture the main muon flux flying into the neutrino detector area. As a result, it im-

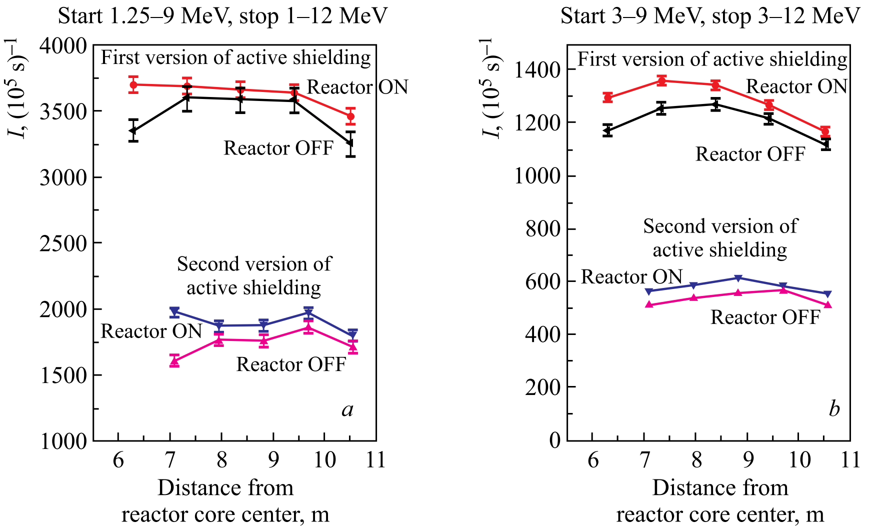

Fig. 9. *a*) Measuring results on count rate of correlated events for start signals within the energy range of 1.25–9 MeV and for stop signals 1–12 MeV at the reactor on and off, as well as for two versions of the active shielding; *b*) results of the same measurements for start signals within the energy range of 3–9 MeV and for stop signals 3–12 MeV

proved the effect-background ratio by 15% only and the ratio increased up to the level of 0.32. The remaining correlated background is likely to be related to fast neutrons which are only partly blocked by the active shielding. Thus, we mainly hope for employing the technique of signal separation according to the impulse shape.

5.3. Measuring the Dependence of Reactor Antineutrino Flux on the Distance from the Reactor Core Center. At the next stage measurements were made of antineutrino flux from SM-3 reactor and its distance dependence. Measuring results of correlated signals depending on distance with the reactor on and off were presented in Fig. 9. From the difference of these results the dependence of the reactor antineutrino flux on the distance from the reactor core center was derived (Fig. 10). Unfortunately, attempt to increase statistics for the sake of a wider energy interval does not improve the situation, since in a small energy area the contribution of correlated events from cosmic background is growing.

In order to verify that the difference effect is mainly relevant to antineutrino of SM-3 reactor, additional measurements were made, when another lining of borated polyethylene of 0.3 m was installed near the reactor wall. It could attenuate the flux of fast neutrons from the reactor 3–4 times. Measuring results with an additional wall show that difference decrease (reactor on – reactor off) was not found within the statistical measuring accuracy of 20%.

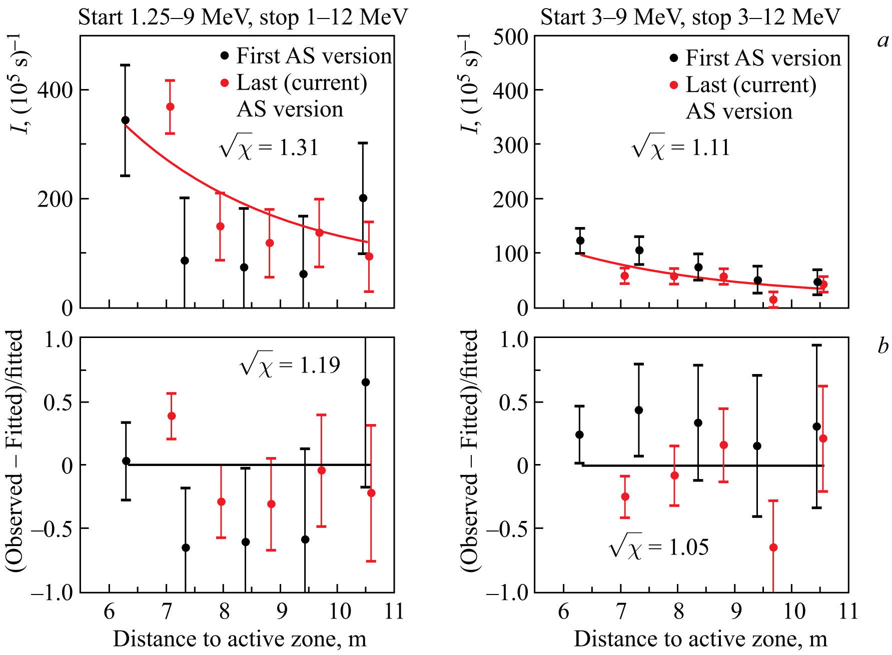

Fig. 10. *a*) On the left — dependence of count rate difference of correlated events (reactor on — reactor off) on distance from the reactor core center within the range of 1.25–9 MeV and for stop signals 1–12 MeV, on the right — the same for the energy range of 3–9 MeV and 3–12 MeV; *b*) treatment of the same data on deviation from the law $1/R^2$

CONCLUSIONS

Summarizing, the following conclusions can be done.

1. For the first time, an attempt was realized to measure the reactor antineutrino flux dependence at short distances (6–11 m) from the reactor core center. Undoubtedly, the accuracy is not sufficient for making conclusions concerning the statement of the task on search for a sterile neutrino. The task was only aimed at studying the possibility of performing such an experiment at the cosmic background level on the Earth surface and at the reactor operation background level. This experiment made use of a prototype of a small volume detector.

2. The main problem of this experiment is concerned with correlated background related to cosmic radiation. Cosmic background depends on the distance from the reactor core center due to the distribution structure of concrete mass of the building. Moreover, cosmic background is altering with time because of atmospheric pressure and temperature fluctuations in the lower layers of the atmosphere. However, to overcome these problems the following measures can be

suggested. Firstly, one can perform monitoring of cosmic ray intensity regarding the high-energy part of the detector spectrum starting with 10 MeV. Secondly, measurements on distance dependence should be made by the method of scanning distance. It provides considerable averaging of the temporary variation effect of cosmic rays.

3. Employment of the active shielding allows suppressing correlated background of cosmic radiation only by 66%. This cosmic background component seems to be related to muons. It can be controlled by the active shielding. The active shielding is practically not capable of controlling the neutron component, thus, it is required that the technique of separating signals from recoil protons and positrons according to impulse shape should be applied.

The carried out work gave enough information for development of the full-scale detector. At the moment the project of the full-scale detector with a full volume of 3 m^3 is developed. We assume that implementation of the project and the pulse shape discrimination method will bring the effect-background ratio closer to value of 1 and will considerably increase the statistical accuracy of the experiment. It will allow starting the studies connected with the search for oscillation of reactor antineutrino at short distances.

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