Current Results of NEUTRINO-4 Experiment

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Abstract. The main goal of experiment "Neutrino-4" is to search for the oscillation of reactor antineutrino to a sterile state. Experiment is conducted on SM-3 research reactor (Dimitrovgrad, Russia). Data collection with full-scale detector with liquid scintillator volume of 3m\textsuperscript{3} was started in June 2016. We present the results of measurements of reactor antineutrino flux dependence on the distance in range 6–12 meters from the center of the reactor. At that distance range, the fit of experimental dependence has good agreement with the law 1/L\textsuperscript{2}. Which means, at achieved during the data collecting accuracy level oscillations to sterile state are not observed. In addition, the spectrum of prompt signals of neutrino-like events at different distances have been presented.

1. Introduction
At present there is a widely spread discussion about possible existence of a sterile neutrino having much less cross-section of interaction with matter, compared, for instance, with that of a reactor electron antineutrino \cite{1, 2}.

To search for neutrino oscillation in sterile state one has to observe the deviation of reactor antineutrino flux. Oscillation process can be described by the following equation:

\[
P(\tilde{\nu}_e \rightarrow \tilde{\nu}_e) = 1 \sin^2 2\theta_{14} \sin^2(1.27 \frac{\Delta m^2_{14}[\text{eV}^2]\text{L[m]}}{E_{\tilde{\nu}_e}[\text{MeV}]})
\]

(1)

where $E_{\tilde{\nu}_e}$ is antineutrino energy, $\Delta m^2_{14}$ and $\sin^2 2\theta_{14}$ are the unknown oscillation parameters.

To carry out the model independent experiment it is required to perform measurements of antineutrino flux and spectrum at short reactor distances, e.g. 6 – 12 meters from almost point-like antineutrino source. Due to some peculiar characteristics of its construction, research reactor SM-3 provides the most favorable conditions for conducting the experiment \cite{3}. However, SM-3 reactor is at the Earth surface, hence cosmic background is the main difficulty with this experiment. Here we present last results of measurements of flux distance dependence and neutrino spectrum at different distances within range 6 – 12 m from reactor obtained with full-scale detector.
2. Full-scale antineutrino detector

Scheme of full-scale detector is presented in figure 1. The full-scale detector with liquid scintillator has volume of 3 m³ (5×10 sections). The scintillation type detector is based on IBD (inverse beta decay) reaction: $\nu_e + p \rightarrow e^+ + n$. Detector model was designed multi-sectional to distinguish between positron emitted in inverse beta decay reaction and recoil proton from fast neutron elastic scattering. The internal active shielding is located on the top of detector and under it.

![Figure 1](image_url)

**Figure 1.** General scheme of experimental setup. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor, 9 – iron shot.

Detector can be placed in different positions for measurement with 0.47 m distance between them to avoid influence of section efficiency distinction. Shift could be made from one position to any other. The sectioned detector structure allows us to present the distance dependence with 0.47-meter step. The technique of making measurements was to move detector for 0.94 m starting with the end position. On the second stage the measurements were repeated with translation of starting position for 0.47 meters. Thus, practically each row of the detector measured the same point, averaging in this way somewhat different recording efficiency of detector’s rows. For a full-scale detector, we use the first and the last rows of cells not for detecting a positron signal itself, but for annihilation gamma quanta at 511 keV.

Multi-section model was designed especially for detecting positron emitted in inverse beta decay reaction. Fast neutrons from cosmic rays are the main problem for Earth-surface experiments. Fast neutron scattering imitates neutrino reaction. The recoil proton mimics the prompt signal from positron. The delayed signal emits during neutrion capturing by Gd in both reactions. The difference in prompt signals is that in neutrino process two $\gamma$-quanta are emitted due to positron annihilation. The recoil proton path with high probability lies in single section. 511 keV $\gamma$-quanta can be detected in adjacent sections. However, Monte-Carlo modelling of full-scale detector shows that only ~37% (on the average for detector considering the peculiarities of detection) of neutrino events are multi-section due to $\gamma$-quanta detection in neighbouring sections with respect to section where positron annihilated. The fact that event statistics is almost 3 times less if we consider only multi-section events is hardly acceptable, so we considered data analysis model with both multi and single section events. But we use ratio for multi and single section as additional examination. Hence, if the signal difference for reactor turning on (off) is in ~37% to ~63% ratio for multi and single section events then we consider them to be neutrino-like signals.

Difference in count rates in reactor on and off regimes for double and single starts integrated over all distances for full-scale detector was (37±4)% and (63±7)%. With considered precision this ratio allows us to regard registrated events as neutrino-like events.
Multi-sectional structure of full-scale detector allow us to improve statistical accuracy by increasing signal/background ratio from 0.3 to 0.6 and by suppressing accidental coincidences background.

3. Results

Results of measurements of difference in counting rate of neutrino-like events for full-scale detector is shown in figure 2 (left) as dependence of antineutrino on distance from reactor center. To increase statistical accuracy data was averaged in the range of 1 meter (last point in the range of 2 meters). At the same time, there is an experimental result of DANSS, kindly provided by M. V. Danilov, and presented at the 52nd Rencontres de Moriond [4], which points out that in the range of 10 – 13 meters the law 1/L^2 holds true with rather good accuracy. We can make use of this information and combine results of measurements in the range of their overlapping of 10 – 12 meters. Results of association of the Neutrino-4 and DANSS experiments data are presented in figure 2 (right).

![Figure 2](image)

**Figure 2.** Reactor antineutrino flux distance dependence for full-scale detector itself (left) and after combining with DANSS experimental data (right). Solid line is the fit for dependence 1/L^2, where L is the distance from the center of reactor core.

The difference spectra (reactor ON - reactor OFF) of prompt signals with 6 distance points (normalized to unity) are presented in figure 3.

![Figure 3](image)

**Figure 3.** Results of spectrum measuring at various distances.
As one can see from figure 3, statistical accuracy is not enough for the further analysis of ratio of spectra at different distance. Figure 4 illustrates the spectrum of prompt signals summarized on all distances for increasing statistical accuracy (averaged distance 8.6 meters). This spectrum contains statistics of all measurements.

Figure 4. Spectrum of prompt signals for a total cycle of measurements summarized on all distances (average distance 8.6 meters). The red dotted line shows Monte Carlo simulation with neutrino spectrum for $^{235}\text{U}$, as the SM-3 reactor works on highly enriched uranium.

It is of great interest to use the obtained experimental data of the Neutrino-4 and DANSS experiments for global fit of sterile neutrino model parameters. At the same time, it must be kept in mind that at long distances results of fit should satisfy the results of measurements at these long distances. As both experiments in DANSS and in Neutrino-4 use relative measurements, it is necessary to mention, how points of DANSS and Neutrino-4 together applied on an overall picture with results of other experiments [5]. In the picture of global fit, they can be fixed either with attaching to average value, which define “reactor anomaly”, or to unity. In second case, data of other experiments are not used. It is reasonable to assume that the errors of DANSS points must have been determined by an error of binding procedure (i.e. error of average value of ratio observed/predicted of other reactor experiments [6,7]). Analysis of confidence level for parameters of oscillations $\Delta m^2_{14}$ and $\sin^2 2\theta_{14}$ is presented in figure 5 for spatial distribution for both cases. It is necessary to mention these areas on the ($\sin^2 2\theta_{14}$, $\Delta m^2_{14}$) - plane of confidence level are mainly determined by high accuracy of DANSS experiment data.

Figure 5. Confidence Level (CL): left – for spatial distribution of data for experiments of the Neutrino-4, DANSS (bound to RAA) and other reactor experiments from [2]; right – for spatial distribution of data for experiments of the Neutrino-4, DANSS attached to unity. Black curve corresponds to 99% CL.
Global picture with Neutrino-4 and DANSS data attached to average value 0.936 ± 0.021 with curve corresponding to minimum of $\chi^2$ shown on figure 6.

![Graph](image)

Figure 6. Global fit of the sterile neutrino model parameters with experimental data of the Neutrino-4, DANSS and data of the known experiments at long distances [6, 7].

4. Conclusion
Measurements of the flux of an antineutrino from the reactor at small distances of 6 – 12 m by means of the moveable detector are carried out for the first time. In the frame of the available statistical accuracy it is not revealed if there are any reliable deviations of antineutrino flux distance dependence from the law $1/L^2$ where L – distance from the center of reactor core, which is in a good agreement with data of DANSS experiment.

Measurements with full-scale detector will be continued in the same way (movement, spectrum measurement) to reach better statistical accuracy, but it does not solve the main problem of cosmic background in general. Therefore, our plan is to create second neutrino laboratory with longer base (up to 15m) on reactor SM-3 with two identical detectors (one stationary and one moveable). New detectors will have sectional structure too, but with smaller sections and scintillator with higher gadolinium concentration and better PSD capability will be used. DANSS (Russia) and NEOS (Korea) collaborations will be participants in this project.

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References
[1] Mueller T et al. 2011 Phys. Rev. C 83 054615
[2] Mention G et al. 2011 Phys. Rev. D 83 073006
[3] Serebrov A et al. 2014 Tech. Phys. Lett. 40 456 (Preprint 1310.5521)
[4] Danilov M 2017 The 52nd Rencontres de Moriond Electroweak Interactions and Unified Theories, Thuile https://goo.gl/c8WUsV
[5] Serebrov A et al. 2017 Preprint 1708.00421
[6] Giunti C 2016 Neutrino 2016 27th Int. Conf. on Neutrino Physics and Astrophysics, London
https://goo.gl/v1WrUi

[7] Li Yu-Feng 2016 Applied Anti-neutrino Physics 2016, Liverpool https://goo.gl/m2QJIj