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The first observation of oscillation effect in Neutrino-4 experiment and analysis of measurement results

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Abstract. We report Neutrino-4 experiment results of measurements of reactor antineutrinos flux and spectrum dependence on the distance in range 6-12 meters from the center of the reactor core. Using experimental spectrum, we performed the model independent analysis of restrictions on oscillation parameters Δm_{14}^2 and $\sin^2 2\theta_{14}$. The results of this analysis exclude area of reactor and gallium anomaly at C.L more than 99.7% ($> 3\sigma$) for values $\Delta m_{14}^2 < 3\mathrm{eV}^2$ and $\sin^2 2\theta_{14} > 0.1$. However, we observed an oscillation effect at C.L 2.8σ in vicinity of $\Delta m_{14}^2 \approx 7.3\mathrm{eV}^2$ and $\sin^2 2\theta_{14} \approx 0.39$. The method of coherent addition of results of measurements, which allows us to directly observe the effect of oscillations, is proposed. The analysis of that effect is presented. In general, it seems that the effect predicted in gallium and reactor experiments is being confirmed but at sufficiently large value of Δm_{14}^2. An additional analysis of the measurements was performed taking into account inhomogeneity of the detector and background instability.

1. Introduction

At present, there is a widely spread discussion on the possible existence of a sterile neutrino. It is assumed, that due to possible reactor antineutrino transition to the sterile state, the oscillation effect at short reactor distances can be observed [1,2].

Ratio of observed/predicted antineutrino flux in various reactor experiments is estimated as 0.934 ± 0.024 [3]. The effect is 3 standard deviations. This, however, is not yet sufficient to have a confidence in existence of the reactor antineutrino anomaly.

Our experiment focuses on the task of exploring the possible existence of a sterile neutrino at certain confidence level or refuting this hypothesis. Method of measurements is direct observation of antineutrino flux distance dependence and antineutrino flux at different distances in range 6 – 12 m. This method of relative measurements does not base on precise calculation of neutrino flux. A detector is supposed to be movable and spectrum sensitive. If such a process does occur, it can be described at short distances by the equation:

$$\mathrm{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{14} \sin\left(1.27\frac{\Delta m_{14}^2[\mathrm{eV}^2]L[\mathrm{m}]}{E_{\bar{\nu}_e}[\mathrm{MeV}]}\right) \quad (1)$$

where $E_{\bar{\nu}}$ is antineutrino energy, with oscillations parameters Δm_{14}^2 and $\sin^2 2\theta_{14}$ being unknown. For the experiment to be conducted, one needs to carry out measurements of the antineutrino flux and spectrum as near as possible to a practically point-like antineutrino source. Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances [4, 5]. However, SM-3 reactor, as well as other research reactors, is located on the Earth surface, hence, cosmic background is the major difficulty in considered experiment.

2. Detector design

Detector scheme with active and passive shielding is shown at figure 1. Scintillator with gadolinium concentration 0.1% was using to detect inverse beta decay (IBD) events $\bar{\nu}_e + p \rightarrow e^+ + n$. The neutrino detector active shielding consists of external and internal parts in respect to passive shielding. The internal active shielding is located on the top of the detector and under it. The detector has a sectional structure. It consists of 50 sections – ten rows with 5 sections in each. The first and last detector rows were also used as a passive shielding from the fast neutrons and to detect gamma-quanta from positron annihilation or Gd(n, γ) reaction. Thus, fiducial volume of scintillator is 1.42 m3.

We use selection criteria listed below: occurring of two correlated signals – prompt signal in one or two adjacent sections, single delayed signal in interval of 300μs observed in 2-5 sections which is not far than 5 cells from prompt signal section; total energy of prompt signal is in range 1.5-8MeV; total energy of delayed signal in range 3.2-8MeV. Accidental coincidence background is subtracted.

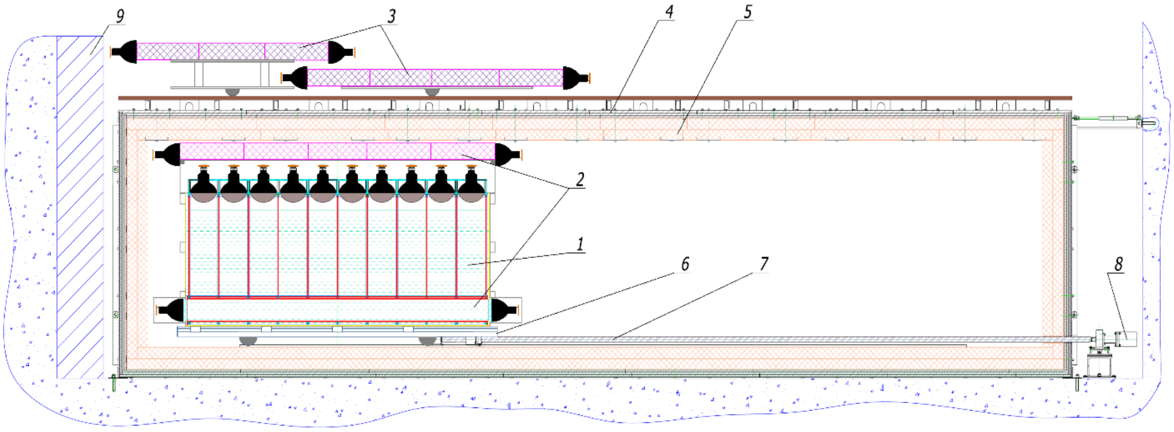

Figure 1. General scheme of an experimental setup. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor, 9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

3. Results

Measurements with the detector have started in June 2016. Measurements with the reactor ON were carried out for 480 days, and with the reactor OFF- for 278 days. In total, the reactor was switched on and off 58 times.

Fit of an experimental dependence with the law A/L^2 yields satisfactory result. Goodness of that fit is 81%. Corrections for finite size of reactor core and detector sections are negligible – 0.3%, and correction for difference between detector movement axes and direction to center of reactor core is also negligible – about 0.6%.

The spectral measurements are required for more detailed analysis of the area of parameters Δm_{14}^2 and $\sin^2 2\theta_{14}$. Energy calibration of the detector was performed with γ-quanta source and neutron source (^{22}Na by lines 511 keV and 1274 keV, by line 2.2 MeV from reaction np-dγ, by gamma line

4.44 MeV from Pb-Be source, and also by total energy of gamma quanta 8 MeV from neutron capture in Gd)[7]. As a result, spectrum of prompt signals registered by detector was measured. Its connection with antineutrino energy is determined by equation: $E_{promt} = E_{\bar{\nu}} - 1.8\ \text{MeV} + 2 \cdot 0.511\ \text{MeV}$, where $E_{\bar{\nu}}$ – antineutrino energy, 1.8MeV – energy threshold of IBD, and $2 \cdot 0.511$ MeV corresponds to annihilation energy of a positron.

Model independent analysis, for which precise knowledge of spectrum is not necessary, can be performed using equation (2). Numerator is the rate of antineutrino events per 10^5s with correction to geometric factor L^2 and denominator is its value averaged over all distances:

$$\frac{(N_{i,k} \pm \Delta N_{i,k}) L_k^2}{K^{-1} \sum_k^K (N_{i,k} \pm \Delta N_{i,k}) L_k^2} \approx \frac{1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i)}{K^{-1} \sum_k^K [1 - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{14}^2 L_k / E_i)]} \quad (2).$$

Left part includes only experimental data $k = 1, 2, \dots K$ for all distances in range 6.5-11.7m; $i = 1, 2, \dots 9$ corresponding to 500keV energy intervals in range 1.5MeV to 6.0MeV. The right part is the same ratio obtained within oscillation hypothesis. It should be noticed, that the product of expected spectrum (spectrum of ^{235}U in assumption of no oscillations) and oscillation factor for each distance are integrated over intervals corresponding to energy intervals in left hand side (1.5MeV – 2MeV, 2 – 2.5MeV …). However, as shown in figure 4, the resulting function of L/E is independent on the initial expected spectrum, hence with high accuracy one can consider that the energy spectrum is cancelled out in right hand side. Left part is normalized to spectrum averaged over all distances, hence oscillation effect is considerably averaged out in denominator if oscillations are frequent enough in considered distances range. It should be emphasized, that spectrum shape does not influence the expression, because it appears in equation (2) in numerator and denominator.

Using all 24 positions instead of 3 as we did before [7], we increase analysis sensitivity to high values of Δm_{14}^2. Averaging the results over 3 positions (2 meters each) one cannot observe oscillations with period less than 2 meters.

The results of the analysis of experimental data using equation (2) and with applying CLs method are shown in figure 2 (left). The area of oscillation parameters colored in pink are excluded with CL more than 99.73% (>3σ). However, in area $\Delta m_{14}^2 = (7.34 \pm 0.1)\text{eV}^2$ and $\sin^2 2\theta_{14} = 0.39 \pm 0.12$ and the oscillation effect is observed at C.L. 99% (3σ), and it is followed by a few satellites. Minimal value χ^2 occurs at $\Delta m_{14}^2 \approx 7.34\text{eV}^2$.

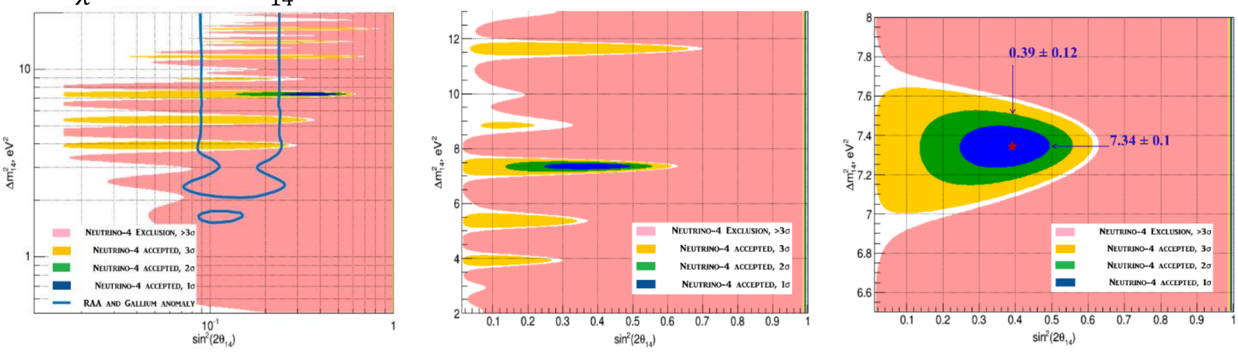

Figure 2. left – restrictions on parameters of oscillation into sterile state with 99.73% CL (pink), area of acceptable with 99.73% C.L. values of the parameters (yellow), area of acceptable with 95.45% C.L. values of the parameters (green), area of acceptable with 68.30% C.L. values of the parameters (blue). middle – area around central values in linear scale and significantly magnified, right – even further magnified central part.

Since, according to equation (1), oscillation effect depends on ratio L/E, it is beneficial to make experimental data selection using that parameter. That method we call the coherent summation of the

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experimental results with data selection using variable L/E and it provides direct observation of antineutrino oscillation.

For this purpose, we used 24 distance points (with 23.5 cm interval) and 9 energy points (with 0.5MeV interval). The selection for left part of equation (2) (of total 216 points each 8 points are averaged) is shown in figure 3 with blue triangles. Number of energy bins and averaging step are chosen in convenient way. However, selection of the arbitrary values of the parameters would not result in any significant difference, as shown in figure 5.

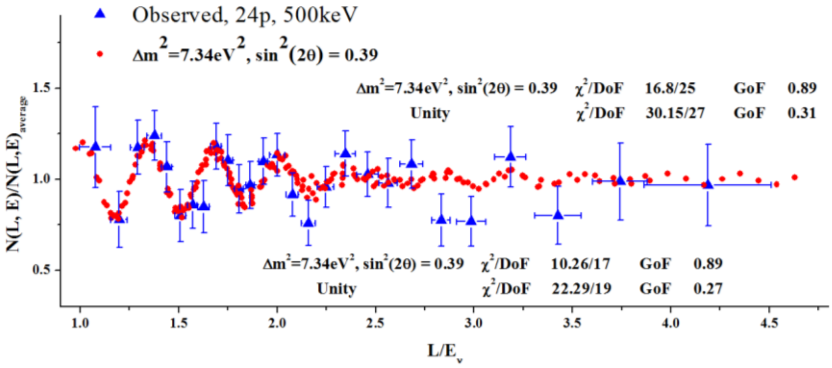

Figure 3. Coherent addition of the experimental result with data selection by variable L/E for direct observation of antineutrino oscillation. Comparison of left (blue triangles) and right (red dots, with optimal oscillation parameters) parts of equation (2).

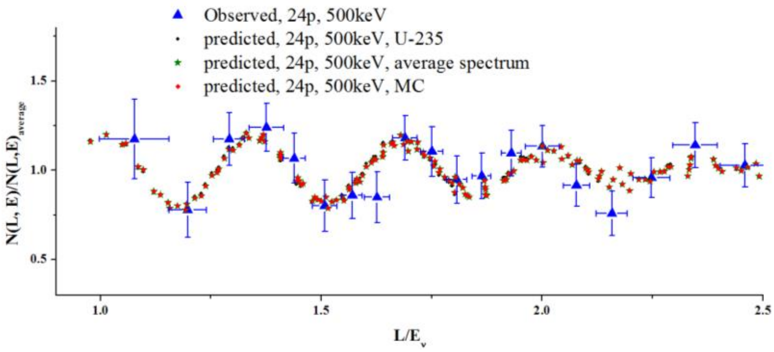

Figure 4. Comparison of experimental data with expected forms of the dependences in assumption of various initial neutrino spectra. Black dots - the spectrum of ^{235}U, green stars - experimental spectrum averaged over all distances, red rhombuses - the results of Monte-Carlo simulation of neutrino spectrum for full-scale detector.

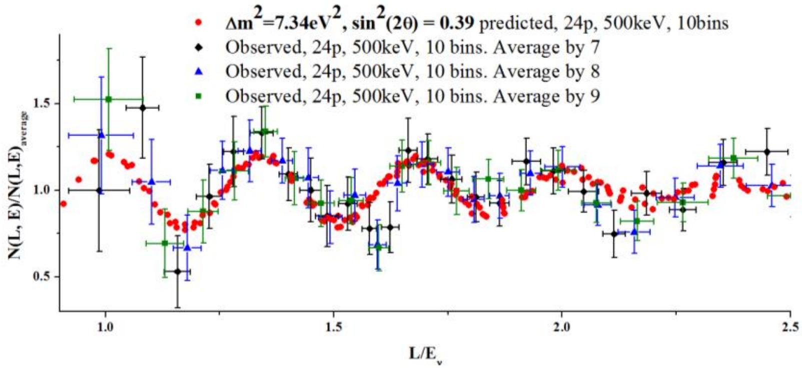

Figure 5. The results of coherent summation with various averaging steps of energy spectrum in range 1.5 - 6.5 MeV.

To carry out analysis of possible systematic effects one should turn off antineutrino flux (reactor) and perform the same analysis of obtained data, which consist of signals of fast neutron from cosmic rays. The result of that analysis is shown in figure 6 and it indicates the absence of oscillations in analyzed area.

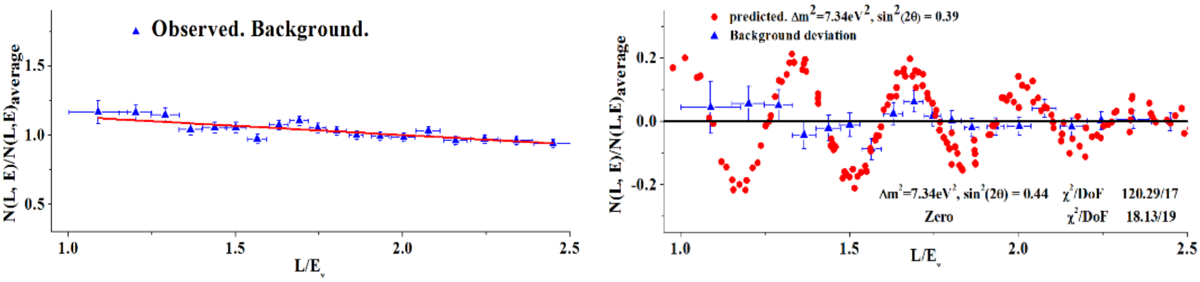

Figure 6. Analysis of data obtained with turned off reactor carried out to test on possible systematic effects: data analysis using coherent summation method (left); dots corresponds to deviation of expected effect from the unit, triangles - deviation of background from the linearly decreasing trend (right).

Correlated background (fast neutrons from cosmic rays) slightly decreases at farther distances from reactor due to inequality of concrete elements of the building, which comes out as linear decrease (red line) in figure 6 (left). The deviation of results from linear law, showed in figure 6 (right), cannot be the reason of observation of oscillations effect. Thus, no instrumental systematic errors were observed.

The scheme of reactor operation and detector movements is shown in figure 7 at the top. The measurements of the background (OFF) and measurements with reactor in operation mode (ON) are carried out within the exposure period at single detector position. A reactor cycle is 8-10 days long. Reactor stops are 2-5 days long and usually alternates (2-5-2-...). The reactor stops at summer for a long period for scheduled preventive maintenance. The movement of the detector to the next measuring position occurs in the middle of reactor operational cycle. The stability of the results of measurements is characterized by distributions of ON-OFF difference fluctuations normalized on its statistical uncertainties, in measurements within one period. The distribution is shown in figure 7 at the bottom.

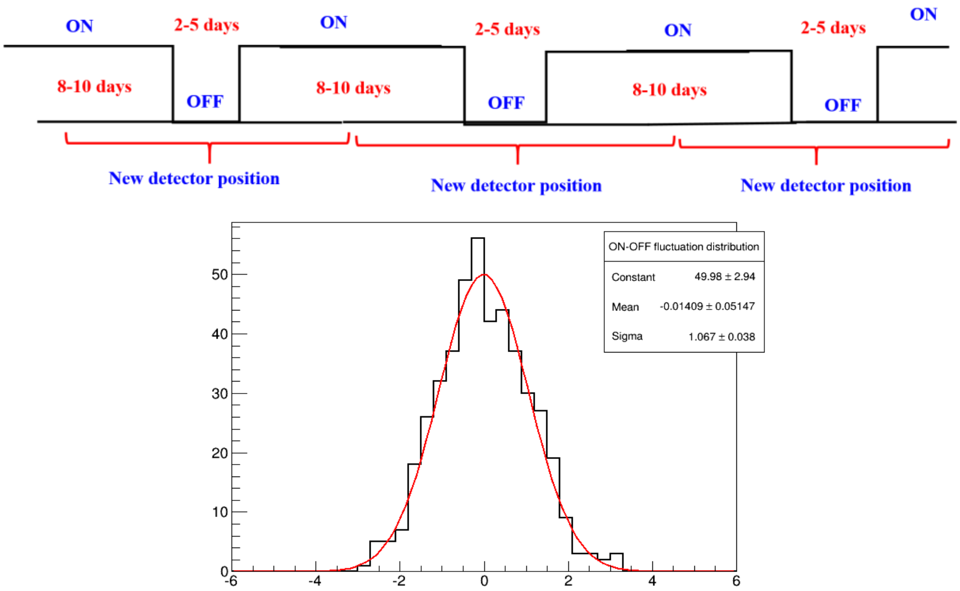

Figure 7. Top - scheme of detector operation; bottom - the distribution of deviations from average value of correlated events rates differences (ON-OFF) normalized on its statistical uncertainties.

That distribution has the form of normal distribution, but its width exceeds unit by 7%. This is a result of additional dispersion which appears due to fluctuations of cosmic background and impossibility of simultaneous measurements of the effect and background. Since the measurements of the background carried out during the annual scheduled reactor repair works, when the reactor is stopped for a month, are added to total obtained data, then total additional dispersion, which is a result of background measurements, increases up to 9%. That is considered as systematic correction of uncertainties of results of measurements and it results in decreasing of confidence level of the results shown in figure 2 (right) to 2.8σ.

The distances of detector movements are multiples of section size (23.5cm). All movements are controlled with laser distance measurer. The measurements were carried out at 10 detector positions in the way that the same distance from the reactor is measured with various detector rows. Spectra measured with various rows at same distance are averaged afterwards.

Average distribution of prompt signal counts obtained in background measurements during the whole period of reactor stop is shown in figure 8 (left). It was mentioned before, that cosmic background of fast neutrons in lab room is inhomogeneous due to the building structure. It appears as a slope of background dependence on L/E in figure 6 (left), and as the profile of that distribution (red line in figure 8 left). Therefore, to estimate how the detector inhomogeneity can affect the results, one should consider the deviation of counts from that profile, as shown in figure 8 (right). We should remind that first and last rows are not used for obtaining the final dependence on L/E and mean value of the deviation is ~ 8%.

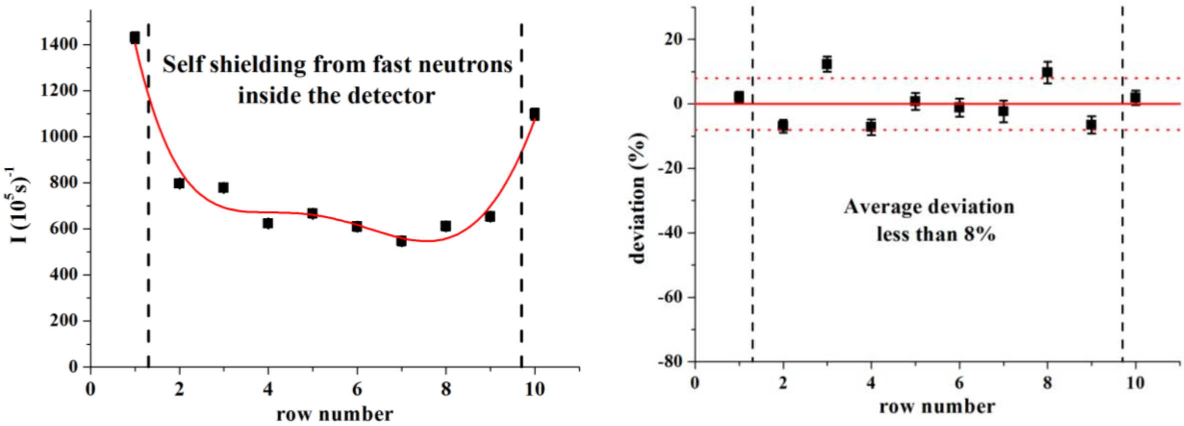

Figure 8. Average distribution of correlated background prompt signals in detector over all positions (left). Deviation average distribution of prompt signals from profile. Profile was caused by inhomogeneity of fast neutrons background in the lab room (right).

To consider how differences in rows efficiencies affect the final results, one must take into account that averaging of spectra obtained with various rows at the same distance. Hence the relative contribution of each row must be accounted. In that approach the square deviation from the mean value is ~ 2.5%, as shown in figure 9. It indicates that the influence of detector inhomogeneity on the L/E dependence is insignificant and cannot be the origin of oscillation effect.

To provide an additional test one can exclude from analysis the measurements made by second and third rows at the position closest to the reactor and by eighth and ninth rows at the farthest from the reactor position, for those are extreme positions and corresponding measurements are not averaged with any other rows. The result of the test is shown in figure 10 where one can see that oscillation effect remains, but the statistical accuracy decreases after data exclusion and CL reduced to ~2σ.

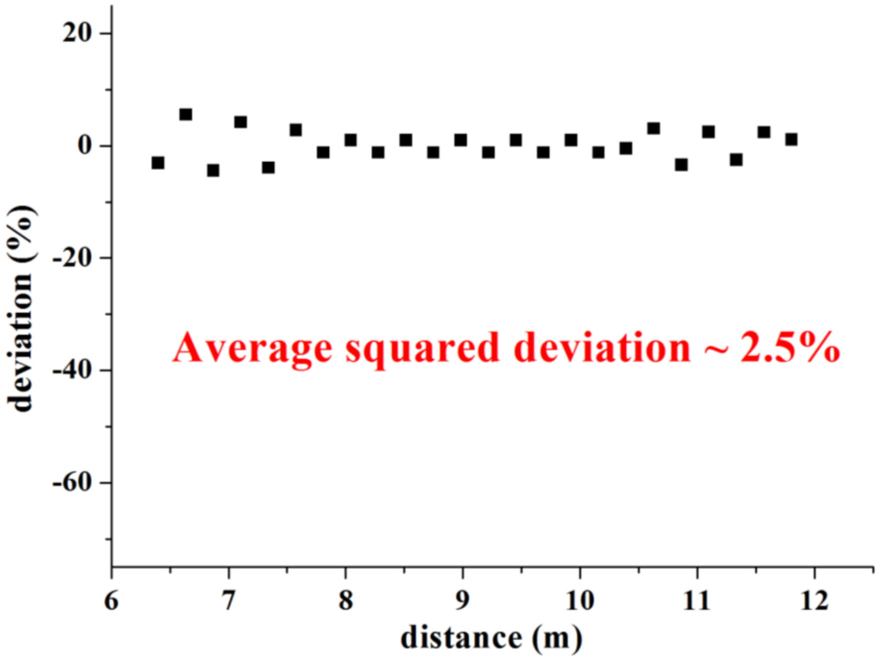

Figure 9. Deviation of counts of correlated background of each distance from the reactor after averaging over rows from the mean value.

The result of presented analysis can be summarized in several conclusions. Area of reactor and gallium anomaly for $\Delta m_{14}^2 < 3\mathrm{eV}^2$ and $\sin^2 2\theta_{14} > 0.1$ is excluded at C.L. more than 99.7% (>3σ).

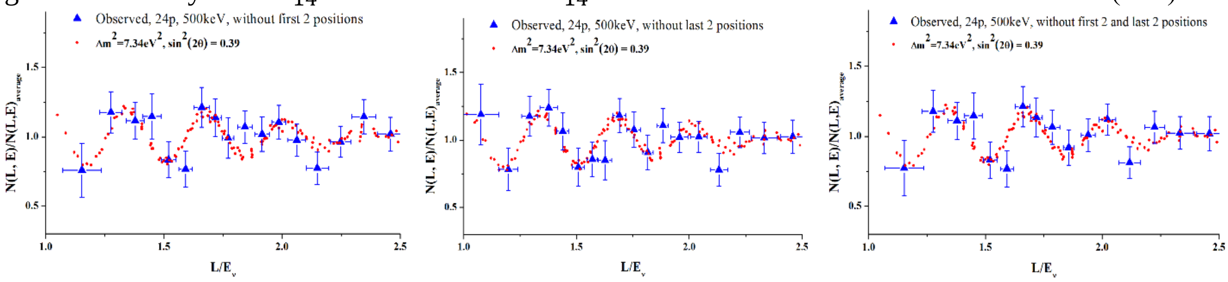

Figure 10. The result of coherent summation in data analysis without two first and two last distances (left), without two first distances (middle) and without last two distances (right).

However, oscillation effect is observed in area $\Delta m_{14}^2 \approx 7.3\mathrm{eV}^2$, $\sin^2 2\theta_{14} \approx 0.4$. Taking into consideration the instability of cosmic background we have to increase the uncertainties of experimental results by 9% relatively to statistical uncertainties, hence confidence level of observation of oscillation effect decrease to 2.8σ. In general, it seems that the effect predicted in gallium and reactor experiments is being confirmed but at sufficiently large value of Δm_{14}^2. Moreover, presented mixing parameter $\sin^2 2\theta_{14}$is rather big in comparison with existing limits obtained in experiments Daya Bay and Bugey-3, which gave an upper limit at level 0.2 with 90% C.L. i.e. 0.20 ± 0.12. While our result after applying the correction is $\sin^2 2\theta_{14} = 0.39 \pm 0.14$. Therefore, discrepancy between the results is 0.19±0.18 i.e. one standard deviation. Thus, there is no obvious contradiction. However, confidence level is not sufficient. Therefore, increasing of experimental accuracy is essential as well as additional analysis of possible systematic errors of the experiment.

Experiment Neutrino-4 has some advantages in sensitivity to big values of Δm_{14}^2 owing to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements. Next highest sensitivity to large values of Δm_{14}^2 belongs to PROSPECT [8] experiment.

Currently its sensitivity is two times lower than Neutrino-4 sensitivity, but it recently has started data collection, so it possibly can confirm or refute our result.

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