Observation of sterile antineutrino oscillation in Neutrino-4 experiment at SM-3 reactor

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Neutrino-4 collaboration

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Reactor antineutrino anomaly

- Observed/predicted averaged event ratio: $R=0.927 \pm 0.023$ (3.0 $\sigma$)

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

The first observation of effect of oscillation on search for sterile neutrino

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

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The period of oscillation is 1.4 m for neutrino energy 4 MeV

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A.P. Serebrov, et al.
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arxiv:1809.10561
arxiv:2003.03199
arxiv:2005.05301
Reactor antineutrino anomaly with oscillation curve obtained in experiment Neutrino-4

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{14} \sin^2 (1.27 \frac{\Delta m^2_{14} [eV^2]}{E_{\bar{\nu}} [MeV]} ) \]
Reactor SM-3

- Week protection from cosmic rays (3-5 m w. e.)
- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched $^{235}$U fuel

Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth’s surface, hence, cosmic background is the major difficulty in considered experiment.
Movable and spectrum sensitive antineutrino detector at SM-3 reactor

1. detector (5x10 cells)
2. internal active shielding
3. external active shielding
4. steel and lead
5. borated polyethylene
6. moveable platform
7. feed screw
8. step motor
9. shielding

Range of measurements is 6 - 12 meters

Passive shielding - 60 tons

Detector prototype

Full-scale detector

Liquid scintillator detector
50 sections 0.235x0.235x0.85m³
Gamma background in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor.
The background of fast neutrons in passive shielding does not depend neither on the power of the reactor nor on distance from the reactor.

Fast neutron flux $10^{-3}s^{-1}cm^{-2}$, cosmic background level

outside (near reactor wall)

The background of fast neutrons outside of passive shielding is defined by cosmic rays and practically does not depend on reactor power.

Fast neutron flux $9 \times 10^{-5}s^{-1}cm^{-2}$

inside

The background of fast neutrons in passive shielding is 10 times less than outside.
Absence of noticeable dependence of the background on both distance and reactor power was observed. As a result, we consider that difference in reactor ON-OFF signals appears mostly (> 95%) due to antineutrino flux from operating reactor.
Measurements with the detector have started in June 2016. Measurements with the reactor ON were carried out for 720 days, and with the reactor OFF - for 417 days. In total, the reactor was switched on and off 87 times.

The difference ON - OFF is 223 events per day in the range from 6.5 to 9.0 meters. The signal/background ratio is 0.54.

\[
\text{(ON – OFF)/ OFF} = 50\%
\]
Additional dispersion of measurement result which appears due to fluctuations of cosmic background

\[ \sigma = 1.070 \pm 0.045 \]

That distribution has the form of normal distribution, but its width exceeds unit by 7%.
Energy calibration of the full-scale detector

Pu-Be neutron source

22 Na- gamma source

Energy resolution ±250 keV.
There is problems with energy spectrum therefore we proposed the spectrum independent method of the experimental data analysis

Spectrum ratio (observed/expected) of prompt signals in the detector for a total cycle of measurements summed over all distances. Expected - Monte Carlo simulation with neutrino spectrum of $^{235}\text{U}$, as the SM-3 reactor works on highly enriched uranium.
The spectrum independent method of experimental data analysis

\[ N(E_i, L_k) \]

Number of antineutrino events

\[ R_{i,k}^{\text{exp}} = \frac{N(E_i, L_k) L_k^2}{K^{-1} \sum_k N(E_i, L_k) L_k^2} = \frac{[1 - \sin^2 2\theta_{14} \sin^2(1.27\Delta m_{14}^2 L_k / E_i)]}{K^{-1} \sum_k [1 - \sin^2 2\theta_{14} \sin^2(1.27\Delta m_{14}^2 L_k / E_i)]} = R_{i,k}^{th} \]

For \( \Delta m_{14}^2 \approx 7 \text{eV}^2 \) period of oscillation for neutrino energy 4 MeV is 1.4 m.

For range of measurement 6 m (6-12m) it is possible the approximation.

\[ K^{-1} \sum_k (1 - \sin^2 2\theta_{14} \sin^2(1.27\Delta m_{14}^2 L_k / E_i)) \rightarrow (1 - 1/2 \sin^2 2\theta_{14}) \]

The method of the analysis of experimental data should not rely on precise knowledge of spectrum. One can carry out model independent analysis using equation (2), where numerator is the rate of antineutrino events with correction to geometric factor 1/L^2 and denominator is its value averaged over all distances at the same energy.

\[ \sum_{i,k} [(R_{i,k}^{\text{exp}} - R_{i,k}^{th})^2 / (\Delta R_{i,k}^{\text{exp}})^2] = \chi^2 (\sin^2 2\theta_{14}, \Delta m_{14}^2) \]
The expected effect for the different energy resolution from MC calculation

energy resolution ±50 keV

the reactor core 42x42x35cm³ was simulated, as well as a detector of antineutrino taking into account its geometrical dimensions (50 sections of 22.5x22.5x75cm³).

energy resolution ±100 keV
The expected effect for the different energy resolution from MC calculation energy resolution ±250 keV (our case) energy resolution ±375 keV

the reactor core 42x42x35cm³ was simulated, as well as a detector of antineutrino taking into account its geometrical dimensions (50 sections of 22.5x22.5x75cm³).
It is often discussed that stricter limitations on the confidence level of the result can be obtained using the Feldman-Cousins method. Really, it is good to put the restriction of possible effect. But in compliance Wilks theorem method is possible to apply successfully if effect is observed at the level of reliability $3\sigma$ and more. Our result of processing without taking into account systematic errors is $(3.2-3.5)\sigma$.

Since the reliability of the effect we observe exceeds $3\sigma$, we do not consider it mandatory to use the Feldman-Cousins method and we use more convenient method.

\[
\sum \left( \frac{(R_{i,k}^{\exp} - R_{i,k}^{th})^2}{(\Delta R_{i,k}^{\exp})^2} \right) = \chi^2 \left( \sin^2 2\theta_{14}, \Delta m_{14}^2 \right)
\]
The results of the analysis of optimal parameters $\Delta m^2_{14}$ and $\sin^2 2\theta_{14}$ using $\chi^2$ method:

$$\sum_{i,k}[(R_{i,k}^{\text{exp}} - R_{i,k}^{\text{th}})^2 / (\Delta R_{i,k}^{\text{exp}})^2] = \chi^2(\sin^2 2\theta_{14}, \Delta m^2_{14})$$

We observed the oscillation effect at C.L. 99.7% (3.5 $\sigma$) in vicinity of:

$\Delta m^2_{14} \approx 7\text{eV}^2$

$\sin^2 2\theta_{14} \approx 0.4$
The method of coherent addition of results of measurements allows us to directly observe the effect of oscillations.

\[ R_{i,k}^{\text{exp}} = \frac{N(E^\nu_i, L_k) L_k^2}{K^{-1} \sum_k N(E^\nu_i, L_k) L_k^2} = \frac{[1 - \sin^2 2\theta_{14} \sin^2 (1.27\Delta m_{14}^2 L_k / E^\nu_i)]}{K^{-1} \sum_k [1 - \sin^2 2\theta_{14} \sin^2 (1.27\Delta m_{14}^2 L_k / E^\nu_i)]} = R_{i,k}^{\text{th}} \]

\[ 1 - \sin^2 2\theta_{14} \sin^2 (1.27\Delta m_{14}^2 L_k / E^\nu_i) \]

\[ \frac{1}{1 - 1/2 \sin^2 2\theta_{14}} \]
The period of oscillation is 1.4 m for neutrino energy 4 MeV
Results of analysis of data with energy interval 500keV

Results of data analysis with average by energy intervals 125keV, 250keV и 500keV

For reasons of reliability of the final result we choose the case of data processing with averaging.
Dependence of antineutrino flux on the distance to the reactor core. a - direct experimental dependence, b – normalized experimental dependence, c - oscillation curve with the experimental results in range 6-12 m.
Analysis of possible systematic effects
To carry out analysis of possible systematic effects one should turn off antineutrino flux (reactor) and perform the same analysis of background data.

The spectrum for neutrino signal and background signal are similar therefore test for systematic effect have to be adequate.
Test of systematic effects

To carry out analysis of possible systematic effects one should turn off antineutrino flux (reactor) and perform the same analysis of obtained data.

Thus no instrumental systematic errors were observed.
\[ \Delta m^2_{14} = 7.25 \pm 0.13_{\text{st}} \pm 1.08_{\text{sys}} = (7.25 \pm 1.09) \text{eV}^2 \]

\[ \sin^2 2\theta = 0.26 \pm 0.08_{\text{stat}} \pm 0.05_{\text{syst}} = 0.26 \pm 0.09(2.8\sigma) \]
COMPARISON OF THE RESULT OF EXPERIMENT NEUTRINO-4 WITH OTHER EXPERIMENT
Reactor antineutrino anomaly with oscillation curve obtained in experiment Neutrino-4


Our result
COMPARISON OF THE RESULT OF EXPERIMENT NEUTRINO-4 WITH REACTOR AND GALLIUM ANOMALIES

\[
\sin^2 2\theta_{14} \approx 0.26 \pm 0.09 \ (2.9\sigma)
\]

Neutrino-4 experiment

\[
\sin^2 2\theta_{14} \approx 0.32 \pm 0.10 \ (3.2\sigma)
\]

gallium anomaly

New result is expected from BEST experiment

\[
\sin^2 2\theta_{14} \approx 0.13 \pm 0.05 \ (2.6\sigma)
\]

reactor antineutrino anomaly

Combination of these results gives an estimation for mixing angle

\[
\sin^2 2\theta_{14} \approx 0.19 \pm 0.04 \ (4.6\sigma)
\]
In experiments on nuclear power plants sensitivity to identification of effect of oscillations with $\Delta m_{14}^2 \approx 7.25\text{eV}^2$ is considerably suppressed because of the big sizes of an active zone. The period of oscillation for neutrino energy 4 MeV is 1.4 m. But size of reactor core is about 4 m.

Experiment Neutrino-4 has some advantages in sensitivity to large values of $\Delta m_{14}^2$ owing to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements.
### Comparison of parameters of the Neutrino-4 with parameters of PROSPECT and STEREO

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Days with reactor ON</th>
<th>Days with reactor OFF</th>
<th>S/B ratio</th>
<th>Number of events, d⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino-4</td>
<td>720 (90 MW)</td>
<td>417</td>
<td>0.5</td>
<td>223 (6-9 m)</td>
</tr>
<tr>
<td>PROSPECT</td>
<td>33 (85 MW)</td>
<td>28</td>
<td>1.3</td>
<td>771 (7-9 m)</td>
</tr>
<tr>
<td>STEREO</td>
<td>179 (58 MW)</td>
<td>235</td>
<td>1.1</td>
<td>366 (9 – 11m)</td>
</tr>
</tbody>
</table>

Comparison of planes of parameters (E,L) in experiments Neutrino-4, STERO and PROSPECT.
COMPARISON OF EXPERIMENT NEUTRINO-4 RESULTS WITH RESULTS OF THE ICECUBE EXPERIMENT

• Spencer Axani, arXiv:2003.02796

$$\Delta m_{14}^2 = 4.47^{+3.53}_{-2.08} \text{ eV}^2$$

$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$

$$\sin^2 2\theta_{\mu\mu} = 4 \sin^2 \theta_{24} \cos^2 \theta_{14} (1 - \sin^2 \theta_{24} \cos^2 \theta_{14}) \approx \sin^2 2\theta_{24}$$
COMPARISON OF EXPERIMENT NEUTRINO-4 RESULTS WITH RESULTS OF ACCELERATOR EXPERIMENTS MINIBOONE AND LSND


The experiments MiniBooNE and LSND are aimed to search for a second order process of sterile neutrino – the appearance of electron neutrino in the muon neutrino flux (ν_μ → ν_e) through an intermediate sterile neutrino.

A comparison of \( \sin^2 2\theta_{\mu e} \) obtained in MiniBooNE and LSND and \( \sin^2 2\theta_{14} \) obtained in Neutrino-4 can be performed using results of the IceCube experiment:

\[
\sin^2 2\theta_{24} \approx 0.03 \div 0.2
\]

Values of \( \sin^2 2\theta_{\mu e} \) and \( \sin^2 2\theta_{24}, \sin^2 2\theta_{14} \) are related by the expression:

\[
\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{14} \sin^2 2\theta_{24}
\]
COMPARISON WITH EXPERIMENT KATRIN ON MEASUREMENT OF NEUTRINO MASS

$$m_{\nu_e}^{\text{eff}} = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

$$\Delta m_{14}^2 \approx m_4^2, \ldots |U_{14}^2| \ll 1$$

$$m_{\nu_e}^{\text{eff}} \approx \sqrt{m_4^2 |U_{e4}|^2} \approx \frac{1}{2} m_4^2 \sin^2 2\theta_{14}$$

$$m_4 = (2.68 \pm 0.13) \text{eV}$$

$$\sin^2 2\theta_{14} \approx 0.19 \pm 0.04 (4.6\sigma)$$

$$m_{\nu_e}^{\text{eff}} = (0.58 \pm 0.09) \text{eV}$$

$$m_1^2, m_2^2, m_3^2 \ll m_4^2$$

Limitations on the sum of mass of active neutrinos

$$\sum m_\nu = m_1 + m_2 + m_3$$

from cosmology are in the range $0.54 \pm 0.11 \text{eV}$

$$\sin^2 2\theta_{14} = 4 |U_{14}|^2 (1 - |U_{14}|^2)$$

$$|U_{14}^2| \approx \frac{1}{4} \sin^2 2\theta_{14}$$

$$m_{\nu_e}^{\text{eff}} \leq 1.1 \text{eV} \quad (\text{CL } 90\%)$$


arXiv:1909.06048
In the same way we can use data about \( \sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07} \) obtained in the IceCube experiment to estimate muon neutrino mass:

\[
m_{\nu_\mu}^{\text{eff}} = (0.42 \pm 0.24)\text{eV}
\]

Finally, considering upper limit of \( \sin^2 2\theta_{34} \leq 0.21 \) we can calculate upper limit of tau neutrino mass:

\[
m_{\nu_\tau}^{\text{eff}} \leq 0.65\text{eV}
\]
\[ \Delta m^2_{14} = 7.25 \pm 0.13_{\text{stat}} \pm 1.08_{\text{syst}} = 7.25 \pm 1.09 \]

\[ \sin^2 2\theta = 0.26 \pm 0.08_{\text{stat}} \pm 0.05_{\text{syst}} = 0.26 \pm 0.09(2.8\sigma) \]

\[ \sin^2 2\theta_{14} \approx 0.19 \pm 0.04(4.6\sigma) \]

\[ m_4 = (2.68 \pm 0.13)\text{eV} \]

\[ m_{\nu_e}^{\text{eff}} = (0.58 \pm 0.09)\text{eV} \]

\[ m_{\nu_\mu}^{\text{eff}} = (0.42 \pm 0.24)\text{eV} \]

\[ m_{\nu_\tau}^{\text{eff}} \leq 0.65\text{eV} \]
Thank you for attention

Best regards from Gatchina

Best regards from Dimitrovgrad
# Neutrino mass

3 **complementary** methods to measure:

<table>
<thead>
<tr>
<th>Method</th>
<th>Observable</th>
<th>curr. [eV]</th>
<th>near/far [eV]</th>
<th>pro</th>
<th>con</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurie</td>
<td>$\sqrt{\sum</td>
<td>U_{ei}</td>
<td>^2 m_i^2}$</td>
<td>2.3</td>
<td>0.2/0.1</td>
</tr>
<tr>
<td>Cosmo.</td>
<td>$\sum m_i$</td>
<td>0.7</td>
<td>0.3/0.05</td>
<td>best; NH/IH</td>
<td>systemat.; model-dep.</td>
</tr>
<tr>
<td>$0\nu\beta\beta$</td>
<td>$</td>
<td>\sum U_{ei}^2 m_i</td>
<td>$</td>
<td>0.3</td>
<td>0.1/0.05</td>
</tr>
</tbody>
</table>

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