The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino

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Reactor antineutrino anomaly

- Observed/predicted averaged event ratio: $R=0.927\pm0.023$ (3.0 $\sigma$)

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{14} \sin^2 (1.27 \frac{\Delta m^2_{14}[eV^2]}{E_{\bar{\nu}_e}[MeV]} L[m])$$
- Observed/predicted averaged event ratio: $R=0.927\pm0.023$ (3.0 $\sigma$)
The first observation of effect of oscillation in Neutrino-4 experiment on search for sterile neutrino

$\Delta m^2_{14} = 7.26$, $\sin^2 2\theta_{14} = 0.38$

$\Delta m^2 = 7.25 \text{eV}^2$, $\sin^2 (2\theta) = 0.38$

$\chi^2/\text{DoF}$: 17.09/17, $\text{GoF} = 0.45$

$\chi^2/\text{DoF}$: 27.98/19, $\text{GoF} = 0.08$
SM-3 research reactor

- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched $^{235}$U fuel
- Separated rooms for experimental setup
- The laboratory is poorly protected from cosmic rays
Reactor SM-3

- Week protection from cosmic rays (3-5 m w. e.)
- 100 MW thermal power
- Compact core 42x42x35cm
- Highly enriched $^{235}\text{U}$ 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.
The full-scale detector with liquid scintillator volume of 3 m³ (5x10 sections) have been prepared in NRC “KI” PNPI, Gatchina, Russia
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

Neutrino channel outside and inside
Passive shielding - 60 tons
Range of measurements is 6 - 12 meters
Detector prototype
Full-scale detector
Liquid scintillator detector 50 sections 0.235x0.235x0.85m³
Energy calibration of the full-scale detector

The source $^{22}\text{Na}$ is installed above the detector at distance about 0.8 meters and irradiate about 16 sections at once. PMTs were normalized to one energy scale by selecting voltage on them. Simultaneous calibration of several sections is required. For all detector only 6 positions of the source were used. Overlapping of the irradiated sections unifies the calibration.

The neutron Pu-Be source irradiated all sections at once. This method has advantage relatively to using of internal sources. The difficulty of calibration at energy 8MeV is that quanta from neutron capture by gadolinium can't be absorbed in the same row. Therefore the detector calibration should be conducted on a diffuse edge of spectrum.
Energy calibration of the full-scale detector

In the left - ranges of sources. In the right - the calibration of gamma quanta scale. Registration of positrons includes inevitable loss of a part of energy of 511keV gamma-quanta. Because of the threshold of registration in the adjacent section we have to increase errors up to ±250 keV.

It is the calibration which needs to be used at data processing.
Energy calibration of the full-scale detector

\( E_v = E_{\text{prompt}} + 0.8 \text{MeV} \)

\[ \Delta E_v / E_v(2\text{MeV}) = 21\% \]
\[ \Delta E_v(2\text{MeV}) = 440\text{keV} \]

\[ \Delta E_v / E_v(3\text{MeV}) = 18\% \]
\[ \Delta E_v(3\text{MeV}) = 550\text{keV} \]

\[ \Delta E_v / E_v(6\text{MeV}) = 14\% \]
\[ \Delta E_v(6\text{MeV}) = 830\text{keV} \]
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 $10^{-3}\text{s}^{-1}\text{cm}^{-2}$, cosmic background level

outside (near reactor wall)

The background of fast neutrons in passive shielding is 10 times less than outside. The background of fast neutrons outside of passive shielding is defined by cosmic rays and practically does not depend on reactor power.
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 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.

\[
\frac{\text{ON} - \text{OFF}}{\text{OFF}} = 50\%
\]
There is problems with energy spectrum therefore we proposed the spectrum independent method of the experimental data analysis.

Spectrum (observed/expected) of prompt signals in the detector for a total cycle of measurements summed over all distances (average distance — 8.6 meters).

Expected - Monte-Carlo simulation with neutrino spectrum of $^{235}\text{U}$, as the SM-3 reactor works on highly enriched uranium.
Probability of antineutrino disappearance

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

The spectrum independent method of experimental data analysis

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

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.

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

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

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

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

$\sin^2 2\theta_{14} \approx 0.4$

Expected from RAA and Gallium anomalies

Expected from Neutrino-4 CL 99.7%

Excluded from Neutrino-4 CL >99.9% CL
All data 2017 - 2019 + background 2019
The method of coherent addition of results of measurements allows us to directly observe the effect of oscillations.

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

(2)
The period of oscillation for neutrino energy 4 MeV is 1.4 m.

\[ \Delta m^2_{14} = 7.26, \sin^2 2\theta_{14} = 0.38 \]

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arxiv:1809.10561
The expected effect for the different energy resolution from MC calculation

energy resolution 0.1 MeV

energy resolution 0.25 MeV
The expected effect for the different energy resolution from MC calculation.

Energy resolution 0.5 MeV (our case)

Energy resolution 0.75 MeV
All data 2017 - 2019 + background 20119

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

$\Delta m^2_{14} = 7.26, \sin^2 2\theta_{14} = 0.38$

$\Delta m^2 = 7.25\text{eV}^2, \sin^2 (2\theta) = 0.38$

Unity

$\chi^2$/DoF 17.09/17, GoF 0.45

$\chi^2$/DoF 27.98/19, GoF 0.08

A.P. Serebrov, et al.

arxiv:1809.10561
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.

The problem of fast neutrons

False event

Neutrino event

Fast neutron

Neutron scattering imitate neutrino reaction
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.
Additional dispersion of measurement result which appears due to fluctuations of cosmic background

\[ \sigma = 1.070 \pm 0.045 \]

Since the measurements of the background carried out during the annual scheduled reactor repair works, then total additional dispersion is increased up to \( \sim 9\% \).

Considering the instability of cosmic background, we increased the uncertainties of the experimental results by 9\% relatively to statistical uncertainties, therefore the instability of cosmic background is already considered. It may be an overestimation, but this guarantees the reliability of the final result.

That distribution has the form of normal distribution, but its width exceeds unit by 7\%. 
Possible conformation of our results

First of all there is no contradiction with Gallium Anomaly

The combined result of the Neutrino-4 and gallium anomaly gives

$$\sin^2 2\theta_{14} \approx 0.35 \pm 0.07 \, (5.0\sigma)$$
The BEST experiment started in August 2019 in BNO has good sensitivity at $\Delta m_{14}^2 > 5\text{eV}^2$ area.
There is contradiction with reactor anomaly \( (2\sigma) \). However, it should be noted that the results of the reactor anomaly do not yet include a systematic calculation error, which is currently under discussion.

- **Observed/predicted averaged event ratio:** \( R = 0.927 \pm 0.023 \ (3.0 \sigma) \)
Where our result can be **confirmed or refuted**?

1. **PROSPECT, STEREO, SoLiD** - can be …… because small size of reactor core.
2. **DANSS** – it is difficult because big size (3.7m) of reactor core.
3. **NEOS** – it is very difficult because big size of reactor core and distance 24 m.
4. **BEST** - new measurements is going right now.
5. **KATRIN, Troisk**

The period of oscillation for $\Delta m_{14}^2 \approx 7.3\text{eV}^2$ and neutrino energy 4 MeV is **1.4 m**
Comparison of Neutrino-4 results with other experiments: – sensitivity regions of various experiments
STEREO together with Neutrino-4.
Comparison with other results

Neutrino-4

Stereo

Prospect

Neutrino-4

Result

DANSS

90% CL

Prospect

95% CL

NEOS

90% CL

\[ \Delta m^2, \text{eV}^2 \]

\[ \sin^2(2\theta_{14}) \]

\[ E, \text{MeV} \]
Experiment Neutrino-4 has some advantages in sensitivity to big value $\Delta m_{14}^2$ due to a compact reactor core, close minimal detector distance from the reactor and wide range of detector movements. It should be noted that without method of the coherent summation of data by L/E parameter, it is practically impossible to extract the effect of the oscillations. So far, the method of coherent summation of data by the parameter L/E has been actively used only by experimental Neutrino-4. This may determine the difference between the results of these experiments.
If effect of Neutrino-4 is correct then it is possible to predict neutrino mass
Experiment KATRIN and sterile neutrino from Neutrino-4

\[ \Delta m_{14}^2 = 7.26 \text{eV}^2, \quad \sin^2 2\theta_{14} = 0.38 \]

\[ m_\beta = \sqrt{\sum_i m_i^2 / U_{ei}^2} \]

\[ \Delta m_{14}^2 \approx m_4^2, \quad \sin^2 2\theta_{14} = 4 / U_{14}^2 (1 - U_{14}^2) \text{ with } U_{14}^2 \ll 1 \]

\[ m_\beta \approx \frac{1}{2} \sqrt{7.3 \cdot 0.38} \approx 0.87 \text{eV} \]

1. There is no contradiction with restriction from experiment KATRIN - \( m_\beta \leq 1 \text{eV} \)

2. If effect of Neutrino-4 is correct then prediction for neutrino mass is \( m_\beta \approx 0.87 \text{eV} \)
Two problems of fundamental interaction – baryon asymmetry of the universe and dark matter (left-right asymmetry in nature)

Sterile neutrino it is mirror neutrino – candidate for dark matter particle
Conclusion

1. It is probable that sterile neutrino exist

2. If effect of Neutrino-4 is correct then prediction for neutrino mass is

\[ m_\beta \approx 0.87 eV \]

3. Sterile neutrino is probably a dark matter particle
Thank you for attention

Best regards from Gatchina

Best regards from Dimitrovgrad
Back up
More detailed analysis of comparison between Neutrino-4 and KATRIN gives the following estimations.

Upper 1.1eV(90%) limit for KATRIN result means neutrino mass estimation $m_\beta = 0.30 \pm 0.49$eV;
Neutrino-4 estimation for neutrino mass is $m_\beta = 0.87^{+0.07}_{-0.17}$eV

That means discrepancy is $\Delta m_\beta = 0.57 \pm 0.50$ (1$\sigma$) and it is not serious contradiction like it was declared in C. Giunti, Y.F. Li, and Y.Y. Zhang. arXiv:1912.12956v2 [hep-ph]
Future: Neutrino-6 experiment
Future: Neutrino-6 experiment

Neutrino Laboratory No. 1

Neutrino Laboratory No. 2

Scheme of two detectors

SM-3 reactor

AS

AS (active shielding)

Fe 10 cm

CH₂B 50 cm

PMT 9354 (25X2)
Neutrino-6 experiment location

SM-3 reactor core
Detector’s design.
Transport system

Platforms

Inner cavities
Detector’s design.
Transparent tank
Detector’s design.
Case
Expecting improvements of statistical accuracy for Neutrino-6

<table>
<thead>
<tr>
<th>Method</th>
<th>Consequence</th>
<th>Increasing accuracy factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 detectors</td>
<td>3x larger volume</td>
<td>1.6</td>
</tr>
<tr>
<td>Gd concentration</td>
<td>4x less accidental background</td>
<td>1.5</td>
</tr>
<tr>
<td>PSD</td>
<td>4x less correlated background</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3.1</td>
</tr>
</tbody>
</table>
Мы используем эффект полного внутреннего отражения света на границе сцинтиллятор - воздух при малых углах падения, чтобы улучшить сбор света с разных расстояний. Поэтому калибровка может быть сделана, используя источники, расположенные снаружи – над детектором.

Водяная ванна

Размеры: 75 см x 14 см x 8 см

Внутренний объем: заполнен воздухом

Прямоугольная контейнерная емкость с зеркальными стенками

Пластиковый сцинтиллятор с гамма-источником 22Na прикреплен
Energy calibration of the full-scale detector

\[
E_v = E_{\text{prompt}} + 0.8\text{MeV}
\]

\[
\Delta E_v / E_v(2\text{MeV}) = 21\%
\]

\[
\Delta E_v(2\text{MeV}) = 440\text{keV}
\]

\[
\Delta E_v / E_v(3\text{MeV}) = 18\%
\]

\[
\Delta E_v(3\text{MeV}) = 550\text{keV}
\]

\[
\Delta E_v / E_v(6\text{MeV}) = 14\%
\]

\[
\Delta E_v(6\text{MeV}) = 830\text{keV}
\]
a) The ratio of an experimental spectrum of prompt signals to the spectrum, expected from MC calculations for 3 ranges (~2m) with centers 7.3m, 9.3m and 11.1m
b) polynomial fit of results averaged by distance (red curve)

Problems with energy spectrum

Spectrum of prompt signals in the detector for a total cycle of measurements summed over all distances (average distance — 8.6 meters). The red line shows Monte-Carlo simulation with neutrino spectrum of $^{235}$U, as the SM-3 reactor works on highly enriched uranium.
• Sectioning of the detector
• Problem of fast neutrons
• Allocation of a neutrino signal

**The problem of fast neutrons**

**False event**

**Neutrino event**

24 central and 16 side cells for full-scale detector

<table>
<thead>
<tr>
<th>central cell</th>
<th>side cell</th>
<th>angular cell</th>
<th>in all cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>42%</td>
<td>29%</td>
<td>19%</td>
<td><strong>37%</strong></td>
</tr>
</tbody>
</table>

Calculated percentage of multi-start events

Experimental average percentage of multi-start events for full-scale detector

\[(37 \pm 4)\%\]
Independence of identification of effect of oscillations of a form of a neutrino spectrum

3 different ranges were chosen: 1) U-235, 2) Experiment, 3) Monte-Carlo

- Observed, 24p, 500keV
- Expected, 24p, 500keV, U-235
- Predicted, 24p, 500keV, experiment
- Predicted, 24p, 500keV, Monte-Carlo

Inexact measurement of energy influences to definition of: $\Delta m_{14}^2$

Apparently there is no difference. It also should not be because spectra are strictly canceled in formula (2)

\[
R_{i,k}^{\text{exp}} = \frac{N(E_i, L_k) L_k^2}{K^{-1} \sum_k N(E_i, L_k) L_k^2} = \frac{[1 - \sin^2 2\theta_{14} \sin^2 (1.27\Delta m_{14}^2 L_k / E_i)]}{K^{-1} \sum_k [1 - \sin^2 2\theta_{14} \sin^2 (1.27\Delta m_{14}^2 L_k / E_i)]} = R_{i,k}^{\text{th}}
\]
Analysis of possible difference in efficiency of rows of the detector, using the background of fast neutrons which is given rise into the building from cosmic muons.

Selfshielding from fast neutrons inside detector

The background of fast neutrons is asymmetric because of structure of the building.

The dispersion on a background when moving the detector is within the same 8%.

We use only 8 internal rows, the first and tenth are protective.
**Averaging of detector rows efficiencies due to movements (above estimation)**

<table>
<thead>
<tr>
<th>L(m)</th>
<th>Numbers of detector row</th>
</tr>
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<tbody>
<tr>
<td>6.4025</td>
<td>2</td>
</tr>
<tr>
<td>6.6375</td>
<td>3</td>
</tr>
<tr>
<td>6.8725</td>
<td>4</td>
</tr>
<tr>
<td>7.1075</td>
<td>5</td>
</tr>
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<td>7.3425</td>
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<tr>
<td>7.5775</td>
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</tr>
<tr>
<td>7.8125</td>
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</tr>
<tr>
<td>8.0475</td>
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</tr>
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<td>11.3375</td>
<td>7</td>
</tr>
<tr>
<td>11.5725</td>
<td>8</td>
</tr>
<tr>
<td>11.8075</td>
<td>9</td>
</tr>
</tbody>
</table>

Average squared deviation ~ 2.5%
Conclusion
There is no reason to consider that the effect can be caused by structure of the detector. The possibility of averaging of efficiency of various sections by placing them at the same distance is the advantage of our experiment.

Test of stability of the effect by means of removal of extreme positions
Accidental background practically does not depend on reactor, but it is rather big at low energies.

Threshold for delayed coincidences 3.2MeV
Signal of correlated events

\[ \tilde{\nu}_e + p \rightarrow e^+ + n \]

Time of arrival of the second impulse

Prompt signal

Delayed signal

Time window

10 µs

100 µs

Sum amplitude start/stop - square/triangle

Entries 4706
Integral 2302

Signal of correlated events

Time Spectrum

Entries 4706
Integral 2245
χ²/ndf 76.97/143
p0 5.251 ± 0.239
p1 99.06 ± 3.48

Sum (backgr) 0 - 100 mcrs 1347 ± 31

Sum 0 - 100 mcrs 1649 ± 28

Gd