FIRST RESULTS OF "TROITSK NU-MASS" EXPERIMENT ON SEARCH FOR STERILE NEUTRINO BELOW 2 KEV

Troitsk nu-mass group
Motivation from cosmology:
Visible matter only 5%. What is the rest?
Cold or warm Dark Matter?

Heavy particles? 1-10 keV particles?

Simulations favor Warm Dark Matter
So, why keV- neutrino?
Candidate for Warm Dark Matter

- LHC results confirm expectations from Standard Model, but
- Neutrino mass, Dark Energy and Dark Matter are well beyond SM
- There is a set of candidates for DM, like WIMPs, they should be heavy and cold – but it contradicts cosmological structures at small scales
- Sterile neutrino with keV-scale mass is a good candidate for Warm Dark Matter.


PS. keV mass range is not available in oscillation experiments
What is the situation now? Current limits for keV-sterile neutrino

Troitsk nu-mass
The setup

- **Spectrometer**
  - Electrons energy analyzed
  - Ultra-high vacuum

- **Transport system**
  - Electrons transported
  - But tritium pumped out

- **Circulation system**
  - Pumped tritium is injected back into the system

- **Tritium pipe**
  - Tritium decays here

- **Detector**
  - Electrons are registered and counted
Integral spectrometer
Spectrum shape

\[ F(U) = \int S(E_{in}) \cdot Tr(E_{in}, E_{out}) \cdot R(E_{out}, U) dE_{in} dE_{out} \]

\( E_{in} \) - energy at decay,
\( E_{out} \) - energy entering spectrometer,
\( U \) – spectrometer potential.
Spectrum shape: beta spectrum

\[
N(E, E_0, m_\nu) = CF(Z, E)(E + m_e)p_e(E_0 - E)^2 \sqrt{1 - \frac{m_\nu^2}{(E_0 - E)^2}}
\]

\[F(Z, E)\text{–Fermi correction for electrostatic interaction}\]

Correction for final states spectrum:

\[
S(E, E_0, m_\nu) = \sum N(E, E_0 - E_i, m_\nu) \cdot P_i
\]
Spectrum shape: sterile neutrinos

\[ |\nu_\alpha > = \sum U_{\alpha i} |\nu_i > \]

\[ S(E) = U_{ex}^2 S(E, m_x) + (1 - U_{ex}^2)S(E, 0) \]
Spectrum shape: transmission

\[ Tr(E_{in}, E_{out}) = P_0 \cdot \delta(E_{in} - E_{out}) + \sum P_iL_i(E_{in}, E_{out}) + trap(E_{in}, E_{out}) \]

Passage without losses (includes quasi-elastic)

Inelastic losses (i – number of collisions)

Trapping effect

\[ P_0 = \frac{1}{X} (1 - e^{-X}), \quad P_1 = \frac{1}{X} (1 - e^{-X}) - e^{-X}, \quad P_2 = \frac{1}{2X} (2 - e^{-X} (X^2 + 2X + 2)), \quad P_3 = \ldots \]
Transmission: energy loss function

\[ \varepsilon = E_{\text{in}} - E_{\text{out}} \]

\[ X \text{ depends on } E_{\text{in}} \]

\[ L_{i+1} = L_i \otimes L_1 \]

\[ L(\varepsilon) \xrightarrow{\varepsilon \to \infty} \frac{1}{\varepsilon^2} \]

[Graph showing loss probability vs. energy (eV)]
Systematics

- Trapping effect / Rear wall backscattering
- Dead time / pileup
- Detector efficiency / threshold underflow
- Adiabaticity violation / detector backscattering
- Source thickness
- Spectrometer voltage instability
- Final states distribution

See details in https://arxiv.org/abs/1504.00544
Trapping: basics

Field configuration in tritium source forms a bottle – magnetic Trap

Trapped electrons can run back and forth up to thousand times passing few kilometers
Trapped electrons distort the actual $\beta$-spectrum

Simulation

Energy dependence
Systematics: dead time

The correction factor:

\[ N = N_0 \left(1 - N_0 \frac{\tau}{T}\right) \]

The dead time uncertainty is the main current limit on experiment sensitivity.

P.S. We wish to switch to completely new readout with continues signal digitization in upcoming run in May 2017
Detector spectrum

Signal amplitudes in Si(Li) detector at different spectrometer potentials – different intensity
Dead time calibration by pulser and two delayed signals
Dead time amplitude dependence
Pileup time calibration by pulser and two delayed signals
Pileup in real Tritium spectrum

Monte-Carlo simulation using real spectrum and pulser calibration

Life time versus measured count rate
Detector threshold

Spectrum shape near cutoff point

The estimated correction factor vs. $U_{sp}$

$$D = A \cdot e^{\frac{c}{\sigma}}$$

$$corr = 1 + A1 \cdot e^{-\frac{U}{t1}}$$
Simulation: Adiabaticity is not violated above 13.5 kV
Detector backscattering

Up to 20% electrons scatter back from Si-detector. 
*CASINO simulation*

NIM A832 (2016) 15
arXiv:1511.06129
Detector backscattering: experimental

Count rate for 25 keV electrons vs spectrometer retarding potential
Uncertainties summary

![Graph showing uncertainties as a function of mX (eV) with various error sources like Fit error, Dead time, Detection threshold, Detector backscattering, and Source thickness.](image)
Result

95 % Confidence Level (sensitivity limit) on mixing matrix element
Summary

- Two successful experiment runs with tritium in October 2016 and January 2017. One data set with $U_{\text{low}} = 16 \, kV$ and two with $U_{\text{low}} = 14 \, kV$.
- All the systematic effects on current level of precision were accounted for.
- The resulting limit is 2-5 times better than existing ones.

- Agreement and Proposal for collaboration with KATRIN-TRISTAN group on new detector development and electronics.
Thank you for your attention
ADDITIONAL SLIDES
\[
\frac{V_{\perp}^2}{B_{\parallel}} = \text{const}
\]

\[
B_{\parallel} \cdot S = \text{const}
\]
Electrostatic and magnetic field configuration

Main vessel, about 10 m long

Magnetic field 7.2 T at the entrance, 1.2 mT in the center

Warm correction coils

"Теплые" соленоиды
"Компенсирующие" соленоиды

Inner electrostatic electrode, 13-19 kV
Run 2016_10

Count rate in monitor point at 16.0 kV
The DataForge

- *The DataForge is a scientific framework based on modern trends and solutions in programming.*
- *It introduces a few new concepts into scientific (hep-physics) software:*
  - The analysis as a metadata process
  - Declarative description of analysis process (the analysis as a build system)
  - Convention over configuration on a large scale
- *It is completely and “true” cross-platform (not “compile wherever you want on your own risk”).*
- *It is modular!*
- *It has a few very important ideological effects that could be expanded further and can open a whole new world of possibilities for scientific data processing.*
Data from 1994-2005.
Sterile neutrino search in 300 eV below the spectrum endpoint

Some results on sterile neutrino could be obtained from data acquired in search for electron neutrino mass!

Comparison of errors for heavy neutrinos between Troitsk and Mainz experiments

Comparison of errors for heavy neutrino mass obtained by the analysis, black symbols connected by solid lines, and approximate estimation $\sigma(U_{\nu_4}^2) = 2.53/m_{\nu_\ell}^2$ based on the result for the electron antineutrino mass V. N. Aseev et al., Phys. Rev. D84, 112003 (2011), red dashed line.

The blue dotted line corresponds to the estimation $\sigma(U_{\nu_4}^2) = 3.04/m_{\nu_\ell}^2$ for the total error from C. Kraus, et al., Eur. Phys. J. C 40, 447 (2005)

Final states spectrum
Gun measurements

![Graph showing count rate vs. U with intercept and slope values labeled.]

- Intercept = 1528.13395
- Slope = 0.00369

Legend:
- gun
- dark
- dif