First measurements in search for keV-sterile neutrino in tritium beta-decay by Troitsk nu-mass experiment

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We present the first measurements of tritium β-decay spectrum in the electron energy range 16–18.6 keV. The goal is to find distortions which may correspond to the presence of a heavy sterile neutrinos. A possible contribution of this kind would manifest itself as a kink in the spectrum with a similar shape but with end point shifted by the value of a heavy neutrino mass. We set a new upper limits to the neutrino mixing matrix element U²₄ which improve existing limits by a factor from 2 to 5 in the mass range 0.1–2 keV.

1. Introduction. Neutrino studies nowadays belong to the most active and promising research domain in particle physics. Neutrinos are massive and this property cannot be accommodated in the Standard model. Therefore, studies of the neutrino mass matrix give us unique opportunity to probe a new physics in the laboratory directly. The simplest mechanism to provide neutrino with the mass assumes the existence of a new particles - right handed (or ”sterile”) neutrinos. Their number, masses and mixing angles with left handed (”active”) neutrinos, apart from the existing observational restrictions, are free parameters of the theory, for the review see [1].

Interestingly, sterile neutrino in the keV mass range is one of the best motivated [1] dark matter particle candidates. Therefore, sterile neutrino searches in this mass range are most important. Troitsk nu-mass experiment, which had been designed for the active neutrino mass measurements, and where the strongest direct limit on it [2, 3] has been obtained so far, is well suited for the above task [4]. Moreover, currently, it is the only installation in operation which is capable for the sterile neutrino searches in the keV mass range.

Detailed description of Troitsk nu-mass experiment, hardware, procedures and important systematic errors inherent to the spectrum measurements on this apparatus, can be found in Ref. [4]. This paper presents the first physical results and restrictions obtained in 2016 in searches for sterile neutrinos in the mass range up to a few keV.

2. Troitsk nu-mass. Our equipment consists of two main components which are the Windowless Gaseous Tritium Source (WGTS) and the Electrostatic Spectrometer with Magnetic Adiabatic Collimation (MAC-E filter). Gaseous source allows to avoid solid state effects which distort spectra if tritium is frozen or implanted. The radioactive gas freely circulates in a source and there are no effects associated with a ”wall” or ”window”. Electrons originating in the tritium decay are transported by the system of superconducting solenoids to the spectrometer entrance. MAC-E filter works as the electrostatic rejector of all electrons with energy less than a given spectrometer potential. All electrons with higher energy are counted by the detector. Measurements with different values of retarding potential give integral energy spectrum of electrons. The operation of the spectrometer requires the adiabatic transport system to contain magnetic fields up to 8 Tesla, which are formed by the superconducting magnets.

We count electrons by a single channel Si(Li) detector with 30 nm palladium window and Si 100 nm dead zone. Signals from the detector are shaped by the amplifier-shaper with 2 microseconds integration time and then digitized by a system with constant (approximately 6.5 microseconds) dead time. Such a long integration time is required in order to minimize the back scattering effect of electrons from the detector, which reaches 10-15% probability. Then these scattered electrons are reflected with some delay by the electrostatic and magnetic mirrors back to the detector. Relevant details of this feature...
of the MAC-E filter are described in Ref. [5].  

As a working gas we have used DT molecules with small concentration of HT and T₂. The total column density of the tritium source corresponded to approximately 10% probability of electron scattering in the gas and was periodically measured employing the electron gun located at the rear side of the WGTS. To stabilize the amount of working gas in the WGTS pipe, its temperature was adjusted to 26-28 K by the combination of cold helium gas from the cryogenic system and additional heater. During each set of measurements the pipe temperature was stable with precision better than 0.1 K. The maximum rate of electron counting on the detector was reaching 15 kHz at 16 kV spectrometer potential. One gas fill lasted for 5-6 days. At the end of a fill the intensity of the tritium source was dropping by a few tens of a percent.

3. Measurements. The spectrum measurement procedure has been fixed to the following scheme. The spectrometer electrostatic potential was scanned from 18700 V (which exceeds the end point of the spectrum located at 18570 eV) down to 16000 V, with steps of 50 V. At each point the high voltage was controlled with the precision of about ±0.2 V and measurements were taken during 30 seconds. To avoid possible distortion of the spectrum caused by the temporal instabilities we scan in series of high voltage going down and up. In addition, to control the stability of the radioactive tritium source, point at 16000 V was selected as the monitor point and was measured after every 6-8 steps.

At the end of a fill, when the working gas was pumped out, we performed control measurements of the empty source with four spectrometer cycles up and down. That was used to subtract physical background.

In addition, precise measurements of the spectrometer transmission function were done using electron gun operating at energies between 16 keV and 19 keV. Transmission function deviates from the step function characterizing an ideal spectrometer due to effect described in [5], and, at even lower potentials, due to break up of adiabaticity for the electron motion in the spectrometer magnetic field (which does not happen for potentials above 16 kV). We used e-gun calibration results to describe spectrometer response function.

4. Corrections and systematics. The expected list of systematic uncertainties in our experiment is presented in Ref. [4]. With the current level of statistical sensitivity the most important systematic uncertainties are: electronics dead time. If two events are close enough, namely in the range of about 2.5 μs, we get “pileup event” which is indistinguishable from a single event, but creates greater registered amplitude of the signal. In order to disentangle pileup and to find real counts, N_{real}, we made a Monte-Carlo simulation using the following calibration data:

- dependence of the electronics dead time on the signal amplitude, measured by the two-signal pulser with adjustable distance between signals;
- pileup probability and amplitude for different delays using the same pulser;

The comparison of simulated and real detector responses is presented in Fig. 1 and shows very good agreement between them. Simulation started with the initial distribution which was close to the amplitude spectrum of real events in the experiment, but with slightly larger intensity of count rate, and without pileup, see red curve in Fig. 1. Integral under this curve gives desired N_{real}, while integral under experimental curve we denote N_{det} in what follows.

Simulation was repeated for each spectrometer potential using real amplitude spectra as a template. Resulting dependence of N_{det}/N_{real} on the count rate is shown in the Fig. 2, and represents dead time correction factor.

![Figure 1: Amplitude spectrum of the detector at the spectrometer potential fixed to 16.0 kV. Solid line corresponds to the measured spectrum. Red dashed line represents the initial distribution used in simulation. Dotted line corresponds to the simulated spectrum. Dot-dashed line shows extracted contribution of pileup events.](image-url)
This dependence can be described by the formula:

$$N_{\text{real}} = \frac{N_{\text{det}}}{1 - f\tau},$$

(1)

where $f$ is measured count rate integrated over all channels and $\tau = 6.55 \pm 0.05\,\mu$s is the effective dead time, which was found by fitting Eq. (1) to the MC results shown in Fig. 2 by black boxes. This effective dead time should not be confused with dead times found in the calibration procedure. The latter depend slightly on the amplitude of a signal, the former is proper average.

4.2. Events under threshold. We register electrons which produce signal with amplitude above some threshold, the loss of undetected electrons should be corrected for. This threshold is seen in Fig. 1 as the left edge of the amplitude spectrum, while Fig. 3 shows the shape of spectra near the threshold for different spectrometer potentials. The threshold was set by electronics to cut down the noise.

The observed shape is difficult to simulate, but empirically it follows exponential distribution at low amplitudes; simulation of the back scattering processes from the detector with reflection of the scattered particles back to the detector by electrostatic and magnetic mirrors [5], which dominate in this region of amplitudes, qualitatively shows similar exponential tendency. The slope of this exponent is almost the same for different spectrometer potential or the electron energy. We extrapolate the ADC spectra using exponential fits in the narrow region 400 – 600 ADC channels, and estimate the number of events under the threshold as an integral of this exponential function. The correction could not be calculated in this way for higher retarding potentials (above 17.5 kV), where the number of events is insufficient to do a reliable fit. Therefore, correction itself was extrapolated into this region using its shape at lower potentials, which is also exponential. The final correction for the threshold effect is 2-4 %. We assume that the systematic error here comes from the uncertainty of the fitting procedure.

4.3. Other corrections. Besides electronics dead time and events under threshold we applied our usual corrections which were already discussed in detail in Refs. [2, 4, 5]. Important corrections and corresponding effects are listed below.

- Trapping effect. We have included the amplitude of the trapping effect as a free parameter in the analysis of the tritium beta-decay spectrum.
- Spectrometer transmission function. There is a small variation of the transmission in the energy range 16 – 19 keV caused by the detector backscattering effect, and spectra were corrected assuming linear interpolation of transmission function between these points.

There are also less important systematic effects, which were treated in the same way as in our previous work. Those are: correction for the final state spectrum of residual ion of the daughter molecule $D^3He^+$, high voltage instability and electron scattering in the source. Density of radioactive gas was rather low, only $\approx 12\%$ of electrons scatter. Its column density was measured during runs by the electron gun with the accuracy better than 10 %.

Figure 2: Dead time correction factor as a function of $f$.

Figure 3: Detector amplitude spectrum near threshold at three spectrometer potentials.
5. Results. The final spectrum of tritium $\beta$-decay (after corrections) was fitted by the function

$$S(E) = U^2_{ex} S(E, m_x^2) + (1 - U^2_{ex}) S(E, 0),$$

(2)

where $S(E, 0)$ is beta spectrum with zero neutrino mass; $S(E, m_x^2)$ – spectrum with finite mass, $m_x$, of additional neutrino, and $U_{ex}$ is mixing angle between two states.

In Fig. 4 we present contributions into fitting error of $U^2_{ex}$ coming from statistics and from important (for the current analysis) systematics. After summing all errors and applying sensitivity limit procedure (see ref. [6] for details), we obtain upper limits for $U^2_{ex}$ which are shown in Fig. 5. In the same figure we also present the existing published limits [7, 8, 9, 10].

To conclude, we present our first results on the search in tritium $\beta$-decay of a heavy sterile neutrinos in the mass range of a few keV. We have improved the existing limits on their mixing with electron neutrinos by the factor of 2 to 5, depending upon $m_x$, in the mass range $0.1 - 2$ keV.

Acknowledgements. We are grateful to D. Gorbunov and A. Lokhov for useful discussions. This work was supported by the RFBR grant numbers 14-22-03069-ofi-m and 14-02-00570-a. IT also acknowledges the support of the Grant of President of Russian Federation for the leading scientific Schools of Russian Federation, NSh-9022-2016.2.

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