TRISTAN measurements at the Troitsk nu-mass experiment

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Abstract. The KATRIN (Karlsruhe Tritium Neutrino) experiment investigates the energetic endpoint of the tritium beta-decay spectrum to determine the effective mass of the electron anti-neutrino with a sensitivity of 200 meV (90 % C.L.) after an effective data taking time of three years. The TRISTAN (tritium beta-decay to search for sterile neutrinos) group aims at detecting a sterile neutrino signature by measuring the entire tritium beta-decay spectrum with an upgraded KATRIN system. One of the greatest challenges is to handle the high signal rates generated by the strong activity of the KATRIN tritium source. Therefore, a novel multi-pixel silicon drift detector is being designed which is able to handle rates up to 100 Mcps with an excellent energy resolution for electrons of 300 eV (FWHM) at 10 keV. First seven-pixel prototype detectors were successfully installed and operated at the Troitsk nu-mass experiment, one of KATRIN’s technological predecessors. In this work, we present the results of these measurement campaigns.

1. Introduction

Several theories beyond the Standard Model of particle physics consider the existence of a right-handed partner of the left-handed neutrino. This right-handed neutrino would be sterile regarding the weak interaction. A keV-scale sterile neutrino is a viable candidate for cold and warm Dark Matter [1]. Both telescope experiments and cosmological considerations constrain the active-sterile mixing amplitude to $\sin^2(\theta) < 10^{-6}$–$10^{-8}$ [2]. A widely used method for a direct search is based on high-precision measurements of the energy spectrum of tritium β-decay. The signature of a keV-scale sterile neutrino would manifest itself as a broad distortion and a kink in the continuous electron energy spectrum [3]

$$\frac{d\Gamma}{dE} = \cos^2(\theta) \frac{d\Gamma(m_{\text{light}})}{dE} + \sin^2(\theta) \frac{d\Gamma(m_{\text{heavy}})}{dE}.$$  (1)

While the signal strength of the broad distortion is governed by the active-sterile mixing amplitude $\sin^2(\theta)$, the position of the kink depends on the mass of the sterile neutrino $m_{\text{heavy}}$.

2. Troitsk nu-mass experiment

The Troitsk nu-mass experiment is conducted by the Institute for Nuclear Research of the Russian Academy of Sciences. The two main components of the setup are the Windowless Gaseous Tritium Source (WGTS) and the Magnetic Adiabatic Collimation spectrometer combined with an Electrostatic filter (MAC-E). Electrons created in the WGTS are magnetically...
guided towards the spectrometer. A retarding potential $U$ in the center of the spectrometer acts as a high-pass filter. All electrons that overcome the retarding energy $qU$ are counted by a detector. By varying the retarding energy, an integral spectrum is measured. The latest sterile neutrino search yielded new upper limits on the active-sterile mixing amplitude $\sin^2(\theta)$ in the mass range of 0.1 to 2 keV [4]. Events under detection threshold and electronics dead time were the dominant sources of systematic uncertainties, both arising from the detector system. By using the novel TRISTAN detector system, Troitsk nu-mass overcomes these uncertainties. Furthermore, a sterile neutrino search on the differential spectrum becomes possible.

3. TRISTAN detector
The goal of the TRISTAN project is to utilize the KATRIN experiment to search for a keV-scale sterile neutrino signature. This signature may appear anywhere in the tritium $\beta$-spectrum, where the count rate is increased by several orders of magnitude compared to KATRIN standard operation. Since the KATRIN detector is not designed to handle such high count rates, the TRISTAN group is currently developing a novel detector system. The requirements on the TRISTAN detector system are an energy resolution of less than 300 eV (fwhm) at 20 keV, a low energy detection threshold of around 1 keV and the ability to manage high count rates in the order of $10^8$ cps. The detector will be segmented into an array of 3486 3 mm-diameter pixels in silicon drift detector (SDD) technology. Several prototype chips with seven 2 mm-diameter pixels were produced at the semiconductor laboratory of the Max Planck Society (HLL) [5]. The front-end electronics consist of a CUBE [6] pre-amplifier application-specific integrated circuit (ASIC) for each pixel. The 8-channel DANTE digital pulse processing system is used as back-end electronics. An excellent performance of the prototype system was demonstrated in the laboratory [7].

4. Measurements with TRISTAN at Troitsk nu-mass
Thanks to the TRISTAN detector’s excellent performance, it was possible to operate the Troitsk nu-mass experiment in both an integral and for the first time a differential mode.

4.1. Measurements in integral mode
The detector counted the electrons that passed through the MAC-E spectrometer depending on the retarding energy setting. By scanning the retarding energy between 12 keV and 18.6 keV, an integral tritium spectrum was measured. The energy resolution was determined by the spectrometer. In total 5.8 million electrons were detected. Additionally, measurements were performed to determine the source column density and the background as well as to monitor the tritium activity.

4.2. Measurements in differential mode
The retarding energy was set to 13 keV. A differential tritium spectrum was measured by the detector to analyze the electrons’ energy. In this case, the energy resolution was determined by the detector. A total of 1.7 million electrons was detected. Additionally, calibration measurements of mono-energetic electrons emitted by the spectrometer electrode were performed to determine the experimental response.

5. Data analysis
The model for the differential tritium spectrum is composed of the Fermi function $F$ [8], small term corrections $S$ [9] and an energy-dependent final state distribution. The response of the entire Troitsk nu-mass setup is expressed in response matrices, which are determined by simulations and calibration measurements. The matrices are convolved with the tritium model prior to the least-squares fit of the data.
5.1. Analysis of the integral mode
For each retarding energy setting, corrections on the measured differential spectrum are conducted. Integrating the differential spectrum yields one point in the integral spectrum. The most dominant uncertainties of the integral mode are undetected events below threshold, the subtraction of a undesired low energy structure, decrease of the decay rate over time and trapping of electrons in the source magnetic field. For each of them, a covariance matrix is generated, taking point-to-point correlated uncertainties into account. Free fit parameters are normalization, spectral endpoint, and background. The fit with a p-value of 35.5 % is shown in figure 1.

5.2. Analysis of the differential mode
The largest systematic uncertainty in the differential measurement mode arises from the parameterization of the detector response. To take this uncertainty into account, the parameters of the detector response function are treated as nuisance parameters in the differential fit. Additional free fit parameters are slope and offset of the energy calibration of the model as well as normalization, spectral endpoint, and background. Other systematic effects were found to be negligibly small. The fit with a p-value of 2.0 % is shown in figure 2.

![Figure 1. Integral fit.](image1)
![Figure 2. Differential fit.](image2)

Figure 1. Integral fit. The residuals are normalized to the overall uncertainty that consist of a statistical (dark green) and systematic contribution.

Figure 2. Differential fit. The statistical error bars of the data are too small to be seen. The retarding energy is 13 keV. The residuals are normalized to the statistical uncertainty.

5.3. Limit setting
The 95 % C.L. exclusion curves are shown in figure 3. The explored mass range is enlarged by a factor of 3 compared to the previously analyzed range of the Troitsk nu-mass experiment [4]. An indication for a sterile neutrino signature is apparent neither in the integral nor in the differential exclusion curve. As both modes are prone to largely different systematic effects, a false-positive signal can be excluded by comparing the results of both.

6. Conclusion
In this work, a 7-pixel TRISTAN prototype detector was successfully installed at the Troitsk nu-mass experiment. Data was taken in both integral and differential measurement mode. Sophisticated models, analysis strategies and detailed budgets of systematic uncertainties were developed for both modes. It could be demonstrated that both measurement modes are prone to largely different systematic uncertainties. Hence, a combination of both modes allows to exclude
Figure 3. **Sensitivity and exclusion curves.** The confidence level is 95 %. The sensitivity provides an expectation for the exclusion based on the given statistical uncertainty. The exclusion is the actual realization given the measured data. The latest result of the Troitsk nu-mass collaboration is shown in black [4].

Possible false-positive signals in future sterile neutrino searches with more data. Furthermore, the accessible mass range of the Troitsk nu-mass experiment was enlarged by a factor of 3. The analysis methods developed in this work depict a major milestone in the TRISTAN project and will serve as the basis for future sterile neutrino searches with the TRISTAN detector integrated at the KATRIN experiment.

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