PROCEEDINGS OF SCIENCE

A model for the measured KATRIN differential Tritium spectrum to search for keV sterile neutrinos

Andrea Nava on behalf of the KATRIN collaboration[a,b,*]

[a] *Università di Milano - Bicocca, Dipartimento di Fisica G.Occhialini, Piazza della Scienza 3, Milano, Italy*
[b] *INFN Sezione di Milano - Bicocca, Piazza della Scienza 3, Milano, Italy*

E-mail: andrea.nava@mib.infn.it

KATRIN (Karlsruhe Tritium Neutrino Experiment) aims to measure the neutrino mass by analyzing the endpoint region of a Tritium spectrum using a high-luminosity source and a high-resolution MAC-E filter technique. KATRIN holds the current best limit on the neutrino mass of 0.8 eV, coming from the joint analysis of the first two measurement campaigns. After KATRIN's data taking, a detector upgrade, called TRISTAN, is planned. The choice for this new detector is a matrix of Silicon Drift Detectors (SDDs) made of 9 modules with 166 pixels each.
SDDs, able to sustain a high count rate, will allow a high-statistics measurement of the whole Tritium spectrum, and thus the search for new physics, like sterile neutrinos with mass in the keV-range, candidates to be Dark Matter particles. A model for the measured Tritium spectrum is therefore needed. In this work, I will present the status of such a model, together with experimental tests of one of its parts, the detector response.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08-01.09.2023
University of Vienna

---

[*] Speaker

1. Introduction

Sterile neutrinos are particles predicted by several minimal Standard Model extensions. In particular, with a mass of O(keV), they would be a suitable candidate to explain the Dark Matter [1]. The presence of a sterile neutrino leads to a kink signature in the β spectrum, which position and amplitude are related to m_4 and $|U_{e4}|^2$, respectively the new mass eigenstate and its mixing amplitude with the electron flavor, as can be seen in figure 1. Such a signal can be searched in the Tritium spectrum by KATRIN [2] with an upgraded detector: TRISTAN [3]. The goal is to reach a sensitivity of $|U_{e4}|^2 < 10^{-6}$, and thus a high statistics measurement is needed. KATRIN exploits a high-intensity gaseous Tritium source and a magnetic field designed to guide β electrons to the detector, where a total rate of $\sim 10^8 counts/s$ is expected. To sustain this interaction rate, the choice for TRISTAN is a Silicon Drift Detectors (SDDs) matrix, where detectors are grouped in 9 modules with 166 pixels each.

2. Model of the Tritium spectrum

Electron spectroscopy in the keV energy range is challenging because electrons can change their energy and angle in the path from the source to the detector.

Some of the main systematic effects in the KATRIN beamline are scattering in the source, scattering on the Rear Wall (RW, the gold surface close to KATRIN's source), electromagnetic transport and incomplete charge collection in the SDD.

All these effects modify the measured energy of the electrons, and must therefore be taken into account in the sterile neutrino search. A model for the measured Tritium spectrum that includes these experimental effects has been developed [4]; its input is the 1D theoretical Tritium spectrum. Experimental effects are simulated using Monte Carlo simulations or analytical calculations and are stored in response matrices, that give the probability to change energy and angle for a given initial energy and angle of the electrons. Multiple scatterings along the beamline are computed through an iterative convolution of the input spectrum with these matrices. In this way, the electron's energy-angle distribution before the detector is calculated. Detector effects are thus applied through another response matrix convolution to obtain the prediction for the measured spectrum.

Response matrices are produced for different scenarios. For example, it is possible to change the material of the Rear Wall (from Gold to a low-Z material, like Beryllium, to reduce the backscattering probability) or the values of the electromagnetic fields along the beamline. In figure 1 the shape of the expected Tritium spectrum and the impact of a sterile neutrino ($m_4 = 10keV$, $|U_{e4}|^2 = 10^{-6}$) are shown for different scenarios. Experimental effects in a nominal KATRIN beamline would largely modify the spectral shape and broaden the sterile signal. With the Tritium model, it is possible to optimize the beamline parameters (here the electromagnetic fields and the Rear Wall material) to reduce the impact of systematic effects on the spectrum and consequently restore the characteristic kink due to sterile neutrinos.

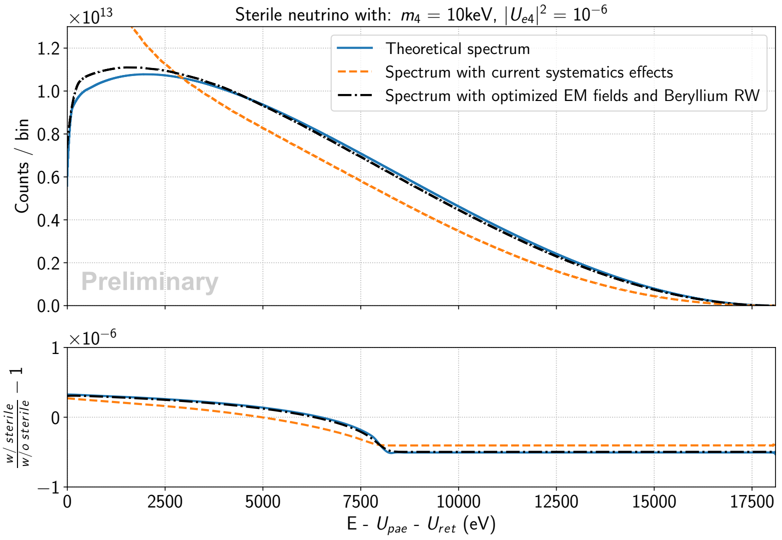

Figure 1: Predicted shape of Tritium spectrum compared to the theoretical one for two different scenarios, nominal and optimized (top). The kink induced from a sterile neutrino is also shown (bottom).

3. Tests of the detector model

In order to have realistic results, dedicated calibration measurements must be done to assess the accuracy of each part of the model. Here, SDDs response tests are discussed.
O(keV) electrons, when interacting with Silicon, can be backscattered without depositing all their energy. This can be simulated with MC simulations, and in particular, we use a Geant4 code (version 10.07) with Penelope model [5]. Moreover, non-idealities of the detector must be included. The main effects are:

- entrance window: part of the electron's energy is left close to the surface, a region with incomplete charge-collection efficiency. We follow the parametrization described in [6], where an exponential depth-dependent charge collection efficiency is assumed;
- energy resolution: added through a convolution with a Gaussian. Both the intrinsic energy-dependent and the energy-independent noise contributions are included;
- charge-sharing: part of the energy can be shared with neighboring pixels if the electron hits the SDD close enough to one of the borders. A Gaussian model for the charge cloud produced in the detector is assumed.

All these non-idealities come with free parameters that can be estimated through a comparison with experimental data. We used monochromatic spectra (10, 15, and 20 keV) acquired with SDDs using an electron gun.
The experimental spectra, together with the combined best fit, are shown in figure 2. The χ^2 are good and all the structures, the main peak, the Silicon X-ray escape peak, and the incomplete charge collection tail, are well reproduced.

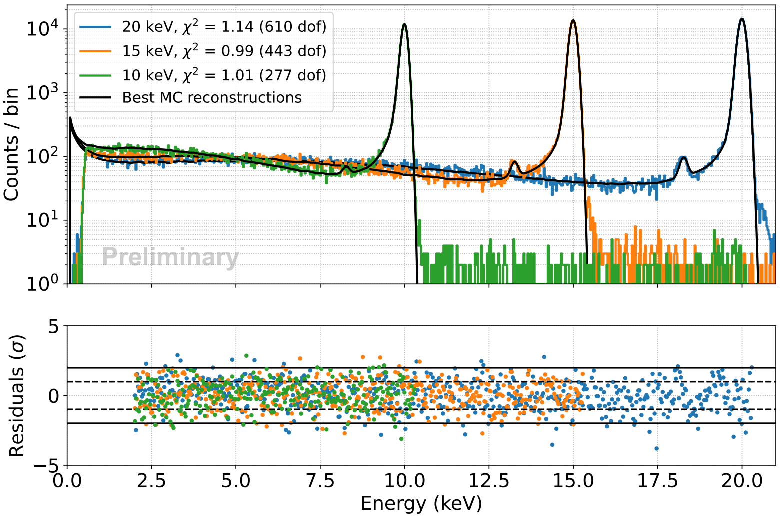

Figure 2: Best fit for the three electron input energies.

4. Conclusion

A model able to predict the shape of the Tritium spectrum in the KATRIN beamline by taking into account the main systematics is in development. In particular, a good understanding of the detector response measured in a laboratory was found. Further measurements with higher statistics, as well as measurements in a KATRIN-like environment, are planned to thoroughly assess the accuracy of the model.

References

[1] Adhikari R. et al "A White Paper on keV Sterile Neutrino Dark Matter", DOI: 10.1088/1475-7516/2017/01/025

[2] Aker M. et al "Direct neutrino-mass measurement with sub-electronvolt sensitivity", DOI: 10.1038/s41567-021-01463-1

[3] Mertens S. et al "A novel detector system for KATRIN to search for keV-scale sterile neutrinos", DOI: 10.1088/1361-6471/ab12fe

[4] Descher M. "Systematics modeling and sensitivity for keV sterile neutrino search at KATRIN", [Unpublished doctoral dissertation], Karlsruhe Institute of Technology

[5] Nava A. et al "A Geant4-based model for the TRISTAN detector", DOI: 10.1088/1742-6596/2156/1/012177

[6] Biassoni M. et al "Electron spectrometry with SDDs: a GEANT4 based method for detector response reconstruction", DOI: 10.1140/epjp/s13360-021-01074-y