PROCEEDINGS OF SCIENCE

Direct neutrino mass measurement at the KATRIN experiment

Jaroslav Štorek[a,*] **for the KATRIN collaboration**

[a] *Institute for Astroparticle Physics, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*

E-mail: jaroslav.storek@kit.edu

The KArlsruhe TRItium Neutrino experiment (KATRIN) is performing a high precision spectroscopy of the tritium beta-decay spectrum to search for the signature of the neutrino mass. It combines a high-intensity gaseous molecular tritium source and a high-resolution electrostatic spectrometer with magnetic adiabatic collimation. This allows KATRIN to reach a sub-eV sensitivity to the neutrino mass. Moreover, existence of the fourth neutrino-mass eigenstate (sterile neutrino), a new light boson and exotic general weak interactions are investigated.

The analysis of the first five KATRIN measurement campaigns results in a new neutrino-mass upper limit $m_\nu < 0.45\,\mathrm{eV}$ at 90% confidence level (CL) and the existence of a sterile neutrino is excluded in the studied region with 95% CL. In the analysis of the second measurement campaign we derive competitive constrains on general neutrino interactions and evaluate the campaign's sensitivity to the existence of the new light bosons.

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*Speaker

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1. Introduction

Neutrino oscillations [1, 2] imply non-zero masses of at least two neutrino mass eigenstates. A precise knowledge of the absolute neutrino mass uncovers origin of the neutrino masses and provides a key input for cosmological structure formation models.

There are multiple neutrino mass determination methods. Current observations of the cosmological structures indicate an upper limit on the sum of three neutrino mass eigenstates of 0.12 eV [3]. However, this result strongly depends on the used cosmological model. Since the release of the latest results from the DESI collaboration [4], the essential model assumptions are under intense scrutiny. Neutrino mass can also be investigated in the neutrinoless beta decay processes under the assumption that the neutrinos are their own antiparticles [5]. Nevertheless, the neutrino mass upper limits from these searches depend on the precision of the nuclear matrix element calculations [6]. Last, experiments based on β-decay kinematics provide a direct, model-independent way to assess the neutrino mass. In the KATRIN experiment we perform a precision measurement of the molecular tritium β decay spectrum

$$\mathrm{T}_2 \rightarrow {}^3\mathrm{HeT}^+ + \mathrm{e}^- + \bar{\nu}_\mathrm{e} \tag{1}$$

with a focus on the endpoint region where the impact of the neutrino mass is the largest. Challenges of this measurement arise from a sub-eV effect of the neutrino mass and low decay rate in the endpoint region.

2. The KATRIN experiment

In the 70-m-long beamline of the KATRIN experiment, β-electrons are adiabatically guided along the magnetic field lines from the windowless gaseous tritium source into the main spectrometer through the transport and pumping section. The main spectrometer acts as an electrostatic high-pass filter and electrons that pass the retarding potential are counted by a segmented silicon detector. Details of the experimental setup are described in [7].

Due to the nature of the electrostatic high-pass filter, the observed spectrum is an integrated spectrum. The observed rate $R(qU)$ at a specific retarding potential qU is described by

$$R(qU) = A_s N_T \int_{qU}^{E_0} R_\beta(E, m_\nu^2) f(E, qU)\, dE + R_\mathrm{bg}(qU), \tag{2}$$

where N_T is the signal normalization calculated from the number of tritium atoms in the source and maximum acceptance angle. A_s is an additional normalization factor, E_0 is the endpoint of the tritium β spectrum and $R_\beta \propto (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2} \cdot \theta\,(E_0 - E - m_\nu)$ is the differential spectrum rate given by Fermi's theory with the Heaviside θ function and electron energy E. Here $m_\nu^2 = \Sigma_i |U_{\mathrm{e}i}|^2 m_i^2$ is the effective electron anti-neutrino mass with elements of the Pontecorvo–Maki–Nakagawa–Sakata matrix $U_{\mathrm{e}i}$ and neutrino mass eigenvalues m_i. Last, f is the response function governing the transmission of electrons through the main spectrometer including energy losses due to scattering on T_2 and R_bg is the background rate. A detailed description of the spectrum calculation can be found in [8].

3. Neutrino mass results

The current neutrino mass analysis results [9] are based on 36 million collected electrons in the region of interest close to the beta spectrum endpoint E_0, $\langle E_0 - 40\,\text{eV}, E_0 + 135\,\text{eV}\rangle$. The dataset includes 5 different KATRIN Neutrino Mass (KNM) measurement campaigns. Each campaign consists of hundreds of β-scans, sequences of up to 40 different retarding potentials qU with a typical total measurement time of 3.5 hours. An excellent stability of the measured parameters within a campaign allows us to combine all the scans from one campaign into one single spectrum.

Major measurement optimizations have been applied between the campaigns. The intensity of the tritium source has been increased by more than factor of 3 since the first measurement campaign, electric and magnetic field settings in the main spectrometer have been modified to reduce the background by a factor of 2 and the distribution of the retarding potentials and measurement time has been tuned for a better neutrino mass sensitivity. Details on the optimization process can be found in [9]. Because of the gradual application of the optimizations, the total dataset consists of 7 different β-spectra[1] whose analysis is performed in one single fit with free fit parameters A_s, E_0, R_{bg} and one common free fit parameter m_ν^2. The best fit value $m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\text{eV}^2$ yields a new world-best upper limit of $m_\nu < 0.45\,\text{eV}$ at 90% confidence level (CL) [9] using the Lokhov-Tkachov method [10]. Negative m_ν^2 is allowed in the model to account for statistical fluctuations of low count rate near the endpoint. The Lokhov-Tkachov calculation converts negative m_ν^2 into the median sensitivity of the experiment and prevents shrinking of the upper limits for more negative m_ν^2 values, unlike Feldman-Cousins method [11]. The analyzed dataset together with the fit can be seen in Fig. 1.

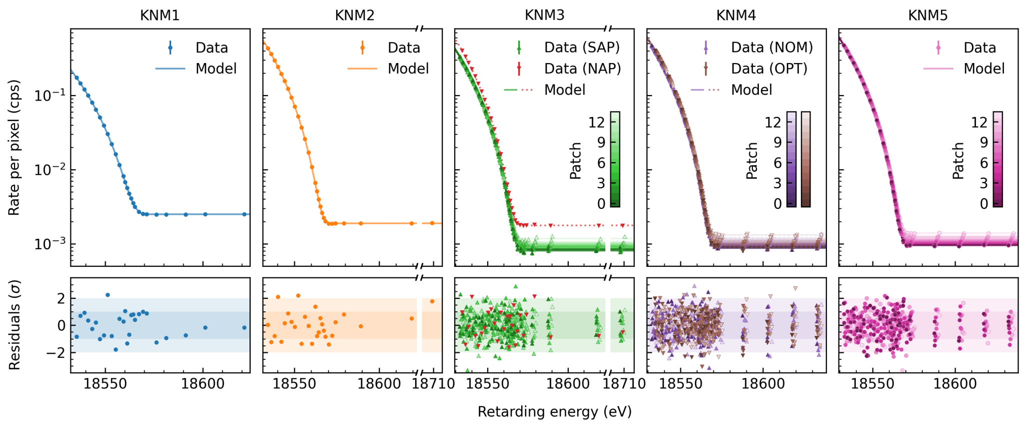

Figure 1: Spectra, fit models and normalized residuals of each measurement campaign. The KNM3-SAP, KNM4-NOM, and KNM4-OPT, and KNM5 data are subdivided into 14 detector patches. The squared neutrino mass is a common fit parameter over all data sets. Figure adapted from [9].

[1] The seven β-spectra are chronologically labeled as KNM1, KNM2, KNM3-SAP, KNM3-NAP, KNM4-NOM, KNM4-OPT, KNM5. In KNM3-SAP the new electric and magnetic field settings have been tested and the distribution of the retarding potentials and measurement time has been used since KNM4-OPT.

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4. Sterile neutrino search

The same dataset of 36 million electrons has been used to search for a hypothetical fourth neutrino mass eigenstate m_4 [12], an eV-scale sterile neutrino. Sterile neutrinos do not take part in the weak interaction, however, they have a small active flavor component that allows oscillation into active flavor states. The oscillation amplitude is described in the framework of 3 active + 1 sterile neutrino by the extended 4×4 PMNS matrix with mixing $|U_{e4}|^2$ equivalent to $\sin^2(\theta_{\mathrm{ee}})$. Existence of eV-scale sterile neutrinos is motivated by appearance [13], [14] and disappearance [15] anomalies observed in the short baseline oscillation experiments.

Sterile neutrino signal would manifest itself as a discontinuity in the β-spectrum at the energy of $E_0 - m_4$ (shown in the left graph in Fig. 2). To model such a signal we modify the differential spectrum rate $R_\beta(E, m_\nu^2)$ from (2) to

$$R_\beta(E, m_\nu^2, m_4^2, \theta_{\mathrm{ee}}) = \cos^2(\theta_{\mathrm{ee}}) \cdot R_\beta(E, m_\nu^2) + \sin^2(\theta_{\mathrm{ee}}) \cdot R_\beta(E, m_4^2). \tag{3}$$

The analysis of the first 5 measurement campaigns shows no sterile neutrino signal at 95% CL. Exclusion contour assuming $m_\nu^2 = 0$ is presented in the right graph in Fig. 2 (black curve) together with results of oscillation experiments. Here, a transformation of the KATRIN observables m_4^2 and $\sin^2(\theta_{\mathrm{ee}})$ has been made: $\sin^2(2\theta_{\mathrm{ee}}) = 4\sin^2(\theta_{\mathrm{ee}})(1 - \sin^2(\theta_{\mathrm{ee}}))$ and $\Delta m_{41}^2 \approx m_4^2 - m_1^2$, where $m_1^2 = 0$ is assumed. Cases of a free m_ν^2 and m_ν^2 constrained to positive values below m_4^2, $0 \leq m_\nu^2 < m_4^2$, have been studied in [12]. The analysis results of the first 5 campaigns exclude large parts of the parameter space in the region of $\Delta m_{41}^2 > 5\,\mathrm{eV}^2$ and mixing angles above a few percent. As a result, the combined best fit of the BEST [15], GALLEX [16] and SAGE [17] experiments is excluded at the confidence level of 96.56% and the Neutrino-4 result [18] is challenged at 99.99% CL.

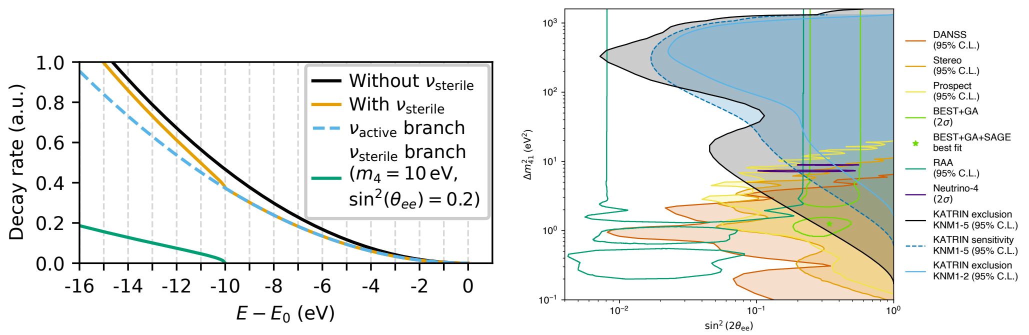

Figure 2: Manifestation of the sterile neutrino signal in the differential β-spectrum with endpoint E_0 is shown in the left graph. Right graph shows parameter space of sterile neutrino mass Δm_{41}^2 in terms of mixing angle $\sin^2(2\theta_{\mathrm{ee}})$ explored by different experiments. Black solid curve shows the current KATRIN exclusion contour under the assumption $m_\nu^2 = 0$. Both figures are adapted from [12].

5. General neutrino interactions and light bosons

The high precision β-spectrum collected at KATRIN offers a unique way to look for physics beyond the Standard Model at low energy scale. Results of the general neutrino interactions searches

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and sensitivities to new light boson processes are presented in this section.

In the theory of general neutrino interactions (GNI) all possible Lorentz-invariant operators for four-fermion interactions involving at least one neutrino are included. Both left- and right-handed neutrinos are considered, including energy-dependent contributions to the β-spectrum rate. Moreover, no assumption about the neutrino-mass-generation mechanism is made.

The modeling of the differential spectrum rate R_β from Eq. (2) is modified to

$$R_\beta(E, m_\nu^2) \propto \sum_{k=\beta,N} \sqrt{(E_0 - E)^2 - m_k^2}\, \xi_k \left[1 - b'_k \frac{m_k}{E_0 - E}\right] \theta(E_0 - E - m_k), \tag{4}$$

where the contribution of both light (indicated by index β) and additional heavier neutrinos (index N) is considered. The parameters ξ_k and b'_k express coupling strength of GNI to left- and right-handed neutrinos. The parameter b'_k takes into account an energy dependent contribution to the rate while ξ_k is the amplitude of the process.

The presented GNI analysis is based on the KNM2 measurement campaign featuring 4×10^6 collected electrons in the region $\langle E_0 - 40\,\mathrm{eV}, E_0 + 135\,\mathrm{eV}\rangle$. No significant indication of a GNI-like spectral distortion was identified in either case, with or without an additional heavy neutrino-mass state [19]. In Fig. 3 the exclusion contours at 95% CL for the GNI acting on both light and additional heavier neutrino-mass state are displayed.

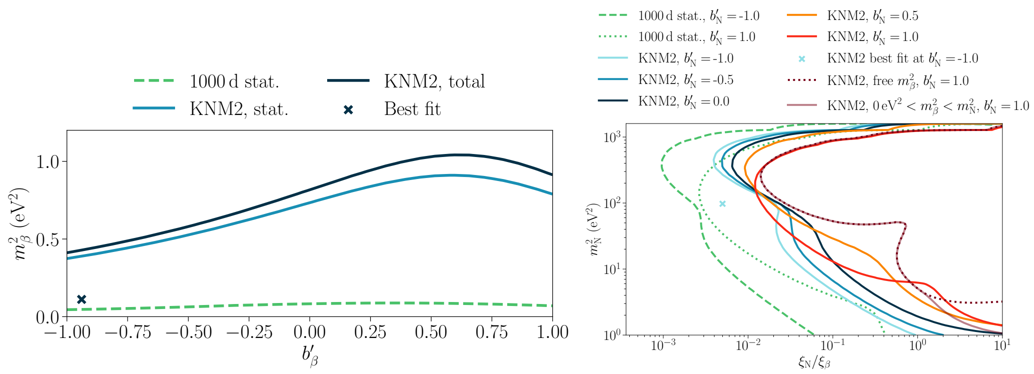

Figure 3: Exclusion contours for GNI contributions on light (left) and additional heavier (right) neutrino-mass state at 95% CL based on the KNM2 dataset. Excluded region in case of the light neutrino is for $m_\beta^2 > 0.5\,\mathrm{eV}^2$ and in case of the heavier neutrino for $\xi_N/\xi_\beta > 0.5$ depending on the strength b'_N. Green dashed line shows a projection of the final KATRIN dataset sensitivity. Both treatments of fixing $m_\beta^2 = 0\,\mathrm{eV}^2$ and constraining it to $0\,\mathrm{eV}^2 < m_\beta^2 < m_N^2$ have been considered in the right graph. Both graphs are adapted from [19].

Last, the emission of a new eV-scale light boson X in β-decay can be studied at KATRIN. In a hypothetical four-body decay $\mathrm{T_2} \longrightarrow {}^3\mathrm{HeT}^+ + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + \mathrm{X}$ we consider pseudoscalar or vector coupling of a new beyond-Standard-Model light boson X to either the electron or the neutrino.

The additional new light boson differential decay rate can be parametrized as

$$R_\mathrm{X}(E, m_\nu, m_\mathrm{X}, g_\mathrm{X}) \propto g_\mathrm{X}^2 \sqrt{\frac{E}{m_\mathrm{e}}} \left(\frac{(E_0 - (m_\nu + m_\mathrm{X})) - E}{(E_0 - (m_\nu + m_\mathrm{X})) + m_\mathrm{e}}\right)^{n(m_\mathrm{X})}, \tag{5}$$

where g_X is the boson coupling strength, m_e the electron mass, m_X the boson mass and $n(m_X)$ a spectral index depending on the coupling type and boson mass. The resulting differential spectrum rate $R_\beta(E, m_\nu^2)$ from (2) is modified to $R_{\beta,X} = R_\beta(E, m_\nu^2) + R_X(E, m_\nu, m_X, g_X)$.

In Fig. 4 we show the calculated KNM2 campaign sensitivities to the pseudoscalar and vector boson couplings g_X for different boson masses m_X at 95% CL [20]. The analysis of the KNM2 data is ongoing and a significant boost in the sensitivity is expected for the future TRISTAN project that will probe the β-spectrum in its full energy range.

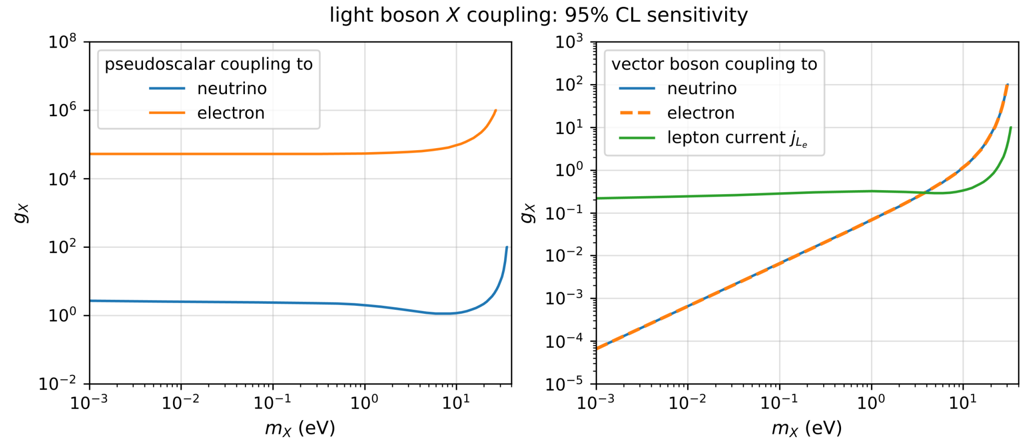

Figure 4: Sensitivity to the pseudoscalar and vector boson couplings g_X at 95% CL [20].

6. Conclusion

Various physics phenomena can be studied with the ultra-precise β-spectrum data collected by the KATRIN experiment. The neutrino-mass analysis of the first five measurement campaigns results in a new neutrino-mass upper limit of $m_\nu < 0.45$ eV at 90% CL. Furthermore, the existence of sterile neutrinos and light bosons, along with new possible types of interactions are probed at KATRIN. In the presented analyses, no evidence of sterile neutrinos, new light bosons or general neutrino interactions has been observed.

The KATRIN data collection is currently ongoing and is scheduled to be completed by the end of 2025. The final KATRIN dataset will consist of more than 200 million electrons in the analysis range close to the endpoint, reaching the 0.3 eV sensitivity to the neutrino mass at 90% CL. The sevenfold increase in the statistics boosts the sensitivity of the sterile neutrino and GNI searches as well. Furthermore, a substantial increase in the sensitivities of the beyond-Standard-Model searches is expected from the succeeding TRISTAN detector upgrade of the KATRIN experiment, which will probe the full energy range of the tritium β-decay spectrum in the search of heavy, keV-scale sterile neutrinos [21].

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