PROCEEDINGS OF SCIENCE

Search for a Light Sterile Neutrino with KATRIN

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Sterile neutrinos at the electron-volt (eV) scale have emerged as an enigmatic frontier in the realm of particle physics and astrophysics. The Karlsruhe Tritium Neutrino (KATRIN) experiment, renowned for its precision to measure the mass of the electron antineutrino with a target sensitivity of 0.2 eV$/c^2$ (90% C.L.), extends its reach to explore the existence and properties of eV-scale sterile neutrinos. In this pursuit, KATRIN seeks to unlock the secrets of these elusive particles through meticulous tritium β-decay endpoint spectroscopy. By scrutinizing the electron energy spectrum, KATRIN aims to detect or constrain the presence of sterile neutrinos, their mixing with active neutrinos and their mass hierarchy, thereby contributing invaluable insights into neutrino oscillations, cosmology and the broader landscape of particle physics. In 2022, KATRIN reported the most stringent limit on the neutrino mass with $m_\nu < 0.8$ eV$/c^2$ (90% C.L.) based on data acquired during the first two science runs of 2019. This paper summarizes KATRIN's search for an eV sterile neutrino, analyzing 5.24×10^6 tritium β-electrons from the first two runs. Additionally, the sensitivity studies based on five measurement campaigns are presented. KATRIN's enhanced sensitivity has the potential to probe a substantial portion of the sterile neutrino parameter space.

PoS(EPS-HEP2023)164

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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1. Introduction

The experimental confirmation of three neutrino flavors (electron, muon and tau) is based on substantial evidence, primarily the discovery of neutrino oscillation, which challenges the initial assumption of neutrino masslessness and deepens our understanding of these particles. Prior anomalies, especially in short baseline (SBL) experiments like LSND, have intensified interest in sterile neutrino oscillations with masses around or below 1 eV, offering potential insights into the mass hierarchy and neutrino properties. While the standard neutrino mixing framework indicates specific squared-mass differences, SBL neutrino oscillation anomalies suggest the existence of an additional light massive neutrino. The necessity for such an expansion of the neutrino mixing framework entails the incorporation of an additional light massive neutrino alongside the conventional three. The theoretical basis for sterile neutrinos is reinforced by their potential connection to dark matter. Sterile neutrinos may not exclusively constitute dark matter but could belong to a broader "dark sector" that interacts with Standard Model neutrinos, making their potential existence across various mass scales an area of active investigation. Tritium β-decays, which provide measurements of the β-particle mass (m_β), offer a unique opportunity for studying these phenomena.

2. KATRIN experiment

The KATRIN experiment [1] conducts high-precision measurements of the electron spectrum in tritium β-decay ($^3\text{H} \longrightarrow {}^3\text{He}^+ + \text{e}^- + \bar{\nu}_e$) near an endpoint energy (E_0) of 18.57 keV and with a half-life ($t_{1/2}$) of 12.32 years. Tritium (T) transforms into helium, releasing an electron and an antineutrino, with their energy shared between kinetic energies and potentially rest masses. The experiment spans 70 meters, housing a gaseous tritium source (WGTS), employing MAC-E-Filters for high-energy pass filtering. The main spectrometer offers high luminosity, low background noise and superior energy resolution crucial for neutrino mass extraction from the β-decay spectrum. After traversing the spectrometer's retarding potential, all β-electrons regain their initial energy and are magnetically directed to the focal plane detector (FPD) for precise counting. Utilizing retarding potential scanning, the β-spectrum is acquired in an integrating mode with an energy resolution $O(1\text{ eV})$, which further facilitates data collection and analysis.

3. Modeling experimental spectra for neutrino and sterile neutrino analysis

The KATRIN neutrino mass measurement (KNM) involves observing spectral shape alterations depending on neutrino mass. To determine important physics parameters, such as m_ν^2 (effective squared neutrino mass), the measured integral spectrum $N_{\text{exp}}(qU)$ is fitted to the model $N_{\text{model}}(qU, \Theta)$:

$$N_{\text{model}}(qU, \Theta) = A \cdot \int R_\beta(E, \Theta) \cdot f(E, qU) + B$$

In this model, the signal comprises two crucial elements: the theoretical prediction of the differential tritium β-spectrum $R_\beta(E, \Theta)$ and the experimental response function $f(E, qU)$. The signal's strength is governed by the normalization factor A and an energy-independent background rate component B is also included. The electron-flavor neutrino exists as a combination of distinct neutrino mass eigenstates. This implies that the electron-flavor neutrino may also include a small component of a new, fourth neutrino mass eigenstate, labeled as m_4. In KATRIN, the sterile analysis is performed using the modified differential spectrum as:

$$R_\beta(E, m_\nu^2, m_4^2, |U_{e4}|^2) = (1 - |U_{e4}|^2) \cdot R_\beta(E, m_\nu^2) + |U_{e4}|^2 \cdot R_\beta(E, m_4^2) \quad (1)$$

where m_4 is given by the extended 4×4 unitary PMNS mixing matrix. The parametrisation for the active to sterile mixing is given by $\sin^2\theta = |U_{e4}|^2$. A light active neutrino primarily causes a noticeable shift in the endpoint of the spectrum, while a massive sterile neutrino, with its larger mass, induces distortions deeper within the spectrum, producing a characteristic "kink". The distinction between the signatures of a sterile neutrino and a massive electron neutrino becomes feasible when the mass of the sterile neutrino is substantial enough to be distinguishable through experimental resolution and exceeds the mass of the electron neutrino.

4. Revisiting KATRIN's eV sterile neutrino results

The initial quest for a light sterile neutrino in KATRIN relies on data collected during the first two campaigns held in 2019. During the second campaign, the average source activity increased from 2.45×10^{10} Bq to 9.5×10^{10} Bq, leading to a remarkable rise in the signal-to-background ratio from 70 to 235 in the energy range of $\langle qU \rangle = (E_0 - 40)$ eV. The analysis probed $m_4^2 \leq 1600\,\mathrm{eV}^2$ and $|U_{e4}|^2 \geq 6 \times 10^{-3}$ in the 3 + 1 neutrino framework. In the combined analysis, no significant sterile-neutrino signal was detected. Large Δm_{41}^2 solutions related to reactor and gallium (GA) anomalies were excluded and the Neutrino-4 signal for $\sin^2(2\theta_{ee})$ above 0.4 was disfavored. The study highlighted the influence of systematic effects on the sterile neutrino search, with statistical uncertainties dominating the analysis. The experimental findings are published in [2]. With the dataset at hand, KATRIN interrogates a substantial region within the parameter space, offering a complementary perspective to the results of other experiments. The absence of prior sterile neutrino evidence doesn't preclude their potential existence and KATRIN continues to improve techniques to enhance detection capabilities.

5. Sensitivity analyses in five KATRIN science runs

Ongoing KATRIN phases explore the sterile neutrino hypothesis, requiring a tenfold reduction in background rates via the "shifted analyzing plane" (SAP) configuration [3]. Our analysis of the initial five measurement campaigns, utilizing diverse source temperatures and spectrometer configurations, contributes about 20% of the anticipated complete KATRIN dataset and employs simulated data from KATRIN's SAP mode, in contrast to the published results [2, 4], which were obtained using the nominal analyzing plane (NAP) configuration.

We develop and validate a comprehensive analytical framework using simulated tritium scans, referred to as Monte Carlo twin datasets (MC twins). These datasets include individual and combined data from KNM-1, KNM-2, KNM-3a, KNM-3b, KNM-4 and KNM-5, totaling 35.8 million tritium β-electrons, used to establish the analysis procedure with complete slow-control parameters, spanning an energy range 40 eV below the tritium endpoint at E_0 = 18.57 keV. This range optimizes the experiment's objectives, including background reduction, neutrino mass determination, precision enhancement and understanding systematic factors' impact. The set of slow-control parameters associated with an experimental tritium scan include, isotopologue concentrations, source temperature, magnetic fields and retarding potentials. The integral spectra from each measurement campaign are combined into a uniform stacked spectrum, a method validated during previous neutrino mass analyses. Data selection and combination follow the methodology outlined in [5], with systematic uncertainties consistent with recent analyses of the first five science runs. This investigation adheres to the $3\nu + 1$ framework, encompassing three active and one sterile neutrino flavor. The differential spectrum, defined by eq. 1, assumes that $m_{1,2,3}$ are all significantly smaller than m_4, thus setting m_ν^2 to zero. Sterile-neutrino constraints are derived through a grid search in the parameter space $(m_4^2, \sin^2\theta)$, employing a 50×50 grid with m_4^2 ranging from $0.1\,\mathrm{eV}^2$ to $1600\,\mathrm{eV}^2$ and $\sin^2\theta$ from 0.001 to 0.5. At each grid point, sterile parameters are held constant and a fitting process is executed, minimizing the negative log likelihood ($\mathcal{L}$)[1] with respect to four basic nuisance parameters $\mathbf{\Theta} = (m_\nu^2, E_0, \mathrm{A}, \mathrm{B})$. Here $\chi^2 = -2\log\mathcal{L}(\mathbf{\Theta})$. The analysis involves computing $\Delta\chi^2 = \chi^2 - \chi^2_{\mathrm{min}}$, where χ^2_{min} is determined directly from the grid. For a confidence level (C.L.) of 95%, a χ^2 distribution with two degrees of freedom corresponds to $\Delta\chi^2_{\mathrm{crit}} = 5.99$. Sensitivity contours are determined using the Newton-Raphson method for calculating $\sin^2\theta$ corresponding to $\Delta\chi^2 = 5.99$ at each m_4^2 value. KATRIN's sensitivity to eV scale sterile neutrino is evaluated in two manners: one incorporating the entire uncertainty budget (statistical and all systematic uncertainties), while the other exclusively considers statistical uncertainties (statistical only). Figure 1a reflects the results obtained using the former approach. Initially, the sensitivities of individual measurement campaigns were compared to each other, as well as to the sensitivity of all combined campaigns (KNM 1-5). A substantial boost in sensitivity is achieved when the datasets are combined. Maximum sensitivity occurs at $m_4^2 \approx 400\,\mathrm{eV}^2$, with sensitivity decreasing for smaller m_4^2 due to signal strength and signal-to-background ratio reduction.

To ensure the robustness of measurements in the KATRIN experiment, it is crucial to accurately account for systematic uncertainties. These systematic effects considered within the analysis interval $(E_0 - 40)$ eV include various factors like background slope, background from Penning trap, rear wall, source magnetic field, plasma, electromagnetic fields, column density, non-Poisson background and pinch magnetic field [5]. To quantify how each systematic factor contributes to our overall uncertainty, we conduct separate evaluations known as "raster scans" for each of these factors. For various values of sterile mass m_4^2, we assess how individual systematic uncertainties affect the mixing parameter, $\sin^2(\theta)$, using equation: $\sigma_{\mathrm{syst}} = \sqrt{\sigma^2_{\mathrm{total}} - \sigma^2_{\mathrm{stat}}}$. Here, σ_{total} represents the combined statistical (stat) and a specific systematic (syst) uncertainty on $\sin^2\theta$ at a 68% C.L. Subsequently, we calculate the collective impact of all these systematic factors on our sensitivity, which we refer to as "Total Systematics", as illustrated in fig. 1b. Here the solid grey line indicates that statistical uncertainty dominates over systematic effects. For $m_4^2 < 10\,\mathrm{eV}^2$, the primary systematic effect is driven by the Penning background rate. Penning background primarily affects early datasets in the first five science runs but is later eliminated. However, for $m_4^2 > 100\,\mathrm{eV}^2$, systematic contributions from column density and plasma, notably gain relevance. In the $30\,\mathrm{eV}^2$ to $40\,\mathrm{eV}^2$ range, longer measurement times can mitigate systematic uncertainties related to time, leading to the systematics

[1]The likelihood function, denoted as $\mathcal{L}(\mathbf{\Theta}|N_{\mathrm{obs}})$, is a mathematical measure used to assess the probability of the proposed parameter set $\mathbf{\Theta}$ being compatible with the observed data N_{obs}.

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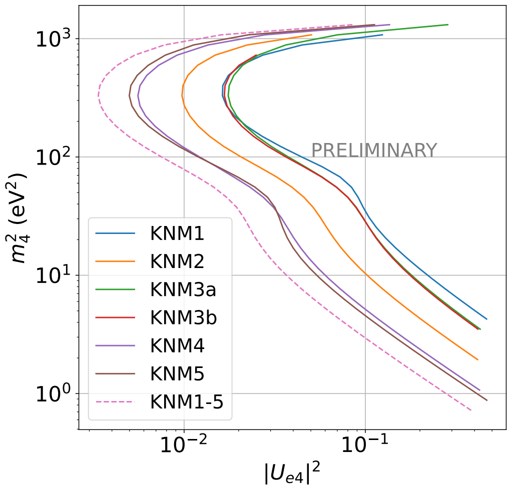
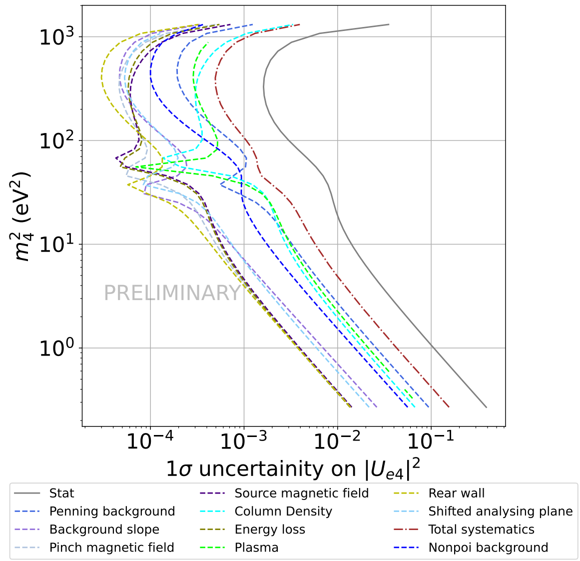


(a) KATRIN sensitivity contours at 95% C.L., originating from MC data sets for five measurement campaigns, both as standalone and combined. The contour lines correspond to $m_\nu^2 = 0\,\mathrm{eV}^2$.



(b) Influence of systematic uncertainties on $sin^2(\theta)$ for various m_4^2 at 1σ. The systematic budget is based on simulated twin data set of five science runs with $m_\nu^2 = 0\,\mathrm{eV}^2$.

Figure 1

having smaller impact on the uncertainty.

We conduct a comparative analysis of our sensitivity contours with constraints derived from a diverse array of experiments, with a specific focus on sterile neutrino searches within the electron disappearance channel, as delineated in fig. 2. KATRIN primarily probes $|U_{e4}|^2$ directly, while sterile neutrino oscillations are characterized by $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$. Additionally, the mass splitting can be expressed as $\Delta m_{41}^2 \approx m_4^2 - m_1^2$. In our analysis, this approximation equates to $\Delta m_{41}^2 \approx m_4^2$ as $m_1^2 = 0$ (since $m_4 \gg m_{1,2,3}$). The parameter space for eV-scale sterile neutrino is currently under scrutiny, taking into account findings from various experiments. The solid blue line represents KATRIN's 95% C.L. exclusion limit derived from the combined data of KNM-1 and KNM-2, while the solid cyan line shows the 95% C.L. sensitivity contour for simulated twin data sets amalgamated from five consecutive science runs (KNM 1-5). This improved sensitivity reaches a substantial portion of the BEST+GA parameter space, particularly the portion that remains unexplored by other experiments. The KNM 1-5 sensitivity contour offers the potential for more rigorous constraints, surpassing the exclusion limits established by KNM-1 and KNM-2. It also raises the possibility to probe significant parameter space associated with the alleged Neutrino-4 observation, as well as results from PROSPECT and STEREO experiments.

6. Conclusion

Sterile neutrinos, considered in the context of the 3ν+1 framework, are a potential solution to anomalies in short-baseline neutrino oscillations. KATRIN's unique approach to investigate sterile neutrinos relies solely on the electron energy spectrum from tritium β-decay, allowing for model-independent analysis. The presence of a sterile neutrino would manifest as a distinct distortion in the

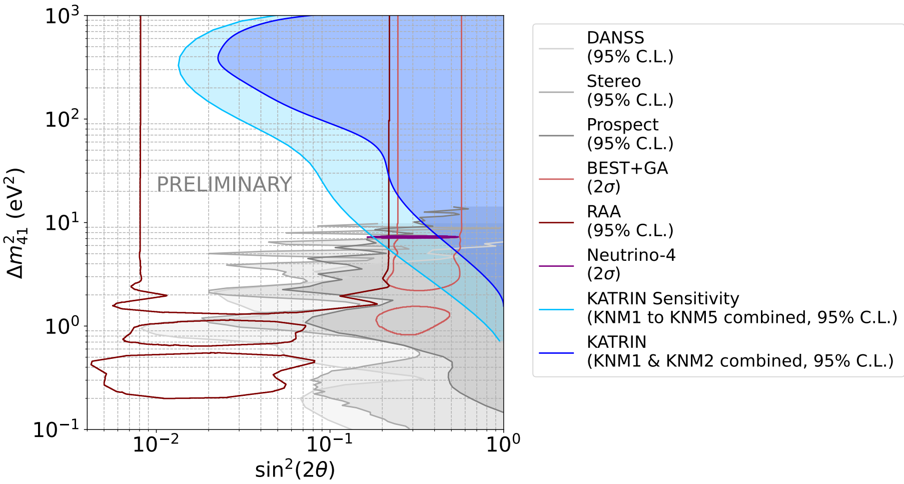


Figure 2: This figure summarizes the parameter space of light sterile neutrinos based on various experiments. Allowed regions from BEST+GA, RAA and Neutrino-4 are highlighted, while excluded regions from other experiments are shaded. BEST+GA and RAA show tension without overlap. PROSPECT and STEREO refute Neutrino-4. KATRIN excludes certain regions and aims to explore the unexcluded area of other experiments with its sensitivity. The KATRIN exclusion and sensitivity contour lines correspond to $m_\nu^2 = 0\,\text{eV}^2$.

spectrum, detectable for sterile neutrino masses up to about 1600 eV^2. Based on the data from the first two measurement campaigns, it is feasible to explore mixings as low as $|U_{e4}|^2 \approx 6\times10^{-3}$. While no sterile neutrino signal is found, KATRIN's exclusion contours provide improved constraints on active-to-sterile mixing, refuting large m_{41}^2 solutions and contradicting Neutrino-4's claim at a 95% confidence level when $\sin^2(2\theta_{ee}) \leq 0.4$. Ongoing measurement campaigns (KNM 1-5) of KATRIN continue to investigate the sterile neutrino hypothesis and sensitivity enhances with combined datasets. Statistical uncertainties dominate over systematic effects and the analysis delves into various systematic uncertainties and their influence on sensitivity. KATRIN's new data sets have the potential to challenge previous observations in the eV sterile neutrino parameter space.

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