PROCEEDINGS OF SCIENCE

Beta decay and neutrino mass: KATRIN and beyond

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The precise measurement of neutrino masses represents a critical frontier in particle physics, with implications that extend beyond the Standard Model and into cosmology. While cosmological observations and neutrinoless double beta decay experiments provide stringent constraints on neutrino properties, direct neutrino mass measurements are uniquely model-independent and critical for cross-validating of results.

The Karlsruhe Tritium Neutrino (KATRIN) experiment is a leading initiative in this domain, employing beta-decay spectroscopy to measure the incoherent sum of neutrino masses (m_β) with unprecedented sensitivity. KATRIN has progressively improved the upper limit on neutrino mass, achieving $m_\beta < 0.45\,\text{eV}$ at 90% confidence level with the combined analysis of its first five campaigns. With ongoing data acquisition and improved methodologies, KATRIN aims to reach a final sensitivity of $m_\beta < 0.3\,\text{eV}$ by 2025.

Looking ahead, KATRIN is expanding its scope to include searches for sterile neutrinos at the keV scale with the novel TRISTAN-detector. Furthermore, it is actively exploring next-generation technologies, such as atomic tritium sources and differential detection methods, to push sensitivities below the inverted ordering range ($m_\beta < 0.05\,\text{eV}$). KATRIN++ is envisioned to be a next-generation m_β experiment and follows the mission to identify and develop scalable technology by using the existing KATRIN and TLK infrastructures.

12th Neutrino Oscillation Workshop (NOW2024)
2-8, September 2024
Otranto, Lecce, Italy

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ISSN 1824-8039. Published by SISSA Medialab.

PoS(NOW2024)049

1. Introduction

The importance of measuring neutrino masses is evident, as these subatomic particles introduce a fundamental energy scale beyond the Higgs scale. Understanding neutrino masses necessitates the development of a theory beyond the Standard Model of Particle Physics that can predict both the elements from the mixing matrix and the mass scale. Therefore, a combination of oscillation experiments and those that determine the absolute mass value is required.

The determination of the neutrino mass is pursued through a variety of complementary experimental undertakings. There are three key approaches that researchers employ to access this elusive parameter. One prominent method involves cosmology, where the observable sought is the sum of neutrino masses, $\sum_i m_i$. This approach deeply intertwines with multi-parameter cosmological models, yielding a current upper limit of 0.12 eV as reported by Planck [1] and 0.072 eV from DESI [2]. Another approach resides in the search for neutrinoless double beta decay ($0\nu\beta\beta$), targeting the effective Majorana mass, $m_{\beta\beta}^2 = \left|\sum_i U_{ei}^2 m_i\right|^2$ [3]. This method is heavily contingent on whether neutrinos are Majorana or Dirac particles, among other model-dependent factors. The upper limit is currently set at 0.156 eV by KamLANDZen [4].

Finally, experiments measuring weak decays, such as beta-decay or electron capture, offer a direct route through the incoherent sum of masses $m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$. As the most direct approach, it involves purely kinematic analysis, with the latest experiments such as KATRIN reporting an improved upper limit of 0.45 eV [5], which will be discussed further in this paper.

Although measuring the neutrino mass turns out to be a challenging endeavour, especially in the direct approach, neutrino oscillation observations prove that there are lower limits. For neutrinos, lower mass limits are established as greater than 10 meV for normal mass ordering and greater than 50 meV for inverted mass ordering.

2. Direct measurement of the (anti)-neutrino mass

Several methods direct mass experiments aim to achieve neutrino mass measurement without model dependencies. Electron capture (EC) experiments are related to the emission of an neutrino and the measurement principle is determining the internal excitation of the daughter atom after EC [6]. β-decay efforts are related to emission of anti-neutrinos and use the measurement of the kinetic energy of the emitted electron. These approaches help in pinpointing the (anti-)neutrino mass by analyzing shape distortions at the kinematic endpoint.

Tritium (β-decay) and Holmium-163 (EC) are the primary isotopes used in such experiments because they exhibit favourable properties: low Q values and available amounts of nuclear material. Tritium's Q value stands at 18.575 keV and holmium-163's at 2.833 keV. The half-lives of these isotopes also contribute to their high accessible activity for experiments — 12.3 years for tritium and 4,570 years for holmium-163.

Key challenges for achieving high experimental sensitivity in order to approach low neutrino mass ranges are to achieve a high signal-to-noise ratio, low background, well-quantified systematic effects, and exceptional energy resolution.

Established measurement principles for neutrino mass There are several established measurement principles for direct neutrino mass measurements. Cyclotron Radiation Emission Spectroscopy (CRES) is a technique that measures the electron energy via frequency [7]. It involves detecting the cyclotron radiation emitted by charged particles. The approach is currently pursued for tritium spectroscopy by the Project8 [8, 9] as well as the QTNM collaborations [10]. Another approach is the MAC-E filter which stands for Magnetic Adiabatic Collimation with an Electrostatic Filter [11]. It measures energy by applying a high-pass filter, allowing only particles above a specific energy threshold to pass. This technology was employed by KATRIN's predecessors at Mainz [12] and Troitsk [13] and now by KATRIN itself. The holium-based experiments (ECHo [14, 15] and Holmes [16, 17]) employ low-temperature microcalorimeters that measure decay energy deposited in absorbers loaded with ^{163}Ho by detecting small temperature variations.

3. Status of the Karlsruhe Tritium Neutrino experiment (KATRIN)

The Karlsruhe Tritium Neutrino experiment (KATRIN) is designed to directly measure the neutrino mass with a sensitivity of 0.3 eV/c^2 [18]. It features two unique selling points: an ultra-stable high-luminosity windowless gaseous tritium source with activity of 10^{11} Bq, and a high-resolution MAC-E filter with energy resolution around 1 eV. The setup spans 70 meters in length at the KIT campus north and is hosted at the Tritium Laboratory Karlsruhe (TLK). TLK is licensed for handling 40 grams of tritium, maintaining a closed cycle for the recycling and purification of gram-scale tritium amounts.

The KATRIN experiment has made significant advancements in setting upper limits on the neutrino mass through successive data releases. In 2019, the first experimental campaign reported an upper limit of the neutrino mass, m_ν, to be less than 1.1 eV at a 90% confidence level [19]. Building on this, the 2022 data release from the first two experimental campaigns improved the limit to $m_\nu < 0.8$ eV [20]. Up until that point, about 6 million electrons were recorded at the detector.

Measurement and data combination The latest data comprises the combination of the initial five experimental campaigns, focusing on data acquisition while still finding optimal operational conditions. This current dataset includes 259 measurement days, 1,757 scans of the tritium-beta-spectrum, and approximately 36 million electron events [5].

Key improvements in the methodology included new spectrometer settings that reduced the background by a factor of two [21, 22], novel calibration methods using quasi-mono-energetic electrons from the photoelectron source and $^{83\mathrm{m}}$Kr, and a new approach to assess the molecular final-states uncertainty [23].

Combining data from different KATRIN campaigns poses several challenges. One of the significant issues is the simultaneous analysis of seven sub-data sets, each featuring different experimental settings (source temperature, tritium column density and an optimized MAC-filter configuration).

Results In recent analyses, systematic uncertainties have been notably reduced, though statistical uncertainties remain predominant. A significant decrease in background-related systematics is observed, alongside improved management of source scattering, albeit still with some conservative uncertainties in this release. Current data show reduced uncertainties, particularly those in molecular final-states, and it is forecast that individual systematic uncertainties in the final KATRIN analysis post-2025 will fall below 0.01 eV^2.

The combined analysis of the initial five measurement campaigns resulted in a squared neutrino mass $m_\beta^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$ with excellent goodness-of-fit [5]. The spectrum model permitted negative m_β^2 estimates due to statistical fluctuations. The total uncertainty was primarily influenced by statistical error, followed by uncertainties in column density, the energy-loss function, the time-dependent background rate, and variations in source potential. Based on this best-fit, an upper limit of $m_\beta < 0.45\,\mathrm{eV}$ was determined at 90 % CL, utilizing the Lokhov-Tkachov method [24]. This reflects an improvement of approximately a factor of two in the upper limit compared to the preceding data release from KATRIN [20].

Finalizing KATRIN's neutrino mass mission KATRIN is currently continuing its data-taking efforts, having already completed 15 measurement campaigns, which represents four times the amount of data discussed here. The project aims to achieve 1,000 measurement days by the end of 2025. This will amount to roughly five times the current statistics. Given the existing operational conditions, it is anticipated that the final sensitivity will be better than 0.3 eV at 90% CL [25].

4. KATRIN's search for keV-sterile neutrinos

KATRIN will soon expand its scope from β-decay spectroscopy near the 18.6 keV endpoint exploring the full tritium phase space for sterile neutrinos and new physics at the keV scale [26]. To achieve this, KATRIN requires an upgrade to the so-called TRISTAN high-countrate and high-resolution silicon drift detector system [27] and adjustments in the source region, enhancing sensitivity to sterile/active neutrino mixing ratios to the ppm range. Key contributions come from the Max Planck Institute for Physics in Munich, which include replacing the focal plane detector. Starting in 2026, the two-year measurement program aims to improve lab-based bounds by two orders of magnitude to achieve 10^{-6} sensitivity on the active-sterile mixing.

5. Towards the ultimate direct neutrino mass experiment

The methodology currently employed for KATRIN will not reach below the neutrino mass range of inverted ordering ($m_\beta < 0.05$ eV). For that endeavour, new technologies are necessary. KATRIN++ is envisioned to be a next-generation m_β experiment and follows the mission to identify and develop scalable technology by using the existing KATRIN and TLK infrastructures. Currently, for the detector part, high-resolution differential measurement principles are considered.

The differential detection of beta-electrons needs to achieve eV resolution or better. This approach would outperform the current integrating MAC-E filter by using statistics more efficiently, as the energy of individual electrons is measured. In particular, it allows for the distinction between signal electrons and those originating from known KATRIN backgrounds. Both are boosting the prospect of improved sensitivity. Current research and development efforts focus on i) large arrays of quantum sensors and ii) time-of-flight measurements to improve the overall sensitivity to m_β.

Arrays of calorimeter-based quantum sensors Micro-calorimetric quantum sensors operated at millikelvin (mK) baseline promise extreme resolution for energy measurements by recording the temperature increase in a tiny absorber [28]. The integration of a quantum sensor detector array with sub-eV resolution into the KATRIN infrastructure presents several challenges. These include

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selecting an appropriate type of quantum sensor that can operate effectively within a magnetic field of approximately 10 mT. Furthermore, it is necessary to achieve a coupling between the mK cryo-platform and the room temperature (RT) spectrometer. The system must also accommodate a large-area detector capable of multiplexing approximately one million channels, which brings about further complexities in the design. Moreover, there are limits to the energy resolution that must be considered during this integration process.

Recently, the first studies by the KATRIN++ team have focused on the interaction between metallic microcalorimeters (MMCs) [28, 29] and external light charged particles, specifically electrons. In that context, the lack of information in this area necessitates demonstrating the suitability of MMC-based detectors for high-resolution spectroscopy of external electron sources. The study presented the first-ever measurements of external electrons using a metallic microcalorimeter. The characteristics of the signal shape and the calibration were studied by comparing well-defined conversion electron and X-ray photon signals from the same ^{83}Rb/^{83m}Kr source. [30]

Single electron tagging with time-of-flight measurement The implementation of time-of-flight (ToF) electron spectroscopy at KATRIN would represent a 'single channel' detection approach [31], potentially simpler than a quantum sensor array thereby serving as an interim solution during the development phase of this detector system. In the ToF configuration, the source operates at a nominal intensity of 10^{11} Bq, with the pre-spectrometer limiting the electron transmission rate to under 1 kHz. An electron tagger then generates start-signals at this frequency, while the main spectrometer, acting as a delay line due to its retardation potential, works in conjunction with a fast detector to provide stop signals.

Single electron tagging presents challenges due to the tiny signals against a minimal noise floor. Initial concepts explore Cyclotron Radiation Emission Spectroscopy (CRES) [7] or coreless cryogenic current comparators. Beyond the role of the tagger, additional efforts are necessary to enhance ToF resolution to sub-eV.

Development of an atomic tritium source For the source part, atomic tritium is considered to replace molecular tritium as a source for the beta-electrons.

Molecular tritium beta decay $T_2 \to {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e$ differs from atomic tritium decay $T \to^3 \mathrm{He}^+ + e^- + \bar{\nu}_e$ mainly in the final state spectrum ^{3}HeT$^+$ [32]. Molecular tritium decay leaves only 57% daughter molecules in the electronic ground state, whereas atomic tritium decay leaves about 70% atoms in that state, increasing decay electrons near the endpoint. In addition, ^{3}HeT$^+$ ends up in an excited ro-vibrational state, broadening the beta-spectrum to about 1 eV (FWHM), limiting neutrino mass sensitivity despite potentially advanced detector resolutions. Furthermore, the electron scattering probability is lower for T atoms compared to T_2 molecules, reducing energy losses. Unlike T_2, the fermionic ($s = 1/2$) tritium atom can be manipulated by inhomogeneous magnetic fields, allowing trapping and cooling below the freeze-out temperature of T_2, thus minimizing Doppler-broadening of beta-electrons.

Atomic tritium will be needed in huge quantities similar to the current KATRIN source in order to achieve the required statistics. For this purpose, a large-scale demonstration experiment needs to be set up with the following goals: a) Generation of large quantities of atomic tritium. b) Development and implementation of effective atom cooling mechanisms. c) Studying of trapping times and maximum densities in a magnetic trap. d) Investigation of the interplay of beta-driven plasma (meV-eV) and ultra-cold trapped atoms (neV).

We expect that the generation, cooling, and trapping of tritium atoms will suffer from low efficiencies in each step. Therefore, even for the demonstration experiment, macroscopic amounts of tritium need to be employed which are estimated to be on the level of 10 g (T_2). This can only be done in a large-scale laboratory able to host and operate such a loop. A first stage of an atomic tritium source is currently in the build-up phase at TLK.

Joint research on atomic tritium source KATRIN++ and other next-generation projects (Project8 [8], QTNM [10], PTOLEMY [33]) are exploring cutting-edge technologies for neutrino mass determination. Currently, there is no proven technology to reach ultimate sensitivity, and it is imperative that neutrino mass detection is confirmed by independent technologies. The atomic tritium trap emerges as a key element, regardless of the detection techniques employed. Technologies such as CRES, microcalorimeters, and ToF offer complementary benefits in this research. The mission is to realize a global Atomic Tritium Demonstrator (ATD) at the Tritium Laboratory Karlsruhe (TLK). To achieve this, a joint working group is in the process of being formed. The partners for the ATD consortium will include those from various specialized areas: Neutrino mass partners such as KATRIN++, Project 8, and QTNM. It is noteworthy that KATRIN++ and Project 8 are already linked by individual groups at TLK and the University of Mainz through the KAMATE collaboration. In addition, partners from atomic and molecular physics, quantum gases, and precision spectroscopy will be involved in the consortium.

6. Conclusion and outlook

The KATRIN experiment is making significant progress in its efforts to measure the neutrino mass, with the current sensitivity already reaching $m_\nu < 0.45\,\text{eV}$ and aiming for $m_\nu < 0.3\,\text{eV}$ with 1000 days of measurement. Looking forward, the experiment is preparing for the TRISTAN operation by 2026 to explore keV sterile neutrinos. To push the boundaries even further, an ultimate neutrino mass measurement with sensitivity $m_\nu < 50\,\text{meV}$ will require an atomic tritium source and a differential detector principle, for which a R&D plan is foreseen until the beginning of the next decade. The collaborative spirit of KATRIN++, inviting research groups to address future challenges, showcases its commitment to advancing in the field.

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