PROBING THE NEUTRINO MASS SCALE WITH THE KATRIN EXPERIMENT

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The absolute mass scale of the neutrino is one of the most fundamental open questions in contemporary particle physics, with implications from particle theory to cosmology. Through precision measurements of beta-decay kinematics, the KATRIN experiment probes the neutrino mass with unprecedented sensitivity.

▲The interior of the KATRIN main spectrometer is lined with wire electrodes to fine-tune the retarding potential. Credit: M. Zacher/ KATRIN Collaboration.

The puzzle of neutrino mass

When Wolfgang Pauli postulated the existence of a new particle, later dubbed the "neutrino", in 1930 in order to explain nuclear beta decay spectra and save energy conservation and spin statistics, he could not anticipate its central role in the nascent field of particle physics. Indeed, estimating that the new, electrically neutral particle should carry at most 1% of the proton mass, Pauli deemed it unlikely that it should ever be experimentally detected. Now, more than 90 years later, neutrino experiments have launched an era of high rates and high statistics — yet many of the neutrino's basic characteristics remain unknown. One of these basic properties is the rest mass of neutrinos, which has eluded the grasp of experimentalists despite more than seven decades of effort.

Of course, the history of neutrino physics is built on efforts spanning decades. By the mid-1950s, in spite of Pauli's skepticism, the neutrino had been detected in an experiment using a nuclear reactor as a strong neutrino source. Over the next few decades, it was established that neutrinos come in three flavours, each associated with the charged electron, muon or tau leptons in the Standard Model of elementary particles, and neutrino measurements bolstered our understanding of the weak nuclear force that is their sole discernible means of particle interaction. Meanwhile, neutrino detectors watched deep underground for electron neutrinos from the fusion processes that fuel the sun, and they uncovered a new mystery: the detected electron-neutrino rate fell a factor of three short of theoretical models of stellar fusion. This "solar neutrino problem" persisted for three decades, until the Super-Kamiokande and SNO experiments conclusively established that neutrinos undergo flavour oscillation as they propagate between the source and the detector. The solar neutrinos were all there, as expected — but by the time they reached detectors, many of them weren't observed as electron neutrinos anymore.

After two fruitful decades of flavour-oscillation experiments, we understand each neutrino flavour state as a quantum superposition of three distinct neutrino-mass states. The neutrino is now established as a mass-carrying particle, although it is by far the most lightweight of the Standard Model fermions — Pauli's original estimate was too generous by at least seven orders of magnitude.

Tiny mass, big impact

Non-zero neutrino masses are tangible evidence pointing beyond the Standard Model, in which neutrinos are *a priori* included as massless leptons. Oscillation experiments can determine the splittings between the mass states with great precision, but they have no sensitivity to the absolute mass scale that tells us how far from zero the lightest neutrino mass lies. This mass scale has a far more fundamental role to play than just filling in a number in our textbooks.

Theorists have proposed a dazzling array of novel, possible mechanisms for generating neutrino mass. The absolute neutrino-mass scale will give critical guidance in constraining these possibilities. Massive neutrinos are a key to understanding various astrophysical processes, such as matter-enhanced oscillations across the energy spectrum of solar neutrinos arriving at Earth, or the mechanisms driving certain classes of supernova explosions. And, perhaps most profound of all, neutrinos are by far the most abundant known massive particle species in the universe: even with tiny individual masses, neutrinos have collectively played the role of "cosmic architects". In modern, precision cosmology, bounds on the neutrino-mass scale are inferred from searches for the neutrino signature, as imprinted on the formation of structures in the early universe.

The massive neutrino thus sits at the intersection of elementary particle physics, astrophysics, and cosmology, and neutrino-oscillation experiments cannot fully complete our understanding.

A kinematic trick opening direct access to neutrino masses

Two of the three principal paths towards neutrino-mass measurement, namely the interpretation of cosmological structure data and the search for hypothesized neutrinoless double beta decay, rely on intricate model assumptions. The third path is more direct, relying only on the basic kinematic principles of energy-momentum conservation and energy-mass equivalence. In a nuclear beta decay, the neutrino mass constitutes a packet of energy that cannot be carried away by the created electron. Thus, although the neutrino is experimentally undetected, we can infer the signature of its mass from the associated shape distortion at the high-energy tail of the measured electron spectrum.

This was first realised by Enrico Fermi in his 1934 seminal work on "a tentative theory of beta decay" [1]. His "Golden Rule" for the calculation of the phase space delivered all the tools necessary for experimentalists to start out on the problem. It was quickly realised that the super-allowed tritium beta decay,

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He}^{+} + e^{-} + \overline{\nu}_{e},$$

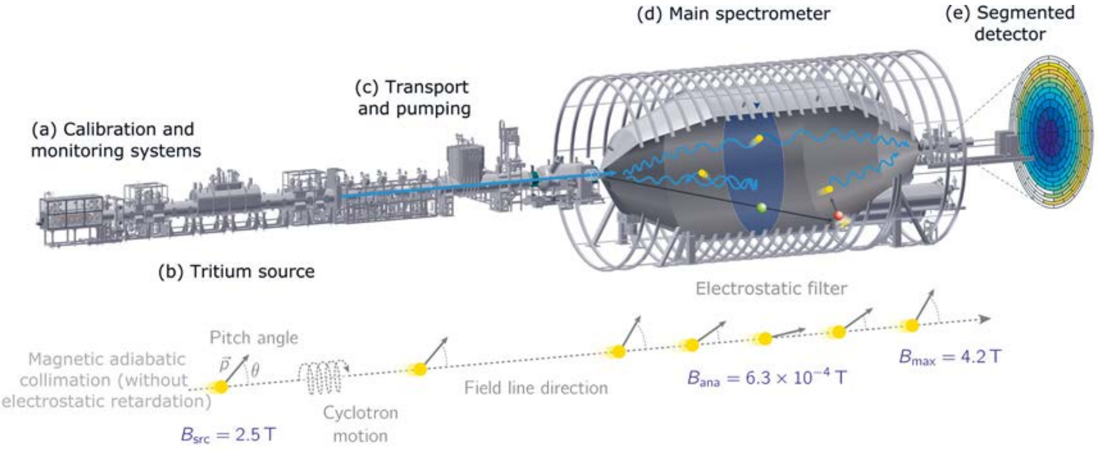
which transforms a tritium nucleus made of two neutrons and one proton into its mirror nucleus consisting of two protons and a single neutron while emitting an electron and an electron antineutrino, is ideally suited for a neutrino-mass search. This is mainly due to three favourable features:

(1) Tritium's half-life of 12.3 years is short enough to give relatively high count rates from limited amounts of the isotope, and long enough to make production, shipping and storage practical.

(2) The beta-decay endpoint of tritium is very low, at $E_0 = 18.6$ keV. This maximises the fraction of events close to the endpoint region of the beta spectrum, where the impact of the neutrino mass is most pronounced.

(3) Tritium and helium have rather simple nuclear and electronic configurations, and the T_2 molecule has only two electrons. This facilitates high-accuracy theoretical modeling of the spectrum.

In the quasi-degenerate regime in which KATRIN operates — in which the mass splittings are small compared to the absolute mass scale — the observable is an effective electron-neutrino mass square, an incoherent sum of the square of each neutrino-mass • • •



▾ **FIG. 1:** Overview of the 70-m long KATRIN beamline. The key components are the calibration and monitoring systems (a) which are located at the far end of the gas-filled cryogenic tritium source (b), the transport and pumping section (c) that guides the beta electrons to the main spectrometer (d) for energy filtering. Finally, only electrons with sufficient energy are transmitted onto the segmented focal-plane detector for counting (e). For reasons of simplicity, the magnetic adiabatic collimation is illustrated neglecting the electric potentials.

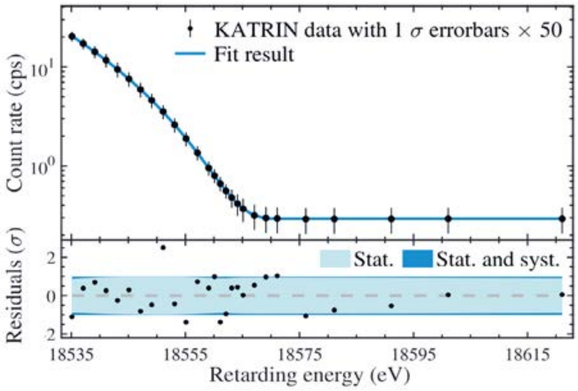
value[1] m_i weighted by its contribution $|U_{ei}|^2$ to the electron-flavour neutrino created in beta decay:

$$m^2(\nu_e) := \sum_{i=1}^{3} |U_{ei}|^2\, m_i^2.$$

Since the 1940s, experimentalists have exploited tritium beta decay for the neutrino-mass search (see [2] for a recent review). The advent of MAC-E-filter[2] technology brought a major advance in experimental accuracy, resulting in an upper bound on the electron-based neutrino mass of 2 eV/c^2 (95% C.L.) [3,4]. This held for more than a decade until the next-generation experiment, KATRIN.

A gigantic scale to weigh the lightest particles

In the Karlsruhe Tritium Neutrino experiment[3] (KATRIN), operated at the Karlsruhe Institute of Technology and hosted by the Tritium Laboratory Karlsruhe (TLK), the technology developed by the Mainz and Troitsk predecessors culminates in an ultra-luminous gaseous tritium source and a colossal main spectrometer (see opening illustration). With its diameter of 10 m and length of 24 m, the spectrometer ensures the adiabatic transport and high-resolution energy filtering of decay electrons. KATRIN pushes technological limits along its entire 70-m beamline, exemplified by the source throughput of highly purified gaseous molecular tritium at several kilograms per year, the stability of the source operational parameters at the per-mille level, successive pumping stages that reduce the tritium partial pressure by over 13 orders of magnitude without windows or barriers, the ultra-high vacuum of the main spectrometer at a residual gas pressure of 10^{-11} mbar, a monolithic silicon p-i-n diode detector with 148 pixels, and precision high voltage with part-per-million stability. Figure 1 gives an overview of the full KATRIN beamline. A comprehensive description of the set-up, commissioning and performance of the experimental apparatus is presented in [5].



▸ **FIG. 2:** Beta-decay spectrum measured in the first neutrino-mass campaign, displayed along with the fit model used to infer the neutrino mass (from [6]).

First KATRIN results, and the road ahead

After 18 years of planning, construction, and commissioning, working on the scientific and technological cutting edge in areas from tritium technology to ultra-high vacuum, the 150 scientists of the international KATRIN collaboration were finally ready to start neutrino-mass measurements in the spring of 2019. With just a four-week first science campaign and a burn-in phase limiting the source activity to a quarter of the nominal value, KATRIN collected about two million events in the region of interest extending to 40 eV below the spectral endpoint. By fitting modelled spectra to a combination of a few hundred individual up-and-down scans measuring the beta-decay spectrum, displayed in Figure 2, a new upper limit on the neutrino mass of $m(\nu_e) < 1.1$ eV/c^2 (90% C.L.) was obtained [6,7]. This first result is still strongly dominated by statistical uncertainties, but KATRIN was able to surpass the bounds obtained by its predecessors by about a factor of two. The second, longer measurement campaign has already pushed this constraint below the 1 eV/c^2 mark, setting a limit of $m(\nu_e) < 0.8$ eV/c^2 (90% C.L.) in combination with the first data set [8].

To achieve its target sensitivity of 0.2 eV/c^2 (90% C.L.), KATRIN will need to continue scanning the beta spectrum for about four more years. The overall factor of 10 improvement on the neutrino mass translates to a factor of 100 in terms of the kinematic observable, $m^2(\nu_e)$. Aside from the gain in statistics that comes with long-term operations, the collaboration is also working on improvements on key systematics through dedicated calibration measurements, and on a further reduction of the background rate.

KATRIN's unprecedented scale and precision requires exquisite care to understand and control the ways the apparatus affects the spectrum. A few examples will illustrate our detailed activities up and down the entire beamline. One calibration source, an electron gun at the far upstream end of the beamline, sends electrons with precisely controlled energies and angles all the way through to the detector — producing a uniquely precise measurement of electron scattering on tritium at low energies. Radioactive krypton gas, which emits monoenergetic electrons, can be circulated in the source alongside the tritium in order to probe the details of local space charges. A laser Raman spectroscopy system, devised to monitor the isotopic composition of the source, has introduced several novel techniques. The retarding potential is monitored with the world's highest-precision voltage dividers. The collaboration has already implemented several measures to mitigate backgrounds.

Even as KATRIN collects more data and improves systematics and performance, a future generation of neutrino-mass experiments is on the horizon. Project 8, which measures energy via the cyclotron radiation of individual beta electrons, aims to deploy an atomic tritium source to

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[1] Here, we assume that neutrinos and antineutrinos share the same mass scale, as predicted by CPT symmetry in the Standard Model. We therefore use "neutrino mass" to encompass both.

[2] Magnetic Adiabatic Collimation with Electrostatic filtering – an instrument which allows sensitive electrostatic analysis of the electron energy by exploiting the magnetic bottle principle for momentum collimation.

[3] www.katrin.kit.edu

avoid spectral broadening due to molecular bonds. ECHo and HOLMES will probe the electron-capture spectrum of ^{163}Ho, complementing the tritium measurements with microcalorimetric techniques pioneered by X-ray astronomers.

Next to KATRIN's flagship neutrino-mass measurement, its treasure trove of high-precision and high-statistics tritium beta-decay spectra opens up promising additional physics sensitivity. As a first example, KATRIN was able to obtain new direct constraints on the existence of light sterile neutrinos from its first two data set [9,11] and is continuing to improve these bounds with more data. Other analyses in progress seek to constrain local over-density of cosmic relic neutrinos, Lorentz invariance violation in the neutrino sector, and exotic modifications of weak interactions. A future detector upgrade (TRISTAN) will allow a precision measurement of a wider range of the tritium spectrum, thereby enabling KATRIN to probe heavier sterile neutrinos (masses of order keV/c^2), as well [10]. With a growing data set and a wide vista of questions, KATRIN is looking ahead to some exciting answers. ■

About the Authors

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References

[1] E. Fermi, *Zeitschrift für Physik* **88** *(1934) 161; English translation in Am. J. Phys.* **36,** 1150 (1968)

[2] J. A. Formaggio, A. L. C. de Gouvêa, R. G. H. Robertson, *Physics Reports* **914**, 1 (2021)

[3] C. Kraus *et al., Eur. Phys. J. C* **40**, 447 (2005)

[4] V. N. Aseev *et al., Phys. Rev. D* **84**, 112003 (2011)

[5] M. Aker *et al.* (KATRIN Coll.), *JINST* **16,** T08015 (2021)

[6] M. Aker *et al.* (KATRIN Coll.), *Phys. Rev. Lett.* **123**, 221802 (2019)

[7] M. Aker *et al.* (KATRIN Coll.), *Phys. Rev. D* **104**, 012005 (2021)

[8] M. Aker *et al.* (KATRIN Coll.), *Nature Physics* **18**, 160 (2022), https://doi.org/10.1038/s41567-021-01463-1

[9] M. Aker *et al.* (KATRIN Coll.), *Phys. Rev. Lett.* **126**, 091803 (2021)

[10] S. Mertens *et al., J. Phys. G* **46**, 065203 (2019)

[11] M. Aker *et al.* (KATRIN Coll.), *Improved eV-scale Sterile-Neutrino Constraints from the Second KATRIN Measurement Campaign,* arXiv:2201.11593