Snowmass2021 - Letter of Interest

Direct Neutrino-Mass Measurements with KATRIN

NF Topical Groups: (check all that apply ☐/■)

☐ (NF1) Neutrino oscillations
☐ (NF2) Sterile neutrinos
☐ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
☐ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors
☐ (Other) *[Please specify frontier/topical group(s)]*

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Abstract: (maximum 200 words) The Karlsruhe Tritium Neutrino-Mass (KATRIN) experiment has recently set the world's best direct limit on the neutrino mass, from the measurement of the electron energy spectrum of tritium β-decay near its endpoint. This first result is based on the equivalent of only 9 days of data-taking in the experiment's design configuration. Here, we discuss KATRIN's plans for further exploring the neutrino mass in the next 1000 days of data-taking, including research and development toward still-greater sensitivities.

The neutrino-mass scale is one of the most pressing open questions in particle physics, affecting not only neutrino theory within the Standard Model, but also the possible rates of neutrinoless double-beta decay and structure formation in the early universe. Cosmological observations have set extremely tight constraints on the sum of neutrino-mass values m_i, recently reporting $\sum m_i < 0.26$ eV (95% confidence level, CL) from cosmic-microwave-background power spectra alone [1]. However, the interpretation of these limits implicitly relies upon the paradigm of the cosmological standard model. The neutrino mass offers a rare opportunity to test a cosmological observable in the laboratory, via the β-decay of tritium: $\mathrm{T} \to {}^3\mathrm{He}^+ + \beta^- + \bar{\nu}_\mathrm{e}$. Near the spectral endpoint of tritium at $E_0 \approx 18.6$ keV, the kinematics of this process are sensitive to the effective neutrino-mass-squared observable

$$m_\nu^2 = \sum_i |U_{\mathrm{e}i}|^2 m_i^2, \tag{1}$$

where $U_{\mathrm{e}i}$ gives the PMNS-matrix element coupling the electron flavor to the i^{th} neutrino-mass state.

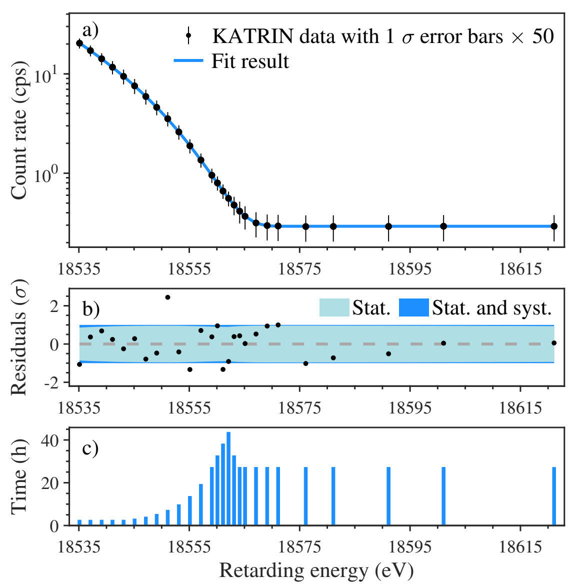

Figure 1: a) Spectrum of β-electrons acquired during KATRIN's first neutrino-mass measurement campaign, with 1σ uncertainties enlarged by 50x for visibility; this data set represents the combination of all spectral scans. The line shows the best-fit model. b) Residuals, relative to the 1σ uncertainty band of the best-fit model. c) Measurement-time distribution, showing the total accumulated acquisition time at all scan steps of the spectrum. Taken from Ref. [2].

The KATRIN experiment [3] employs an intense, windowless, gaseous molecular T_2 source, providing some 10^{11} tritium decays each second. β-electrons arising from these decays are guided along magnetic field lines toward a tandem pair of MAC-E filter (magnetic adiabatic collimation with electrostatic filter) [4, 5] spectrometers for energy analysis. The retarding potential applied to the high-resolution, main spectrometer sets a threshold on the β-electron kinetic energy: β-electrons with energy below this threshold are reflected back toward the source, while β-electrons with energy above this threshold are transported through the spectrometer to reach a Si *p-i-n*-diode detector for counting. The MAC-E filter thus effectively acts as an integrating high-pass filter, and KATRIN explores the endpoint region of the β-spectrum by systematically scanning this energy threshold near E_0.

Figure 1 shows the β-spectrum acquired during KATRIN's first neutrino-mass measurement campaign, during Spring 2019. The source was operated at a reduced intensity, and the four-week measurement was therefore equivalent to about 9 days of running at nominal activity. A four-parameter model – amplitude, energy-independent background rate, E_0 and m_ν^2 – was fit to the spectrum. The best-fit value of $m_\nu^2 = -1.0^{+1.1}_{-0.9}$ eV^2, obtained via independent, blind analyses, results in an upper limit on the neutrino-mass scale of 1.1 eV at 90% CL. The fitted value of E_0, when corrected for the energy scale of the experiment, is consistent with the Q-value obtained in Penning-trap measurements of the mass difference between T and ^{3}He [2].

Since this first campaign, KATRIN has continued to acquire both neutrino-mass and systematics data sets. The overall stability of the system, both in individual scan steps and scan-to-scan, has been further improved. We are continuing to improve the theoretical calculations that allow us to incorporate molecular effects in the analysis of our T_2 decay data set [6, 7]. The source now runs at a high tritium activity, but at these higher densities the plasma systematics must be fully understood. Based on early studies, we are testing modifications to the source configuration that may assist in these efforts.

In addition to these investigations, KATRIN is also working to mitigate the effects of higher-than-expected backgrounds, which have been traced to two sources [2]. In both cases, low-energy electrons released within the main spectrometer are accelerated by the retarding potential of the MAC-E filter, so that they arrive at the detector with energies indistinguishable from the transmitted β-electrons. In the first case, ^{219}Rn emanates from the getter pumps that establish the main-spectrometer vacuum, and decays inside the volume; shakeoff electrons are trapped within the vessel, producing large numbers of secondaries that reach the detector. In the second, α-decays of ^{210}Po – the progeny of ^{210}Pb implanted in the spectrometer wall – stimulate the sputtering of highly excited Rydberg atoms from the inner surface of the main spectrometer. These neutral atoms diffuse into the vessel volume, but their excitation levels are high enough that they can be ionized by black-body radiation – releasing secondary electrons that reach the detector.

The background from ^{219}Rn can be nearly eliminated by deploying liquid-nitrogen-cooled copper baffles at the pump ports [8, 9]. The background from Rydberg atoms cannot be eliminated at its source, but the collaboration is pursuing several promising avenues for mitigating it. Since the background rate from this process scales with the volume of the main spectrometer that is imaged by the detector, it can be reduced by passing the β-electron flux through a smaller imaging volume. This can be achieved by using air-cooled magnet coils, mounted around the main spectrometer, to effectively shift the spectrometer analyzing plane further downstream. Early tests are extremely promising.

Other possible mitigation strategies, presently being developed in test setups, rely on differences between Rydberg secondaries and β-electrons. Compared to β-electrons, Rydberg secondaries have much smaller pitch angles relative to the KATRIN magnetic field lines; we are testing an apparatus that could be inserted in the beamline to filter electrons based on their angular distribution. Meanwhile, only β-electrons travel through the beamline between the source and the main spectrometer. We are exploring methods for tagging β-electrons, or otherwise measuring their time-of-flight distributions, in order to isolate the signal – and to allow the possibility of measuring the *differential* β-spectrum, rather than an integrated spectrum. Finally, we are studying possible mechanisms for rapidly de-exciting Rydberg atoms, ionizing them before they can reach the imaged volume.

The exquisitely precise KATRIN measurement of the tritium β-spectrum affords sensitivity to a range of fascinating physics topics. Two additional letters of interest from the collaboration will highlight KATRIN's potential in searches for keV-scale sterile neutrinos [10], and for other signatures of beyond-Standard-Model physics [11]. The neutrino-mass scale remains our primary scientific goal, and the first KATRIN result has improved on historical limits by nearly a factor of 2 [12, 13]. The acquisition and analysis of the spectrum shown in Fig. 1 has laid a foundation for future KATRIN measurement campaigns. With greater statistics, reduced backgrounds, and improved systematics, we expect to achieve a sensitivity near our design goal of 0.2 eV (90% CL) after five calendar years of running.

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