Snowmass2021 - Letter of Interest

Searches for Beyond-Standard-Model Physics with the KATRIN Experiment

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) CF7 (Cosmic probes of fundamental physics)

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Abstract: (maximum 200 words) The Karlsruhe Tritium Neutrino (KATRIN) experiment is designed to make an extremely precise measurement of the tritium β-decay spectrum near its endpoint. This measurement affords sensitivity not only to the neutrino-mass scale, but also to a range of phenomena beyond the Standard Model. In this letter of interest, we discuss several sensitivity studies and preliminary work towards these searches.

The KATRIN experiment [1] is designed to measure the integrated β-decay spectrum of molecular tritium, near the spectral endpoint of $E_0 \approx 18574$ eV. Some 10^{11} tritium decays,

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

occur each second within a windowless, gaseous molecular T_2 source. The outgoing $\bar{\nu}_\mathrm{e}$ is not detected, but the β-electron is guided along magnetic-field lines to a pair of MAC-E filter (magnetic adiabatic collimation with electrostatic filter) [2, 3] spectrometers for energy analysis. In a smooth transition between a region of strong magnetic field and a region of weak magnetic field, the motion of the β-electron transverse to the magnetic field is converted into longitudinal motion, producing a broad, collimated beam. The addition of an electrostatic retarding potential therefore sets a threshold on the β-electron kinetic energy. Below the threshold, β-electrons are turned back toward the source; above the threshold, they are transported to a detector for counting. We scan the retarding potential, and thus the lower limit of the integration, near E_0 to map out the integral spectrum.

Another letter of interest from the collaboration will highlight KATRIN's sensitivity to the neutrino-mass scale, the primary physics goal of the experiment [4]. However, our detailed measurement of the tritium spectrum will also afford sensitivity to numerous beyond-standard-model (BSM) phenomena. Below, we summarize our efforts in this area. KATRIN's searches via the tritium β-spectrum are complementary to other types of experiment, offering very different systematics.

eV-scale sterile neutrinos In contrast to the tiny splittings between the known neutrino-mass states, KATRIN is capable of resolving the splitting between the active sector and an eV-scale mass state m_s if the mixing angle is sufficiently large. The experimental signature of a sterile neutrino – a distinctive "kink" in the spectrum at $E_0 - m_s$ – is accessible to KATRIN's shape-only analysis. Early sensitivity studies have forecast that KATRIN's complete data set will be able to cover a large portion of the sterile-neutrino parameter space favored by the reactor antineutrino anomaly [5] or the MiniBooNE/LSND anomalies [6], setting competitive limits even when considering the unknown active-neutrino mass scale [7]. Analyses of KATRIN's first neutrino-mass dataset, acquired in 2019, support these sensitivity projections [8, 9].

keV-scale sterile neutrinos For sufficiently large mixing angles, via the same type of "kink" signature, KATRIN could in principle detect the signature of a fourth mass state up to the Q-value of tritium decay, about 18.6 keV [10]. Sterile neutrinos at this scale are an intriguing candidate for warm dark matter [11]. KATRIN plans to improve on current laboratory limits on the admixture of a keV-scale sterile neutrino by four orders of magnitude, relying on an upgrade of its primary detector. A new silicon drift detector array ("TRISTAN") [12], currently under development, could be inserted in the KATRIN beamline after the conclusion of the neutrino-mass data-taking. This detector will enable a differential measurement of the full β-decay spectrum at high energy resolution. Promising tests with prototype arrays have been performed [13, 14, 15]. Details are described in an additional letter of interest [16].

Cosmic neutrino background The cosmic neutrino background is not a beyond-standard model effect, but nonetheless is a tantalizing target for a tritium experiment. Neutrino capture on tritium is a thresholdless process, and would imprint a unique signature on the tritium β-spectrum: a spike of events, located two neutrino-masses above the actual endpoint of tritium β-decay. It has been suggested that KATRIN may be able to detect such events [17], but sensitivity studies suggest that detection will require substantial local overdensities of relic neutrinos [18, 19]. Significantly increased tritium target mass would allow a direct detection of relic-neutrino capture.

Lorentz-invariance violation The neutrino sector of weak interactions offers an opportunity to probe the validity of Lorentz invariance. Violation of Lorentz invariance is predicted in some BSM frameworks, for instance in the generalized Standard Model Extension (SME) [20] based on effective field theory. Anisotropic effects might introduce observable consequences in direct kinematic experiments, as proposed e.g. in Ref. [21], which are complementary to observables in neutrino oscillation experiments. KATRIN's precision energy scale and long-term data-taking open up promising prospects to search for two perturbations of the effective spectral endpoint, predicted by SME theory: an absolute shift, and a sidereal oscillation. A search for the latter perturbation would provide the first-ever experimental access to the SME operator with complex coefficient $\left(a_{of}^{(3)}\right)_{11}$ [21].

Right-handed weak currents Precision kinematics of weak decays allow searches for exotic forms of the interaction, such as additional non-standard right-handed currents departing from the established $V - A$ structure of SM weak interactions. Left-right symmetric models are hypothetical extensions of the SM in which right-handed weak currents occur. The imprint of right-handed currents on the tritium β-decay spectrum with active neutrinos has been the subject of earlier studies (e.g., Refs. [22, 23]). Dedicated experiments (most notably, neutron decay, reviewed in Ref. [24]) have yielded very stringent limits. The sensitivity of the standard KATRIN analysis is limited by the fact that E_0 is one of the free fit parameters. Sensitivity to right-handed currents with active neutrinos can potentially be improved by fixing the endpoint in the fit, which would require a very accurate measurement of the Q-value (through the ^{3}H-^{3}He mass difference) and knowledge of the absolute potentials in KATRIN at the level of 30–100 meV or better.

Recently, the interplay of right-handed currents with potential sterile neutrinos has become a focus of interest (see, e.g., Refs. [25, 26, 27]. It has been shown in these works that KATRIN will be able to set bounds on the strength of the left-right interference terms as a function of m_s, a low-energy search complementary to LHC-based efforts. New limits could be obtained for a Fierz-like interference term that does not originate in the left-right symmetric model [27].

New light bosons In the Standard Model picture, β-decay is a three-body process (Eq. 1). Alternately, a four-body process might occur if an extra boson (pseudoscalar or vector) were emitted either from the neutrino or charged lepton, or (in the case of a vector boson) from both [28]. Complementary to the energy scale of accelerator-based experiments (e.g. at the LHC), nuclear β-decays address very light extra bosons, with masses less than 18.6 keV in the case of tritium. For the standard neutrino-mass-measuring operation of KATRIN, this search is confined to boson masses of some tens of eV, whereas the TRISTAN detector upgrade will allow access to the full kinematic phase space. Sensitivity studies for the pseudoscalar and vector scenarios are presented in Ref. [28], both for the nominal energy range close to the spectral endpoint and for the extended search with a broad energy range. In contrast with stringent existing limits from gauge-boson decays in high-energy experiments and from cosmological or astrophysical observations, the kinematic search offers an independent test of the new physics hypothesis in a low-energy range.

Exotic neutrino-mass models Mainstream neutrino-mass models require that the squared neutrino mass be non-negative, so that the effective neutrino mass is real. However, certain more exotic theories postulate that at least one neutrino-mass state is spacelike or tachyonic, which would push the squared neutrino mass into the otherwise unphysical, negative region (see, e.g., Refs. [29, 30]). It must be noted that unaccounted-for systematic uncertainties tend to drive the observed neutrino-mass squared toward more negative values [31], and several historical results in this range have indeed been traced to previously unsuspected systematics [32, 33], so caution is essential. With robust, improved systematics and unprecedented statistics, KATRIN's future neutrino-mass measurements would be sensitive to this new physics.

The physics harvest of the final KATRIN dataset will be rich and varied. Beyond the measurement of the neutrino mass and illumination of the corresponding models, a precisely measured β-spectrum is sensitive to sterile neutrinos, relic neutrinos from the earliest moments of the universe Lorentz-invariance-violating operators, right-handed weak currents, new light bosons. With the operations and analysis of the neutrino-mass measurement now established [34], the collaboration is actively studying experimental sensitivity to these tantalizing observables.

Acknowledgments We acknowledge the support of Helmholtz Association, Ministry for Education and Research BMBF (5A17PDA, 05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), Helmholtz Alliance for Astroparticle Physics (HAP), Helmholtz Young Investigator Group (VH-NG-1055), Max Planck Research Group (MaxPlanck@TUM), and Deutsche Forschungsgemeinschaft DFG (Research Training Groups GRK 1694 and GRK 2149, Graduate School GSC 1085 - KSETA, and SFB-1258) in Germany; Ministry of Education, Youth and Sport (CANAM-LM2011019, LTT19005) in the Czech Republic; and the United States Department of Energy through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, DE-SC0011091, and DE-SC0019304, and the National Energy Research Scientific Computing Center. This project has also received funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation program (grant agreement No. 852845).

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