Snowmass2021 - Letter of Interest

Prospects for keV Sterile Neutrino Searches with KATRIN

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

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☐ (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
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Abstract: Right-handed neutrinos are a minimal extension of the Standard Model of Particle Physics which leads to the existence of new neutrino mass eigenstates with arbitrary mass scale. Neutrinos with masses in the keV range and very weak mixing with active species form viable dark matter candidates. A promising model-independent way to search for keV-scale sterile neutrinos is via high-precision beta spectroscopy, where these particles manifest themselves as tiny distortion of the spectral shape. The Karlsruhe Tritium Neutrino (KATRIN) experiment, equipped with a novel multi-pixel silicon-drift-detector focal plane array and read-out system, named the TRISTAN detector, has the potential to surpass the sensitivity of previous laboratory-based searches.

As prominent dark matter candidates, sterile neutrinos in the keV mass range are at the crossroads of particle physics, astrophysics and cosmology [1, 2]. Depending on their production mechanism in the early universe, they can act as effectively cold, cool, or even warm dark matter, which in turn have drastically different influences on the structure formation of our cosmos [3]. A sizable fraction of warm dark matter can mitigate tensions between observations and predictions of purely cold-dark-matter scenarios [4].

Both cosmological and astrophysical data yield strong bounds on keV-scale sterile neutrinos, but these rely on an underlying cosmological model [5]. Applying such bounds assumes that all dark matter is composed of sterile neutrinos, that a certain production mechanism was realized in the early universe, and that the distribution of dark matter and the astrophysical foregrounds are understood. Therefore, model-independent, laboratory-based experiments are indispensable to directly probe the existence and properties of these hypothetical particles.

The current limits from laboratory-based searches are several orders of magnitude weaker than astrophysical and cosmological limits. Yet, through renewed interest in the field, many promising proposals to push the sensitivity of laboratory-based experiments have been put forward in recent years [6, 7, 8, 9]. One of the most feasible approaches, to be realized in the near future, is to search for sterile neutrinos in beta decays. The sterile neutrino, emitted in a beta-decay, would lead to a small, but characteristic distortion of the beta-decay spectrum at an energy $E = E_0 - m_s$, where E_0 is the kinematic endpoint and m_s corresponds to the sterile-neutrino mass. The main challenge of a keV-sterile neutrino search in beta decays is to reduce both the statistical and systematic uncertainties to the sub-ppm level, in order to probe parameter space of interest for particle physics and cosmology.

A world-leading beta-spectroscopy experiment is the KATRIN experiment [10]. The main objective of KATRIN is the determination of the absolute neutrino-mass scale [11] with an unprecedented sensitivity of 200 meV, by measuring the tritium beta decay spectrum close to its endpoint in an integral way [10]. Yet, its ultra-high source activity and excellent spectral analysis quality allow it to extend its physics program to search for a wide variety of beyond-standard-model phenomena [12], including sterile neutrinos in a wide mass range.

The targeted sensitivity for keV-scale sterile neutrino admixture is 10^{-6}. From a statistical point of view the enormous source activity of KATRIN allows to reach mixing angles at the 10^{-8} level with approx. 1 year of measurement time. However, reducing systematic uncertainties to the ppm-level poses a major challenge.

A major technological challenge arises when operating KATRIN to search for keV-scale sterile neutrinos. The signal of the new particle would appear far away from the endpoint, where the rate of tritium-decay electrons is high. Accordingly, the counting rate at the detector will be many orders of magnitude higher than in normal KATRIN operation, where only the spectral endpoint region is observed.

KATRIN is presently pursuing a research and development program into an advanced detector and readout system known as TRISTAN [13]. TRISTAN is built of Silicon Drift Detectors (SDDs), an ideally suited technology designed for high-rate and high-resolution applications [14]. The upgraded detector is expected to handle high rates (up to 10^9 cps) while at the same time providing excellent energy resolution (300 eV FWHM @ 18 keV for electrons) and energy linearity (ppm-level). High-precision beta spectroscopy is a novel application for SDDs, which are typically used for x-ray spectroscopy. To improve response to electrons, we are exploring new production techniques to reduce the SDD entrance window thickness to less than 30 nm.

New technology will be needed to integrate the 20-cm-diameter TRISTAN focal-plane array, with more than 1000 channels, into ultra-high vacuum and high magnetic- and electric-field conditions. An advanced data acquisition system, still located in the high-field regions, will perform a full waveform digitization. The data, at rates exceeding Gb/s, will be sent via optical links to a high-performance FPGA system (situated in the low-field regions) to perform event-by-event energy filtering and multiplicity analysis.

The TRISTAN detector system will complement the standard integral measurement of KATRIN (in which the detector only counts electrons) with a high-resolution differential measurement (in which the detector determines the energy of each electron). This novel idea of combining differential and integral measurement modes will be a key to ruling out large classes of systematic uncertainties.

Over the past years major advances with respect to the keV-scale sterile neutrino search with KATRIN have been made. An important milestone for the keV-scale sterile neutrino program of KATRIN was achieved with the first tritium measurement in 2018 [15]. Thanks to a rather low tritium activity during this commissioning campaign, an extended measurement interval was possible, which allowed the search for sterile neutrinos in a mass range of up to about 1.6 keV. An excellent agreement of the undistorted spectrum calculation to the data could be demonstrated in this broad energy range, improving the current laboratory-based limits in the sterile neutrino mass range between 0.1 and 0.5 keV to the level of 10^{-3} [16].

To extend the mass range and improve the sensitivity further, the novel TRISTAN detector system will be necessary. With the first generation of prototype detectors, the excellent performance of SDDs [13] and their applicability for beta-spectroscopy [17] was demonstrated. The development of the first TRISTAN detector modules has been completed in the beginning of 2020. A TRISTAN module comprises 166 detector pixels with an integrated read-out amplification. A fully equipped detector module is planned to be installed at the KATRIN monitor spectrometer [18] in 2021. The final detector system will be integrated into the KATRIN beamline in a staged approach. Phase 1 is defined as a 9-module system, which requires minimal changes to the current KATRIN focal-plane detector chamber. Phase 2 is a further upgrade to 21 modules, for which a new detector chamber with an optimized electromagnetic field configuration is required. All upgrades will take place after the successful completion of the neutrino-mass measurement program of KATRIN.

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