Recent results from the Karlsruhe Tritium Neutrino Experiment (KATRIN) and the future atomic tritium source for KATRIN++

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The absolute value of the neutrino mass plays an important role in cosmology and is a critical missing parameter of the Standard Model. Studying the kinematics of beta decays offers a uniquely model-independent access to the neutrino mass, which is complementary to stringent constraints from neutrinoless double-beta decay and cosmological observations.

Using this method, the Karlsruhe Tritium Neutrino (KATRIN) experiment has improved the upper bound on the incoherent sum of neutrino masses down to $m_\beta < 0.45$ eV (90% C.L.), with its full data set, acquired by then end of 2025, targeting a final sensitivity of < 0.3 eV. To further improve this sensitivity down to the 0.05 eV level, which allows cross-validation of the other mass measurement approaches, and answer the question of normal or inverted neutrino mass ordering, fundamentally new technological developments are necessary.

The state-of-the-art KATRIN experiment employs a molecular tritium source, operating at approximately 10^{11} beta decays per second, alongside an integration filter possessing a filter width of $\Delta E = 2.7$ eV, and a background rate of 0.1 counts per second, attributed to the ionization of neutral Rydberg atoms within the spectrometer volume. Reaching down to inverted ordering with such a "KATRIN-like" configuration would necessitate either a significantly stronger source or a decades-long measurement program, both of which are impractical from a technical standpoint. In principle, any integral spectroscopy method, such as the MAC-E filter technique, is burdened by a measurement-time expansion-factor of $\mathcal{O}(30)$, due to its point-by-point nature, in contrast to a truly differential measurement that captures the entire spectrum simultaneously. Substantial improvement in neutrino-mass sensitivity could be realized by transitioning to a detection method employing high-resolution differential measurement techniques. However, such a differential method needs to achieve an energy resolution of well below 1 eV (FWHM). 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 backgrounds. Both are boosting the prospect of improved sensitivity.

Current research and development efforts in the KATRIN context focus on (i) time-of-flight measurements and (ii) large arrays of quantum sensors.

To further enhance neutrino-mass sensitivity in future experiments, atomic tritium must replace the current molecular tritium-based β-electron source. The β-decay of molecular tritium, $T_2 \rightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$, differs from that of atomic tritium, $T \rightarrow {}^3He^+ + e^- + \overline{\nu}_e$, primarily in the final state spectrum of the daughter molecular ion, ${}^3HeT^+$. Moreover, molecular tritium decay leaves only 57% of daughter molecules in the electronic ground state, while atomic tritium decay increases this fraction to 70% for daughter atoms, boosting the number of relevant decay electrons near the spectral endpoint.

Additionally, ${}^3HeT^+$ remains in an excited ro-vibrational state, broadening the β-spectrum to approximately 1 eV (FWHM) and inherently limiting neutrino mass sensitivity, even with advanced detector resolutions. Moreover, electron scattering is less probable in atomic tritium than in T_2, reducing energy losses. Unlike T_2, the fermionic ($s = 1/2$) tritium atom can be manipulated using inhomogeneous magnetic fields, enabling trapping and cooling below the freeze-out temperature of T_2 to minimize Doppler broadening of β-decay electrons.

For implementation in KATRIN++, atomic tritium will be needed in copious amounts – comparable to the current molecular source of KATRIN – 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) Study 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 must be used, which are estimated to be at 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. The mission is to realize a global Atomic Tritium Pathfinder (ATP) at the Tritium Laboratory Karlsruhe (TLK). To achieve this, a joint working group is in the process of being formed. The partners for the ATP consortium will include those from various specialized areas: Neutrino mass partners such as KATRIN++, Project 8, and QTNM. In addition, partners from atomic and molecular physics, quantum gases, and precision spectroscopy are welcome to join this consortium.