First neutrino mass measurement with the KATRIN experiment

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Abstract. The KATRIN (Karlsruhe Tritium Neutrino) experiment is designed to determine the effective mass of the electron anti-neutrino with an unprecedented sensitivity of 0.2 eV/c\(^2\) (90% C.L.) in a direct and model-independent way. Tritium β\(-\)decay electrons, emitted in a high-luminosity molecular source, are analyzed with a MAC-E filter. The effective electron anti-neutrino mass squared is inferred from a fit to the integral spectrum in an energy window close to the tritium endpoint. In this work, we report on the analysis of the first four-week science run of KATRIN in spring 2019. Considering statistical and systematic uncertainties, we find a central value of the effective electron anti-neutrino mass of \(m^2_{\nu} = (-1.0^{+1.3}_{-1.0})\) eV\(^2\). Following the method of Lokhov and Tkachov, we derive an upper limit of 1.1 eV at 90% C.L. on the absolute neutrino mass scale.

1. Introduction

The observation of neutrino flavor oscillations demonstrated that neutrinos possess a non-vanishing rest mass, disproving the prediction of the Standard Model. Despite this revolutionary finding, neutrino oscillations are not sensitive to the absolute neutrino mass scale. Kinematic studies of weak-interaction processes such as tritium β\(-\)decay offer a direct and model-independent method to probe the neutrino mass scale in laboratory experiments. A precise measurement of the electron energy spectrum close to the tritium endpoint energy \((E_0 = 18.57\) keV\)) allows for the inference of the effective electron anti-neutrino mass squared \(m^2_{\nu}\). Since the anti-neutrino is emitted in its electron flavor eigenstate in the β\(-\)decay, it does not have a definite mass. Rather, \(m^2_{\nu}\) is defined as the incoherent sum of the squared neutrino mass eigenstates \(m_i^2\) and the absolute square of the electron-flavor matrix elements \(|U_{ei}|^2\):

\[
m^2_{\nu} = \sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2.
\]

In this work, we report on the first neutrino mass result from the KATRIN experiment.

2. KATRIN experiment

The KATRIN experiment is the state of the art tritium β\(-\)decay experiment, designed to measure the effective electron anti-neutrino mass to a sensitivity of 0.2 eV at 90% C.L. after 5 calendar years [1]. After being emitted in the high-purity gaseous molecular tritium source, β\(-\)electrons are guided adiabatically by the transport section to the main spectrometer. This high-resolution MAC-E filter [2] acts as a high-pass filter to analyze the energy of the β\(-\)electrons close the tritium endpoint. Electrons with energies above a certain threshold are counted by the focal plane detector (FPD) [3], which results in an integral tritium spectrum.
3. First neutrino mass measurement
The first neutrino mass measurement campaign in KATRIN was conducted from April 10 to May 13, 2019 [4]. The full functionality of all system components is demonstrated. Due to radiochemical reactions of T₂ with the previously unexposed metals in the source, drifts of the source column density by ±2% over the full measurement time are observed at an average source column density of 1.11 · 10^{17} molecules/cm². Together with the high tritium purity (97.6%), an activity of 2.45 · 10^{10} s⁻¹ is reached, which corresponds to 22% nominal activity. The integral tritium spectrum is scanned repeatedly at non-equidistant HV set points in an energy window between −40 eV below and 50 eV above the endpoint as illustrated in figure 1 c). The total measurement time per scan of 2 h is unevenly distributed among the HV set points, so that the measurement time attributed to one HV set point varies between 20 s and 10 min.

Figure 1. Fit to the integral tritium spectrum. Figure a) shows the overlay of the data and the model, combining all golden scans and pixels. The residuals displayed in figure b) exhibit no pattern. The measurement time, spent at each high-voltage set point is shown in figure c). Figure d) shows the probability density function, given zero neutrino mass. Negative and positive values for \( m_\nu^2 \) occur with the same probability.

4. Data Analysis
The analyzed golden data set comprises 274 scans of the tritium spectrum, which corresponds to 23.4 days of net measurement time. Based on strict quality criteria to ensure uniform detector coverage and efficiency, 117 out of 148 FPD pixels are taken into account. To guarantee a bias free analysis, a two-folded blinding scheme is applied: 1) The tritium β-decay model is blinded by replacing the ground state of the Final State Distribution [4] with a Gaussian of unknown width. 2) The full analysis chain, including the final fit and the treatment of systematic effects, is developed exclusively on Monte Carlo data, which mimics the actual data set with respect to all operational parameters. In the following the results of one of two independently developed analyses is presented.

The experimental spectrum is accurately described with a detailed model of the KATRIN response to tritium β-electron and background. Four free parameters are inferred from the fit: the effective electron anti-neutrino mass squared \( m_\nu^2 \), the effective β-decay endpoint \( E_0^{fit} \), the signal amplitude \( N \) and the background \( B \). Every pixel in every scan measures its own tritium spectrum. When multiple tritium spectra are analyzed with a common model assuming pixel- and scanwise \( N \) and \( B \), the number of free parameters increases linearly with the number of tritium spectra. In order to reduce the number of free fit parameters, all golden pixels are described with one uniform model. Due to an excellent homogeneity of the magnetic and electric...
fields inside the spectrometer, the arising systematic uncertainty is negligible. Furthermore, all 274 golden tritium scans are combined by summing the count rate and averaging the operational parameters. The induced systematic uncertainty from this run combination technique is $O(10^{-2})$ and accounted for in the systematics treatment. Systematic uncertainties are propagated with the covariance matrix approach [5]. The covariance matrix is calculated by simulating $O(10^4)$ Monte Carlo tritium spectra, varying the relevant set of parameters according to their joint probability density function. The method of covariance matrices enables a consistent energy dependent consideration of systematic effects in both simulation and data analysis.

![Figure 2. Upper limits on the effective electron anti-neutrino mass are derived following two different statistical procedures.](image)

**Figure 2.** Upper limits on the effective electron anti-neutrino mass are derived following two different statistical procedures. Figure a) shows our confidence belt and the corresponding upper limit of $m_\nu \leq 0.8 \text{ eV}^2$ (90\% C.L) according to Feldman and Cousins [6]. The confidence belt employing the method of Lokhov and Tkachov [7] is displayed in figure b). The upper limit of $1.1 \text{ eV}^2$ (90\% C.L) coincides in this strategy with the sensitivity.

### 5. Result
We find a best fit value for the neutrino mass of $m_\nu^2 = (-1.0 \pm 0.9 - 1.0) \text{ eV}^2$ with an excellent p-value of 0.56. The overlay of data and the model is shown in figure 1 a) and the corresponding residuals in figure 1 b). As illustrated in figure 1 d), the probability to find $m_\nu^2 \leq -1.0 \text{ eV}^2$ assuming zero neutrino mass is large (18.7\%). The statistical uncertainty alone amounts to 0.94 eV$^2$. This demonstrates that our first neutrino mass campaign is strongly statistics dominated. It is found that the background is the dominant systematic effect of this measurement campaign ($\sigma(m_\nu^2) = 22 \times 10^{-2} \text{ eV}^2$). The Poisson uncertainty on the background rate is increased by 6.4\% due to a non-Poisson background contribution from radon decay. Furthermore, the possible energy dependence of the background is investigated. We perform $O(10^4)$ fits to statistically randomized Monte Carlo background data, allowing for linear background slopes. The associated covariance matrix is then calculated from the resulting sample background spectra ($\sigma(m_\nu^2) = 9 \times 10^{-2} \text{ eV}^2$). Comparing the statistical (systematic) uncertainties of our first neutrino mass measurement to the final numbers of the predecessor experiments in Mainz and Troitsk, we find an improvement by a factor of 2 (6). Furthermore, the methods of Feldman and Cousins (F.C.) [6] and Lokhov and Tkachov (L.T.) [7] are used to calculate an upper limit on $m_\nu$. Both confidence belt construction techniques constrain the neutrino mass to non-negative values. We report an improved upper limit of 0.8 eV (F.C.) and 1.1 eV (L.T.) at 90\% C.L.. The confidence belts are displayed in figure 2.

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