

The KATRIN neutrino mass experiment

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The Karlsruhe Tritium Neutrino experiment aims to determine the neutrino mass in a model-independent way from the kinematics of tritium β -decay. It combines a Windowless Gaseous Tritium Source (WGTS) with a column density of 5×10^{17} molecules/cm² and a high resolution electrostatic retarding spectrometer (MAC-E filter) to measure the spectral shape of β -decay electrons close to the endpoint energy at 18.6 keV with an unprecedented precision. KATRIN's sensitivity to the neutrino mass will be 0.2 eV/c² after 3 years of full data taking. This number corresponds to an upper limit with 90% confidence level, in case no neutrino mass signal is observed; a neutrino mass of 0.35 eV would be discovered with a 5σ significance. At present the experiment is being installed at the Karlsruhe Institute of Technology and many components are undergoing extensive testing.

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1. Introduction

Experimental results from neutrino oscillation experiments have established the fact that neutrinos are massive and that the neutrino flavor eigenstates ν_α can actually be expressed as a superposition of mass eigenstates $\nu_\alpha = \sum_i U_{\alpha i} \nu_i$ [1]. However, since neutrino oscillation experiments are only sensitive to the difference of the squared masses $\Delta m_{\nu}^2 = |m^2(\nu_i) - m^2(\nu_j)|$ the absolute scale of neutrino masses cannot be determined from these measurements.

Different methods have been applied to learn about neutrino masses. The most promising ones are the deduction of the overall neutrino mass density from cosmological structure formation data, time of flight measurements of supernova neutrinos, experimental searches for neutrinoless double β -decays and finally the analysis of β -decay kinematics near the endpoint energy E_0 .

Kinematic neutrino mass measurements exploit the phase space dependence of the energy spectra of weak decays to extract information about the masses of the emitted neutrinos, and therefore offer a model-independent method to probe the absolute neutrino mass scale. The investigations of nuclear β -decays have yielded upper neutrino mass limits in the eV range [2, 3, 4] that probe part of the cosmologically interesting region of degenerate neutrino masses. A lot of effort is currently put into the construction of the KATRIN experiment [5], which will push down the limit into the sub-eV range and will allow to verify claims of a mass signal from the observation of $0\nu\beta\beta$ decays in the Heidelberg-Moscow experiment [6].

2. β -decay kinematics

The energy spectrum of nuclear β -decay can be calculated starting from Fermi's golden rule and has the following form [7] (with units $\hbar = c = 1$):

$$\frac{d\Gamma}{dE} = \frac{G_F^2 \cos^2 \theta_C}{2\pi^3} |M|^2 S(E) F(E, Z+1) p(E + m_e) \sum_i \sum_j |U_{ei}|^2 P_j \varepsilon_j \sqrt{\varepsilon_j^2 - m_i^2} \Theta(\varepsilon_j - m_i), \quad (2.1)$$

where G_F is the Fermi coupling constant, θ_C the Cabbibo angle and M the nuclear matrix element of the transition. $S(E)$ is a shape factor that takes into account the energy dependence of the nuclear matrix element. This factor equals 1 for allowed and super-allowed transitions as in tritium β -decay. The Fermi function $F(E, Z+1)$ takes into account the final state interaction of the emitted electron with the daughter nucleus and $p(E + m_e)$ is the phase space factor of the outgoing electron. The product of the neutrino momentum and its energy given by $\varepsilon_j = E_0 - E_j^* - E$ is the phase space of the emitted neutrino, which shapes the β -spectrum near its endpoint. The neutrino phase space factor has to be summed over all final states E_j^* of the daughter molecule that are populated with probabilities P_j and over the neutrino mass eigenstates m_i . The inclusion of the Θ function in eq. 2.1 ensures that $\varepsilon_j - m_i > 0$. The observable $m_{\nu_e}^2$ that can be extracted from the spectral shape near the endpoint is defined by an incoherent sum over the mass eigenstates weighted by the matrix elements of the U_{PMNS} mixing matrix [8] known from oscillation experiments:

$$m_{\nu_e}^2 = \sum_{i=1}^3 |U_{ei}|^2 m_i^2. \quad (2.2)$$

The problem of partial cancellation of the mass terms that can arise in measurements of $0\nu\beta\beta$ -decays, where the observable is a coherent sum over the mass eigenstates $m_{\beta\beta} = |\sum_i U_{ei}^2 m(\nu_i)|$,

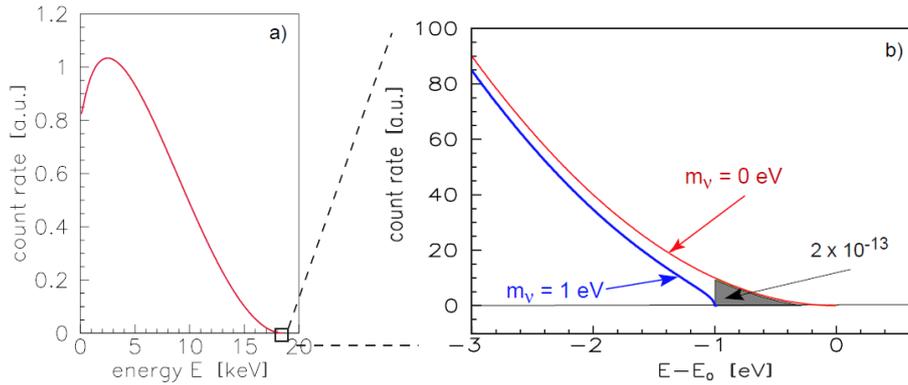


Figure 1: Energy distribution of electrons emitted in tritium β -decay (figure taken from [5]).

does therefore not occur here. The influence of the neutrino mass on the observed spectra is most pronounced in the endpoint region as shown in figure 1, where the right hand side provides a zoom into the last few eV of the electron energy distribution of tritium β -decay. This also highlights the biggest problem of the measurements, as in the case of tritium only $2 \cdot 10^{-13}$ of all decay electrons fall into the last 1 eV of the distribution. The prime requirements to set up a sensitive β -decay experiment are therefore a high overall source luminosity, high energy resolution and a very low background in order to gain sufficient statistics in the endpoint region. Besides the statistics of the measurement, challenges arise in the precise treatment of systematic effects, such as inelastic scattering of electrons on their way to the detector.

3. The KATRIN experiment

An overview of the KATRIN experiment is shown in figure 2. The experiment works with a windowless gaseous tritium source (WGTS) where T_2 molecules are injected in the center of the

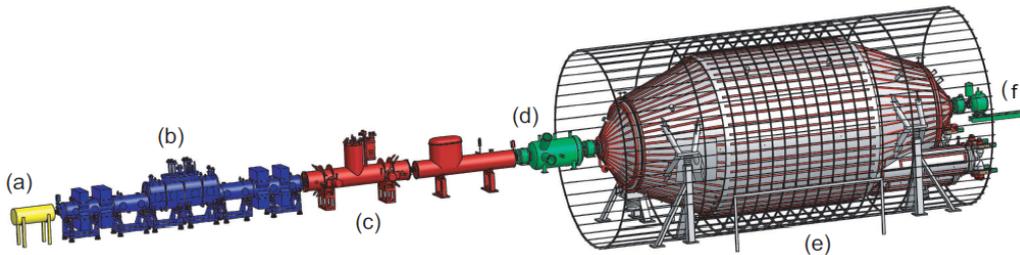


Figure 2: Overview of the KATRIN experiment. The main components are: (a) rear section calibration and monitoring system, (b) windowless gaseous tritium source, (c) transport and pumping section, (d) pre-spectrometer, (e) main spectrometer, (f) detector system. Overall length ca. 70 m.

source and are removed again by turbo-molecular pumps at both ends. The T_2 gas is kept at a constant temperature of 30 K within the source that is operated at a column density of $5 \cdot 10^{17} \text{cm}^{-2}$. The parameters of the source are monitored by a complex sensor network and a dedicated calibration and monitoring section at the rear of the source system. About 10^{10} decay electrons are emitted per second in the forward direction and are guided magnetically through the transport section to the

spectrometer tandem consisting of the pre- and the main spectrometers. The task of the transport section, made up of a differential pumping section and a cryo-pumping section, is to suppress the flow of T_2 molecules into the direction of the spectrometers by at least a factor of 10^{14} in order to reduce experimental background from tritium decays within the spectrometers. A first energy discrimination is performed by the pre-spectrometer which rejects the low energy part of the beta spectrum and thereby reduces the rate of electrons going into the main spectrometer to approximately 10^3 s^{-1} . The purpose of this reduction is to suppress background from electron interactions with residual gas molecules in the main spectrometer.

Like the pre-spectrometer the main spectrometer operates as a so-called MAC-E filter [9] and has the task to perform a precise energy analysis of the decay electrons. In a MAC-E filter electrons are guided magnetically against an electrostatic retardation potential that can only be surpassed by electrons with a sufficiently high velocity parallel to the electric field lines. The spectrometer therefore acts as a high pass filter. To reduce the amount of transversal energy of the electrons that is not analyzed by the spectrometer, the technique of magnetic adiabatic collimation is used. The idea is that the magnetic guiding field drops by several orders of magnitude from the entrance of the spectrometer to the analyzing plane, where the electric potential reaches its maximum. If the gradient of the magnetic field is small enough, such that the field is approximately constant along one cyclotron loop of the electron movement, the magnetic moment of the cyclotron motion $\mu = E_{\perp}/B$ (non-relativistic) is constant and as B drops the transversal energy of the electrons is converted into longitudinal energy E_{\parallel} that can be analyzed by the spectrometer. The energy resolution of a MAC-E filter is therefore determined by the ratio of the maximum magnetic field encountered along the flight path to the minimal field in the analyzing plane of the spectrometer. In the case of KATRIN this ratio is $B_{max}/B_{min} = 20000$ which corresponds to an energy resolution of 0.93 eV at the endpoint of the tritium β -spectrum. By varying the electric potential of the spectrometer it is then possible to scan the relevant region around the endpoint energy of the decay and accumulate a spectrum. Electrons with sufficient energy to pass the spectrometer are detected by a 148 pixel silicon PIN detector at the end of the setup.

Among the main systematic uncertainties of the experiment are inelastic scatterings of electrons in the source, fluctuations of the source density, fluctuations of the spectrometer analyzing potential, uncertainties in the transmission function and uncertainties in the final state distribution of the daughter molecules. A sophisticated calibration and monitoring system, employing two of the world's most precise high voltage dividers [10] and a dedicated monitor spectrometer to measure mono-energetic conversion electrons from a ^{83m}Kr source [11], is being set up to keep the aforementioned systematic effects under control.

Another major topic that has to be dealt with in order to reach the desired sensitivity is the suppression of experimental background. To reduce the rate of background electrons created in the materials of the large main spectrometer by radioactive decays or cosmic muons, a modular, two-layer wire electrode system has been installed on the inside of the spectrometer vessel. This electrode system is kept on a slightly more negative (about 200 V) electric potential than the vessel itself, such that low energy secondary electrons created at the vessel surface are reflected back into the stainless steel. Combined with the magnetic shielding of background electrons intrinsic to the operation of a MAC-E filter this will allow the background count rate to reduce to an acceptable level of $< 10 \text{ mHz}$ [12]. Besides background suppression, the wire electrode system will be used

to shape the electric fields inside the main spectrometer in order to achieve the highest possible homogeneity of the retardation potential, and to suppress unwanted Penning traps in the spectrometer.

The KATRIN experiment is currently in an advanced stage of construction by an international collaboration at the Karlsruhe Institute of Technology (KIT) in Germany, with many major components already on site and undergoing extensive testing. Among the recent achievements are tests of a subset of the WGTS in which a temperature stability of < 9 mK over 24 h has been demonstrated for the two-phase neon cooling system of the source (the required stability is $\Delta T < 30$ mK) [13]. Other important milestones in the source section have been the commissioning of the tritium inner loop system and the Laser Raman spectroscopy system [14] to monitor tritium purity. The pre-spectrometer has been used as a testing ground for spectrometer related issues. After the residual background in the spectrometer has been identified as originating from ^{219}Rn decays [15] and removed by a LN2 cooled baffle, the pre-spectrometer has been moved to the main spectrometer hall. Meanwhile the installation of the inner wire electrode system of the main spectrometer has been completed and the main spectrometer is currently awaiting a complete bake-out in order to reach the required ultra-high vacuum of 10^{-11} mbar in the spectrometer vessel. The focal plane detector system, developed by collaborating groups from the US, has been set up and is being tested at KIT. For systematic studies of the main spectrometer properties a new kind of angular-selective pulsed UV photoelectron source has been developed [16] and will be used in the commissioning of the spectrometer.

4. Summary

The study of tritium β -decay close to the endpoint energy is currently the most sensitive method for a model-independent determination of m_{ν_e} . While previous experiments in Mainz and Troitsk have reached upper limits of about $2 \text{ eV}/c^2$ [2, 3], KATRIN aims at a sensitivity of $0.2 \text{ eV}/c^2$ (95% C.L.) after 5 years of data taking (corresponding to 3 live years worth of data) [5]. Construction and tests of the setup are under way at KIT with numerous activities taking place around the source and transport section, the monitoring systems and the recently completed main spectrometer. Commissioning of the main spectrometer is expected to take place in spring 2013.

Acknowledgments

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