Status of the Karlsruhe Tritium Neutrino Experiment KATRIN

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Precision measurements of the kinematics of weak decays represent the only model independent approach to address the still unknown absolute scale of neutrino masses in a laboratory experiment. The KATRIN experiment, currently under construction at the Karlsruhe Institute of Technology, aims to improve the neutrino mass sensitivity obtained through precision spectroscopy of tritium β decay by an order of magnitude to 200 meV/c^2 (90% CL). In this contribution we present an overview of the status of the major components of the experimental set-up and report results from first commissioning measurements.

1 Introduction

Neutrino properties, and in particular the open question regarding the scale of neutrino rest masses, bear fundamental relevance to many current research topics in cosmology, theoretical particle physics, and astroparticle physics. Neutrino oscillation experiments, while providing us with a consistent neutrino mixing scheme and accurate measurements of two independent neutrino mass differences, cannot address the absolute mass scale.

Precision cosmology and the search for neutrinoless double beta decay can be used as sensitive probes of neutrino masses. However, these methods rely on multi-parameter cosmological models or on the assumption of neutrinos being of Majorana nature, respectively. By contrast, precision measurements of the kinematics of β decays (^{3}H, ^{187}Re) or electron capture processes (^{163}Ho) allow for a direct, i.e. model independent, neutrino mass search (see [1] for a recent review). The most mature technique relies on the spectroscopy of tritium β decay near its kinematic endpoint at 18.6 keV. Due to the phase space factor, the shape of the β-decay energy spectrum $\mathrm{d}N/\mathrm{d}E$ carries an imprint of the neutrino mass values m_i ($i = 1, 2, 3$):

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto F(Z,E) \cdot p_\mathrm{e} \cdot (E + m_\mathrm{e}) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} |U_\mathrm{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2} \cdot \Theta(E_0 - E - m_i). \quad (1)$$

Here, p_e and E are the electron momentum and energy, the Fermi function $F(Z,E)$ describes the Coulomb interaction of the outgoing electron with the daughter nucleus, and E_0 is the Q-value of the decay. Given the smallness of neutrino mass splittings, typical experimental resolution will not be sufficient to resolve the individual m_i. Hence, the observable is an effective squared "electron type" neutrino mass, $m^2_{\nu,\beta} = \sum_{i=1}^{3} |U_\mathrm{ei}|^2\, m_i^2$, where the U_{ei} denote elements of the PMNS mixing matrix.

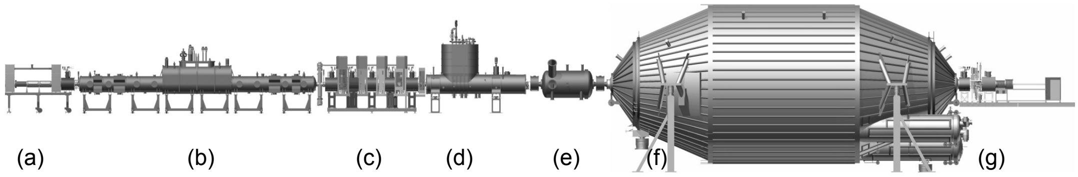

Figure 1: Overview of the KATRIN set-up: (a) calibration and monitoring system, (b) windowless gaseous tritium source, (c) differential and (d) cryogenic pumping sections, (e) pre-spectrometer, (f) main spectrometer, (g) detector system.

The present state of the art of tritium β-decay experiments is defined by electrostatic spectrometers using magnetic adiabatic collimation (MAC-E filters), a technique which allowed two experiments at Mainz and Troitsk to place upper limits on $m_{\nu,\beta}$ at about 2 eV/c^2 [2, 3]. Using the same basic principle, the upcoming KArlsruhe TRItium Neutrino experiment (KATRIN) will push the sensitivity on $m_{\nu,\beta}$ further by an order of magnitude. KATRIN is currently in its construction and commissioning phase at the Karlsruhe Institute of Technology. In the following we review the status of the major components and present results from the initial commissioning runs of the spectrometer and detector section.

2 The KATRIN Experiment

Main components An overview of the KATRIN set-up, spanning about 70 m in length, is presented in Fig. 1. The principal components can be grouped into the tritium-bearing Source and Transport Section (**a**–**d**) and the tritium-free Spectrometer and Detector Section (**e**–**g**).

Source and Transport Section. A high-luminosity windowless gaseous tritium source delivers 10^{11} β-decay electrons per second. The active volume consists of a 10 m long beam tube of 90 mm diameter. Molecular tritium gas is injected at the center and differentially pumped and recycled at both ends. The closed loops of the tritium processing system circulate about 40 g of T_2 per day. A complex cryostat system utilising a novel two-phase neon cooling concept will allow to maintain an extremely stable operating temperature inside the beam tube ($\Delta T <$ 30 mK at $T = 30$ K). Tests of the refrigeration system validated the concept, even surpassing the stringent stability requirement [4]. A comprehensive control and monitoring apparatus has been developed [5] to ensure the stability and to monitor minute fluctuations of the column density – a key parameter of the experiment which critically affects both the statistical accuracy of the measurement and the energy loss of the electrons traversing the source.

Electrons starting in the source are adiabatically guided through the pumping units and towards the spectrometer via a strong magnetic field produced by a chain of superconducting solenoids. The purpose of the successive differential (DPS) and cryogenic (CPS) pumping sections is to reduce the tritium flow rate by a combined factor of 10^{14}, thus preventing tritium from entering the spectrometer section. Manufacturing of both pumping sections is scheduled to be completed in 2015; the five superconducting solenoids of the DPS have already been delivered and are currently being tested on site. Likewise, the assembly of the source cryostat is under way and scheduled to be finished in mid-2015, when all components of the Source and Transport Section will be integrated and subject to a staged commissioning process.

Spectrometer and Detector Section. The KATRIN beam line features a pre-spectrometer to select the upper few 100 eV portion of the tritium β spectrum, and a large, high-resolution main spectrometer ($\Delta E = 0.93$ eV at $E \approx 18.6$ keV). With its length of 23 m, diameter of 10 m and volume of about 1240 m^3, the main spectrometer is one of the largest ultra-high vacuum recipients ever built. The spectrometer vessel has been on site at Karlsruhe since end of 2006. Since then, in a multi-year effort, an elaborate two-layer inner electrode made up of $\sim$ 22,000 wires has been installed inside the main spectrometer, which allows to apply a screening electric potential to shield against cosmics-induced background electrons. After completion of the wire electrode installation, the spectrometer was prepared for UHV conditions by performing a baking cycle at $T \approx 300°$C. The detector system [6], comprising a 148-pixel PIN diode, passive and active background shielding, calibration devices and two superconducting magnets, was installed and commissioned together with the data acquisition unit in 2011-12.

Neutrino mass sensitivity. The aim of improving the neutrino mass sensitivity by a factor 10 demands an improvement by a factor of 100 in the experimental observable $m^2_{\nu,\beta}$ (cf. Eq. 1). It also implies that a background level of 10^{-2} cps is required – similar to what has been achieved at previous, much smaller experiments. KATRIN is expected to reach its full sensitivity potential after 3 net years of measurement (corresponding to about 5 calendar years of running), at which point statistical and systematic uncertainties will contribute about equally to the total measurement uncertainty [7]. At its full sensitivity, KATRIN can discover a neutrino mass as small as 350 meV at 5σ significance, or place an upper limit at 200 meV (90% CL).

3 Results of the first commissioning phase

In summer 2013, an extensive campaign of commissioning runs was conducted, with two major objectives: (a) to test the transmission properties of the main spectrometer, and (b) to investigate the overall background rate and validate the background model based on simulations and on previous tests with the smaller pre-spectrometer. For this measurement programme, a high-definition calibration electron source (small energy spread, angular selectivity, fast-pulse operation; see [9] for a general concept) was attached to one end of the main spectrometer, and the detector system was connected at the opposite side.

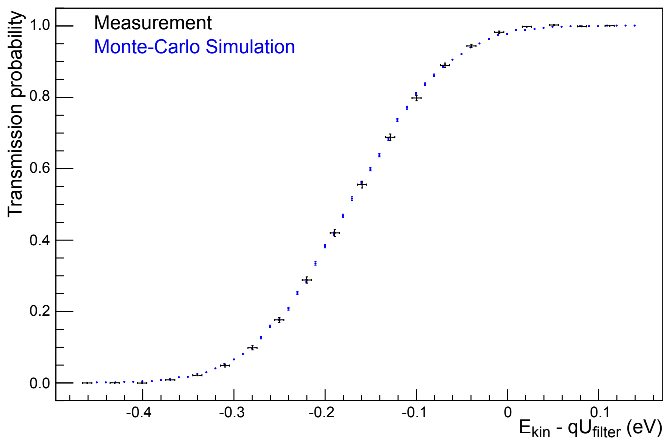

Figure 2: Transmission test of the KATRIN main spectrometer at filter potential $U_{\mathrm{filter}} = 18.6$ kV [8].

These first commissioning measurements successfully validated the design concepts of the KATRIN Spectrometer and Detector section: Firstly, they demonstrated that the main spectrometer indeed acts as a precision MAC-E filter. Figure 2 shows that the shape of the high-pass transmission characteristics is well understood by Monte-Carlo simulations taking into account the small residual energy spread of the calibration electron source. Furthermore, the thorough simulation-optimised electromagnetic design of the main spectrometer paid off, as the spectrometer did not exhibit any signs of elevated background rates caused by Penning trap-type storage conditions. Such effects had plagued previous experiments and also the KATRIN pre-spectrometer in its initial configuration [10]. First investigations regarding background composition have been carried out; in compliance with the expectation from simulation models [11], a considerable portion was found to originate from stored electrons deposited by ^{219}Rn and ^{220}Rn decays in the spectrometer volume. Countermeasures have been implemented successfully [12] and will be tested further in the upcoming second round of commissioning runs, along with additional passive and active background suppression methods.

4 Summary

While components of the Source and Transport Section are still in the construction phase, commissioning of the already completed Spectrometer and Detector Section has commenced. Important concepts employed in the realisation of the experiment have been proven to be successful (e.g., vacuum and precision high-voltage systems, electromagnetic design of the spectrometers). As of fall 2014, a second commissioning campaign is ongoing to investigate details of the transmission characteristics and to test further background reduction mechanisms. Integration of the Source and Transport components into the beam-line are foreseen for 2015, and data-daking with the completed KATRIN set-up is expected to begin in 2016.

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