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KATRIN: Directly Measuring the Neutrino Mass

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The Karlsruhe Tritium Neutrino (KATRIN) experiment aims to measure the neutrino mass using tritium beta decays. It is currently under construction and commissioning at the Karlsruhe Institute of Technology in Karlsruhe, Germany. The use of a high-luminosity, gaseous source and a large, high-precision spectrometer will allow KATRIN to discover a neutrino mass as small as 350 meV, or place an upper limit at 200 meV. The status of the various components of the KATRIN experiment will be described in this report.

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1. Introduction

While neutrino oscillation experiments have successfully shown that neutrinos change flavor, and therefore have non-zero mass, the absolute mass scale remains unknown. Oscillation experiments have accurately measured two independent mass differences between the three known mass states.

So far the data only provide upper limits on the neutrino mass, but experiments continue to probe lower mass ranges. If zero-neutrino double-beta-decay is measured, it can be interpreted as a measurement of neutrino mass, provided that the decay occurs via light neutrino exchange. Neutrino mass limits can be implied from cosmological data, as well, due to the effects of neutrino mass on structure formation in the universe. The third method is using single beta decays. The oscillation data indicate that the neutrino mass measured by beta decay experiments, $m_{\beta\nu} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$, must satisfy either $m_{\beta\nu} > 0.005$ eV or $m_{\beta\nu} > 0.05$ eV, depending on the ordering of the mass states.

The best prospects for directly measuring the mass of the neutrino, and the current limits for such measurements, come from the use of beta decays. The neutrino mass is probed by carefully measuring the energy of the outgoing electron from the decay, as the neutrino mass affects the kinematics of the decay process [1]. The energy spectrum for beta-decay electrons is given in Eq. 1.1:

$$\frac{dN}{dK_e} \propto F(Z, K_e) \cdot p_e \cdot (K_e + m_e) \cdot (E_0 - K_e) \cdot \sum_{i=1}^{3} |U_{ei}|^2 \sqrt{(E_0 - K_e)^2 - m_i^2} \cdot \Theta(E_0 - K_e - m_i). \quad (1.1)$$

The Fermi function, $F(Z, K_e)$, takes into account the Coulomb interactions of the electron with the recoiling nucleus; Z is the proton number of the final-state nucleus, K_e is the electron's kinetic energy, p_e is the electron's momentum, E_0 is the Q-value of the decay, and U_{ei} are the elements of the PMNS matrix for neutrino mass states m_i, $i = 1-3$. The only dependence on the neutrino mass comes from the phase-space factor. It is independent of all other properties of the neutrino, including whether neutrinos are Majorana or Dirac particles.

Two primary techniques have been considered for measuring the neutrino mass with beta decays. Cryogenic bolometers are being employed by the MARE collaboration [2] to measure the heat deposited in the calorimeters by the beta decays of ^{187}Re. The first iteration of the experiment aims to place a limit at the eV level. The follow-up experiment, MARE-II, will reach for the sub-eV level.

The second technique involves the use of a spectrometer to precisely select high-energy electrons from tritium decays. The greatest sensitivity to neutrino mass comes from the electrons nearest the beta-decay endpoint energy, since the daughter nucleus and the neutrino received little kinetic energy in those decays. Therefore, instead of measuring the entire beta-decay energy spectrum, one can best measure the neutrino mass by removing the low-energy electrons, and carefully measuring the energy spectrum near the beta-decay endpoint energy.

A variety of techniques have been used to filter low energy electrons in tritium beta-decay experiments. The best type of filter used so far is called a Magnetic Adiabatic Collimation and Electrostatic (MAC-E) filter. Figure 1 shows the basic setup of a MAC-E filter. Two solenoids produce a magnetic field that guides the beta-decay electrons; the source is contained inside the magnet on the left, and the detector in the magnet on the right. In the region between the solenoids the field strength drops; as the electrons travel through the low-field region, the direction of the electron momentum is adiabatically changed to be parallel to the direction of motion. With all of the electrons traveling in parallel, an electrostatic retarding potential is applied; all electrons with energies below that potential are rejected, and higher-energy electrons proceed through the filter to be counted by the detector. The MAC-E filter acts as a low-pass energy filter, and by varying the electrostatic potential, an integrated measurement of the beta-decay spectrum can be made.

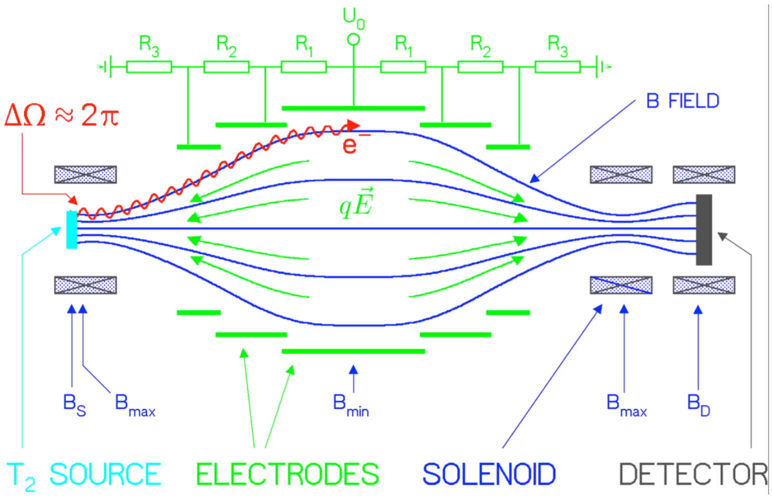

Figure 1: Experimental setup demonstrating the MAC-E filter technique. Figure is from [3].

The most recent experiments to use the MAC-E technique are the Mainz and Troitsk experiments. They placed similar limits on the neutrino mass: $m_{\beta\nu} < 2.3$ eV [4, 5]. A more recent analysis of the Troitsk data lowered that limit to $m_{\beta\nu} < 2.1$ eV [6].

The next-generation experiment is taking advantage of the techniques developed by the Mainz and Troitsk experiments, and aims to lower the sensitivity to the neutrino mass by an order of magnitude. The Karlsruhe Tritium Neutrino (KATRIN) Experiment is currently under construction and commissioning at the Karlsruhe Institute of Technology in Karsruhe, Germany.

The KATRIN experiment, shown in Figure 2 is 70 m long, and consists of seven major subsystems:

- Rear section
- Windowless, gaseous tritium source
- Differential pumping section
- Cryogenic pumping section
- Pre-spectrometer
- Main spectrometer

- Detector system

Electrons are emitted from tritium beta decays in the source section, and travel adiabatically, guided by magnetic field lines through the rest of the experiment. The spectrometers filter low energy electrons, allowing only the electrons near the beta-decay endpoint to reach the detector.

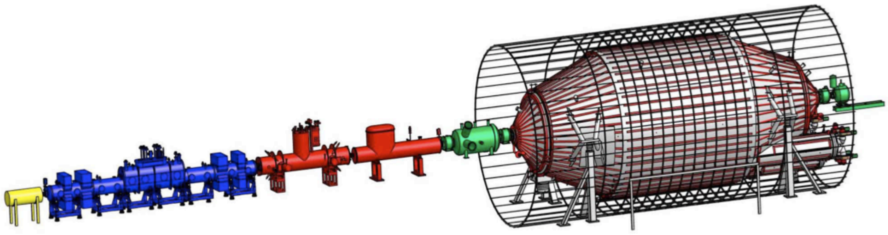

Figure 2: Layout of the KATRIN experiment

Once data-taking begins, the experiment will continue over the course of five years, taking a total of three years of data. The remaining time will be used primarily for calibrations. With that amount of data the statistical and systematic uncertainties will be approximately equal. KATRIN will be able to discover $m_{\beta\nu}$ as low as 350 meV (5σ), or place an upper limit at 200 meV (90% CL).

In the following sections I will describe the major components of the KATRIN experiment (with the exception of the rear section) in more detail and provide updates on current stages of construction and commissioning.

2. Windowless Gaseous Tritium Source

An ideal tritium beta-decay source would provide an enormous number of beta-decay electrons that are able to exit the source adiabatically. The Windowless Gaseous Tritium Source (WGTS) at KATRIN comes as close to that goal as is currently technologically possible. It consists of a cylindrical tube 10 m in length, with a diameter of 90 mm. An axial magnetic field of 3.6 T is produced by a series of seven superconducting solenoid magnets. It will deliver 10^{10} beta-decay electrons per second by circulating 40 g of the T_2 source gas. Figure 3 shows a basic diagram of the WGTS, along with the profile of the gas density inside the beam tube. The gas is injected at the center of the source at a rate of 1.8 mbar l/s. The source must be windowless to allow the electrons to escape; the pumping mechanisms described below are used to remove the tritium gas before it reaches the spectrometers. Tritium purity, another important contribution of source-related systematic uncertainties, will be monitored using laser Raman spectroscopy [7].

The design of the WGTS balances the need for a higher gas density to provide a stronger source with the desire to lower the gas density so that electrons will have a smaller chance of scattering before they leave the source. Furthermore, the density profile of the gas must be well understood to reduce the systematic uncertainty associated with electron energy loss in the gas. To achieve this, the temperature of the gas must be extremely stable, along with having well-measured gas pressures, and injection and pumping rates. The temperature stability is achieved with a complex

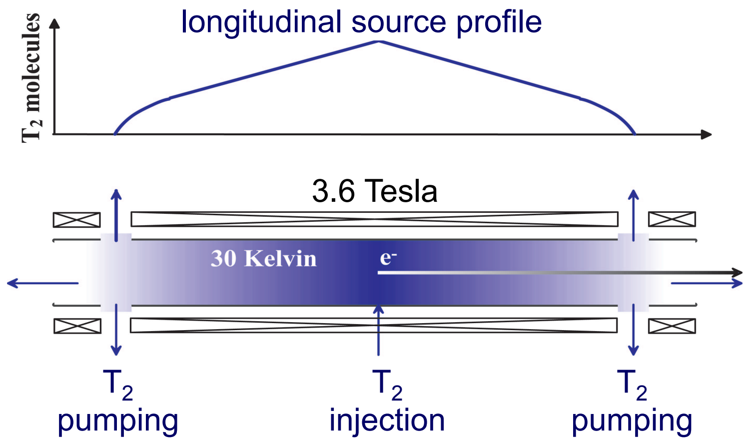

Figure 3: Basic diagram of the Windowless Gaseous Tritium Source. The T_2 gas is injeected in the center and pumped out on both sides. Above the source diagram is a qualitative plot of the source profile at the center of the beam tube.

refrigeration system that maintains an extremely stable beam-tube temperature ($\Delta T < 10$ mK at 30 K). The capabilities of the refrigeration system have already been demonstrated, achieving a stability that surpassed the 10 mK requirement: $\Delta T \sim 3$ mK over the course of 24 hours [8].

Current work on the WGTS includes completing tests on the superconducting magnets and the vacuum systems, and will proceed with the careful assembly of the complete source. Magnet tests were performed at the CEA facility in Saclay, France. They demonstrated the safety of operating the magnets together, and that in the event of a magnet quench the forces between the magnets and the energy dump from the current could be safely handled. Furthermore, they showed that the magnets could be operated stably in driven mode at the specified field strength of 3.6 T. The transition of the source components from their testing and demonstration setups to the final assembly is underway and scheduled to be complete in mid-2015.

3. Tritium Pumping Sections

3.1 Differential Pumping

The first of two T_2 pumping sections is the "Differential" Pumping Section (DPS). Tritium gas is removed by a series of turbo-molecular pumps. The first set of pumps is actually integrated into the WGTS, while a second set is located downstream of the source. At the end of the DPS, the tritium flow rate will have been reduced by a factor of 10^7 [9].

Electrons are transported adiabatically through the DPS following the magnetic field produced by a series of five superconducting solenoids operated at 5.6 T. The beam tube is not straight to prevent neutral atoms or molecules from traveling straight from the source region to the spectrometers.

The DPS recently underwent a major redesign to address a flaw in one of the magnet safety systems and an overall design that made it prohibitively difficult to repair. Components for the new system, including five new superconducting magnets, are under construction. Completion of the DPS is scheduled for the end of 2014.

3.2 Cryogenic Pumping

A second pumping method is used to bring the final residual gas flow rate down by another factor of 10^7: cryogenic pumping [10]. The Cryogenic Pumping Section (CPS) utilizes cryosorption of T_2 molecules onto argon frost that is condensed onto the walls of the beam tube. The beam tube is kept at a temperature of ~ 3 K. The magnetic field used to adiabatically transport the electrons through the CPS is produced by a set of seven superconducting magnets operated at 5.6 T. Assembly of the CPS is progressing well, with most sections of the beam tube and the magnets being assembled. The CPS is on schedule to be ready for use in early 2015.

4. Spectrometers

The pre- and main spectrometers provide the energy analysis for the beta decay electrons. Both spectrometers utilize the MAC-E filtering technique described above to remove low-energy electrons.

4.1 Pre-Spectrometer

The pre-spectrometer is responsible for reducing the electron flux from 10^{10} s^{-1} to 10^3 s^{-1}. It will be set at a fixed electrostatic potential of -18.3 kV, filtering out electrons with energies less than 18.3 keV.

The pre-spectrometer was initially used as a test-bed for the techniques used to build an operate the main spectrometer. An electron gun was placed at one end of the spectrometer, and a silicon detector at the other end, as is shown in Figure 4. A variety tests were performed, and the lessons learned were critical for the future success of the experiment:

- Vacuum tests showed that it was possible to routinely pump down a large vessel to the required 10^{-11} mbar ultra-high-vacuum level.
- The end-cap electrode design was finalized by testing a variety of geometries to minimize electrostatic discharges and the formation of Penning traps.
- It was found that radon emanating from the non-evaporable getter material used to maintain the ultra-high vacuum caused a significant increase in trapped electrons [11]. A method for suppressing this background (cryogenic baffles in front of the getter material) was developed and tested using the test setup.
- Various active methods for removing trapped electrons were tested, including the formation of a dipole electric field within the spectrometer that forces trapped electrons out of the magnetic bottle formed by the two solenoid magnets, and into the walls of the spectrometer.

Overall the tests made with the pre-spectrometer were a remarkable success. The spectrometer itself is currently awaiting integration with the main spectrometer when main spectrometer commissioning is complete.

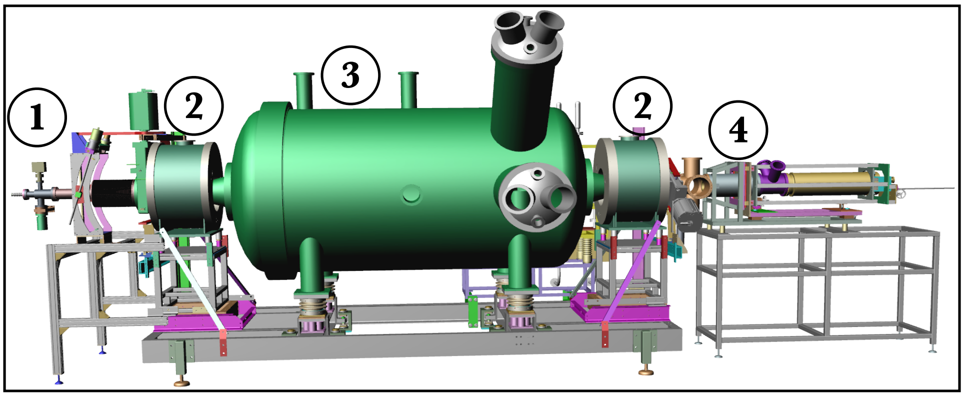

Figure 4: The pre-spectrometer test setup. 1: electron gun; 2: superconducting magnets; 3: pre-spectrometer vessel; 4: detector.

4.2 Main Spectrometer

KATRIN's main spectrometer is responsible for the ultra-precise final energy analysis of the electrons that get through the pre-spectrometer. The electron rate after the main spectrometer will be approximately 1 s^{-1}. The spectrometer itself is 10 m in diameter, and 23 m long; with a volume of 1240 m^3 and an operational pressure of 10^{-11} mbar, it is one of the largest ultra-high-vacuum chambers ever built. The vacuum level is necessary to reduce the systematic uncertainty associated with electrons scattering on residual gas molecules. The electrostatic potential of the main spectrometer can be varied near the beta-decay endpoint, and will filter out low-energy electrons with a resolution of $\Delta E = 0.93$ eV at $E \approx 18.6$ keV. A complex, two-layer wire electrode system lines the inside wall of the spectrometer. These electrodes are intended to be held at electric potentials slightly higher than the spectrometer itself to reject electrons knocked off the wall by cosmic rays.

The main spectrometer has successfully met a number of recent milestones. The inner wire electrode was completed in January 2012. Lessons learned from the pre-spectrometer test setup were incorporated into the main spectrometer, including the end-cap electrode design, and the cryogenic baffles in front of the non-evaporable getter pumps. Baking and vacuum tests were performed, successfully reaching the ultra-high vacuum levels required for the experiment. Unfortunately, in the course of vacuum bake-out, electrical shorts formed in several places between the two layers of wire electrodes; no wires were broken, fortunately, but the wire-electrode system can currently only be run at a single potential. The consequences to the experiment and plans for fixing the problem are currently under investigation. Between April and October 2013 a variety of commissioning measurements will be performed on the main spectrometer, providing a much-improved understanding of its performance.

5. Detector

The purpose of the detector system is to count the electrons that get through the main spectrometer; as the electrostatic potential of the main spectrometer is varied, an integrated measurement of the electron energy spectrum can be made. The detector section of KATRIN primarily consists of the detector itself, which is a 148-pixel silicon PIN diode detector, and two solenoid magnets, one forming the downstream-end of the main-spectrometer MAC-E filter, and the second focusing the electron flux onto the detector. Cosmic rays are shielded with layers of lead and copper surrounding the detector, and vetoed with a set of plastic-scintillator panels. The detector section had a successful initial commissioning, and is being used for commissioning measurements made with the main spectrometer. It will be upgraded in late 2013, and is scheduled for the next round of commissioning in 2014.

6. Summary

Significant progress has been made recently on all components of the KATRIN experiment. Some components, including the full tritium source and the differential and cryogenic pumping sections, are currently under construction, while the spectrometers and the detector section have been are are undergoing commissioning measurements. The experiment is scheduled to begin taking data in 2015. Funding for KATRIN is provided by the Helmholtz Gemeinschaft, the Bundesministerium für Bildung und Forschung, and the US Department of Energy, Office of Nuclear Physics.

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