The KATRIN Neutrino Mass Experiment

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The Karlsruhe Tritium Neutrino experiment (KATRIN) aims to measure the mass of electron neutrinos from beta-decay of tritium with an unprecedented sensitivity of $0.2 \, \text{eV}/c^2$ improving present limits by one order of magnitude. The decay electrons will originate from a 10 m long windowless, gaseous tritium source. Superconducting magnets guide the electrons through differential and cryogenic pumping sections to the electro-static tandem spectrometer (MAC-E-filter), where the kinetic energy will be measured. The experiment is presently being built at the Forschungszentrum Karlsruhe by an international collaboration of more than 120 scientists. The largest component, the 1240 m$^3$ main spectrometer, was delivered end of 2006 and first commissioning tests have been performed. This presentation describes the goals and technological challenges of the experiment and reports on the progress in commissioning first major components. The start of first measurements is expected in 2012.

1. Introduction

The Standard Model of particle physics describes neutrinos as massless, neutral fermions, which can be detected only via weak interactions. The observations of neutrino flavour oscillation [1] indicate the existence of massive neutrinos. Since experiments investigating these neutrino oscillations are only sensitive to differences of the square of mass eigenvalues $\Delta m^2_{ij} = |m^2(\nu_i) - m^2(\nu_j)|$ and not to the absolute values, the scale and hierarchy of neutrino masses are not determined yet. An identification of the mass scheme realized in nature would not only solve the puzzle of absolute neutrino masses but could also point to the mechanisms of mass generation in extensions of the Standard Model.

In standard cosmological models, our universe is filled with primordial neutrinos arising from freeze-out in the early universe. These neutrinos are natural candidates for non-baryonic hot dark matter. Depending on the actual neutrino mass, the neutrino content of the universe can exceed the baryonic mass density.

The above arguments demonstrate the importance of the absolute neutrino mass scale for both particle physics and cosmology. A model-independent approach to determine the neutrino mass is the kinematical analysis of electrons from radioactive $\beta$ decay near the endpoint energy $E_0$. A non-vanishing neutrino mass reduces the electron endpoint energy and distorts the shape of the electron spectrum in the vicinity of $E_0 - m(\nu)$.

2. KATRIN Experiment

The scheme of a measurement investigating the endpoint region of the electron energy spectrum from tritium $\beta$ decay ($^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$) with an electrostatic filter is illustrated in figure 1.

Electrons emitted by $\beta$ decay in the source are guided magnetically through the electrostatic retarding potential of the spectrometer, to be counted by a segmented silicon detector. This magnetic adiabatic collimation followed by the electrostatic (MAC-E) filter represents an integrating high pass filter for $\beta$-electrons. This technique has been used in the Mainz and Troitsk experiments with different tritium sources, providing the most stringent, model-independent limits on the neutrino mass so far, with ($2, 3, 4, 5$)

$m(\nu_e) < 2.2 \, \text{eV}/c^2$ (95\% C.L.$^1$).

With well understood systematic effects, both experiments have now reached their sensitivity limits. The energy resolution of a MAC-E-filter depends on the ratio of the strongest magnetic field $B_{\text{max}}$ in the beam-line and the

\[ m(\nu_e) < 2.2 \, \text{eV}/c^2 \, (95\% \, \text{C.L.}) \]

\[ 1 \text{Confidence Limit} \]
weakest field $B_{\text{min}}$ in the centre of the spectrometer. Flux conservation requires that $B \cdot A$ remains constant, where $A$ is the cross section of the magnetic flux tube, guiding the electrons from the source to the detector. Improving the energy resolution of such an experiment needs a much lower $B_{\text{min}}$ and therefore a spectrometer with a much larger cross section, which will be able to contain the magnetic flux. An improved sensitivity requires not just size, but also a stronger source with higher statistics and a better understanding of systematic uncertainties.

The KArlsruhe TRItium Neutrino (KATRIN) experiment will use the techniques developed in Mainz and Troitsk with a strong gaseous molecular tritium source and an electro-static filter of unprecedented energy resolution ($\Delta E < 0.93 \, \text{eV}$ [6]). The expected sensitivity for the neutrino mass will be $0.2 \, \text{eV}/c^2$ after three years of measurement. As the experimental observable is $m^2_{\nu_e}$, an improvement in sensitivity on $m(\nu_e)$ of one order of magnitude corresponds to an improvement of a factor $\approx 100$ in accuracy on $m^2_{\nu_e}$ leading to numerous technical challenges for this experiment. Figure 2 outlines the experimental set-up of KATRIN [7], which adds up to a total length of about 70 m.

Figure 2: Katrin overview: a) tritium source (WGTS), b) differential pumping (DPS) and cryo-pumping section (CPS), c) pre-spectrometer and main spectrometer, d) detector.

The KATRIN experiment is currently under construction at Forschungszentrum Karlsruhe (FZK), Germany. With the Tritium Laboratory Karlsruhe (TLK), a unique lab is available on site, which will house the complete tritium inventory, including the source and transport section. First components such as the pre-spectrometer (2003), main spectrometer (2006), some magnets and a prototype detector array are on site, being thoroughly tested. The experiment is now in the construction and commissioning phase. First measurements are expected to start in 2012, with a total measuring time of 5 years.
2.1. Source and Transport Section

The source and transport section includes the windowless gaseous tritium source (WGTS), followed by differential pumping sections (DPS) and a cryogenic pumping section (CPS). The beam tubes inside the super-conducting solenoids have a diameter between 75 mm and 90 mm, interspersed with pump ports for turbo-molecular pumps (TMP). These pumps are integrated in the closed loop tritium circulation system. The pressure inside the vacuum beam-line will range from $3.4 \times 10^{-3}$ mbar at the source to less than $10^{-11}$ mbar in the spectrometer section.

2.1.1. Windowless Gaseous Tritium Source

The WGTS will be the standard $\beta$-electron source for long-term tritium measurements. Ultra-cold molecular tritium gas ($T = 27 K \pm 30 mK$) will be injected through a set of capillaries at the centre of the 10 m long WGTS tube with an injection pressure of $p_{in} = 3.4 \times 10^{-3}$ mbar and a flow rate of about $1.8 \text{ mbar} l/s$ ($40 g(T_2)/\text{day}$). The density profile of the gas inside the beam-tube has to be kept stable on the $10^{-3}$ level. The stability depends on a constant beam-tube temperature and inlet pressure in the WGTS. Maintaining these conditions is a very challenging task, and the technical feasibility will be demonstrated with the partly assembled WGTS in 2009.

After injection the $T_2$ molecules will be transported by diffusion over a length of 5 m to both ends of the source tube, where most of the tritium will be pumped out by TMPs of the first stage of the differential pumping section. This process leads to an almost linear decrease of the tritium number density $B$. Electrons from $\beta$-decays will be guided adiabatically by a magnetic field of $B_S = 3.6 T$.

2.1.2. Tritium Pumping System

The background generated by tritium decay within the spectrometers must be less than $10^{-3}$ counts/s, which limits the amount of tritium permissible in the main spectrometer to a partial pressure of about $10^{-20}$ mbar. With a pumping speed of $10^6 l/s$ this leads to a maximum allowed tritium flow rate into the spectrometer section in the order of $10^{-14} \text{ mbar} l/s$. This very large suppression factor will be achieved in two stages, based on a combination of differential (DPS) and cryogenic (CPS) pumping sections, with each stage providing a suppression factor in the order of $10^{-7}$.

The first part of the tritium flow suppression is based on differential pumping $[9,10,11]$. Along the beam-line turbo-molecular pumps with high pumping speed reduce the tritium flow both at the rear and front ends of the source. As the DPS elements adjacent to the WGTS (DPS1-F, DPS1-R) influence the stability of the gas flow in the source, they have to be operated under almost identical conditions as the WGTS. Therefore these first DPS sections are included in the source cryostat. The TMPs have to be operated close to the beam-line, in order to minimize conductance losses. Due to the strong magnets extensive tests have been made to investigate the behaviour of TMPs in magnetic fields.

The differential pumping system will reduce the tritium flow into the subsequent passive cryo-trapping system (CPS) to $10^{-7} \text{ mbar} l/s$ (at 273 K). The CPS will reduce the tritium flow by another 7 orders of magnitude, allowing only a remaining flow below $10^{-14} \text{ mbar} l/s$ into the pre-spectrometer. During a normal measuring period of 60 days a total amount of about 0.5 $\text{mbar} l$ of tritium molecules can be accumulated in the CPS, corresponding to an activity of 1 Ci$^2$. The beam-tube of the CPS will be kept at a temperature of 4.5 K. At this temperature tritium molecules are passively adsorbed on the wall. To enhance the trapping probability, the cold surfaces of the CPS beam-tubes will be covered by a thin layer of argon frost. The main advantage of a condensed gas layer, compared to a solid adsorbent like charcoal, lies in the easy removal of both the adsorbent and the adsorbed tritium, thus minimizing the residual tritium contamination of the beam-tube. After each measuring period the CPS will be re-heated and the tritium gas will be returned to the closed tritium cycle.

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$^2$The half-life of tritium is 12.3 a
Although data on hydrogen and deuterium adsorption on condensed gases are available, no data on tritium adsorption were found. The effect of electron stimulated desorption from tritium $\beta$-decay on the migration of tritium molecules along the cryo-sorption pump of the CPS beam-tube and the influence on the suppression factor have been investigated in Monte Carlo simulations. In order to experimentally explore the adsorption properties of condensed argon for tritium, the test experiment TRAP\(^4\) has been set up by the KATRIN collaboration and first results have been published for deuterium and tritium, confirming the CPS design values.

All three major components of the source and transport section are expected to be delivered between 2009 (DPS) and 2011 (WGTS and CPS). After commissioning tests of each components they will be connected to the spectrometer section. The source is expected to provide first tritium electrons to be analysed in the spectrometer early 2012.

### 2.2. Tandem Spectrometer and Detector

The central part of the experiment will be the tandem spectrometer section. It consists of two electrostatic spectrometers of MAC-E-Filter type: the pre-spectrometer, allowing only electrons with the highest energies to pass into the main spectrometer, where their kinetic energy will be analysed with a resolution of 0.93 eV. The high energy resolution of the main spectrometer requires large dimensions (see fig. 3). It has a diameter of 10 m, an overall length of 23.4 m, a surface area of 690 m\(^2\) and a volume of 1240 m\(^3\). The pre-spectrometer with a diameter of 1.7 m, a length of 3.4 m, a surface of 25 m\(^2\) and a volume of 8.5 m\(^3\) served as a prototype for the design of the main spectrometer. It demonstrated the scalability of the vacuum layout and the reliability of the large 1.7 m flange design at all temperatures.

![Figure 3: Left: in November 2006 the main spectrometer vessel (200 t) arrived at FZK after a 9000 km long journey. Right: a custom made adjustable cleanroom scaffolding has been set up inside the spectrometer to install the wire electrodes on the inner wall.](image)

During standard operation very good UHV conditions of $p < 10^{-11}$ mbar have to be maintained in both spectrometer vessels at room temperature in order to keep a low background rate. The vacuum systems are based on a combination of cascaded turbo-molecular pumps (TMP) and NEG-pumps made of double-coated 30 mm wide Zr-V-Fe getter strips\(^4\). Both vessels are made of electro-polished stainless steel (316LN). Hydrogen outgassing from the walls is expected to be the main source of gas, which limits the final pressure in each vessel. The surface of each vacuum vessel can be baked at temperatures up to 350°C for reduction of outgassing and activation of the

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\(^4\)TRitium Argon frost Pump
\(^4\)SAES St707\(^6\) non-evaporable getter strips
NEG-pumps. The temperature of the walls is controlled by heat-transfer oil pumped through a system of stainless steel pipes, welded to the surface of each vessel.

The pre-spectrometer vacuum measurements showed in 2004, that a hydrogen outgassing rate of $10^{-12}$ mbar l/s cm$^2$ can be reached with 316LN stainless steel, using standard manufacturing procedures [18]. The cleaning process after manufacturing included pickling, electro-polishing and rinsing with de-ionized water. Based on this measured outgassing rate the main spectrometer requires a total pumping speed of $10^6$ l/s, which will be provided by 3000 m of NEG strips [19],[20].

For the main spectrometer similar production methods and cleaning procedures were used. During manufacturing a large workshop hall was reserved for KATRIN. Before manufacturing started the floor was coated and the whole hall was cleaned. The distance between the manufacturer and FZK is about 400 km. Due to the large size of the main spectrometer, it had to be shipped on a river barge down the river Danube to the black sea, around Europe and up the river Rhine on a 9000 km detour (see fig.3 left). After delivery and installation of the heating and vacuum systems in first commissioning tests in 2007 confirmed an outgassing rate of $10^{-12}$ mbar l/s cm$^2$, as expected from pre-spectrometer measurements.

The electrostatic field will be generated by connecting the outer wall of each spectrometer to high voltage ($-18.6$ kV). The field will be fine-tuned by an inner electrode system, made of very thin stainless steel wires. Both pre-spectrometer and main spectrometer have large, metal-sealed vacuum flanges (diameter: 1.7 m), which allow to enter the vessel for installation of the inner electrode system. The beam-tubes end in cone-shaped ground electrodes, which are attached to the vacuum vessels via conical ceramic insulators. The shape of the inner electrodes have been calculated in extensive Monte Carlo simulations and tested with the pre-spectrometer. A lot of effort went into the investigation of penning traps in the $\vec{E}x\vec{B}$ fields, which can lead to a strong increase of background rates. Currently the pre-spectrometer is used to optimize the electrode design.

The electrode system of the main spectrometer consists of 248 individual wire electrode frames with a total of 23120 stainless steel wires, with each wire electrically insulated against the frame. These electrodes are presently produced at the university Münster. At the same time preparations have been started to install these electrodes inside the main spectrometer under cleanroom conditions (see fig.3 right). The electrodes will be installed in 2009.

Another challenge is the high voltage system of the spectrometer. The variable retarding voltage has to be known with ppm accuracy. Since no known commercially available precision high voltage divider meets this requirement, a unique voltage divider with an appropriate stability has been developed at the university Münster together with PTB Braunschweig. Together with this high voltage system the electro-magnetic properties of the spectrometer will be investigated in an intensive test programme, which also includes the segmented silicon detector, currently being built at the university of Washington in Seattle.

3. Conclusions

The KATRIN experiment has ambitious goals, both in particle physics and in the technical realization of the experimental set-up. Currently all major components are either under construction or have already been delivered to FZK. First vacuum measurements with the large main spectrometer vessel indicate an outgassing behaviour, which agrees well with results from earlier measurements with the much smaller pre-spectrometer. After installing the final vacuum system, we expect to reach the required pressure of $p < 10^{-11}$ mbar in the spectrometer section. Other components of the experiment face different challenges, like the DPS, where TMPs have to be operated close to super-conducting solenoids or the WGTS with its stringent requirements on stability of temperature and pressure.

The next step will be the installation of the inner electrode system of the main spectrometer in 2009 an a test of its energy resolution. After delivery and test of all components we expect first tritium measurements in 2012.

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