The neutrino mass experiment KATRIN

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Abstract. The KArlsruhe TRItium Neutrino (KATRIN) experiment is a large-scale experiment with the objective to determine the effective electron anti-neutrino mass with an unprecedented sensitivity of 0.2 eV/c^2 at 90% C.L. in a model-independent way. The measurement method is based on precision β-decay spectroscopy of molecular tritium. The experimental setup consists of a high luminosity windowless gaseous tritium source, a magnetic electron transport system with differential and cryogenic pumping for tritium retention, and an electro-static spectrometer section for energy analysis, followed by a segmented detector system for counting transmitted β-electrons. The experiment was constructed at the Karlsruhe Institute of Technology in Germany and is currently in the final commissioning phase before the commencement of tritium operation.

This proceedings will give an overview of the KATRIN experiment and its current status. Furthermore, initial results of recent commissioning measurements of the completed KATRIN beamline will be presented.

1. Introduction

The absolute neutrino mass scale is one of the big open questions in particle physics, astrophysics and cosmology. Cosmological observations and neutrinoless double beta decay experiments provide an indirect access to the absolute neutrino mass scale, but are model-dependent. A model independent, direct approach to determine the neutrino mass is the precise investigation of weak decays such as β-decay.

In nuclear β-decay a neutron in the atomic nucleus decays into a proton, thereby emitting an electron (e^-) and an electron anti-neutrino ($\overline{\nu}_e$). The energy released in the decay is divided between the e^- and $\overline{\nu}_e$ in a statistical way. The energy spectra of the electron is given by the well known Fermi theory of β-decay [1]:

$$\frac{dN}{dE} \propto p(E + m_e c^2)(E_0 - E)\sqrt{(E_0 - E)^2 - m_{\overline{\nu}_e}^2 c^4} \qquad (1)$$

with the the electron energy E, the endpoint energy E_0, the electron mass m_e and the effective electron anti-neutrino mass $m_{\overline{\nu}_e}^2 = \sum |U_{ei}|^2\ m(\nu_i)^2$. This is the incoherent sum of neutrino mass eigenstates and therefore not sensitive to phases of the neutrino mixing matrix (in contrast to neutrinoless double β-decay). As one can see in equation 1, it is the square of the neutrino mass $m_{\overline{\nu}_e}^2$ that enters as a parameter. Its effect on the shape of the spectrum is significant only in a very narrow region close to E_0. The current upper limit on the neutrino mass of 2 eV/c^2 [2] was determined from investigating the tritium β-spectrum near the endpoint of 18.6 keV by experiments in Mainz [3] and Troitsk [4].

2. The KATRIN experiment

The **KA**rlsruhe **TRI**tium **N**eutrino (KATRIN) experiment [5] is a next generation, large scale experiment to determine the effective mass of the electron anti-neutrino by investigating the kinematics of tritium beta decay with a sensitivity of 0.2 eV/c^2. The experiment is located at the Karlsruhe Institute of Technology (KIT) in Germany. The measurement setup (see figure 1) has an overall length of ≈ 70 m. Molecular tritium is injected into the windowless gaseous tritium source (**b**) where it decays with an activity of 10^{11} Bq, thus providing a sufficient number of β-decay electrons close to the endpoint energy E_0. The activity of the source is monitored at the rear section (**a**). The tritium is removed from the beamline in the differential pumping section (**c**) and the cryogenic pumping section (**d**) while electrons from the source are magnetically guided towards the spectrometer section. Both pre-spectrometer and main spectrometer are operated as electrostatic retarding high pass filters of MAC-E filter type [6]. The pre-spectrometer (**e**) is operated as a pre-filter in order to reduce the flux of electrons into the main spectrometer (**f**) which performs the energy analysis of the β-decay electrons near the endpoint with an energy resolution of $\Delta E = 0.93$ eV at 18.6 keV. The main spectrometer is equipped with a dual layer wire electrode system for electrostatically shielding secondary electrons from the inner vessel surface and for fine-tuning of the retarding potential. The transmitted β-decay electrons are counted in the detector system (**g**) with a segmented silicon detector [7].
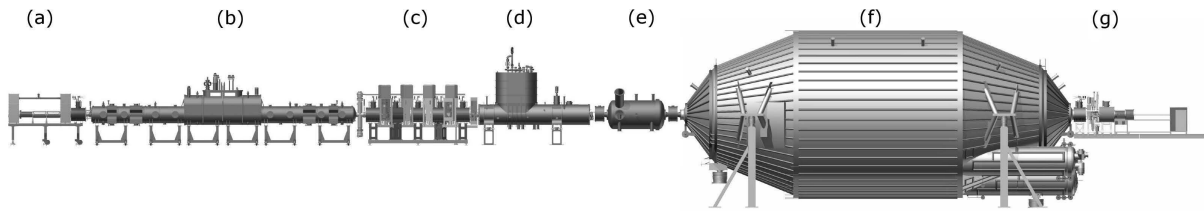

Figure 1. The KATRIN experimental setup with its main components: (a) rear section; (b) windowless gaseous tritium source (WGTS); (c) differential pumping section (DPS); (d) cryogenic pumping section (CPS); (e) pre-spectrometer; (f) main spectrometer; (g) focal plane detector.

2.1. Windowless gaseous tritium source

The Windowless gaseous tritium source (WGTS) consists of a 10 m long tube with a diameter of 90 mm and is operated at a temperature of about 30 K by circulation of two phase neon. Molecular tritium (T_2) is injected into the center of the source tube and decays with an activity of 10^{11} Bq to provide a sufficient number of electrons close to the tritium endpoint energy E_0. The β-electrons are guided via an axial magnetic field of up to 3.6 T towards the spectrometer section. The T_2 is collected via turbo-molecular pumps at both ends of the WGTS and is recirculated via an "inner loop" which removes contaminants (particularly ^{3}He) and is capable to process 40 g of T_2 per day. A prototype system to investigate the performance of the temperature stabilization of the beam tube showed that the stringent thermal performance specifications (temperature stability ± 30 mK) could be met and a factor of twenty better temperature stability was achieved [8]. The WGTS was delivered to KIT in September 2015 and integrated into the KATRIN beam line. The magnet system was successfully tested to maximum field. Initial tests of the temperature stabilization confirmed the better than specified performance already observed at the prototype system.

2.2. Differential and cryogenic pumping section

The task of the Differential Pumping Section (DPS) is to reduce the T_2 partial pressure by a factor of $>10^5$ and to guide β-electrons via a strong magnetic field of up to 5.6 T. The beam tube has four bends to avoid beaming of T_2 molecules towards the spectrometers. In order to remove tritium ions, the DPS is equipped with electric dipole electrodes. The magnet system was successfully commissioned and the installation of the beam tube is complete.

Any remaining T_2 that passes the DPS is trapped in the Cryogenic Pumping Section (CPS) by argon frost frozen on the 4 K cold beam tube. The argon frost forms a highly efficient, large-area and radiation-immune surface. The feasibility of this approach was successfully tested in a test experiment called TRAP [9] which achieved a T_2 reduction factor of about 10^7. The CPS was delivered to KIT in July 2015 and was successfully cooled to the operational temperature of about 4 K. Simulations based on the performance of the initial cool-down indicate that the T_2 reduction factor could be two or more orders of magnitude better than specified.

2.3. Spectrometer section

The pre-spectrometer, as well as the main spectrometer, are electrostatic retarding potential spectrometers of MAC-E filter type [6] (**M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter).

The pre-spectrometer is intended to be used as a pre-filter on a potential a few hundred volts below E_0. The pre-filtering reduces the flux of β-electrons into the main spectrometer by many orders of magnitude and minimizes β-electron induced background processes in the main spectrometer.

The purpose of the 10 m in diameter and 24 m long main spectrometer is to analyze the energy of the β-decay electrons. It has an energy resolution of 0.93 eV at 18.6 keV. In order to reduce the spectrometer background rate, a double layer inner electrode system made of thin wires - mounted with submillimeter precision - is installed. The wire layers are put on a more negative potential with respect to the tank voltage in order to shield secondary electrons produced in the vessel wall. The absolute voltage of -18.6 kV needs to be stable on the 1 ppm level and is monitored with a high precision voltage divider and an independent monitoring and calibration beam line [10]. The vacuum system of the main spectrometer is capable of reaching a pressure of about 10^{-10} mbar with one active non-evaporable getter pump [11]. After a recent baking of the spectrometer, a second getter pump was activated and a pressure on the order of 10^{-11} mbar was achieved inside the main spectrometer.

2.4. Detector

Electrons that are able to overcome the potential barriers of the spectrometers are detected in a monolithic 148 pixel silicon PIN diode [7]. The energy resolution of the detector system is 1.4 keV (FWHM). Selection of materials, shielding and an active veto are used to keep the intrinsic detector background at a low level of 1.2 mcps/keV.

3. KATRIN beamline commissioning measurements

After completion of the KATRIN beamline in October 2016, a series of commissioning measurements was performed. The first campaign was part of the KATRIN "first light" and focused on electron transport and alignment of the beamline. For a second campaign, gaseous krypton (^{83m}Kr) was injected into the source tube in order to perform high-resolution spectroscopy of the well-known krypton conversion electrons.

3.1. First light measurements

On October 14th, 2016 the KATRIN experiment celebrated its "first light": for the first time electrons were transmitted along the complete beamline, from the rear section to the detector.

The electrons were produced via photoelectric effect due to UV irradiation of a gold-plated rear wall at the upstream end of the WGTS beam tube. A voltage of typically -100 V was applied to the rear wall in order to accelerate the electrons towards the detector. A major result of these measurements was that the 191 Tcm^2 magnetic flux tube, which will be used for the neutrino mass measurements, is transported unobstructed along the complete beamline. Corresponding electro-magnetic tracking simulations of electrons using Kassiopeia [12] show a good agreement with the observed pixel patterns at the detector, confirming that the beamline alignment is well understood.

3.2. Krypton measurements

A dedicated measurement campaign with ^{83m}Kr was performed in July 2017 in order to test the KATRIN apparatus prior to the injection of tritium. There are several advantages of using ^{83m}Kr. It has a short half life (1.83 h), which eliminates the risk of permanent contamination. The electron emission is isotropic, which is important for probing the characteristics of the MAC-E filter. There are many narrow conversion electron lines between 7 and 32 keV, with natural line widths comparable to the typical energy resolution of the main spectrometer. Of particular interest for KATRIN is the K-32 line at 17.8 keV which is very close to the tritium endpoint energy.
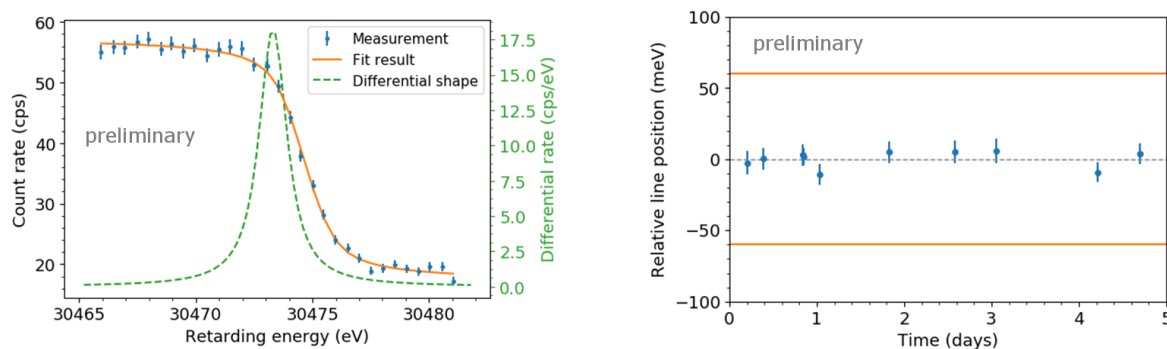

Figure 2. left: L$_3$-32 line scan. The differential shape was reconstructed from the fit. The natural Lorentzian width is about 1.4 eV, the spectrometer energy resolution about 2 eV. **right:** Line position for repeated L$_3$-32 line scans, the horizontal orange lines indicate the KATRIN stability goal of ±60 meV.

^{83m}Kr, emanating form a 1 GBq ^{83}Rb source, was injected in the WGTS beam tube and cryogenically pumped by the CPS. Conversion electrons produced by the decay of ^{83m}Kr in the beamline volume of WGTS and DPS were magnetically guided to the main spectrometer. Integrated energy spectra of the conversion electrons were measured by changing the spectrometer voltage in small increments (typically 0.2 to 0.5 V), see left plot in figure 2 for an example L$_3$-32 line scan. The differential spectrum is obtained from a fit to the integrated spectrum. The relative line position as a function of time, for repeated L$_3$-32 line scans, is shown in the right plot of figure 2. The stability of the line position is well within the KATRIN goal of ±60 meV.

4. Conclusions

Direct neutrino mass measurements are a model independent way to determine the neutrino mass. A major improvement of the neutrino mass sensitivity by one order of magnitude is expected of the KATRIN experiment, which completed construction and is currently in the final commissioning phase. Commissioning measurements with the complete beamline showed that

the system is well aligned. ^{83m}Kr was injected in the WGTS as a benchmark isotope to test the overall functionality of the apparatus. The official KATRIN inauguration is scheduled for June 11th, 2018.

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