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THE NEUTRINO MASS EXPERIMENT KATRIN

The KArlsruhe TRItium Neutrino (KATRIN) experiment is a large-scale experiment with the objective to determine the effective electron antineutrino mass in a model-independent way with an unprecedented sensitivity of 0.2 eV/c^2 at 90% C.L. The measurement method is based on the 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 cryogenic pumping for the tritium retention, and an electrostatic spectrometer section for the energy analysis, followed by a segmented detector system for the counting of transmitted β-electrons. The first KATRIN neutrino mass measurement phase started in March 2019. Here, we will give an overview of the KATRIN experiment and its current status.

K e y w o r d s: neutrino mass, tritium β-decay, spectrometers.

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 β-decay experiments provide an indirect access to the absolute neutrino mass scale, but are model-dependent. A model-independent direct method to determine the neutrino mass is the precise investigation of weak decays such as the β-decay.

In the nuclear β-decay, the neutron in an atomic nucleus decays into a proton, thereby emitting an electron (e^-) and an electron antineutrino ($\overline{\nu}_e$). 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]:

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

with the electron energy E, the endpoint energy E_0, the electron mass m_e, and the effective electron antineutrino mass $m_{\overline{\nu}_e}^2 = \sum |U_{ei}|^2 \ m(\nu_i)^2$. This is the incoherent sum of neutrino mass eigenstates and is therefore insensitive to the phases of the neutrino mixing matrix (in contrast to the neutrinoless double β-decay). As one can see in Eq. 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 the experiments in Mainz [3] and Troitsk [4].

2. 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 an electron antineutrino by investigating the tritium β-decay kinematics with a sensitivity of 0.2 eV/c^2. The experiment was executed at the Karlsruhe Institute of Technology (KIT) in Germany. The measurement setup (see Figure 1) has an overall length of $\approx$ 70 m. Molecular tritium is injected into a 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). 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 toward the spectrometer section. Both a pre-spectrometer and a main spectrometer are operated as electrostatic retarding high

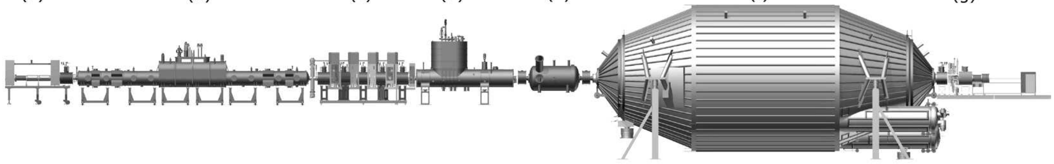

Fig. 1. The KATRIN experimental setup with its main components: rear section (*a*); windowless gaseous tritium source (WGTS) (*b*); differential pumping section (DPS) (*c*); cryogenic pumping section (CPS) (*d*); pre-spectrometer; (*f*) main spectrometer (*e*); focal plane detector (*g*)

pass filters of the MAC-E filter (**M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic 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 the energy resolution $\Delta E = 0.93$ 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 the fine-tuning of a retarding potential. The transmitted β-decay electrons are counted in the detector system (*g*) with a segmented silicon detector [7].

2.1. Windowless gaseous tritium source

The windowless gaseous tritium source (WGTS) consists of a 10 m long tube 90 mm in diameter and is operated at a temperature of about 30 K by the 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 toward the spectrometer section. 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 a beam tube showed that the stringent thermal performance specifications (temperature stability ±30 mK) could be met, and the temperature stability better by a factor of twenty 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 the maximum field. Initial tests of the temperature stabilization confirmed the performance better than the specified one already observed at the prototype system.

2.2. Differential 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 the beaming of T_2 molecules toward 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 spectrometer section consists of two spectrometers of the MAC-E filter type: a pre-spectrometer and a much larger main spectrometer.

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.

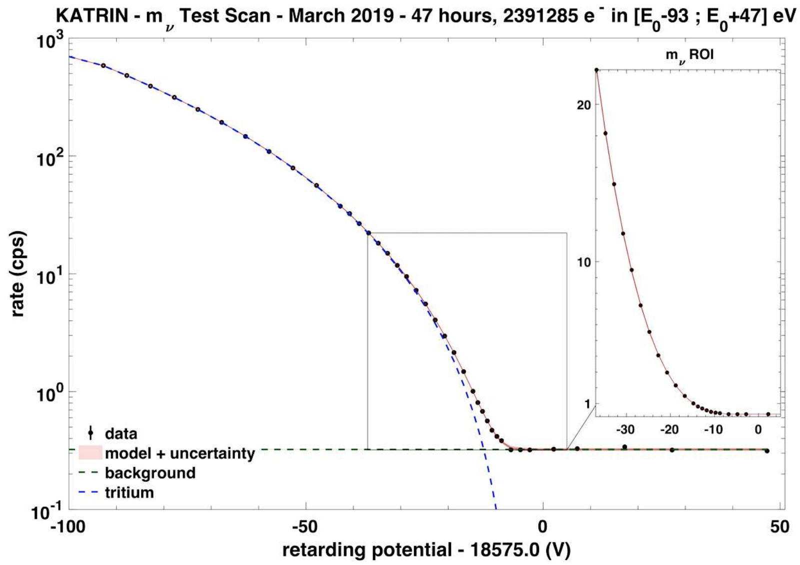

Fig. 2. Test scan of the tritium β-spectrum close to the endpoint

The purpose of the 10-m-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 an independent 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). The 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. Tritium Commissioning Measurements

The official inauguration of the KATRIN experiment took place on June 11th, 2018. In the following months, the tritium activity was increased step-by-step. The results of an initial test scan of the β-spectrum close to the endpoint are shown in Fig. 2. The plot shows the integral rate at the detector as a function of the main spectrometer retarding voltage. The spectrum is composed of two components: a voltage-independent background and the tail of the β-spectrum close to the endpoint.

The first KATRIN neutrino mass measurement phase started in March 2019 and concluded in May. The first results of this measurement phase are expected to be announced in September of this year.

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 has completed its first neutrino mass measurement following its construction phase.

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ЕКСПЕРИМЕНТ KATRIN
ДЛЯ ВИМІРЮВАННЯ МАСИ НЕЙТРИНО

Р е з ю м е

Karlsruhe Tritium Neutrino (KATRIN) є широкомасштабним експериментом, метою якого є визначення маси електронного антинейтрино модельно-незалежним шляхом з безпрецедентною точністю 0,2 eВ/c^2. Метод вимірювання базується на точній спектроскопії бета-розпаду молекулярного тритія. Експериментальна установка складається з безвіконного газовидного джерела молекулярного тритія високої світимості, магнітної електронної транспортної системи з диференційованою кріогенною помпою для затримки тритію, а також електростатичною спектрометричною секцією для контролю за енергією, за якою слідує сегментована система детекторів для підрахунку переданих бета-електронів. Перша фаза вимірювання маси нейтрино почалася у березні 2019 року. В роботі ми даємо огляд експерименту KATRIN та його сучасного стану.