Project KATRIN: First results and future plans.

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Abstract. The KARlsruhe TRItium Neutrino (KATRIN) experiment aims to make a model-independent determination of the active electron antineutrino mass with an upper limit of 0.2 eV/c^2 from the analysis of Tritium beta-spectrum shape near the endpoint. Experimental set-up is fully assembled and undergoes multiple tests. Small amount of Tritium molecules were injected at June 2018 and first spectra were measured. Experimental program for the nearest future includes determination of active electron antineutrino mass with an upper limit of 1.0 eV/c^2 and preliminary search for sterile neutrinos with several keV mass.

1. Historical remarks

The history of the neutrino mass search started 84 years ago with the E. Fermi article [1], where he showed that the neutrino mass value manifests itself in the form of β-decay spectrum. Already in 1938, A. I. Alichanian, A. I. Alichanow, and B. S. Dželepow for the first time were experimentally searched for neutrino mass in the RaE (210Bi) decay spectrum [2]. In 1949, Hanna and B. Pontecorvo were the first who successfully used tritium decay in their measurements and showed that m_ν < 1 keV/c^2 [3]. The study of the decay of tritium became the source of the most accurate data on the magnitude of the neutrino mass. In the work of Bergkvist [4], where the limit was set m_ν < 55-60 eV/c^2, for the first time it was necessary to take into account the main systematic corrections, including the excitation of the residual ion.

The increase in measurement sensitivity achieved over past 30 years is associated with the invention of an electrostatic spectrometer with adiabatic magnetic collimation. The principle of operation of the spectrometer is based on the adiabaticity of the movement of an electric charge in a slowly varying magnetic field [7]. Due to the preservation of the first adiabatic invariant, when moving from a strong magnetic field to a weak one, the charges move along the magnetic field lines, lining up along their direction (fig. 1). The tritium source is placed in a strong magnetic field, and the electrostatic spectrometer is placed in a weak field where electron moments are almost parallel (fig. 2). It is important that the spectrometer resolution does not depend on the transverse dimensions of the source. At the same time, the detector is shielded by a magnetic field from electrons produced at the electrodes of the spectrometer.
V.M. Lobashev and P.E. Spivak (see fig. 3, 4 below), realized their proposal [5] in the “Troitsk ν-mass” installation. E. Ottein and J. Bonn from Mainz University (see fig. 5, 6 below), independently developed similar ideas and implemented them in the “Mainz Neutrino Mass Experiment” installation [6].

**Figure 1.** Adiabatic motion in the slowly varying magnetic field. First adiabatic invariant preservation.

**Figure 2.** Proposed set up from [5]. Isotropic source is placed in (or close to) the pinch magnet. Longitudinal electric field retards part of electrons. Transmitted fraction is detected inside the detector magnet.

**Figure 3.** Petr Spivak  
23.04.1911 - 30.03.1991

**Figure 4.** Vladimir Lobashev  
29.07.1934 – 03.08.2011
Both experiments provided joint result $m_{\nu} < 2 \text{ eV}/c^2$.

Another achievement of the 80s is the invention of a windowless gaseous tritium source in the LANL experiment [7] (see also figures 7, 8). Tritium was injected into a cold pipe with open ends. The molecules departing in the direction of the spectrometer were pumped out by a series of pumps separated by diaphragms (differential pumping). The decay of a free tritium molecule was observed without corrections associated with solid-state effects like crystal excitation, formation of a space charge, etc. Until now, this type of source provides minimal systematic corrections to the decay electron spectrum.

2. Project KATRIN

By the end of the 80s, it became clear that the capabilities of the existing installations were exhausted. The tritium source activity of 0.6 GBk (as in Troitsk), should have been increased by several orders of magnitude, which is a difficult task. First of all, an expertise of a safe operation with so much of tritium was required. The solution was found through the involvement of a Tritium Laboratory of the Research centre Karlsruhe (Kursruhe Institute for Technology now) licensed to operate with 40g ($\approx 16 \text{ TBk}$) of tritium.

In 2001, the Karlsruhe Institute of Technology (KIT, Karlsruhe, Germany) adopted the KATRIN project to create a new facility (see Fig. 9), with a goal to set the upper limit of electronic antineutrino mass at 0.2 eV/c² (90% C.L.). Participants of previous experiments [6-8] also joined the project. Many of the parameters of the new installation are record: the total length is 70 m, the spectrometer with diameter of 10 m and vacuum of $1.10^{-11} \text{ mbar}$, a windowless tritium source of 100 GBq activity stable
within 0.1% and temperature maintained within 25 mK, a 25 m long transport channel formed by a chain of 29 superconducting solenoids, etc.

A more detailed description of the KATRIN facility and relevant publications can be found at KATRIN homepage [9].

3. KATRIN Project in 2018.
On October 14, 2016, commissioning of the installation as a whole began. For the first time, electrons emitted from the “back wall” of installation were detected by a detector located at its opposite end, at a distance of 70 m.

Figure 9. KATRIN facility.
RS-Rear Section, DPS-R- Differential Pumping Section-Rear, WGTS- Windowless Gaseous Tritium Source, DPSF-1- Differential Pumping Section Forward-1, DPSF-2 Differential Pumping Section Forward-2, CPS-Cryogenic Pumping Section, PS- pre-Spectrometer, MS- Maim Spectrometer, FPD- Focal Plane Detector
In 2018, commissioning was completed to study the tritium spectrum in design mode. Two measurement sessions were held. The first is from 18.05 to 20.06. The main objective was to verify the basic parameters of the WGTS system. This is the stabilization of the temperature of the WGTS source pipe, the stability of the magnetic field of the transport system, the stability of the pressure in the buffer volume of the injection system, the stability of the composition of the gas mixture. The stability of the obtained parameters was within the specification and even exceeded them. The first injection of tritium, which took place on 11.06.2018, was marked by the “Inauguration of KATRIN” ceremony.

The first tritium was injected into the system at the level of 1% of the nominal value. At that time, the tritium circulation system was not fully installed, and the injection was carried out from vessels with a pre-prepared gas mixture. The first measurement of the tritium spectrum was carried out and the systems of interception of tritium ions between the source and the spectrometer were tested.

The full scale gas circulation system of WGTS was tested at the session 03.09 - 22.10. The circulating gas was pure deuterium. Stable operation of the system was demonstrated with the amount of gas at the source varying from 1% to 100% of the nominal value. A continuous cleaning of non-hydrogen gases was carried out. The “Rear Section” was commissioned. It contains a gold-plated electrode for leveling the electric potential in the gaseous source and an electron gun for generating a test electron beam. Different schemes of electron gun photocathode illumination were tested. A new method of beam tuning through Rear Section was tested as well.

Energy losses by electron passing through the source constitute the main contribution to the budget of systematic corrections in the search for neutrino mass. The study of this effect was carried out earlier at the “Troitsk ν-mass” facility [10]. To analyze the KATRIN data it is necessary to have a new measurement of the inelastic energy loss spectrum of electron scattering from molecular Tritium with significantly increased accuracy. At the session 03.09 - 22.10, measurements of the electron loss spectrum in deuterium were carried out in two different modes.

The classic approach is to measure the energy spectrum of monochromatic electrons that have passed WGTS with a spectrometer in the integral mode. It is discussed in detail in [11] and requires measurements at several different source thicknesses and subsequent deconvolution.

A new approach is to use the spectrometer as a base in time-of-flight mode. The trigger signal is generated by a pulsed electron gun of a new type [12]. The new method has the advantage of measuring the differential spectrum instead of the integral one and does not require an ambiguous deconvolution procedure.

**KATRIN Plans for 2019.**

Three two-month sessions are proposed for 2019. In the first of them, it is planned to increase the activity of tritium in three steps: 10 Gbk – 50 GBk – 100 GBk (design value) and conduct a full-scale check of the reliability of interception of ions, the behaviour of the background, and the operation of the electron gun.

The first priority is to reach the limit on the electron antineutrino mass $m_{\nu_e} < 1 \text{ eV/c}^2$ (90% C.L.). The possibility of conducting a preliminary search for a heavy sterile neutrino with a mass of several keV is also under consideration.

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