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HOW HEAVY IS A NEUTRINO?

Pfeiffer Vacuum and KATRIN

Neutrinos are one of the most fascinating types of elementary particles. They are the lightest particles in the universe. Determining their mass has stretched the limits of physics research for many decades now. Neutrinos are the key, in fact, to many as yet unsolved scientific questions - ranging from the microcosmos of elementary particles to the biggest structures of our universe. For neutrinos can be described as cosmic architects; they play a role in shaping the visible structures of the universe and also influence the formation and distribution of galaxies.

To answer these fundamental questions of astrophysics and cosmology and obtain valuable information to allow us to understand elementary particles, it is crucially important to precisely identify the neutrino mass. The Karlsruhe Tritium Neutrino Experiment, or KATRIN for short, has committed itself to achieving this objective.

For over 15 years now, more than 150 national and international experts have been working together on the KATRIN project to determine the neutrino mass through high-precision model-independent measurement of the kinematics of electrons during the beta decay of tritium. The experimental setup required for this purpose is currently being assembled on the campus at Karlsruhe Institute of Technology (KIT). The demands that high-precision experiments place on the technology of the test instruments used represent a huge challenge.

Figure 1: The imposing KATRIN main spectrometer tank

Experimental setup of the Karlsruhe Tritium Neutrino (KATRIN)

KATRIN is 70 meters long in total and is made up of several sections containing five essential components:

- A windowless tritium source
- A transport section in which the tritium is removed with turbopumps and cryotraps and which leads the electrons to the spectrometer
- An electrostatic pre-spectrometer
- The gigantic electrostatic main spectrometer, and
- An electron detector

Inside the main spectrometer, a precisely positioned network of over 23,000 thin wires forms an electrostatic filter with high resolution for measuring the electron energy. The shape of the main spectrometer, with its cylindrical middle section tapering towards the ends, is dictated by the filter geometry. The dimensions of the main spectrometer measuring 9.80 meters in diameter and 23.28 meters long are defined by the energy resolution required.

High demands placed on vacuum technology

The design and manufacture of the main spectrometer have to meet the high demands placed on ultra-high vacuum systems. A total pressure of 10^{-11} mbar is called for in the spectrometer. The area-related outgassing rate for hydrogen should amount to less than 10^{-12} mbar l s^{-1} cm^{-2}. This is about ten thousand times lower than the outgassing rate of a clean surface after pumping for about one hour.

High quality standards and controls

Globally, there are only very few companies that are capable of building a vessel of this type. The MAN DWE GmbH in Deggendorf on the Danube River (today a member of the MAN Diesel & Turbo SE) is one of the prime addresses for chemical reactors and large vessels. This company was commissioned with the manufacture of the main spectrometer.

The relatively thin walls for a vessel of this size are made of pure stainless steel EN 1.4429. The many nozzles, particularly for the pump system as well as the heating and cooling system, give it its distinctive look. Probably no other large vessel has ever placed such high demands on the welding techniques and cleanliness during assembly. This precision work was continuously monitored by checking for leaks, for example, and verified with extensive vacuum testing. Leak detection solutions by Pfeiffer Vacuum were used for this purpose. Leak detection tests were conducted initially in 2006 when the spectrometer tank had to pass its first key stress test.

The spectrometer tank was evacuated for this test with a 2,600-l/s turbopump to 10^{-7}. Already after only two days' pumping, the final pressure attained was three orders of magnitude higher than the estimated testing pressure required for leak testing.

Figure 2: The foil-covered spectrometer tank impressively shows that engineers also need to be packaging artists.

Requirements to be met by leak detection solutions

During leak testing, it is essential that all possible contamination is avoided. All test methods that include even the slightest risk of contamination of the vessel, such as dye penetration tests or the use of foaming agents, were ruled out.

An all-round concept for conducting leak testing was developed by MAN DWE together with experts from Karlsruhe Institute of Technology (KIT). Products from Pfeiffer Vacuum were also used for this purpose. The final pressure required for leak testing was determined by the pump capacity to be installed.

The limit value specified for the integral helium leak testing of the ready-assembled main spectrometer was $< 5 \cdot 10^{-9}$ mbar l/s. The helium background signal was required to be $< 5 \cdot 10^{-10}$ mbar l/s. Initial calculations made it clear that the pump-down time for the chamber with its volume of 1,240 m^3 would be about three days in order to attain the required helium background.

The response time during leak testing would therefore be about 20 minutes, even if a powerful turbopump with a nominal helium pumping speed of about 2,600 l/s was used. The signal maximum would not be reached until about one and a half hours, and signal decay would take considerably longer.

In view of this, it did not seem practicable to conduct only one single integral test with the risk of several leaks. A procedure was therefore established for leak testing during production, encompassing a significant number of individual tests and as few integral tests as possible. The aim of this method was to prevent the risk of having to rework sealing surfaces or welded seams, for instance, at a later date. Testing during production can pinpoint any leaks at the time of manufacture, and quality deviations can be reworked precisely and at an earlier point in time. Time-consuming repeat testing and potential damage to the finished surface can be prevented in this way.

Individual testing

For testing individual root weld seams, small chambers were made of a cast elastomer that could be adapted to the curves of the wall. The chambers were used either as a tracer gas tank or as a vacuum chamber on the leak detector itself.

Individual flanges and components of a size and weight that allowed them to be tested at a single workstation were tested on permanently fixed test benches.

Helium sniffer leak detection was used for mobile testing of welded seams. This was the case wherever low-level leak tightness requirements applied, such as in cooling circuits.

Figure 3: Testing a welded seam at the transition between the main vessel and a socket.

Customized test hoods were developed for testing individual flanges that had already been assembled. The hoods were connected directly to the helium leak detector and evacuated.

Preparing for integral testing

For integral testing, the vessel was wrapped in a foil which only has a minimal permeation rate for helium. To prepare the cover, all flanges and projections on the vessel were padded to prevent damaging the foil. A final sheet of foil was attached to the spectrometer, before the component revolved on a rotator together with the sheet of foil. After one turn of the rotator, the ends of the foil were stuck to the floor of the production hall, leaving only one free opening.

In addition to determining the leak rate from the ambient air into the vessel, the leak rate outwards from the heating/cooling system and into the vessel was measured. Before testing, the response time and quantification of all leak detector assemblies was precisely calibrated.

The solution created by Pfeiffer Vacuum

For the most demanding measurement tasks, the integral testing of the spectrometer tank and testing of the heating/cooling system for leakage into the spectrometer tank, the ASM 122 D(*) dry leak detector was used. Particular features of this leak detector:

- Fast reduction of background signal during pump-down
- Best long-term stability during measurements
- Maximum sensitivity
- Ultra-rapid response time
- Very fast signal decay after leak detection
- Background signal not affected by fluctuating tracer gas concentrations in the ambient air
- Excellent portability and easy handling

The HLT 550(*) leak detector equipped with oil-lubricated backing pumps was used, for example, for testing leakage from the heating/cooling circuits. Unlike measurements conducted on the vacuum tank, these applications are insensitive to contamination with operating fluid from the backing pump.

The KATRIN vacuum laboratory was also equipped with the ASM 142 D* from Pfeiffer Vacuum. This leak detector enables single components to be tested. For more demanding tasks, the ASM 122 D and the ASM 192 T2D+ high-performance dry helium leak detectors are available for mobile and stationary use.

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* Note: Since conducting these measurements, the ASM 122 D leak detector described has been superseded by the new high-performance ASM 380 leak detector. The HLT 550 and ASM 142 D leak detectors that were also mentioned have meanwhile been superseded by the new generation ASM 340. These are available in oil-lubricated and dry versions.
For more information on Pfeiffer Vacuum helium leak detectors, visit our website at www.pfeiffer-vacuum.com.

Figure 4: Work on the main spectrometer tank called for great dedication on the part of KATRIN staff

All measurements were carried out in line with stringent test conditions, taking care to maintain high quality standards. At no time during the measurements was the specific integral leak rate for the vessel exceeded. Once leak testing had been successfully completed, the KATRIN main spectrometer was aired and then spectacularly transported from its production site in the town of Deggendorf to the Institute of Technology in Karlsruhe. Although this was a distance of only about 330 kilometers as the crow flies, it was nevertheless impossible to transport this gigantic 200 ton and 24 meter long spectrometer, with its 10 meter span, over land to its final destination.

So on September 28, 2006, the 8,800 kilometer journey began along creeks and rivers from the Bavarian town of Deggendorf to its destination in the town of Leopoldshafen in the Baden region of Germany. The final leg of the journey on a flat bed truck from the “NATO ramp” beside the Rhine River, near the Leopoldshafen suburb of the town of Eggenstein, may have been a mere seven kilometers long but it proved to be the greatest logistical challenge. The narrow streets of Eggenstein-Leopoldshafen called for meticulous planning. So it was not until November 29, 2006 that the spectrometer could finally be lifted into position through the roof of its purpose-built experiment hall by one of Europe’s biggest cranes.

Outlook

After installation in the dedicated experiment hall, the spectrometer tank was prepared for its final use. Cleanliness requirements made it necessary to work under cleanroom conditions.

Between 2007 and 2012, the complex internal system of electrodes, comprising no less than about 120,000 individual components, was fitted under cleanroom conditions, practically doubling the internal surface area in the process. The spectrometer and detector system was commissioned in 2013, and initial tests were conducted with a monoenergetic electron source. During these tests, a pressure in the upper 10^{-11} mbar range was attained.

After connections for the tritium source and the transport section are installed, experiments began with KATRIN in June 2018 to finally answer the question: how heavy is a neutrino?

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