Eur Phys J C **33**, s01, s808–s810 (2004)
Digital Object Identifier (DOI) 10.1140/epjcd/s2003-03-903-8

EPJ C direct
electronic only

KATRIN – Direct measurement of ν-masses in the sub-eV range

Guido Drexlin for the KATRIN Collaboration

Institut für Kernphysik, Forschungszentrum Karlsruhe, P.O. Box 3640, 76021 Karlsruhe, Germany

Received: 31 October 2003 / Accepted: 10 November 2003 /

Abstract. The KArlsruhe TRItium Neutrino (KATRIN) experiment is a next-generation direct neutrino mass experiment with sensitivity to sub-eV ν-masses. It combines an ultra-luminous molecular windowless gaseous tritium source with a high resolution electrostatic retarding spectrometer (MAC-E filter) to measure the spectral shape of β-decay electrons close to the T_2 end point at 18.6 keV with unprecedented precision. If no neutrino mass signal is found, the KATRIN sensitivity after 3 years of measurements is $m_\nu < 0.2$ eV (90 % CL.); a ν-mass signal of $m_\nu = 0.35$ (0.30) eV can be measured with 5 (3) σ evidence.

PACS. 23.40.-s Beta decay; double beta decay; electron and muon capture – 14.60.Pq Neutrino mass and mixing

1 Introduction

The recent observations of flavour oscillations of solar and atmospheric neutrinos (as well as of oscillations of reactor and accelerator neutrinos at long baseline) have provided convincing evidence for massive neutrinos. Thus, one of the essential tasks of experimental neutrino physics over the next years will be the determination of the absolute mass scale of neutrinos. This mass scale is of fundamental importance for cosmology and particle physics. In cosmology, neutrino hot dark matter could play an important role in the evolution of large scale structures (LSS). In particle physics, a precision measurement of m_ν would discriminate among different ν-mass models, commonly grouped as either of hierarchical type ($m_1 \ll m_2 \ll m_3$) or of quasi-degenerate type ($m_1 \simeq m_2 \simeq m_3$).

So far, the study of LSS evolution with galaxy surveys (2dFGRS, SDSS) and cosmic microwave background radiation experiments (WMAP) is not conclusive, providing either upper limits on the neutrino mass (per species) of the order of $m_\nu \sim 0.2$-1 eV [1], or tentative evidence for non-zero neutrino masses $m_\nu \approx 0.2$ eV [2]. Therefore, it is essential to probe sub-eV neutrino masses with laboratory experiments. There are two complementary approaches: a) the precise spectroscopy of β-decay at the kinematic end point and b) the search for neutrinoless double β decay ($0\nu\beta\beta$).

The investigation of β decays (^{3}H, ^{187}Re) is the only direct and *model independent* way to investigate neutrino masses, relying only on the relativistic energy-momentum relation and energy conservation. Over the last 20 years the most sensitive experiments have been using molecular tritium (T_2) as β-emitter. This is due to several reasons: a) the low end point of E_0=18.6 keV ensures that the relative decay fraction at the endpoint is comparatively high b) the short half life $t_{1/2}$=12.3 years corresponds to a high specific activity c) the superallowed transition has an energy independent nuclear matrix element and d) the atomic shell has a simple structure allowing precise calculations of the final state spectrum.

During the 1990's a new high sensitivity technique for β-spectroscopy at the T_2 end-point was developed at Troitsk and at Mainz: the electrostatic filters with magnetic adiabatic guiding (see [3] and references therein). In this so-called MAC-E filter technique, β-decay electrons from a molecular tritium source are adiabatically guided by strong magnetic fields ($\sim$ several Tesla) to a spectrometer, where a variable retarding high voltage allows to scan the spectrum in an integral way (only those electrons with longitudinal kinetic energies above the retarding potential are transmitted onto the detector for counting).

The current tritium β-decay experiments at Mainz (using a quench condensed source) and Troitsk (using a windowless gaseous source) have both reached their intrinsic level of sensitivity. The final results of the Mainz experiment, reported at this conference, correspond to a 95% CL. upper limit of $m_\nu < 2.3$ eV [4]. Pushing forward into the cosmologically important sub-eV range of neutrino masses therefore requires a new experimental effort: the next-generation tritium β-decay experiment KATRIN.

2 The KATRIN experiment

The KATRIN experiment will be built up and operated on the site of Forschungszentrum Karlsruhe, which offers general infrastructure matching well the extensive experimental demands. In particular, it allows to make use of the infrastructure of Tritium Laboratory Karlsruhe, which is the only laboratory certified to handle the amounts of tritium required for KATRIN.

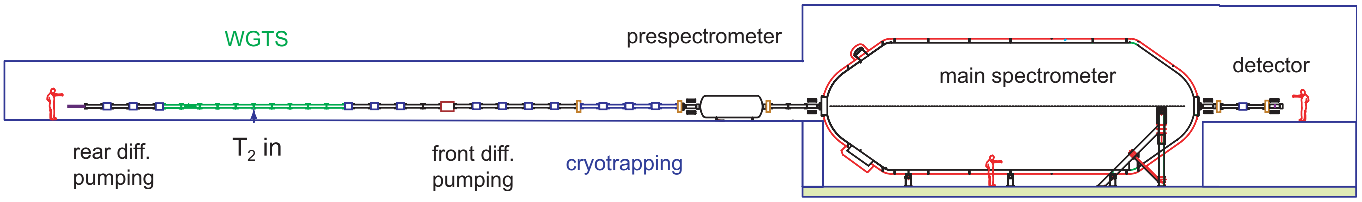

Fig. 1. The side view of the KATRIN reference setup with its major components: **a** the windowless gaseous source WGTS, **b** the transport elements consisting of an active pumping part and a passive cryotrapping section, **c** the two electrostatic spectrometers and **d** the detector for β-counting

2.1 Reference design

The layout of KATRIN is based on the MAC-E filter technique pioneered at Mainz and Troitsk. To improve the current sensitivity of $m_\nu \sim 2$ eV by *one* order of magnitude, the sensitivity with regard to the experimental observable m_ν^2 in β-decay has to be increased by *two* orders of magnitude. This requires significant improvements with regard to source luminosity, energy resolution, background reduction techniques as well as a very high degree of control of systematic errors. Over the last two years the KATRIN Collaboration has worked on designing a reference setup for a next-generation tritium β-decay experiment, which fulfills all of the above mentioned requirements (for details of the KATRIN set-up see [5] and [6]). A schematic view of KATRIN is shown in Fig. 1.

The experimental configuration can be grouped into the following major components:

- a windowless gaseous tritium source (WGTS) and a quench condensed tritium source (QCTS)
- an electron transport and tritium elimination section, comprising an active differential pumping followed by a passive cryo trapping section
- a system of two electrostatic spectrometers (pre- and main spectrometer)
- a segmented solid state electron detector

The standard β-source of the KATRIN experiment will be an ultra-luminous 10 m long windowless gaseous molecular tritium source (WGTS) delivering 10^{10} β-decays per second. High purity T_2 will be circulating within the WGTS under stable operating conditions at 30K with a design column density of $\rho d = 5 \times 10^{17}$ molecules/cm^2. In a major design change of the WGTS with regard to [5] and [6], the source diameter was increased to 90mm. This doubles the analysed β-decay luminosity of the WGTS and improves the statistics for the ν-mass measurements, while leaving all other parameters (energy resolution, background rate) unchanged. As the magnetic flux is conserved, this change required a complete redesign of the electromagnetic layout of KATRIN.

The transport system will guide the β-decay electrons adiabatically from the source to the spectrometer, while at the same time eliminating any tritium flow towards the spectrometer, which has to be kept practically free of tritium for background reasons. This will be done by a combination of differential (DPS-F) and cryogenic (CPS-F) pumping sections.

The energies of β-decay electrons are analysed in a system of two electrostatic retarding spectrometers (see Fig. 1). The tandem spectrometer set-up consists of a smaller pre-spectrometer working at a fixed retarding voltage and rejecting low-energy β-electrons with energies below 18.4 keV, thereby reducing the background from ionising collision of electrons in the main spectrometer. The larger main spectrometer has a diameter of 10 m and thus is characterised by a very high energy resolution of $\Delta E = 0.93$ eV at the spectral endpoint of T_2. The β-electrons passing the spectrometers are finally counted in a segmented semiconductor detector (either an array of silicon drift or Si-PIN diodes or DEPFET's).

2.2 Neutrino mass sensitivity

Over the past two years the ν-mass sensitivity of KATRIN could be improved in several steps by MC methods. A MC generated spectrum of β-electrons close to the end point of molecular tritium is shown in Fig. 2 a, both for a vanishing neutrino mass and a non-zero ν-mass $m_\nu = 0.5$ eV. The insert shows the residuals if both spectra a compared to each other (this clearly underlies that a ν-mass of 0.5 eV can be detected by KATRIN with a very high degree of confidence).

In [5], an initial sensitivity estimate of $m_\nu < 0.35$ eV (90% CL.) was given (sensitivity is defined as the average upper limit in the case of a vanishing neutrino mass). This value (see Fig. 2 b-curve 1) could be improved due to the following reasons: a) the tritium purity has been adjusted from an initial estimate of 75% to the new reference value of 95%, corresponding to the T_2 purity delivered by TLK, b) the analysed WGTS luminosity has been improved by a factor of 2 by enlarging the source diameter from 75mm to 90mm and by redesigning the electromagnetic layout of the beam line (see Fig. 2 b-curve 2), c) the measuring point distribution has been optimised with regard to ν-mass sensitivity. Instead of using a uniform measuring point distribution as reported in [5] and [6], an optimised distribution with enhanced measuring time at points ~ 5 eV below E_0 has now been adopted.

With the current reference setup of a 10 m spectrometer and a background rate of 10 mHz, one achieves a statistical error $(1\,\sigma)$ of $\sigma m_\nu^2\,(\mathrm{stat.}) = 0.016$ eV^2 after 3 'full beam' years of measurement. Further work was devoted to a careful study of systematic effects, in particular to improving measurements of the electron energy losses

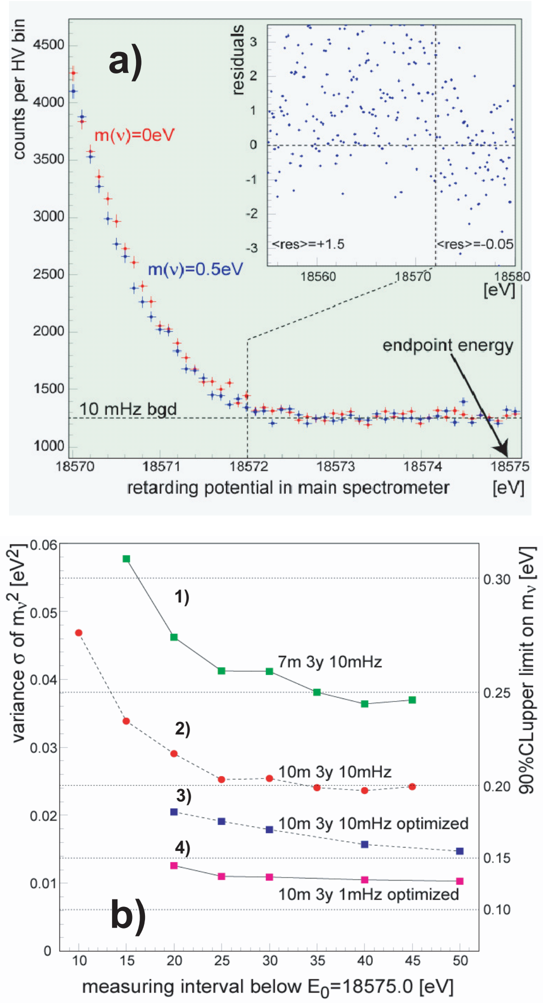

Fig. 2. a Simulated experimental spectra close to the β-endpoint of T_2 for the KATRIN reference set-up after 1 year of measuring time and a background level of 10 mHz. **b** Improvement of statistical errors of KATRIN for different configurations: 1) set-up of [5] (7 m spectrometer, 10 mHz background) 2) 10 m spectrometer and 10 mHz background, 3) same as 2) but with optimised measuring point distribution (KATRIN reference configuration), 4) same as 3) but with reduced background level of 1 mHz

via inelastic scattering in the WGTS, which constitute the largest systematic error in KATRIN. Based on these studies, the systematic error for the KATRIN measurements is expected to be $\sigma m_\nu^2\,(\text{syst.}) = 0.018\ \text{eV}^2$, so that statistical as well as systematic errors will contribute about equally. From these values (stat. and syst. errors added quadratically), the new sensitivity estimate for the KATRIN reference setup is

$m_\nu < 0.2$ eV (90 % Confidence Level)

for a vanishing neutrino mass. In case of a positive ν-mass signal, the KATRIN discovery potential for a neutrino mass of 0.35 eV is $5\,\sigma$. Correspondingly, a neutrino mass of 0.3 eV can be detected at $3\,\sigma$. Further design optimisation will not improve these values significantly.

2.3 Project status

The main emphasis of the KATRIN hardware activities has been on the commissioning of the pre-spectrometer as the first major hardware component 'on site'. The pre-spectrometer is a UHV recipient with 1.7 m diameter and 3.4 m length. A major design cornerstone is the Ø=1.7 m flange with double metal sealing to insert in the inner electrode system. An overview of the pre-spectrometer and its support structure is shown in Fig. 3.

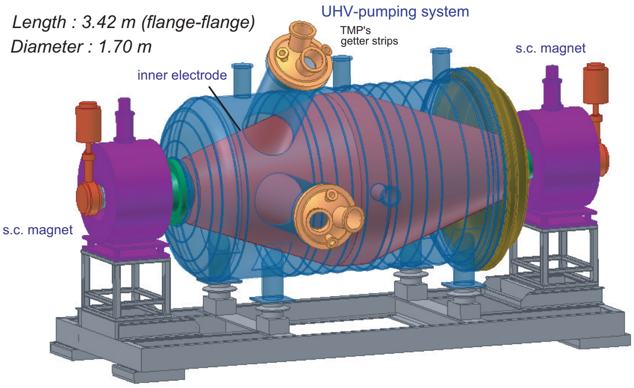

Fig. 3. Schematic view of the KATRIN pre-spectrometer and its main components: a UHV vessel on HV potential with a 1.7 m diameter flange for insertion of an inner wire-based electrode system and two pumping ports for NEG getters and turbo pumps. Two super-conducting magnets provide a stray field for adiabatic guiding of electrons

After manufacturing and welding of the vessel, the end caps, the large flange and the pumping ports, the completed vessel was vacuum-tested and delivered to FZK, where assembly works have started. Detailed tests of the vacuum system as well as of the electromagnetic properties of the pre-spectrometer will start in early 2004. These tests will be essential for validating both the UHV concept of KATRIN (pressure in spectrometers $< 10^{-11}$ mbar) and its novel electromagnetic design (HV applied directly onto spectrometer vessels). In parallel to these investigations, the first transport elements as well as a helium liquefier will be ordered soon.

The commissioning of the KATRIN components and first test measurements with the entire system are expected for 2007.

References

1. S. Hannestad: these proceedings
2. S.W. Allen, R.W. Schmidt, and S.L. Bridle: astro-ph/0306386
3. C. Weinheimer: in *Neutrino Mass* (Springer, Berlin 2003) pp. 25–52
4. C. Kraus: these proceedings
5. A. Osipowicz et al. (KATRIN Collab.): FZKA report 6691, hep-ex/0109033
6. T. Thümmler et al. (KATRIN Collab.): FZKA report 6752