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The KATRIN experiment - direct measurement of neutrino masses in the sub-ev region

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ABSTRACT: With the evidence for massive neutrinos from recent ν-oscillation experiments, one of the most fundamental tasks of particle physics over the next years will be the determination of the absolute mass scale of neutrinos, which has crucial implications for cosmology, astrophysics and particle physics. The KArlsruhe TRItium Neutrino (KATRIN) experiment is the next-generation direct neutrino mass experiment with a 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 endpoint 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/c^2 (90 % CL.); a ν-mass signal of $m_\nu = 0.35$ (0.30) eV/c^2 can be measured with 5 (3) σ evidence.

1. Introduction

The recent observations of flavour oscillations of solar (e.g. [1, 2]) and atmospheric neutrinos (e.g. [3]) as well as of oscillations of reactor (e.g. [4]) and accelerator neutrinos at long baseline (e.g. [5]) 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 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

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upper limits on the neutrino mass (per species) of the order of $m_\nu \sim 0.2$-1 eV/c^2 [6], or tentative evidence for non-zero neutrino masses $m_\nu \approx 0.2$ eV/c^2 [7]. Therefore, it is essential to probe sub-eV neutrino masses with laboratory experiments. There are two complementary approaches: a) the spectroscopy of β-decay just below the kinematic endpoint 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 with a sensitivity in the (sub)eV range. These experiments are only relying on the relativistic energy-momentum relation $E^2 = p^2c^2 + m^2c^4$.
This paper is organized as follows: In section 2 the basic ideas of tritium β-decay experiments are discussed and the requirements for a next-generation β–decay experiment are outlined. In section 3 the upcoming KArlsruhe TRItium Neutrino experiment KATRIN is described and the actual status of the experiment is given.

2. Tritium β–decay experiments

The most sensitive direct searches for the electron neutrino mass up to now are based on the investigation of the electron spectrum of tritium β–decay

$$\mathrm{T} \longrightarrow {}^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} \tag{2.1}$$

The electron energy spectrum of tritium β–decay for an electron neutrino with mass $m_{\bar{\nu}_\mathrm{e}}$ is given by ([8], velocity of light reintroduced):

$$\frac{d^2N}{dtdE} = C \times F(E, Z+1)\, p \left(E + m_\mathrm{e}c^2\right) \left(E_0 - E\right) \sqrt{(E_0 - E)^2 - {m_{\bar{\nu}_\mathrm{e}}}^2 c^4}\; \Theta(E_0 - E - m_{\bar{\nu}_\mathrm{e}}c^2), \tag{2.2}$$

where E is the kinetic energy of the electron, m_e the electron mass, p the electron momentum and $m_{\bar{\nu}_\mathrm{e}}$ the neutrino mass. E_0 corresponds to the total decay energy, $F(E, Z+1)$ is the Fermi function, taking into account the Coulomb interaction of the outgoing electron in the final state, the step function $\Theta(E_0 - E - m_{\bar{\nu}_\mathrm{e}}c^2)$ ensures energy conservation and C is given by

$$C = \frac{G_\mathrm{f}^2}{2\pi^3\hbar^7c^5}\; \cos^2(\Theta_\mathrm{c})\; |M_\mathrm{had}|^2. \tag{2.3}$$

Here G_f is the Fermi constant, Θ_c the Cabibbo angle and M_had the nuclear matrix element. Equ. 2.2 holds only for the decay of a bare, infinitely heavy nucleus. In case of an atom or a molecule, the possible excitation of the electron shell due to the sudden change of the nuclear charge by one unit has to be taken into account. The atom or molecule will end up in a specific state of excitation energy V_i with a probability W_i. Therefore equation 2.2 has to be modified into a sum of β spectra with amplitude W_i and endpoint energies $E_{0,\mathrm{i}} = E_0 - V_\mathrm{i}$. Since both, $|M_\mathrm{had}|^2$ and F(E,Z+1) are independent of $m_{\bar{\nu}_\mathrm{e}}$, the dependence of the spectral shape on $m_{\bar{\nu}_\mathrm{e}}$ is given by the phase space only. The square-root term of equation 2.2 shows first that ${m_{\bar{\nu}_\mathrm{e}}}^2$ is the experimental observable and second that the neutrino mass influences the β–spectrum only at the upper end just below E_0.

Fig. 1 shows the signature of an electron neutrino with a mass of $m_\nu = 1$ eV/c^2 in comparision with the undistorted β-spectrum. The influence of a non-zero neutrino mass

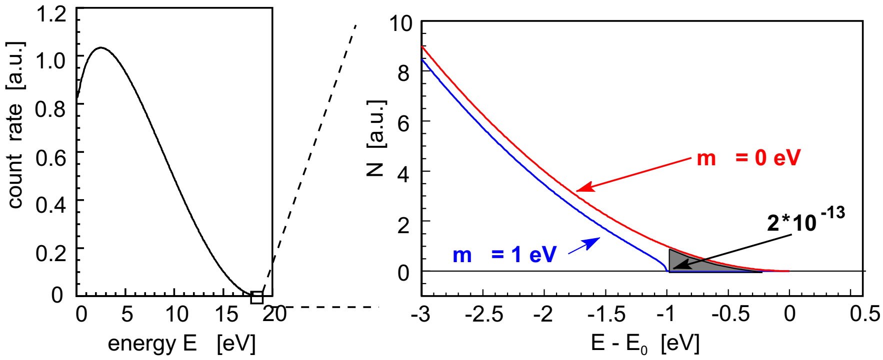

Figure 1: The electron energy spectrum of tritium β-decay: complete (left side) and zoom into the region around the endpoint E_0. The spectrum is displayed for neutrino masses of 0 and 1 eV/c^2, showing effects on spectral shape due to a neutrino mass of 1 eV/c^2. The gray shaded area corresponds to a fraction 2×10^{-13} of all tritium β-decays.

is statistical significant only in a region close to the β endpoint. Therefore, only a very narrow region close to the endpoint need to be analyzed. Since the fraction of β decays in this region is proportional to a factor $(1/E_0)^3$, the very low tritium energy of 18.6 keV maximizes the fraction of β–decays in this region.
Nevertheless, the requirements for a tritium decay experiment with a sub-eV sensitivity on the neutrino mass are quite demanding. These experiments require a high β–decay rate (fraction of β–particles within 1 eV below E_0: 2×10^{-13}), a huge luminosity (which is equal to a large source area multiplied with a large accepted solid angle) and a spectrometer with a very high energy resolution and a very low background rate. Apart from offering a low endpoint energy E_0 tritium has further advantages in neutrino mass investigations:

- Tritium has a short half life of 12.3 y, which corresponds to a high specific activity. Only a small amount of source material is needed and the fraction of inelastic scattered decay electrons is low.

- The tritium β–decay is a super-allowed nuclear transition, the nuclear matrix element is energy independent. Therefore, no corrections from the nuclear matrix element have to be taken into account.

- Tritium and its daughter, the $^3He^+$ ion, have a simple electronic shell configuration allowing precise calculations of the final state spectrum. Therefore, corrections due to the interaction of the outgoing β–electron with the tritium source can be calculated in a simple and straightforward manner.

The almost ideal features of tritum as a β–emitter have been the reason for a long series of tritum β–decay experiments (Fig. 2). It is remarkable that the error bars on m_ν^2 have decreased by nearly two orders of magnitude. Equally important is the fact that the problem of negative values of m_ν^2 of the early nineties has disappeared due to better understanding of systematic effects and improvements in the experimental set-ups.

2.1 Standard experimental setup and MAC-E-Filter

The standard set-up of a tritium β–decay experiment consists of four main components: the tritium source, the (magnetic) transport system, the spectrometer and the detector. The β–decay electrons are guided into the spectrometer by a magnetic transport system. This transport system must not disturb the kinetic energy of the β–decay electrons and has to pump residual tritium molecules originating from the source. Electrons, which have passed the spectrometer are then counted by the detector. Fig. 3 gives a list of the main requirements for each component. Details of the KATRIN components are discussed in section 3.

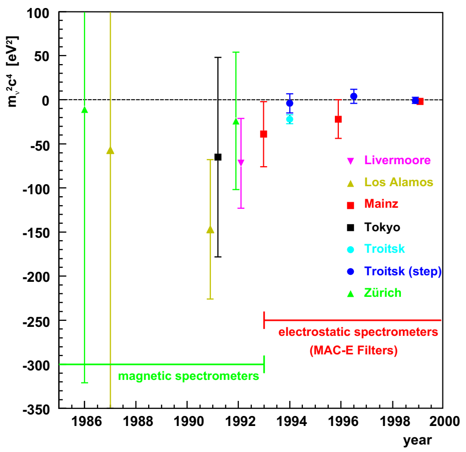

Figure 2: Results of tritium β decay experiments on the observable m_ν^2 over the last 15 years ([9, 10, 11, 12, 13, 15, 17])

The high sensitivity of the Troitsk and the Mainz neutrino experiments (see Fig. 2) is due to a new type of spectrometers, so-called MAC-E-Filters (Magnetic Adiabatic Collimation combined with an Electrostatic Filter). It combines high luminosity and low background with a high energy resolution, both essential to measure the neutrino mass from the endpoint region of a β–decay spectrum (see [8] and references therein). The main features of the MAC-E-Filter are illustrated in Fig. 4. Two superconducting solenoids are providing a guiding magnetic field. The β–electrons, which are starting from the tritium source in the left solenoid into the forward hemisphere, are guided magnetically on a cyclotron motion around the magnetic field lines into the spectrometer, thus resulting in an accepted solid angle of up to 2π. On their way into the center of the spectrometer the magnetic field B drops by many orders of magnitude. Therefore, the magnetic gradient force transforms most of the cyclotron energy $E_\perp$ into longitudinal motion. This is illustrated in Fig. 4 by a momentum vector. Due to the slowly

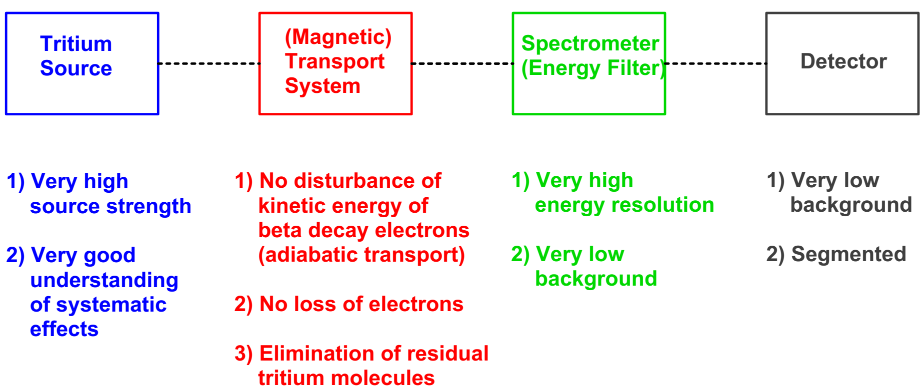

Figure 3: Standard experimental set-up of a tritium β–decay experiment

varying magnetic field the momentum transforms adiabatically and therefore the magnetic moment μ keeps constant (equation is given in non-relativistic approximation)

$$\mu = \frac{E_\perp}{B} = \text{const} \tag{2.4}$$

This transformation can be summarized as follows: The β–electrons, isotopically emitted at the source, are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines. This parallel beam of electrons is energetically analyzed by applying an electrostatic potential generated by a system of cylindrical electrodes. All electrons which have enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector, all others are reflected. The spectrometer, therefore, acts as an integrating high-energy pass filter.

The relative sharpness $\Delta E/E$ of this filter is given by the ratio of the minimum magnetic field $B_{\min}$ in the analyzing plane to the maximum magnetic field $B_{\max}$ between β–electron source and spectrometer:

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}} \tag{2.5}$$

The β–spectrum can by measured by scanning the electrostatic retarding potential.

2.2 Scaling factors for a next generation tritium β–decay experiment

The current tritium β–decay experiments at Troitsk [13, 14] (using a windowless gaseous source) and Mainz [15, 16] (using a quench condensed source) are approaching their sensitivity limit of about 2 eV/c^2. Pushing forward into the cosmologically important sub-eV range of neutrino masses therefore requires a new experimental effort - a next-generation tritium β–decay experiment.

A strong argument for the continuation of tritium β–decay experiments is the experience based on the Mainz and the Troitsk experiments: All former difficulties seem to be solved [18] and the strength and reliability of the new type of spectrometer, the MAC-E-Filter, which combines high energy resolution with high luminosity and low background, has been demonstrated.

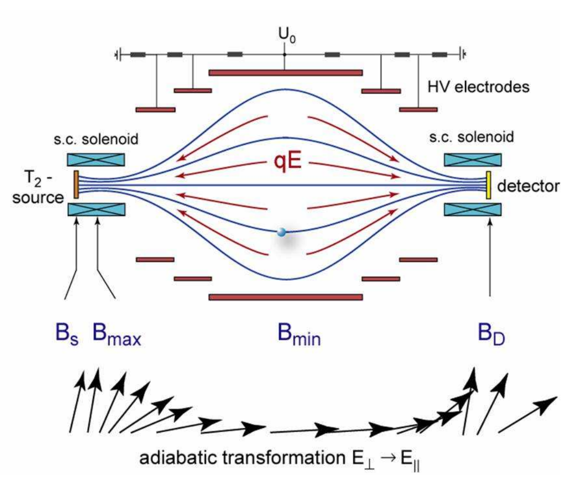

Figure 4: Principle of a MAC-Filter.

The aim is to improve the sensitivity for $m_{\bar{\nu}_e}$ by one order of magnitude (2 eV/c^2 $\rightarrow$ 0.2 eV/c^2) which corresponds to an improvement of m_ν^2 by two orders of magnitude. This significant improvement on the neutrino mass requires an energy resolution of the spectrometer of $\Delta E \approx 1$ eV at the tritium β–decay endpoint of 18.6 keV. This resolution corresponds to an improvement of a factor of 4 compared to the experiments in Troitsk and Mainz. Since the energy interval of interest below the β–decay endpoint rapidly decreases with

smaller neutrino mass, the signal rate has to be increased. This can be achieved by a higher tritium source strength which is equivalent to a larger source area and a higher and optimized column density. Since the magnetic flux is conserved ($\Phi = B \cdot A = \text{const}$), any increase of the source area requires the increase of the analyzing plane of the spectrometer. The same holds for a decrease of ΔE (Equ. 2.5).
To summarize: Compared with the current operated experiments at Mainz and Troitsk the next-generation tritium β–decay experiment requires

- a larger tritium source strength ($\approx$ factor 80).
- a larger analyzing plane of the spectrometer ($\approx$ factor 10).
- a better energy resolution of 1 eV ($\approx$ factor 4).
- a reduction of systematic uncertainties ($\approx$ factor 10).
- an increase of measurement time ($\approx$ factor 10).

3. The KATRIN experiment

KATRIN the next generation tritium β–decay experiment. A strong collaboration has been established, including nearly the complete worldwide expertise on tritium β–decay experiments. KATRIN is being built up and will be 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 Tritium Laboratory Karlsruhe, which is the only scientific tritum laboratory, which is licensed to handle the required amount of tritium and which can provide the infrastructure as well as the experience necessary to run the tritium source over years.
Fig. 5 shows a schematic view of the proposed experimental configuaration. KATRIN will have two molecular tritium sources, a windowless gaseous tritium source (WGTS) and

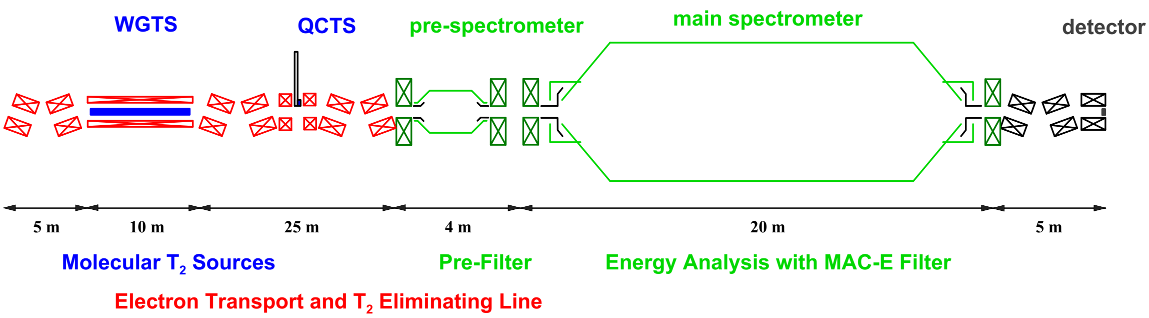

Figure 5: Schematic view of the KATRIN reference set-up. The main components of the system comprise a windowless gaseous tritium source (WGTS), a quench condensed tritium source (QCTS), an electron transport and differential pumping system, two MAC-E-Filters (pre- and main spectrometer) and an electron detector. The overall length of this linear set-up amounts to about 70 m. The transported magnetic flux from source to detector will be 191 Tcm^2.

a quench condensed tritium source (QCTS). KATRIN will employ two spectrometers, a pre-spectrometer, working as a pre-filter and a main spectrometer for the energy analysis. A detailed description of the KATRIN set-up can be found in [19, 20]. The following subsections are focused on the discussion of the basic ideas and the actual status of the main components of the KATRIN experiment.

3.1 Windowless gaseous tritium source

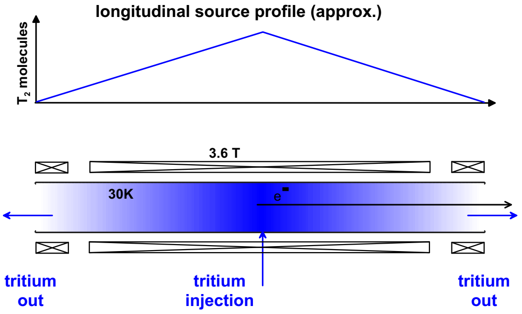

Figure 6: Schematic view of the WGTS.

The standard β-source of the KATRIN experiment will be an ultra-luminous windowless gaseous T_2 source (WGTS) delivering 10^{10} β-decays per second. The WGTS will consist of a 10 m long cylindrical tube of 90 mm diameter filled with molecular tritium gas of high isotopic purity ($>$ 95%) and kept at 30 K. Compared to [19, 20] the source diameter was increased in a major design change to 90 mm to double the analysed β-decay luminosity of the WGTS and to improve the statistics for the ν-mass measurements. The tritium gas will be injected through a capillary at the middle of the tube (see Fig. 6). It diffuses over a length of 5 m to both ends of the tube, resulting in an almost linear decrease of the tritium density by a factor of 100 from the injection point to the ends of the tube. It is proposed to place the tritium tube inside a chain of ten superconducting solenoids of 1 m length each. The solenoids will generate a homogeneous magnetic field of 3.6 T, which adiabatically guides the decay electrons to the tube ends. The requirements for the WGTS are quite challenging:

- To maintain the required column density of ρd$=5\times10^{17}$ molecules/cm^2 the tritium injection rate has to be in the order of 1 Ci/s $\approx$ 10 g T_2 per day. The tritium purity should be higher than 95%.
- To minimize systematical errors, the column density should be stable in the order of 0.1%. This requires an appropriate stability of parameters as e.g. tube temperature, inlet pressure etc. over a whole measuring periode (actual numbers: 60 days/run, 3 - 5 runs per year).

Since the TLK tritium inventory is 25 g, the task can only be solved by using a closed tritium loop and withdrawing only a small tritium fraction (few percent) for a clean-up. The actual work on the WGTS is focussed on the final specification of the WGTS, taking into account other modes of source operation, which are necessary for systematic investigations (e.g. energy loss measurements, calibrations).

3.2 Electron transport and differential pumping system

The electron transport system will guide the β–decay electrons adiabatically from the source to the spectrometer, while at the same time reducing the tritium flow rate towards

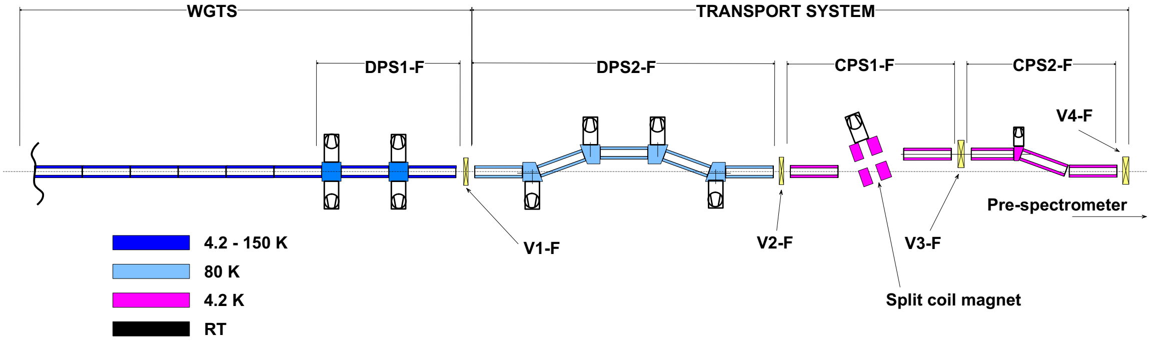

Figure 7: Schematic view of WGTS and transport system (reference set-up).

the spectrometer. Since the maximal allowed tritium flow rate into the pre-spectrometer is in the order of 10^{-11} mbar l/s, a tritium suppression factor of more than 10^{10} is needed between the outlet of the WGTS tube and the entrance of the pre-spectrometer. This will be done by a combination of differential (DPS-F) and cryogenic (CPS-F) pumping sections. The cryo pumps consist of the liquid helium cold surface of the transport tube, covered by a thin layer of argon for better trapping. The split coil magnet will enable the insertion of quench condensed sources into the beamline.
The decision of the reference set-up of source and transport system for KATRIN was made in February 2003. The specification of the DPS2-F was completed in June 2003 and it was ordered at the end of 2003. The specification of the remaining components is in progress.

3.3 Electrostatic spectrometers

The energy of the β–decay electrons are analyzed in a system of two electrostatic retardings spectrometers, a small pre-spectrometer and a large main spectrometer (see Fig. 8).

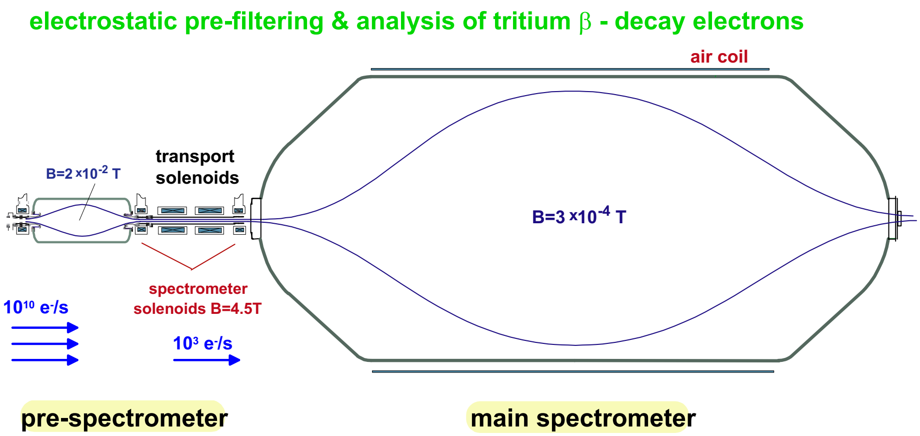

Figure 8: Tandem spectrometer design.

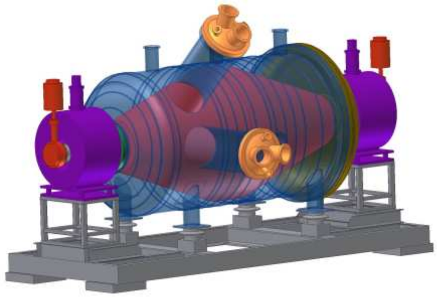

Figure 9: Schematic view of the KATRIN pre-spectrometer and its main components: a UHV vessel with a 1.7 diameter flange for insertion of an inner wire-based electrode system and two super-conducting magnets.

3.3.1 Pre-spectrometer

The pre-spectrometer will work as a pre-filter rejecting all β–decay electrons except the ones in the region of interest close to the endpoint E_0 (reduction factor 10^7). This will minimize the background by ionization of residual gas. Since the designs of the pre- and main spectrometer will be similar, the former can also act as a test facility for the larger main spectrometer. The pre-spectrometer is a UHV recipient with 3.4 m length. A major design concern was the $\varnothing$ = 1.7 m flange with double metal sealing to insert the inner electrode system. An overview of the pre-spectrometer and the support structure is shown in Fig. 9.
The main emphasis of the KATRIN hardware activities are actually focussed on the commissioning of the pre-spectrometer which is the first major component 'on site'. After manufacturing, the vessel was vacuum-tested and delivered to the Forschungszentrum Karlsruhe, where assembly works have started. Since the pre-spectrometer magnets were delivered in 2003, too, it is planned to start detailed tests of the vacuum system as well as of the electromagnetic properties of the pre-spectrometer 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 (high voltage applied direct onto spectrometer vessels).

3.3.2 Main spectrometer

A key component of the KATRIN experiment wil be the main spectrometer with a diameter of 10 m, an overall length of about 22 m and an energy resolution of $\Delta E = 1\ eV$. The design of the vacuum vessel as well as the shape and the mounting of the inner electrodes is currently being optimized. The combination of large tank dimensions together with the stringent XUHV requirements represents a technological challenge, as XUHV vessels of this size have not been manufactured before. A study in collaboration with several industrial partners has demonstrated the feasibility of the construction of a spectrometer of this size. The early tests with the pre-spectrometer vacuum system will allow to optimize the final design. In 2004 it is planned to finish the specification of the spectrometer and to start the tender action.

3.4 Detector

The detector optimally has to detect all β–electrons, which passed the energy filter and besides this has to enable systematic investigations of the whole KATRIN experiment. Therefore, the detector has to fulfill some demanding requirements:

- High efficiency for electron detection (> 90%).

- A certain position resolution a) to enable the radial monitoring of the source density, b) to track the particles within the spectrometer (for compensation of inhomogeneities of electric potential and magnetic field in the analyzing plane) and c) to suppress background originating outside the interesting magnetic flux (e.g. coming from the electrodes of the spectrometer).

- High background suppression ($<$ 1 mHz): This requires a good passive and active shielding as well as a good energy resolution ($<$ 600 eV). The latter is essential to suppress background events at different energies.

- Ability to take high count rates (up to a total count rate in the order of 1 MHz) to enable test and calibration measurements with sources such as Kr-83m as well as an appropriate time resolution ($<$ 100 ns) to enable measurements in a time of flight mode.

Currently intensive R&D is devoted to the detector. The present detector concept is based on a large monolithic array of PIN diodes. The array has to be sensitive over the whole magnetic flux tube area, coresponding to a diameter of 110 mm. The PIN diodes will have a very thin dead layer of only 50 nm in order to reduce energy losses and thus to improve the energy resolution. A thin sensitive layer of about 300 μm will help to reduce the detection of γ's (background suppression). The typical pixel size will be 5×5 mm^2 leading to about 500 read-out channels. This will allow a detailed source mapping.

3.5 Neutrino mass sensitivity

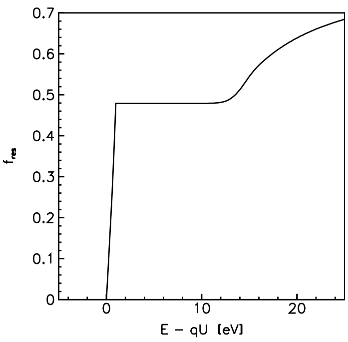

Figure 10: Response function of the KATRIN experiment for isotropically emitted electrons with fixed energy E as a function of the retarding energy qU (after [19]).

For a high sensitivity tritium β–decay experiment like KATRIN, the relevant region of the β–spectrum close to the endpoint E_0 is very narrow. A narrow energy interval means a large statistical error. On the other hand, a narrow energy interval strongly reduces possible systematic uncertainties, since these uncertainties mainly arise from processes connected to atomic and molecular physics, such as inelastic scattering of tritium β–electrons in the tritium source.

Fig. 10 shows the response function $f_{\rm res}$ of the KATRIN experiment for isotropically emitted monoenergetic particles. The response function is calculated by convoluting the energy loss distribution of electrons in the source with the transmission function of the spectrometer. The figure is based on the following given standard parameters: a) energy resolution ΔE = 1 eV, b) WGTS column density $\rho d = 5 \times 10^{17}$cm^{-2} and c) maximum accepted starting angle $\Theta_{\rm max} = 51°$. Due to the small energy resolution ΔE of KATRIN and due to the high threshold of the T_2 excitation, the "no energy loss" fraction of transmitted electrons can clearly be separated from those electrons which have undergone inelastic collisions. The "no energy loss" fraction corresponds

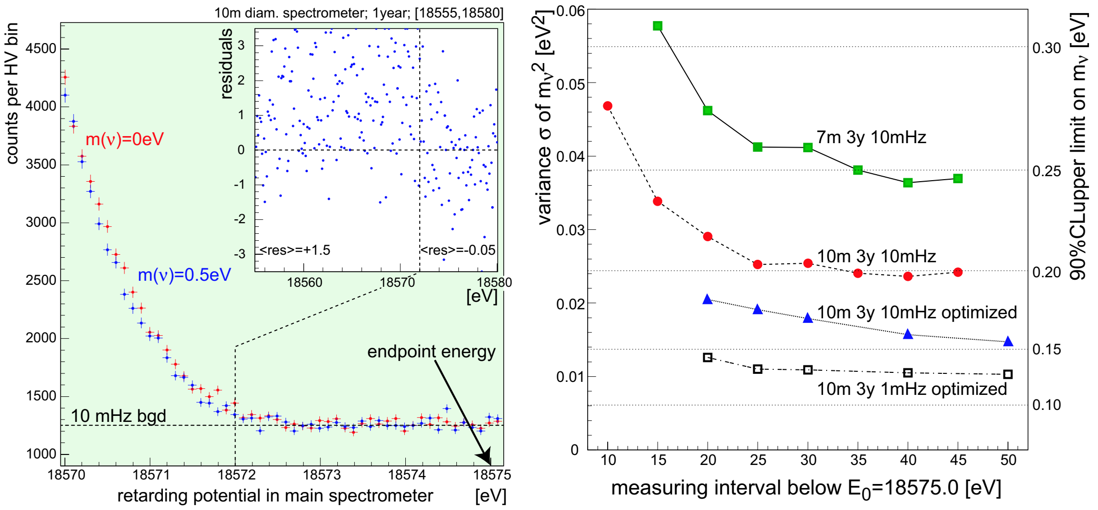

Figure 11: Monte Carlo simulations. Left picture: Simulated experimental spectra close to the β–endpoint of T_2 for the KATRIN reference set-up after 1 year of measuring time and a background level of 10 Hz. Right picture: Improvement of statistical errors of KATRIN for different configurations. "7m 3y 10 mHz" stands e.g. for 7 m diameter spectrometer, 3 years measuring time and 10 mHz background level, "optimized" means optimized measuring point distribution. See text for further explanations.

to the sharp rise of from 0 to the flat plateau, the latter part represents the second step at about 12 eV.

For the case of measuring the β–decay spectrum near its endpoint E_0, the response function of KATRIN implies that the last 10 eV below E_0 are fully covered by the elastic plateau of f_{res}. Even with a larger measuring interval of 25 eV below E_0, inelastic events contribute to only 2% of the signal rate. Therefore, KATRIN is nearly investigating a single final state like in a cryogenic bolometer experiment.
Over the past two years a list of systematic uncertainties concerning inelastic scattering, inhomogeneities of the tritium source, precision of final state calculations, determination of transmission function or trapping of electrons have been investigated. Based on these studies, the systematic error for the KATRIN measurements is expected to be $\sigma_{\mathrm{sys}}(m_\nu^2) = 0.018\ \mathrm{eV}^2/\mathrm{c}^4$.
The uncertainties given by systematic effects were included in the determination of the KATRIN detection limit on the neutrino mass. Two MC generated spectra of β–electrons close to the endpoint of T_2 are shown in Fig. 11 assuming massless neutrinos and $m_{\bar{\nu}_e} = 0.5\ \mathrm{eV/c}^2$. The insert shows the residuals if both spectra are compared to each other, clearly underlying that a neutrino mass of 0.5 eV/c^2 can be detected by KATRIN with a very high degree of confidence.
In [19] an initial sensitivity estimate of $m_{\bar{\nu}_e} < 0.35\ \mathrm{eV/c}^2$ (90% CL.) was given (sensitivity is defined as the average upper limit in the case of a vanishing neutrino mass). This value could be improved in several steps with the help of Monte Carlo simulations:

- The tritium purity has been adjusted from an initial estimate of 75% to the new reference value of 95%, corresponding to the tritium purity, which can be delivered by the Tritium Laboratory Karlsruhe.
- The analyzed WGTS luminosity has been improved by a factor of 2 by enlarging the source diameter from 75 mm to 90 mm and by redesigning the electromagnetic layout of the beamline ("10 m spectrometer").
- The distinct measuring points and their distribution has been optimized with regard to the neutrino mass sensitivity. Instead of using a uniform measuring point distribution, as reported in [19] and [20], an optimized distribution with enhanced measuring time at points about 5 eV below E_0 has now been adopted.

With the current reference set-up of a 10 m spectrometer and a background rate of 10 mHz, one achieves a statistical error (1σ) of $\sigma_{\rm stat}(m_\nu^2) = 0.016$ eV^2/c^4 after 3 years measuring time. Therefore, statistical and systematical errors will contribute about equally. From these values (stat. and syst. errors added quadratically), the new sensitivity estimate for the KATRIN reference set-up is

$$m_{\bar{\nu}_{\rm e}} < 0.2 \text{ eV/c}^2 \text{ (90\% Confidence Level)} \tag{3.1}$$

for a vanishing neutrino mass. In case of a positive neutrino mass signal, the potential of KATRIN to detect a neutrino mass of 0.35 eV/c^2 is 5 σ. Correspondingly, a neutrino mass of 0.3 eV/c^2 can be detected at 3 σ. Further design optimization will not improve these values significantly.

4. Summary

The question whether neutrino masses are significant for cosmology and whether the neutrino masses follow a degenerated or hierarchical pattern can be answered with a direct neutrino mass experiment with sub-eV sensitivity. For this task the investigation of the tritium β–spectrum is the most promising way free of additional assumptions. KATRIN, the next-generation tritium β–decay experiment, is being built up on the site of the Forschungszentrum Karlsruhe.

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