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STATUS OF THE KATRIN EXPERIMENT*

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The convincing evidences for neutrino flavor oscillation are a clear proof of non-vanishing neutrino masses. However, the absolute values of the neutrino masses cannot be determined by oscillation experiments alone. There are different approaches to set the neutrino mass scale, but the only model-independent one is the investigation of the electron energy spectrum of a β decay near its endpoint. The tritium β decay experiments at Mainz and Troitsk have recently been finished yielding upper limits of $m(\nu_e) < 2.3\mathrm{eV}/c^2$ (95% C.L.). The new Karlsruhe Tritium Neutrino Experiment (KATRIN) aims to improve the sensitivity on the neutrino mass by another order of magnitude down to $0.2\mathrm{eV}/c^2$. The status of KATRIN and the ways to handle the extreme challenges are briefly outlined in this paper.

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1. Introduction

The recent discovery of neutrino oscillation proved that neutrinos mix and can change their flavor. We are convinced that these neutrino oscillations are caused by non-zero masses of neutrinos in contrast to their current description in the Standard Model of particle physics. Unfortunately, oscillation experiments are sensitive to $|\Delta m_{ij}^2| = |m^2(\nu_i) - m^2(\nu_j)|$, but not directly to $m(\nu_i)$. In the case of matter effects involved — like for solar neutrinos — the sign of Δm_{ij}^2 can be resolved. On the other hand, if one neutrino mass is measured absolutely the whole neutrino mass spectrum can be calculated using the values Δm_{ij}^2 from the oscillation experiments.

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There are different ways to determine the neutrino mass scale:

Cosmology

Information on the absolute scale of the neutrino mass can be obtained from astrophysical observations like the power spectrum of the matter and the energy distribution in the Universe at different scales. In most cases they give upper limits on the neutrino mass of several 0.1 eV/c^2 [1], in some cases non-zero neutrino masses are found [2] illustrating the dependence on the assumptions and the data used to obtain the limits.

Neutrinoless double β decay

One laboratory way to access the neutrino mass scale is the search for the neutrinoless double β decay [3, 4]. The observable of double β decay is the so-called effective neutrino mass

$$m_{\mathrm{ee}} = \sum_i |U_{\mathrm{ei}}^2 \cdot m(\nu_{\mathrm{i}})| \tag{1}$$

which is a coherent sum over all neutrino mass eigenstates $m(\nu_i)$ contributing to the electron neutrino with their (complex) mixing matrix elements U_{ei}. Recently new data and a re-analysis of the old data of the Heidelberg–Moscow experiment on ^{76}Ge have been presented [6] showing a line at the position expected for neutrinoless double β decay with $4\,\sigma$ significance. Due to the uncertainties of the nuclear matrix element [3] this signal translates into $0.1\,\mathrm{eV}/c^2 \leq m_{ee} \leq 0.9\,\mathrm{eV}/c^2$.

Direct neutrino mass determination

In these experiments the neutrino mass is determined using the relativistic energy-momentum relationship without further assumptions. Therefore, $m^2(\nu)$ is the observable in most cases.

The non-observation of a dependence of the arrival time on energy of supernova neutrinos from SN1987a gave an upper limit on the neutrino mass of 5.7 eV/c^2 [7]. Nearby supernova explosions are too rare and too less understood to allow a further improvement to a sub-eV sensitivity on the neutrino mass.

Therefore, the investigation of the electron energy spectrum of a β decay is still the most sensitive model-independent and direct method to determine the neutrino mass. The mass of the electron neutrino is determined by investigating the shape of the β spectrum near its endpoint E_0 where the neutrino is not fully relativistic (see Fig. 1). From Fig. 1 it is clearly visible that the main requirement for such an experiment is to cope with the vanishing count rate near the endpoint by providing the strongest possible signal at lowest background.

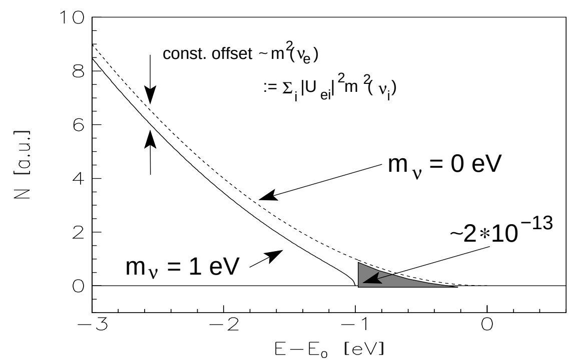

Fig. 1. Expanded β spectrum around its endpoint $E_0$for $m(\nu_\mathrm{e}) = 0$ (dashed line) and for a arbitrarily chosen neutrino mass of $1\,\mathrm{eV}/c^2$(solid line). The offset between the two curves explains what the "$m(\nu_\mathrm{e})$" is: the average over all neutrino mass states with their contribution according to the neutrino mixing matrix U. In the case of tritium, the grey shaded area corresponds to a fraction of 2×10^{-13} of all tritium β decays.

Additionally, to become sensitive to the neutrino mass dependent shape of the β spectrum an energy resolution on the order of eV is required. Tritium is the standard isotope for this kind of study due to its low endpoint of 18.6 keV, its rather short half-life of 12.3 y, its super-allowed shape of the β spectrum, and its simple electronic structure. For each neutrino mass state $m(\nu_i)$ contributing to the electron neutrino a kink at $E_0 - m(\nu_i)c^2$ with a size proportional to $|U_{ei}^2|$ will occur. However, due to the smallness of Δm_{ij}^2 only an incoherent sum or an average neutrino mass can be obtained [5], which can be defined as the *electron neutrino mass* $m(\nu_e)$ by

$$m^2(\nu_\mathrm{e}) = \sum_i |U_\mathrm{ei}|^2\, m^2(\nu_\mathrm{i})\,. \tag{2}$$

From comparing equations (1) and (2) it becomes obvious that the neutrinoless double β decay and the investigation of the β decay spectrum yield complementary information.

2. Neutrino mass experiments from tritium β decay

A major break-through in tritium β decay experiments was achieved by a new type of spectrometer, the so-called MAC-E-Filter (Magnetic Adiabatic Collimation followed by an Electrostatic Filter). This new type of spectrometer — based on early work by Kruit [8] — was developed for the application to tritium β decay at Mainz and Troitsk independently [9, 10]. The MAC-E-Filter combines high luminosity at low background and a high energy resolution.

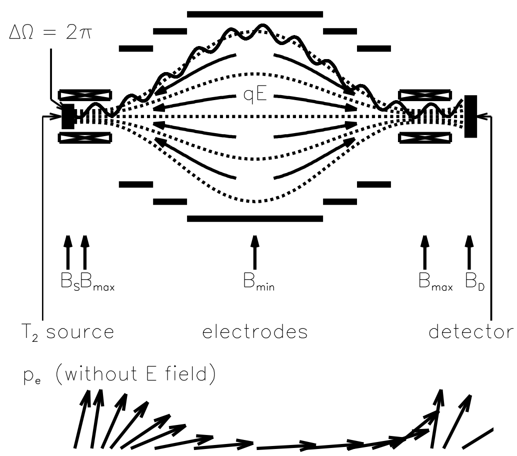

Fig. 2. Principle of the MAC-E-Filter. Top: experimental setup, bottom: momentum transformation due to adiabatic invariance of the orbital magnetic momentum μ in the inhomogeneous magnetic field.

The main features of the MAC-E-Filter are illustrated in Fig. 2: two superconducting solenoids produce a magnetic guiding field. The β electrons, starting from the source in the left solenoid into the forward hemisphere, are guided along the magnetic field lines into the spectrometer resulting in an accepted solid angle of nearly 2π. On their way into the centre of the spectrometer the magnetic field B drops adiabatically by several orders of magnitude keeping the magnetic orbital moment μ invariant:

$$\mu = \frac{E_\perp}{B} = \text{const}\,. \tag{3}$$

Therefore, nearly all cyclotron energy $E_\perp$ is transformed into longitudinal motion (see Fig. 2 bottom) giving rise to 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 barrier. The relative sharpness of this energy high-pass filter is only given by the ratio of the minimum magnetic field $B_{\rm min}$ reached at the electrostatic barrier in the so-called analyzing plane and the maximum magnetic field between β electron source and spectrometer $B_{\rm max}$:

$$\frac{\Delta E}{E} = \frac{B_{\rm min}}{B_{\rm max}}\,. \tag{4}$$

The two recent tritium β decay experiments at Mainz and at Troitsk use similar MAC-E-Filters with an energy resolution of 4.8 eV (3.5 eV) at Mainz (Troitsk). The major differences between the two setups are the tritium sources: Mainz uses a thin film of molecular tritium quench-condensed on a cold graphite substrate, whereas Troitsk has chosen a windowless gaseous molecular tritium source.

From its first data taking the Troitsk experiment reports an anomalous excess in the experimental β spectrum, a sharp step of the count rate at a varying position of a few eV below the endpoint of the β spectrum [12], which seems to be an experimental artefact appearing with varying intensity at the Troitsk setup. Troitsk is correcting for this anomaly by fitting an additional line to the β spectrum run-by-run.

Combining the 2001 results with the previous ones since 1994 gives [13]

$$m^2(\nu_{\rm e}) = (-2.3 \pm 2.5 \pm 2.0)\,{\rm eV}^2/c^4\,, \tag{5}$$

from which the Troitsk group deduces an upper limit

$$m(\nu_{\rm e}) < 2.05 \ {\rm eV}/c^2 \quad (95\ \%\ {\rm C.L.})\,. \tag{6}$$

The values of Eq. (5) and (6) do not include the systematic uncertainty which is needed to account for, when the timely-varying anomaly is described run-by-run with an additional line.

The most sensitive analysis of the Mainz data on the neutrino mass, in which only the last 70 eV of the β spectrum below the endpoint are used, resulted in the following [11]

$$m^2(\nu_{\rm e}) = (-0.6 \pm 2.2 \pm 2.1) \ {\rm eV}^2/c^4, \tag{7}$$

which corresponds to an upper limit of

$$m(\nu_{\rm e}) < 2.3 \ {\rm eV}/c^2 \quad (95\ \%\ {\rm C.L.})\,. \tag{8}$$

This is the lowest model-independent upper limit of the neutrino mass.

3. The KATRIN experiment

To distinguish hierarchical from quasi-degenerate neutrino mass scenarios and to check the cosmological relevance of neutrino dark matter requires the improvement of the direct neutrino mass search by one order of magnitude at least.

The KATRIN collaboration has taken this challenge and is currently setting up an ultra-sensitive tritium β decay experiment based on the successful MAC-E-Filter spectrometer technique and a very strong Windowless Gaseous Tritium Source (WGTS) [14, 15] at Forschungszentrum Karlsruhe (FZK), Germany. Fig. 3 shows a schematic view of the proposed experimental configuration.

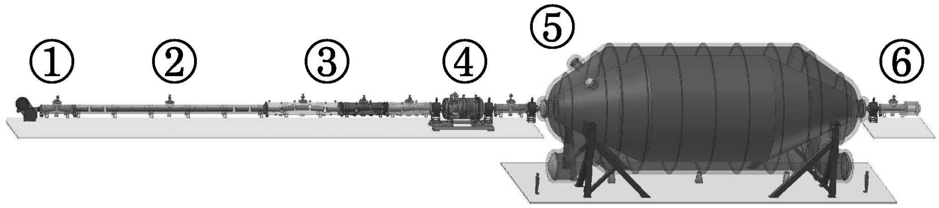

Fig. 3. Schematic view of the KATRIN experiment with the rear monitoring and calibration system (1), the windowless gaseous tritium source (WGTS) (2), the differential and cryopumping electron transport section (3), the pre spectrometer (4), the main spectrometer (5) and the electron detector array (6).

The WGTS consists of a 10 m long tube of 90 mm diameter filled with molecular tritium gas of high isotopic purity (> 95 %). The tritium gas will be continuously injected by a capillary at the middle with a rate of 4.7 Ci/s and pumped out by a series of differential turbo molecular pump stations at both ends giving rise to a column density of $5 \times 10^{17}/\mathrm{cm}^2$ about a factor 100 larger than in Mainz and Troitsk.

With the "Test of Inner LOop" setup TILO the required stability was reached at FZK. To allow a very stable and low WGTS temperature at about 27 K the WGTS tube will be placed inside a pressure-stabilized LNe cryostat. The isotopic composition will be continuously monitored with the help of Laser-Raman spectroscopy. By calculations and simulations and by dedicated experiments at Troitsk a possible distortion of the electrical potential within the WGTS due to the plasma has been investigated. It seems, that a electrical potential inside the WGTS can be sufficiently well defined by the rear plate. The WGTS setup is under construction.

The electron transport system adiabatically guides β decay electrons from the tritium source to the spectrometer by a system of superconducting solenoids. At the same time it eliminates any tritium flow towards the spectrometer by a differential pumping system consisting of 1 m long tubes inside the solenoids, alternated by pump ports with turbo molecular pumps yielding a tritium reduction factor of 10^7. To reduce the molecular beaming effect, the direct line-of-sight is prohibited by 20 degree bents between the magnets. The active differential pumping section is followed by a cryotrapping section to suppress the tritium partial pressure further to an insignificant level. With the dedicated TRAP experiment at FZK the cryosorption of tritium molecules at LHe cold surfaces covered by Argon frost is being checked yielding no measurable penetration of D_2 molecules, the retention factor for tritium was above the design value. The design of the cryopumping section will be finalized and the order shall be placed in 2006.

Between the tritium source and the main spectrometer a pre-spectrometer of MAC-E-Filter type will be installed. It acts as an electron pre-filter at a retarding energy 200–300 eV below the endpoint of the β spectrum to reject all β electrons except the very high energetic ones. This minimizes ionization of residual gas by β electrons in the main spectrometer.

A key component of the new experiment will be the large electrostatic main spectrometer with a diameter of 10 m and an overall length of about 23 m. This high-resolution MAC-E-Filter will allow to scan the tritium β decay endpoint at a resolution of $\Delta E = 0.93\,\mathrm{V}$ which is, at a much higher luminosity, a factor of 4–5 better than for the MAC-E-Filters in Mainz and Troitsk.

The KATRIN detector requires high efficiency for electrons at $E_0 = 18.6\,\mathrm{keV}$ and low γ background. A high energy resolution of $\Delta E < 600\,\mathrm{eV}$ for 18.6 keV electrons should suppress background events at different energies. The present concept of the detector is based on a large array of photodiodes surrounded by passive and active shielding to reduce background. A possible post-acceleration of the β electrons to about 30 keV will shift the signal line into a region of low background.

The price we have to pay for large luminosity and high energy resolution is that electrons, which are born in the spectrometer volume, *e.g.* by inelastic scattering, may be accelerated by the electrical potential and counted at the detector (see Fig. 2). Therefore, the pre-spectrometer limits the electron input rate of the huge main spectrometer but still we ask for a residual gas pressure of better than 10^{-11} mbar. To reduce surfaces inside the vacuum chamber a system of solid electrodes is avoided and the vacuum vessel itself will be put on high voltage and thus will create the electric retarding potential.

A second type of background arises from secondary electrons from the walls created by cosmic muons or by environmental radioactivity. Although the magnetic field will prohibit most of these electrons to enter the magnetic flux tube, which is connected to the detector, measurements at Mainz [16] yielded a transmission rate of 10^{-5}–10^{-7}, which is critical considering the surface of $650\,\mathrm{m}^2$ of the KATRIN main spectrometer. To suppress this background the vessel walls at high potential will be covered by a nearly massless wire electrode put to a slightly more negative potential. This method reduced background rate at the Mainz spectrometer by a factor 10 [17, 18]. To achieve an even higher suppression factor the KATRIN main spectrometer will be instrumented by a two-layer wire electrode system being under construction at Münster.

These ideas and other technical solutions will be applied also to the KATRIN pre-spectrometer, which is already set up at FZK. The vacuum tests with the pre-spectrometer yielded a final pressure of less than

10^{-11} mbar and an outgasing rate of less than 10^{-13} bar l/(s cm^2). Both values are better than the KATRIN requirements.

A wire electrode system for background reduction, built at Seattle, has been installed in the KATRIN pre-spectrometer. Becoming instrumented with a scanning electron gun and a 64-pixel silicon PIN-detector the electromagnetic and background properties of the KATRIN pre-spectrometer will be investigated soon.

Compared to the Letter of Intent [14] the sensitivity of KATRIN has been significantly increased. The major improvements to increase the statistics are a re-circulating and purification system providing a tritium purity of > 95 %, the increase of the diameter of the WGTS from 75 mm to 90 mm and, correspondingly, of the diameter of the main spectrometer from 7 m to 10 m. Additionally an optimization of the measurement point distribution around the endpoint has been performed.

The main systematic uncertainties comprise the energy spectrum and the probability of inelastic scattering within the tritium source and the stability of the retarding voltage of the main spectrometer. The former will be determined and repeatedly monitored by injecting electrons from the rear system. For the latter, a dedicated high-precision high voltage divider with a precision in the ppm range has been developed [19] with the support of the Physikalisch Technische Bundesanstalt at Braunschweig, Germany.

For redundancy, the retarding high voltage of the main spectrometer is applied in parallel to a third spectrometer, the monitor spectrometer[1], which continuously measures a sharp electron line. Different sources are in preparation by the Rez, Münster and Bonn groups, *e.g.* a photoelectron source consisting of a cobalt foil irradiated by γs from ^{241}Am, or a condensed ^{83m}Kr conversion electron source.

Another possible systematic uncertainty is the electrical potential distribution within the WGTS due to plasma effects. This will be checked by running the WGTS at 120–150 K with the conversion electron emitter ^{83m}Kr added to the gaseous molecular tritium.

The detailed simulations of the KATRIN experiment yield the following (see Fig. 4): A sensitivity of $0.20\,\mathrm{eV}/c^2$ (90 % C.L.) will be achieved with the KATRIN experiment after 3 years of pure data taking. Statistical and systematic uncertainties contribute about equally. A non-zero neutrino mass of $0.30\,\mathrm{eV}/c^2$ would be detected with $3\,\sigma$ significance, a mass of $0.35\,\mathrm{eV}/c^2$ even with $5\,\sigma$.

The design of the experiment is nearly finished and a detailed description was documented [15]. Some parts (*e.g.* the pre-spectrometer) have been set up already. Four major components have been ordered, the WGTS, the

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[1] The Mainz spectrometer will be modified for this purpose into a high-resolution spectrometer with $\Delta E \approx 1\,\mathrm{eV}$.

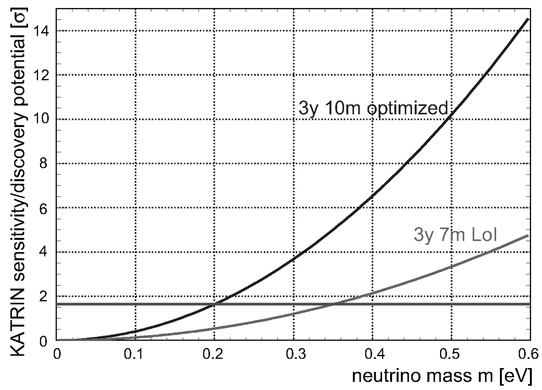

Fig. 4. KATRIN‘s discovery potential or sensitivity in units of the total uncertainty σ for a 3 years measurement as function of the neutrino mass. The horizontal line shows the upper limit with 90 % C.L. in case that no neutrino mass is found.

differential pumping system, the main spectrometer vessel, and the helium liquefier. Many dedicated test experiments are being performed at different places to investigate the inner tritium loop, the cryotrapping, methods to improve the vacuum conditions, new background suppression methods, calibration sources, detector, and data acquisition, *etc.* The ground-breaking of the new KATRIN halls at FZK has been celebrated in late summer 2005.

4. Conclusions

Neutrino oscillation experiments have pointed to new physics beyond the Standard Model by proving that neutrinos mix and that they have non-zero masses. The next goal is to determine the absolute scale of the neutrino mass.

Among various ways to address the absolute neutrino mass scale the investigation of the shape of β decay spectra around the endpoint is the only model-independent method. This direct method is complementary to the search for the neutrinoless double β decay and to the information from astrophysics and cosmology.

The investigation of the endpoint spectrum of the tritium β decay is still the most sensitive direct method. The tritium β decay experiments at Mainz and Troitsk have been finished yielding upper limits of about $2\,\mathrm{eV}/c^2$. The KATRIN experiment is being set up at FZK by an international collaboration. KATRIN will enhance the sensitivity on the neutrino mass by one order of magnitude to $0.2\ \mathrm{eV}/c^2$. Critical points of the experiments are checked by dedicated experiments, the design will be finalized in 2006 to be ready for data taking in late 2009.

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