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# Direct determination of the neutrino masses

Christian Weinheimer

*Institut für Kernphysik, Wilhelm-Klemm-Strasse 9, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany*

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**Abstract**

The only model-independent method to determine the absolute neutrino mass scale is still the investigation of a $\beta$ decay spectrum near its endpoint. The tritium $\beta$ decay experiments at Mainz and Troitsk have recently been finished yielding upper limits on the neutrino mass of about 2 eV. The bolometric experiments using $^{187}$Re reached a sensitivity on the neutrino mass of 15 eV. The new Karlsruhe Tritium Neutrino Experiment (KATRIN) will enhance the sensitivity on the neutrino mass by another order of magnitude down to 0.2 eV by using a very strong windowless gaseous molecular tritium source and a huge ultra-high resolution electrostatic spectrometer of MAC-E-Filter type to probe the cosmological relevant neutrino mass range and scenarios of quasi-degenerated neutrino masses. ***To cite this article: C. Weinheimer, C. R. Physique 6 (2005).***
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**Résumé**

**Mesures directes de la masse des neutrinos.** Pour déterminer l'échelle absolue de la masse des neutrinos, la seule méthode directe consiste à analyser le spectre de désintégration $\beta$ près de son extrémité. Les expériences au tritium de Mayence et Troitsk sont maintenant terminées et donnent une limite supérieure sur la masse du neutrino d'environ 2 eV. Les expériences bolométriques utilisant le $^{187}$Re ont atteint une sensibilité de 15 eV. Une nouvelle expérience, KATRIN (Karlsruhe Tritium Neutrino Experiment), est en construction. Elle augmentera la sensibilité sur la masse du neutrino par un ordre de grandeur, jusqu'à 0.2 eV en utilisant une source très intense de tritium moléculaire gazeux et un gigantesque spectromètre électrostatique à très haute résolution. Elle permettra d'atteindre un domaine de masse d'intérêt cosmologique et de tester plusieurs scénarios de hiérarchie des masses des neutrinos. ***Pour citer cet article : C. Weinheimer, C. R. Physique 6 (2005).***
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*Keywords:* Neutrino mass; Direct neutrino mass determination; Tritium $\beta$ spectrum; MAC-E-Filter

*Mots-clés :* Masse du neutrino ; Mesure directe de la masse ; Désintégration $\beta$ du tritium ; Filtre MAC-E

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## 1. Introduction

The recent discovery of neutrino oscillation by experiments with atmospheric, solar, reactor and accelerator neutrinos [1] proved that neutrinos mix and that they have non-zero masses in contrast to their present description in the Standard Model of particle physics. Unfortunately, these oscillation experiments are sensitive to the differences of squared neutrino mass states $\Delta m_{ij}^2 = |m^2(\nu_i) - m^2(\nu_j)|$, but not directly to the neutrino masses $m(\nu_i)$ themselves. On the other hand, if one neutrino mass

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*E-mail address:* weinheimer@uni-muenster.de (C. Weinheimer).

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is measured absolutely the whole neutrino mass spectrum can be obtained from the values $\Delta m_{ij}^2$ gained by the oscillation experiments. In the case of the matter effects involved, even the hierarchy of the different $m_i$ can be resolved.

Theories beyond the Standard Model try to explain the smallness of neutrino masses in comparison with the much heavier charged fermions [2]. One prominent explanation is the Seesaw type I mechanism using heavy Majorana neutrinos yielding a hierarchical pattern of neutrino masses. Alternatively, Seesaw type II models usually produce a scenario of quasi-degenerate neutrino masses with the help of a Higgs triplet. In the latter case, usually all masses are of order 0.1 eV or heavier exhibiting small mass differences between each other to explain the oscillations. In this quasi-degenerate case—due to the huge abundance of relic neutrinos in the universe left over from the big bang—neutrinos would make up not the major, but a significant contribution to the dark matter. Therefore, the open question of the neutrino mass scale is not only crucial for particle physics to decide between different theories beyond the Standard Model but it is also very important for astrophysics and cosmology.

There are different ways to determine the absolute neutrino masses:

– *Cosmology*. Astrophysical observations of the energy and matter distribution in the Universe at different scales give information on the neutrino mass. Usually these analyses use the combination of Cosmic Microwave Background data (e.g., from the WMAP satellite), the distribution of the galaxies in our universe, the so-called 'Large Scale Structure', and information from the so-called 'Lyman $\alpha$-Forest' or X-ray clusters to describe the distribution at large, medium and small scales, respectively. In most cases they give upper limits on the mass of the neutrinos on the order of several 0.1 eV [3] , in some cases non-zero neutrino masses are found [4] illustrating the dependence on the assumptions and on the data used to obtain the cosmological limits. One should not forget that the limits on the neutrino mass rely on the existence of the yet not observed relic neutrinos [5].

– *Neutrinoless double $\beta$ decay*. One laboratory way to access the neutrino mass scale is the search for the neutrinoless double $\beta$ decay [6]. In the case, that neutrinos are Majorana particles (particles are equal to their antiparticles) the double $\beta$ decay could occur without emission of any neutrinos. The transition matrix element is directly proportional to the neutrino mass (in the absence of right-handed weak charged currents or the exchange of other new particles). The observable of double $\beta$ decay is the so-called effective neutrino mass

$$m_{ee} = \sum_i \left| U_{ei}^2 \cdot m(\nu_i) \right| \tag{1}$$

which is a coherent sum over all neutrino mass eigenstates $m(\nu_i)$ contributing to the electron neutrino with their (complex) mixing matrix elements $U_{ei}$. Therefore, this method is very sensitive on Majorana neutrinos, but not so well suited to perform a precise determination of the neutrino masses. The main reasons are that the phases of the complex mixing matrix elements $U_{ei}$ are completely unknown and that the nuclear matrix element still has a theoretical uncertainty of about a factor of 2.

– *Direct neutrino mass determination*. In contrast to the other methods, the direct method does not require further assumptions. The neutrino mass is determined kinematically using the relativistic energy-momentum relationship $E^2 = p^2 + m^2$ (with $c = 1$). Therefore $m^2(\nu)$ is the observable in most cases. In principle, a kinematical neutrino mass measurement yields information on the different mass eigenstates $m(\nu_i)$, since it performs a projection on energy and mass. But the different neutrino mass eigenstates could not be resolved by the experiments yet. Therefore an average over neutrino mass eigenstates is obtained which is specific for the flavor of the weak decay and hence termed $m(\nu_e)$, $m(\nu_\mu)$ or $m(\nu_\tau)$, e.g.,

$$m^2(\nu_\alpha) := \sum_i |U_{\alpha i}^2| \cdot m(\nu_i)^2 \tag{2}$$

It should be noted, that this average may also depend on how the experiment is analyzed.
One direct determination is the time-of-flight measurement of neutrinos. Due to the smallness of the masses of neutrinos and the weakness of their interaction with matter only catastrophic cosmological events like a nearby supernova of type II could provide reasonable path lengths and count rates. The only observation of a supernova by neutrinos was SN1987a in the Large Magellan Cloud in 1987. The non-observation of a dependence of the arrival time of the supernova neutrinos on their energy gave an upper limit on the 'electron neutrino mass' [7] of

$$m(\nu_e) < 5.7\ \text{eV} \quad (95\%\ \text{C.L.}) \tag{3}$$

Unfortunately, nearby supernova explosions are too rare and even less understood to allow a further significant improvement.
The second and more sensitive direct method to determine neutrino masses is the investigation of the kinematics of a weak decay. It is based on measurements of the charged decay products. Using energy and momentum conservation, the missing neutrino mass can be reconstructed from the kinematics of the charged particles. The part of the phase space which is most

sensitive to the neutrino mass is the one which corresponds to the emission of a non-relativistic massive neutrino. Therefore decays releasing charged particles with little free kinetic energy are preferred.

Following this idea the pion decay and the tau decay have been investigated yielding mass limits of the 'muon neutrino mass' [8] of

$$m(\nu_\mu) < 190\ \text{keV} \quad (90\%\ \text{C.L.}) \tag{4}$$

and of the 'tau neutrino mass' [9] of

$$m(\nu_\tau) < 18.2\ \text{keV} \quad (95\%\ \text{C.L.}) \tag{5}$$

Considering the smallness of the squared neutrino mass differences $\Delta m^2_{ij}$ only the direct determination of the electron neutrino mass $m(\nu_e)$ (see below) is relevant.

This paper is organized as following: in Section 2 the direct electron neutrino mass determination is discussed. A brief review of the previous and current $\beta$ decay experiments in direct search for the electron neutrino mass is given in Section 3. Section 4 describes the new KATRIN experiment aiming for a 0.2 eV neutrino mass sensitivity. The conclusions are given in Section 5.

## 2. Direct determination of $m(\nu_e)$

The mass of the electron neutrino is determined by the investigation of the electron energy spectrum ($\beta$ spectrum) of a nuclear $\beta$ decay [10–13]. In a $\beta^-$ decay

$$(Z, A) \to (Z+1, A)^+ + e^- + \bar{\nu}_e \tag{6}$$

the available energy is shared between the $\beta$ electron and the electron antineutrino, because the recoiling nucleus practically receives no kinetic energy due to its much heavier mass. The phase space region of non-relativistic neutrinos, where the highest sensitivity to the neutrino mass is achieved, corresponds to the very upper end of the $\beta$ spectrum. To maximize this part, a $\beta$ emitter with a very low endpoint energy $E_0$ is required. This requirement is fulfilled by $^{187}$Re and tritium (T or $^3$H), which have the two lowest endpoint energies of $E_0 = 2.6$ keV and $E_0 = 18.6$ keV, respectively.

Although tritium has a higher endpoint energy as compared to $^{187}$Re its use has several advantages:

- Tritium decays by a super-allowed transition into its mirror nucleus $^3$He resulting in a half life of 12.3 years, compared to the primordial half life of the forbidden transition of $^{187}$Re of $5 \times 10^{10}$ y. The short half life yields a high specific activity and minimizes the inelastic processes of $\beta$ electrons within the tritium source.
- Due to the super-allowed decay the transition matrix element does not depend on the electron energy: the $\beta$ spectrum is determined entirely by the available phase space.
- Tritium has the simplest atomic shell minimizing the necessary corrections due to the electronic final states or inelastic scattering in the $\beta$ source.

These arguments clearly favor tritium for a standard setup, which consists of a $\beta$ source connected to a $\beta$ spectrometer (sometimes called 'passive source' setup). The advantage of the lower $^{187}$Re endpoint energy can only be exploited if the $\beta$ source and the spectrometer are identical (sometimes called 'active source' setup), which is realized in the case of cryogenic bolometers for instance.

The $\beta$ spectrum of an allowed $\beta^-$ decay is a pure phase space spectrum

$$\frac{\mathrm{d}^2 N}{\mathrm{d}t\,\mathrm{d}E} = \frac{G_\mathrm{F}^2 \cdot \cos^2 \Theta_\mathrm{C}}{2\pi^3 \hbar^7} \cdot M_\mathrm{nucl}^2 \cdot F(E, Z+1) \cdot p \cdot (E+m) \cdot \varepsilon \cdot \sum_i |U_{ei}^2| \cdot \sqrt{\varepsilon^2 - m^2(\nu_i)} \cdot \Theta\big(\varepsilon - m(\nu_i)\big) \tag{7}$$

with the Fermi constant $G_\mathrm{F}$, the Cabibbo angle $\Theta_\mathrm{C}$, the nuclear matrix element $M_\mathrm{nucl}$, the Fermi function $F$ accounting the Coulomb interaction of the out-going $\beta$ electron with the remaining daughter nucleus of charge $Z+1$, the mass $m$, momentum $p$ and kinetic energy $E$ of the electron, and the energy difference $\varepsilon = E_0 - E$. As Eq. (7) holds for the decay of a bare and infinitely heavy nucleus, for the more realistic case of a $\beta$-decaying atom or molecule the nuclear recoil and the possible excitation of the electron shell [32] due to the sudden change of the nuclear charge by one unit has to be taken into account.

Fig. 1 shows that the tiny change of the spectral shape due to the neutrino mass in the region just below the endpoint $E_0$, where the count rate is going to vanish, has to be resolved. Therefore, high energy resolution and large acceptance is required combined with large source strength as well as low background rate.

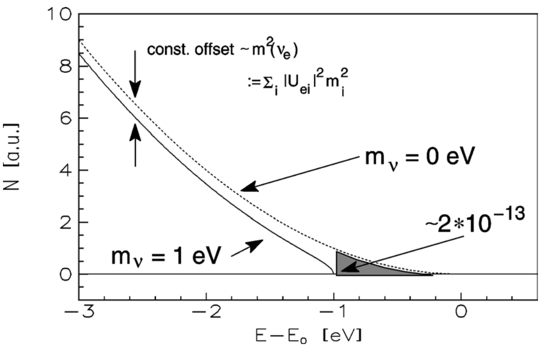

Fig. 1. Expanded tritium $\beta$ spectrum around tritium endpoint $E_0$ for $m(\nu_e) = 0$ (dashed line) and for an arbitrarily chosen neutrino mass of 1 eV (solid line). The gray shaded area corresponds to a fraction of $2 \times 10^{-13}$ of all tritium $\beta$ decays. The offset between the two curves explains the definition of '$m(\nu_e)$' Eq. (2).

For each neutrino mass state $m(\nu_i)$ contributing to the electron neutrino a kink at $E_0 - m(\nu_i)$ with a size proportional to $|U_{ei}^2|$ will occur. However, due to the smallness of differences of squared neutrino masses $\Delta m_{ij}^2$ observed in oscillation experiments and as a consequence of the limited sensitivity of present and upcoming direct neutrino mass experiments only an incoherent sum or an average neutrino mass can be obtained [13], which can be defined as the *electron neutrino mass* $m(\nu_e)$ (compare also to Eq. (2)) by

$$m^2(\nu_e) := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i) \tag{8}$$

The comparison of Eqs. (1) and (8) shows that the investigation of the $\beta$ decay spectrum is a direct determination of the (electron) neutrino mass, since neither the phases of the neutrino mixing matrix $U$ do not change the result of Eq. (8) nor other assumptions on neutrino properties (like Majorana- or Dirac-particle) do. Secondly, since we know from neutrino oscillation experiments that $U_{e1}$ and $U_{e2}$ are big, the determination of the electron neutrino mass $m(\nu_e)$ is a good measure of the absolute neutrino mass scale.

## 3. Direct electron neutrino mass experiments

The majority of the published direct laboratory results on $m(\nu_e)$ originates from the investigation of tritium $\beta$ decay, while only two results from $^{187}$Re has been reported very recently (there are also results from investigations of electron capture [14] and bound state $\beta$ decay [15], which are about 2 orders of magnitude less stringent on the neutrino mass). In the long history of tritium $\beta$ decay experiments, about a dozen of experiment results have been reported starting with the experiment of Curran in the late 1940s yielding $m^2(\nu_e) < 1$ keV [16].

In the beginning of the 1980s a group from the Institute of Theoretical and Experimental Physics (ITEP) at Moscow [17] claimed the discovery of a non-zero neutrino mass of around 30 eV. The ITEP group used as $\beta$ source a thin film of tritiated valine combined with a new type of magnetic 'Tretyakov' spectrometer. The first results testing the ITEP claim came from the experiments at the University of Zürich [18] and the Los Alamos National Laboratory (LANL) [19]. Both groups used similar Tretyakov-type spectrometers, but more advanced tritium sources with respect to the ITEP group. The Zürich group used a solid source of tritium implanted into carbon and later a self-assembling film of tritiated hydrocarbon chains. The LANL group developed a gaseous molecular tritium source avoiding solid state corrections. Both experiments disproved the ITEP result. The reason for the ITEP 'mass signal' at ITEP was twofold: the energy loss correction was probably overestimated, and a $^3$He–T mass difference measurement [20] confirming the endpoint energy of the ITEP result, turned out only later to be significantly wrong [21].

Also in the 1990s tritium $\beta$ decay experiments yielded controversially discussed results: Fig. 2 shows the final results of the experiments at LANL and Zürich together with the results from other more recent measurements with magnetic spectrometers at University of Tokyo, Lawrence Livermore National Laboratory and Beijing. The sensitivity on the neutrino mass has much improved, but the values for the observable $m^2(\nu_e)$ populated the unphysical negative $m^2(\nu_e)$ region. In 1991 and 1994 two new experiments started data taking at Mainz and at Troitsk, which used a new type of electrostatic spectrometer, so-called MAC-E-Filters, which were superior in energy resolution and luminosity with respect to the previous magnetic spectrometers. However, even their early data were confirming the large negative $m^2(\nu_e)$ values of the LANL and Livermore experiments when being analyzed over the last 500 eV of the $\beta$ spectrum below the endpoint $E_0$. But the large negative values of $m^2(\nu_e)$

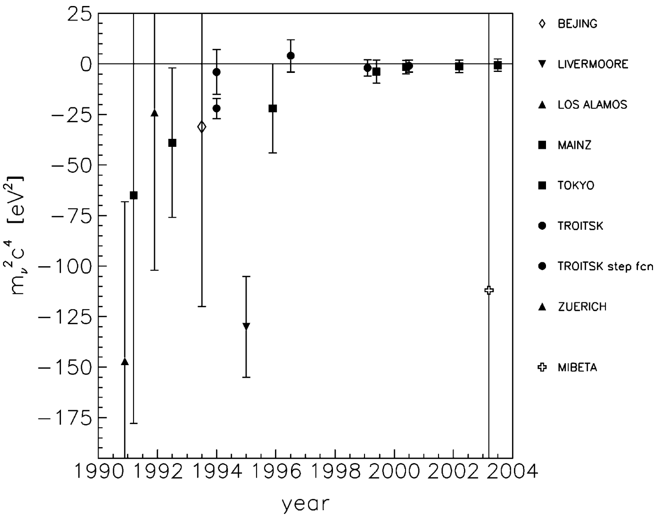

Fig. 2. Recent results of $\beta$ decay experiments on the observable $m^2(\nu_e)$. The tritium experiments at Los Alamos, Zürich, Tokyo, Beijing and Livermore [22–26] used magnetic spectrometers, the tritium experiments at Mainz and Troitsk [27–30] are using electrostatic spectrometers of the MAC-E-Filter type (see text), the MiBeta result originates from a cryobolometer measurement with $^{187}$Re [31].

disappeared when analyzing only small intervals below the endpoint $E_0$. This effect, which could only be investigated by the high luminosity MAC-E filters, pointed towards an underestimated or missing energy loss process, seemingly to be present in all experiments. The only common feature of the various experiment seemed to be the calculations of the electronic excitation energies and excitation probabilities of the daughter ions. Different theory groups checked these calculations in detail. The expansion was calculated to one order further and new interesting insight into this problem was obtained, but no significant changes were found [32].

Then the Mainz group found the origin of the missing energy loss process for its experiment. The Mainz experiment used as tritium source a film of molecular tritium quench-condensed onto aluminum or graphite substrates. Although the film was prepared as a homogeneous thin film with flat surface, detailed studies showed [33] that the film undergoes a temperature activated roughening transition into an inhomogeneous film by formation of microcrystals leading to unexpected large inelastic scattering probabilities.

The Troitsk experiment on the other hand used a windowless gaseous molecular tritium source, similar to the LANL apparatus. Here, the influence of large angle scattering of electrons magnetically trapped in the tritium source was not considered in the first analysis. After correcting for this effect the negative values for $m^2(\nu_e)$ disappeared.

The fact that more experimental results of the early 1990s populate the region of negative $m^2(\nu_e)$ values (see Fig. 2) can be understood by the following consideration [10]: for $\varepsilon \gg m(\nu_e)$, Eq. (7) can be expanded into

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto \varepsilon^2 - m^2(\nu_e)/2 \tag{9}$$

On the other hand the convolution of a $\beta$ spectrum (7) with a Gaussian of width $\sigma$ leads to

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto \varepsilon^2 + \sigma^2 \tag{10}$$

Therefore, in the presence of a missed experimental broadening with Gaussian width $\sigma$ one expects a shift of the result on $m^2(\nu_e)$ of

$$\Delta m^2(\nu_e) \approx -2 \cdot \sigma^2 \tag{11}$$

which gives rise to a negative value of $m^2(\nu_e)$ [10].

### 3.1. MAC-E-Filter

The significant improvement in the neutrino mass sensitivity by the Troitsk and the Mainz experiments are due to MAC-E-Filters (Magnetic Adiabatic Collimation with an Electrostatic Filter) [34]. It combines high luminosity at low background and a high energy resolution.

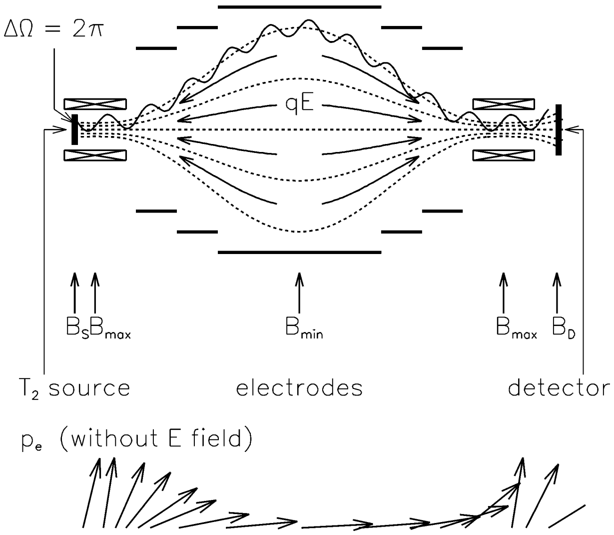

Fig. 3. Principle of the MAC-E-Filter. Top: experimental setup, bottom: momentum transformation due to adiabatic invariance of the orbital magnetic momentum $\mu$ in the inhomogeneous magnetic field.

The main features of the MAC-E-Filter are illustrated in Fig. 3: two superconducting solenoids are producing a magnetic guiding field. The $\beta$ electrons, starting from the tritium source in the left solenoid into the forward hemisphere, are guided magnetically on a cyclotron motion along the magnetic field lines into the spectrometer, thus resulting in an accepted solid angle of nearly $2\pi$. On their way into the center of the spectrometer the magnetic field $B$ drops adiabatically by several orders of magnitude keeping the magnetic orbital moment $\mu$ invariant (equation given in non-relativistic approximation):

$$\mu = \frac{E_\perp}{B} = \text{const} \tag{12}$$

Therefore nearly all cyclotron energy $E_\perp$ is transformed into longitudinal motion (see Fig. 3 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 made up of a system of one or more cylindrical electrodes. The relative sharpness of this energy high-pass filter is only given by the ratio of the minimum magnetic field $B_{\text{min}}$ reached at the electrostatic barrier in the so-called analyzing plane and the maximum magnetic field between $\beta$ electron source and spectrometer $B_{\text{max}}$:

$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \tag{13}$$

### 3.2. The Mainz neutrino mass experiment

The Mainz setup was upgraded in 1995–1997, including the installation of a new tilted pair of superconducting solenoids between tritium source and spectrometer and the use of a new cryostat providing tritium film temperatures of below 2 K. The first measure eliminated source correlated background and allowed the source strength to be increased significantly. The second measure avoids the roughening transition of the homogeneously condensed tritium films with time [33], which previously gave rise to negative values of $m^2(\nu_e)$ when the data analysis used large intervals of the $\beta$ spectrum below the endpoint $E_0$. The upgrade was completed by the application of HF pulses on one of the electrodes in between measurements every 20 s, and a full automation of the apparatus and remote control. This former improvement lowers and stabilizes the background, the latter allows long-term measurements.

Fig. 4 shows the endpoint region of the Mainz 1998, 1999 and 2001 data in comparison with the earlier Mainz 1994 data. An improvement of the signal-to-background ratio by a factor 10 by the upgrade of the Mainz experiment as well as a significant enhancement of the statistical quality of the data by longterm measurements are clearly visible. The main systematic uncertainties of the Mainz experiment are the inelastic scattering of $\beta$ electrons within the tritium film, the excitation of neighbor molecules due to sudden change of the nuclear charge during $\beta$ decay, and the self-charging of the tritium film by its radioactivity. As a result of detailed investigations in Mainz [35,36,28]—mostly by dedicated experiments—the systematic corrections became much better understood and their uncertainties were reduced significantly. The high-statistics Mainz data from 1998–2001 al-

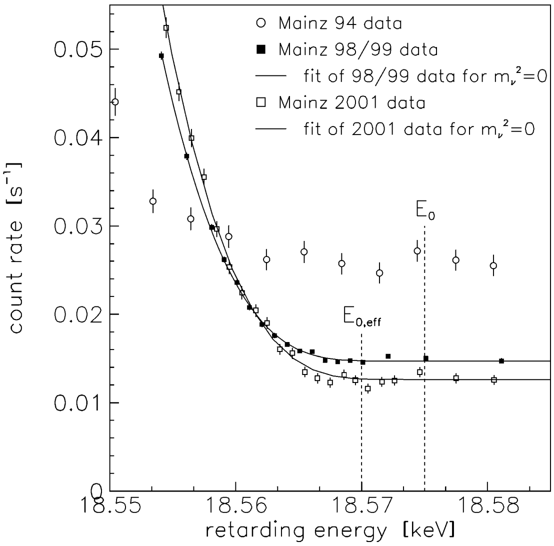

Fig. 4. Averaged count rate of the Mainz 1998/1999 data (filled squares) with fit for $m(\nu_e) = 0$ (line) and of the 2001 data (open squares) with fit for $m(\nu_e) = 0$ (line) in comparison with previous Mainz data from 1994 (open circles) as a function of the retarding energy near the endpoint $E_0$ and effective endpoint $E_{0,\text{eff}}$ (accounting for the width of response function of the setup and the mean rotation-vibration excitation energy of the electronic ground state of the $^3\text{HeT}^+$ daughter molecule).

lowed the first determination of the probability of the neighbor excitation to occur in $(5.0 \pm 1.6 \pm 2.2)\%$ of all $\beta$ decays [28] in good agreement with the theoretical expectation [37].

The analysis of the last 70 eV below the endpoint of the 1998, 1999 and 2001 data, resulted in [28]

$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\ \text{eV}^2/\text{c}^4 \tag{14}$$

which corresponds to an upper limit of

$$m(\nu_e) < 2.3\ \text{eV} \quad (95\%\ \text{C.L.}) \tag{15}$$

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

### 3.3. *The Troitsk neutrino mass experiment*

The windowless gaseous tritium source of the Troitsk experiment [30] is essentially a tube of 5 cm diameter filled with $T_2$ resulting in a column density of $10^{17}$ molecules/cm$^2$. The source is connected to the ultrahigh vacuum of the spectrometer by a series a differential pumping stations.

From their first measurement in 1994 on the Troitsk group has reported the observation of a small, but significant anomaly in its experimental spectra starting a few eV below the $\beta$ endpoint $E_0$. This anomaly appears as a sharp step of the count rate [29]. Since a MAC-E-Filter is integrating, this step should correspond to a narrow line in the primary spectrum with a relative intensity of about $10^{-10}$ of the total decay rate. In 1998 the Troitsk group reported that the position of this line oscillates with a frequency of 0.5 years between 5 eV and 15 eV below $E_0$ [30]. In 2000 the anomaly did not follow the 0.5 year periodicity anymore, but still existed in most data sets. The reason for such an anomaly with these features is not clear.

In Mainz a similar behaviour has been found only in one run taken under unfavorite conditions [28]. In dedicated measurements at Mainz, synchronously taken with the Troitsk experiment, the anomaly was seen at Troitsk, but not at Mainz. After some experimental improvements the first two runs of 2001 at Troitsk either gave no indication for an anomaly or only showed a small effect with 2.5 mHz amplitude if compared to the previous ones with amplitudes between 2.5 mHz and 13 mHz. These findings as well as the Mainz data clearly support the assumption that the Troitsk anomaly is due to an still unknown experimental artefact.

In presence of this problem, the Troitsk experiment is correcting for this anomaly by fitting an additional line to the $\beta$ spectrum run-by-run. Combining the 2001 results with the previous ones since 1994 gives [38]

$$m^2(\nu_e) = (-2.3 \pm 2.5 \pm 2.0)\ \text{eV}^2/\text{c}^4 \tag{16}$$

from which the Troitsk group deduce an upper limit of

$$m(\nu_e) < 2.05 \text{ eV} \quad (95\% \text{ C.L.}) \tag{17}$$

The values of Eqs. (16) and (17) do not include the systematic uncertainty which is needed to account for, when the timely-varying anomalous excess count rate at Troitsk is described run-by-run by an additional line.

### *3.4. Rhenium $\beta$ decay experiments*

Two groups are working on $^{187}$Re $\beta$ decay experiments at Milan (MiBeta) and at Genoa (MANU2) using cryo-bolometers with $AgReO_4$ and metallic rhenium absorbers, respectively. Arrays of many detectors have to be used, since with the bolometer-technique always the whole $\beta$ spectrum has to be measured. The lowest neutrino mass limit of $m(\nu_e) < 15$ eV comes from MiBeta [31]. Further improvements in the energy resolution and the number of crystals are envisaged aiming for a sensitivity of a few eV.

## 4. The KATRIN experiment

The very important tasks presented in the introduction—to distinguish hierarchical from quasi-degenerate neutrino mass scenarios and to check the cosmological relevance of neutrino dark matter for the evolution of the universe—require the improvement of the direct neutrino mass search by one order of magnitude at least.

The KATRIN collaboration has taken up this challenge and has started to build an ultra-sensitive tritium $\beta$ decay experiment [39] at the Forschungszentrum Karlsruhe based on the successful MAC-E-Filter spectrometer technique and a very strong Windowless Gaseous Tritium Source (WGTS). The international KATRIN collaboration consists of many groups from Czech Republic, Germany, Russia, UK and US, combining the worldwide expertise on tritium $\beta$ decay and groups providing special knowledge with the strength and the possibilities of a big national laboratory including Europeans biggest tritium facility. Fig. 5 shows a schematic view of the proposed experimental configuration.

The windowless gaseous tritium source (WGTS) allows for the measurement of the endpoint region of the tritium $\beta$ decay and consequently the determination of the neutrino mass with a maximum of signal strength combined with a minimum of systematic uncertainties from the tritium source. The WGTS consists of a 10 m long cylindrical tube of 90 mm diameter filled with molecular tritium gas of high isotopic purity ($> 95\%$) at a magnetic field of 3.6 T. The tritium gas will be continuously injected by a capillary at the middle and pumped out by a series of differential pump stations at the end giving rise to a density profile over the source length of nearly triangular shape with a total column density of $5 \times 10^{17}/\text{cm}^2$ providing a count rate about a factor 100 larger than in Mainz and Troitsk. Of special importance is the control of the column density on the 1 per mill level by regulating the pressure in the tritium supply buffer vessel and the temperature of the WGTS tube. To allow a very stable and low WGTS temperature the WGTS tube is placed inside a pressure-stabilized LNe cryostat.

The electron transport system adiabatically guides $\beta$ decay electrons from the tritium source to the spectrometer by a system of superconducting solenoids at a magnetic field of 5.6 T. At the same time it is eliminating any tritium flow towards the spectrometer by a differential pumping system consisting of 1 m long tubes inside the magnets alternated by pump ports with turbo molecular pumps yielding a tritium reduction factor of about a factor of $10^7$. The pumped-out tritium gas is then purified and re-injected into the WGTS. In the second part the surfaces of the liquid helium cold vacuum tube act as a cryo-trapping section to suppress the tritium partial pressure further to an insignificant level.

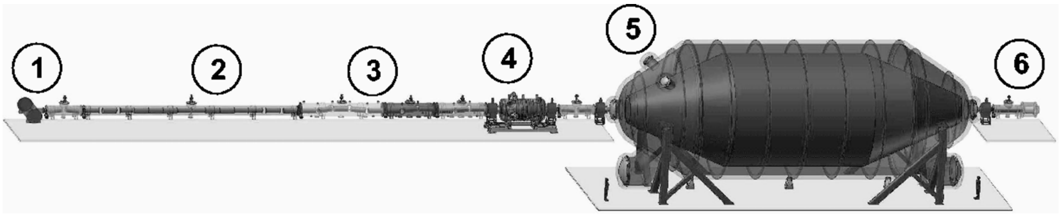

Fig. 5. Schematic view of the KATRIN experiment with the rear monitoring and calibration system (1), the windowless gaseous tritium source (WGTS) (2), the differential and cryopumping electron transport section (3), the pre spectrometer (4), the main spectrometer (5) and the electron detector array (6). The main spectrometer has a length of 23 m and a diameter of 10 m, the overall length over the experimental setup amounts to about 70 m. Not shown is the monitor spectrometer.

Between the tritium source and the main spectrometer a pre-spectrometer of MAC-E-Filter acts as an electron pre-filter running at a retarding energy about 200 eV below the endpoint of the $\beta$ spectrum to reject all $\beta$ electrons except the very high energetic ones in the region of interest close to the endpoint $E_0$. This minimizes the chances that $\beta$ electrons cause background in the main spectrometer by ionization of residual gas. The KATRIN pre-spectrometer has already been set up at the Forschungszentrum Karlsruhe. The vacuum tests with the pre-spectrometer have been successfully finished yielding at a temperature of $-20\,^\circ\mathrm{C}$ a final pressure of less than $10^{-11}$ mbar and a outgasing rate of less than $10^{-13}$ mbar l/s cm$^2$. Both values are better than or meeting the stringent KATRIN design parameters.

The electrostatic main spectrometer (of MAC-E-Filter type as well) with a diameter of 10 m and an overall length of about 23 m will allow the scanning of the tritium $\beta$ decay endpoint at a resolution of $\Delta E = 0.93$ eV, which is—at a much higher luminosity—a factor of 4–5 better than for the MAC-E-Filters in Mainz and Troitsk. Although limiting the electron input rate by the pre-spectrometer, stringent vacuum conditions have to be fulfilled to suppress background. Special selection of materials as well as surface cleaning and out-baking at $350\,^\circ\mathrm{C}$ will allow to reach a residual gas pressure of better than $10^{-11}$ mbar. To reduce the size of surfaces inside the vacuum chamber the vacuum vessel itself will be put on high voltage and thus will create the electric retarding potential.

A new idea of strong background suppression has been developed and successfully tested at the Mainz spectrometer, where it resulted in a factor 10 reduced background rate. It will be applied also to the KATRIN spectrometers: the vessel walls at high potential will be covered by a system of nearly massless wire electrodes, which are put to a slightly more negative potential. Secondary electrons ejected from the vessel walls by cosmic rays or environmental radioactivity, which could increase the background rate at the detector, will thus be repelled.

The final KATRIN detector requires high efficiency for electrons at $E_0 = 18.6$ keV and low $\gamma$ background. The present concept of the detector is based on a large array of about 400 PIN photodiodes surrounded by low-level activity passive shielding and an active veto counter to reduce background.

The KATRIN collaboration [39] has done significant work to increase the sensitivity of the experiment. To statistics will be improved by the new design of a tritium re-circulating and purification system providing a near to maximum tritium purity of $> 95\%$, by the increase of the diameter of the windowless tritium source (75 to 90 mm) and, correspondingly, of the diameter of the main spectrometer (7 to 10 m) and by an optimization of the measurement point distribution around the endpoint. Instrumental improvements have been developed as well as plans for dedicated experiments and their analysis have been worked out in order to determine systematic corrections and to reduce their uncertainties. The main systematic uncertainties comprise the inelastic scattering within the tritium source, the stability of the potential in the tritium source and of the retarding voltage of the main spectrometer, which will be checked by an additional monitor spectrometer with electron calibration lines.

The detailed simulations of the KATRIN experiment yield that a sensitivity of 0.20 eV/c$^2$ will be achieved with the KATRIN experiment after 3 years of pure data taking. Statistical and systematic uncertainties contribute about equally. This value of 0.20 eV/c$^2$ corresponds to an upper limit with 90% C.L. in the case that no neutrino mass will be observed. To the contrary, a non-zero neutrino mass of 0.30 eV/c$^2$ would be detected with $3\sigma$ significance, a mass of 0.35 eV/c$^2$ even with $5\sigma$.

The full setup of the KATRIN experiment will be finished and data taking will start in 2008.

## 5. Conclusions

Neutrino oscillation experiments have pointed to new physics beyond the Standard Model by proving that neutrinos mix and that they have non-zero neutrino masses. The next goal is to determine the absolute scale of the neutrino mass due to its high importance for particle physics, astrophysics and cosmology.

Among various ways to address the absolute neutrino mass scale the investigation of the shape of a $\beta$ decay spectrum near its endpoint is the only model-independent method. This direct method is complementary to the search for the neutrinoless double $\beta$ decay and to the information from astrophysics and cosmology. Possible isotopes are $^{187}$Re and tritium. The first experiments with $^{187}$Re resulted in a limit on the neutrino mass of 15 eV. The tritium $\beta$ decay experiments at Mainz and Troitsk have been finished yielding upper limits of about 2 eV/c$^2$. The new KATRIN experiment—also investigating the tritium $\beta$ spectrum—will enhance the sensitivity further by one order of magnitude down to 0.2 eV/c$^2$ to be able to probe the cosmological relevant neutrino mass region and to distinguish quasi-degenerate from hierarchical neutrino mass scenarios.

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