

Neutrino Mass

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By the clear evidence of neutrino oscillations the existence of non-zero neutrino masses is proven. With the various neutrino oscillation experiments their mixing angles and their squared mass differences but not the absolute neutrino mass scale are being determined. This absolute scale of neutrino masses is very important for understanding the evolution and the structure formation of the universe as well as for nuclear and particle physics beyond the present Standard Model. Complementary to deducing statements on the sum of all neutrino masses from cosmological observations two different methods to determine the neutrino mass scale in the laboratory are pursued: the search for neutrinoless double β decay and the direct neutrino mass search by investigating single β decays. For both methods currently experiments with a sensitivity of $O(100)$ meV using quite different techniques are being set up or commissioned.

1 Introduction

The various oscillation experiments with solar, atmospheric, reactor and accelerator neutrinos have shown, that the different neutrino flavors mix and can oscillate during flight from one flavor state into another. The analysis of all neutrino oscillation experiments yields the mixing angles and the differences of squared neutrino mass eigenstates [1, 2]. Clearly these findings prove that neutrinos have non-zero masses, but they cannot determine the absolute neutrino mass scale. The huge abundance of neutrinos left over in the universe from the big bang ($\approx 336/\text{cm}^3$) and their contribution to structure formation and the evolution of the universe (*e.g.* [3]) as well as the key role of neutrino masses in finding the new Standard Model of particle physics (*e.g.* [4]) make the absolute value of the neutrino mass one of today's most urgent questions of astroparticle physics and cosmology as well as of nuclear and particle physics.

There exist 3 different approaches to the absolute neutrino mass scale:

- Cosmology
Essentially, information on the sum of all neutrino masses $\sum m(\nu_i)$ is obtained by observing the size of cosmological fluctuations at different scales using cosmic microwave background and large scale structure data. Since light – and therefore relativistic at the time of structure formation – neutrinos would have smeared out fluctuations at small scales the power spectrum at small scales is sensitive to the sum of the neutrino masses. Up to now, no non-zero value but only limits on the sum of the 3 neutrino masses have been obtained around $\sum m(\nu_i) < 0.61 \text{ eV}/c^2$ (*e.g.* [5]), which are to some extent model and analysis dependent [6].
- Neutrinoless double β decay ($0\nu\beta\beta$)

A neutrinoless double β decay¹ is forbidden in the Standard Model of particle physics. It could exist, if the neutrino is its own antiparticle (“Majorana-neutrino” in contrast to “Dirac-neutrino”). Furthermore, a finite neutrino mass is required in order to produce in the chirality-selective interaction a neutrino with a small component of opposite handedness on which this neutrino exchange subsists. The decay rate would scale with the absolute square of the so called effective neutrino mass m_{ee} . This effective neutrino mass takes into account the neutrino mixing matrix U and represents the coherent sum of the $m(\nu_i)$ -components of the $0\nu\beta\beta$ -decay amplitudes and hence carries their relative phases²:

$$\Gamma_{0\nu\beta\beta} \propto \left| \sum U_{ei}^2 m(\nu_i) \right|^2 := m_{ee}^2 \quad (1)$$

A significant additional uncertainty entering the relation of m_{ee} and the decay rate comes from the uncertainties of the nuclear matrix elements of the neutrinoless double β decay [10].

- Direct neutrino mass determination

The direct neutrino mass determination is based purely on relativistic kinematics without further assumptions. Therefore it is sensitive to the neutrino mass squared $m^2(\nu)$. In principle there are two methods: time-of-flight measurements and precision investigations of weak decays. The former requires very long baselines and therefore very strong sources, which only cataclysmic cosmological events like a core-collapse supernova could provide. The non-observation of a dependence of the arrival time on energy of supernova neutrinos from SN1987a gave upper limits on the neutrino mass of about 6 eV/c² [8, 9]. Unfortunately nearby supernova explosions are too rare and too little understood to allow an improvement into the sub-eV range.

Therefore, aiming for a sub-eV sensitivity, the investigation of the kinematics of weak decays and more explicitly the investigation of the endpoint region of a β decay spectrum is still the most sensitive model-independent and direct method to determine the neutrino mass. Here the neutrino is not observed but the charged decay products are precisely measured. Using energy and momentum conservation the neutrino mass can be obtained. In the case of the investigation of a β spectrum usually the “average electron neutrino mass” $m(\nu_e)$ is determined:

$$m(\nu_e)^2 := \sum |U_{ei}^2| m(\nu_i)^2 \quad (2)$$

This incoherent sum is not sensitive to phases of the neutrino mixing matrix.

Figure 1 demonstrates that the different methods are complementary to each other and compares them. It shows, that the cosmological relevant neutrino mass scale $\sum m(\nu_i)$ has a nearly full correlation to $m(\nu_e)$ determined by direct neutrino mass experiments. The observable of neutrinoless double β decay, the effective neutrino mass m_{ee} , does not allow a very precise neutrino mass determination, *e.g.* to determine $\sum m(\nu_i)$, due to the unknown CP and Majorana phases and the uncertainties of the nuclear matrix elements [10]. On the other hand

¹Two β decays in the same nucleus at the same time with emission of two β electrons (positrons) while the (anti)neutrino emitted at one vertex is absorbed at the other vertex as a neutrino (antineutrino).

²These are the usual CP-violating phase of an unitary 3×3 mixing matrix and two so-called Majorana-phases, which only exist for Majorana particles.

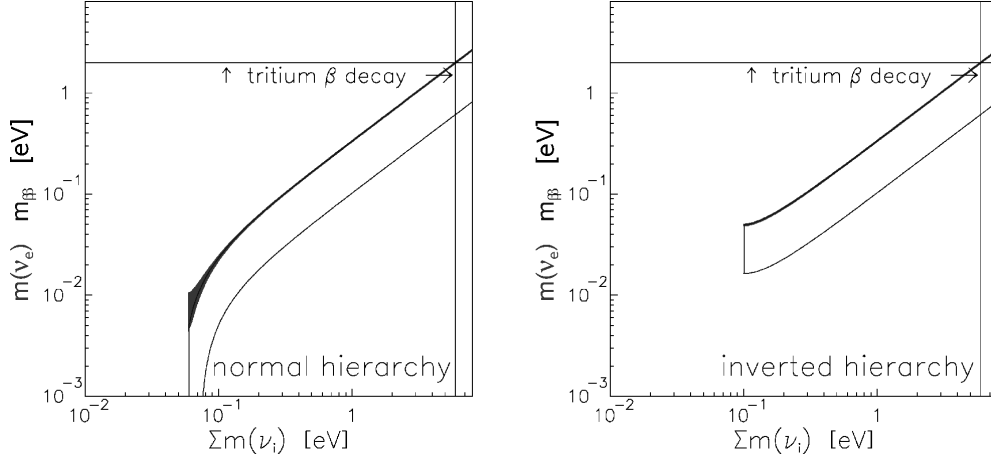


Figure 1: Observables of neutrinoless double β decay m_{ee} (open band) and of direct neutrino mass determination by single β decay $m(\nu_e)$ (gray band on upper boarder of m_{ee} band) versus the cosmologically relevant sum of neutrino mass eigenvalues $\sum m(\nu_i)$ for the case of normal hierarchy (left) and of inverted hierarchy (right) [7]. The width of the bands/areas is caused by the experimental uncertainties of the neutrino mixing angles [1] and in the case of m_{ee} also by the completely unknown Majorana- and CP-phases. Uncertainties of the nuclear matrix elements [10], which enter the experimental determination of m_{ee} , are not considered.

the combination of all three methods gives an experimental handle on the Majorana phases. Furthermore, the search for the neutrinoless double β decay is the only way to prove the Majorana character of neutrinos and one of the most promising ways to search for lepton number violation.

This article is structured as follows: Section 2 reports on the various searches for neutrinoless double β decay. In section 3 the neutrino mass determination from tritium and ^{187}Re β decay are presented. The conclusions are given in section 4.

2 Search for neutrinoless double β decay

There are more than 10 double β decay isotopes. For most of them the normal double β decay with neutrino emission has been observed. For neutrinoless double β decay there is only one claim for evidence at $m_{ee} \approx 0.4 \text{ eV}/c^2$ by part of the Heidelberg-Moscow collaboration [11], all other experiments so far set upper limits. A couple of experiments with sensitivity $\mathcal{O}(100) \text{ meV}$ are being set up to check this claim. Common to all these experiments is the use of ultrapure materials with very little radioactivity embedded in a passive and an active shield placed in an underground laboratory.

The most important signature of neutrinoless double β decay is, that the sum of the energy of both decay electrons (in case of double β^- decay, positrons for double β^+ decay) is equal to the Q -value of the nuclear transition. The experimental approaches can be classified into two methods (see Figure 2) [13]:

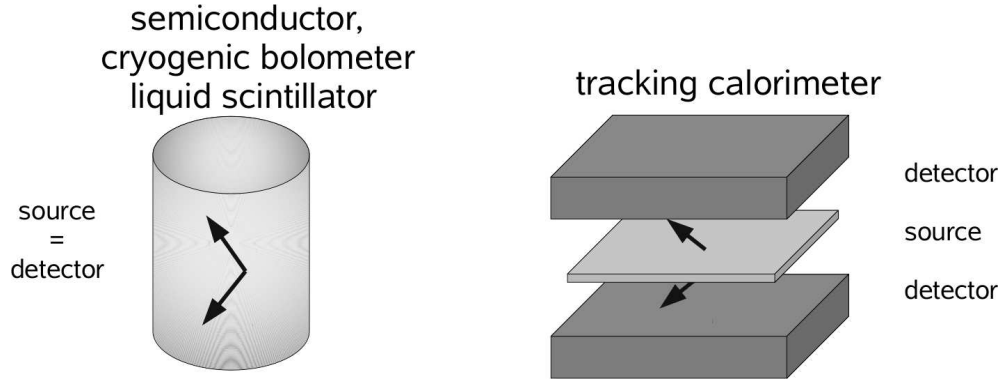


Figure 2: Two different experimental configurations in search for the neutrinoless double β decay.

2.1 “Source=detector” configuration

In the “source=detector” configuration the double β decay nuclei are part of the detector, which measures the sum of the energy of both β electrons. The experimental implementation of these calorimeters are semiconductors (*e.g.* isotopes: ^{76}Ge , ^{116}Cd , experiments: GERDA, MAJORANA, COBRA), cryo-bolometers (*e.g.* isotope: ^{130}Te , ^{82}Se , experiments: CUORICINO and its successor CUORE), LUCIFER and liquid scintillators (*e.g.* isotope: ^{48}Ca , ^{136}Xe , ^{152}Nd , experiments: EXO-200, SNO+, NEXT, KamLAND-Zen, CANDLE). In general, this method allows more easily to install a large target mass.

Currently the most sensitive limits comes from the CUORICINO experiment, which consisted of a tower of 62 tellurium oxide³ cryo-bolometers with an active mass of 40.7 kg at the Gran Sasso underground laboratory LNGS yielding [12]⁴:

$$t_{1/2}(^{130}\text{Te}) > 3 \cdot 10^{24} \text{ y} \quad \text{and} \quad m_{ee} < 0.19 - 0.68 \text{ eV} \quad (3)$$

The CUORICINO experiment has been completed and the installation of the nearly 20 times larger successor experiment CUORE has started.

The GERDA experiment [14] at Gran Sasso is being proceeded in two phases at the Gran Sasso underground laboratory with the option of a third phase together with the MAJORANA experiment [15]. GERDA uses enriched Germanium⁵ embedded in a shielding cryostat filled with liquid argon, which itself sits in a water veto tank. This new shielding technique and the use of segmented or point-contact detectors in phase 2 should improve the background rate compared to the Heidelberg Moscow experiment by orders of magnitude. The commissioning of the GERDA experiment is nearly finished and the data taking will start in 2010.

The EXO collaboration starts with the EXO-200 detector [16], a liquid Xenon TPC with 200 kg of enriched Xenon (80 % enrichment of the double β decay isotope ^{136}Xe). The data

³The Cuoricino TeO_2 crystals are made out of natural tellurium with a 34 % fraction of the double β decay isotope ^{130}Te .

⁴The range of the effective neutrino mass limits originates from the different nuclear matrix elements calculated by different theory groups (see *e.g.* [10]).

⁵The enrichment of the double β decay isotope ^{76}Ge is about 86 %. The total mass of the phase 1 detectors amounts to 18 kg.

taking, first with natural xenon, will start in 2010.

The SNO+ experiment [17] is using the former solar neutrino detector SNO. The inner acrylic vessel will be filled with liquid scintillator, which will be doped by the double β decay isotope ^{152}Nd . Start of data taking is planned for 2013.

2.2 “Source \neq detector” configuration

In this configuration the double β decay source is separated from two tracking calorimeters, which determine direction and energy of both β electrons separately (*e.g.* isotope ^{82}Se , ^{100}Mo , experiments: NEMO3 and its much larger successor SuperNEMO, ELEGANT, MOON).

By this method the most sensitive limit comes from the NEMO3 experiment [18] in the Modane underground laboratory LSM. NEMO3 is using thin source foils of a total area of 20 m^2 . These foils contain 7 kg of the double β decay isotope ^{100}Mo and 1 kg of the double β decay isotope ^{82}Se . The foils are surrounded by a tracking chamber in a magnetic field composed of 6400 drift cells working in Geiger mode and calorimeter made out of 1940 plastic scintillators. The recent upper limits on neutrinoless double β decay from NEMO3 are [18]⁴:

$$\begin{aligned} t_{1/2}(^{100}\text{Mo}) &> 1.1 \cdot 10^{24} \text{ y} & \text{and} & & m_{ee} < 0.45 - 0.93 \text{ eV} \\ t_{1/2}(^{82}\text{Se}) &> 3.6 \cdot 10^{23} \text{ y} & \text{and} & & m_{ee} < 0.89 - 1.61 \text{ eV} \end{aligned}$$

Although it requires much larger detectors to accumulate similar large target masses as in the “source=detector” case, there is the advantage, that the independent information of both electrons allows to study double β decay processes with 2 neutrinos in detail. In case neutrinoless double β decay would be detected, the angular correlation of both electrons will allow to draw some conclusion on the underlying process⁶.

3 Direct neutrino mass experiments

The signature of a non-zero neutrino mass is a tiny modification of the spectrum of the β electrons near its endpoint (see Figure 3), which has to be measured with very high precision. To maximize this effect, β emitters with low endpoint energy are favored.

3.1 “Source \neq detector” configuration: Tritium β decay experiments

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. Tritium β decay experiments using a tritium source and a separated electron spectrometer have been performed in search for the neutrino mass for more than 50 years [7] yielding a sensitivity of 2 eV by the experiments at Mainz [20] and Troitsk [21]. The huge improvement of these experiments in the final sensitivity as well as in solving the former “negative $m^2(\nu_e)$ ” problem with respect to previous experiments is mainly caused by the new spectrometers of MAC-E Filter type and by careful studies of the systematics.

The international KATRIN collaboration has taken the challenge set by the astrophysics and particle physics arguments to increase the sensitivity on the neutrino mass down to 0.2 eV.

⁶A theorem by Schechter and Valle [19] requests the neutrinos to have non-zero Majorana masses, if neutrinoless double β decay is proven to exist, but the dominant process could still be different, *e.g.* based on the exchange of a SUSY particle or by the contribution of right-handed weak charged currents.

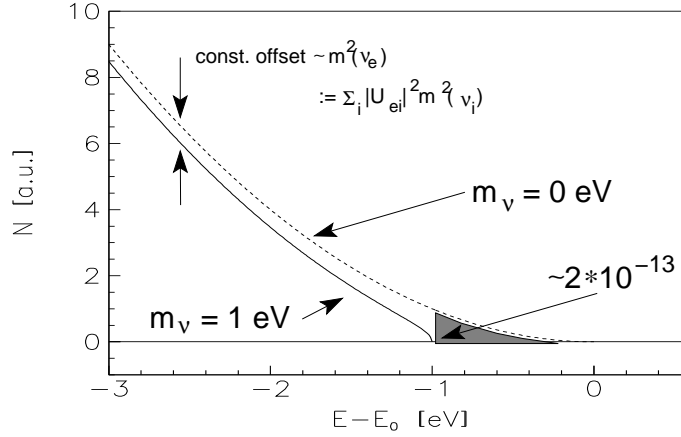


Figure 3: Expanded β spectrum around its endpoint E_0 for $m(\nu_e) = 0$ (dashed line) and for an arbitrarily chosen neutrino mass of 1 eV (solid line). In the case of tritium, the gray-shaded area corresponds to a fraction of $2 \cdot 10^{-13}$ of all tritium β decays.

It 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) [22, 23] at the Karlsruhe Institute of Technology, Germany (formerly Forschungszentrum Karlsruhe). Improving tritium β -spectroscopy by a factor of 100 in the observable $m^2(\nu_e)$ evidently requires brute force, based on proven experimental concepts, and further improvements in many aspects. It was decided, therefore, to build a spectrometer of MAC-E-Filter type with a diameter of 10 m, corresponding to a 100 times larger analyzing plane as compared to the pilot instruments at Mainz and Troitsk, fed by β electrons from a high-luminosity windowless gaseous molecular tritium source. Figure 4 depicts a schematic plan of the whole 70 m long setup.

A decay rate of 10^{11} Bq is aimed for in a source with a diameter of 9 cm requiring extraordinary demands in terms of size and cryo-techniques to handle the flux of 10^{19} T_2 -molecules/s safely and with per mille stability. T_2 is injected at the midpoint of a 10 m long source tube kept at a temperature of 30 K by a 2-phase liquid neon bath [24]. The integral column density of the source of $5 \cdot 10^{17}$ molecules/cm² has to be stabilized within 0.1 %. Owing to background considerations, the T_2 -flux entering the spectrometer should not exceed 10^5 T_2 -molecules/s. This will be achieved by differential pumping sections (DPS), followed by cryo-pumping sections (CPS) which trap residual T_2 on argon frost at about 3 K. Each system reduces the throughput by 10^7 , which has been demonstrated for the cryo-pumping section by a dedicated experiment at Karlsruhe [25]. The T_2 -gas collected by the DPS-pumps will be purified and recycled. All these components possess strong superconducting solenoids to guide the β electrons from the source to the spectrometer within a magnetic flux tube of 191 T cm². In summer 2009, the DPS arrived at Karlsruhe and is now being commissioned. As this chain of superconduction solenoids also guides ions from the source electrical barriers, radial drift fields and monitoring devices [28] will be installed in the DPS section.

A pre-spectrometer of MAC-E-Filter type will transmit only the uppermost part of the

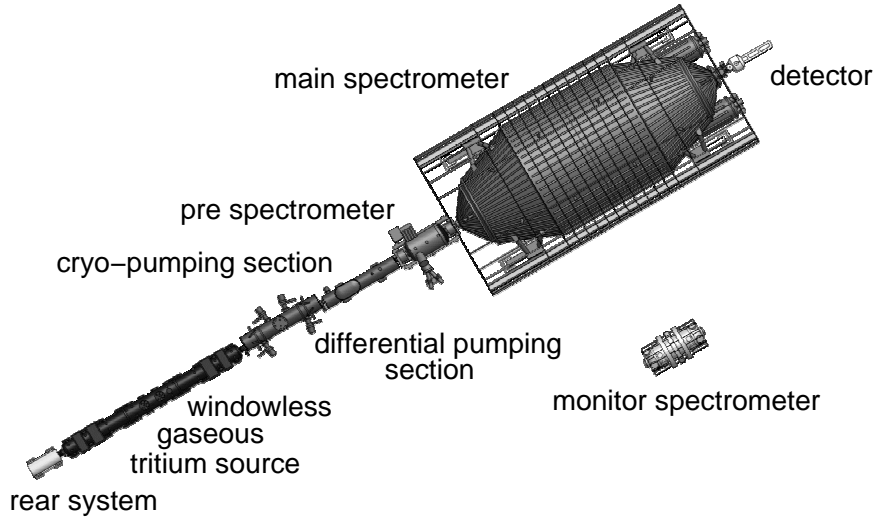


Figure 4: Schematic view of the 70 m long KATRIN experiment consisting of calibration and monitor rear system, windowless gaseous T_2 -source, differential pumping and cryo-trapping section, small pre-spectrometer and large main spectrometer, segmented PIN-diode detector and separate monitor spectrometer.

β spectrum into the main spectrometer in order to reduce the rate of background-producing ionization events therein. Both pre- and main spectrometer will fulfill extreme vacuum conditions with a residual gas pressure of 10^{-11} mbar. The entire pre- and main spectrometer vessels will each be put on their respective analyzing potentials, which are shifted inside by about -200 V, however, due to the installation of a background reducing inner screen grid system (Fig. 5). A ratio of the maximum magnetic field in the pinch magnet over the minimum magnetic field in the central analyzing plane of the main spectrometer of 20000 provides an energy resolution of $\Delta E = 0.93$ eV near the tritium endpoint E_0 . The residual inhomogeneities of the electric retarding potential and the magnetic fields in the analyzing plane will be corrected by the spatial information from a 148 pixel PIN diode detector [29]. Active and passive shields will minimize the background rate at the detector. Additional post-acceleration will reduce the background rate within the energy window of interest. Special care has to be taken to stabilize and to measure the retarding voltage. In addition to an ultra-precise HV divider [30], the spectrometer of the former Mainz Neutrino Mass experiment will be operated at KATRIN as a high voltage monitor spectrometer which continuously measures the position of the ^{83m}Kr -K32 conversion electron line at 17.8 keV [31], in parallel to the retarding energy of the main spectrometer. To that end its energy resolution has been refined to $\Delta E = 1$ eV.

The β electrons will be guided from the source through the spectrometer to the detector within a magnetic flux tube of 191 T cm^2 , which is provided by a series of superconducting solenoids. This tight transverse confinement by the Lorentz force applies also to the 10^{11} daughter ions per second, emerging from β decay in the source tube, as well as to the 10^{12} electron-ion pairs per second produced therein by the β electron-flux through ionization of T_2 molecules. The strong magnetic field of 3.5 T within the source is confining this plasma strictly in the transverse direction such that charged particles cannot diffuse to the conducting wall of



Figure 5: A double-layer wire electrode module on the 3-axis measurement table for quality assurance. The fixing of the wires inside the ceramics holders (see inserted smaller photos right) with the connecting wires is checked with a high-resolution camera, whereas wire position and wire tension are monitored by a specially developed 2-dim. laser sensor [26].

the source tube for getting neutralized. The question how the plasma in the source becomes neutralized then or to which potential it might charge up eventually, has been raised and dealt with only recently [32]. The salient point is, however, that the longitudinal mobility is not influenced by the magnetic field. Hence the resulting high longitudinal conductance of the plasma will stabilize the potential along a magnetic field line to that value which this field line meets at the point where it crosses a rear wall. This provides a lever to control the plasma potential. Meanwhile the Troitsk group has performed a first experiment on the problem [33]. They have mixed $^{83\text{m}}\text{Kr}$ into their gaseous T_2 and searched for a broadening of the $\text{L}_{\text{III}}32$ -conversion line at 30.47 keV which might be due to an inhomogeneous source potential. Their data fit is compatible with a possible broadening of 0.2 eV, which would not affect their results but suggests further investigation at KATRIN.

The sensitivity limit of KATRIN on the neutrino mass has been simulated on the basis of a background rate of 10^{-2} cts/s, observed at Mainz and Troitsk under optimal conditions. Whether this small number can also be reached at the so much larger KATRIN instrument – or even be lowered – has yet to be proven. At Mainz the main residual background originated from secondary electrons from the walls/electrodes on high potential caused by passing cosmic muons or by γ s from radioactive impurities. Although there is a very effective magnetic shielding by the conservation of the magnetic flux, small violation of the axial symmetry and other inhomogeneities allowed a fraction of about 10^{-5} of these secondary electrons to reach the

detector and to be counted as background. After finishing tritium measurements in 2001, electrostatic solutions were developed at Mainz, which strengthened shielding of surface electrons by an additional factor of ≈ 10 . This was achieved by covering the electrodes with negatively biased grids built from thin wires. Even more refined 2-layer wire electrode modules[27] have been developed and constructed for the KATRIN main spectrometer (Fig. 5) to achieve a background suppression of 2 orders of magnitude. They are currently being installed. In addition to secondary electrons from the walls/electrodes on high potential sneaking in from the outside, there is the danger of electrons created inside the spectrometers by little Penning discharges. By careful simulating all the electric and magnetic fields and redesigning the electrodes these discharges have been avoided completely at the pre spectrometer [34]. For the unavoidable Penning trap between pre and main spectrometer a solution by a sweeping wire has been tested [35]. The main spectrometer vessel has already passed successfully out-baking and out-gasing tests [36].

Since the KATRIN experiment will investigate only the very upper end of the β spectrum, quite a few systematic uncertainties will be small because of excitation thresholds. Others systematics like the inelastic scattering fraction or the source intensity will be controlled very precisely by measuring the column density online by an electron gun [37], by keeping the temperature and pressure within the tritium source at the per mille level constant and by determining the tritium fraction of the gas in the source by laser Raman spectroscopy to the per mille level [38]. Therefore each systematic uncertainty contributes to the uncertainty of $m^2(\nu_e)$ with less than 0.0075 eV^2 , resulting in a total systematic uncertainty of $\Delta m^2(\nu_e)_{\text{sys}} = 0.017 \text{ eV}^2$. The total uncertainty will allow a sensitivity on $m(\nu_e)$ of 0.2 eV to be reached [23]. If no neutrino mass is observed, this sensitivity corresponds to an upper limit on $m(\nu_e)$ of 0.2 eV at 90 % C.L., or, otherwise, to evidence for (discovery of) a non-zero neutrino mass value at $m(\nu_e) = 0.3 \text{ eV}$ (0.35 eV) with 3σ (5σ) significance.

For the future there are some new proposals to improve the neutrino mass sensitivity with tritium β decay experiments even beyond KATRIN, *e.g.* cyclotron radiation from spiraling β decay electrons from a KATRIN-like tritium source could be detected by a set of radio antennas [39]. The Fourier analysis of the detected radio signal would result in a spectrum of the electron energy.

3.2 “Source=detector” configuration: ^{187}Re β decay experiments

^{187}Re is a second isotope suited to determine the neutrino mass. Due to the complicated electronic structure of ^{187}Re and its long half life of $4.3 \cdot 10^{10} \text{ y}$ the advantage of the 7 times lower endpoint energy $E_0 = 2.47 \text{ keV}$ of ^{187}Re with respect to tritium can only be exploited if the β spectrometer measures the entire released energy, except that of the neutrino. This situation can be realized by using a cryogenic bolometer as the β spectrometer, which at the same time contains the β emitter.

One disadvantage connected to the rhenium bolometer method is the fact that one measures always the entire β spectrum. Even for the case of the very low endpoint energy of ^{187}Re , the relative fraction of ^{187}Re β decay events in the last eV below E_0 is of order 10^{-11} only (compare to Figure 3). Considering the long time constant of the signal of a cryogenic bolometer (typically several hundred μs) pile-up is a severe problem, since it changes the spectral shape near the endpoint. In order to limit the pile-up fraction to $\leq 10^{-4}$ only large arrays of cryogenic bolometers could deliver the signal rate needed. Another technical challenge is the energy resolution of rhenium bolometers. Although cryogenic bolometers with an energy resolution of

a few eV have been produced with other absorbers, this resolution has yet not been achieved with rhenium.

Two groups have started the field of ^{187}Re β decay experiments at Milan (MiBeta) and Genoa (MANU): The MANU experiment was using one metallic rhenium crystal of 1.5 mg working at a temperature of 100 mK and read out by Germanium doped thermistor. The β environmental fine structure was observed for the first time giving rise to a modulation of the shape of the β spectrum by the interference of the out-going β electron wave with the rhenium crystal [40]. The spectrum near the endpoint allowed to set an upper limit on the neutrino mass of $m(\nu_e) < 26$ eV. The MiBeta collaboration was using 10 crystals of AgReO_4 with a mass of about 0.25 mg each. The energy resolution of a single bolometer was about 30 eV. One year of data taking resulted in an upper limit on the “electron neutrino mass” of $m(\nu_e) < 15$ eV [41].

Both groups are now working together with other groups from different countries within the MARE collaboration [42]. The aim of MARE is to improve the energy resolution by new type of sensors (e.g. transition edge thermistors), to increase the thermalization and read-out speed and to increase the number of detectors significantly. In MARE phase 1 300 detectors with an energy resolution of 20 eV and a read-out time of 100 μs should provide a sensitivity on the neutrino mass of 2-3 eV. Although this is just the sensitivity which has already been reached in tritium β decay experiments this approach is interesting since it is very complementary in experimental techniques and systematic uncertainties. Presently a first array of detectors is being commissioned with 30 eV energy resolution and with a read-out time of 250 μs .

The goal is, to increase in MARE phase 2 the number of detectors to 50000. Together with the energy resolution goal of $\Delta E \leq 5$ eV and the aim to achieve a read-out and thermalization time of $\leq 5\mu\text{s}$ the MARE could improve in phase 2 another order of magnitude in sensitivity on the neutrino mass. Of course this will only be possible if the very challenging improvements in detector performance will really be reached and if no other problem with the bolometer technique (like any tiny process giving rise of an energy leakage, e.g. by soft photons or meta-stable excitations) will appear when improving the sensitivity on the observable m_ν^2 by 4 orders of magnitude.

The MARE collaboration also considers to investigate the electron capture of ^{163}Ho instead of the β decay of ^{187}Re by an array of cryo-bolometers as an alternative for MARE phase 2. Here the detected Auger electrons and photons will give rise to a β -like spectrum, which in principle allows to determine the neutrino mass [43].

4 Conclusions

The absolute neutrino mass scale is addressed by three different methods. The analysis of large scale structure data and the anisotropies of the cosmic microwave background radiation are very sensitive but model dependent. The search for neutrinoless double β decay requires neutrinos to be their own antiparticles (Majorana neutrinos) and is measuring a coherent sum over all neutrino masses contributing to the electron neutrino with unknown phases. Therefore the value of the neutrino mass cannot be determined very precisely, but the discovery of neutrinoless double β decay would be the detection of lepton flavor violation. A few double β decay experiments of the second generation are currently being commissioned and will deliver data soon. Among the 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. The KATRIN experiment is being setup at Karlsruhe and will start data taking in 2012, whereas

the MARE experiment is commissioning a small array of detectors starting MARE phase 1. From both laboratory approaches we expect in the coming years sensitivities on the neutrino mass of $O(100)$ meV.

5 Acknowledgments

The work of the author is supported by the German Ministry for Education and Research BMBF.

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Discussion

Poonam Metha (Bangalore): Comment on $0\nu\beta\beta$ process: The mass term depends on the Majorana phases which could conspire in such a way that m_{ee} can become zero if we are very unlucky but this does not rule out the possibility that neutrinos are Majorana particles.

Answer: Yes, indeed. In the case that the non-zero neutrino masses are the only process responsible for neutrinoless double β decay this situation could exist in the non-inverted hierarchy scenario only, *i.e.* the three neutrino mass eigenstates are arranged as $m(\nu_1) < m(\nu_2) < m(\nu_3)$. The exact cancelation of the neutrinoless double β decay amplitude could in principle also happen, when another process (*e.g.* the exchange of a SUSY particle) adds destructively to the β decay amplitude of the non-zero neutrino masses, but such a lucky or unlucky coincidence is considered to be very unlikely.

Gianluca Introzzi (Padova, INFN): Why the detector had to travel 8800 km just to cover a distance of a few hundred kilometers?

Answer: The main spectrometer has to reach the very low residual gas pressure of 10^{-11} mbar to suppress the scattering of β electrons on the residual gas. Therefore, special welding techniques and surface treatments (*e.g.* electropolishing) had to be applied. This could not be done easily for a 10 m diameter vessel at Karlsruhe Institute of Technology as no extra hall was available. Therefore the big vessel was built completely at the company and had to be transported in one piece. A vessel of more than 23 m in length and 10 m in diameter can only be transported on big rivers or the sea but not on streets. A transport by air was not possible due to the weight of the vessel of 200 t.

Ahmed Ali (DESY): Measuring the neutrinoless double β decay will be a landmark measurement in particle physics. However, converting the half-life to the neutrino weighted mass m_{ee} will not be easy. It will become even more complicated in the presence of other competing mechanisms. Some help can come by measuring also the angular correlation coefficient of the two electrons in $0\nu\beta\beta$ decay. Which of the current and forthcoming experiments are sensitive to the angular measurements?

Answer: Especially the double β decay experiments with the “source \neq detector” configuration are measuring both electrons separately and are able to do this. The experiment NEMO3 has shown excellent electron correlation data for $2\nu\beta\beta$ processes. NEMO3 and its successor SuperNEMO, which is under construction, are ideally designed to measure the angular correlation.

Hans Bienlein (DESY): Did you consider internal bremsstrahlung in β decay? It may influence the measurement of the endpoint of β spectrum.

Answer: In the analysis of the former Mainz Neutrino Mass Experiment as well as in KATRIN’s simulation and analysis internal bremsstrahlung has been considered. The description by two different groups (W.W Repco, C.E. Wu, Phys. Rev. C **28**, 2433 (1983), S. Gardner, V. Bernard, U.G. Meissner, Phys. Lett. B **598**, 188 (2004)) were

applied. It was checked, that at KATRIN's sensitivity there is no significant difference using one or the other of the descriptions.