Noname manuscript No.
(will be inserted by the editor)

Direct Neutrino Mass Measurements

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Received: date / Accepted: date

Abstract Direct neutrino mass experiments are complementary to searches for neutrinoless double β-decay and to analyses of cosmological data. The previous tritium beta decay experiments at Mainz and at Troitsk have achieved upper limits on the neutrino mass of about 2 eV/c^2. The KATRIN experiment under construction will improve the neutrino mass sensitivity down to 200 meV/c^2 by increasing strongly the statistics and – at the same time – reducing the systematic uncertainties. Huge improvements have been made to operate the system extremely stably and at very low background rate. The latter comprises new methods to reject secondary electrons from the walls as well as to avoid and to eject electrons stored in traps. As an alternative to tritium β-decay experiments cryo-bolometers investigating the endpoint region of ^{187}Re β-decay or the electron capture of ^{163}Ho are being developed. This article briefly reviews the current status of the direct neutrino mass measurements.

Keywords Neutrino mass · β-decay · electron spectroscopy

1 Introduction

The various experiments with atmospheric, solar, accelerator and reactor neutrinos provide compelling evidence that neutrino flavor states are non-trivial superpositions of neutrino mass eigenstates and that neutrinos oscillate from one flavor state into another during flight. By these neutrino oscillation experiments the neutrino mixing matrix U containing the mixing angles as well as the differences between the squares of neutrino masses can be determined [1].

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The values of the neutrino masses are very important for astrophysics and cosmology to describe the role of neutrinos in the evolution of the universe. Although neutrinos are very light they contribute to the mass density of the universe: with 336 neutrinos per cm^3 left over from the Big Bang they are about a billion times more abundant than atoms. On the other hand the values and the pattern of the neutrino masses are very important for nuclear and particle physics, since they can decide between different models or theories accounting for the non-zero but very tiny neutrino masses beyond our present Standard Model of particle physics.

Clearly, neutrino oscillation experiments prove that neutrinos have non-zero masses, but they – being a kind of *interference experiment* – cannot determine absolute masses. Therefore, we need other ways to determine the absolute values of the neutrino masses. Three methods are sensitive to the values of the neutrino mass eigenstates and their mixing angles in different ways:

Cosmology The relic neutrinos would have smeared out fluctuation on small scales, depending on their mass. By analysing the power spectrum of the universe limits on the sum of the three neutrino mass states, e.g. $\sum m(\nu_\mathrm{i}) < 0.5$ eV [2], have been obtained which are to some extent model and analysis dependent.

Neutrinoless double β-decay ($0\nu\beta\beta$) Neutrinoless double β-decay 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 the most natural explanation to produce in the chirality-selective interaction a neutrino with a small component of opposite handedness on which this neutrino exchange subsists. Then the decay rate will scale with the absolute square of the so-called effective neutrino mass, which takes into account the neutrino mixing matrix U:

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

There is one claim for evidence at $m_\mathrm{ee} \approx 0.3$ eV/c^2 by part of the Heidelberg-Moscow collaboration [3] and limits from different experiments in the same range, e.g. the recent results from the EXO-200 experiment [4].

Direct neutrino mass determination The direct neutrino mass determination is based purely on kinematics or energy and momentum conservation without further assumptions. 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 astrophysical events like a core-collapse supernova could provide. From the supernova SN1987a in the Large Magellanic Cloud upper limits of 5.7 eV/c^2 (95 % C.L.) [5] or of 5.8 eV/c^2 (95 % C.L.)[6] on the neutrino mass have been deduced, which depend somewhat on the underlying supernova model.

Unfortunately nearby supernova explosions are too rare and seem to be not well enough understood to compete with the laboratory direct neutrino mass experiments.

Therefore, the investigation of the kinematics of weak decays and more explicitly the investigation of the endpoint region of a β-decay spectrum (or an electron capture) 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 squared" $m^2(\nu_\mathrm{e})$ is determined [7,8]:

$$m^2(\nu_\mathrm{e}) := \sum |U_\mathrm{ei}^2| m^2(\nu_\mathrm{i}) \tag{2}$$

This incoherent sum is not sensitive to phases of the neutrino mixing matrix in contrast to neutrinoless double β-decay.

Up to now the most sensitive direct neutrino mass searches have been made by investigating the endpoint region of β-spectrum, where the neutrino reveals its mass by the shape of the energy spectrum of the β-electron. The two most recent experiments at Mainz and Troitsk investigating the β-spectrum near the endpoint of tritium at 18.6 keV obtained neutrino mass limits of about 2 $\mathrm{eV/c^2}$ [9,10]. Recently the collaboration of the neutrino mass experiment at Troitsk published a new analysis of their data [10]. Special care was taken for calculating the time-dependent column density of the windowless tritium source and applying these values to the analysis. Secondly the data were very carefully selected with regard to data quality and stability of the experiment. Now also the Troitsk data do not exhibit an anomaly anymore. The Troitsk group had reported before (e.g. see [11]), that in order to describe their measured β-spectra they need to apply to the integrated β-spectrum an additional step function. This step had different positions for different runs between 5 eV and 15 eV below the endpoint of the β-spectrum.

This paper is structured as follows: the upcoming tritium β-decay experiment KATRIN is described in section 2. An alternative way to tritium β-decay spectroscopy investigating the ^{187}Re β-decay or the electron capture of ^{163}Ho with cryogenic bolometers is presented in section 3. Our conclusions are given in section 4.

2 The KATRIN experiment

The KArlsruhe TRItium Neutrino experiment KATRIN is currently being set up at the Karlsruhe Institute of Technology KIT. The aim of KATRIN is to improve the sensitivity to the neutrino mass down to 200 $\mathrm{meV/c^2}$. Since $m^2(\nu_\mathrm{e})$ is the observable, this requires an improvement by two orders magnitude compared to the previous tritium β-decay experiments at Mainz and

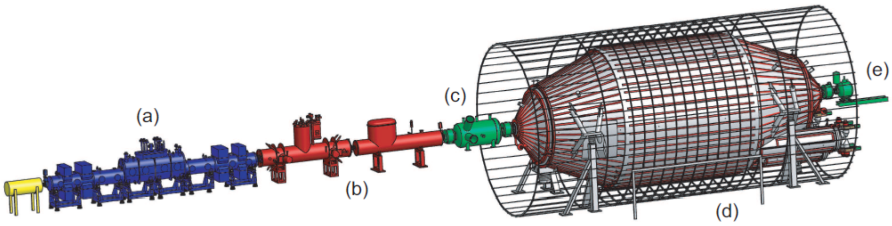

Fig. 1 Schematic view of the 70 m long KATRIN experiment consisting of calibration and monitor rear system (yellow), windowless gaseous T_2-source (a), differential pumping and cryo-trapping section (b), small pre-spectrometer (c) and large main spectrometer (d) and segmented PIN-diode detector (e). Not shown is the separate monitor spectrometer.

Troitsk. The KATRIN design is based on the successful MAC-E-Filter spectrometer technique combined with a very strong windowless gaseous molecular tritium source [12]. Figure 1 illustrates the whole 70 m long setup.

The windowless gaseous molecular tritium source (WGTS) essentially consists of a 10 m long tube of 9 cm diameter kept at 30 K. Molecular tritium gas injected in the middle of this tube is freely streaming to both ends of the beam tube. The tritium gas is pumped back by huge turbo-molecular pumps placed at pump ports intersected with straight sections. The β-electrons are guided by superconducting solenoids housing the beam tubes. A so-called WGTS demonstrator has been set up to prove that the new concept of the ultra-stable beam-pipe cooling works: gaseous and liquid neon is sent through two tubes welded onto the beam tube. By stabilizing the pressure of this two-phase neon the temperature of the beam tube can be stabilized well below the requirement of 10^{-3} [13]. The input pressure is chosen to obtain a total column density of $5 \cdot 10^{17}$ molecules/cm^2 allowing a near maximum count rate at moderate systematic uncertainties. Currently the WGTS demonstrator is being upgraded into the full WGTS.

The electron guiding and tritium retention system consists of a differential and a cryogenic pumping unit. It has been demonstrated that the tritium flow reduction by the differential pumping is about as large as expected by Monte Carlo simulations [14]. Inside the differential pumping sections Fourier transform ion cyclotron resonance Penning traps will be installed to measure the ion flux from the tritium source [15]. Ions will be ejected from the beam by a transverse electric field. The principle of the cryogenic pumping section based on argon frost at $3-4.5$ K has been demonstrated in a test experiment [16]. The overall tritium reduction amounts to 10^{-14}.

A pre-spectrometer will transmit only the interesting high energy part of the β-spectrum close to the endpoint into the main spectrometer [17], in order to reduce the rate of background-producing ionization events therein. The big main spectrometer is of MAC-E-Filter type as the pre spectrometer. It is essentially an electric retarding spectrometer with a magnetic guiding and collimating field [18]. In order to achieve the strong energy resolution of 1:20,000 the magnetic field in the analyzing plane in the centre of the spectrometer has to be 20,000 times smaller than the maximum magnetic field of 6 T provided by the pinch magnet. Due to conservation of the magnetic flux from the WGTS to the spectrometer it needs to have a diameter of 10 m in the analyzing plane. To avoid background by scattering of β-electrons inside the spectrometer extreme requirements for the vacuum pressure of $p \approx 10^{-11}$ mbar are necessary [19]. The β-electrons which have enough energy to pass the MAC-E-Filter are counted with a state-of-the-art segmented PIN detector. The spatial information provided by the 148 pixels allow to correct for the residual inhomogeneities of the electric retarding potential and the magnetic fields in the analyzing plane. Active and passive shields minimize the background rate at the detector.

Of crucial importance is the stability of the retarding potential. KATRIN is using a twofold way to achieve the necessary redundancy: A custom-made ultra-high precision HV divider [20] developed together with the PTB Braunschweig and a state-of-the-art 8.5 digit digital voltmeter measure directly the retarding voltage. In addition the retarding voltage is applied to a third MAC-E-Filter, the so-called monitor spectrometer reusing the former MAC-E-Filter at Mainz. The line position of ultra-stable electron sources based on the isotope $^{83\mathrm{m}}$Kr [21] is continuously compared to the retarding voltage of the main spectrometer. Both methods reach the required ppm precision.

The sensitivity limit of 200 meV/c^2 on the neutrino mass for the KATRIN experiment is based on a background rate of 10^{-2} cts/s, observed under optimal conditions at the experiments at Mainz and Troitsk using similar MAC-E-Filters. To reach this low background rate with the so much larger KATRIN instrument requires new methods. At Mainz the main residual background originated from secondary electrons ejected from the walls/electrodes on high potential by passing cosmic muons or by γs from radioactive impurities. Although there is a very effective magnetic shielding by the conservation of the magnetic flux, small violations of the axial symmetry or other inhomogeneities allowed a fraction of about 10^{-5} of these secondary electrons to reach the detector and to be counted as background. A new method to reject these secondary electrons from the electrodes has been developed and successfully tested at the Mainz spectrometer [22]: nearly mass-less wires are installed in front of these electrodes, which are put on a more negative electrical potential than the electrode potential by -100 V to -200 V. For KATRIN a double layer wire electrode system consisting of 248 modules with 23440 wires in total has been developed, which should reduce the secondary electron background by a factor 100 [29]. Its installation (fig. 2) has been completed in early 2012.

Other relevant background sources are decays of radioactive atoms in the spectrometer volumes, e.g. the fast decaying radon isotope ^{219}Rn from emanation out of the non-evaporable getter pumps [24] or small amounts of tritium originating from the WGTS [25]. They create electrons, which might be stored by the magnetic mirror effect and/or by the negative potentials of the two MAC-E-Filters or within the non-avoidable Penning trap between the pre and the main spectrometers. For these backgrounds new methods have been developed to avoid storage of electrons or to eject them [26, 27, 28].

Fig. 2 Wire electrode system inside the KATRIN main spectrometer during installation, photo: M. Zacher.

Since the KATRIN experiment will investigate only the very upper end of the β-spectrum, quite a few systematic uncertainties will become negligible 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 angular-selective electron gun [29,30], by keeping the temperature and pressure within the tritium source at the per mille level constant [31] and by determining the tritium fraction of the gas in the source by laser Raman spectroscopy to the sub per mille level [32]. KATRIN's sensitivity will allow to fully investigate the *quasi-degenerate neutrino mass* regime to distinguish between different neutrino mass models as well as to fully investigate the cosmological neutrino mass range. In addition, the KATRIN experiment will be sensitive to contributions to sterile neutrinos [33, 34] as suggested by the so-called reactor anomaly.

The commissioning of the KATRIN spectrometer and detector system will start at the end of 2012. The tritium source as well as the electron transport and tritium elimination section will be put into operation in 2014. First tritium data with the full KATRIN setup are expected for 2015.

3 Cryo-bolometer experiments

Compared to tritium the isotope ^{187}Re has a 7 times lower endpoint energy of 2.47 keV resulting in a 350 times higher relative fraction of the β-spectrum in the interesting endpoint region. Unfortunately ^{187}Re exhibits a very complicated electronic structure and a very long half life of $4.3 \cdot 10^{10}$ y. This disadvantage can be compensated by using it as β-emitter in cryo-bolometers, which measure the entirely released energy, except that of the neutrino.

A cryo-bolometer is not an integral spectrometer like the MAC-E-Filter but measures always the entire β-spectrum. Pile-up of two random events may pollute the endpoint region of a β-decay on which the neutrino mass is imprinted. Therefore cryo-bolometers with mg masses are required to suppress pile-up by 4 or more orders of magnitude. Unfortunately large arrays of cryo-bolometers are then required to reach the necessary sensitivity to the neutrino mass. Another technical challenge is the energy resolution of the cryo-bolometers. Although cryo-bolometers with an energy resolution of a few eV have been produced with other absorbers, this resolution has not yet been achieved with rhenium.

Two groups have started the field of ^{187}Re β-decay experiments: The MANU experiment at Genoa was using one metallic rhenium crystal of 1.6 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 [35]. The spectrum near the endpoint allowed to set an upper limit on the neutrino mass of $m(\nu_\mathrm{e}) < 26$ eV [36]. The MiBeta collaboration at Milano was using 10 crystals of $\mathrm{AgReO_4}$ with a mass of about 0.25 mg each [37]. The energy resolution of a single bolometer was about 30 eV. One year of data taking resulted in an upper limit of $m(\nu_\mathrm{e}) < 15$ eV [37].

Both groups are now working together with additional groups in the MARE project [38] to further the development of sensitive micro-calorimeters investigating the ^{187}Re β-decay. MARE consists of two phases [39]: MARE-1 aims to investigate alternative micro-calorimeter concepts to improve the energy resolution, to shorten the rise time of the signals and to develop possibly a multi-plexing read-out. Among these technologies are transition edge and neutron-doped thermistors for the temperature read-out, but also new technologies based on magnetic micro-calorimeters [40]. These new dectectors are being tested in medium-size arrays with up to 300 cryo-bolometers enabling MARE-1 to reach a sensitivity to the neutrino mass of a few $\mathrm{eV/c^2}$. After selection of the most successful technique a full scale experiment with sub-$\mathrm{eV/c^2}$ sensitivity to the neutrino mass will then be set up in MARE phase 2 comprising about 50000 detectors.

MARE is not only aiming at the ^{187}Re β-decay but also wants to investigate the electron capture of ^{163}Ho, triggered by the persisting difficulties with superconducting metallic rhenium absorbers coupled to the sensors [41]. The isotope ^{163}Ho could be implanted into well-suited cryo-bolometers. The very upper end of the electromagnetic de-excitation spectrum of the ^{163}Ho daughter ^{163}Dy looks similar to the endpoint spectrum of a β-decay and is sensitive to the neutrino mass. Additionally, the ECHO collaboration has been set up to investigate the direct neutrino mass search with ^{163}Ho implanted in magnetic micro-calorimeters. A first ^{163}Ho spectrum has been presented [40].

4 Conclusions

The direct neutrino mass measurements are complementary to searches for neutrinoless double β-decay and to cosmological analyses. A major improvement in sensitivity to the neutrino mass by one order of magnitude will be achieved by the KATRIN experiment currently under construction. An alternative to tritium β spectroscopy is the use of cryo-bolometers investigating the ^{187}Re β-decay or ^{163}Ho electron capture. If a break-through in cryo-bolometer technology will be achieved allowing to set up arrays with ten thousands of cryo-bolometers with an energy resolution of $\mathcal{O}$(eV) and a rise time of $\mathcal{O}(100\ \mu s)$, experiments like MARE-2 or ECHO may reach KATRIN's sensitivity or go even beyond in the long-term. There is also R&D on rather different approaches, like Project-8, which wants to measure the endpoint spectrum of tritium β-decay by detecting the radio emission of coherent cyclotron radiation from a KATRIN-like tritium source [42,43].

Acknowledgements The work of the author is supported by the German Ministery of Education and Research BMBF.

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