Absolute neutrino mass measurements

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Abstract. The neutrino mass plays an important role in particle physics, astrophysics and cosmology. In recent years the detection of neutrino flavour oscillations proved that neutrinos carry mass. However, oscillation experiments are only sensitive to the mass-squared difference of the mass eigenvalues. In contrast to cosmological observations and neutrino-less double beta decay ($0\nu 2\beta$) searches, single β-decay experiments provide a direct, model-independent way to determine the absolute neutrino mass by measuring the energy spectrum of decay electrons at the endpoint region with high accuracy.

Currently the best kinematic upper limits on the neutrino mass of 2.2 eV have been set by two experiments in Mainz and Troitsk, using tritium as beta emitter. The next generation tritium β-experiment KATRIN is currently under construction in Karlsruhe/Germany by an international collaboration. KATRIN intends to improve the sensitivity by one order of magnitude to 0.2 eV. The investigation of a second isotope (^{137}Rh) is being pursued by the international MARE collaboration using micro-calorimeters to measure the beta spectrum. The technology needed to reach 0.2 eV sensitivity is still in the R&D phase. This paper reviews the present status of neutrino-mass measurements with cosmological data, $0\nu 2\beta$ decay and single β-decay.

Keywords: neutrino mass, beta-decay, direct measurement
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INTRODUCTION

The Standard Model of particle physics describes neutrinos as massless, neutral fermions, which can be detected only via weak interactions. The observations of neutrino flavour oscillations [1] indicate the existence of massive neutrinos. Since experiments investigating neutrino oscillations are only sensitive to differences of the square of mass eigenvalues $\Delta m^2_{\nu_{ij}} = |m^2(\nu_i) - m^2(\nu_j)|$ and not to the absolute values, the scale and hierarchy of neutrino masses are not determined yet.

In standard cosmological models, our universe is filled with primordial neutrinos ($\approx 336\,\nu/\mathrm{cm}^3$) arising from freeze-out in the early universe. Apart from photons, neutrinos are the most abundant particles in the universe. They are natural candidates for non-baryonic hot dark matter. Depending on the actual neutrino mass, the neutrino content of the universe could exceed the baryonic mass density.

The above arguments demonstrate the importance of the absolute neutrino mass scale for both particle physics and cosmology. Currently three different approaches are pursued to determine the neutrino mass: (i) Cosmological models describe the effect of neutrinos on structure formation in the early universe and extract a neutrino mass by comparing prediction and observation. (ii) Neutrino-less double beta decay ($0\nu 2\beta$) can occur if neutrinos are Majorana particles and have mass. (iii) Direct neutrino mass measurements investigate the kinematics of weak decays (β-decays). In principle the neutrino mass can also be determined from time of flight measurements of supernova neutrinos. However, this kind of measurement can only be a by-product of the physics programme of large neutrino detectors, which happen to be on-line when a supernova explodes at the right distance.

NEUTRINO MASS AND COSMOLOGY

The effect of massive neutrinos on structure formation depends on the total energy density of neutrinos. Assuming that all neutrino flavours were produced in equal numbers, cosmology can provide an upper bound on the sum of the neutrino mass eigenvalues $\sum m_\nu$. However, this limit strongly depends on the actual model and cosmological parameters used in the analysis. Combining the latest data from large scale structure surveys (SDSS-DR7) and cosmic microwave background (CMB) measurements (WMAP-7) in a minimal ΛCDM model, an upper bound of $\sum m_\nu < 0.44\,\mathrm{eV}$ can be reached. A comprehensive review of the present status of neutrino physics from precision cosmology is given by S. Hannestad in [2]. He concludes that the current bound on the sum of neutrino masses can be in the range between 0.3 and 2 eV, depending on the data and models used.

It should also be noted that the bound on $\sum m_\nu$ from cosmic structure formation applies to any other, hypothetical particle species which decoupled while still relativistic. These could be low mass sterile neutrinos [3] or relatively high mass axions, which decoupled after the

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QCD phase transition [4].

In the coming years a multitude of new experiments will probe cosmic structures with high precision. Examples are the Planck satellite mission, currently measuring the CMB anisotropy, weak lensing surveys and upcoming galaxy surveys such as BOSS. The expected sensitivities, reachable in the next 5 to 7 years are in the range between 0.1 eV and 0.6 eV, depending on the model used in the analysis [2].

DOUBLE BETA DECAY EXPERIMENTS

Double beta decay, first proposed by M. Goeppert-Mayer in 1935, is a second order nuclear transition, with four possible decay processes(ε: electron capture): $2\beta^-$, $2\beta^+$, $\varepsilon\beta^+$ and 2ε. Present double beta experiments concentrate mainly on $2\beta^-$ decays, where two possible decay modes are investigated: two neutrino decay (2ν), allowed by conservation laws, and neutrino-less decay (0ν), which violates lepton-number conservation. There are about 35 candidates for $2\nu2\beta^-$ decays. For 10 of these isotopes this decay has been observed [5].

The $0\nu2\beta$ decay can only occur, if neutrinos are their own anti-particles (Majorana particles), implying that the only distinction between neutrinos and anti-neutrinos is their helicity. With the exchange of a light virtual neutrino between the two decaying nucleons of a nucleus, almost all energy released in this process is carried away by the electrons, leading to a mono-energetic peak at the endpoint of the $2\nu2\beta$ energy spectrum. For pure (V-A) interactions a finite neutrino mass is required for the reabsorption of a Majorana neutrino. In addition mechanisms beyond the Standard Model could also contribute to the $0\nu2\beta$ decay rate.

Double beta experiments measure the rate of the neutrino-less decay, which can be expressed as [6]:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_\nu \rangle_{\beta\beta}|^2 \qquad (1)$$

with the phase space integral $G^{0\nu}$ and the nuclear matrix element $|M^{0\nu}|^2$. The effective neutrino mass is a linear combination of the neutrino mass eigenvalues m_k and the mixing matrix elements U_{ek}^L:

$$\langle m_\nu \rangle_{\beta\beta} = \sum_{k=1}^{3} |U_{ek}^L|^2 \cdot m_k \cdot e^{i\alpha_k} \qquad (2)$$

The Majorana phases α_k can lead to partial cancellation of the mass terms. Assuming pure (V-A) interaction, $\langle m_\nu \rangle_{\beta\beta}$ represents therefore a lower limit for the mass measured in single β-decay.

The derivation of $\langle m_\nu \rangle_{\beta\beta}$ from the measured decay rate requires precise knowledge of the nuclear matrix element (NME). The value of $|M^{0\nu}|^2$ has to be calculated, which introduces a large systematic uncertainty in $\langle m_\nu \rangle_{\beta\beta}$. A review of the present status of NME calculations is given in [6], as well as an overview of present and future $0\nu2\beta$ experiments.

The only evidence for a positive $0\nu2\beta$ signal has been claimed by part of the Heidelberg-Moscow collaboration [7] for ^{76}Ge with a confidence level of more than 6σ. The observed half-life is $T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y, leading to an effective neutrino mass of $\langle m_\nu \rangle_{\beta\beta} = 0.32 \pm 0.03$ eV, under the assumption, that there is no contribution from right-handed currents or other non-standard model interactions. The errors quoted do not include the model-dependent uncertainties of the NME.

The next generation of $0\nu2\beta$ experiments will be sensitive enough to verify this result with ^{76}Ge (GERDA, Majorana) and other isotopes (e.g. Cuore, EXO-200, SuperNEMO, SNO+). Over the next 5 years they are expected to reach sensitivities in the 0.1 to 0.5 eV region, limited mainly by statistics and by the uncertainties of NME calculations [8].

SINGLE BETA DECAY EXPERIMENTS

The neutrino mass can be determined in a model-independent way by a kinematic analysis of electrons from single β-decay near the endpoint E_0. A non-vanishing neutrino mass reduces the maximum electron energy and leads to a significant spectral distortion only in the vicinity of the reduced endpoint $E_0 - \langle m_\nu \rangle_\beta$. The shape of the energy spectrum can be calculated with high accuracy, using Fermi's golden rule [9]:

$$\frac{d\Gamma}{dE} = C \cdot F(E) \cdot p(E+m_e)(E_0-E) \cdot \sqrt{(E_0-E)^2 - \langle m_\nu \rangle_\beta^2} \qquad (3)$$

with a constant C and the Fermi-function $F(E)$. Since the energy resolution of present experiments can not resolve the difference between the neutrino mass eigenvalues m_k, an effective neutrino mass can be written as:

$$\langle m_\nu \rangle_\beta^2 = \sum_{k=1}^{3} |U_{ek}^L|^2 \cdot m_k^2 \qquad (4)$$

Close to the endpoint of the β-spectrum there are only very few events. Taking for instance tritium, a beta emitter with one of the lowest decay energies, one finds only 2×10^{-13} of all β-electrons in the last eV below the endpoint (see fig. 1). Therefore it is crucial having an excellent energy resolution $\Delta E/E$ and a β-source with low endpoint energy and high activity. Current experiments investigate two isotopes, tritium (^{3}H) and rhenium (^{187}Re), employing different techniques for energy measurement.

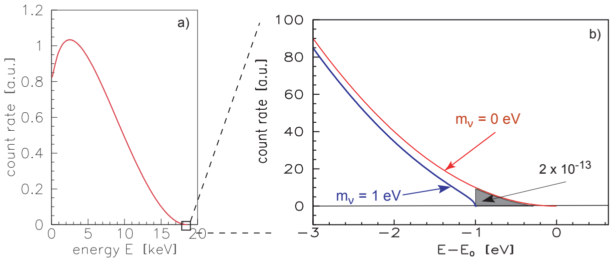

FIGURE 1. Electron energy spectrum of tritium β-decay: (a) complete and (b) narrow region around the endpoint E_0.

Tritium experiments

Presently the most sensitive direct searches for the electron neutrino mass are based on the investigation of the energy spectrum of tritium β-decay $^3H \rightarrow ^3 He^+ + e^- + \bar{\nu}_e$. With an endpoint energy of $E_0 = 18.6\,\mathrm{keV}$ and a half-life of 12.3 years, tritium is an ideal candidate for this measurement. Other advantages are the pure phase space spectrum due to the super-allowed decay of tritium and the simple electron shell configuration, allowing straightforward calculations of corrections for the outgoing β-electron.

So far the lowest model-independent limit of 2.2 eV has been set independently by two experiments in Troitsk [10] and Mainz [11]. Both experiments owe their high sensitivity to a new type of spectrometer, a so-called MAC-E-Filter[2]. It combines high luminosity with high energy resolution.

The main features of a MAC-E-Filter are illustrated in fig. 2. Two super-conducting solenoids are producing a magnetic guiding field. For a large fraction (up to 2π) of the solid angle electrons follow the magnetic field lines in a cyclotron motion through the spectrometer. On their way into the centre of the spectrometer the magnetic field B drops by several orders of magnitude. The magnetic gradient force transforms most of the cyclotron energy $E_\perp$ into longitudinal motion. Due to the slowly varying magnetic field the momentum transforms adiabatically, therefore the magnetic moment μ remains constant:

$$\mu = \frac{E_\perp}{B} = const. \tag{5}$$

The isotropically emitted β-electrons are transformed into a broad beam of electrons flying almost parallel to the magnetic field lines against an electro-static retarding potential U_0, formed by one or more cylindrical electrodes. Only electrons with enough energy to pass the electro-static barrier are re-accelerated and collimated onto a detector, where they are counted. All other electrons are reflected. By varying the retarding potential the integral β-spectrum can be measured. The energy resolution is defined by the remaining fraction of the cyclotron energy, which can not be analysed at the centre of the spectrometer. With equ. 5 follows $\Delta E/E_0 \approx B_{min}/B_{max}$.

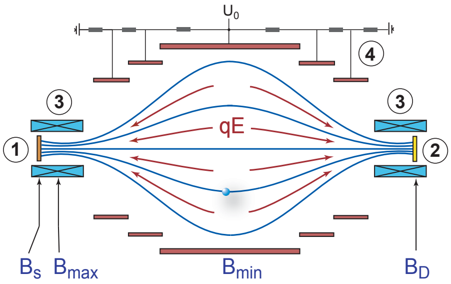

FIGURE 2. Scheme of a MAC-E-filter with tritium source (1), electron detector (2), super-conducting solenoids (3) and electro-static electrode system (4).

The cross section A of the spectrometer is determined by conservation of the magnetic flux $\Phi = \vec{B} \cdot \vec{A}$, the diameter of the source and the required energy resolution. Beside the energy resolution the second requisite for measuring small neutrino masses is a very high activity of the source. This constrains the minimum size of the source area. Therefore higher sensitivity can only be achieved by increasing the size of the spectrometer. This correlation eventually limits the final sensitivity achievable with the MAC-E-Filter technology.

The **KA**rlsruhe **TRI**tium **N**eutrino experiment (KATRIN), currently under construction at the Karlsruhe Institut of Technology (KIT) in Germany, will improve the techniques developed in Mainz and Troitsk with a strong gaseous molecular tritium source (10^{11} Bq) and a MAC-E-filter with unprecedented energy resolution of 0.93 eV. The goal of the experiment is an improvement of the sensitivity for the neutrino mass by one order of magnitude to 0.2 eV after 5 years of measurement. Figure 3 outlines the experimental set-up of KATRIN [12], which adds up to a total length of about 70 m.

KATRIN source and transport section

The source and transport section includes the *windowless gaseous tritium source* (WGTS), followed by *differential pumping sections* (DPS) and a *cryogenic pumping section* (CPS). The rear end of the setup ends with the *calibration and monitoring system* (CMS), which defines the electrical potential inside the source-tube and provides the means to monitor crucial parameters of the experiment. The beam-tubes are surrounded by superconducting solenoids, guiding the electrons adiabatically through the experiment with fields between 3.6 T and 5.6 T. The tubes have diameters between 75 mm and 90 mm, interspersed with pump ports for turbo-molecular

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[2] Magnetic Adiabatic Collimation combined with an Electrostatic Filter

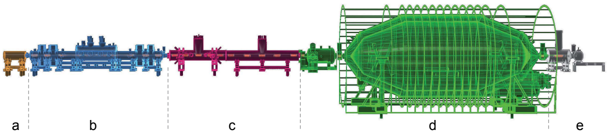

FIGURE 3. Drawing of the KATRIN setup: (a) rear section, (b) tritium source (WGTS), (c) differential and cryogenic pumping sections, (d) spectrometer section, (e) detector. The setup has a total length of about 70 m.

pumps (TMP). These pumps are integrated in the closed loop tritium circulation system, removing most of the tritium, before it can enter the spectrometer section. The pressure inside the beam-tubes will range from 3.4×10^{-3} mbar in the source to less than 10^{-11} mbar in the spectrometer section.

In the WGTS ultra-cold molecular tritium gas ($T = 27\,\mathrm{K} \pm 30\,\mathrm{mK}$) will be injected continuously through a set of capillaries at the centre of the 10 m long source-tube. The cryostat of the WGTS already integrates the first stages of the differential pumping system at both ends of the source-tube. The density profile of the gas inside the source-tube has to be kept stable on the 10^{-3} level. Maintaining these conditions is a very challenging task, requiring a highly stabilized cryo-system. After some delays in manufacturing, tests of the cryogenic performance are currently under way with the partly assembled WGTS, consisting mainly of the source-tube, part of the vacuum system and the cryo-system. After a successful test full assembly will commence. The WGTS is expected to be the last component of the KATRIN system, arriving by the end of 2012.

The background rate generated by tritium decay within the spectrometer volume has to be less than 10^{-3} cps, which limits the amount of tritium permissible in the main spectrometer. The large suppression factor between source and spectrometer will be achieved by the combination of DPS [13] and CPS[14], with each pumping sections reducing the tritium flow by 7 orders of magnitude. The DPS system has been delivery in mid 2009, and extensive tests are being prepared to verify the tritium reduction factor. The CPS will be delivered in 2011. In addition to the transport section strong pumps in the spectrometer section with a pumping speed in the order of $10^{6}\,\mathrm{l/s}$ will remove most of the remaining tritium molecules, before they decay.

KATRIN spectrometer and detector

A major component of the experiment will be the spectrometer section. It consists of two electro-static spectrometers of MAC-E-Filter type: the *pre-spectrometer* with moderate energy resolution, which provides the option to reduce the β-electron flux by 7 orders of magnitude and the *main spectrometer*, where the energy of the remaining β-electrons will be analyzed with a resolution of 0.93 eV. The high energy resolution of the main spectrometer requires large dimensions. It has a diameter of 10 m and a length of 23.4 m. The pre-spectrometer with a diameter of 1.7 m and a length of 3.4 m has served as a prototype for the stringent vacuum conditions and for tests of the electro-magnetic design.

During standard operation very good ultra-high vacuum conditions of $p < 10^{-11}$ mbar have to be maintained in both spectrometers in order to maintain a low background rate. The vacuum systems are based on a combination of cascaded turbo-molecular pumps (TMP) and NEG-pumps made of over 3000 m of double-coated getter strips (SAES St707®), which provide a total pumping speed of $10^{6}\,\mathrm{l/s}$ [15]. Both vessels are made of electro-polished stainless steel (316LN). Hydrogen outgassing from the walls is the main source of gas, which limits the final pressure. The surface of each vacuum vessel can be baked at temperatures up to 350°C for reduction of outgassing and activation of the NEG-pumps. In both spectrometers a hydrogen outgassing rate of $10^{-12}\,\mathrm{mbar\,l/s\,cm^2}$ has been measured after bake-out, which guarantees a final pressure of 10^{-11} mbar [16].

The electro-static field will be generated by connecting the outer wall of each spectrometer to high voltage ($-18.6\,\mathrm{kV}$). The field will be fine-tuned by an inner electrode system, made of over 23000 very thin stainless steel wires. The variable retarding voltage has to be known with ppm accuracy. Since no known commercially available precision high voltage divider meets this requirement, a unique voltage divider with ppm stability has been developed at the University of Münster together with PTB Braunschweig. For fine-tuning the magnetic field in the main spectrometer and for compensation of the earth magnetic field a large air-coil system with a diameter of 12.6 m has been installed.

The segmented silicon detector, which counts electrons after the main spectrometer, has been built by the University of Washington in Seattle. It is currently being prepared for shipment and will be installed at KIT in May 2011. After integrating spectrometer and detector the first engineering runs are planned in 2011 with an electron gun.

As mentioned above the WGTS is expected to be the last component to be integrated into the KATRIN system in 2012. After full system integration commissioning and engineering runs will take another year until neutrino data can be taken in 2013.

Rhenium experiments

The ^{187}Re isotope has the lowest known β-endpoint energy with $E_0 = 2.47\,\mathrm{eV}$. However, due to its long half life of 4.3×10^{10} years and its complicated electronic structure the entire energy released in the decay process (apart from the neutrino energy) has to be detected. This can be done by using cryogenic bolometers made of rhenium, which measure the total energy absorbed inside the crystal through a temperature rise. In such an experiment rhenium is the detector and source at the same time. One disadvantage of this method is that it always measures the entire β-spectrum. Considering the long time constant of the temperature signal, pile-up is a severe problem, since it changes the shape of the spectrum near the endpoint. This problem can only be overcome by operating large arrays of small bolometers in parallel and by reducing the time constant of the signal.

Two ^{187}Re experiments have already proven the feasibility of this method. The MiBeta group at Milan has set an upper limit of $m_\nu < 15\,\mathrm{eV}$ with 10 $\mathrm{AgReO_4}$ crystals (0.25 mg each) and an energy resolution of 30 eV [17]. The MANU group in Genoa used one metallic rhenium crystal (1.5 mg) and has set a limit of $m_\nu < 26\,\mathrm{eV}$ [18].

Both groups are now working, together with groups from other countries, in the MARE collaboration. The aim of MARE is the direct and calorimetric measurement of the *electron anti-neutrino mass* with sub-eV sensitivity, comparable or possibly below the KATRIN reference sensitivity of 0.2 eV [19]. The MARE project is based on a two step approach. In the first step (MARE-1) small scale experiments are planned as R&D effort for the next stage. The initial goal is to reach a sensitivity in the eV-range, comparable to the Mainz and Troitsk experiments. Issues like energy resolution (ΔE), signal relaxation time (τ) and pile-up, improvement of the sensor – absorber coupling and multiplexed sensor read-out are investigated in these experiments. As an alternative to rhenium the ^{163}Ho isotope (electron capture) is also under investigation. Currently the Milan group sets up two arrays with a total of 72 $\mathrm{AgReO_4}$ ($\Delta E \approx 30\,\mathrm{eV}, \tau \approx 250\,\mu\mathrm{s}$) crystals. After one year of tests the experiment will be upgraded to 288 crystals. After another three years of running the a sensitivity of 3 eV can be reached [20].

In the second phase MARE-2 is expected to reach a sensitivity of 0.2 eV. Extensive Monte-Carlo simulations investigate the detector exposure required to reach this goal as a function of activity per crystal, relaxation time τ and energy resolution ΔE [21]. The envisaged sensitivity can be reached, for instance, with an array of 40000 ^{187}Re crystals, $\tau = 3\,\mu\mathrm{s}$ and $\Delta E = 3\,\mathrm{eV}$ after 10 years of measurement. New sensor R&D and new read-out techniques are needed to reduce present sensor parameters.

CONCLUSIONS

Three different methods are currently pursued to determine the neutrino mass: cosmological observations, neutrino-less double-β-decay and single β-decay spectroscopy. The three techniques measure different combinations of the neutrino mass eigenvales, complementing each other rather than competing for the same number. Though the first two methods can reach lower sensitivities, they suffer from considerable model dependencies. The kinematic analysis of the single β-decay provides a model-independent approach to neutrino masses, but it is limited by the technological feats involved in pushing limit further down. Therefore the KATRIN experiment is expected to be the final effort in a successful series of spectrometer tritium experiments. Different approaches like MARE still have to conquer technical challenges. New ideas have been published recently, trying to overcome these limitations of direct methods [22],[23],[24],[25]. As new, more sensitive experiments start taking data and novel ideas are emerging, the coming decade promises exciting insights into neutrino mass schemes and mass generation in general.

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