Direct neutrino mass determination: Status and prospects

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Abstract.   More than 80 years after the prediction of their existence, there are still many open questions regarding the nature and properties of neutrinos. Among these questions is the issue of neutrino mass. While oscillation experiments have proven that neutrinos possess non-zero masses, these measurements cannot determine the absolute mass scale. Information on absolute neutrino masses can be deduced either from cosmological observations of large scale structure formation, from the search for neutrino-less double β-decay or from the study of the kinematics of weak decays. While the first two methods are subject to model dependencies or rather large systematical uncertainties, measurements based on the kinematics of nuclear β-decay or electron-capture reactions offer a model-independent way to determine the neutrino mass. This paper provides an overview of status and sensitivities of direct neutrino mass experiments currently under construction (KATRIN, MARE) or in development (Project 8, ECHO).

1. Introduction

The nature and properties of neutrinos are of great interest to the fields of particle physics, astroparticle physics and cosmology. Open issues from the particle physics point of view are e.g. a possible Majorana nature of neutrinos [1] which would enable neutrino-less double beta decay, or the existence of sterile neutrinos that might provide an explanation for the observed reactor neutrino anomaly [2]. In models of leptogenesis [3] neutrinos can help to explain the matter-antimatter asymmetry present in our universe. In astroparticle physics, neutrinos play an important role as messenger particles, that can probe dense regions in space not accessible by the observation of other types of radiation and thereby deliver additional information e.g. on processes going on in supernova explosions. In the field of cosmology, the prime interest in neutrinos arises from their huge abundance and the corresponding contribution to the hot dark matter content of the universe.

The particular question of neutrino mass can be attacked from different directions. Oscillation experiments have shown that neutrinos do actually have a mass and that the flavor eigenstates created in weak interactions are not identical to the mass eigenstates of neutrinos that propagate in space. As the observables in neutrino oscillation experiments depend on squared mass differences $\Delta m_{ij}^2 = |m_i^2 - m_j^2|$ of the mass eigenstates we can only determine the splittings between these eigenstates, but not the absolute mass scale from the measurements.

Observations of the cosmic microwave background and large scale structure formation in the universe allow to extract upper limits on the sum of neutrino masses by fitting the results of cosmological model calculations to the experimental data. These methods currently provide the most stringent upper limits on neutrino masses of $\sum_i m_i < 0.44$ eV [4]. One has to keep in

mind however that the limits extracted from cosmological observations depend on the particular model chosen to describe the data.

Another way to learn about neutrino mass is the search for neutrino-less double β-decays. Extremely sensitive low background detectors are used to look for $0\nu\beta\beta$-decays in isotopes where the usual single β-decay is energetically forbidden [1]. The observable in these measurements is an effective mass given by a coherent sum over the mass eigenstates and the squares of the corresponding mixing matrix elements: $m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$. Due to the phase angles present in the mixing matrix elements U_{ei} it is possible that the terms in the sum partially cancel, which would cause the measured effective mass to differ from the actual neutrino mass. Together with uncertainties in the nuclear matrix elements required to calculate $m_{\beta\beta}$ from the observed $0\nu\beta\beta$ lifetimes this causes a rather large uncertainty when trying to extract information about the neutrino mass from the experiments. The current upper limit on the effective mass from the Heidelberg-Moscow Experiment is $m_{\beta\beta} < 0.35$ eV [5] at 90% confidence level (CL) with a claim for a signal in the range of 0.1 eV$< m_{\beta\beta} < 0.9$ eV from part of the collaboration [6].

A model independent and therefore termed direct method to measure neutrino masses is provided by the study of the kinematics of weak decays [7]. The energy spectra of ejectiles measured in these decays depend on the squared neutrino mass via the phase space factor of the reactions. The most stringent upper limits in this field have been established from the investigation of the tritium β-decay spectrum near the endpoint in the Mainz [8] and Troitsk [9] experiments with $m_{\nu_e} < 2.3$ eV at 95% CL (PDG adopted value [10]).

The following sections will provide an overview of status and sensitivities of direct neutrino mass experiments currently under construction.

2. Kinematic neutrino mass measurements

Kinematic neutrino mass measurements exploit the phase space dependence of the energy spectra of weak decays to extract information about the masses of the emitted neutrinos. The investigation of nuclear β-decay has yielded upper neutrino mass limits in the eV range [8, 9, 11] that probe part of the cosmologically interesting region of degenerate neutrino masses. A lot of effort is currently put into the construction of the KATRIN experiment [12] which will push down the limit into the sub-eV range and will allow to verify claims of a mass signal from the observation of $0\nu\beta\beta$ decays in the Heidelberg-Moscow experiment [6].

A promising alternative to the study of nuclear β-decays is the observation of electron capture (EC) decays in ^{163}Ho. Like the energy spectra of β-electrons, the de-excitation spectra of the daughter nuclei in EC decays exhibit a phase space dependence that allows to extract information about the neutrino mass terms.

2.1. β-decay experiments

The energy spectrum of nuclear β-decay can be calculated starting from Fermi's golden rule and has the following form [7] (with units $\hbar = c = 1$):

$$\frac{d\Gamma}{dE} = \frac{G_F^2 \cos^2\theta_C}{2\pi^3}|M|^2 \, S(E) \, F(E, Z+1) \, p\,(E+m_e) \sum_i \sum_j |U_{ei}|^2 P_j \epsilon_j \sqrt{\epsilon_j^2 - m_i^2}\, \Theta(\epsilon_j - m_i) \,, \quad (1)$$

where G_F is the Fermi coupling constant, θ_C the Cabbibo angle and M the nuclear matrix element of the transition. $S(E)$ is a shape factor that takes into account the energy dependence of the nuclear matrix element. This factor equals 1 for allowed and super-allowed transitions as in tritium β-decay. The Fermi function $F(E, Z+1)$ takes into account the final state interaction of the emitted electron with the daughter nucleus and $p(E + m_e)$ is the phase space factor of the outgoing electron. The product of the neutrino momentum and its energy given by $\epsilon_j = E_0 - E_j^* - E$ is the phase space of the emitted neutrino, which shapes the β-spectrum
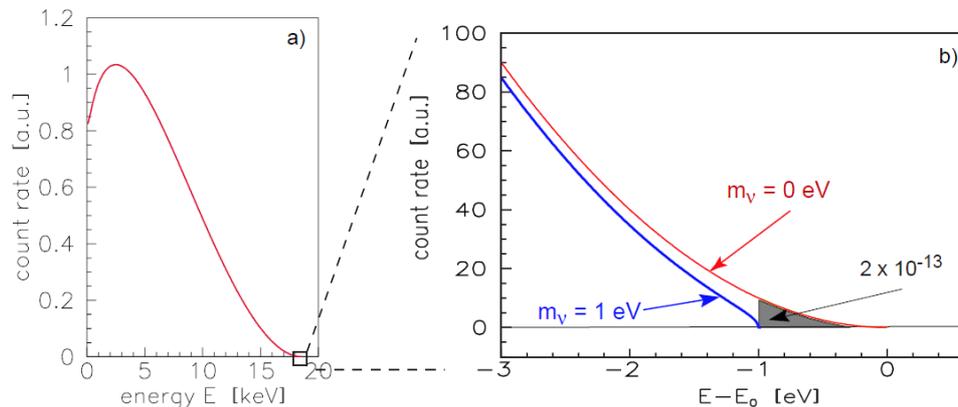
Figure 1. Energy distribution of electrons emitted in tritium β-decay (figure taken from [12]).

near its endpoint. The neutrino phase space factor has to be summed up over all final states E_j^* of the daughter molecule that are populated with probabilities P_j and over the neutrino mass eigenstates m_i. The inclusion of the Θ function in eq. 1 ensures that $\epsilon_j - m_i > 0$. The observable $m_{\nu_e}^2$ that can be extracted from the spectral shape near the endpoint is defined by an incoherent sum over the mass eigenstates weighted by the matrix elements of the U_{PMNS} mixing matrix [10] known from oscillation experiments:

$$m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \ . \tag{2}$$

The problem of partial cancellation of the mass terms that can arise in measurements of $0\nu\beta\beta$-decays does therefore not occur here. The influence of the neutrino mass on the observed spectra is most pronounced in the endpoint region as shown in figure 1, where the right hand side provides a zoom into the last few eV of the electron energy distribution of tritium β-decay. This also highlights the biggest problem of the measurements, as in the case of tritium only $2 \cdot 10^{-13}$ of all decay electrons fall into the last 1 eV of the distribution. The prime requirements to set up a sensitive β-decay experiment are therefore a high overall luminosity, high energy resolution and a very low background in order to gain sufficient statistics in the endpoint region. Besides the statistics of the measurement, challenges arise in the precise treatment of systematic effects like e.g. the inelastic scattering of electrons in the source volume.

The main experimental methods for these measurements are spectrometric experiments like KATRIN [12] which work with separate source and detector regions and calorimetric experiments like MARE [13] which use the source equals detector approach.

2.2. Electron capture on ^{163}Ho
A promising alternative to β-decay measurements is the study of electron capture (EC) decays of ^{163}Ho using calorimetric detectors. The decay process considered is:

$$^{163}\text{Ho}^+ + e^- \rightarrow^{163} \text{Dy}_i^* + \nu_e \rightarrow^{163} \text{Dy} + E_i + \nu_e \ . \tag{3}$$

The de-excitation spectrum of the intermediate state $^{163}\text{Dy}_i^*$ is given by a series of lines at energies $Q - E_i$ where Q is the mass difference of mother and daughter nucleus in the ground state and E_i is the dissipated binding energy of the electron hole in the final atom. Like the
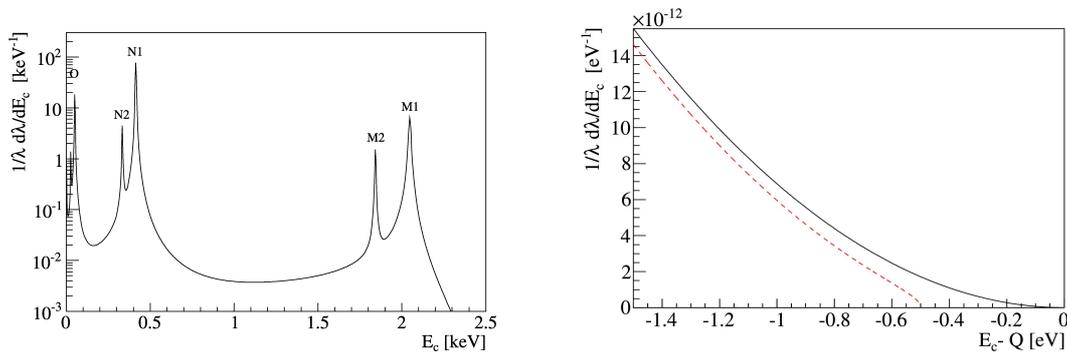
Figure 2. De-excitation spectrum of ^{163}Ho for $Q = 2.5$ keV (left). The right plot shows a zoom into the endpoint region of the spectrum with the effect of a 0.5 eV neutrino mass indicated by the red dashed line (Reprinted from [14], Copyright 2011, with permission from Elsevier).

electron energy spectrum in β-decays this spectrum depends on the square of the neutrino mass [14]:

$$\frac{d\lambda_{EC}}{dE_C} = \frac{G_F^2 \cos^2\theta_C}{4\pi^2}(Q - E_C)\sqrt{(Q - E_C)^2 - m_{\nu_e}^2} \cdot \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_C - E_i)^2 + \Gamma_i^2/4} \; . \quad (4)$$

The calorimetric energy E_C that is measured when the source is embedded in a cryo-bolometer contains the complete de-excitation energy of the daughter nucleus that is dispersed in the form of electrons and x-rays emitted during the process. The atomic levels involved are described by Breit-Wigner resonances with finite widths Γ_i. Additionally, n_i is the fraction of occupancy of the i-th atomic shell, C_i is the nuclear shape factor, β_i is the Coulomb amplitude of the electron radial wave function and B_i is an atomic correction for electron exchange and overlap. The use of ^{163}Ho is favored due to its very low Q-Value in the range of 2.3 keV to 2.8 keV [14]. Due to the low Q-value only electrons from the M_1, M_2, N_1, N_2, O_1, O_2 and P_1 shells can be captured and the spectrum is expected to have the shape shown in figure 2, left plot, with the influence of the neutrino mass most pronounced near the endpoint as shown in figure 2, right plot. The count rate in the endpoint region strongly drops with the distance between the closest atomic level and the Q-value of the reaction. At the same time the amount of activity that can be allowed in a single bolometric detector has to be limited in order to reduce pile-up of the signals which otherwise distorts the measured spectrum. In order to gather the required statistics to reach sub-eV sensitivity with this method it is therefore necessary to operate large numbers of small detectors in parallel.

3. Experiments under construction
Neutrino mass experiments currently under construction are centered around the study of nuclear β-decay, where the KATRIN experiment [12] is working with a tritium source and is based on the successful concepts of its predecessor experiments in Mainz [8] and Troitsk [9]. The MARE collaboration [13] on the other hand is conducting a R&D effort to set up arrays of sensitive cryo-bolometers working with ^{187}Re as β-emitter, based on the experiences obtained in the predecessor experiments MANU [15] and MIBETA [11].

3.1. MARE
The "Microcalorimeter Arrays for a Rhenium Experiment" (MARE) collaboration is working on the development of sensitive micro-calorimeters to investigate the β-decay of ^{187}Re which

provides a very low endpoint energy of $E_0 = 2.47$ keV. The basic principle of these detectors, operated at cryogenic temperatures in the mK range, is to use an absorber material that contains the β-emitter and is read out with a sensitive thermometer to measure the rise in temperature caused by the dissipation of the decay energy in the absorber. The current activities in the MARE collaboration are organized in two phases: in MARE-1 several groups are working on alternative micro-calorimeter concepts which will be tested by setting up neutrino mass experiments with sensitivities in the order of a few eV. Besides the selection of the most sensitive detector technology, this phase will also be used to investigate the use of the EC decay of ^{163}Ho as an alternative to the study of rhenium β-decay. In MARE-2 the most successful technique will then be used to set up a full scale experiment with sub-eV sensitivity to the neutrino mass. The technical developments aim at two main goals: first to improve the energy resolution of the detectors and secondly to shorten the response time of the signals in order to reduce pile-up problems. The various groups in the MARE collaboration work on different techniques to achieve these goals: The Group in Genoa is working on the development of Transition Edge Sensors (TES) coupled to metallic rhenium absorber crystals [16]. Their planned experiment will accommodate 300 TES detectors with about 1 mg rhenium each. For a projected energy and time resolution of 10 eV and 10 μs, respectively, the sensitivity will be about 1.8 eV at 90% CL for in total $3 \cdot 10^{10}$ decays detected [13].

Groups from Milano, Como, NASA, GSFC and Wisconsin are working together to developed arrays of silicon implanted thermistors coupled to $AgReO_4$ absorbers [17]. The experiment that is currently being set up uses up to eight 36 pixel arrays with 0.5 mg absorbers. So far the established energy and time resolutions are 25 eV and 250 μs, respectively. With all pixels instrumented a sensitivity of 3.3 eV at 90% CL would be reached with a statistics of $7 \cdot 10^9$ rhenium decays.

At the University of Heidelberg work is ongoing on the development of so-called Metallic Magnetic Calorimeters (MMC) [18]. In contrast to TES sensors or thermistors that exploit the change of resistivity of the sensors with temperature these detectors are measuring the change in magnetization of a paramagnetic material. Promising results have been obtained with gold absorbers, where resolutions < 5 eV have been achieved [19], while the resolution with rhenium absorbers was found to be 45 eV at signal rise times below 10 μs. The same detector concept is also envisaged for the upcoming ECHO project (see section 4.2).

3.2. KATRIN
An overview of the KATRIN experiment is shown in figure 3. The experiment works with a windowless gaseous tritium source (WGTS) where T_2 molecules are injected in the center of
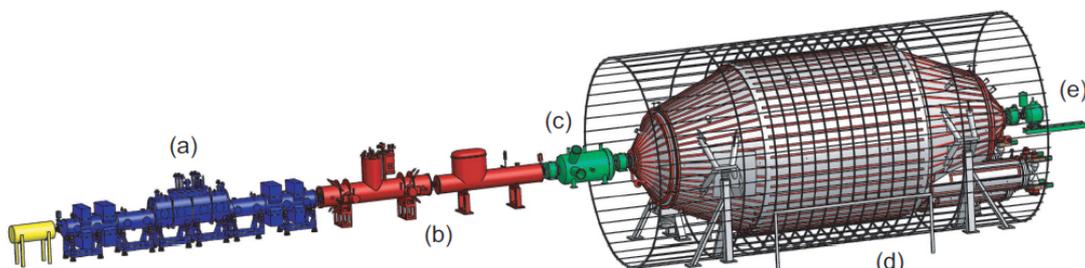

Figure 3. Overview of the KATRIN experiment. The main components are: (a) windowless gaseous tritium source, (b) transport and pumping section, (c) pre-spectrometer, (d) main spectrometer, (e) detector system. Overall length ca. 70 m.

the source and are removed again by turbo-molecular pumps at both ends. The T_2 gas is kept

at a constant temperature of 30 K within the source that is operated at a column density of $5 \cdot 10^{17} \mathrm{cm}^{-2}$. The parameters of the source are monitored by a complex sensor network and a dedicated calibration and monitoring section at the rear of the source system. About 10^{10} decay electrons are emitted per second in the forward direction and are guided magnetically through the transport section to the spectrometer tandem consisting of pre- and main-spectrometers. The task of the transport section made up of a differential pumping section and a cryo-pumping section is to suppress the flow of T_2 molecules into the direction of the spectrometers by at least a factor 10^{14} in order to reduce experimental background from tritium decays within the spectrometers. A first energy discrimination is performed by the pre-spectrometer which rejects the low energy part of the beta spectrum and thereby reduces the rate of electrons going into the main spectrometer to ca. $10^3 \, \mathrm{s}^{-1}$. Like the pre-spectrometer the main spectrometer operates as a so-called MAC-E filter (for a discussion of this technique see [20]) and has the task to perform a precise energy analysis of the decay electrons. The energy resolution of a MAC-E filter is determined by the ratio of the maximum magnetic field encountered along the flight path to the minimal field in the analyzing plane of the spectrometer. In the case of KATRIN this ratio is $B_{max}/B_{min} = 20000$ which corresponds to an energy resolution of 0.93 eV at the endpoint of the tritium β-spectrum. Electrons with sufficient energy to pass the spectrometer are detected by a 148 pixel silicon PIN detector at the end of the setup.

Among the main systematical uncertainties of the experiment are inelastic scatterings of electrons in the source, fluctuations of the source density, fluctuations of the spectrometer analyzing potential, uncertainties in the transmission function and uncertainties in the final state distribution of the daughter molecules left after the decay reaction. A sophisticated calibration and monitoring system employing among others two of the worlds most precise high voltage dividers [21] and a dedicated monitor spectrometer to measure mono-energetic conversion electrons from a ^{83m}Kr source used as a natural standard for energy calibration [22], is being set up to keep the afore mentioned systematic effects under control.

After five years of data taking the projected sensitivity of the KATRIN experiment is 0.2 eV at 90% CL if no neutrino mass signal is found, while a mass of 0.35 eV would be detected with 5σ significance. The experiment is currently in an advanced stage of construction by an international collaboration at the Karlsruhe Institute of Technology (KIT) in Germany with many major components already on site and undergoing extensive testing. Among the recent achievements are tests of a subset of the WGTS in which a temperature stability of < 9 mK over 24 h has been demonstrated for the two-phase neon cooling system of the source (required: $\Delta T < 30$ mK) [23]. Other important milestones in the source section have been the commissioning of the tritium inner loop system and the Laser Raman spectroscopy system [25] to monitor tritium purity. In the transport section the differential pumping section has been installed and tested. The gas-flow reduction factor of the device has been measured and found to be in agreement with simulations [24]. The pre-spectrometer has been used as a testing ground for spectrometer related issues for many years. After the residual background in the spectrometer has been identified as originating from Radon decays [26] and removed by a LN2 cooled baffle, the pre-spectrometer has been moved to the main spectrometer hall. Meanwhile the installation of the inner wire electrode of the main spectrometer is nearing completion. The focal plane detection system, developed by collaborating groups from the US, has been set up and is currently tested at KIT. For systematic studies of the main spectrometer properties a new kind of angular-selective pulsed UV photoelectron source has been developed [27]. Commissioning of the main spectrometer is expected to take place in summer 2012.

4. Upcoming projects
To overcome limitations of the neutrino mass experiments currently under construction and to push down the sensitivity limit beyond the value of 0.2 eV projected for the KATRIN experiment,

several new projects have been started, investigating alternative experimental approaches to the study of weak decays.

While the full kinematic reconstruction of the decays of trapped Tritium atoms proposed by Jerkins and co-workers [28] seems to be hampered by conceptual difficulties [29], there are promising activities from the groups around Project 8 [30] investigating tritium β-decay and the ECHO collaboration [31], looking at the electron capture decay of ^{163}Ho.

4.1. Project 8

Project 8 uses technology from KATRIN's gaseous tritium source combined with a sensitive array of microwave antennae to extract energy spectra of decay electrons from the coherent cyclotron radiation emitted by these electrons in the magnetic field of the source. In this setup the electrons will follow a circular or spiral path with a cyclotron frequency ω of

$$\omega = \frac{\omega_0}{\gamma} = \frac{qB}{m_e + E} \, , \tag{5}$$

where E is the kinetic energy of the electron, B the magnetic field of the source, q the electron charge, m_e its mass, ω_0 the unshifted cyclotron frequency and γ the Lorentz factor. With a suitable set of source parameters, the power of the cyclotron radiation emitted by a single electron will be large enough to be detected, but not large enough to rapidly change the electron's momentum and will therefore allow to reconstruct its kinetic energy.

The energy resolution ΔE of the method depends on the relative uncertainty with which the cyclotron frequency can be determined, which in turn depends on the observation time for an individual decay electron. In the paper of Monreal and Formaggio [30] the authors discuss a reference design with 1 T magnetic field strength. In this design we have $f_0 = \omega_0/2\pi \approx 27$ GHz for decay electrons near the endpoint energy. For a resolution of $\Delta E = 1$ eV we therefore require a relative uncertainty $\Delta f/f = \Delta E/m_e = 2 \cdot 10^{-6}$ and, via the Nyquist theorem $t_{min} = 2/\Delta f$, a minimum observation time of 38 μs. This observation time determines the necessary mean free path of decay electrons in the source before they undergo inelastic scattering from T_2 molecules and therefore places constraints on the density of the source. Signals of high energy electrons will show up as a triplet of lines (their cyclotron frequency plus two sideband signals) in the lower part of the frequency spectrum. Because this region is also populated by sideband signals from lower energy electrons, the coincident detection of at least two of the three lines is required to confidently identify an endpoint electron.

The proposed technique presents very different systematic errors than present in MAC-E filter experiments like KATRIN. Care has to be taken to eliminate the effects of Doppler shifts that alters the frequency picked up by the microwave antennas. Inhomogeneities in the B-field are a source of line broadening, while drifts of the magnetic field will shift the overall spectrum. Electron - T_2 scattering and signal pile-up will limit the allowed source density and therefore influence the achievable signal rate in the important endpoint region of the spectrum. Neglecting systematic uncertainties the authors of reference [30] estimate the statistics required to reach KATRIN's sensitivity of 0.2 eV to be $3 \cdot 10^{15}$ tritium decays or 10^8 Bq-years.

4.2. ECHO

Groups from Heidelberg, the Saha institute, ISOLDE/CERN and the Petersburg Nuclear Physics institute are working on the development of the Electron Capture ^{163}Ho experiment ECHO [31], that is based on micro-structured MMC type detectors. The relatively short half-life of about 4570 years allows to work with ^{163}Ho implanted gold absorbers that enable a good energy resolution of < 12 eV and very fast rise times of the signals of about 90 ns. Measurements with a prototype detector resulted in the most precise ^{163}Ho calorimetric spectrum to date from which a Q-value of (2.8 ± 0.1) keV has been extracted [32]. Work is ongoing to further improve

the energy resolution of the detectors into the < 3 eV region. In order to allow for the readout of large arrays of MMCs coupled to rf-SQUIDs, frequency domain multiplexing techniques in the microwave region are employed.

5. Outlook

Experiments studying the kinematics of weak decays allow for a model independent determination of the neutrino mass, complementary to results obtained from cosmology and from searches for $0\nu\beta\beta$ decays. From the experiments that are presently being constructed, KATRIN is most advanced and will push the sensitivity to the neutrino mass down to 0.2 eV. Alternative approaches that employ calorimetric methods, such as MARE or ECHO, or the detection of microwave radiation emitted by β-decay electrons in magnetic fields, as in Project 8, are in the phase of methodological R&D and may, in the future, provide a more scalable approach to neutrino mass measurements. Eventually, it will become very important to cross check results from different experiments.

Acknowledgments

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