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The MARE Project

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Abstract The international project "Microcalorimeter Arrays for a Rhenium Experiment" (MARE) aims at a direct and calorimetric measurement of the electron antineutrino mass with sub-electronvolt sensitivity.

MARE is divided in two phases. The first phase consists of two independent experiments using the presently available detector technology to reach a sensitivity of the order of 1 eV and to improve the understanding of the systematic uncertainties peculiar of this technique. In parallel to these experiments, a wide R&D program will single out the appropriate detector configuration, the read-out scheme and the large array technology for the second phase of MARE. In the second phase, the selected techniques will be applied to the realization of large arrays with as many as 10000 detectors each. At least five arrays will be then deployed to collect the statistics required to probe the antineutrino mass with a sensitivity of at least 0.2 eV, comparable to the one expected for the Katrin experiment (KATRIN Design Report, 2004).

Keywords Neutrino mass · Beta decay · Thermal detectors · ^{187}Re

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1 Introduction

The measurement of the neutrino mass scale is the most important piece of information still missing to the picture recently disclosed by neutrino oscillation experiments. Although cosmological observations and neutrinoless double decay searches may be

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more sensitive, the kinematical neutrino mass measurement is the only model independent method to assess the mass scale. A deeper analysis shows that the three methods are indeed complementary tools for studying the neutrino properties.

Fixing the neutrino mass scale requires to measure the mass of one of the three neutrinos. This is done best for the electron anti-neutrino by precisely analyzing the kinematics of electrons emitted in beta decays. To date, the study of the ^{3}H beta decay end-point by means of electrostatic spectrometers has proved to be the most sensitive approach, yielding an upper limit on the electron anti-neutrino mass of 2.2 eV [1]. A large international collaboration is setting up the new experiment KATRIN [2]. Starting from 2010, KATRIN will analyze the ^{3}H beta decay end-point measurement with a much more sensitive electrostatic spectrometer and with an expected statistical sensitivity of about 0.2 eV, reached in 5 calendar years.

However, these experiments suffer from many systematic uncertainties due to final state corrections, energy losses in the ^{3}H source, scattering losses through the spectrometer, and more. These uncertainties have been much reduced in last spectrometer experiments so that their contribution to the 2.2 eV limit is comparable to the statistical error. Therefore, to improve the sensitivity, it is necessary to reduce both the systematic and the statistical uncertainty. Because of the large weight of systematics, it is inherent in this type of measurement that confidence in the results can be obtained only through confirmation by independent experiments. The best would be an independent experiment characterized by different systematics.

A complementary approach for the direct neutrino mass measurement is the calorimetric one. With this technique the beta source is embedded in the detector so that all the energy emitted in the decay is measured, except the one taken away by the neutrino. With this configuration, the systematic uncertainties arising from the electron source being external to the detector are eliminated.

Future direct experiments will probe neutrino masses as low as 0.1 eV: a neutrino mass of this size would imply that the three neutrinos have similar masses (quasi-degenerate mass hierarchy). This is the mass scale indicated by the still unconfirmed $\beta\beta$-0ν evidence claimed for ^{76}Ge by H.V. Klapdor-Kleingrothaus et al. [3]. Taking this claim as correct and adding the results from oscillation experiments and cosmological observations, the m_ν neutrino mass measured in kinematical experiments is expected to be between about 0.4 eV and 0.8 eV [4]. It is worth noting that in this mass range kinematical experiment actually measure an averaged neutrino mass $m_\nu = m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$ where m_i are the masses of the three neutrino mass eigenstates and U_{ei} are the elements of the electron sector of the neutrino mixing matrix.

2 Calorimetric Rhenium Experiments and the MARE Project

A perfect practical way to make a calorimetric measurement is to use thermal detectors. At thermal equilibrium, the temperature rise of the detector is due to the sum of the energy of the emitted electron and of all other initial excitations. The measurement is then free from the systematics induced by any possible energy loss in the source and is not affected by problems related to decays on excited final states. In principle one remaining systematics may be due to energy lost in metastable states living longer than the detector integration time which is always more than 1 μs.[1] On the other hand, since in this configuration the detector is always exposed to the entire beta energy spectrum, the source activity must be limited to avoid spectral distortions and background at the end-point due to pulse pile-up. As a consequence the statistics near the end-point is limited as well. Since the fraction of decays in a given energy interval ΔE below the end-point E_0 is only $\propto (\Delta E/E_0)^3$ [5], the limitation on the statistics may be partially balanced by using as beta source ^{187}Re, the beta-active nuclide with the lowest known transition energy ($E_0 \sim 2.5$ keV).

To date, only two experiments have been carried out with thermal detectors containing ^{187}Re: the MANU [6, 7] and MIBETA [8, 9] experiments. MANU used one detector with a NTD thermistor glued to a 1.6 mg metallic rhenium single crystal, while MIBETA used an array of eight silicon implanted thermistors with $AgReO_4$ crystals for a total mass of about 2.2 mg. The two experiments collected statistics corresponding to 10^7 and 1.7×10^7 decays respectively, yielding limits on m_ν of about 26 eV at 95% CL and 15 eV at 90% CL respectively. The systematics affecting these experiments are still small compared with the statistical errors. The main sources are the background, the detector response function, the theoretical spectral shape of the ^{187}Re β decay, the Beta Environmental Fine Structure [10, 11] (BEFS), and the pile-up [13].

Lowering this limit requires better detectors and larger statistics. From a simple statistical analysis, in absence of background, for the 90% CL limit on m_ν $\Sigma(m_\nu)_{90}$ one can write

$$\Sigma(m_\nu)_{90} = 0.74 \sqrt[4]{\frac{2E_0^3 \Delta E}{t_M A_\beta N_{det}} + \frac{9\tau E_0^5}{5 t_M N_{det} \Delta E}} \tag{1}$$

where ΔE, τ, t_M, A_β, and N_{det} are the detector energy and time resolution, the measuring time, the β activity of each detector, and the number of detectors respectively. The time resolution τ is the ability to distinguish two β decays happening in a short time interval and is strictly related to the detector rise time: two decays closer than τ are mistaken as one single decay with energy equal to the sum of the two decay energies. The frequency of these piling up events is about τA_β and their spectrum ($N_{pile\text{-}up}(E) \propto N(E) \otimes N(E)$, where $N(E)$ is the ^{187}Re β spectrum) extends from 0 to about $2E_0$. The two terms in (1) arise respectively from the statistical fluctuations of the β and pile-up spectrum. Equation (1) shows the importance of improving the detector energy resolution and of minimizing pile-up by reducing the detector rise time. But it shows also that the largest reduction on the limit can only come by substantially increasing the total statistics $N_{ev} = t_M A_\beta N_{det}$. If the effect of pile-up is kept negligible the sensitivity improves as $\sqrt[4]{1/N_{ev}}$. Therefore improving the present limit of the MIBETA and MANU experiments by a factor 100, would require to increase the statistics by a factor 10^8, i.e. to collect a statistics of about 10^{15} decays.

A more accurate estimate of the sensitivity is obtained with a Monte Carlo frequentist approach [16] where the important experimental parameters are the total

[1] The probability of transitions to an osmium atomic excited state has been estimated to be lower than 7×10^{-5} [18].

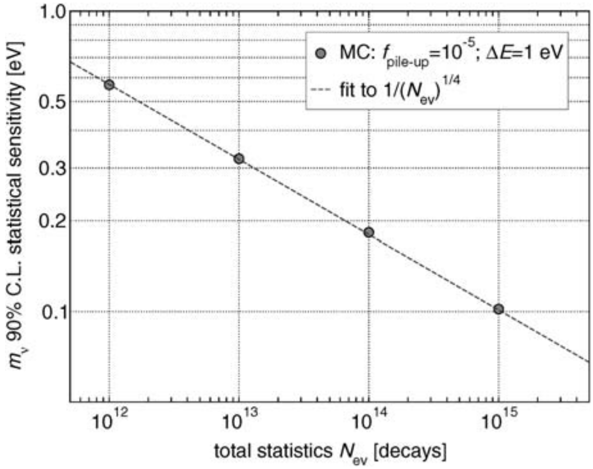

Fig. 1 Statistical sensitivity evaluated with Monte Carlo simulations

statistics N_{ev}, the energy resolution ΔE, and the fraction of pile-up events $f_{pile\text{-}up} = \tau A_\beta$. Figure 1 shows the results of this approach for a hypothetical future experimental configuration and confirms the $\sqrt[4]{1/N_{ev}}$ dependence of the sensitivity.

The MANU and MIBETA results together with the constant advance in the thermal detector technology make it reasonable to propose a new larger scale experiment able to explore the sub-eV neutrino mass range. This is the final aim of the Microcalorimeter Arrays for a Neutrino Mass Experiment (MARE) project which has been started in 2005 by a large international collaboration [12, 17]. Monte Carlo studies tell that for a sub-eV sensitivity MARE needs large arrays (of the order few 10^4 elements) of detectors with energy and time resolutions of the order of 1 eV and 1 µs respectively. Each pixel should have a source activity of about few counts per second and the measurement should last up to ten years to collect a total statistics of about 10^{14} beta decays (see Fig. 1) [12].

Such an experiment is of course extremely challenging, therefore the project development is divided in two phases.

Phase I, called MARE-1, has two major targets. First of all, an intermediate size experiment should reach a neutrino sensitivity of the order of 1 eV and improve the understanding of the systematics peculiar of the calorimetric approach with ^{187}Re. This intermediate experiment would also scrutinize the present results of the spectrometer experiments, possibly before KATRIN new results. In parallel to this experimental effort an activity is in progress to weigh the effect of the various sources of systematics with Monte Carlo methods [14, 15], to improve the quality of β spectral shape parametrization, and to better understand how the BEFS affects the beta decay spectrum close to the end-point by means of EXAFS measurements together with more sophisticated models. At the same time a preliminary R&D should single out the most appropriate technique to realize the final MARE arrays. This requires to improve the understanding of superconducting rhenium absorbers and of their optimal coupling with sensors, and to develop the appropriate array technology and multiplexed read-out scheme [12].

MARE-2 will be the second and final phase where the large scale experiment will be carried out.

3 The MARE-1 Experiments

To be useful, the intermediate MARE-1 experiment should start as soon as possible. It is therefore necessary to employ the presently available technique putting at work the established expertise of the Genova and Milano groups to reach by 2010 a neutrino mass sensitivity of few electronvolts. MARE-1 will therefore consist of two independent experiments located in Genova and Milano and based on the technologies developed by the two groups.

The Genova group has developed microcalorimeters with TES sensors coupled to metallic rhenium absorbers for the MANU2 experiment [18]. The planned experiment will consist of an array of 300 TES detectors with about 1 mg rhenium single crystals. For energy and time resolutions of about 10 eV and 10 µs respectively, the sensitivity attainable in three years is about 1.8 eV at 90% CL for a statistics of about 3×10^{10} decays [19–21].

The Milano/Como group, together with the NASA/GSFC and Wisconsin groups, has developed arrays of silicon implanted thermistors coupled to $AgReO_4$ absorbers [22]. The experiment, which is presently being assembled, uses the XRS2 36 pixels arrays with about 500 µg $AgReO_4$ crystals. By the end of 2007 two arrays will be running, but the set-up is able to host up to eight of these arrays for a total of 288 pixels [24]. So far, the established energy and time resolutions are about 25 eV and 250 µs respectively. With all 288 pixels instrumented, a sensitivity of about 3.3 eV at 90% CL would be reached in 3 years with a statistics of about 7×10^9 decays [23].

Using two different absorbers will help understanding the BEFS and its role as one of the most important sources of systematic uncertainties.

With both experiments successfully run until their expected sensitivity one would be able to further increase the sensitivity by analyzing the data from both experiments simultaneously. Moreover it would be possible to cross-check the results reducing the risk of unexpected systematics weakening the sensitivity. The situation would be similar to that of the electrostatic spectrometer experiments, where the presence of two similar experiments helped validating their neutrino mass limits.

4 The R&D for MARE-2

The sensor technologies which may be used for the second phase are Transition Edge Sensors (TES), Metallic Magnetic Calorimeters (MMC) and Microwave Kinetic Inductance Detectors (MKID) [12]. TES and MMC have proved already to be extremely sensitive. Both sensors have reached energy and time resolutions close to the MARE-2 specifications—when coupled to suitable absorbers—showing therefore to have no intrinsic limitation. While TES have been already integrated in large ($\approx 10^4$) arrays with multiplexed read-out (SCUBA2 [25]), MMC are more suitable for coupling to large size absorbers. MKID represent a relatively new and promising technique which offers a natural multiplexed read-out possibility.

While the interest for these sensor technologies, their integration in large arrays, and the design of suitable multiplexing schemes, is shared with the next generation X-ray space observatory, the optimization of the rhenium absorber coupling is specific to the MARE experiment. Therefore the R&D activity which is now starting focuses on the properties of rhenium as superconducting absorber and on its coupling to the selected sensors [12]. First tests with rhenium absorbers coupled to MMCs are giving interesting results [26]. A R&D program on the coupling of rhenium absorbers with TES has been since long carried out by the Genova group, but new efforts in the collaboration are starting up soon. An activity on MKIDs is also planned to start shortly.

Within $3 \div 4$ years, these activities should end with the definition of the optimal single pixel and the design of a multiplexed 10^4 pixel array. Many of these arrays will be then deployed in the refrigerators of the participating groups. A staged approach with five 10^4 pixel arrays deployed one per year would give a statistical sensitivity better than 0.25 eV after 10 years from starting.

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