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The MARE experiment: "Microcalorimeter Array for a Rhenium Experiment"

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Summary. — The experiments dedicated to effective electron-neutrino mass determination are the kinematic ones from single β-decay. In this context an international collaboration is growing around the project of Microcalorimeter Arrays for a Rhenium Experiment (MARE) for a direct calorimetric measurement of the neutrino 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 specific of the microcalorimetric technique. The two experiments are: MARE-1 in Milan, in collaboration with NASA/GSFG and the University of Wisconsin at Madison, and MARE-1 in Genoa. The goal of the second phase (MARE-2) is to achieve a sub-electronvolt sensitivity on the neutrino mass. The Milan MARE-1 arrays are based on semiconductor thermistors and dielectric Silver Perrhenate absorbers, $AgReO_4$.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `07.20.Mc` – Cryogenics; refrigerators, low-temperature detectors, and other low-temperature equipment.
PACS `23.40.-s` – β decay; double β decay; electron and muon capture.

1. – Introduction

Neutrino oscillation experiments have shown that neutrinos are massive particles, but they are not able to determine the absolute neutrino mass scale. Therefore, the absolute value of neutrino mass is still an open question in elementary particle physics. Although neutrinoless double-beta decay searches and cosmological observation should be more sensitive, the experiments dedicated to effective electron-neutrino mass determination are the ones based on kinematic analyses of electrons emitted in single β-decay. The most stringent results come from electrostatic spectrometers on tritium decay ($E_0 = 18.6\,\text{keV}$). The Mainz Collaboration has reached $m_\nu \leq 2.3\,\text{eV}/c^2$ [1]. With the Troitsk neutrino mass experiment an upper limit on electron-antineutrino mass of $2.5\,\text{eV}/c^2$ has been obtained [2]. The next generation experiment KATRIN is designed to reach a sensitivity of about $0.2\,\mathrm{eV}/c^2$ in five years.

These experiments suffer from systematic uncertainties due to atomic/molecular final excited states, energy losses in the ^{3}H source and scattering losses while passing through the spectrometer. In the last spectrometer experiment these systematic uncertanties have been reduced insomuch as their contribution to the 2.2 eV limit is comparable to the statistical error. In order to improve the sensitivity on neutrino mass, it is necessary to reduce both the systematic and statistical uncertainties. The weight of systematics is not negligible so confidence in the results can be obtained only through confirmation by indipendent experiments affected by different systematics.

To scrutinize the current and future results of Mainz, Troitsk and KATRIN, an entirely different method to determine the neutrino mass from single β-decay has been investigated. This complementary approach is the calorimetric one. With this technique the beta source is embedded in the detector so that all the energy emitted in beta decay is measured, except for the one taken away by the neutrino. In this way the systematic uncertanties due to an external beta source are eliminated. It has been demonstrated in the past that observing the β-decay spectrum of ^{187}Re provides a suitable method to determine the mass of the anti-neutrino from the Kurie-plot. At the beginning, a sensitivity of $m_\nu \leq 15\,\mathrm{eV}/c^2$ was achieved with the experiments MIBETA in Milan and MANU in Genoa [3]. In these experiments the systematic uncertanties are still small compared to the statistical errors. The main sources of systematics are the background, the pile-up, the theoretical shape of the ^{187}Re β spectrum, the detector response function and the Beta Enviromental Fine Structure (BEFS) [4,5]. The MANU and MIBETA results together with the constant advance in the performance of low-temperature detectors open the door to a new large-scale experiment able to explore the sub-eV neutrino mass range. In this context, an international collaboration is growing around the project of Microcalorimeter Arrays for a Rhenium Experiment (MARE) for a direct calorimetric measurement of the neutrino mass with sub-electronvolt sensitivity.

2. – Calorimetric experiments

Thermal detectors measure the portion of deposited energy converted into phonons, through the corresponding temperature rise. At low temperatures these phonon-mediated detectors provide better energy resolution, lower energy theresholds and wider material choice than conventional detectors in many applications.

Phonon-mediated detectors were proposed initially as perfect calorimeters, *i.e.* as devices able to thermalize through the energy released by the impining particle (the term *microcalorimeters* is used when the total detector mass does not exceed 1 mg and the linear dimensions are few hundreds of μm maximum). In this approach, the energy deposited by a single quantum into an absorber (weakly connected to a heat sink) determinates an increase of its temperature T. This temperature variation corrisponds to the ratio between the energy E released by the impinging particle and the heat capacity C of the absorber. The only requirements are to operate the device at low temperature in order to make the heat capacity low enough, and to have an enough sensitive thermometer coupled to the absorber.

At thermal equilibrium, microcalorimeters measure the temperature rise induced by the energy deposition of the β-electron and of all other initial excitations in an absorber of low heat capacity. In this way the measurement is completely free from systematics induced by any possible energy loss in the source and due to decays into excited final states. The remaining systematics may be due to energy lost in metastable states living longer than the detector response time. In contrast to the spectrometer approach, the full beta spectrum is acquired. Therefore, the source activity has to be limited to avoid pile-up which would deform the shape of beta spectrum near the end-point. Since the fraction of beta events in a given energy range ΔE below the end-point E_0 is proportional to $(\Delta E/E_0)^3$, the best choice is to use as beta source ^{187}Re, the nuclide with the lowest known transition energy ($E_0 = 2.47\,\mathrm{keV}$) and a half-life of 43.2 Gy.

From a simple statistical analysis, setting the signal-to-noise ratio equal to 1.7 for a 90% confidence level, it is possible to derive an approximate expression for the statistical sensitivity of a calorimetric neutrino mass experiment with a set-up made of an array of identical detectors [6, 7]. In the absence of background for the 90% confidence level on m_ν one can write

$$\Sigma_{90}(m_\nu) \approx 0.74 \sqrt[4]{\frac{2\Delta E E_0^3}{N_{\mathrm{ev}}} + \frac{9 f_{pp} E_0^5}{5 N_{\mathrm{ev}} \Delta E}}, \tag{1}$$

$$N_{\mathrm{ev}} = A_\beta t_M N_{\mathrm{det}}, \tag{2}$$

$$f_{pp} = A_\beta \tau, \tag{3}$$

where ΔE is the energy range of interest near the end-point, t_M is the measuring time, A_β is the β activity of each detector, τ is the detector time resolution, N_{det} is the number of detectors, N_{ev} is the number of total events and f_{pp} is the frequency of pile-up events given by the product between A_β and τ, respectively. The time resolution is the ability to resolve two β decays happening in a short time interval, two events with a separation smaller than τ are interpreted as one single decay with energy equal to the sum of the two decay energies. In practice, τ is of the order of the detector rise time. The coincidence rate is τA_β^2 and the pile-up spectrum extends from 0 to $2E_0$ (it is assumed to be simply the convolution of the beta spectrum with itself, $N_{\text{pile-up}}(E) \propto N(E) * N(E)$, where $N(E)$ is the ^{187}Re beta spectrum). Equation (1) shows the importance of mimizing the pile-up by reducing the detector rise time. But the greatest reduction on the limit of m_ν happens when increasing the statistics. In fact if the pile-up is neglegible the 90% confidence limit sensitivity is proportional to $\sqrt[4]{1/N_{\mathrm{ev}}}$.

Figure 1 shows the results of this approach for two different experimental configurations. The number of the detectors is increased during the years: in the first year the number of the detectors is 72, in the second one 144 and in the last three years 288.

3. – The MARE project

The final aim of MARE project is to explore the sub-eV neutrino mass range. Monte Carlo results have shown that for a sub-eV sensitivity on neutrino mass MARE needs a huge number of detectors (of the order few 10^4) with an energy and time resolution of the order of 1 eV and 1 μs, respectively. With a single detector β activity of around few counts per second, in ten years or less it is possible to collect 10^{13}–10^{14} beta decays.

Since such an experiment is challenging, 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 specific of the microcalorimetric technique. The goal of the second phase is to achieve a sub-electronvolt sensitivity on the neutrino mass. The

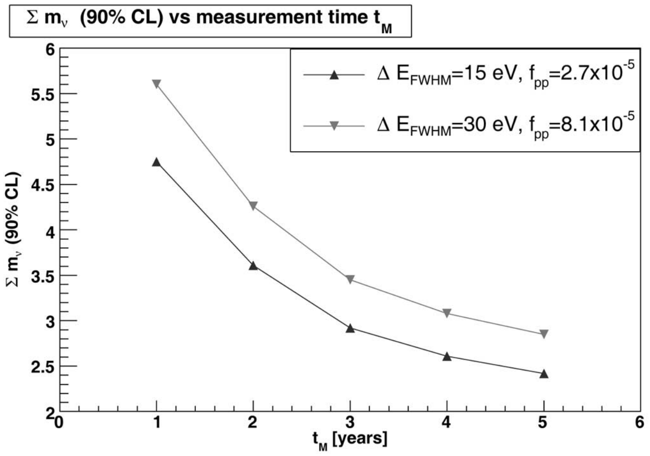

Fig. 1. – Statistical sensitivity evaluated with a statistical approach for two different experimental configurations. In the first year the number of the detectors is 72, in the second one 144 and in the last three years 288.

two experiments are: MARE-1 in Milan, in collaboration with NASA/GSFG and the University of Wisconsin at Madison, and MARE-1 in Genoa, in collaboration with PTB Berlin and the University of Miami, Florida.

For MARE-1 the Genoa group has developed microcalorimeters with Transition Edge Sensors (TES) coupled to metallic rhenium absorbers. Each detector consists of about 1 mg rhenium single crystals. The final experiment will consist of 300 TES detectors. For energy and time resolution of 10 eV and 10 μs, respectively, a sensitivity on neutrino mass of 1.8 eV at 90% CL is expected in three years for a statistics of about 3×10^{10} events [7].

4. – MARE-1 in Milan

The Milan MARE-1 arrays (288 detectors) are based on semiconductor thermistors coupled to dielectric silver perrhenate ($AgReO_4$) absorbers. These arrays, provided by the NASA/Goddard group, consist of 6 × 6 implanted Si:P thermistors with a size of $300 \times 300 \times 1.5\,\mu m^3$. An energy resolution of 3.2 eV FWHM at 5.9 keV has been obtained with these thermistors and HgTe absorbers [8]. On their top single crystals of $AgReO_4$ are glued with epoxy resin. The crystals, the mass of which is around 500 μg, are cut in regular shape of $600 \times 600 \times 250\,\mu m^3$. To realize a defined thermal coupling between the thermistor and the rather large absorber, silicon pieces of $300 \times 300 \times 10\,\mu m^3$ are glued between them. With all 288 detectors with an energy and time resolution of about 25 eV and of 250 μs, respectively, a sensitivity of 3.3 eV at 90% CL on the neutrino mass will be reached within 3 years. This corresponds to a statistics of about 7×10^9 decays [7].

The performance of such bolometers, which are characterized by high impedance (1–10 MΩ) at low temperature, depends not only on the thermistors and the quality of the crystals but also on the read-out electronics and the wiring of the apparatus. So a cold preamplifier stage, based on JFETs which work at about 135 K, is installed to reduce the impedance of the thermistors. This first stage is followed by an amplifier stage at room temperature. The wiring has been optimized to reduce the parasitic capacitance and the microphonic noise. To electrically connect the cold electronics to the detectors with low thermal conductance wires, microbridges are fabricated by the ITC-irst in Trento, Italy. The microbridges are thin wires (thickness around 200 nm) made of Ti or Al deposited onto polyamid. The microbridges provide thermal decoupling between detectors and JFETs, but they do not guarantee mechanical stability. Therefore, materials with very low thermal conductivity are used as mechanical support, namely Kevlar and Vespel.

A first microbridge stage provides a thermal decoupling between the detectors and the JFET holder (4 K). These microbridges are made of titanium. The 4 K parts are suspended by three kevlar crosses. A second step of thermal decoupling is made in the JFET box. This stage is between the JFET structure and the dedicated PCB where the JFETs are soldered. The microbridges connecting the JFETs to the JFET holder are made of alluminium. The dedicated PCB is suspended by two thin Vespel rods.

The cryogenic set-up is mounted in the Kelvinox KX400 dilution refrigerator located in the Cryogenic laboratory in the Physics Departement of Milano-Bicocca University. The dilution unit is equipped with a copper rod which is used to hold the structure of the JFET electronics at 4.2 K, very close to the arrays at 85 mK. The energy calibration system is located between the detector holder and the JFETs boxes. The calibration system consists of a fluorescence source with 10 mCi of ^{55}Fe as a primary source movable in and out of a lead shield [9]. The fluorescence targets are made of Al, Ti, CaF_2 and NaCl to allow a precise energy calibration around the end-point of ^{187}Re with the K_α X-rays at about 1.49, 1.74, 2.31, 2.62 and 3.69 keV.

Figure 2 shows the design of the cryogenic set-up of MARE-1 in Milan.

We are currently assembling the experimental set-up of MARE-1 in Milan to be able to start as soon as possible the 72 channels measurement.

5. – Detector performance

To optimize the detector performance we have equipped two test arrays to determine the best thermal coupling between Si thermistors and $AgReO_4$ absorbers. Therefore different kinds of glues were tested to attach silicon spacers on the thermistors and $AgReO_4$ crystals on the spacers, respectively.

Figure 3a shows a single element of the XRS2 array and fig. 3b a sketch of a $AgReO_4$ microcalorimeter.

The results indicate that the combination Araldit R/Araldit R is favourable over the other glue combinations, but this epoxy resin deteriorates during the years and probably also due to thermal cycling. Therefore, the ST2850 has to be used to glue $AgReO_4$ absorbers on the silicon spacers. We would like to point out that MIBETA also used ST2850 to directly glue the $AgReO_4$ crystals onto the thermistors; no spacers were needed in that experiment. A spectrum of one detector can be seen in fig. 4.

6. – Enviromental background

To identify the best shielding approach that minimizes radioactivity background in the energy region of the ^{187}Re β spectrum, a preliminary study of the Cryogenic laboratory environmental background was performed. Using a planar germanium detector for the energy range below 10 keV, different shielding configurations have been set up to find the ideal thickness and the best material to shield the microcalorimeter arrays. The detector, characterized by an energy resolution of 195 eV at 5.9 keV, is covered by a very thin Be window, the thickness of which is around 0.127 mm. The detection threshold is

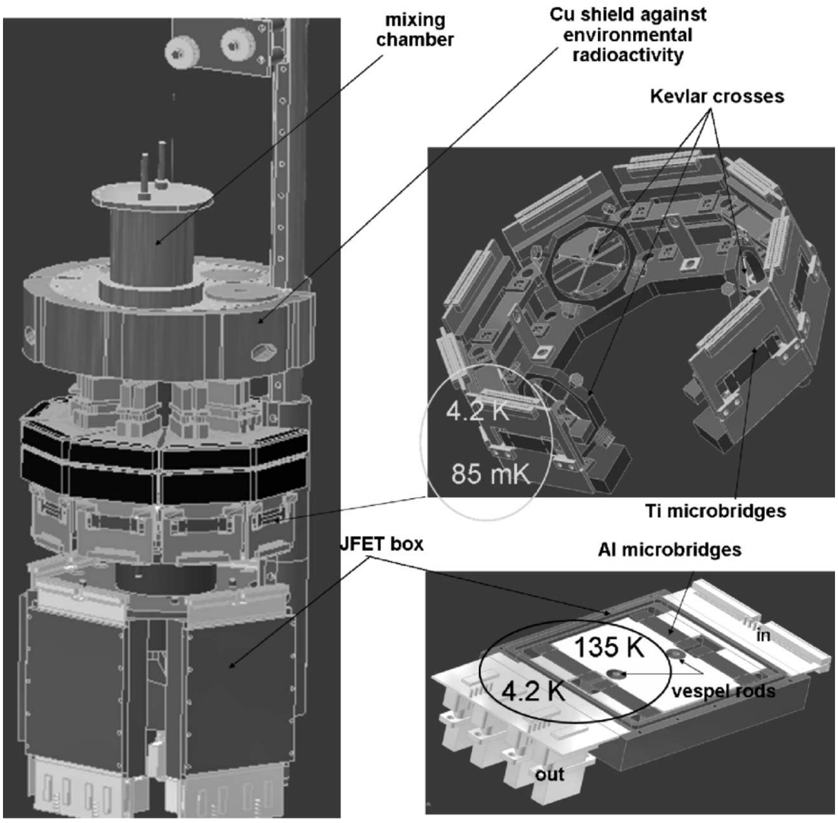

Fig. 2. – Cryogenic set-up of MARE-1 in Milan.

around 1 keV. The background spectrum shows peaks at the position of Pb K_{α_1}, K_{α_2} and K_{β_1} lines, which pronounce above a continuous background.

In order to reduce the environmental background, different shields have been built around the germanium detector made of lead, copper and two layers shielding, lead plus

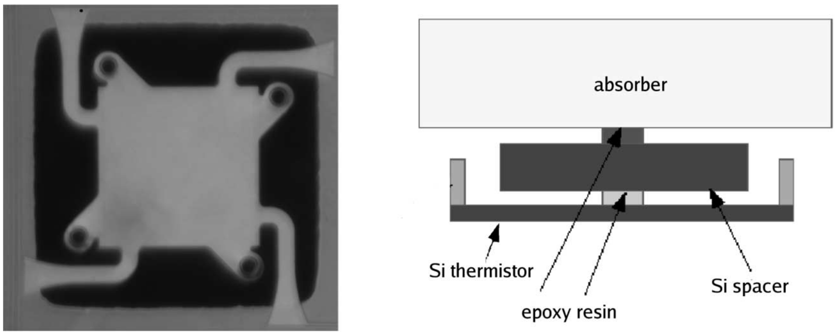

Fig. 3. – a) Single element of the XRS2 array. b) Structure of a $AgReO_4$ microcalorimeter.

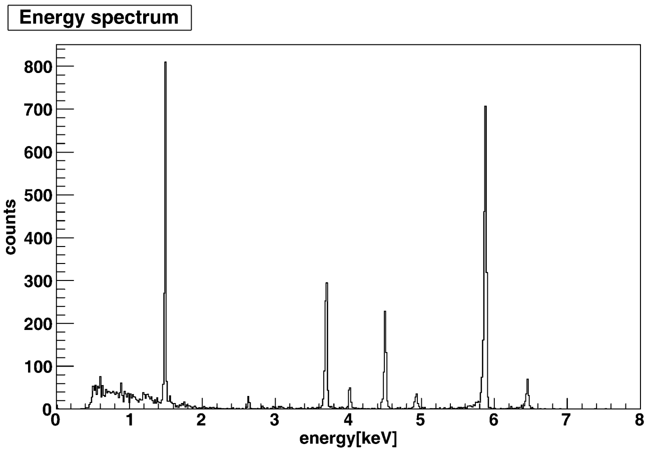

Fig. 4. – A spectrum of one detector with an energy resolution at 2.6 keV of 33 eV. The thermal coupling is made of Araldit Rapid between the thermistor and the silicon spacer and made of ST2850 between silicon spacer and $AgReO_4$absorber. The mass of the crystal is 381 μg.

copper. It turned out that the best configuration is a lead shield. But in the past, background spectra acquired in the MIBETA experiment have shown that a shield made of lead increases the background due to escape peaks resulting from the interaction of the Pb X-rays with Ag and Re atoms in the $AgReO_4$ absorbers [3]. Therefore, since copper is better than lead for shielding the $AgReO_4$ microcalorimeter, the background reduction due to a copper shield has been studied. The germanium detector has been shielded putting a copper cup with variable thickness. With a thickness of around 40 mm, the maximum space in the cryostat, we achieve a reduction of 70%.

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