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Section A

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MARE, Microcalorimeter Arrays for a Rhenium Experiment: A detector overview

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Abstract

We describe and discuss the features of MARE, an experiment based on arrays of rhenium low temperature microcalorimeters that have the potential to bring the sensitivity to the neutrino mass down to 0.2 eV, by studying the beta spectrum of ^{187}Re (Q-value $=$ 2.47 keV).

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1. The physics case

Single beta decay is the only laboratory measurement that can determine the neutrino mass scale in a fully model independent approach. Neutrino mass is extracted by studying the shape of the beta spectrum in a region close to the end point Q. The parameter which is actually inferred from the measurement is $m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$, where U_{ei} are the elements of the first row of the neutrino mixing matrix. Presently, the upper bound on m_ν is 2.2 eV, provided by the MAINZ and TROITZK [1] experiments, which have studied the ^{3}H beta decay ($Q = 18.6$ keV) by means of electrostatic spectrometers. A large expansion of this experiment, named KATRIN [2], is under development. Its projected sensitivity is 0.2 eV and data taking

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should start within 2010. However, as the systematic uncertainties connected to these types of measurement are quite complicate, an alternative technique able to reach similar sensitivities would be of invaluable importance in neutrino physics. In the framework of the MARE experiment, we are proposing arrays of low temperature calorimeters, measuring the beta decay of ^{187}Re ($Q = 2.47\,\text{keV}$, the lowest known in nature), as an additional method to constrain m_ν. The MARE approach would have a totally different systematics with respect to KATRIN, and its intrinsic modularity allows in principle a progressive expansion of the experiment down to and perhaps lower than 0.2 eV sensitivity.

2. MARE-1: a 2 eV neutrino mass experiment

The specific beta activity of natural rhenium (of the order of 1 Bq/mg), is ideally tailored to low temperature microcalorimeters, detectors consisting of a Re-based energy absorber and a sensitive thermometer which converts the temperature increase induced by a single beta decay into an electrical signal. In an experiment based on microcalorimeter arrays, the statistical sensitivity to neutrino mass $\Sigma(m_\nu)$ scales as $(\Delta E/N_{\text{ev}})^{1/4}$. Large progresses in sensitivities can be attained acting mainly on the number of collected counts N_{ev}. Present limits obtained with precursor calorimetric experiments are around 15 eV, with a number of registered events of the order of 6×10^6 [3,4]. Pulse pile-up affects the experimental spectral shape producing a continuous spectrum almost flat in the region of the end point which adds up to the pure beta spectrum. The statistical fluctuations of the pile-up counts nearby Q represent the main intrinsic limitation of the calorimetric technique. The pulse-pair resolving time T_{R}, of the same order of the pulse rise time, is therefore a crucial parameter for the experiment figure of merit, together with ΔE, N_{ev} and λ, the beta event rate in a single element of the detector array. The pile-up fraction f_{pup} is given by $\sim T_{\text{R}} \times \lambda$. Once the single element size and technology are fixed (this choice nails energy resolution and pile-up fraction down), it is possible to determine $\Sigma(m_\nu)$ as a function of N_{ev}. Present technologies allow to achieve energy resolutions of the order of 10–20 eV for single elements with counting rates of the order of 0.2–0.3 Bq, and T_{R} around 100–500 μs. That corresponds to typically to $f_{\text{pup}} \simeq 10^{-5} - 10^{-4}$. From Fig. 1, it is possible to see that the statistics target to scrutinize the MAINZ and TROITZK experiments is of the order of 10^{10} events, collectable in a few years with an array of about 300 elements. This figure corresponds to the first phase of the experiment, named MARE-1.

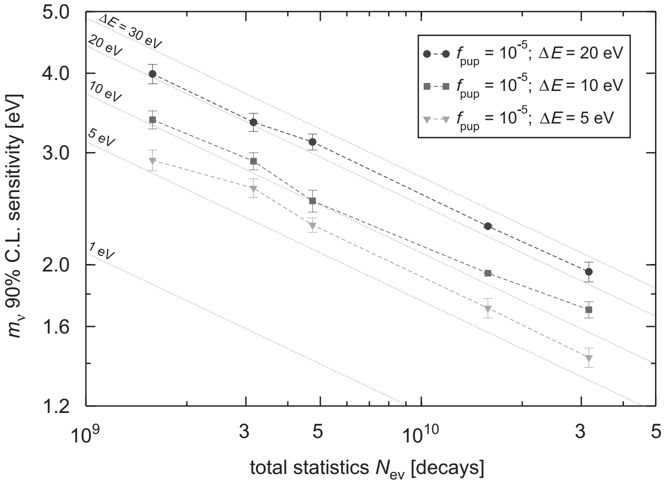

Fig. 1. MARE-1: sensitivity vs. statistics (points: Monte Carlo simulation; lines: analytical approach).

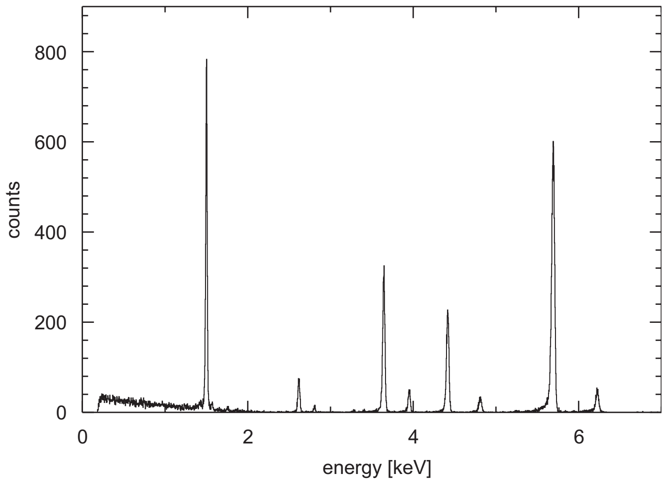

Fig. 2. Calibration spectrum of a Re microcalorimeter (see text for details).

Two parallel technologies are being pursued for MARE-1. In one case, the single element thermometer is a transition edge sensor (TES) consisting of an Ir–Au multilayer film grown on a silicon substrate. A metallic superconductive Re crystal with a mass of about 200–300 μg is attached to the opposite side of the silicon substrate. The multilayer thicknesses are tuned so that the critical temperature of the film is around 80 mK. The present developments have allowed to achieve 11 eV FWHM energy resolution and 160 μs rise time. In the other technology, the thermometer is a single pixel of a square matrix of 6×6 elements, obtained with Si micromachining. The Si pixel is doped by implantation close to the metal-to-insulator transition, providing a thermometric element whose resistance grows exponentially as the temperature decreases. Single AgReO$_4$ crystals (a dielectric compound of Rhenium) with a mass of about 500 μg are epoxied to each pixel. Energy resolutions down to 19 eV FWHM and 230 μs rise time were achieved. A calibration spectrum is shown in Fig. 2. In both cases, the single pixel has already reached the requested performance for a meaningful neutrino mass experiment, able to approach the 2 eV present limit. In the next months, the corresponding arrays will be assembled and data taking will start up. This experiment, quite interesting by itself because it is able to compete with the best results obtained up to now with the electrostatic spectrometers, is also crucial to study the systematic uncertainties which could affect the sensitivity of the second phase of MARE, aiming at a further one-order-of-magnitude improvement in $\Sigma(m_\nu)$.

3. Technologies for MARE-2

The sensitivity goal of 0.2 eV envisaged for MARE-2 requires a further increase of statistics up to 10^{14} beta events, with a moderate improvement of the energy resolution. In order to keep the total numbers of elements at a reasonable level (of the order of 50000–100 000), a substantial increase of the single element mass is foreseen (up to 1–5 mg). This requires that T_R be reduced down to 1–10 μs, in order to keep the pile-up fraction around 10^{-5}. This very demanding performance may require new technologies with respect to MARE-1. Three approaches will be followed in parallel in an initial R&D phase which is starting now. TES technology has the potential to provide the required microcalorimeter features [5] and remains the baseline technique for MARE-2. A second promising technology is offered by magnetic microcalorimeters (MMC) [6]. In these devices, the thermometer is a gold film embedding paramagnetic ions. A small bias magnetic field is applied in order to magnetize the thermometer, and the temperature change is registered through a magnetization change. A preliminary Re-based device has already been assembled and operated. Finally, kinetic inductance detectors (KID) [7] will be studied and adapted to Re absorbers. These devices consist of an Al superconductive strip whose inductance depends on the quasiparticle concentration. The strip is inserted in a resonant circuit with a typical proper frequency of the order of 10 GHz. When excess quasiparticles are produced by a beta event in a Re crystal connected to the strip, the strip inductance changes abruptly and the circuit is driven almost out of resonance for a sensitive configuration. The consequent phase change represents the signal, proportional to the deposited energy. The three discussed technologies are compatible with a multiplexed read-out, allowing a substantial wiring reduction.

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