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ScienceDirect

Physics Procedia 61 (2015) 227 – 231

Physics Procedia

The status of the MARE experiment with ^{187}Re and ^{163}Ho isotopes

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Abstract

Neutrino oscillation experiments have proved that neutrinos are massive particles but the assessment of their absolute mass scale is still an outstanding challenge in today particle physics and cosmology. The laboratory experiments dedicated to effective electron-neutrino mass determination are the ones based on the study of single beta decay or electron capture (EC) decay. Exploiting only on energy-momentum conservation, this kinematic measurement is the only one which permits to estimate neutrino masses without theoretical assumptions on neutrino nature and it is truly model-independent. To date the most competitive isotopes for a calorimetric measurement of the neutrino mass are ^{187}Re and ^{163}Ho. While the first decays beta, the latter decays via electron capture, and both have a Q-value around 2.5 keV. The measurement of ^{163}Ho EC is an appealing alternative to the ^{187}Re beta decay measurement because few nuclei are needed and it is a self-calibrating measurement. In this context the MARE project, based on rhenium thermal detectors has been born.

We report here the status of MARE in Milan with Rhenium and the activity concerning the production of radioactive ^{163}Ho isotope in the framework of MARE.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords: neutrino mass, single beta decay, electron capture decay, microcalorimeter

1. Introduction

Neutrino oscillations experiments have brought to the discovery of a non-zero neutrino mass. Since these experiments are sensitive to the difference between the squares of neutrino masses eigenvalues (Δm^2_{ij}), they do not lead to an absolute value for the masses. Therefore, the determination of the neutrino mass scale is an outstanding question in particle physics and cosmology. To date, laboratory experiments based on the study of nuclear processes involving neutrino have been used to directly measure the neutrino masses.

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Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

doi:10.1016/j.phpro.2014.12.037

Historically, single beta decay has been the most direct method to investigate the electron (anti)neutrino mass. Exploiting only on energy-momentum conservation, this kinematic measurement is the only one which permits to estimate neutrino masses without theoretical assumptions on neutrino nature and it is truly model-independent. The method consists in looking for a tiny deformation of the beta spectrum close to the end-point energy due to a non vanishing neutrino mass. Calorimetric technique, where the β source is embedded in the detectors, is a promising and suitable tool to perform these kinematics measurements since they measure the entire energy except the one carried away by neutrinos. The calorimetric approach eliminates the systematic effects connected with the use of an external source as in β-spectrometers. A disadvantage is that the isotope used in calorimetric measurements must be characterized by a low transition energy Q in order to allow a trade off between keeping the isotope activity low to minimize pile-up events and still achieving a high statistical sensitivity. Up to this time, the two isotopes under investigations are ^{187}Re and ^{163}Ho.

2. Calorimetric ^{187}Re Beta Decay Measurement

In the last years several experiments have been carried out on microcalorimeters for a calorimetric neutrino mass measurement based on single beta decay. Since the fraction of decays in a given energy interval ΔE below the end-point Q is proportional to $(\Delta E/Q)^3$, the limitation on the statistics might be partially balanced by using as beta source ^{187}Re, the beta-active nuclide with one of the lowest transition energy known in nature ($Q \sim 2.5$ keV). Thanks to its natural abundance of 63%, a metallic Rhenium crystal can be used as detector absorber in microcalorimeters. Rhenium metal undergoes a superconducting transition at $T_c = 1.7$ K, so that the electronic specific heat vanishes at very low temperature $T \ll T_c$. This allows the use of a relatively large amount of Rhenium metal (about 1 mg). However, the low specific activity of about 1 Bq/mg and the relative slowness of the thermalization are the major difficulties which metallic Rhenium shows. To circumvent the latter problem dielectric compounds have been used. But also dielectric compounds present an incomplete thermalization of the deposited energy, which limits the achievable energy resolution at 2.5 keV to about 20 eV.

About 10 years ago, two pilot experiments were carried out with thermal detectors and ^{187}Re: MANU [1, 2] and MIBETA [3]. The first used metallic Rhenium crystals as absorbers, while the latter used $AgReO_4$ crystals. Both experiments collected a statistics of about 10^7 decays, yielding a limit on neutrino mass of about 15 eV at 90% CL. The sensitivity of these experiments was limited by statistics and detector performance, while systematic effects were relatively small. Since then, the project Microcalorimeter Arrays for a Rhenium Experiment (MARE) has been coping with the demanding task of improving and scaling up those pioneer experiments. After several years of attempts, however, Rhenium seems to be not fully compatible with the technical requirements of MARE and the focus of the community is shifting from this isotope to ^{163}Ho.

3. Calorimetric ^{163}Ho Electron Capture Measurement

The electron capture (EC) decays with low Q-values could be used as an alternative to single beta decay for the direct determination of the neutrino mass. As proposed by Rujula and Lusignoli in 1982 [4], an appealing method consists in studying the end-point of the calorimetric spectrum of ^{163}Ho. ^{163}Ho decays via electron capture EC to ^{163}Dy with a half-life of about 4570 y. Due to the low Q-value, the capture is only allowed from the M shell or higher. So far, the Q-value have been experimentally determined by the ratios of the capture probability from different atomic shells. This kind of determination is affected by large uncertainties - i.e error on the theoretical atomic physics factors involved - so that the Q-value ranges from 2.2 eV to 2.8 keV, with a recommended value of 2.555±0.016 keV [5]. As in beta decay spectrum the same neutrino phase space factor $[(Q - E_c)^2 - m_\nu^2]^{1/2}$ appears, but in this case the total de-excitation energy E_c replaces the electron energy E_e. The de-excitation energy is the energy released by all the atomic radiation emitted in the process of filling the vacancy left by the EC process. The emitted radiation consists mostly of electrons, while the fluorescence yield is less than 1‰ of the total radiation. The calorimetric spectrum

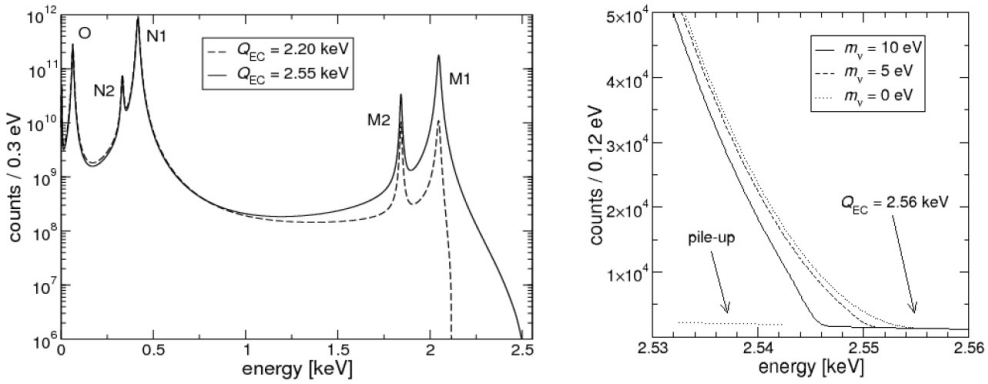

Fig. 1. Right panel: Calorimetric energy spectrum for ^{163}Ho EC decay calculated for an energy resolution of 2 eV and for two different Q-values. Left panel: Zoom of the spectrum near the end-point.

is a series of lines at the ionization energies E_i of the captured electrons. These lines are characterized by a natural width of a few eV and therefore the spectrum is a continuum with Breit-Wigner peaks (left panel of figure 1) and it ends at $Q - m_\nu$ (right panel of figure 1). Thanks to the presence of the capture peaks in the spectrum, the ^{163}Ho EC measurement is a self-calibrating measurement. As for the beta experiments, the neutrino mass sensitivity depends on the fraction of events close to the end-point. Then the closer is the Q-value of the decay to one of the E_i, the larger the resonance enhancement of the rate near the end-point, where the effects of a non-vanishing neutrino mass are relevant. In conclusion, the resulting functional dependence of the end-point rate on the Q-value for the EC case is steeper than the $1/Q^3$ observed for beta decay spectra.

Only few calorimetric experiments on ^{163}Ho EC have been carried out so far. The first two measurements go back to 1984 and used a standard Si(Li) detector [6] and a gas proportional counter [7]. In 1997, the ^{163}Ho decay was measured in Genoa with cryogenic microcalorimeter by F. Gatti [8]. Recently, the ECHO collaboration [9] has implanted a very small amount of ^{163}Ho in Metallic Magnetic Calorimeters (MMCs) and has acquired a first ^{163}Ho EC spectrum with a low threshold [10]. The detector technology used by ECHO, is not readily scalable to the large arrays needed for a high neutrino mass sensitivity measurement because of both detector fabricating and reading out large arrays. Despite that, its contribution to the understanding of the ^{163}Ho electron capture spectrum will be evaluable for the community. Recentely, a new experiment - HOLMES - has been funded by the European Research Council Advanced Grant Agreement no. 340321. The HOLMES experiment is aimed at directly measuring the electron neutrino mass using the electron capture (EC) decay of ^{163}Ho. The main purpose of this experiment is to probe the electron neutrino mass down to about 0.4 eV. For a next generation neutrino mass experiment with Holmium, the Milano-Bicocca group in collaboration with FBK (Fondazione Bruno Keisler) in Trento and Peter Day at JPL, who has been pioneering the development of microresonator detector arrays since their first introduction [11], is developing superconducting pair breaking detectors [12, 13].

4. The MARE project

The goal of MARE is to perform a direct measurement of the neutrino mass with a calorimetric technique. Although the baseline of the project consists in a large array of rhenium thermal detectors, a different option for the nuclide is also being considered. Indeed, the MARE collaboration is now focusing on ^{163}Ho.

4.1. MARE-1 in Milan with Re

An experiment using ^{187}Re as beta source is being carried out by the group of Milan-Bicocca in collaboration with NASA/Goddard and Wisconsin group. The main goals of this experiment are to achieve

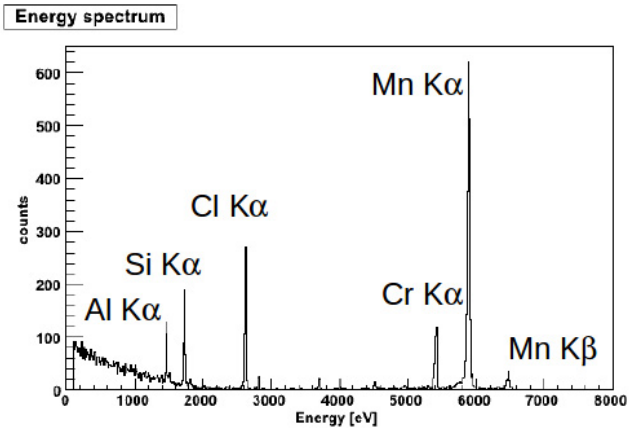

Fig. 2. One of the first spectra acquired with the cryogenic set-up of MARE in Milan. The peaks in the spectrum are due to the presence of the calibration source together with several escape peaks resulting from the interaction between Mn X-rays with Re and Ag atoms present in the $AgReO_4$ absorber. In addition, near the Mn K_α it is possible to see a peak at 5.4 keV which is the Cr K_α peak (i.e the holder of the calibration source is made off Stainless Steel which contains Chromium). The working temperature of this detector is 85 mK and it has an energy and time resolution of 29 eV FWHM @ 2.6 keV and 900 μs, respectively.

a sensitivity on the neutrino mass of a few eV and to investigate the systematic errors of ^{187}Re neutrino mass measurements, focusing on those caused by the Beta Environmental Fine Structure [14] and the beta spectrum theoretical shape [15]. Finally, the experiment is a very important cross-check for spectrometer results [16, 17].

The MARE-1 detectors consist of an array of phosphorus-implanted silicon thermistors. The array, developed as detectors for the XRS2 experiment on the ASTRO-E2 mission, is composed by 6x6 pixels. The size of one single pixel is 300 x 300 x 1.5 μm^3. An energy resolution of 3.2 eV FWHM at 5.9 keV has been obtained with these thermistors and HgTe absorbers [18]. For our purpose, we glued on these thermistors single crystals of silver perrhenate, $AgReO_4$. The absorber mass is around 500 μg, which corresponds to a beta activity of about 0.3 Hz. In order to realize a defined thermal coupling between the thermistor and the rather large absorber (600 x 600 x 250 μm^3), Si spacers (300x300x10 μm^3) have been glued between them. To energy calibrate the spectra acquired with these detectors, a primary 10 mCi ^{55}Fe source irradiating a composite target containing Al, Si, NaCl and $CaCO_3$ is used. As a consequence they are exposed to the Rayleigh scattered K_α and K_β X-rays of Mn and to the fluorescence K_α X-rays at 1.5, 1.7, 2.6, 3.7 keV excited in Al, Si, Cl, Ca.

The read-out system is composed of a buffer stage based on JFETs working at 135 K, followed by an amplifier stage at room temperature [19, 20]. To electrically connect the detector at 85 mK to the JFETs at 135 K two decoupling stages are necessary. The two stages have also to guarantee the mechanical stability. The first stage decouples the detectors from the JFETs box, while the second one decouples the cold electronics box from the JFETs. The entire set-up is installed in a Kelvinox400 dilution refrigerator located in the Cryogenic Laboratory of the University of Milan-Bicocca. Firstly, only one array equipped with 11 crystals of $AgReO_4$ was installed in the cryostat. The average energy resolution obtained with these detectors was 30 eV FWHM @ 2.6 keV. In figure 2 a spectrum acquired with one of these detectors in the presence of the calibration source is reported.

After these results we have decided to equip the array with the omitted crystals. Unfortunately, only 16 detectors are usable and the average energy and time resolution obtained with them were 47 eV FWHM @ 2.6 keV and 1 ms, respectively. These performances are not adequate for improving previous neutrino mass limit. In fact, a sensitivity on neutrino mass of about 10 eV could be achieved in one year with them.

5. MARE-Ho

In the last years, due to the problems came up with ^{187}Re the MARE collaboration is shifting its attention from this isotope to ^{163}Ho. The community is focusing its efforts in the production of the radioactive and metallic ^{163}Ho nuclide. So that, different ^{163}Ho radioactive samples by neutron activation of enriched ^{162}Er oxide (^{162}Er(n,γ)^{163}Er$\rightarrow$ ^{163}Ho) have been produced. Therefore, the final product is mainly composed by Ho and Er oxides. The further purification techniques of the produced samples is under investigation at two different sites: the Paul Scherrer Institute (PSI) and the Los Alamos National Lab (LANL). In the meantime, the Genoa group has demonstrated the feasibility of the reduction of holmium oxide into metallic form. The metallic form is required to ensure high resolution detectors and to avoid systematics due to the different chemical form. The process consists in using a Knudsen cell in which the reduction distillation process takes place (Ho_2O_3+2Y(m) $\rightarrow$ 2Ho(m)+Y_2O_3).

6. Conclusion

Assessing the neutrino mass scale is an outstanding question in today particle physics and cosmology. The experiments dedicated to effective electron-neutrino mass determination are the ones based on the study of single beta decay or electron capture (EC) decay. The goal of the MARE experiment is a direct neutrino mass measurement using ^{187}Re and ^{163}Ho as beta source. Regarding to the Rhenium isotope, an experiment is carried out in Milan using Si thermistors equipped with $AgReO_4$ absorbers. In the meantime, the MARE collaboration is focusing on the ^{163}Ho EC measurement. First samples of Ho in metallic form are produced.

7. Acknowledgments

These activities are partially supported by Fondazione Cariplo through the project Development of Microresonator Detectors for Neutrino Physics (grant 2010-2351).

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