Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 273–275 (2016) 1922–1927

www.elsevier.com/locate/nppp

Neutrino mass experiments with Ho

E. Ferri

University of Milano-Bicocca and INFN Milano-Bicocca

Abstract

Neutrino oscillation experiments have proven that neutrinos are massive particles, nevertheless the assessment of their absolute mass scale is still an outstanding challenge in nowadays particle physics and cosmology. The experiments dedicated to the effective electron-neutrino mass determination are the ones based on the study of nuclear processes involving neutrino, like single beta decay and electron capture decay. The end-point measurement of ^{163}Ho Electron Capture (EC) is an appealing alternative respect to the single beta decay because fewer nuclei are needed and it is a self-calibrating measurement. Although the calorimetric measurement of the energy released in the EC decay of ^{163}Ho was proposed in 1982 by A. Rujula and M. Lusignoli, only recent detector technological progresses have allowed to design a sensitive experiment. Nowadays the two experiments dedicated to this delicate measurement are ECHO and HOLMES. This contribution gives an outlook for both experiments underling their technical challenges and perspectives.

Keywords: neutrino mass, single beta decay, Ho EC, microcalorimeters

1. Introduction

Neutrino oscillation experiments have clearly shown that neutrinos are massive particles, nevertheless being sensitive only to the difference between the squares of neutrino mass eigenstates they do not lead to an absolute value for the masses. Therefore, the assessment of the absolute neutrino mass scale is still an outstanding challenge in today particle physics and cosmology. For years, laboratory experiments based on the study of proper nuclear process involving neutrino have been used to directly measure the neutrino masses. Historically, the traditional and most direct method to investigate the electron (anti)neutrino mass has been the single beta decay [11]. Based only on energy-momentum conservation, this kinematic measurement is the only one which permits to estimate neutrino masses without theoretical assumptions on neutrino nature. It is also 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. To date, the best limit on the absolute neutrino mass has been set using MAC-E filter spectrometers to analyze the end-point of ^{3}H beta decay. The achieved upper limit was of 2.5 eV/c^2 by Troitsk experiment [1], while the Mainz collaboration has reached $m_\nu \leq 2.3$ eV/c^2 [2]. During the next years the next generation spectrometer of the KATRIN experiment will become operational with the aim to reach a sensitivity of 0.2 eV/c^2 in five years [3, 4]. With KATRIN this approach reaches its technical limit. Therefore, it is mandatory to define an alternative and complementary method. One possible alternative is the calorimetric approach which has been successfully applied to ^{187}Re beta decay end-point measurement. About ten years ago the MANU [5] and MIBETA [6] experiments, collected a statistics of around 10^7 decays, set an upper limit on neutrino mass of about 15 eV at 90% CL. Since then, the international project MARE (Microcalorimeter Array for a Rhenium Experiment) has been facing with the demanding task of improving and scaling up those experiments using Rhenium metal and $AgReO_4$ as source and detector material [7, 8]. Unfortunately, the Rhenium seems to be not fully

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.310

compatible with the technical requirements of such an experiment and the MARE collaboration has shifted its interest on Holmium. So that, the use of ^{163}Ho has been widely revived and two new projects performing a high precision and high statistic calorimetric measurement of the ^{163}Ho spectrum have born: ECHo (Electron Capture in ^{163}Ho) [9] and HOLMES [10].

2. The calorimetric approach

In the calorimetric approach the β-source is embedded in the detector so that all the energy emitted in the decay is measured, except for the one taken away by the neutrino. 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 could be due to energy lost in metastable states living longer than the detector response time. Acquiring the entire spectrum, the source activity has to be limited to avoid pile-up which would deform the shape of the spectrum. As a consequence the statistics near the end-point is limited as well. To partially balance this limitation, β-emitting isotopes with an end-point energy as low as possible are chosen. The low Q-value involves the use of detectors with high energy resolution in the keV range and good time resolution. The detectors that fulfill these requirements are low-temperature microcalorimeters operating at temperatures below 100 mK. In a naive description, microcalorimeters can be described as an absorber of heat capacity C connected to a heat sink kept at constant temperature T through a weak thermal link with a finite thermal conductance G. The absorption of particle of a given energy results in an increase of temperature T which corresponds to the ratio between the energy E released and the heat capacity C. The energy deposited will then flow to the heat sink with a time constant $\tau \approx C/G$. The little change of temperature can be measured by sensitive thermometers as transitions edge sensor (TES) or paramagnetic sensor used in metallic magnetic calorimeters.
A TES is a superconducting film operated in the narrow temperature region between the normal and superconducting state, where the electrical resistance varies between zero and its normal value. A small change of the temperature of the sensor leads to a large change of the resistance of the film which produces a large change of current in the pick-up coil of a SQUID.
Metallic magnetic calorimeters (MMC) use a paramagnetic material located in a weak magnetic field as temperature sensor. The paramagnetic material is typically Au with a few hundreds ppm of Er. The magnetization of the sensor has a strong dependence on temperature according the Curie law $M \approx T^{-1}$. The increase of the temperature sensor due to an energy deposition leads to a change of the sensor magnetization M which generates a change of the magnetic flux in a pick-up coil of a SQUID.

3. ^{163}Ho Electron Capture Measurement

In 1982 Rujula and Lusignoli [12] proposed the calorimetric measurement of the ^{163}Ho spectrum as an appealing method for directly measuring the electron neutrino mass m_ν. ^{163}Ho decays via electron capture (EC) to ^{163}Dy with a half-life of about 4570 y and with a low Q-value. Due to the low Q-value, the capture is only allowed from the M shell or higher. Up to now, the Q-value has 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 2.3 eV to 2.8 keV, with a recommended value of 2.555±0.016 keV [13].
In a calorimetric EC experiment all the de-excitation energy is recorded. 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.

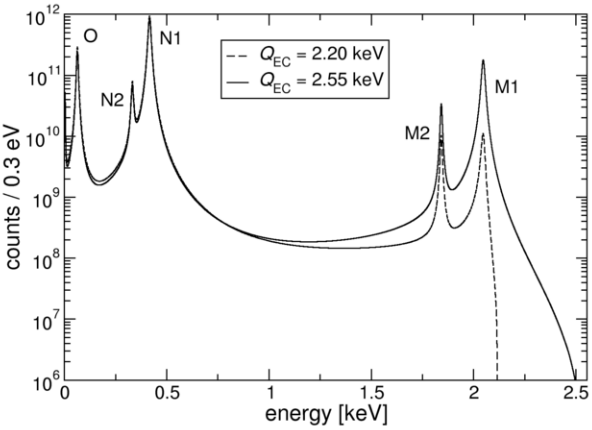

Figure 1: ^{163}Ho total absorption spectrum calculated for an energy resolution $\Delta E_{FWHM} = 2$ eV, a fraction of pile up event of 10^{-6} and a number of events equal to 10^{14}.

As shown in figure 1, the calorimetric spectrum consists of a a series of lines with a natural width Γ_i of a few

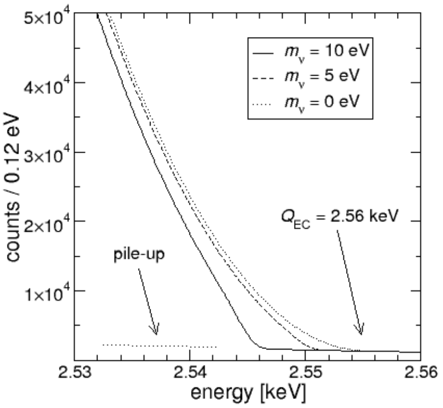

Figure 2: A zoom of the last part of the ^{163}Ho total absorption spectrum.

eV at the ionization energies E_i of the captured electrons. The spectrum is trunked at $Q - m_\nu$. As in beta decay spectrum the same neutrino phase space factor $[(Q-E_c)^2 - m_\nu^2]^{1/2}$ is present, but in this case the total de-excitation energy E_c replaces the electron energy E_e. For a non-vanishing neutrino mass, the de-excitation energy E_c distribution is expected to be:

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2}\times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2 + \Gamma_i^2/4} \tag{1}$$

where $G_\beta = G_F \cos\theta_C$ (with the Fermi constant G_F and the Cabibbo angle θ_C), n_i is the fraction of occupancy, 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. As for the beta experiments, the neutrino mass sensitivity depends on the fraction of events close to the end-point. The closer is the Q-value to the highest E_i, the larger the resonance enhancement of the rate near the end-point, where the effects of a non-zero 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. The sensitivity that could be achieved in a neutrino mass experiment depends on the Q-value, on the energy and time resolution of the detector and on the intrinsic background due to a unresolved pile-up events. In the case of ^{163}Ho, the energy spectrum of pile-up events, given by the self-convolution of the calorimetric EC spectrum, is quite complex (see figure 3). In fact, unresolved pile-up events cause a series of pile-up peaks close to the end-point energy. The intensity of the pile-up spectrum is given by the two pile-up probability $f_{pp} = \tau_R A_{EC}$, where τ_R is the time resolution and A_{EC} is the EC activity. In order to solve pile-up events, detectors characterized by a fast response are needed as well as new pile-up recognition algorithms.

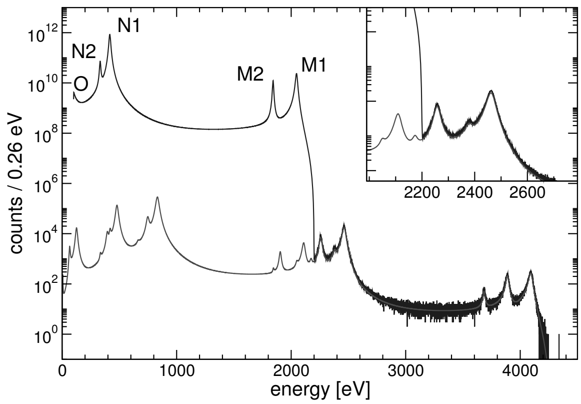

Figure 3: Full ^{163}Ho decay experimental spectrum simulated for Q = 2200 eV, an energy resolution ΔE_{FWHM} = 2 eV, m_ν = 0. The bottom curve is a fit of the pile-up spectrum. The insert shows the end-point region of the spectrum. Figure from [14].

4. The HOLMES experiment

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. It will also establish the potential of this approach to extend the sensitivity down to 0.1 eV. The optimal experimental configuration has been evaluated trough the Monte Carlo technique as in reference [15] and it is based on the present knowledge of the ^{163}Ho decay parameters. In its baseline configuration HOLMES will collect about 3x10^{13} events using detectors characterized by an energy resolution of 1 eV @ 2.5 keV and a time resolution of 1 μs. Running 1000 detectors for three years, each with an activity of 300 decays/s and such performance, the 90% CL statistical sensitivity on neutrino mass ranges from 0.4 to 1.8 eV for Q-values between 2.2 and 2.8 keV as reported in figure 4).

HOLMES is characterized by four key points:

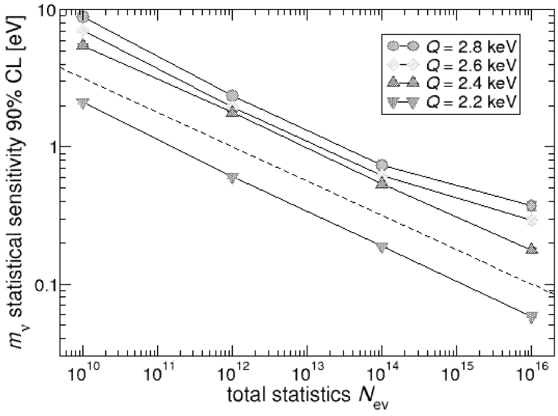

Figure 4: Neutrino mass statistical sensitivity at 90% CL achievable with detectors characterized by an energy resolution of 1 eV and a time resolution of 1 μs. The error on the points is smaller than the symbol size. The background is neglected.

a) Production of ^{163}Ho isotope and preparation of the source. About 25 μg of ^{163}Ho are necessary and they will be produced by neutron irradiation of ^{162}Er. The critical aspects of this part is the radioactive purity of the final sample.
b) Single detector optimization and array fabrication. The main criticality in the array fabrication is the embedding of the ^{163}Ho nuclei.
c) Implementation of an efficient high bandwidth SQUID multiplexing scheme.
d) Unconventional and innovative signal processing approach able to reduce by at least a factor 1000 the size of data to be analyzed and stored off-line.

The ^{163}Ho nuclei needed for the experiment will be produced by neutron activation of enriched ^{162}Er oxide trough the reaction:

$$^{162}Er(n\gamma)^{163}Er \rightarrow ^{163}Ho + \nu_e \qquad (2)$$

The enriched ^{162}Er oxide samples will be irradiated at the nuclear reactor of the Institute Laue-Langevin (ILL) with a thermal neutron flux of about 10^{15}n/s/cm^2. Neutron irradiation will produce also ^{166m}Ho which beta decays with a half life of about 1200 years. ^{166m}Ho is potentially dangerous for a neutrino mass experiment because of the background it causes below 5 keV. Furthermore, the high flux irradiation produces also long living isotopes as ^{170}Tm, ^{171}Tm, ^{159}Dy and ^{160}Tb because of the neutron capture by other Er isotopes present in the ^{162}Er oxide. So that, a chemical purification of the enriched Er_2O_3 power before irradiation as well as a chemical separation of Holmium in hot-cells after the neutron irradiation are mandatory. The purification and the separation will be performed at the Paul Scherrer Institute (PSI, Zurich, CH). Then the ^{163}Ho must be embedded in the detector in order to perform a neutrino mass measurement. To avoid chemicals shifts of the end-point and to ensure high resolution detectors, only Holmium in the metallic chemical form must be introduced. The embedding system is being set-up in Genoa and it is composed by an ion implanter and a Holmium evaporating chemical chamber to produce the metallic target for the ion implanted source. The feasibility of the reduction of holmium oxide into metallic form was demonstrated by the Genoa group in the past years in the framework of MARE. The process consists in using a Knudsen cell in which the reduction distillation process takes place:

$$Ho_2O_3 + 2Y(m) \rightarrow 2Ho(m) + Y_2O_3 \qquad (3)$$

By heating the Kundsen cell, the holmium metal can be distilled and deposited on a cold target.

The HOLMES detectors are based on transition edge sensor (TES) coupled to an absorber where the ^{163}Ho will be implanted. This detector technology presents many advantages: fast and full calorimetric energy measurement can be achieved in metallic absorber, it is possible to fabricate kilo-pixel arrays with photolitographic technology, and finally SQUID multiplexing schemes for large arrays are available. The transition edge sensors will be produced at the National Institute of Standards and Technology (NIST, Boulder, Colorado) and they will consist of Mo/Cu bi-layers fabricated on Si_2N_3 membrane with Bismuth absorbers. The device will be further processed in the INFN-Genova laboratory where ^{163}Ho will be embedded.

HOLMES detectors will operate at low temperature (0.05-0.1 K). To read out a large number of detectors the HOLMES collaboration will use the microwave multiplexing technique developed by NIST group. The NIST group have already shown the performance of this read-out scheme for TES sensor [16]. Microwave SQUID multiplexing (μMux) is a read-out technique that combines the proven sensitivity of TESs and the scalable multiplexing power found with MKIDs (i.e. microwave kinetic inductance detector). It uses radio-frequency rf-SQUIDs coupled to high quality-factor superconducting microwave resonators.

The HOLMES project, funded by the European Research Council, is a five years project. The first three years will be dedicated to optimize the detector design, the source embedding, the read-out and the data acquisition. These R&D activities will also yield to a characterization of the ^{163}Ho spectrum and the results in term of Q-value and atomic parameters will help to tune the baseline configuration. At the end of the third year, a measurement with an array of 16 detector as close as possible to the final configuration is planned. This measurement will give a check of the design and of the technical choices and it will also allow to achieve a neutrino mass sensitivity ranging from 2.5 eV to 13 eV at 90% CL. HOLMES will start data taking with the final design during the fourth year of the project.

5. ECHo experiment

The goal of the ECHo experiment is to investigate the electron neutrino mass in the energy range below 1 eV by means a high precision and high statistics calorimetric measurement of the ^{163}Ho EC spectrum. The ECHo collaboration plans to use metallic magnetic calorimeter (MMC) developed and fabricated at the Kirchoff Institute for Physics of the Heidelberg University. These detectors have shown an energy resolution of around 2 eV and a good linearity. The rise-time of the thermal pulses is of 0.1 ns. The first prototype MMC chip developed by ECHo collaboration for demonstrating the feasibility of the calorimetric measurement of ^{163}Ho spectrum consists of four single pixel detectors [17]. The ^{163}Ho source was ion-implanted in all pixels at a depth of about 5 nm on a 160x160 μm^2 surface of a 190x190x5 μm^3 gold layer which is the first part of the absorber. Then a second layer of the same dimension was deposited on the top of the first one. The production of ^{163}Ho isotopes as well as the implantation process were performed at ISOLDE-CERN. The activity of the single pixel is 0.01 Bq. By simultaneously measuring two of those pixels the most precise measurement of the ^{163}Ho EC spectrum with an energy resolution $\Delta E_{FWHM} = 8.3$ eV was obtained [18]. The rise time of the signal is 130 ns. For the first time, the O-I line corresponding to the capture of a 5s electron was measured. The spectrum acquired by the ECHo collaborations shows additional peaks respects to the lines expected for the ^{163}Ho at around 1.4 keV. These lines are due to the EC in ^{144}Pm presents in the implanted beam. Radioactive contaminants in the source need to be eliminated to avoid background event in the spectrum.

In order to acquire the statistics for a sub-eV neutrino mass measurement a large number of detectors are needed. The ECHo collaboration will read out this large

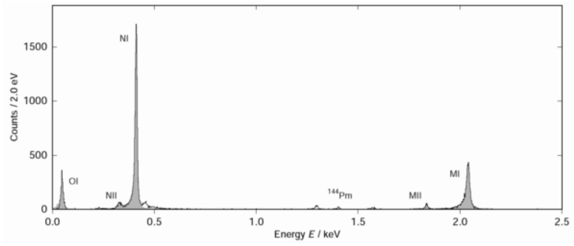

Figure 5: The ^{163}Ho spectrum measured by the ECHo collaboration in black and the theoretical description (grey filled area). The detector energy resolution is of $\Delta E_{FWHM} = 8.3$ eV. It is the first time that O-I line corresponding to the capture of a 5s electron has been measured. Spectrum from [18].

number of MMCs using the microvawe SQUID multiplexing technique. A first chip consisting of 64 pixels read out using the microvawe technique has already been developed [19].

6. LANL

In the last years, groups at Los Alomos National Laboratory (LANL), National Institute for Standard and Technology (NIST) and at the University of Wisconsin have started an R&D work finalized for a new ^{163}Ho experiment [20, 21]. The ^{163}Ho source is produced through the reaction $^{nat}\mathrm{Dy}(p,xn)^{163}$Ho to reduce the production of radioactive contaminates. The LANL groups have already tested several method for embedding radioactive isotopes in absorbers.
The detectors used by the LANL collaboration are TES produced by NIST, but the way to embed the source in the absorber has still not been selected. A first run dedicated to test the detector performance was performed using 1 Bq ^{55}Fe source and the energy resolution achieved was ΔE=7.5 eV.

7. Conclusions

In the last years the interest of the community to carry out experiments aimed to reach a sub-eV sensitivity on neutrino mass studying the ^{163}Ho electron capture is increasing. This is the common goal of the two international collaborations recently formed, i.e. ECHo HOLMES. In a couple of years, all of them have been planing to perform pilots experiment able to reach a few eV sensitivity on neutrino mass useful to define the design for the next large scale experiment. Furthermore, groups at LANL and at the University of Wisconsin have shown interest in Ho and they have started an R&D work finalized for a new ^{163}Ho experiment.

8. Acknowledgements

The author would like to thank the members of the HOLMES and ECHo collaborations and the LANL groups.

References

[1] V. M. Lobashev, *Nucl. Phys. B (Proc Suppl.)*, **91** 280-286 (2001).
[2] Ch. Kraus, *Eur. Phys. J. C*, **40** 447-468 (2005).
[3] Osipowic A et al, *Letter of intent* hep-ex/0109033 (2001)
[4] Angrik J. et al, *Design Report* **7090** http://bibliothek.fzk.de/zb/berichte/FZKA7090.pdf (2004)
[5] F. Gatti et al, *Nucl. Phys. B*, **91**, 293, (2001).
[6] M. Sisti et al, *NIM A*, **520**, 125, (2004).
[7] A. Nucciotti, *Nucl. Phys. B (Proc Suppl.)*, **155**, 229 , (2012).
[8] D. Bagliani et al, *J. Loe Temp.*, **176**, 885, 2014
[9] L. Gastaldo, *Nucl. Instrum. Meth. A*, **711**, 150, (2013).
[10] A. Nucciotti, http://artico.mib.infn.it/nucriomib/general-infos/holmes-approved.
[11] F. Gatti et al, it Phys. Lett. B, **398**, 415, (1997)
[12] A. De Rujula and M. Lusignoli, *Phys. Lett. B*, **118**, 72, (1982).
[13] G. Audi and A. H. Wapstra, *Nucl. Phys. A*, **595**, 409, (1995).
[14] A. Nucciotti, arXiv:1405.5060v2 [physics.ins-det]
[15] A. Nucciotti et al, *Astro. Phys.*, **34**, 80 (2010).
[16] O. Noorozian et al, arXiv:1310.7287v1 [physics.ins-det]
[17] L. Gastaldo et al, *Nucl. Instr. and Meth. A*, **711**, 150 (2013).
[18] P.C.O. Ranitzsch et al, arXiv:1409.0071 [physics.ins-det].
[19] S. Kempf et al, *J. Low Temp. Phys.*, **176**, 426 (2014).
[20] J. Engle et al, *Nucl. Instr. and Meth. B*, **311**, 131 (2013).
[21] M. Croce et al, *J. Low Temp. Phys.*, **176**, 1009 (2014).