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Direct measurement of the neutrino mass: The Holmes experiment

S. REPETTO(*) on behalf of the HOLMES COLLABORATION

Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova - Genova, Italy

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Summary. — The Holmes experiment aims to directly measure the neutrino mass using a calorimetric technique, analysing the electron capture decay spectrum of ^{163}Ho. It employs cryogenic microcalorimeters with Transition Edge Sensors (TES) organised in arrays, encapsulating the isotope. Precise implantation of ^{163}Ho into detectors is achieved by a 50 kV isotope separator, eliminating other radioactive isotopes, especially ^{166m}Ho, to minimise background noise in the measurement.

1. – Introduction

The discovery of neutrino flavour oscillations challenges the Standard Model by confirming neutrino mass [1]. Neutrinos, which are at least five orders of magnitude lighter than other fermions, play a crucial role in understanding physics beyond the Standard Model. Determining their absolute mass is key to a better comprehension of phenomena such as mass generation and the formation of large-scale structures in the Universe. The only model-independent method for direct neutrino mass measurement is through the study of beta or electron capture (EC) decay, exploiting momentum and energy conservation [2].

2. – The HOLMES experiment

The Holmes experiment aims to directly measure the electron neutrino mass using a calorimetric technique. This method, enclosing the source within the detector, allows for the measurement of the entire released energy during the electron capture decay of ^{163}Ho, excluding that carried away by the neutrino. ^{163}Ho, which has a half-life of

(*) E-mail: silvia.repetto@ge.infn.it

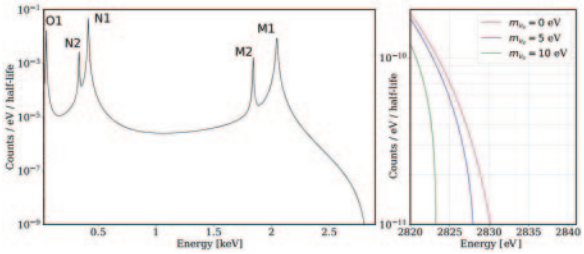

Fig. 1. – The calorimetric spectrum of ^{163}Ho. On the right-hand side, the impact of varying values of m_ν on the shape of the spectrum at the end-point is illustrated [3].

approximately 4570 years and a low Q-value $(2.833(30)_{stat}(15)_{sys}$ keV) [4], undergoes EC decay to ^{163}Dy,

$$^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow ^{163}\mathrm{Dy}^H + \nu_\mathrm{e} \rightarrow ^{163}\mathrm{Dy} + E_\mathrm{C}, \tag{1}$$

where H denotes the hole left in the daughter atom by the electron capture, and E_C is the total de-excitation energy. The resulting calorimetric spectrum is a sum of Breit-Wigner peaks, each corresponding to the binding energy of the captured electron. While the neutrino is not directly detected, its mass influences the de-excitation spectrum's shape, visibly reducing the end-point in fig. 1.

2˙1. *The Holmes detectors*. – A microcalorimeter is a thermal device that consists of an absorber, a thermistor, and a weak link to a heat sink.

When a particle enters the absorber, its released energy induces a temperature rise in the microcalorimeter. This temperature rise generates a heat pulse, which is measured to determine the energy of the particle. In particular, Holmes detectors are cryogenic microcalorimeters based on Transition Edge Sensor (TES) technology, which maximises energy resolution and signal-to-noise ratio. The weak thermal link is necessary to cool the TES back to bath temperature after the energy has been absorbed.

The Holmes detector, whose fabrication step and array arrangement are detailed in 2, is made of three componensts: a gold absorber converting radiation to heat, a TES thermometer transforming heat into a measurable signal, and a Si2N3 membrane isolating components and temporarily containing energy for precise measurements. This setup restores the system's idle temperature after an event thanks to the heat sink.

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2˙2. *The ion implanter*. – The ^{163}Ho source is artificially produced through neutron irradiation of an enriched ^{162}Er sample, but this process introduces contaminants (*e.g.,* ^{165}Ho, ^{166m}Ho, ^{170}Tm, ^{171}Tm, and ^{159}Dy). Chemical purification successfully separates isotopes other than Ho, while holmium isotopes require a different technique. To address this, a dedicated small beamline was developed and commissioned in Genoa's laboratory (see fig. 3).

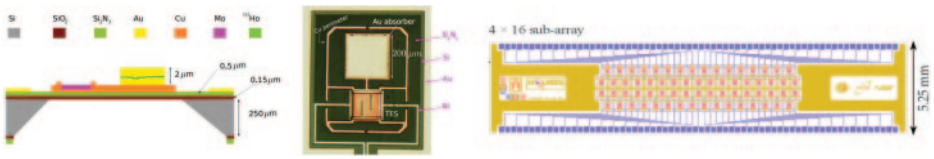

Fig. 2. – Left: side and top view of the Holmes detector. Right: array of TES organised in 4 rows of 16 TES each used in Holmes [5].

As underlined in fig. 3, the apparatus consists of:

- an Argon penning sputter ion source to generate plasma with heavy metals (*e.g.*, holmium);
- a magnetic mass separator for effective mass separation between ^{163}Ho and contaminants, primarily ^{166m}Ho;
- a square slit, rotated by 45°, with a variable opening up to 15 mm to further eliminate ^{166m}Ho contamination;
- a Faraday Cup for sample and continuous beam current measurement;
- a steering magnet for beam movement in the y-direction to compensate for small misalignments.
- a target holder containing detectors for holmium atom implantation, also functioning as a Faraday Cup for continuous current monitoring.

2˙3. *Holmium implantation.* – In June 2023, the first holmium implantation was performed. Prior to this, Monte Carlo simulations were used to assess the geometrical efficiency for fixed-position beam implantation. Additionally, checks were conducted to confirm the absence of ^{166m}Ho contamination.

The peak separation between ^{163}Ho and ^{165}Ho is depicted in fig. 4. Notably, the peak of ^{166m}Ho, being present in negligible amounts, is not visible.

Continuous current measurements during data collection monitored the implantation of holmium atoms on absorbers, providing estimates of activity for each detector. A preliminary holmium spectrum was obtained via multiplexing analysis of implanted detectors. Two ^{55}Fe sources are chosen as calibration sources. They target a mixture of NaCl and $CaCO_3$ and emit X-rays in the holmium energy range. Another calibration

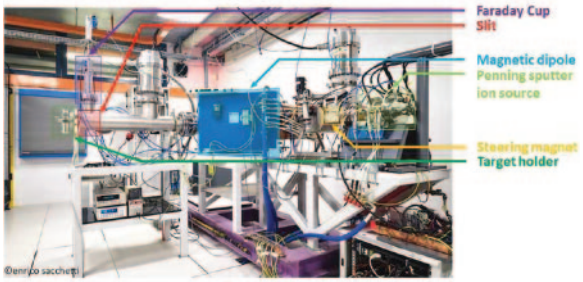

Fig. 3. – Picture of the current implanter with the components highlighted.

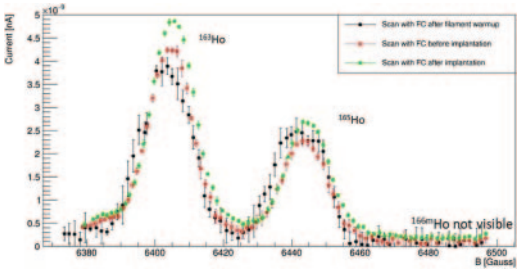

Fig. 4. – Peak separation between the holmium isotopes. Data taken during the first holmium implantation.

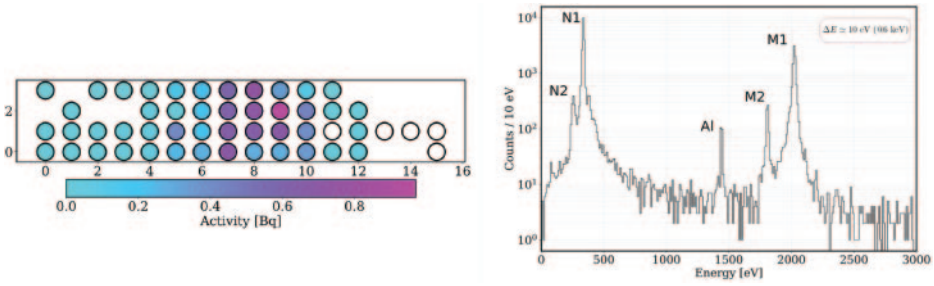

Fig. 5. – Left: map of the real activity on each TES. The TESs are represented by the dots. Right: preliminary spectrum of holmium.

source used is the aluminium, which is placed between the target and the detectors to stop thermal radiation. After removing calibration source contributions, the resulting spectrum is shown in fig. 5 (right).

3. – Conclusions

The reported results support the viability of the calorimetric technique as a feasible alternative to spectrometry. Ongoing analysis of the right-side spectrum in fig. 5 is expected to yield a neutrino mass sensitivity of $\mathcal{O}(10)$ eV. By using about $\mathcal{O}(10^3)$ detectors, each containing $\mathcal{O}(100)$ Bq of ^{163}Ho, it will be possible to increase the sensitivity to the eV or sub-eV level.

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