PROCEEDINGS OF SCIENCE

The status of the HOLMES experiment

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This work summarizes the current status of HOLMES, a calorimetric experiment for the direct neutrino mass measurement. The state-of-the-art in this field is represented by the KATRIN spectrometer that is under data-taking aiming at a sensitivity of 0.2 eV. HOLMES will prove the feasibility of the calorimetric approach, that is an alternative method to the spectrometric one. HOLMES detectors are Transition Edge Sensors in which a source of ^{163}Ho will be ion-implanted. These microcalorimeters allow a multiplexed readout and ensure high energy and time resolutions. ^{163}Ho is an interesting candidate for the direct neutrino mass determination. In fact, the low Q-value (~2.83 keV) of its electron capture decay increases the fraction of useful events in the region close to the end-point. HOLMES will assess m_ν by analyzing the spectrum deformation due to a non-zero m_ν. This contribution describes the detector working principles, their fabrication for HOLMES and their characterization. At the same time, a focus on the ion-implantation is given together with the latest results from its tests. HOLMES is now close to the first low-dose measurement. By implanting a small ^{163}Ho activity per detector it will be possible to fine-tune the entire experimental procedure and also to analyze a preliminary spectrum in order to assess an initial upper limit on m_ν of about ~ 10 eV.

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1. Introduction to HOLMES

Neutrino physics lies among the most interesting sections of the Standard Model particle landscape. In particular, the measurement of their absolute mass is still an unresolved issue pursued by several experiments over the years. The model-independent ν mass research is leaded by the KATRIN experiment [1]. Pursuing its ultimate goal, it will take the spectrometric approach to the extreme in terms of sensitivity limits. An alternative for future research is the calorimetric approach. By enclosing the source inside the detector, this method would avoid many systematic uncertainties due to the spectrometric configuration such as backscattering electrons and undetected excited final states. On the other hand, in a calorimetric experiment the unrecognized pile-up events represent the main background source. These consist of those pile-up events occurring on the rising edge of the signals. The HOLMES calorimetric experiment started in 2014 as an European Research Council (ERC) project and is now close to starting the first data-taking period. It will set an upper limit to the ν_e mass aiming for a sensitivity of the order of 1 eV. At the same time, it will prove the calorimetric approach as a viable alternative for the ν_e mass direct measurement. The goal is to measure the ^{163}Ho electron capture (EC) [2] by means of low-temperature microcalorimeters. The daughter nucleus of the EC decay is left on an excited state of ^{163}Dy. As it relaxes back to the ground state, Dy will emit mainly Auger electrons, while X-rays are emitted in a much smaller portion. Except for the neutrinos, all the decay products are completely detected and the resulting spectrum is depicted in Fig.1. Each peak follows a Breit-Wigner lineshape centered at the Dy characteristic energies. The information about the escaping ν_e mass is then delivered by a spectral fit that involves several other parameters as well. In the HOLMES experiment the spectrum reconstruction is possible thanks to Mo-Cu Transition Edge Sensors (TES). The TES design and the whole detection working principle are explained in the next sections.

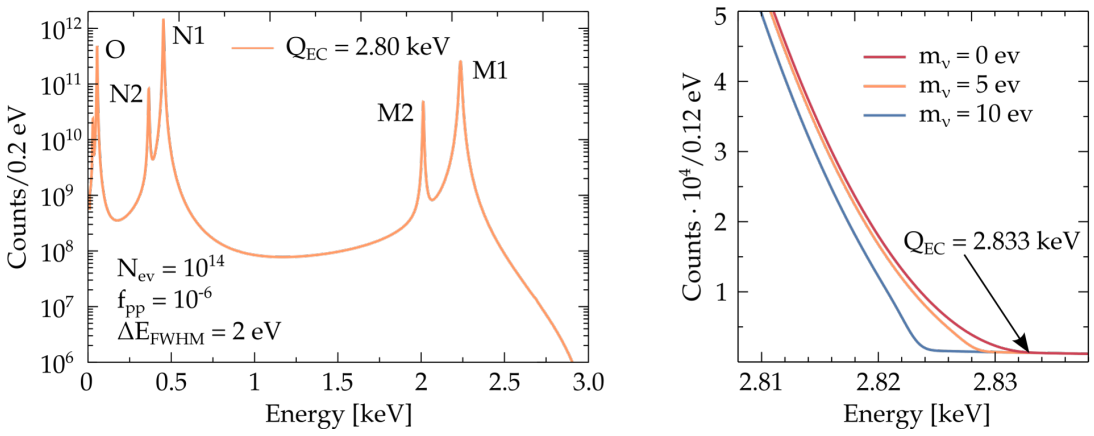

Figure 1: On the left, a simulation of the ^{163}Ho calorimetric spectrum that assumes Q = 2.80 keV. It has been computed considering a statistics of 10^4 events, a pile-up fraction of 10^{-6}, a FWHM resolution of 2 eV. On the right, a zoom on the endpoint region that highlights the reshaping due to a non vanishing neutrino mass.

2. Transition Edge Sensors

Transition Edge Sensors (TESs) represent a well-established low temperature detection technology [3] that is able to provide state-of-the-art energy resolution. These detectors are also suitable to be readout with multiplexing schemes: this is especially critical to HOLMES, since it aims to deploy a large number of detectors in a cryogenic environment. An elaboration on the multiplexed microwave readout system of HOLMES is presented here [4].

A TES is a superconductive device that acts as a sensitive thermometer if biased within its transition curve. When the TES is heated up it moves from the superconductive region to the ohmic one, quickly increasing its resistance as in Fig.2. Applying a constant voltage to the TES is then possible to read each energy deposit as a current signal. The signal rise-time is in first approximation determined by the electrical parameters of the TES circuit, i.e. the L/R_0 ratio where the L is the circuit inductance and R_0 is the TES working resistance. On the other hand, its decay-time depends strictly on the thermal circuit parameters, i.e. the C/G ratio where C is the absorber heat capacity an G is its thermal conductance.

A HOLMES TES [5] is a (125×125) μm^2 Mo-Cu bilayer with a critical temperature of $\sim$ 100 mK side-coupled to a $(200 \times 200 \times 2)$ μm^3 gold absorber. The 2 μm thickness is designed to fully contain the ^{163}Ho decay products. The sensor temperature is linked to the absorber one thanks to a copper connection. Array of 64 TESs are deposed on a silicon substrate ($\sim$250 μm) with an intermediate layer of Si_2N_3. This thin membrane ($\sim$500 nm) isolates the detector from the thermal bath keeping stable its relaxation time to the bath temperature.

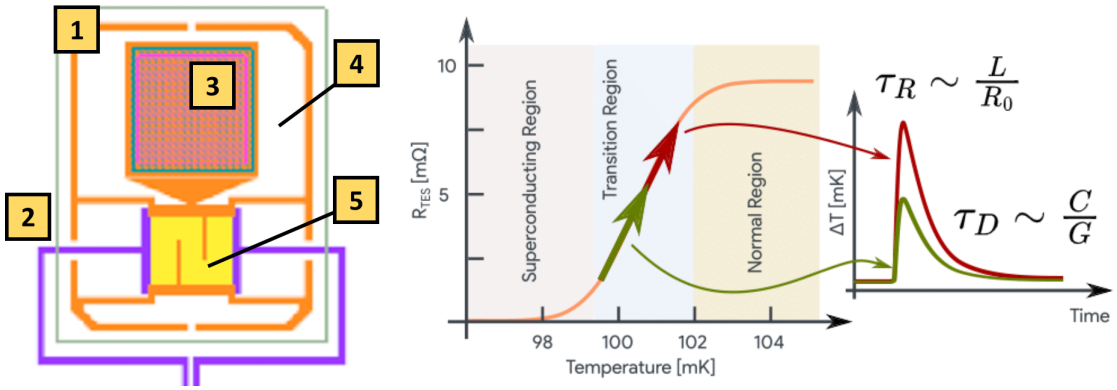

Figure 2: The final TES design on the left and an illustration of the TES working principles on the right. [1] is the Cu perimeter, [2] is the bias circuit, [3] is the gold absorber, [4] is the Si_2N_3 substrate and [5] is the Mo/Cu sensor. In the plot, the red and the green signals are produced by two different energy depositions.

3. TES fabrication

The TES fabrication procedure is split in two steps between the NIST (Boulder, CO) and the Genova section of INFN. In the first part the arrays of TESs are produced at NIST, where the Mo-Cu sensors are deposed on the silicate substrate together with the first absorber layer. The second part of the fabrication provides the embedding of the ^{163}Ho source inside the TESs via ion-implantation.

The custom-made implanter is installed at INFN-Genova and it consists of several modules. An outline description of all the implantation phases follows [6]:

1. An **argon sputter ion source** extracts ions from a custom target by means of an accelerated plasma. This is produced ionizing Ar gas with thermoionic e^- emitted by 4 W filaments. An accurate drawing is described in Fig.3 The ions beam is then accelerated in order to reach ~50 keV (resulting in ~10 nm of implantation depth).

2. A **steering magnet** corrects the motion direction of the beam along the vertical Z-axis.

3. The beam selection is provided by a **magnetic mass analyzer** with a field variable up to 1.1 T. This is a key stage, because only the selected isotopes are intended to be implanted.

4. After the beam has passed through a movable slit, a focusing electrostatic triplet and a magnetic scanning stage position the beam correctly on the XY-plane. A Faraday cup provides the beam current measurement during the implanting runs.

5. Finally the beam enters the **target chamber**. Here the selected ions are implanted in the TES array while the second μm of Au layer is deposed to encapsulate the source.

Currently, the focusing apparatus and the target chamber have not yet been mounted. Nevertheless, by depositing custom targets it is possible to calibrate and characterize the first stages of the implanting process. At the same time, the target chamber has been commissioned in Milano-Bicocca where the uniformity and the rate of the Au deposition were tested. The latter has been measured to be as high as ~50 nm/h.

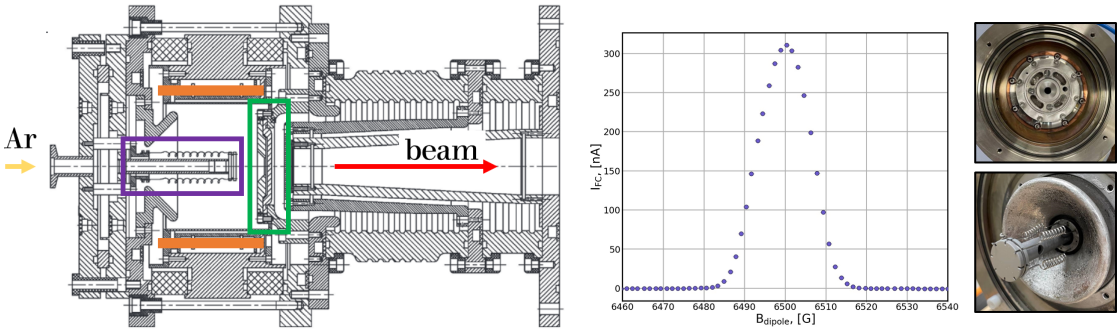

Figure 3: On the left, the HOLMES sputter ion source. *Purple*: the 4 W filaments that emit e^- via thermoionic effect. *Orange*: the cylindrical anode that accelerates the e^- through the chamber, ionizing the Ar gas. *Green*: the Ho target to be sputtered. In the middle, a measured ^{165}Ho mass peak: each data point is a current value read by the Faraday Cup at a fixed selecting magnetic field. Two pictures on the right: one of the sputtered target (top) and one of the W filaments (bottom).

The implanter has been tested with several targets containing natural holmium. The best performing targets were produced as sintered compound of Zr(95%) and Y(5%) with $Ho(NO_3)_3$.

Once the target is mounted and the source is activated, the Faraday cup receives the selected beam and reads the incoming current. Here a conducting ring at an inverted potential of ~100 V contains the secondary electrons. Setting a variable magnetic field around the central mass value,

it is possible to continuously scan the chosen peak. Currently, we can obtain a stable ^{165}Ho current of ~1 μA that lasts for tens of hours resulting in an implantation rate of 0.25 Bq/h. Approaching its first low-activity measurement, HOLMES would be able to implant ~3 Bq of ^{163}Ho in less than a day.

4. TES characterization

The test of several arrays of TESs led to the choice of the best geometry according to HOLMES purposes. The detectors were characterized in terms of their time constants, their energy resolution and their stability over time.

To characterize the TES response we put the detectors array in front of a fluorescence source. Exposing a mixture of NaCl and $CaCO_3$ to a source of ^{55}Fe it was possible to obtain a series of X-rays lines in the 1-6 keV range. The one with the lowest energy is due to the Al-Kα produced by a 6 μm thick window interposed between the source and the TES array to stop low-energy radiations. The TES energy resolution has been measured at the ^{55}Mn Kα peak (~ 5.89 keV). The best performing devices reach a relative FWHM $\leq$ 0.1%.

The requirement of low pile-up probability for improving the m_ν sensitivity sets strict constraints on the characteristic times of the sampled signals. HOLMES signals have a rise-time of 15-20 μs and a decay-time of 200-300 μs. These parameters allow us to sample pulses at a frequency of 500 kHz in time windows lasting 2-3 ms. A complete overview of the characterization results is presented in [7].

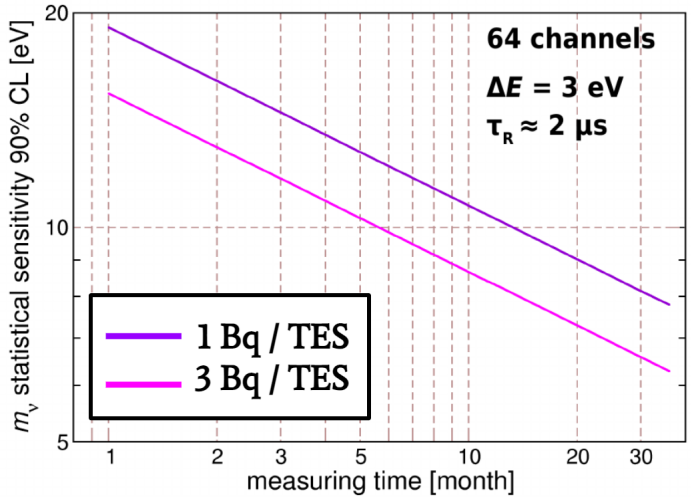

Figure 4: Taking into account a HOLMES low-dose measurement, this plot shows the expected upper limit assessment on m_ν. The simulation involves 64 TESs with an energy resolution of 3 eV and a time resolution of 2 μs (matching a pile-up fraction of events of 10^{-4}).

5. Conclusions: the HOLMES Future

In order to have a periodic calibration of the end-point region during the data-taking, a custom source that can be controlled at room temperature is required. Several projects were investigated and

a prototype of electron-gun to induce X-rays emission is already under development. Once the ion-implantation apparatus has been sufficiently tested, HOLMES will set-up a low-dose measurement. In this phase the experiment will focus on measuring an array of identical TESs with different values of embedded ^{163}Ho low-activity ($\sim$ 1 Bq). In this phase, the influence of the ^{163}Ho on the detector response and performance will be observed.

For the low-dose measurement 64 TESs will be deployed to reconstruct the ^{163}Ho EC-spectrum. The achievable m_ν sensitivity in Fig.4 is computed with respect to the total statistics over the measuring time. The first HOLMES assessment is expected to reach $\sim$ 10 eV in $\sim$ 5 months. The given time resolution of 2μs is supported by HOLMES pile-up rejection studies [8]. The results of this measurement will assess how much activity can be implanted inside a single TES without spoiling the m_ν sensitivity of the collected spectrum. This will be crucial for the future of the holmium-based calorimetric experiment for the m_ν direct measurement.

Acknowledgments

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References

[1] G. Drexlin, *KATRIN - direct measurement of a sub-eV neutrino mass*, *Nuclear Physics B - Proceedings Supplements* **145** (2005) 263.

[2] A. De Rújula and M. Lusignoli, *Calorimetric measurements of 163 holmium decay as tools to determine the electron neutrino mass*, *Physics Letters B* **118** (1982) 429.

[3] K. Irwin and G. Hilton, *Transition-edge sensors*, in *Cryogenic Particle Detection*, C. Enss, ed., (Berlin, Heidelberg), pp. 63–150, Springer Berlin Heidelberg (2005), DOI.

[4] D. Becker, *et al.*, *Working principle and demonstrator of microwave-multiplexing for the HOLMES experiment microcalorimeters*, *Journal of Instrumentation* **14** (2019) P10035.

[5] B. Alpert, *et al.*, *High-resolution high-speed microwave-multiplexed low temperature microcalorimeters for the HOLMES experiment*, *Eur. Phys. J. C* **79** (2019) 304.

[6] M. De Gerone, *et al.*, *^{163}Ho distillation and implantation for the HOLMES experiment*, *Nucl. Inst. and Met. in Phys. Res. A* **936** (2019) 220.

[7] A. Giachero, *et al.*, *Progress in the development of TES microcalorimeter detectors suitable for neutrino mass measurement*, *IEEE Transactions on Applied Superconductivity* **31** (2021) 1.

[8] M. Borghesi, *et al.*, *A novel approach for nearly-coincident events rejection*, *Eur. Phys. J C* **81** (2021) 385.