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Direct neutrino mass measurement by the HOLMES experiment

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Abstract. The assessment of the neutrino absolute mass scale is still a crucial challenge in today particle physics and cosmology. Beta or electron capture spectrum end-point study is currently the only experimental method which can provide a model independent measurement of the absolute scale of neutrino mass. HOLMES is an experiment to directly measure the neutrino mass by performing a calorimetric measurement of the energy released in the electron capture decay of the artificial isotope ^{163}Ho . In a calorimetric measurement the energy released in the decay process is entirely contained into the detector, except for the fraction taken away by the neutrino. This approach eliminates both the issues related to the use of an external source and the systematic uncertainties arising from decays on excited final states. HOLMES will deploy a large array of low temperature microcalorimeters implanted with ^{163}Ho nuclei. The achievable neutrino mass statistical sensitivity is expected in the eV range, thereby making HOLMES an important step forward in the direct neutrino mass measurement with a calorimetric approach as an alternative to spectrometry. HOLMES will also establish the potential of this approach to achieve a sub-eV sensitivity. HOLMES is designed to collect about 3×10^{13} decays with an instrumental energy resolution around 1 eV FWHM and a time resolution around $1 \mu\text{s}$. To achieve this in three years of measuring time, HOLMES is going to deploy 16 sub-arrays of TES microcalorimeters. Each sub-array has 64 pixels ion implanted with ^{163}Ho nuclei to give a pixel activity of 300 Bq per pixel. The TES arrays are read out using microwave multiplexed rf-SQUIDS in combination with a Software Designed Radio data acquisition system. The commissioning of the first implanted sub-array is scheduled for 2018 and it will provide first high statistics data about the EC decay of ^{163}Ho together with a preliminary limit on the neutrino mass. In this contribution we outline the HOLMES project



with its physics reach and technical challenges, along with its status and perspectives. In particular we will present the status of the HOLMES activities concerning the ^{163}Ho isotope production by neutron irradiation and purification, the TES pixel design and optimization, the multiplexed array read-out characterization, the cryogenic set-up installation, and the setting up of the mass separation and ion implantation system for the isotope embedding in the TES absorbers.

1. Introduction

The HOLMES experiment aims at directly measuring the electron neutrino mass using the electron capture (EC) decay of ^{163}Ho [1]. HOLMES performs a calorimetric measurement of the energy released in the decay of ^{163}Ho to measure all the atomic de-excitation energy, except the fraction carried away by the neutrino [2]. The direct measurement exploits only energy and momentum conservation and it is therefore completely model-independent. At the same time, the calorimetric measurement eliminates systematic uncertainties arising from the use of external beta sources, as in experiments with beta spectrometers, and minimizes the effect of the atomic de-excitation process uncertainties.

The expected calorimetric spectrum is shown in figure 1: the distribution of the measured de-excitation energy, carried mostly by electrons with energies up to about 2 keV, presents lines at the binding energies of the captured electrons. These lines have a natural width of a few eV, therefore the actual spectrum is a continuum with marked peaks with Breit-Wigner shapes. The spectral end-point is shaped by the same neutrino phase space factor $(Q_{\text{EC}} - E)\sqrt{(Q_{\text{EC}} - E)^2 - m_\nu^2}$ that appears in a beta decay spectrum, where Q_{EC} is the EC transition energy. A finite neutrino mass m_ν causes a deformation of the energy spectrum which is truncated at $Q_{\text{EC}} - m_\nu$. The sensitivity of this approach depends on the nearness of Q_{EC} to the binding energy of one of the captured electrons: ^{163}Ho was proposed in [3] as an ideal isotope with a Q_{EC} between 2.5 keV and 3.0 keV – with 2.55 keV as recommended value [4], – close to the binding energy of about 2.0 keV for the M1 electrons. Recent measurements [5] established that Q_{EC} is $2833 \pm 30_{\text{stat}} \pm 15_{\text{sys}}$ eV, therefore not as close to the M1 shell binding energy as initially hoped for.

The spectrum shown in figure 1 is calculated neglecting the second order effects in the atomic de-excitation cascade – shake up and shake off – which have been recently considered in many

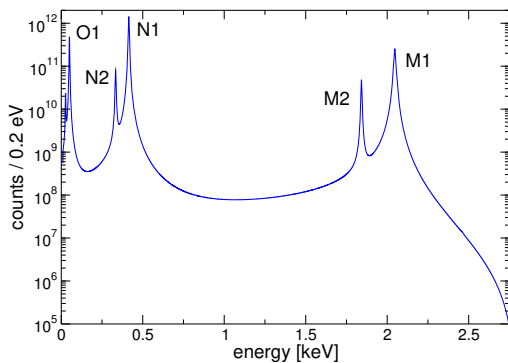


Figure 1. Calculated ^{163}Ho EC calorimetric spectrum for $Q = 2.8$ keV, $\Delta E = 2$ eV, and $N_{ev} = 10^{14}$.

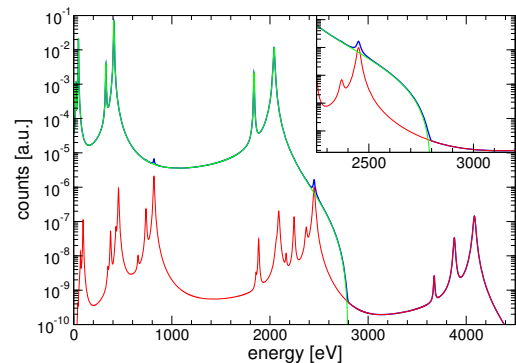


Figure 2. Calculated experimental ^{163}Ho EC calorimetric spectrum for $Q = 2.8$ keV, $\Delta E = 2$ eV, $f_{pp} = 10^{-4}$, and $N_{ev} = 10^{14}$ (blue). The pile-up spectrum is the red curve.

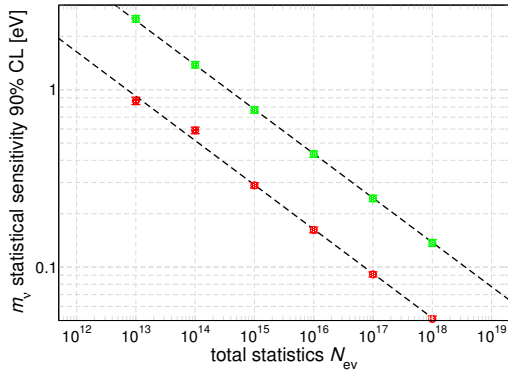


Figure 3. Monte Carlo estimated statistical sensitivity for $\Delta E = 1$ eV, $\tau_R = 1$ μ s, and for both $f_{pp} = 10^{-3}$ and 10^{-6} (from top to bottom). The dashed lines are the extrapolated curves using a $N_{ev}^{-1/4}$ scaling law.

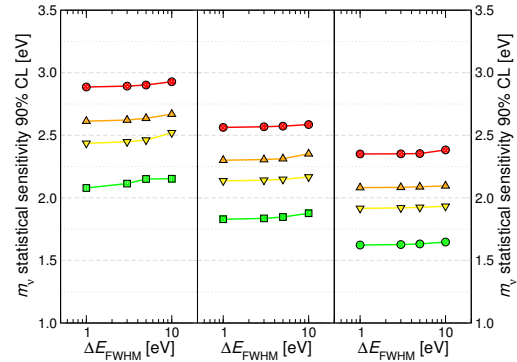


Figure 4. Monte Carlo estimated statistical sensitivity for a fixed exposure $t_M \times N_{det}$ of about 3000 detector \times year and for different A_{EC} (from left to right panel: 30, 100, and 300 Bq/detector) and τ_R (from top to bottom: 10, 5, 3, and 1 μ s).

publications and that are summarized in [2] and references therein.

2. The HOLMES experiment design

The sensitivity of calorimetric experiments is affected by a major drawback of this approach. In a calorimeter the whole decay spectrum is acquired and the decaying isotope activity A_{EC} must be restrained to limit the rate of accidental coincidences. Time unresolved coincidences (pile-up) show up in the spectrum as an additional background which worsens the statistical sensitivity. Figure 2 shows the pile-up spectrum whose normalization f_{pp} relative to single events spectrum (figure 1) is $f_{pp} \approx \tau_R A_{EC}$, where τ_R is the time resolution of the detector. Therefore, when planning a calorimetric experiment, a trade off must be found between the quest for collecting a large statistics in a short time and the need for limiting the pile-up spectrum amplitude. For fixed measuring time t_M and detector performance – ΔE and τ_R , i.e. energy and time resolution, respectively, – the experimental parameters to tweak are the number of detectors N_{det} and the isotope activity A_{EC} in each of them. The statistical sensitivity as a function of the above experimental parameters can be investigated exploiting the Monte Carlo methods described in [6]. Figure 3 shows that the statistical sensitivity improves with the total statistics N_{ev} as $1/\sqrt[4]{N_{ev}}$ and that reaching a sensitivity below 2 eV requires around 10^{13} decays. While matching the current 2 eV sensitivity obtained by spectrometers with ${}^3\text{H}$ [7, 8] is a meaningful first target for current ${}^{163}\text{Ho}$ experiments, the goal for future experiments must be at least 0.1 eV – i.e. better than the KATRIN experiment goal [9]. From figure 3 it is apparent how the 0.1 eV target calls for statistics larger than about 10^{17} events to be collected by arrays of more than 10^7 pixels.

HOLMES optimal configuration is found by means of the simulations plotted in the right side of figure 4 and by appreciating that, for fixed exposure $t_M \times N_{det}$ and time resolution τ_R , the statistical sensitivity constantly improves for increasing pixel activities A_{EC} . As a consequence, in spite of the increasing fraction of pile-up events f_{pp} , it is winning to have the largest tolerable pixel activity. With this in mind, HOLMES plans to deploy an array with 1024 pixels, each with an ${}^{163}\text{Ho}$ activity A_{EC} of about 300 Bq. The right panel of figure 4 shows that to reach a statistical sensitivity below 2 eV the time resolution τ_R plays the main role, while the energy resolution ΔE could be anywhere below about 10 eV. In particular τ_R must be better than about

3 μ s, which translates in a fraction of pile-up f_{pp} better than about 10^{-3} .

Because of the very low fraction of decays in the region of interest close to Q_{EC} , the background is another factor impacting the statistical sensitivity of end-point neutrino mass measurements. A constant background b is negligible as long as it is much smaller than the pile-up spectrum, that is when $b \ll \approx A_{EC}f_{pp}/2Q_{EC}$, as it is confirmed also by Monte Carlo simulations [6]. Therefore, a large activity A_{EC} with a correspondingly large pile-up fraction f_{pp} makes experiments relatively insensitive to cosmic rays and to environmental radioactivity. For HOLMES this translates in the requirement that the background level at the end-point must be lower than about 0.1 count/eV/day/det. From Geant4 Monte Carlo simulations and comparison with past experiments, HOLMES' background due external sources is expected to be of the order of 10^{-4} count/eV/day/det at sea-level. Indeed HOLMES' major source of background is the internally present ^{166m}Ho , an isotope which is produced along with ^{163}Ho [10]. This β decaying isotope, with a half life of about 1200 years and a Q -value of about 1854 keV, according to Geant4 Monte Carlo simulations causes a background below 5 keV of about 0.5 count/eV/day/det/Bq(^{166m}Ho). The ^{166m}Ho activity in the pixels must be then kept lower than 0.2 Bq for a ^{163}Ho activity A_{EC} of 300 Bq, or a factor 1500 lower, i.e. the number of contaminating ^{166m}Ho nuclei must be about a factor 6000 lower than that of ^{163}Ho .

As discussed in more details in the following, the HOLMES project is divided in tasks which are carried out in parallel and on which the HOLMES groups are making steady progresses. The tasks are 1) the ^{163}Ho isotope production and purification, 2) the isotope embedding, 3) the TES pixel and array design and testing, 4) the microwave multiplexed read-out system, and 5) the Digital Acquisition system (DAQ).

3. ^{163}Ho production and embedding

The ^{163}Ho isotope needed to carry out the experiment is produced at the nuclear reactor operated by the Institut Laue-Langevin (ILL, Grenoble, France) by irradiating Er_2O_3 samples enriched in ^{162}Er in a thermal neutron flux of about 10^{15} n/s/cm². The Er_2O_3 samples are purified before irradiation and the accumulated holmium is radiochemically separated in hot-cells after the neutron irradiation. Both processes have been developed and optimized at the Paul Scherrer Institute (PSI, Zurich, CH). Two samples of enriched Er_2O_3 have been already irradiated at ILL and processed at PSI. Inductive Coupled Plasma Mass Spectroscopy (ICPMS) analysis performed at LNGS and PSI on the two samples before and after chemical purification at PSI demonstrated a production of a sufficiently radiopure sample of about 43 MBq of ^{163}Ho (along with about 50 kBq of ^{166m}Ho , measured by γ -spectroscopy). The analysis of these samples yielded also a preliminary estimate of the ^{163}Ho production yield including all these steps. We estimate that the whole HOLMES program requires a total amount of about 250 MBq of ^{163}Ho . This estimate is obtained considering the above mentioned yield and the efficiencies related to the ion implantation process. Since not all the efficiencies are known yet, for the above estimate we made conservative guesses and came up with a global efficiency of the order of 0.1%. About 540 mg of Er_2O_3 enriched in ^{162}Er at 25% along with about 100 mg of Er_2O_3 at 26.9% were irradiated at ILL for 46 days until early 2017. We estimate a production of about 150 MBq of ^{163}Ho which are expected to be enough both for testing the isotope embedding and for the production of the first 512 detectors.

^{163}Ho is introduced in the absorbers of the HOLMES' low temperature microcalorimeters by means of custom system which combines a high efficiency Penning sputter ion source, a mass analyzing magnet, an electrostatic triplet focusing stage, and an XY magnetic beam scanner. The system is designed to achieve an optimal mass separation for ^{163}Ho , thereby eliminating other trace contaminants not removed by chemical methods at PSI, such as ^{166m}Ho or stable ^{165}Ho . The magnetic selection also prevents the implantation of holmium in chemical forms other than metallic, which would likely cause chemical shifts of the end-point energy. The embedding

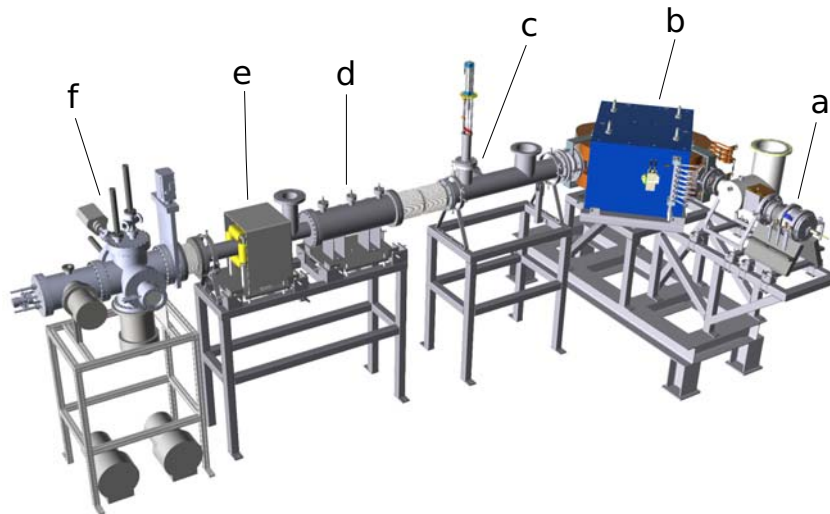


Figure 5. 3D model of the embedding system showing: (a) Penning sputter ion source, (b) analyzing magnet, (c) analyzing slit, (d) electrostatic triplet focusing stage, (e) XY magnetic beam scanner, and (f) Target Chamber.

system includes a focusing stage designed to have a beam cross-section on the detectors of about 4 mm thereby maximizing the geometrical efficiency of the ion implantation. During ion implantation, the detectors are hosted in the UHV Target Chamber which is equipped with an ion beam assisted gold sputtering system to control the ^{163}Ho concentration in the detector absorbers, to compensate the absorber atom sputtering caused by the ion implantation, and to deposit the final absorber layer to complete the ^{163}Ho embedding. The metallic cathode for the ion source is made out of an inter-metallic alloy containing ^{163}Ho in a metallic form. The metallic ^{163}Ho is produced in an evaporation chamber by thermal reduction and distillation of the Ho_2O_3 separated at PSI after neutron irradiation. The details of the ion source cathode fabrication are described in [11]. The whole embedding system is expected to be ready for detector implantation testing early in 2018.

4. TES microcalorimeters, microwave multiplexed read-out, and DAQ

The detectors used for the HOLMES experiment are microcalorimeters on Si_2N_3 membranes with Mo/Cu transition edge sensors (TES) and with $2\ \mu\text{m}$ thick gold absorbers [12]. The pixel design has been optimized to match the experimental specifications in terms of energy and time resolution, pulse duration, and ^{163}Ho decay radiation full absorption [13, 14]. As explained above the most critical parameter is the time resolution. By means of Monte Carlo simulations we find that with rise and decay time constants of about $10\ \mu\text{s}$ and $100\ \mu\text{s}$, respectively, and with signal sampling rate of at least 500 kHz it is possible to obtain a time resolution better than $3\ \mu\text{s}$ exploiting discrimination algorithms based on Singular Value Decomposition [15] or Wiener filtering [19].

The HOLMES arrays are read-out with the microwave multiplexing (μMUX) developed by NIST, which is based on rf-SQUIDs as input devices [17]. The μMUX read-out leverages the Software Defined Radio (SDR) implemented in the firmware of a ROACH-2 board by NIST [18].

The number of pixels which can be read-out simultaneously by one ROACH-2 board is about $n_{\text{TES}} \approx 0.005 f_{\text{ADC}} \tau_{\text{rise}}$ for a signal sampling frequency of about 0.5 MHz, where f_{ADC} is the SDR ADC sampling frequency of 550 MHz. Considering the design τ_{rise} of about $10\ \mu\text{s}$, for the

HOLMES DAQ n_{TES} can be as high as 32 and therefore to read-out the full 1024 pixel array a total of 32 ROACH-2 systems is required.

Two 6×4 prototype arrays were fabricated at NIST (Boulder, Co, USA) with slight variations in the TES pixel designs and were characterized using both ^{55}Fe and a fluorescence multi-line source. The results of these measurements, which are described in details in [19], confirm that the baseline pixel design, while matching the desired time constants, provide an energy resolution well below 10 eV FWHM at Q_{EC} . These measurements also prove that the HOLMES DAQ is ready for the experiment.

According to these results, we have now finalized the design of the 4×16 sub-arrays which will be deployed for the HOLMES experiment: the design aims to 1) minimize the signal bandwidth limitations due to stray self-inductance of the read-out leads, 2) minimize the signal cross-talk due to mutual inductance between read-out lines, and 3) maximize the geometrical filling for an optimal implantation efficiency. The arrays are fabricated in a two step process. The arrays are provided by NIST with a $1 \mu\text{m}$ gold layer and they are further processed after ion-implantation: first in the Target Chamber the thin (few 100\AA) layer of Au: ^{163}Ho is covered by a second $1 \mu\text{m}$ gold layer to fully encapsulate the ^{163}Ho source, then the Si_2N_3 membranes are released by means of a Deep Reactive Ion Etching (DRIE). Preliminary tests on dummy samples from NIST are in progress to tune the DRIE process and define the details of this two-step fabrication process.

5. Future plans

With the embedding system fully operational early in 2018, HOLMES will start soon to optimize the isotope implantation process along with the two-step array fabrication process. As soon as the first implanted arrays will be available, the first high statistics calorimetric measurements of the ^{163}Ho decay will provide relevant information on the spectral shape and new competitive limit on m_ν .

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