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Probing the absolute neutrino mass scale with the ^{163}Ho: the HOLMES project.

M De Gerone[1], B Alpert[2], D Becker[2], D Bennett[2], M Biasotti[1,3], V Ceriale[1,3], R Dressler[4], M Faverzani[5,6], E Ferri[5], J Fowler[2], G Gallucci[1], J Gard[2], F Gatti[1,3], A Giachero[5], J Hays-Wehle[2,5], S Heinitz[4], G Hilton[2], U Koester[7], M Lusignoli[8,9], J Mates[2], S Nisi[10], A Orlando[5], G Pessina[5], A Puiu[5,6], S Ragazzi[5,6], C Reintsema[2], M Ribeiro-Gomes[11], D Schmidt[2], D Schumann[4], D Swetz[2], J Ullom[2] and L Vale[2]

[1] INFN, Sezione di Genova, Genova 16146, IT
[2] National Institute of Standards and Technology (NIST), Boulder, Colorado 80305, USA
[3] Dipartimento di Fisica, Università degli Studi di Genova, Genova 16146, IT
[4] Paul Scherrer Institute, Villigen 5232, CH
[5] INFN, Sezione di Milano Bicocca, Milano - 20126, IT
[6] Dipartimento di Fisica, Università degli Studi di Milano Bicocca, Milano - 20126, IT
[7] Institut Laue-Langevin, Grenoble 38000, FR
[8] INFN, Sezione di Roma 1, Roma - 00185, IT
[9] Dipartimento di Fisica, Università La Sapienza, Roma 00185, IT
[10] INFN, Laboratori Nazionali del Gran Sasso, Assergi 67010, IT
[11] CENTRA, Multidisciplinary Centre for Astrophysics, University of Lisbon, Lisbon 1049-001, PT

E-mail: degerone@ge.infn.it

Abstract. The HOLMES project aims to directly measure the electron neutrino mass using the electron capture decay (EC) of ^{163}Ho down to the eV scale. It will perform a precise measurement of the end-point of the ^{163}Ho calorimetric energy spectrum to search for the deformation caused by a finite electron neutrino mass. The choice of ^{163}Ho as source is driven by the very low Q-value of the EC reaction (around 2.8 keV), which allows for a high sensitivity while keeping the overall activities to reasonable value ($\mathcal{O}(10^2)$Hz/detector), thus reducing the pile-up probability. A large array made of thousands of Transition Edge Sensor based micro-calorimeters will be used for a calorimetric measurement of the EC ^{163}Ho spectrum. The calorimetric approach, with the source embedded inside the detector, eliminates systematic uncertainties arising from the use of an external beta-source, and minimizes the effect of the atomic de-excitation process uncertainties. The commissioning of the first implanted sub-array is scheduled for the end of 2017. It will provide useful data about the EC decay of ^{163}Ho together with a first limit on neutrino mass. In this paper the current status of the main tasks will be summarized: the TES array design and engineering, the isotope preparation and embedding, and the development of a high speed multiplexed SQUID read-out system for the data acquisition.


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1. Introduction

The neutrino mass direct measurement takes advantage of proper nuclear processes, usually exploiting the kinematics of beta decays characterized by low Q-values. This method has the remarkable advantage to be completely model-independent, relying only on energy and momentum conservation. The best current upper limit on electron (anti)neutrino mass, 2.2 eV, was obtained with a spectrometric measurement of the ^{3}H β spectrum [1]. Based on the same approach, the KATRIN [2] experiment is expected to reach the sensitivity of 0.2 eV in few years. The KATRIN spectrometer has currently reached the maximum size and complexity practically achievable for such a kind of detector, thus exploiting the limit of this technique. Another appealing approach is the calorimetric measurement. Differently from the spectrometric one, the calorimetric approach has the advantage to avoid systematic effects coming from possible energy losses in the source or decays to excited states, being the source embedded in the detector. This method has been already tested in the past with ^{187}Re beta decay by using cryogenic micro-calorimeters [3], [4]. Recently, the interest of the community has been renewed again on the electron capture (EC) decay of the ^{163}Ho isotope. In the following, the HOLMES project, funded since 2014 by the European Research Council aiming to directly measure the neutrino mass by exploiting the EC decay of ^{163}Ho, will be described.

2. ^{163}Ho electron capture

The usage of the ^{163}Ho electron capture decay

$$^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow ^{163}\mathrm{Dy}^* + \nu_e \rightarrow ^{163}\mathrm{Dy} + \mathrm{E}_c + \nu_e$$

as a probe for neutrino mass was originally proposed in the 80's [5]. The idea is to perform a calorimetric measurement of the ^{163}Ho spectrum in which all the Dy* de-excitation energy, E_c, is collected. Holmium is a good candidate for neutrino mass searches because of the very low Q-value of the EC reaction (recently evaluated around 2.8 keV [6]) which allows for a high sensitivity while keeping the overall activity to reasonable value (hundreds of Bq), thus reducing unwanted pileup effects.

In the β-decay, the neutrino mass can be evaluated by looking at the end-point of the emitted electron energy spectrum, which is shaped by the space phase factor $(Q-E_e)\sqrt{(Q-E_e)^2 - m_\nu^2}$. In an EC decay, the same phase factor appears, with the total de-excitation energy E_c instead of the electron one. The de-excitation energy is the energy emitted in the process of filling the vacancies left by the EC decay, most of them being electrons with energies up to 2 keV. The calorimetric spectrum appears as a set of lines corresponding to the ionization energies E_i; each line has an intrinsic width of few eV. The actual spectrum is a continuum with marked peaks with Wigner-Breit shapes, as shown in fig. 1, where a couple of simulated spectra with different Q values are shown. The spectrum end-point is shaped by the same space phase factor as β decay, with the total de-excitation energy E_c instead of the electron one. In case of non-zero neutrino mass, the de-excitation energy spectrum is given by [5]:

$$\frac{d\Lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2}\times \sum_i K_i \frac{\Gamma_i}{2\pi}\frac{1}{(E_c-E_i)^2 + \Gamma_i^2/4} \quad (1)$$

where $G_\beta = G_F cos\theta_c$ (G_F and θ_c are the Fermi constant and the Cabibbo angle, respectively), E_i is the binding energy of the i-th atomic shell, Γ_i is the line width, and the K_i term includes all the other terms related to nuclear processes (see [5] for details). The main issues in the measurement arise from the complex pile-up spectrum (resulting by the self-convolution of the calorimetric EC decay spectrum), which could require a dedicated spectral analysis.

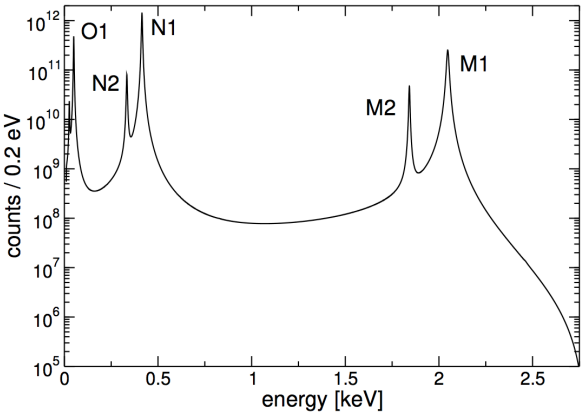

Figure 1. Simulated Ho spectrum for Q=2.8 keV.

3. The HOLMES project

The aim of the HOLMES project is to probe the capability to reach the eV sensitivity on electron neutrino mass by means of a calorimetric measurement of ^{163}Ho EC decay spectrum. The detector will consist of arrays of $\mathcal{O}(10^3)$ micro-calorimeters with the ^{163}Ho source embedded inside. Extensive MonteCarlo simulations have been performed [7] in order to assess the experiment statistical sensitivity and define the performances needed for the μ-calorimeters.

In its baseline configuration HOLMES will collect about 3×10^{13} decays with an expected energy resolution of $3 \div 5$ eV FWHM at the Q-value and a time resolution of $\sim$1 μs. Taking into account a 3 years measuring time, a total activity of about 3×10^5 is required to reach the eV target sensitivity. Considering an array of 1000 detector, each of them should have an activity of about 300 Bq, which translates in 6.5×10^{13} ^{163}Ho nuclei per detector. The limited isotope concentration needed should not interfere with the thermodynamic properties of the detector.

The isotope will be produced by neutron irradiation of enriched Er_2O_3 sample through the reaction

$$^{162}\mathrm{Er}(n,\gamma)^{163}\mathrm{Er} \rightarrow^{163} \mathrm{Ho} + \nu_e. \quad (2)$$

The sample will be irradiated at the high flux nuclear reactor of the Institute Laue-Langevin (ILL, Grenoble, France). Due to the presence of ^{164}Er and ^{165}Ho impurities in the original samples neutron irradiation will produce not only ^{163}Ho but also other species with mass close to 163 a.m.u.. Among them, ^{166m}Ho, a metastable Holmium isotope with half life of 1200 years is the most potentially disturbing one because of the background it causes below 5 keV. Chemical purification of the enriched Er_2O_3 powder before and after irradiation and mass separation after irradiation are therefore mandatory. The chemical purification will be performed at the Paul Scherrer Institute (PSI, Villigen, Switzerland), while the mass separation will be done in Genova, by means of a special designed ion implanter (see fig. 2). The latter also has the purpose of embedding the ^{163}Ho inside the detector. The implanter is basically made of a Penning sputter based ion source, a mass analyzing magnet and a target/diagnostic chamber. The metallic cathode for the ion source consists of a gold matrix containing metallic ^{163}Ho. It will be produced in a Knudsen chamber via thermal reduction at $\sim$2000 K by means of the reaction Ho_2O_3+2Y(met)$\rightarrow$2Ho(met)+Y_2O_3. The beam produced by the ion source will be extracted by the accelerating voltage (30 keV in the current design); masses other than 163 a.m.u. will be deviated from the reference trajectory by the mass analyzing magnet. The target chamber allows a simultaneous gold evaporation to control the ^{163}Ho concentration and to deposit the final gold layer thus encapsulating the ^{163}Ho embedding. Moreover, some diagnostic tools (a

Faraday cup, a charge sensitive wire-cross and a x-y magnetic scanner) will be included in the diagnostic chamber to monitor the beam shape and current during implanting operations.

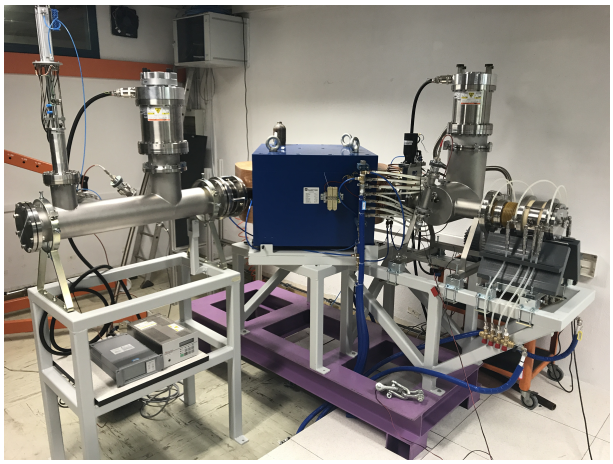

Figure 2. Picture of the ion implanter installed in Genova's laboratory.

The detector used for the HOLMES experiment will be a Mo/Cu Transition Edge Sensor (TES) on SiN_x membrane with gold absorbers. The TES μ-calorimeters will be produced in a multistep process (a schematic view is depicted in fig. 3). The first step is performed at the National Institute for Standards and Technology (NIST, Boulder, Co, USA) where the devices are machined up to the deposition of the Au bottom layer. After that, the devices are shipped to Genova, where ^{163}Ho ions will be implanted in the absorber. Finally, the μ-calorimeter are completed with another Au layer, which guarantees the fully containment of the emitted electrons. The very last step consists of a Deep Reactive Ion Etching process made on the back of the Si wafer in order to release the membrane with the TES μ-calorimeter.

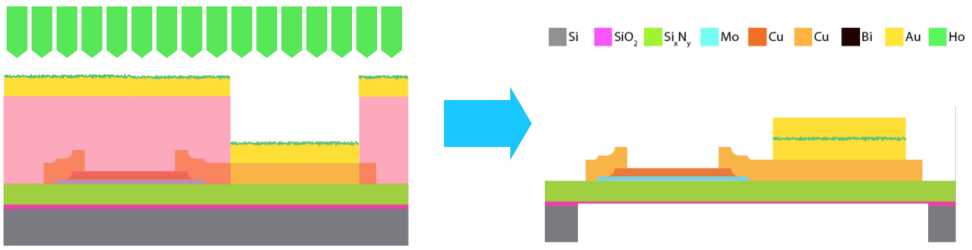

Figure 3. Schematic view of the TES/microcalorimeter production.

The HOLMES readout is based on the microwave multiplexing system (μ-MUX) [8] developed in collaboration with NIST. This scheme uses dissipation-less radio-frequency RF-SQUIDs to transduce TES current into a frequency shift of a resonator. In addiction a flux-ramp modulation is applied to the SQUID to linearize the response [9]. The modulated signals are read out coupling the RF-SQUID to superconducting $\lambda/4$-wave resonators in the GHz range. By tuning the resonators at different frequencies it is straightforward to multiplex many RF carriers. Microwave multiplexing is the most suitable system for HOLMES, since it provides a larger bandwidth for the same multiplexing factor (number of multiplexed detectors). This novel multiplexing and read-out approach was demonstrated for the first time for gamma-ray spectroscopy and has been proposed for many current and future applications based on

superconducting transition-edge sensor where fast pulse response is required. The μ-MUX is suitable for a fully digital approach based on the Software Defined Radio (SDR) technique. In this scenario, a comb of frequency carriers are generated by digital synthesis in the MHz (base-band) range and up-converted to the GHz range (RF band) by IQ-mixing. The GHz comb is sent to the cold μ-MUX chips coupled to the detectors through one semi-rigid cryogenic coax cable, then it is amplified by a low temperature and low noise High Electron Mobility Transistor (HEMT), and finally it is sent back to room temperature through another coax cable. The output signal is down-converted by IQ-mixing and the channelization (i.e. individual channel signal recovery) is performed by software on the digitized signal. A tiny change in temperature due to a X-ray interaction results in a change in the input flux to the RF-SQUID that causes a change of resonant frequency of the μ-MUX resonator and hence a variation of the phase of the transmitted signal. By monitoring the resonances with the technique explained above it is possible to recover the changes in the resonance frequency and phase of each resonator.

In its final configuration HOLMES will realize a SDR multiplexed read-out exploiting the Reconfigurable Open Architecture Computing Hardware (ROACH2 [10]) board with a Xilinx Virtex6 FPGA. The complete system is composed of a digital signal processing board (ROACH2), a DAC (for comb generation) and ADC (512 MS/s, 12 bit, 2 channels) boards, an IF board (for signal up- and down-conversion), and SFP+GbE interfaces optically decoupled for fast data transfer. Software, firmware and set-up are developed in collaboration with NIST. Tests with a preliminary version of the firmware for the multiplexing of 4 channels showed encouraging results. An expanded version for 32 channels is in development and it will be ready by fall 2017. To read out the full 1024 pixel array a total of 32 ROACH2-based systems are required.

4. Conclusion

Currently, all the HOLMES main items are in setting up phase. The first tests on a implanted μ-calorimeter is foreseen by fall 2017.

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