The Electron Capture $^{163}$Ho Experiment ECHo

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Abstract The determination of the absolute scale of the neutrino masses is one of the most challenging present questions in particle physics. The most stringent limit, $m(\bar{\nu}_e) < 2$ eV, was achieved for the electron anti-neutrino mass. Different approaches are followed to reach a sensitivity on neutrino masses in the sub-eV range. Among them, experiments exploring the beta decay or electron capture of suitable nuclides can provide information on the electron neutrino mass value. We present the electron capture $^{163}$Ho experiment ECHo, which aims to investigate the electron neutrino mass in the sub-eV range by means of the analysis of the calorimetrically measured energy spectrum following electron capture in $^{163}$Ho. A high precision and high statistics spectrum will be measured with arrays of metallic magnetic calorimeters. We discuss some of the essential aspects of ECHo to reach the proposed sensitivity: detector
optimization and performance, multiplexed readout, $^{163}$Ho source production and purification, as well as a precise theoretical and experimental parameterization of the calorimetric EC spectrum including in particular the value of $Q_{EC}$. We present preliminary results obtained with a first prototype of single channel detectors as well as a first 64-pixel chip with integrated micro-wave SQUID multiplexer, which will already allow to investigate $m(\bar{\nu}_e)$ in the eV range.

**Keywords** Neutrino mass · Metallic magnetic calorimeters · $^{163}$Ho

1 Introduction

The fact that neutrinos are massive particles has been accepted since the discovery of neutrino flavor oscillations. Experiments investigating neutrino oscillations with solar neutrinos, reactor neutrinos, atmospheric neutrinos and neutrinos produced at accelerator facilities have been able to precisely define the three mixing angles $\theta_{12}$, $\theta_{23}$ and $\theta_{13}$, and the difference in the squared mass eigenvalues $\Delta m^2_{21}$ and $\Delta m^2_{31}$ [1]. While future improved neutrino oscillation experiments will provide information about the hierarchy of the mass eigenvalues, they will not be able to set the mass energy scale. The determination of the neutrino mass energy scale is a complicated task due to the weak interaction of neutrinos and to the smallness of their mass. There exist several approaches which can potentially yield this result: the analysis of the visible structures in the universe [2], the existence of neutrinoless double beta decay [3], the measurement of the time of flight of neutrinos emitted in Supernova explosions [4] and the analysis of the kinematics of low energy beta decays and electron capture (EC) processes [5]. Presently the most stringent limit, $m(\bar{\nu}_e) < 2 \text{ eV}$, was achieved for the electron anti-neutrino mass [6–8] by the analysis of the endpoint region of the $^3$H beta spectrum.

The Electron Capture $^{163}$Ho Experiment, ECHo, has the aim to investigate the electron neutrino mass in the energy range below 1 eV by a high precision and high statistics calorimetric measurement of the $^{163}$Ho electron capture spectrum [9,10]. Among all the nuclides undergoing electron capture processes, $^{163}$Ho has the lowest...
energy available to the decay $Q_{EC} \sim 2.5$ keV, which is given by the difference in the mass of mother and daughter. This is the reason why presently $^{163}$Ho is the best candidate to perform experiments investigating the value of the electron neutrino mass. On the other hand the very low $Q_{EC}$ implies that detectors showing high energy resolution in the energy range below 3 keV need to be used. Presently detectors that can measure energies below 3 keV with the highest precision are low temperature microcalorimeters [11]. Within the ECHo experiment, low temperature metallic magnetic calorimeters (MMCs) will be used [12]. In order to reach the aimed sensitivity on the electron neutrino mass, a number of experimental techniques and investigations have to be brought together, not only the development high energy resolution and fast detectors: $^{163}$Ho source production and purification, precise theoretical and experimental parameterization of the calorimetric EC spectrum including in particular the value of $Q_{EC}$ which should be independently measured. In the following a short discussion on the present investigations within the ECHo experiment will be reported.

2 First Prototype Metallic Magnetic Calorimeters with Implanted $^{163}$Ho

In a recent paper by Galeazzi et al. [13], several scenarios to reach the sub-eV sensitivity on the electron neutrino mass have been described. A total statistics of $10^{14}–10^{16}$ counts in the full spectrum needs to be acquired with detectors meeting the following requirements:

- fast signal rise-time, in order to reduce the un-resolved pile-up background due to the impossibility to de-convolve two or more events which happen in the same detector within a time interval shorter than the signal rise-time;
- energy resolution better than $\Delta E_{FWHM} = 10$ eV to have the right accuracy in the end point description;
- possibility of multiplexing arrays of detectors without degrading the performance of the single pixel;
- good linearity in order to precisely define the energy scale of the $^{163}$Ho EC spectrum and in particular fix the endpoint.

The $^{163}$Ho activity which is required to reach the aimed statistics within few years of measuring time corresponds to more than $10^6$ Bq.

The ECHo experiment will be performed using Metallic Magnetic Calorimeters (MMCs) [12]. MMCs are energy dispersive detectors typically operated at temperatures below 50 mK. These detectors consist of a particle absorber, where the energy is deposited, tightly connected to a temperature sensor which is weakly connected to a thermal bath. The deposition of energy in the absorber leads to an increase of the detector temperature. The temperature sensor of the MMCs is a paramagnetic alloy which resides in a small magnetic field. The change of temperature leads to a change of magnetization of the sensor which is read-out as a change of flux by a low-noise SQUID magnetometer. The sensor material, presently used for MMCs, is a dilute alloy of erbium in gold, Au:Er. The concentration of erbium ions in the sensor can be chosen to optimize the detector performance and usually varies between 200 and 800 ppm. The spectral resolving power of a state of the art MMCs for soft X-rays is above 3,000. For completely micro-structured detectors, an energy resolution of $\Delta E_{FWHM} = 2$ eV
at 6 keV and a signal rise-time $\tau_r = 90$ ns have been achieved [14]. Moreover the typical non-linearity at 6 keV is less than 1 % and the non-linear part can be described very well by a polynomial function of second order. The achieved performance suggests that MMCs are suitable detectors for measuring the high precision and high statistics EC spectrum of $^{163}$Ho.

In order to perform a calorimetric measurement of the $^{163}$Ho EC spectrum, the $^{163}$Ho source has to be:

- part of the sensitive volume of detector to prevent the partial loss of energy;
- homogeneously distributed so that the detector response is position independent;
- completely contained in the detector in order to ensure a quantum efficiency for the emitted particles of 100 %.

The optimum activity per pixel will be a compromise between having a high count rate per pixel and reducing the un-resolved pile-up as well as the heat capacity of the detector. Within our presently favored scenario the maximum activity per pixel can vary between 10 and 100 Bq. The relatively low activity per pixel leads to a relatively large number of pixels to host the required activity of more than $10^6$ Bq. This requires the development of a multiplexed detector readout. The read-out scheme for MMCs is compatible with several multiplexing techniques developed for low temperature micro-calorimeters, in particular with the microwave multiplexing which has the positive aspect to keep the performance of each detector in the array very close to that of a single pixel readout.

A first prototype detector chip consisting of four pixels having a gold absorber with implanted $^{163}$Ho has already been produced and tested [15]. The ion implantation process was performed at ISOLDE-CERN [16]. The $^{163}$Ho ions have been implanted over a reduced area $160 \times 160 \mu m^2$ of the first gold layer of the absorber having dimensions $190 \times 190 \times 5 \mu m^3$. A second gold layer having as well dimensions of $190 \times 190 \times 5 \mu m^3$ was deposited on top of the first layer. With this absorber fabrication, all the three mentioned requirements for embedding the source have been fulfilled [15]. The $^{163}$Ho activity per pixel was about $10^{-2}$ Bq. The first measurements

![Figure 1](image-url)

**Fig. 1** Left fit of the Mn K$_\alpha$ line. The energy resolution is $\Delta E_{FWHM} = 7.6$ eV. Right a rise time of $\tau_r = 134$ ns is extracted by the exponential fit (Color figure online)
performed using only one pixel of the prototype chip showed that the implantation process did not degrade the performance of the MMC [15,17]. An energy resolution of $\Delta E_{\text{FWHM}} \simeq 12$ eV and the rise-time $\tau_r \simeq 100$ ns have been measured. The non-linearity at 6 keV was less than 1 %, as expected. A second experiment had been performed with the same chip. Two pixels have been simultaneously measured for about two months. A $^{55}\text{Fe}$ calibration source was collimated onto one of them for energy calibration and to extract the detector response. Figure 1 shows the performance achieved in this experiment. An energy resolution $\Delta E_{\text{FWHM}} = 7.6$ eV and a signal rise-time $\tau_r \simeq 100$ ns have been measured. Figure 2 shows the spectrum obtained combining more than 30 files for each of the two pixels. The results achieved using the MMC prototypes have shown that the requirements of the single pixel have been met. The ECHO collaboration aims at further improving the energy resolution of the MMC having $^{163}\text{Ho}$ ions embedded in the absorber and reach an energy resolution below 5 eV for multiplexed detectors.

3 MMC and Microwave Multiplexing

Presently new chips consisting of 64 pixels which are read-out using the microwave multiplexing scheme [18] have been developed. In this multiplexing scheme every detector is coupled to a non-hysteretic, un-shunted rf-SQUID which is coupled to a superconducting microwave resonator with high internal quality factor and unique resonance frequency. A change of magnetic flux inside the SQUID caused by an event in the detector leads to a change of the effective SQUID inductance and therefore, due to the mutual interaction, to a change of the resonance frequency of the corresponding microwave resonator. It is possible to measure the signal of each detector simultaneously by capacitively coupling the corresponding number of resonators to a common transmission line, injecting a microwave frequency comb driving each resonator at resonance and monitoring either amplitude or phase of each frequency component of the transmitted signal. Figure 3 shows the design of the 64-pixels chip and the micro-fabricated chip. A detailed description of single pixel geometry, resonator design and
Fig. 3  Above design of the 64-pixel MMC array with integrated microwave multiplexing readout. The magnifications show, from left to right, the elbow coupler of a resonator, the double meander design of the MMC and the rf-SQUID. Below one of the first micro-structured 64-pixel chip. The magnifications show, from left to right, the elbow coupler of a resonator, the double meander design of the MMC and the rf-SQUID (Color figure online)
rf-SQUID properties as well as the expected performance of the detectors in the array is discussed in [19].

4 163Ho Source: Production and Purification

The production of a sufficient amount of 163Ho atoms in a radiochemically pure form is of paramount importance for the success of the ECHo experiment. Preliminary studies of different approaches to produce 163Ho have already been performed by the ECHo collaboration and by others [20]. The production methods for 163Ho can mainly be divided into two branches:

- charged particle activation of suitable targets in reactions that lead to 163Ho or its precursor 163Er which decays to 163Ho (EC and β+ decay) with a half-life $T_{1/2} = 75$ min;
- thermal neutron activation of enriched 162Er targets.

The reaction that is typically used for the direct activation with proton beams is $^{nat}\text{Dy}(p, xn)^{163}\text{Ho}$. Another possible direct reaction uses deuteron projectiles, $^{163}\text{Dy}(d, 2n)^{163}\text{Ho}$. Examples for indirect 163Ho production are $^{nat}\text{Dy}(\alpha, xn)^{165}\text{Er}$ (EC, β+) 163Ho and $^{159}\text{Tb}(7\text{Li}, 3n)^{163}\text{Er}$ (EC, β+) 163Ho. In the ECHo experiment all the described methods for production of 163Ho through charged particle activation processes as well as with neutron irradiation of a 162Er target are being considered, as well as possible new methods. Typically, in the production of 163Ho, contaminants nuclides with decay properties that interfere with the desired clean 163Ho EC spectrum are produced. These include long-lived β−-decaying nuclides like 166mHo. Thus, a careful separation of 163Ho is of paramount importance and will be performed by a combination of chemical and potentially physical separations before as well as after the irradiation of the sample. In this way, samples will be produced that contain contaminants on a level at which their contribution to the background of the calorimetric measurement is smaller than the intrinsic pile-up background. Tests both at accelerator as well as at reactor facilities are already under way. The aim of these tests is to investigate and quantify the production of radioactive contaminants and to improve the purification methods in order to reach the required purity. As a final step, the production of samples suitable for the calorimetric measurements will be optimized. Two methods appear attractive: the formation of intermetallic samples [21] and the ion-implantation.

5 163Ho EC Spectrum Parameterization

In an Electron Capture process a nucleus $^{A}\frac{Z}{2}\text{X}$ decays by capturing an electron from the inner atomic shells and emitting an electron neutrino to $^{A}\frac{Z-1}{2}\text{X}$. The daughter atom is left in an excited state. The atomic de-excitation is a complex process which includes cascades of both X-rays and electron emissions (Auger electrons and Coster–Kronig transitions). The possibility to measure all the energy released in the decay minus the energy taken away by the neutrino simplifies the description of the spectrum. The
The expected shape of the calorimetrically measured EC spectrum is:

\[
\frac{dN}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum C_H n_H B_H \phi_H^2(0) \frac{\Gamma_H}{2\pi} \frac{1}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}
\]

and shows Breit–Wigner resonances centered at about the binding energy of the electron that was captured referred to the daughter atom nuclear potential, \(E_H\), where \(H\) indicates the level from which the electron has been captured, with an intrinsic width \(\Gamma_H\). The intensities of these lines are given by the nuclear shape factors \(C_H\), the fraction of occupancy of the \(H\)-atomic shell \(n_H\), the squared wave-function of the captured electron calculated at the nucleus \(\phi_H^2(0)\) and a small correction, \(B_H\), due to electron exchange and overlap. The Breit–Wigner resonances are then modulated by the phase space factor which depends on the square of the electron neutrino mass \(m(\nu_e)^2\) and the energy available to the decay \(Q_{EC}\). \(A\) is a constant.

The purpose of the ECHo experiment is to improve the theoretical description of the EC spectrum of \(^{163}\text{Ho}\), in particular by investigating the modification due to the environment. This will be done by applying the complete screening approximation of Density Functional Theory (DFT) [22,23], to calculate the energy level of electrons and by improving the calculation of the partial decay rates by considering the finite size of the nucleus. This can be done by calculating the corresponding nuclear matrix elements for the transition \(^{163}\text{Ho}(7/2^-) \rightarrow ^{163}\text{Dy}(5/2^-)\) and capture of \(s_{1/2}\) and \(p_{1/2}\) electrons using the Quasi-Particle Random Phase Approximation (QRPA) approach [24]. The total energy available for the decay of \(^{163}\text{Ho}\) to \(^{163}\text{Dy}\) is a fundamental parameter to reach the sub-eV sensitivity to the electron neutrino mass by the analysis of the high energy part of the \(^{163}\text{Ho}\) EC spectrum. The recommended value is \(Q_{EC} = 2.555(1)\) keV as can be found in [25], but other measurements give values that range from about 2.3 keV [26] to about 2.8 keV obtained by two calorimetric measurements performed using low temperature detectors [17,27].

The aim of the ECHo collaboration is to reach a precision on the \(Q_{EC}\) of 1 eV or better. After preliminary measurements at the double-Penning trap mass spectrometers SHIPTRAP [28] and TRIGA-TRAP [29], the final high accuracy measurement will be accomplished by the novel Penning-trap mass spectrometer PENTATRAP [30,31]. The uniqueness and complexity of this Penning-trap mass spectrometer is associated with the unprecedented relative accuracy of a few parts in \(10^{12}\) with which the \(Q_{EC}\) must be measured.

6 Conclusion

The ECHo experiment has the aim to investigate the electron neutrino mass in the sub-eV range. The performance achieved by the first prototype of MMC detectors with \(^{163}\text{Ho}\) implanted in the gold absorber demonstrated that MMCs already meet the requirements on energy resolution and signal rise time.

We presented the different aspects that are presently under investigation within the ECHo project. The next goal of the ECHo collaboration is to set a small scale experi-
ment based on arrays of MMCs with embedded $^{163}\text{Ho}$ ions, for a total pixel number of about 100, read out by the microwave multiplexing scheme. Within this experiment about $10^{10}$ events will be collected. The analysis of the end part of the spectrum combined with the precise knowledge of the parameters describing the spectrum will allow to reach the sensitivity of below 10 eV on the electron neutrino mass. A full scale experiment holds the prospect of reaching the sub-eV sensitivity.

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