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Recent Results for the ECHo Experiment

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Abstract The Electron Capture in ^{163}Ho experiment, ECHo, is designed to investigate the electron neutrino mass in the sub-eV range by means of the analysis of the calorimetrically measured spectrum following the electron capture (EC) in ^{163}Ho. Arrays

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of low-temperature metallic magnetic calorimeters (MMCs), read-out by microwave SQUID multiplexing, will be used in this experiment. With a first MMC prototype having the ^{163}Ho source ion-implanted into the absorber, we performed the first high energy resolution measurement of the EC spectrum, which demonstrated the feasibility of such an experiment. In addition to the technological challenges for the development of MMC arrays, which preserve the single pixel performance in terms of energy resolution and bandwidth, the success of the experiment relies on the availability of large ultra-pure ^{163}Ho samples, on the precise description of the expected spectrum, and on the identification and reduction of background. We present preliminary results obtained with standard MMCs developed for soft X-ray spectroscopy, maXs-20, where the ^{163}Ho ion-implantation was performed using a high-purity ^{163}Ho source produced by advanced chemical and mass separation. With these measurements, we aim at determining an upper limit for the background level due to source contamination and provide a refined description of the calorimetrically measured spectrum. We discuss the plan for a medium scale experiment, ECHo-1k, in which about 1000 Bq of high-purity ^{163}Ho will be ion-implanted into detector arrays. With one year of measuring time, we will be able to achieve a sensitivity on the electron neutrino mass below 20 eV/c^2 (90 % C.L.), improving the present limit by more than one order of magnitude. This experiment will guide the necessary developments to reach the sub-eV sensitivity.

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

1 Introduction

The study of the calorimetrically measured electron capture (EC) spectrum of ^{163}Ho is presently the most promising method for the investigation of the electron neutrino mass in the sub-eV range. With experiments based on ^{163}Ho, it appears possible to reach sub-eV sensitivity for the electron neutrino mass similar to the one that tritium-based experiments, like KATRIN [1], can achieve for the electron antineutrino mass.

^{163}Ho is the most promising candidate for an experiment on the investigation of the neutrino mass due to its extremely low decay energy, Q_{EC}, of about 2.8 keV. Such a low Q_{EC} allows for a reasonable fraction of counts in the endpoint region of the spectrum where the effects due to a finite neutrino mass are exhibited.

The idea to use the analysis of the calorimetrically measured spectrum of ^{163}Ho to determine the electron neutrino mass was first proposed by De Rujula and Lusignoli in 1982 [2]. After about 30 years the feasibility of such an experiment was demonstrated by the ECHo (Electron Capture in ^{163}Ho) collaboration [3,4] by showing the possibility to perform high-resolution measurements of the ^{163}Ho electron capture spectrum using low-temperature metallic magnetic calorimeters [5,6]. Meanwhile, together with ECHo, two other international collaborations HOLMES [7] and NuMECS [8] have been formed 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 [3,4].

2 ^{163}Ho Electron Capture Spectrum

In an EC process an atom of ^{163}Ho decays to an excited state of ^{163}Dy by capturing an electron from the inner shells and emitting an electron neutrino. The de-excitation to the ground state happens via X-ray emission, Auger electrons and Coster-Kronig transitions. The electrons release their energy over a very short distance. The most penetrating particles are the X-ray photons with an energy close to 2.2 keV. They have an attenuation length of about 0.57 μm in gold. This way a 5 μm gold absorber has a quantum efficiency of about 99.99 %. The Q_{EC} value has been recently measured by the ECHo collaboration to be $2.833 \pm 0.030^{stat} \pm 0.015^{syst}$ keV [9]. This determination of the Q_{EC}, obtained as the difference between the ^{163}Ho and the ^{163}Dy masses, which have been precisely measured at the Penning Trap mass spectrometer SHIPTRAP [10] employing the sample preparation as established at TRIGA-TRAP [11] and the PI-ICR[1] technique [12] is thus independent of the physics related to the EC in ^{163}Ho. Using the first data set measured with MMCs, we have determined the Q_{EC} value with 2.80 ± 0.08 keV [13] extracted from a measured EC spectrum of ^{163}Ho which agrees well with the new Q_{EC} value.

Due to the low Q_{EC} value, only electrons from M or higher shells can be captured. At the first order, the excited state in ^{163}Dy can be described as a hole in the electronic shell corresponding to the electron that has been captured and an additional electron in the $4f$ shell. In this case the calorimetrically measured spectrum can be described as the sum of resonances, corresponding to the capture of the $3s$ (MI), $3p_{1/2}$ (MII), $4s$ (NI), $4p_{1/2}$ (NII), $5s$ (OI), $5p_{1/2}$ (OII), or $6s$ (PI) electrons. The amplitude of these resonances is modulated by the phase space factor. Higher order excitations would include the presence of more than one hole in the atomic shells [14–16]. These processes happen with a much lower probability with respect to the first-order processes, but still their contribution to the spectrum cannot be neglected. Figure 1 shows the expected spectrum including first-order and second-order transitions calculated for $Q_{EC} = 2.833$ keV. The parameters used in the function have been taken from the recent work by Fäßler et al. [15]. The lines corresponding to the first-order excitations MI ($3s$ electron), MII ($3p_{1/2}$ electron), NI ($4s$ electron) and NII ($4p_{1/2}$ electron) are shown. The resonances related to the second-order transitions are indicated. Third-order transitions have not been included since their intensity is yet smaller, see [16], and they will not be considered in this paper.

3 Metallic Magnetic Calorimeters for ECHo

The very low Q_{EC} of about 2.8 keV, which makes ^{163}Ho the most suitable nuclide to be used in experiments for the direct measurement of the electron neutrino mass, implies that detectors showing high energy resolution in the energy range below 3 keV need to be used. Low-temperature micro-calorimeters [18] can presently measure such energies with the highest precision. Within the ECHo experiment, low-temperature metallic magnetic calorimeters (MMCs) will be used [5].

[1] Phase-imaging based on ion-cyclotron-resonance.

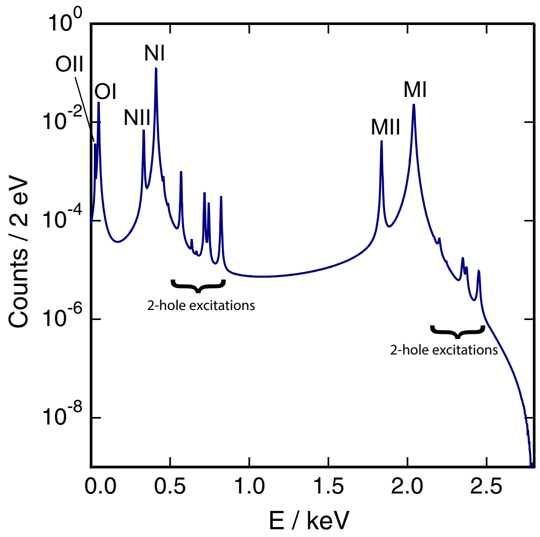

Fig. 1 Expected calorimetrically measured [163] Ho spectrum including first- and second-order transitions according to [15]. For details see text (Color figure online)

MMCs are energy dispersive detectors typically operated at temperatures below 50 mK. They consist of a particle absorber, in which the energy is deposited, thermally well connected to a temperature sensor made of a paramagnetic alloy which resides in a small magnetic field. Sensor and absorber are weakly connected to a thermal bath. The deposition of energy in the absorber increases the detector's temperature, which 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 spectral resolving power of a state of the art MMC for soft X-rays is above 3000 ($E/\Delta E_{\mathrm{FWHM}}$). For completely micro-structured detectors, an energy resolution of $\Delta E_{\mathrm{FWHM}} = 1.6\,\mathrm{eV}$ @ 6 keV has been achieved [19,20]. Sub-eV energy resolution is expected to be reached in a future design with the SQUID readout integrated on the detector chip. Such an energy resolution will allow to obtain a precise characterization of the endpoint region of the spectrum with a minimal spread of events. The goal for the ECHo experiment is to develop detectors containing ^{163}Ho in the absorber with an energy resolution of $\Delta E_{\mathrm{FWHM}} < 2\,\mathrm{eV}$.

The typical signal rise-time of MMCs is $\tau_{\mathrm{r}} = 90\,\mathrm{ns}$ at 30 mK [21]. Among the temperature sensors presently used for micro-calorimeters, MMCs show the fastest rise-time, limited by the electron spin coupling in Au:Er. A fast rise-time is extremely important to reduce un-resolved pile-up events from single ^{163}Ho decays. They contribute to the background and are generated when two or more events occur in the detector within a time interval shorter than the rise-time of the thermal pulse. In this case the detector signal will mimic a single event in the detector having an energy which is approximately the sum of the energies of the single events. The spectral shape of this background is given by the autoconvolution of the ^{163}Ho spectrum. The integral of this background spectrum is given by the so-called un-resolved pile-up fraction which can be written, at first order, as the activity in the detector A times the rise-time of the signal, τ_{r}. For the ECHo experiment an un-resolved pile-up fraction below 10^{-5} is required. This unresolved pile-up fraction, combined with the typical rise-time of MMCs, implies a limit in the maximal activity per detector of a few tens of Becquerel.

A precise calibration of the energy scale for the measured data is needed, which is enabled by well-known spectral shapes, an excellent linearity of MMCs, and the well understood thermodynamic response function. The typical energy 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 with high precision and high statistics the EC spectrum of ^{163}Ho.

The ECHo collaboration has already demonstrated the ability to perform a calorimetric measurement with ^{163}Ho with high energy resolution using MMC detectors. One of the challenges in that experiment was the fabrication of a detector with embedded ^{163}Ho and a quantum efficiency close to 100 % for the energy emitted in the EC process, minus the energy taken away by the neutrino.

3.1 MMC Prototype for the Calorimetric Measurement of the ^{163}Ho Spectrum

The first prototype detector chip consists of four pixels having a gold absorber composed by two gold films, each of them has a dimension of $190 \times 190 \times 5\,\mu\text{m}^3$ which is required to enclose the ^{163}Ho ions [22]. The ^{163}Ho ions have been implanted at the isotope separation on-line facility ISOLDE-CERN. Spallation products produced by 1.4 GeV proton bombardment of a Ta foil target diffused out of the target kept at a temperature around 2000 °C. Then they were surface ionized in a hot W ionizer, accelerated to 35 keV, mass-separated and focused on the surface of the detector chip. The ^{163}Ho ions have been implanted over a reduced area of $160 \times 160\,\mu\text{m}^2$ of the first gold layer of the absorber. The second gold layer was then deposited on top of the first layer to reach a quantum efficiency close to 100 %. The ^{163}Ho activity per pixel was about 10^{-2} Bq. The implantation process did not degrade the performance of the MMC [13,22]. An energy resolution of $\Delta E_{\text{FWHM}} \simeq 7.6\,\text{eV}$, at a working temperature of about 30 mK, and a rise-time $\tau_{\text{r}} \simeq 130\,\text{ns}$ have been measured. The non-linearity at 6 keV was less than 1 %, as expected. In an experiment where two pixels have been simultaneously measured it was possible to characterize the ^{163}Ho spectrum and extract the peak energy for each of the lines and the intrinsic line widths by de-convolving the intrinsic detector response obtained from the analysis of the ^{55}Mn $K_{\alpha1}$ and $K_{\alpha2}$ lines from an external ^{55}Fe calibration source. The most precise spectrum measured with the first prototype of MMC detectors for the ECHo experiment is shown in Fig. 2, which was obtained by analysing about 30 datasets for each of the two pixels [6]. Operating the same detector at a working temperature below 20 mK with an improved set-up and readout scheme a baseline energy resolution of 2.4 eV FWHM and a rise-time of $\tau_{\text{r}} \simeq 130\,\text{ns}$ have been reached.

The achieved results demonstrate that MMCs are promising detectors to perform high-resolution measurements of the ^{163}Ho spectrum.

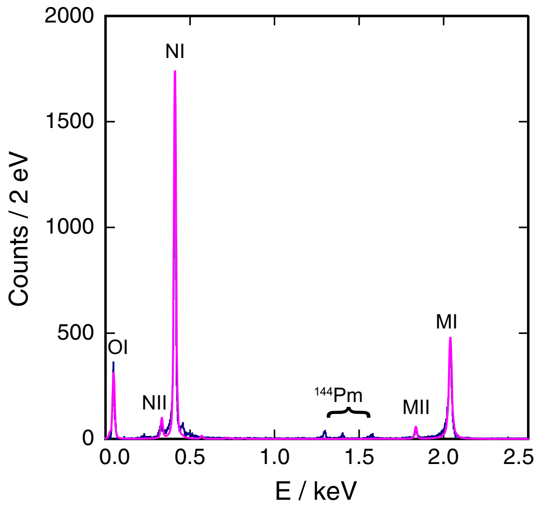

Fig. 2 ^{163}Ho EC spectrum measured with MMC detectors [6] using ^{163}Ho produced by proton-induced spallation of Ta. The data (dark blue histogram) have been fitted using the experimental detector response convolved with the theoretical spectrum (*pink line*). The fit parameters can be found in [13]. In addition, structures due to a contamination of ^{144}Pm are visible around 1.4 keV (Color figure online)

3.2 Analysis of the ^{163}Ho Calorimetric Spectrum

The analysis of the spectrum shown in Fig. 2 revealed some aspects to be improved. In addition to the lines expected for the electron capture in ^{163}Ho, small peaks related to the electron capture in ^{144}Pm are visible at energies around 1.4 keV. The additional small peaks between 0.220 and 0.320 keV are also due to the presence of ^{144}Pm and its decay to excited ^{144}Nd. The nuclide ^{144}Pm was part of the mass-separated beam of ionized particles having mass ^{163}U as ionized molecule ^{144}PmF^{+}. For the success of the ECHo experiment it is important to remove the background in the spectrum due to the presence of other unwanted radioactive nuclides in the ^{163}Ho source.

In addition the shape of the MI-line shows a low energy shoulder due to the loss to the substrate of hot phonons created during the first phase of the energy thermalization in the absorber. To reduce this effect the contact area between absorber and sensor needs to be reduced by the fabrication of a small number of stems between absorber and sensor.

The analysis of the energy region around 450 eV hinted at the existence of structures above the NI-line, which cannot be explained by background sources [6]. A very likely reason for these structures is that a non-negligible fraction of electron capture processes leads to higher order excited states in ^{163}Ho. The theoretical description of these processes and predictions of the effects in calorimetrically measured spectra have been treated in several articles [14–17]. Figure 3 (left) shows the comparison between the data and the predicted shape of the spectrum obtained with a convolution of the theoretical spectrum calculated using the parameters provided in [15] and a Gaussian detector response with a FWHM of 8 eV. While theory predicts structures to appear in the spectrum for the correct energies ($E_{4s5p} = 439.8\,\text{eV}$, $E_{4s5s} = 458.3\,\text{eV}$), the predicted amplitudes still do not agree with the data. More work is presently ongoing to improve the theoretical models.

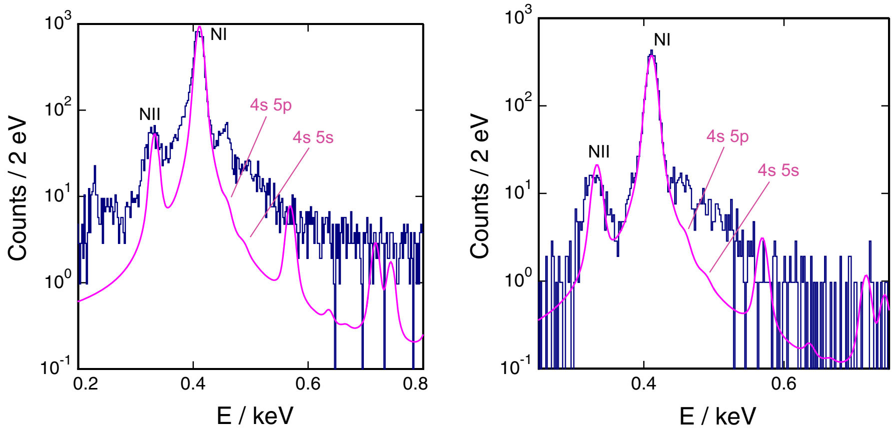

Fig. 3 ^{163}Ho EC spectrum in the energy region around 450 eV. The data (*darkblue* histogram) are compared with the expected spectrum (*pink line*) given as the convolution of the theoretical spectrum calculated using the parameters provided in [15] and a Gaussian detector response with a FWHM of 8 eV. (*left*) Data measured during 3 years with a few month of data acquisition and with an activity per pixel of about 10^{-2} Bq. (*right*) Data obtained during 2015 with an activity per pixel of about 10^{-1} Bq (see section 5) (Color figure online)

4 Production and Purification of the ^{163}Ho Source

After the results with the first detector prototype, it was clear that the production of highly pure ^{163}Ho is of major importance. In the ECHo experiment, the required ^{163}Ho sources are presently produced through neutron irradiation of enriched ^{162}Er targets in the flux reactor [24], while accelerator production is also studied [25]. Due to the presence of impurities in the target material, mainly other lanthanides as well as Er isotopes other than ^{162}Er, radioactive contaminations are co-produced, which have decay properties inducing background events in the relevant energy region of the ^{163}Ho EC spectrum. Among these nuclides, also the long-lived β^--decaying ^{166m}Ho is produced to obtain pure ^{163}Ho sources a chemical separation of the target material before the irradiation as well as after the irradiation to extract the holmium fraction are performed [24]. After this procedure, the main radioactive contaminant in the ^{163}Ho Source is ^{166m}Ho, since isotopes of the same element cannot be chemically separated. The aim of the ECHo collaboration is to reach a ratio of ^{166m}Ho/^{163}Ho smaller than 10^{-9}. This limit is estimated by considering a flat spectrum due to the partial energy release of the electrons emitted in beta-decays of ^{166m}Ho with an endpoint of 10 keV. In this approximation and with a fraction ^{166m}Ho/^{163}Ho of 10^{-9}, the events due to ^{166m}Ho decays at the endpoint region of the ^{163}Ho spectrum are negligible. The fraction of ^{166m}Ho contained in the chemically purified sample can be strongly reduced, to a minor level, using mass separation technique. This step can be naturally combined with ion-implantation for the embedding of the source directly into the detector absorbers [26]. This three-step purification procedure for the production of ^{163}Ho sources allows for the reduction of the radioactive contamination to a negligible level. Within ECHo two facilities are considered to perform the mass separation and the ion-implantation processes: ISOLDE at CERN [23] and RISIKO at the Mainz University [27].

5 Second ^{163}Ho Implantation in MMCs

To determine the optimum approach to remedy the problems, which appeared after the measurements with the first detector prototype an improved experiment was designed and carried out. A fraction of a ^{163}Ho source, which was chemically purified at the institute for Nuclear Chemistry at the University of Mainz was used for an off-line implantation at ISOLDE. The detectors used in this experiment are the maXs-20, optimized for high energy resolution X-ray spectroscopy [21]. They belong to an 1D array and each detector of the array consists of two pixels in a gradiometric configuration. On each chip 16 pixels corresponding to 8 detectors are arranged in one row next to one edge of a 5×5 mm^2 silicon substrate. In this design the absorber is connected to the paramagnetic Au:Er sensor through five stems with a diameter of 12 μm. The absorber is composed of two gold layers with $250 \times 240 \times 5\,\mu\mathrm{m}^3$, as in the first MMC prototype. The area where the ^{163}Ho ions have been implanted with an acceleration voltage of 30 keV is $230 \times 220\,\mu\mathrm{m}^2$, centred on the first absorber layer. Two maXs-20 chips have been implanted during the same run. The fabrication of the second gold layer to enclose the ^{163}Ho source was successfully performed in the clean room of the Kirchhoff-Institute for Physics at the Heidelberg University. Thanks to this second implantation campaign, 32 pixels with embedded ^{163}Ho are available to perform experiments to study the spectral shape with high statistics spectra and investigate the background under different experimental conditions.

5.1 Preliminary Results

A test experiment using one of the two implanted chips was performed in order to have a first characterization of the detectors and an estimate on the activity of the implanted ^{163}Ho. There has been no optimization of the working point and of the signal to noise ratio in this experiment. The expected energy resolution based on thermodynamic properties of the detector and the usual readout noise for this detectors at a working temperature of about 10 mK is below 5 eV. Two detectors, each with two pixels, have been used in these measurements. The activity per pixel is about 0.2 Bq, about one order of magnitude larger that the one of the first detector prototype. Figures 3 and 4 (right) show the regions of the MI-line and the N-lines, respectively. The full spectrum contained about 17500 events and was obtained by summing the events acquired with two pixels over about one day. Figure 3 (right) shows the N-lines region. As the data acquired with the first detector prototype, also in the new spectrum the structure above the NI-line is present. This result supports the interpretation that the origin is due to processes related to the decay of ^{163}Ho. Figure 4 compares the MI histogram with the expected curve obtained with the convolution of the theoretical spectrum calculated using the parameters provided in [15] and a Gaussian detector response with a FWHM of 12 eV. It appears evident that the presence of the stems strongly reduces the loss of hot phonons.

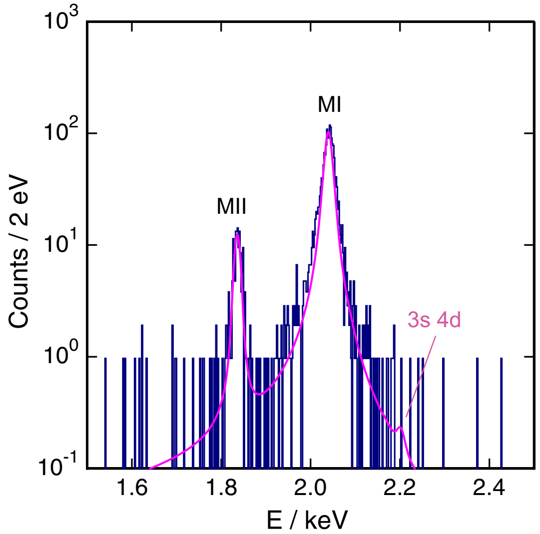

Fig. 4 ^{163}Ho EC spectrum in the energy region around 2000 eV. The data (*darkblue* histogram) are compared with the expected spectrum (*pink line*) given as the convolution of the theoretical spectrum calculated using the parameters provided in [15] and a Gaussian detector response with a FWHM of 12 eV (Color figure online)

6 Neutrino Mass Sensitivity of the ECHo Experiment

In order to achieve sub-eV sensitivity on the electron neutrino mass, it is mandatory that the quality of the measurement allows for identifying the tiny distortions in the spectrum due to a finite neutrino mass. Because of that, the energy resolution of the detectors should be better than $\Delta E_{\mathrm{FWHM}} < 2$ eV. The external background, due to natural radioactivity, cosmic rays and contamination in detectors and detector set-ups, should be kept smaller than the maximum allowed unresolved pile-up background, whose limit in ECHo is defined by a maximum unresolved pile-up fraction $f_{\mathrm{pu}} = 10^{-5}$. These requirements guide the development towards the production of high purity ^{163}Ho sources and towards large arrays of MMCs read out by the microwave multiplexing technique suitable for preserving the performance achieved for single pixels, which already fulfil the requirements for the first stage of ECHo [19,21]. In order not to be limited by systematic uncertainties it is of major importance to precisely understand the spectral shape that is expected for the calorimetrically measured ^{163}Ho EC spectrum. In the near future improved theoretical models as well as the availability of high statistics spectra, for example acquired using the available 32 pixels with about 0.2 Bq of activity, will lead to a better characterization of the ^{163}Ho spectrum. In particular the Q_{EC}-value will be determined with 1 eV uncertainty by means of the newly developed Penning-trap mass spectrometer PENTATRAP [28,29] at the Max-Planck-Institut for Nuclear Physics in Heidelberg.

Figure 5 shows the achievable sensitivity at 90 % C.L. for the electron neutrino mass plotted versus the acquired statistics in the full energy range of the ^{163}Ho spectrum for $Q_{\mathrm{EC}} = 2.8$ keV.

For the calculation we have considered a Gaussian detector response with an energy resolution of $\Delta E_{\mathrm{FWHM}} = 3$ eV and as background source only unresolved pile-up events corresponding to a fraction in respect of the total number of acquired events

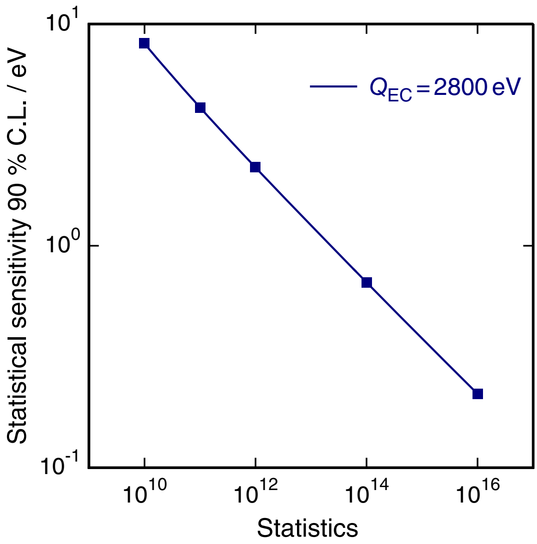

Fig. 5 Statistical sensitivity at 90 % C.L. for the electron neutrino mass versus the acquired statistics in the full energy range of the ^{163}Ho spectrum. The curve corresponds to the energy available to the decay Q_{EC} and is calculated considering a Gaussian detector response with energy resolution $\Delta E_{\mathrm{FWHM}} = 3$ eV and an unresolved pile-up fraction of 10^{-5} (Color figure online)

of 10^{-5}. The theoretical model for the description of the spectrum used to deduce the sensitivity to the electron neutrino mass includes only the first-order excitation, since, at the moment, there is still no precise description available of the effect due to higher order excitations. The sensitivity curve has been calculated by comparing the number of events expected in a well-defined ROI located symmetrically around the Q_{EC} value for a spectrum with massless neutrinos and for massive neutrinos for different values of the neutrino mass. For each set of parameters N_{tot}, f_{pu}, ΔE we look for the value of the neutrino mass which can be defined with 90 % C.L. Figure 5 clearly shows that more than 10^{14} events in the full spectrum range are required to reach sub-eV sensitivity on the neutrino mass. In order to acquire such large statistic in a reasonable time, a ^{163}Ho activity larger than 1 MBq is needed. Combining this constraint with the wish for a low unresolved pile-up fraction below 10^{-5} and with a typical detector response of 1 μs leads to a maximum activity in a detector of about 10 Bq which then leads to the conclusion that more than 10^5 single detectors are needed to complete the measurement in a reasonably small number of years. For the ECHo experiment, large arrays of metallic magnetic calorimeters are planned to be used. These arrays, consisting of 100 to 1000 single pixels, will be read out using the microwave SQUID multiplexing scheme [30,31]. This multiplexing scheme allows to have a large bandwidth for each pixel, to preserve the fast rise-time, and a reduced degradation of the detector performance with respect to the single pixel readout, to preserve the energy resolution. The first chips, containing 64 pixels, have recently been successfully produced and tested [31].

7 Conclusions and Outlook

The performance achieved by the MMCs with ion-implanted ^{163}Ho shows that MMC single pixels will be able to match the requirements for an experiment aiming to investigate the electron neutrino mass with a sub-eV sensitivity. The second generation of MMCs with implanted ^{163}Ho shows a large improvement in terms of ^{163}Ho activity in the pixels, response of the detector and in purity of the ^{163}Ho source. After first theoretical approaches to describe the ^{163}Ho spectrum, a perfect agreement between theory and experimental data is not yet achieved.

The next step of ECHo is to perform a medium scale experiment, ECHo-1k, which will run during the years 2015–2018. In ECHo-1k first prototypes of MMC arrays with implanted ^{163}Ho will be produced. The sum of the activity of all the pixel will be approximately 1 kBq. This stage will be characterized by a number of milestones, both on experimental side as on theoretical models:

- the ability to read out 100 MMCs with microwave SQUID multiplexing and keep single pixel performance,
- the preparation of a suitable cryogenic platform to host the first and second stage of the experiment,
- the production of a large, of the order of 10 MBq, high purity ^{163}Ho source, the identification and reduction of background to reach a level below the unresolved pile-up spectrum,
- the reduction of systematic uncertainties by an improved knowledge of the expected ^{163}Ho spectrum, including the study of higher order excitation states in ^{163}Dy, and
- a more precise determination of the ^{163}Ho Q_{EC}-value.

With this first medium scale experiment the ECHo collaboration aims to reduce the present limit on the electron neutrino mass by more than one order of magnitude, from the present upper limit of $m(\nu_{\mathrm{e}}) \leq 225$ eV [32] to below $m(\nu_{\mathrm{e}}) \leq 20$ eV.

The know-how developed during this first stage will define the scalability of the developed techniques for the construction of the next generation experiment, ECHo-1M. The goal of ECHo-1M is to measure a ^{163}Ho EC spectrum with a statistics of more then 10^{14} events using a ^{163}Ho source of the order of 1 MBq distributed into a very large number of single pixels. With such an experiment it will be possible to reach the sub-eV sensitivity on the electron neutrino mass.

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