EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Embedding of ^{163}Ho and ^{166m}Ho in the energy absorbers of low temperature metallic magnetic calorimeters

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Abstract

The calorimetric measurement of the ^{163}Ho electron capture spectrum is a promising tool to investigate the electron neutrino mass. A suitable method to embed the source in the detectors is the ion-implantation. This process has already been used to embed ^{163}Ho ions in micro-fabricated low temperature metallic magnetic. The ^{163}Ho electron capture spectrum obtained with these first prototypes is presently the most precise with an energy resolution of ΔE_{FWHM} = 7.6 eV. In order to test the performance of the new generation of low temperature metallic magnetic calorimeters, we propose to perform a ^{163}Ho ion-implantation on the new chip having two arrays consisting of 32 pixels each. An activity of about 1 Bq per pixel is required. With this new detector array we will be able to achieve a better energy resolution and to acquire a higher statistics which allows for studying the ^{163}Ho spectral shape. We propose also to perform an ion-implantation of ^{166m}Ho in a few detectors with an activity per pixel of less than 1 Bq. With these detectors we will study the energy deposition in the small volume of the metallic magnetic calorimeters due to decay of ^{166m}Ho.

Keywords: ^{163}Ho, electron neutrino mass, metallic magnetic calorimeters, ^{166m}Ho

Requested shifts: 8 shifts for the ^{163}Ho implantation and 1 shift for implanting ^{166m}Ho

1. Introduction

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, $m(\nu_e) < 2.2$ eV, was achieved for the electron anti-neutrino mass [1]. Different approaches are presently followed to achieve 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 and antineutrino mass values which are model independent since only energy and momentum conservation is used. The nuclides that are presently used in such experiments to are: ^{3}H ($Q_\beta \approx 18$ keV) and ^{187}Re ($Q_\beta \approx 2.4$ keV), both undergoing a beta decay and ^{163}Ho ($Q_{EC} \approx 2.5$ keV) which undergoes an electron capture (EC).

The Electron Capture ^{163}Ho experiment ECHo 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 [2]. A high precision and high statistics spectrum will be measured with arrays of metallic magnetic calorimeters (MMCs) [3].

MMCs are energy dispersive detectors 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 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 ppm and 800 ppm. The spectral resolving power of state of the art MMCs for soft x-rays is above 3500.

For completely micro-fabricated detectors, an energy resolution of $\Delta E_{\mathrm{FWHM}} = 2$ eV at 6 keV and a signal rise-time $\tau_r = 90$ ns, which is presently few order of magnitude shorter than the typical signal rise-time of other microcalorimeters, have been achieved [4]. 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 so that the energy scale of the measured spectra can be defined with high precision.

To achieve high sensitivity on the electron neutrino mass, the requirements for the detectors are quite demanding, as Galeazzi et al. have illustrated in their work [5]. An energy resolution better than $\Delta E_{\mathrm{FWHM}} = 10$ eV and a fast signal rise-time are required. The performance achieved by MMCs suggests that they are suitable detectors for measuring the high precision and high statistics EC spectrum of ^{163}Ho.

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 in the detector so that the response is position independent
- completely contained in the detector to ensure a quantum efficiency for the emitted particles of 100%.

2. Preliminary results

A first prototype detector chip consisting of four pixels having a gold absorber with implanted ^{163}Ho has already been produced and tested [6]. The ion implantation process was performed at ISOLDE-CERN [7]. The ^{163}Ho ions have been implanted over a reduced area 160 x 160 μm^2 of the first gold layer of the absorber having dimensions 190 x 190 x 5 μm^3. A second gold layer having as well dimensions of 190 x 190 x 5 μm^3 was deposited on top of the first layer few months after the implantation. With this absorber fabrication, all the three mentioned requirements for embedding the source have been fulfilled. The ^{163}Ho activity per pixel was about 10^{-2} Bq. Two pixels have been simultaneously measured for about two months. Onto one of them a ^{55}Fe calibration source was collimated for energy calibration and to extract the detector response. An energy resolution of $\Delta E_{\mathrm{FWHM}} = 7.6$ eV was obtained by the analysis of the K$_\alpha$-line of ^{55}Mn. The signal rise-time was $\tau_{\mathrm{r}} \approx$ 130 ns. Fig. 1 shows the most recent spectrum obtained combining more than 20 data sets for each of the two pixels. Due to the high energy resolution achieved with this first prototype of MMC detectors it was possible for the first time to show the calorimetric measurement of the OI line at about 50 eV. In these measurements the background was dominated by the decay of the ^{144}Pm ions in the absorber which were implanted together with the ^{163}Ho ion as ^{144}PmF^{+}. The presence of radioactive contaminants can be reduced if the source will undergo steps of chemical purification before being embedded in the detectors. Then only Ho isotopes will be present in the final source. The only Ho isotope which has a long half-life and could degrade the calorimetric measurement of the ^{163}Ho spectrum is ^{166m}Ho with a half-life of about 1200 years.

Motivated by these results we developed a new detector chip with improved detector properties. We propose to perform a ^{163}Ho implantation on these new detectors. We expect to improve the precision of the measurement and to acquire a relatively high statistics to reach a sensitivity on the electron neutrino mass below the present upper limit $m(\nu_e) < 225$ eV [8]. We propose also to test the background in the calorimetric measurement due to ^{166m}Ho by implanting an activity of about 0.01 Bq in each of the four detectors.

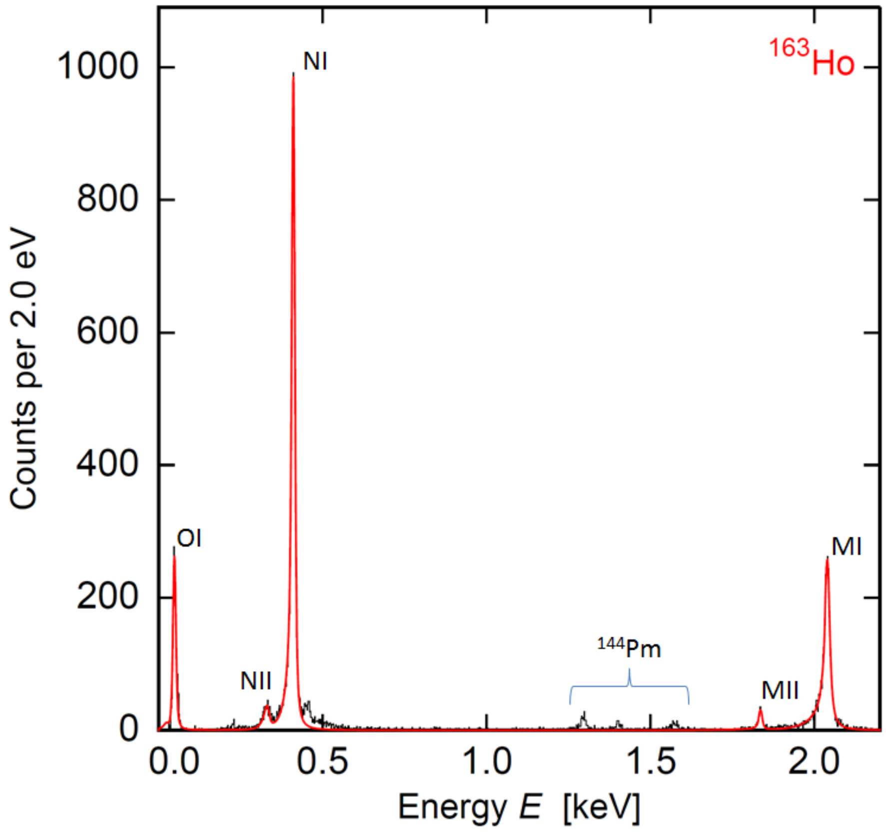

Fig. 1: ^{163}Ho EC spectrum measured with MMC detectors. The data is obtained using the experimental line-width convolved with the theoretical spectrum. In addition, structures due to the contamination of ^{144}Pm in the implanted source are visible around 1.4 keV.

3. Experiment

We propose to perform the implantation of ^{163}Ho and ^{166m}Ho on fully micro-structured MMC detectors. Our aims are: to characterize the performance that the newly designed detectors can achieve for the calorimentric measurement of the ^{163}Ho EC spectrum and to investigate the background due to ^{166m}Ho in calorimetric measurement performed with MMC detectors.

3.1 Test of the new detector chip

The results obtained with the first prototype of MMC detectors having the ^{163}Ho source implanted in the absorbers at the ISOLDE facilities showed that the calorimetric measurement of the ^{163}Ho EC spectrum can be performed with high precision. The ^{163}Ho spectrum measured with MMC detectors, achieving an energy resolution of $\Delta E_{\mathrm{FWHM}} = 7.6$ eV, is presently the most precise ever measured. On the other hand, by performing several experiments with these first detector prototypes, we pointed out a few aspects of the detector design that can be improved leading to a more uniform detector response, to a better energy resolution and to a reduction of the background [6]. A new detector chip has been developed where the design value for the energy resolution is $\Delta E_{\mathrm{FWHM}} = 4$ eV and the background due to thermal cross-talk and events in the substrate will be reduced by using the gradiometric configuration of the pixels in a double-meander configuration. This detector chip consists of 64 pixels divided into two arrays of 32 pixels each (16 double-meanders) which can be read out either with the microwave multiplexing technique or as separate detector channels using the usual dc-SQUID read-out [3]. Fig. 2 shows the design of the new chip. The pixels are located along two lines in the center of chip. The 64 pixels occupy an area of about 1 x 13 mm^2.

We propose to perform ^{163}Ho implantation on two of the new developed chips. The required activity per pixel is about 1 Bq. The implantation on all the pixels in one chip can be performed by sweeping the ion beam, having a cross-section of about 2 mm^2 along the area occupied by the 64 pixels of about 1 x 13 mm^2.

An off-line process, using a high purity ^{163}Ho target produced at the Nuclear Chemistry Institute of Mainz University by the group of Prof. Düllmann and Dr. Eberhardt, is preferred. This should ensure a negligible presence of radioactive contaminants in the beam of selected mass 163 amu.

With the new implanted detectors we will be able to investigate several aspects that are crucial for the future development of the detectors for ECHo. First of all we will characterize the new detector design and evaluate the results in the light of the specifications for the ECHo experiment. We will investigate the background present in the calorimetric measurement due to radioactive contaminants implanted together with the ^{163}Ho ion with the aim to show that this contribution is negligible due to the very good mass resolution. Since we expect mainly no radioactive contaminants from the beam, we will investigate the effect of natural radioactivity and radioactive contaminants of the detector set-up in the calorimetric measurement. A high statistics spectrum will be acquired which will allow for more precisely studying the spectrum parameters and for investigating the electron neutrino mass below the present upper limit $m_\nu < 225$ eV [8].

In case the off-line implantation would not be possible, an on-line implantation will allow the testing of the detectors, even with an increased radioactive contaminants in the implanted ions. In the first implantation test that was performed at ISOLDE on the MMC chip the ^{163}Ho beam was created by bombarding a Ta-W target with protons. Few relatively long living isotopes have been identified: ^{147}Gd ($\tau_{1/2} = 38.06$ h), ^{147}Eu ($\tau_{1/2} = 24.1$ d) and ^{144}Pm ($\tau_{1/2} = 363$ d). In the calorimetric measurements performed with the MMCs few months after the implantation, only the ^{144}Pm was significantly affecting the background. The high statistics measurement can also be performed, but the presence of the mentioned radioactive contaminants might degrade the quality of the analysis.

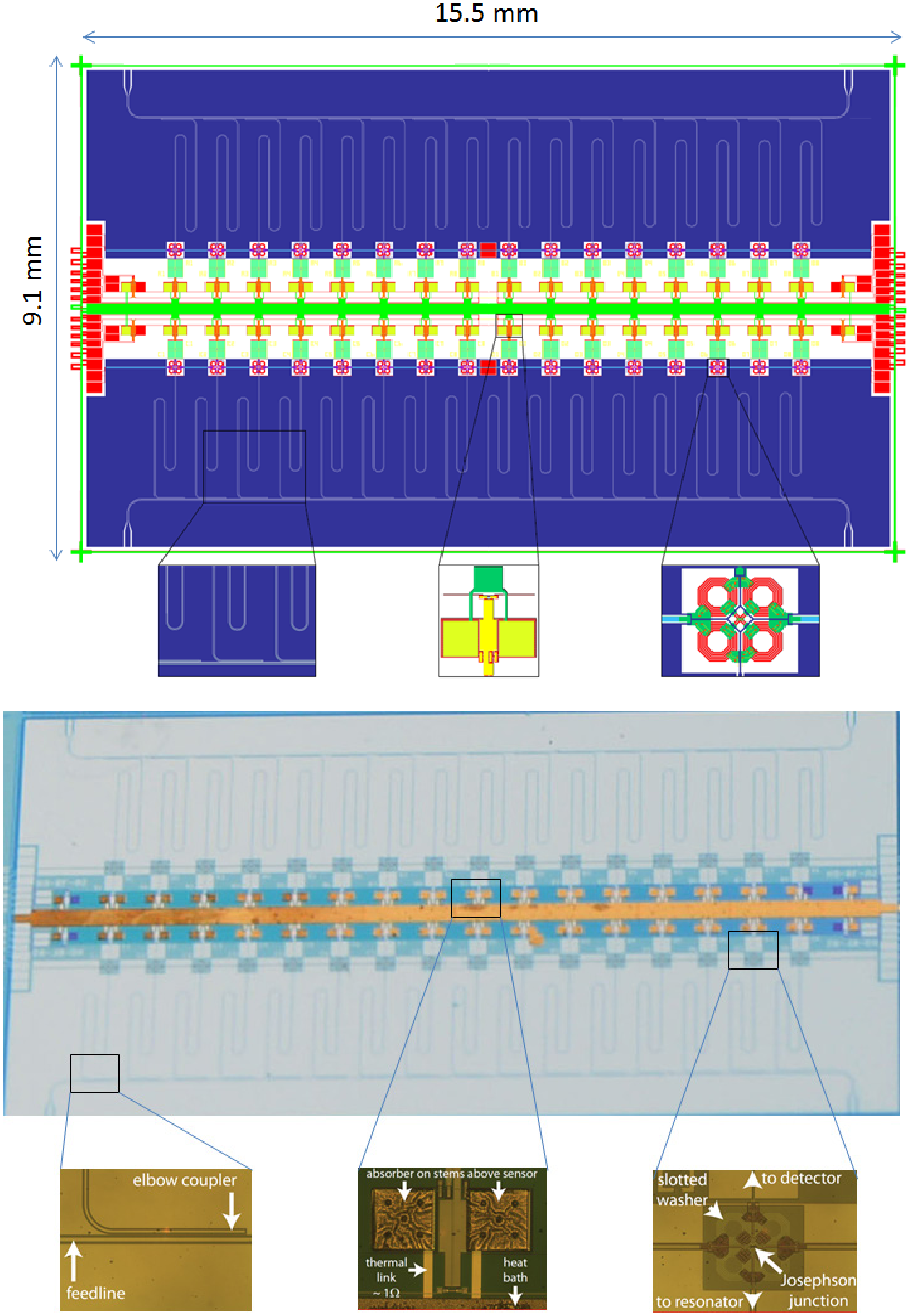

Fig. 2 **Above:** Design of the 64-pixel MMC chip with integrated microwave multiplexing readout. The magnifications show, from left to right, the elbow coupler of a resonator, the double meander design of the MMC and the rf-SQUID [2] [9]. **Below:** One of the first micro-structured 64-pixel chips. The magnifications show,from left to right, the elbow coupler of a resonator, the double meander MMC detector and the rf-SQUID. The region for the implantation is the pale blue band in the center of chip where the double meander detectors are located

3.2 Study of the background due to ^{166m}Ho

The ^{163}Ho can be produced via charged particle activation of suitable targets as for example in ^{nat}Dy (p, xn) ^{163}Ho, or via (n,γ) reaction on enriched ^{162}Er target. In both processes the isotope ^{166m}Ho is also produced. This isotope can not be chemically separated. It is therefore important to study in details the background induced in the calorimetric measurement by the ^{166m}Ho by performing experiments where a well defined activity of ^{166m}Ho is implanted in MMC microcalorimeters. The results of these measurements, together with Monte Carlo simulations will define the maximum allowed activity of ^{166m}Ho in a MMC for the calorimetric measurement of the ^{163}Ho spectrum. In case the allowed activity is well below the one coming from the amount of ^{166m}Ho in the present in the ^{163}Ho sources, the use of a physical ^{163}Ho separation at high resolution mass separators will be required to prepare the detectors for the ECHo experiment.

We propose to perform an off-line ^{166m}Ho implantation using a target with ^{166m}Ho produced at the Nuclear Chemistry Institute at the Mainz University by the group of Prof. Düllmann and Dr. Eberhardt. The implantation will be performed on a chip with the same detector design as the chip used in the first experiment [6]. On this chip there are four pixels positioned within an area of about 500 x 500 μm^2 so that the implantation can be performed simultaneously on all the four absorbers. For each pixel an activity of about 0.01Bq is required.

In case the off-line process will not be possible, we ask for the on-line implantation. In this case we tried to estimate the possible contaminants. For mass number 166 amu there are not long living nuclides besides ^{166m}Ho In case compounds with fluorine will be present in the beam, ^{147}Gd ($\tau_{1/2}$ = 38.06 h), ^{147}Eu ($\tau_{1/2}$ = 24.1 d) and maybe ^{147}Pm ($\tau_{1/2}$ = 2.6234 y) might be implanted. If oxide will be implanted, one might suffer from ^{150}Eu ($\tau_{1/2}$ = 36.9 y) or ^{150}Gd ($\tau_{1/2}$ = 1.79 10^6 y). The accuracy of the measurement for the investigation of the background due to the beta decay of ^{166m}Ho will depend on the fraction of these contaminants respect to the ^{166m}Ho. Nevertheless we will be able to perform a preliminary measurement.

4. Summary of requested shifts:

Herewith we ask for **9 shifts** of **off-line** implantation of radioactive **^{163}Ho** and **^{166m}Ho** beams. The targets will be prepared at the Nuclear Chemistry Institute of Mainz University.

- 8 shifts for implanting ^{163}Ho into micro-structured chip with 64 pixels
- 1 shift for implanting ^{166m}Ho into a detector chip with 4 pixels

In case the off-line implantation is not possible we ask for on-line implantation

- 8 shifts for ^{163}Ho using Ta-W target, RILIS and HRS
- 1 shift for ^{166m}Ho using Ta-W target, RILIS and GPS

References:

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Note: a new GLM implantation chamber is expected to be delivered to CERN in early 2014. The safety file will be updated when this happens.

Part of the Choose an item.	Availability	Design and manufacturing
GLM	☒ Existing	☐ To be used without any modification ☒ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed GLM installation.

1 Additional hazards:

Hazards	*GLM*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure			
Vacuum	1e-6		
Temperature	Room temperature		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			

Use of activated material:			
- Description	☐		
- Dose rate on contact and in 10 cm distance	[dose][mSV]		
- Isotope	^{166m}Ho, ^{163}Ho		
- Activity	100Bq		
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency	Background noise in the hall		
Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling	Samples to be mounted and unmounted using tweezers at the enclosed area in the ISOLDE hall.		
Poor ergonomics	[location]		

1 Hazard identification

3 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*

Nothing beyond standard power needs available in the ISOLDE hall.