PROCEEDINGS OF SCIENCE

The Electron Capture in ^{163}Ho Experiment - a Short Update

N. Kovac,[1,*] F. Ahrens,[1] A. Barth,[1] S. Berndt,[2,3] K. Blaum,[4] M. Brass,[5] E. Bruer,[1] M. Door,[4] H. Dorrer,[2] Ch. E. Düllmann,[2] S. Eliseev,[4] C. Enss,[1] P. Filianin,[4] A. Fleischmann,[1] L. Gastaldo,[1] A. Göggelmann,[6] M. Griedel,[1] R. Hammann,[1] M. Haverkort,[5] D. Hengstler,[1] M. Herbst,[1] W. Holzmann,[1] J. Jochum,[6] K. Johnston,[7] N. Karcher,[8] S. Kempf,[9] T. Kieck,[3] N. Kneip,[3] U. Köster,[10] K. Kromer,[4] F. Mantegazzini,[1] B. Marsh,[7] M. Neidig,[9] Y. N. Novikov,[11] A. Reifenberger,[1] D. Richter,[1] S. Rothe,[7] O. Sander,[8] R. Schüssler,[4] Ch. Schweiger,[4] T. Stora,[7] C. Velte,[1] M. Weber,[8] M. Wegner,[9] K. Wendt[3] and T. Wickenhäuser[1]

[1] *Kirchhoff Institute for Physics, Heidelberg University, Heidelberg, Germany*
[2] *Department of Chemistry - TRIGA Site, Johannes Gutenberg University Mainz, Mainz, Germany*
[3] *Institute of Physics, Johannes Gutenberg University Mainz, Mainz, Germany*
[4] *Max Planck Institute for Nuclear Physics, Heidelberg, Germany*
[5] *Institute for Theoretical Physics, Heidelberg University, Heidelberg, Germany*
[6] *Institute of Physics, Eberhard Karls University Tübingen, Tübingen, Germany*
[7] *CERN, Physics Department, Geneva, Switzerland*
[8] *Institute for Data Processing and Electronics, Karlsruhe Institute of Technology, Karlsruhe, Germany*
[9] *Institute of Micro- and Nanoelectronic Systems, Karlsruhe Institute of Technology, Karlsruhe, Germany*
[10] *Institut Laue-Langevin, Grenoble, France*
[11] *Petersburg Nuclear Physics Institute, Gatchina, Russia*

E-mail: neven.kovac@kip.uni-heidelberg.de

The definition of the absolute neutrino mass scale is one of the main goals of particle physics today. The study of the end-point regions of β- and electron capture (EC) spectra offer a possibility to determine the effective electron (anti-)neutrino mass in a completely model-independent way, as it only relies on energy and momentum conservation.
The ECHo (Electron Capture in ^{163}Ho) experiment [1] has been designed in the attempt to measure the effective mass of the electron neutrino by performing high statistics and high energy resolution measurements of the ^{163}Ho EC spectrum. To achieve this goal, large arrays of low temperature Metallic Magnetic Calorimeters (MMCs), in the order of 10^2 pixels, with implanted with ^{163}Ho are used. Here we report on the structure and the status of the experiment.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

[*] Speaker

PoS(EPS-HEP2021)211

1. Motivation

Electron capture (EC) is a weak-interaction process in which one of the electrons from the inner atomic shell is captured by the nucleus, transforming a proton into a neutron, and a neutrino is emitted. The available decay energy (Q-value) is shared between the neutrino and the atomic excitation of the daughter atom, with a small amount going into the nuclear recoil due to the neutrino emission. Neutrinos are not massless, and their mass has a direct influence on the shape of the end-point region of the EC-spectrum, this provides us with a direct and model-independent way of constraining the neutrino mass. With a small Q-value of around 2.833 keV [2] and its proximity to the highest peak of the spectrum, ^{163}Ho represents an ideal candidate for this purpose [3]. The ECHo experiment has been designed to reach sub-eV sensitivity on the effective electron neutrino mass by performing calorimetric measurements of the ^{163}Ho spectrum using large arrays of Metallic Magnetic Calorimeters (MMCs) [4].

2. The ECHo experiment

Holmium-163 source ^{163}Ho is an artificial radionuclide with a half-life of about 4500 years, that decays via EC process to ^{163}Dy with the emission of an electron neutrino. After the EC has occurred, the ^{163}Dy daughter atom is left in an excited state and the transition to its ground state occurs via emission of radiation, usually in the form of Auger electrons or X-rays. For the needs of the ECHo experiment, ^{163}Ho is produced via neutron-irradiation of Er samples enriched in ^{162}Er in the high-flux reactor at the Institut Laue-Langevin (ILL), Grenoble, France [5]. The chemically isolated holmium sample mainly consists of ^{163}Ho, ^{165}Ho, and ^{166m}Ho. While ^{165}Ho is stable, ^{166m}Ho is a long-lived nuclear isomer with a half-life of about 1200 years which would act as a source of background and therefore needs to be removed prior to the measurement. This is done at the magnetic mass separator, RISIKO, at the Johannes Gutenberg University in Mainz, where the pure holmium sample is mass-separated and ion-implanted into the MMCs using a high transmission magnetic mass separator equipped with a resonance ionisation laser ion source, with an efficiency of around 69% [6].

Detector design and read-out Arrays of low temperature Metallic Magnetic Calorimeters proved to be the optimal choice for the ECHo experiment, with an achievable energy resolution below 3 eV at FWHM and a time resolution well below 1 µs [1]. They feature a particle absorber made of gold, designed to completely stop the penetrating particles, converting their energy into a change of temperature. This leads to a change of magnetisation in a paramagnetic Ag:Er sensor that is strongly thermally coupled to the absorber. The sensor is placed on top of a superconducting pick-up coil which is coupled to a sensitive, low-noise current-sensing SQUID that is used to read out the signal. For a single channel read-out, the voltage signal from the SQUID is directly proportional to the energy deposited in the particle absorber [7]. For the read-out of the large ECHo MMC arrays, multiplexed read-out is foreseen, with the microwave SQUID multiplexing (µMUX) technique currently under development for the coming phases of the ECHo experiment [8].

Q_{EC} value Precise knowledge of the Q-value of the decay is one of the main ingredients needed for a valid description of the ^{163}Ho spectrum. Penning Trap Mass Spectroscopy (PTMS) provides a way to measure the Q-value independently from the EC process. By measuring the difference between the masses of ^{163}Ho and ^{163}Dy, the Q-value can be determined. Currently, the best measured value via PTMS is $Q_{\mathrm{EC}} = 2.833 \pm 0.030^{\mathrm{stat}} \pm 0.015^{\mathrm{syst}}$ keV [2].
In order to reach a precision of 1 eV, the Penning-trap mass spectrometer PENTATRAP at the MPIK in Heidelberg gets employed [9].

Theoretical description of the ^{163}Ho spectrum Of the 67 electrons present in ^{163}Ho, 20 have a substantial overlap with the nucleus which makes them a candidate to undergo a capture process. The de-excitation spectrum is therefore characterised by resonances corresponding to the binding energies of the captured electrons. In addition, higher order excitations occur, in which electrons are emitted in the continuum, and which give rise to the additional tails in the spectrum. Recently, a new description of the EC spectrum of ^{163}Ho has been published [10], where the agreement between the experimental and the theoretical spectrum has been significantly improved.

Background suppression Considering that the expected number of events in the end-point region of the ^{163}Ho spectrum, which is the most important part for the determination of the electron neutrino mass, is very small, effective ways of background suppression need to be employed. Monte Carlo simulations are used in order to understand the radiation emitting contaminants in the used material, as well as to understand the effects of cosmogenic muon generated events in the region of interest. This information, combined with the material screening, is then used to obtain a background model that is then used in the analysis of the background spectrum [11].

3. Outlook

The first phase of the ECHo experiment, called the ECHo-1k phase, has been successfully completed with high-statistics measurements spanning over several months and leading to the acquisition of more than 10^8 ^{163}Ho events, which translates to an achievable sensitivity of $\mathrm{m}(\nu_e) < 20$ eV [1]. ECHo-1k detectors featured 32 MMC based detectors with two pixels each, ion-implanted with ^{163}Ho with the activity per pixel being roughly 1 Bq [12]. Analysis of the acquired data is currently ongoing.

The next phase of the ECHo experiment, the ECHo-100k phase, features a new detector design with a compact absorber geometry that will allow for a more efficient ion-implantation of the ^{163}Ho, while the individual MMC pixels have been optimised for an activity of about 10 Bq. In addition, ECHo-100k detectors will support multiplexed read-out which will allow for a large number of detectors ($\sim 10^5$) to be operated at the same time. Goal of this phase of the ECHo experiment is to acquire 10^{14} events over a three year period, which will improve the sensitivity to $\mathrm{m}(\nu_e) < 2$ eV. To achieve this, 15 ECHo-100k multiplexed read-out channels, each reading out 400 two-pixel detectors, will be used in order to read out 12000 MMC pixels.

PoS(EPS-HEP2021)211

References

[1] L. Gastaldo, K. Blaum, K. Chrysalidis, T. Day Goodacre, A. Domula, M. Door et al., *The electron capture in* ^{163}Ho *experiment - ECHo*, *The European Physical Journal Special Topics* **226** (2017) 1623.

[2] S. Eliseev, K. Blaum, M. Block, S. Chenmarev, H. Dorrer, Ch. E. Düllmann et al., *Direct Measurement of the Mass Difference of* ^{163}Ho *and* ^{163}Dy *Solves the Q-Value Puzzle for the Neutrino Mass Determination*, *Physical Review Letters* **115** (2015) 062501.

[3] A. De Rújula and M. Lusignoli, *Calorimetric measurements of* ^{163}*holmium decay as tools to determine the electron neutrino mass*, *Physics Letters B* **118** (1982) 429.

[4] S. Kempf, A. Fleischmann, L. Gastaldo and C. Enss, *Physics and applications of metallic magnetic calorimeters*, *Journal of Low Temperature Physics* **193** (2018) 365.

[5] H. Dorrer, K. Chrysalidis, T. Day Goodacre, Ch. E. Düllmann, K. Eberhardt, C. Enss et al., *Production, isolation and characterization of radiochemically pure* ^{163}Ho *samples for the ECHo-project*, *Radiochimica Acta* **106** (2018) 535.

[6] T. Kieck, H. Dorrer, Ch. E. Düllmann, V. Gadelshin, F. Schneider, K Wendt, *Highly efficient isotope separation and ion implantation of* ^{163}Ho *for the ECHo project*, *Nucl. Instrum. Meth. A* **945** (2019) 162602.

[7] F. Mantegazzini, S. Allgeier, A. Barth, C. Enss, A. Ferring-Siebert, A. Fleischmann et al., *Multichannel read-out for arrays of metallic magnetic calorimeters*, *Journal of Instrumentation* **16** (2021) P08003.

[8] M. Wegner, N. Karcher, O. Krömer, D. Richter, F. Ahrens, O. Sander et al., *Microwave SQUID Multiplexing of Metallic Magnetic Calorimeters: Status of Multiplexer Performance and Room-Temperature Readout Electronics Development*, *Journal of Low Temperature Physics* **193** (2018) 462.

[9] J. Repp, C. Böhm, J.R. Crespo López-Urrutia, A. Dörr, S. Eliseev, S. George et al., *PENTATRAP: a novel cryogenic multi-Penning-trap experiment for high-precision mass measurements on highly charged ions*, *Applied Physics B* **107** (2012) 983.

[10] M. Braß and M.W. Haverkort, *Ab initio calculation of the electron capture spectrum of* ^{163}Ho*: Auger–Meitner decay into continuum states*, *New J. Phys.* **22** (2020) 093018.

[11] A. Göggelmann, J. Jochum, L. Gastaldo, C. Velte and F. Mantegazzini, *Study of muon-induced background in MMC detector arrays for the ECHo experiment*, *The European Physical Journal C* **81** (2021) 363.

[12] F. Mantegazzini, A. Barth, H. Dorrer, Ch. E. Düllmannd, C. Enss, A. Fleischmann et al., *Metallic magnetic calorimeter arrays for the first phase of the echo experiment*, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **1030** (2022) 166406.