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# Update on $^{163}$Ho based experiments for the determination of the electron neutrino mass

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The determination of the absolute neutrino mass $m_\nu$ is still an open question in particle physics. Currently, the most stringent limit of $m_{\bar{\nu}_e} < 2\,\mathrm{eV}$ was achieved for the electron anti–neutrino mass from the measurement of the endpoint of the decay of $^3$H. Novel experimental approaches exploring the endpoint of the $\beta^-$ decay of $^3$H or the electron capture of $^{163}$Ho offer great potential to reach a sub–eV sensitivity on $m_{\nu_e}$.

We present the three experiments ECHo, HOLMES and NuMECS which are going to investigate the neutrino mass with arrays of cryogenic calorimetric detectors measuring the endpoint of the $^{163}$Ho spectrum. The experiments differ by the used sensors, the production of the $^{163}$Ho and its implantation into the absorber:

The ECHo experiment and HOLMES are using neutron irradiation of $^{162}$Er at a nuclear reactor to produce $^{163}$Ho, while NuMECS uses the $^{nat}\mathrm{Dy}(p,xn)^{163}\mathrm{Ho}$ reaction at an accelerator. ECHo and HOLMES are going to implant the $^{163}$Ho into the absorber via ion–implantation, NuMECS deposits $^{163}$Ho in an aqueous solution into nanoporous gold. Metallic magnetic microcalorimeters are used for the detector read–out by ECHo, transition edge sensors are used by the HOLMES and the NuMECS collaboration. ECHo is currently operating an improved detector prototype for the ECHo–1k demonstrator phase, where an array of $\sim 100$ detectors with a total activity of $^{163}$Ho of 1 kBq will be operated for one year. HOLMES is testing and optimizing its $^{163}$Ho ion implanter for the detector production. The NuMECS collaboration demonstrated the entire process for $^{163}$Ho production and purification and its incorporation into TES microcalorimeters.

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## 1. Introduction

Since the discovery of neutrino flavor oscillations the neutrino is established as a massive particle. Neutrino oscillation experiments were able to determine the three mixing angles and the squared mass–splittings, $\Delta m^2_{12}$ and $\Delta m^2_{23}$, however these experiments cannot determine the absolute mass–scale. The absolute mass–scale can be investigated with the following methods: (1) Analysis of the formation of the large scale structures in the universe[1], (2) time–of–flight measurement of neutrinos emitted in supernova explosions[2], (3) detection of the neutrino–less double–beta decay and the determination of the half–live of this process with the exact knowledge of the matrix elements of the $0\nu2\beta^-$–decay[3, 4], and (4) precise measurement of the endpoint spectrum of $\beta$–decays and electron captures(EC)[5].

While each of the methods has its advantages, the direct measurement of the endpoint of a $\beta$ decay or EC depends least on unknown systematic effects. Since a real electron neutrino is emitted in the decay, the measured mass is given by the incoherent sum of the mass–eigenstates, $m^2_{\nu_e} = \sum_i |\mathcal{U}_{ei}|^2 m^2_i$. The most stringent limit on the mass of the anti–neutrino, $m_{\bar{\nu}_e} < 2\,\mathrm{eV}$, was derived by the Mainz and Troitsk neutrino mass experiments using an electrostatic spectrometer to measure the emitted electrons of the $^3$H $\beta^-$–decay[6, 7, 8]. The KATRIN experiment is the successor of these experiments and aims for a tenfold improved sensitivity of 200 meV[5, 9]. Since further improvements in sensitivity are limited by the size of the electrostatic spectrometer, future experiments have to use novel approaches for a more sensitive measurement of the endpoint region. Cryogenic calorimetric measurement is a promising approach which may reach an improved sensitivity below $\sim 100\,\mathrm{meV}$ in the future. An interesting isotope for these measurements is $^{163}$Ho, which decays via EC with a half–life of $\tau_{1/2} = 4570 \pm 25\,\mathrm{a}$ and has the lowest known $Q_{EC}$ value in nature, which maximizes the sensitivity for the measurement of $m_{\nu_e}$[10, 11]. Recently, the value of $Q_{EC} = 2833 \pm 30 \pm 15\,\mathrm{eV}$ was obtained by a direct measurement of the atomic mass difference of $^{163}$Ho and $^{163}$Dy with the Penning trap mass spectrometer SHIPTRAP[12].

The energy spectrum of an electron capture process is described by Eqn.1.1, the first term describes the phase space of the reaction and the second term contains the capture probabilities of electrons from the atomic shells $H$, the spatial overlap of the electron wave–function $\phi_H$ with the nucleus and the exchange and overlap corrections $B_H$. Fig.1 shows the EC spectrum of $^{163}$Ho. The set of parameters and further atomic shell corrections to the spectrum can be found in refs.[13, 14].

$$\frac{dN}{dE} = const\,(Q_{EC}-E)^2 \sqrt{1-\frac{\sum_i |\mathcal{U}_{ei}|^2 m_i^2}{(Q_{EC}-E)^2}} \sum_H B_H \phi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E-E_H)^2 + \frac{\Gamma_H^2}{4}} \tag{1.1}$$

Presently, the most precise devices available for the measurements in the $^{163}$Ho EC endpoint energy region are low temperature micro–calorimeters[15]. The temperature rise in a calorimeter is connected to the energy deposition by the heat capacity of the detector via $\Delta T = \Delta E/C$ which is in turn read out with a suitable sensor. For the measurement of the $^{163}$Ho decay in particular, cryogenic calorimeters offers two advantages; cryogenic calorimeters have shown a superb energy resolution for energies of a few keV and the $^{163}$Ho source can be fully embedded into the absorber which ensures that all decays are registered with their total detectable energy. The total activity $A_{\mathrm{Ho}}$ of $^{163}$Ho must be limited in such a setup, because the indiscriminable pile–up background is

$\sim A_{\mathrm{Ho}}\tau_{\mathrm{rise}}$, the rate of accidental coincident events within the rise–time of the signal $\tau_{\mathrm{rise}}$.

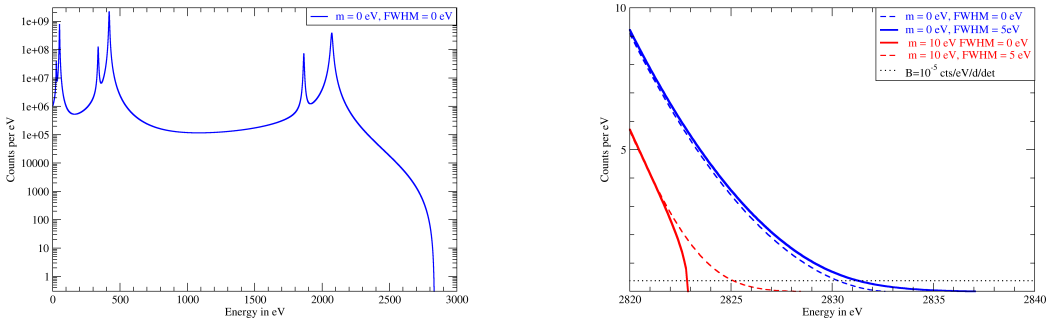


**Figure 1:** The left figure shows the energy spectrum for $3.2 \times 10^{10}$ decays of $^{163}$Ho. The right figure shows the spectrum in the endpoint region near 2.833 keV for $m_\nu = 0\,\mathrm{eV}$ (blue) and $m_\nu = 10\,\mathrm{eV}$ (red) with the two energy resolutions of $E_{\mathrm{FWHM}} = 0\,\mathrm{eV}$ and $E_{\mathrm{FWHM}} = 5\,\mathrm{eV}$ as dashed colored graphs. The black dashed line shows the contribution of a background of $10^{-5}$ events/eV/day/detector within one year of measuring time and 100 detectors as a guideline.

## 2. $^{163}$Ho Experiments

Three collaborations are going to the investigate $m_{\nu_e}$ via the cryogenic calorimetric measurement of the $^{163}$Ho spectrum: ECHo[16, 17], HOLMES[18] and NuMECS[19]. The experimental challenges for a $^{163}$Ho experiment are: (1) Production and preparation of a clean sample of $^{163}$Ho, (2) implantation of the $^{163}$Ho source, (3) single detector optimization and array engineering, and (4) multiplexed read–out of the detector arrays.

The detectors are loaded with $^{163}$Ho, which is produced either by neutron irradiation of enriched $^{162}$Er at a reactor (ECHo,HOLMES) or via proton irradiation of Dysprosium at an accelerator (NuMECS)[20]. Neutron irradiation provides a much higher yield of $^{163}$Ho than proton irradiation but at the cost of higher co–production of other radioactive isotopes, like the dangerous $^{166m}$Ho. After chemical purification of the sample, $^{163}$Ho must be separated from other isotopes by mass separation[21, 22]. The embedding of $^{163}$Ho into the absorber is done by ion implanters (ECHo, HOLMES) or by absorption of an aqueous solution on nanoporous gold (NuMECS).

ECHo uses metallic magnetic calorimeters (MMCs) made of an Au absorber loaded with $^{163}$Ho and Au:Er energy sensors, while HOLMES and NuMECS investigate the use of MoCu transition edge sensors(TES). HOLMES uses Bi absorbers and NuMECS uses Au absorbers.

MMCs are energy dispersive calorimetric detectors offering fast signal rise times in the order of 100 ns operated at cryogenic temperatures of a few tens of mK. A MMC consists of a particle absorber connected to a temperature sensor which weakly connected to the thermal bath. The temperature sensor is made from a paramagnetic alloy with a temperature dependent magnetization located in a weak magnetic field. An energy deposition in the absorber leads to a temperature rise in the system which leads to the change of magnetization in the sensor, which is read out by a

superconducting quantum interferometer device (SQUID). Another realization of the sensor of a cryogenic micro–calorimeter is a TES[15], which is a film operated in the transition between its superconducting and its normal phase. A small increase in the temperature in the absorber results in a large change of the resistivity $R$ of the superconducting film. The detector arrays in all three experiments are foreseen to be read out using the microwave multiplexing scheme[23].

ECHo–1k is the current phase of the ECHo experiment, which is performed using an large array of MMCs[24]. The array of detectors is read out with a microwave multiplexing scheme[25]. It involves a total activity of 1 kBq of high purity $^{163}$Ho in $\sim$ 100 MMCs which will be located on two chips housing 64 detectors each loaded with 10 Bq. The low activity per single detector is chosen to minimize the unavoidable pile–up background in the endpoint region due to accidentally coincident $^{163}$Ho decays within the rise–time of the signal. The measurement is scheduled to start in 2016, collecting about $10^{10}$ ECs of $^{163}$Ho within one year. With an energy resolution of $\Delta E_{FWHM} = 5$ eV, a sensitivity on $m_{\nu_e} \simeq 10\,\mathrm{eV/c^2}$ (90 C.L.) is attainable. After the successful completion of the ECHo–1k demonstrator phase, a measurement phase with sensitivity in the sub eV range on $m_{\nu_e}$ is planned. This phase will employ a total activity of 1 MBq of $^{163}$Ho in $10^4$–$10^5$ detectors with an improved energy resolution of 2 eV.

A new detector chip for ECHo–1k was recently produced and is now operated successfully. In comparison to the first detector prototype, the following improvements have been achieved: (1) The activity per detector is increased to 0.1 Bq, (2) due to a refined ion implantation process at ISOLDE–CERN, co–implants of $^{144}$Pm are not present, and (3) the redesigned coupling between the absorber and the sensor prevents energy dissipation seen in the peaks of the $^{163}$Ho spectrum before[26].

The HOLMES experiment planned to operate 1000 detectors made from an Bi absorber each loaded with 300 Bq of $^{163}$Ho and read out via a MoCu TES for three years, however the recent measurement of $Q_{EC} = 2833$ eV requires a reconfiguration of the setup. It was planned to implant the first detectors with $^{163}$Ho in 2015.

NuMECS uses MoCu TES sensors with Au absorbers. The entire process for $^{163}$Ho production and purification and the incorporation into TES microcalorimeters was demonstrated with the measurement of the $^{163}$Ho spectrum with a prototype detector loaded with 0.1 Bq of $^{163}$Ho.

## 3. Conclusion

Cryogenic calorimetric measurement of the $^{163}$Ho EC spectrum offers a novel approach to measure the neutrino mass with sub eV sensitivity. Presently, three experiments are researching the use of detector arrays for this purpose: ECHo, HOLMES and NuMECS. All experiments are making good progress towards the operation of a large detector array. ECHo is now preparing ECHo–1k, a demonstrator phase of 100 MMCs which is going to start taking data in 2016. After the successful completion of the ECHo–1k phase, the design will be upscaled to ECHo–1M with sub eV sensitivity on $m_{\nu_e}$. HOLMES is testing and optimizing its $^{163}$Ho ion implanter for the detector production. NuMECS collaboration demonstrated the entire process for $^{163}$Ho production and purification and its incorporation into a TES microcalorimeter.

| | ECHo | Holmes | NuMECS |
|---|---|---|---|
| Detector technique | MMC (Au:Er) | TES (MoCu) | TES (MoCu) |
| Activity per detector goal(shown) | 10 Bq(0.1 Bq) | 300 Bq | 100 Bq($\sim$ 0.1 Bq) |
| $E_{\mathrm{FWHM}}$ goal(shown) | 2 eV(7.6 eV) | $\sim$ 1 eV | $\sim$ 1 eV($\sim$ 6 eV) |
| $\tau_{\mathrm{rise}}$ goal(shown) | $\sim$ 100 ns(130 ns) | $\sim 1\,\mu$s | $\sim 1\,\mu$s |
| Multiplexing scheme | microwave | microwave | microwave |
| $^{163}$Ho production | $^{162}$Er(n,$\gamma$)$^{163}$Er $^{163}$Er($\beta^-$)$^{163}$Ho | Er(n,$^{162}\gamma$)$^{163}$Er $^{163}$Er($\beta^-$)$^{163}$Ho | $^{nat}$Dy(p,xn)$^{163}$Ho |
| $^{163}$Ho deposition in the detectors | shown | not shown | shown |

**Table 1:** Overview of the technical parameters of the sub eV sensitivity phases of the ECHo, Holmes and NuMECS $^{163}$Ho experiments.

## 4. Acknowledgments

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## References

[1] J. Lesgourgues and S. Pastor, *Neutrino Cosmology and Planck*, *New J. Phys. 16*, 065002 (2014) [arXiv:1404.1740v1]

[2] G. Pagliaroli *et al.*, *Neutrino Mass Bound in the Standard Scenario for Supernova Electronic Antineutrino Emission*, *Astropart. Phys. 33*, 287 (2010) [arXiv:1002.3349v1]

[3] W. Maneschg, *Review of neutrinoless double beta decay experiments: Present Status and Future*, in proceedings of *The 13$^{th}$ International Workshop on Tau Lepton Physics (Tau2014)*, *Nucl. Part. Phys. Proc. 260*, 188 (2015)

[4] F.T. Avignone III *et al.*, *Double Beta Decay, Majorana Neutrinos and Neutrino Mass*, *Rev. Mod. Phys. 80*, 481 (2008) [arXiv:0708.1033].

[5] G. Drexlin *et al.*, *Current Direct Neutrino Mass Experiments*, *Adv. High Energy. Phys.*, 293986 (2013) [arXiv:1307.0101v1]

[6] K.A. Olive et al., *Particle Data Book Chin. Phys. C 38*, 090001 (2014) [http://pdg.lbl.gov]

[7] C. Kraus *et al.*, *Final Results from Phase II of the Mainz Neutrino Mass Search in Tritium $\beta$ Decay*, *Eur. Phys. J. C 40*, 447 (2005) [arXiv:herp-ex/0412056v2]

[8] V.N. Aseev *et al.*, *An Upper Limit on Electron Antineutrino Mass from Troitsk Experiment*, *Phys. Rev. D 84*, 112003 (2011) [arXiv:1108.5034v3]

[9] K. Valerius, *Status of the Karlsruhe Tritium Neutrino Experiment KATRIN*, in proceedings of *Particles and Nuclei International Conference 2014 (PANIC2014)*, *Proceedings,* 20$^{th}$ *International Conference on Particles and Nuclei (PANIC2014)*, DESY, Hamburg 2015 DOI:http://dx.doi.org/10.3204/DESY-PROC-2014-04/80

[10] A. de Rujula and M.Lusignoli, *Calorimetric Measurements of $^{163}$Ho Decay as Tools to Determine the Electron Neutrino Mass* , *Phys. Lett. B 118* (1982) 429

[11] A. de Rujula, *Two Old Ways to Measure the Electron–Neutrino Mass*, [arXiv:1305.4857v1]

[12] S. Eliseev *et al.*, *Direct Measurement of the Mass Difference of $^{163}$Ho and $^{163}$Dy Solves the Q–Value Puzzle for the Neutrino Mass Determination*, *Phys. Rev. Lett 115*, 062501 (2015)

[13] A. Faessler and F. Simkovic, *Improved Description of One– and Two–Hole Excitations after Electron Capture in $^{163}$Ho and the Determination of the Neutrino Mass*, *Phys. Rev. C 91*, 045505 (2015) [arXiv:1501.04338v2]

[14] A. Faessler *et al.*, *Determination of the Neutrino Mass by Electron Capture in 163 Holmium and the Role of Three–Hole States in 163 Dysprosium*, *Phys. Rev. C 91*, 064302 (2015) [arXiv:1503.02282v2]

[15] C. Enss, *Cryogenic Particle Detection*, *Top. in Appl. Phys. 99*, Springer, New York 2005

[16] L. Gastaldo *et al.*, *The Electron Capture $^{163}$Ho Experiment ECHo*, *J. Low Temp. Phys. 176*, 876 (2014)

[17] *ECHo Collaboration*, *The Electron Capture $^{163}$Ho Experiment*, to be submitted

[18] B. Alpert *et al.*, *HOLMES–The Electron Capture Decay of $^{163}$Ho to Measure the Electron Neutrino Mass with sub–eV sensitivity*, *Eur. Phys. J. C 75*, 112 (2015) [arXiv:1412.5060v3]

[19] M.P. Croce *et al.*, *Development of Holmium-163 Electron–Capture Spectroscopy with Transition Edge Sensors*, *Los Alamos National Laboratory Report* LA–UR–15–27688 (2015) [arXiV:1510.03874v1]

[20] J.W. Engle *et al.*, *Evalution of $^{163}$Ho Production Option for Neutrino Mass Measurements with Microcalorimeter Detectors*, *Nucl. Instr. Meth. Phys. Res. B 311*, 131 (2013)

[21] F. Schneider *et al.*, *Preparatory Studies for a High–Precision Penning–Trap Measurement of the $^{163}$Ho Electron Capture Q–Value*, *Eur. Phys. J. A 51*, 89 (2015)

[22] F.Schneider *et al.*, *Resonance Ionization of Holmium for Mass Separation and Implantation into MMCs*, submitted to *Nucl. Instr. Meth. Phys. Res. B* (2015)

[23] J.A.B. Mates *et al.*, *Demonstration of a Multiplexer of Dissipationless Superconducting Quantum Interference Devices*, *Appl. Phys. Lett. 92*, 023514 (2008)

[24] A. Fleischmann *et al.*, *Metallic Magnetic Calorimeters*, in proceedings of *The Thirteenth International Workshop on Low Temperature Detectors (LTD13)*, *AIP Conf. Proc. 1185*, 571 (2009)

[25] S. Kempf *et al.*, *Multiplexed Readout of MMC Detector Arrays Using Non–Hysteretic RF–SQUIDs*, *J. Low Temp. Phys. 176*, 426 (2014)

[26] C.Hassel *et al.*, submitted to *J. Low Temp. Phys.* (2015)