Neutrino mass measurement with Ho

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HOLMES collaboration:
INFN Ge, INFN Mib, INFN LNGS, Unimib, NIST, Lisbona, PSI, ILL

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- ^{163}Ho Electron capture and Neutrino mass measurement
- Neutrino mass Experiment with ^{163}Ho
  - ECHo
  - HOLMES
  - LALN
- Conclusion

Kinematics of weak decays

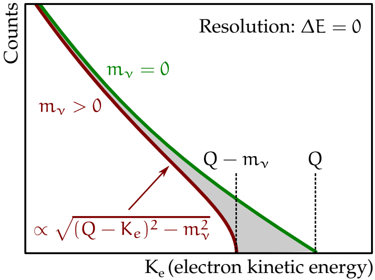
- nuclear decay involving neutrinos
- only energy and momentum conservation
- no further assumptions

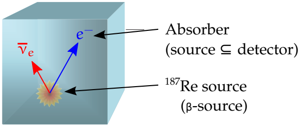
General experiment requirements:

- high statistics at the beta spectrum end-point
  - low E_0 β decaying isotopes: ^{187}Re, ^{163}Ho
- high energy resolution ΔE

Calorimeters: source $\subseteq$ detector:

- the β source is embedded in the detector
- ideally they measure all the energy E released in the decay except for the ν_e energy
- calorimeters measure the entire spectrum at once





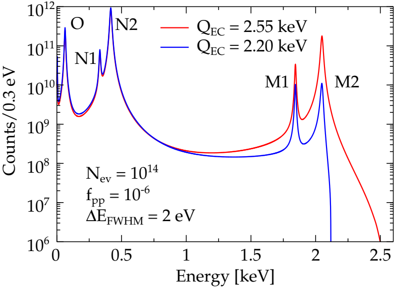
$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \overline{\nu}_e$$

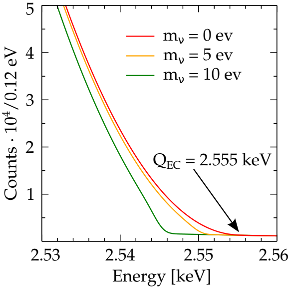
The electron capture of the ^{163}Ho

An interesting isotope suitable for the neutrino mass experiment could be the ^{163}Ho.

$$^{163}Ho + e^- \rightarrow\ ^{163}Dy^* + \nu_e(E_c) \quad \text{electron capture from shell} > M1$$

proposed by A. De Rujula e M. Lusignoli in 1982 [1, 2]





$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q_{EC} - E_c)\sqrt{(Q_{EC} - E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4},$$

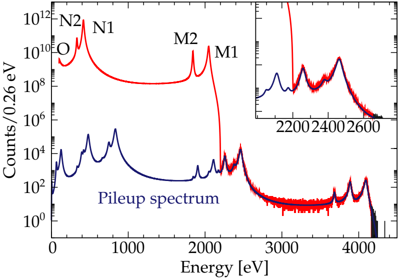
- Series of lines at the ionization energies E_i of the captured electrons
- The peaks have Breit-Wigner shapes (width Γ_i of a few eV)
- End-point shaped by $\sqrt{(Q - E_e)^2 - m_\nu^2}$ (the same of the β-decay)
- Self calibrating spectrum

Calorimetric measurement of EC spectrum

- Calorimetric measurement of Dy atomic de-excitations (mostly non-radiative):
  - ⇒ measurement of the entire energy released except the ν energy
- The rate at end-point may be as high as for ^{187}Re but depends on Q_{EC}:
- Q_{EC} and atomic de-excitation spectrum poorly known:
  - ⇒ Measured: $Q_{EC} = (2.2 \div 2.8)$ keV
  - ⇒ Recommended: $Q_{EC} = 2.555$ keV [3, 4])
- $\tau_{1/2} \simeq 4570$ years ⇒ high specific activity:
  - ⇒ Holmium detector not needed
  - ⇒ ^{163}Ho can be implanted in any suitable microcalorimeter absorber
- Complex pile-up spectrum
- No high statistics and clean calorimetric measurement so far

^{163}Ho: pile-up spectra

Theoretical spectrum measured
by simulated toy experiments



$$S(E_c) = \left[N_{ev}(N_{EC}(E_c, m_\nu) + f_{pp} \times N_{EC}(E_c, 0) \otimes N_{EC}(E_c, 0)) + B(E_c)\right] \otimes R_{\Delta E}(E_c)$$

N_{ev}	: total number of events
$N_{EC}(E_c, m_\nu)$	: ^{163}Ho spectrum
$B(E)$	: background energy spectrum
$R_{\Delta E}(E_c)$	: detector energy response function
f_{pp}	: fraction of pile-up events
$R_{\Delta E}(E_c)$	: detector energy response function
ΔE	intervall of energy

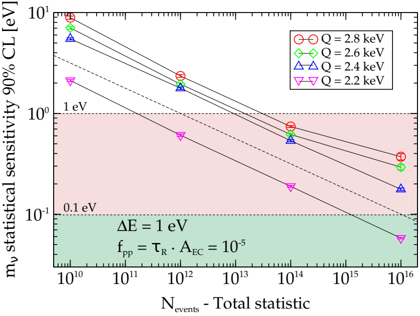
more details in A. Nucciotti, submitted to EPJC, arXiv:1405.5060 [5]

- Pulse pile-up occurs when multiple events arrive within the temporal resolving time of the detector
- Unresolved pile-up produces background close to the end-point
- The ^{163}Ho pile-up events spectrum is quite complex and presents a number of peaks right at the end-point of the decay spectrum
- To resolve pile-up:
  - Detector with fast signal rise-time τ_{rise}
  - Pile-up recognition algorithm

^{163}Ho: statistical sensitivity

Montecarlo Simulation

- The approach is a replica of the one outlined in [6] for beta decay calorimetric experiments:
  - large number of simulated spectra that would be measured by a large number of experiments carried out in a given configuration
  - the spectra are analyzed as the real ones
  - the statistical is sensitivity deduced from the distribution of the obtained m_ν^2



A. Nucciotti, submitted to EPJC, arXiv:1405.5060 [5]

Requirements:

- High energy resolution ($\simeq$ 1 eV)
- Fast response detectors ($\simeq$ 1 μs) to avoid pile-up events
- Multiplexable detectors array ($\simeq$ 1000)

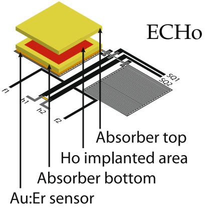
$\Downarrow$

TESs, MMCs, MKIDs, ...

Holmium LTD experiment status

^{163}Ho seems to be better than ^{187}Re:

- higher specific activity ⇒ Holmium detector not needed
- self calibrating ⇒ better systematics control
- Q_{EC} and atomic de-excitation spectrum poorly known
- complex pile-up spectrum
- in case of higher Q ⇒ less sensitive

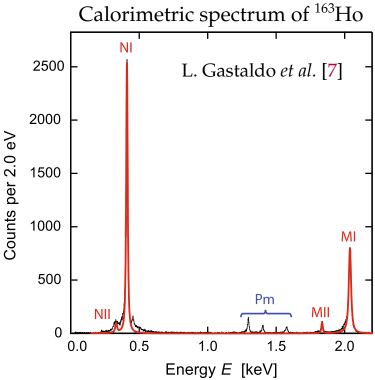


LTD projects with ^{163}Ho:

- ECHo, MMC detectors (Heidelberg)
- HOLMES, TES detectors (Milano, Genova, LNGS, NIST)
- Los Alamos Nat. Lab., ...

Common technical challenges:

- Clean ^{163}Ho production
- ^{163}Ho incorporation
- Large channel number ⇒ high speed MUX
- Data handling (processing, storage, ...)



ECHo

First detector prototype

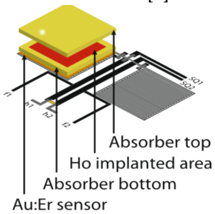
- low temperature metallic magnetic calorimeters
- embedding of 163Ho source
  ⇒ ion implantation @ ISOLDE-CERN
- about 0.01 Bq per pixel
- two pixels have been simultaneusly measured

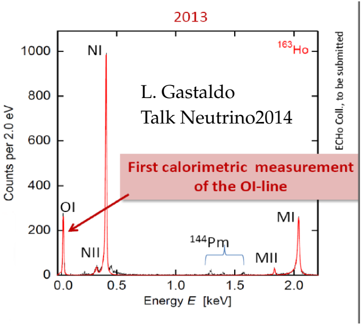
Calorimetric spectrum

- rise time ≈ 130 ns
- $\Delta E_{FWHM} = 7.6$eV @6 keV
- non-linearity <1% @ 6 KeV
- presentely most precise ^{163}Ho spectrum

	E_H lit.	E_H exp	Γ_H lit	Γ_H exp
MI	2.047	2.040	13.2	13.7
MII	1.845	1.836	6.0	7.2
NI	0.420	0.411	5.4	5.3
NII	0.340	0.333	5.3	8.0
OI	0.050	0.048	5.0	4.3

L. Gastaldo *et al.* [7]





P.C.O Ranitzsch et al [8] L. Gastaldo et al [9]

ECHo: ^{163}Ho production and purification

^{163}Ho source - (n,γ) - reaction on ^{162}Er

- June 2012 : one irradiation at BER II Research Rector Berlin
- Summer 2013: Two irradiations at ILL
  - treatment of Er prior to irradiation: all elements lighter than Er separated
  - treatment of Er after irradiation: all elements heavier than Ho are separated

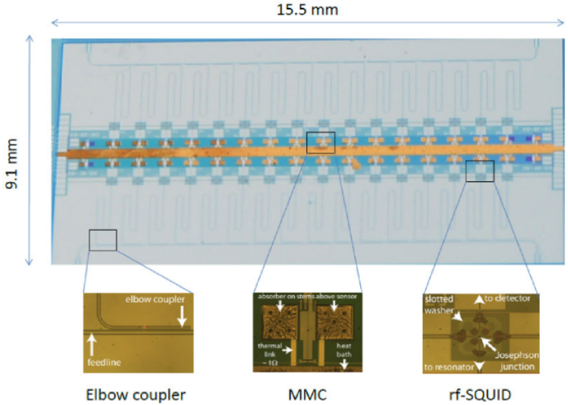
^{163}Ho source purification

- Radionuclides contained in the samples: ^{163}Ho and ^{166m}Ho
- Mass separation/ion implantation
  - Separation at CERN/ISOLDE: Proposal accepted, will run in 2014
  - Use of the RISIKO mass-separator at Uni-Mainz, Summer 2014

ECHo:next step

Next step

- Microvawe multiplexing technique
- 2 chips $\rightarrow$ 64 pixels
- ΔE_{FWHM}=5eV, 10 Bq/pixel
- statistical sensitivity as low as 10 eV
- prove scalability



HOLMES (ERC-Advanced Grant n. 340321)

Goal

- Neutrino mass measurement:
  $\Rightarrow$ m_ν statistical sensitivity as low as 0.4 eV
- Demonstrate technique potential and its scalability (Megapixel experiment)
- assess EC Q-value
- assess systematic errors

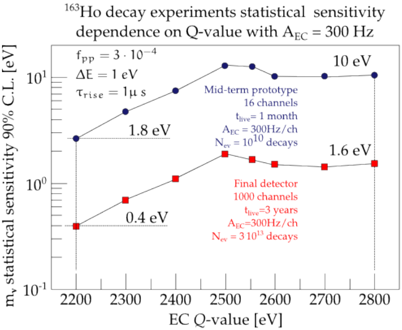
Baseline

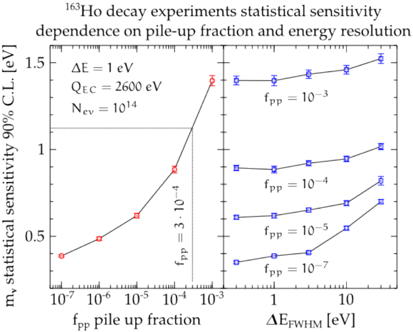
- Transition Edge Sensors (TES) with ^{163}Ho implanted Bi:Au absorbers
- $6.5 \cdot 10^{13}$ nuclei per detector $\Rightarrow$ 300 dec/s
- $\Delta E \simeq 1$ eV and $\tau_{rise} \simeq 1$ μs
- 16 channel demonstrator data taking starting from the second half of 2016
- 1000 channel final array from second half of 2017
  - $6.5 \cdot 10^{16}$ ^{163}Ho nuclei $\Rightarrow$ 18 μg
  - $3 \cdot 10^{13}$ events in 3 years

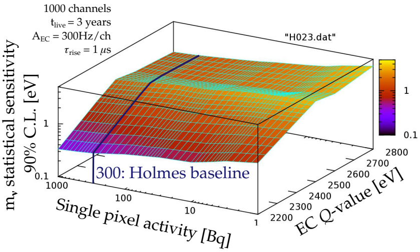
HOLMES tasks

- ^{163}Ho isotope production and ^{163}Ho isotope embedding in detector
- Single TES optimization and testing
- TES array design, engineering and testing
- SQUID read-out and multiplexing optimization and testing (rf-SQUID)
- Real time and offline signal processing and analysis (trigger, OF filter, pile-up rejection)

HOLMES Sensitivity







- The experimental sensitivity is directly related to $f_{pp} = \tau_{rise} \cdot A_{EC}$ (pile-up)
- The impact of the energy resolution is relatively smaller than that of pile-up
- In presence of a high level of pile-up, the experiment is relatively less sensitive to the energy resolution
- A constant background b is negligible if it is much smaller than the pile-up spectrum

^{163}Ho production and embedding

Production of ^{163}Ho: neutron activation of enriched ^{162}Er

$$^{162}Er(n,\gamma)^{163}Er \rightarrow {}^{163}Ho + \nu_e \quad , \quad \sigma_{therm} = 20b \quad , \quad \tau^{1/2}_{EC} = 75 \text{ min}$$

- requires ^{162}Er enrichment and oxide chemical form (Er_2O_3)
- high yield (not all cross sections are measured)
- unavoidable ^{166m}Ho: $^{165}Ho(n,\gamma)^{166m}Ho$ ($\beta,_{12} = 1200$ y) from Ho contaminations or ^{164}Er(n,γ)^{165}Er
- unavoidable ^{164}Ho: fast neutron activation $^{163}Ho(n,\gamma)^{164}Ho$
- nuclear reactor at the Institut Laue Langevin (ILL) in Grenoble

Thermoreduction to obtain the metallic Ho target for implantation:

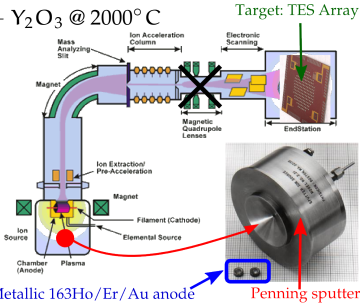
$$Ho_2O_3 + 2Y(met) \rightarrow 2Ho(met) + Y_2O_3 \ @\ 2000^\circ C$$

^{163}Ho sepation from Dy, Er, Tm and Tr

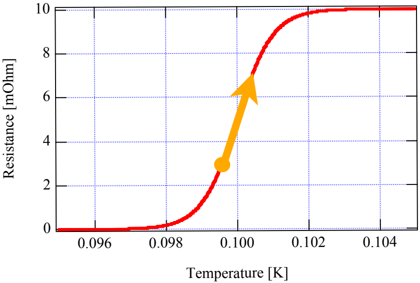
- radiochemistry (before and/or after irradiation) in collaboration with PSI
- magnetic mass separation

^{163}Ho embedding in detector absorber

- implantation + magnetic separation
- Au film seposition for full containment



Transition Edge Sensor (TES): cryogenic particle detector that exploits the strongly temperature-dependent resistance of the superconducting phase transition.

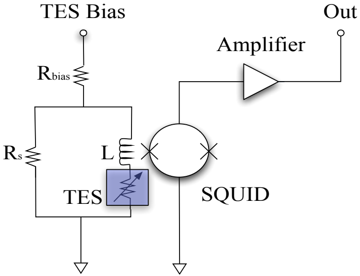


Why TES?

- Widely used by the X-ray astrophysics community over the past twenty years
- Excellent energy resolution:

$$\Delta E_{FWHM} = \begin{cases} 1.26\,eV \,@\, 1.5\ keV \\ 1.58\,eV \,@\, 6\ keV \\ 1.94\,eV \,@\, 8\ keV \end{cases}$$

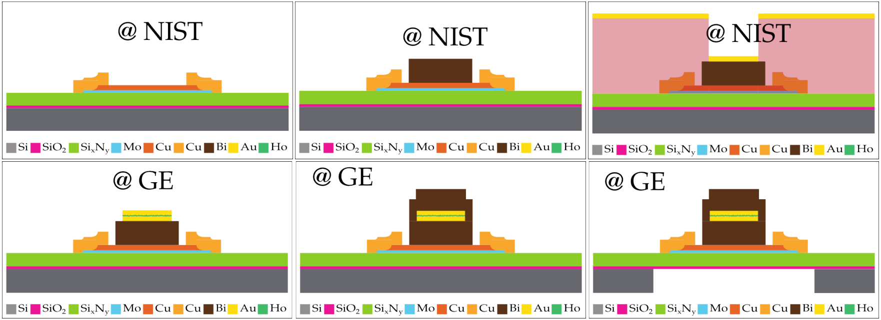
- Low impedence
- Large Array and multiplexing (TDM, CDM, FDM, μmux)
- Tunable critical temperature T_C exploiting the proximity effect [10] ⇒ Mo:Au or Mo:Cu proximity TES ($T_C \simeq 100$ mK)



TES production

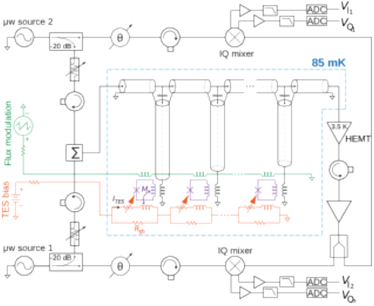
Transition Edge Sensor (TES): MoCu bilayers $\rightarrow T_c \approx 100$mK

- microcalorimeters with electro-thermal feedback
- 3 µm thick Bi absorber with 163Ho/Au encapsulating for full absorbtion
- source: thin electrodeposited Au encapsulating implanted ^{163}Ho
- TES fabricated by subcontractor (NIST, Boulder, CO, USA)
- ^{163}Ho implantation and Si_2N_3 membrane release at Genova



rf-SQUID read-out and ROACH2

Microwave SQUID multiplexing (μMux) is a read-out technique that combines the proven sensitivity of TESs and the scalable multiplexing power found in KIDs. It uses radio-frequency rf-SQUIDs coupled to high quality-factor microwave resonators.



rf-SQUID read-out

- DC biased TES
- SQUID coupled with TES and a resonator circuit
- Microwave rf-SQUID read out with flux ramp modulation (common flux line is inductively coupled to all the SQUIDs)
- Signal reconstructed by homodyne detection and demodulation

ROACH2-based Software Defined Radio

- Xilinx FPGA based digital data processing
- frequency comb generation (up to ≈60 in 0-550 MHz)
- GHz band up/down conversion (5-5.5 GHz)
- homodyne detection: IQ signal de-multiplexing
- signal channelizing and rf-SQUID signal de-modulation
- real time signal processing → 140TB in 3 years

IF Board

ADC/DAC Board

ROACH2

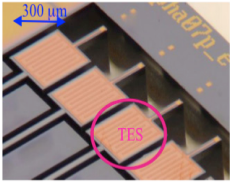
LANL

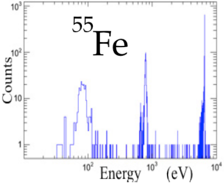
^{163}Ho source

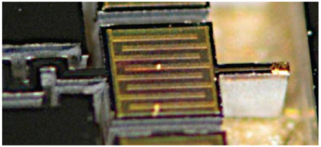
- Proton irradiation of natural Dy at high-current LANL proton accelerator
- Separation of ≈500 µg di Ho from 110 mg di Dy
  J.W. Engle *et al.* [11]

Detector

- Transition Edge Sensor: MoCu superconducting films on solid silicon







- Feasibility demonstrated with embedding ^{55}Fe source
- Recent measurements show ΔE ≈ 7.5 eV FWHM
- Testing several methods of incorporating Ho into absorbers

from L. Gastaldo - talk at Neutrino2014 Conference

Conclusion

- The measurement of the end point of nuclear beta or electron capture (EC) decays spectra is the only model-independent
- The goal of the next generation experiments is the sub-eV neutrino mass sensitivity
- ECHo has acquired the most precise ^{163}Ho spectrum so far
- The ECHo next step is to achieve a sensitivity on neutrino mass of the order of 10 eV
- The HOLMES experiment will performe a direct measurement of the neutrino mass by using microcalorimenter with ^{163}Ho-implanted absorber.
- The Goals of the HOLMES experiment are:
  - assess EC Q-value of the ^{163}Ho
  - assess systematic errors
  - achieve a statistical sensitivity as low as 0.4 eV
  - prove technique potential and its scalability (Megapixel experiment)

References

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