Probing the neutrino mass with calorimetric electron capture spectroscopy

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HOLMES

The HOLMES proejct

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on behalf of the HOLMES collaboration

University and INFN of Milano Bicocca

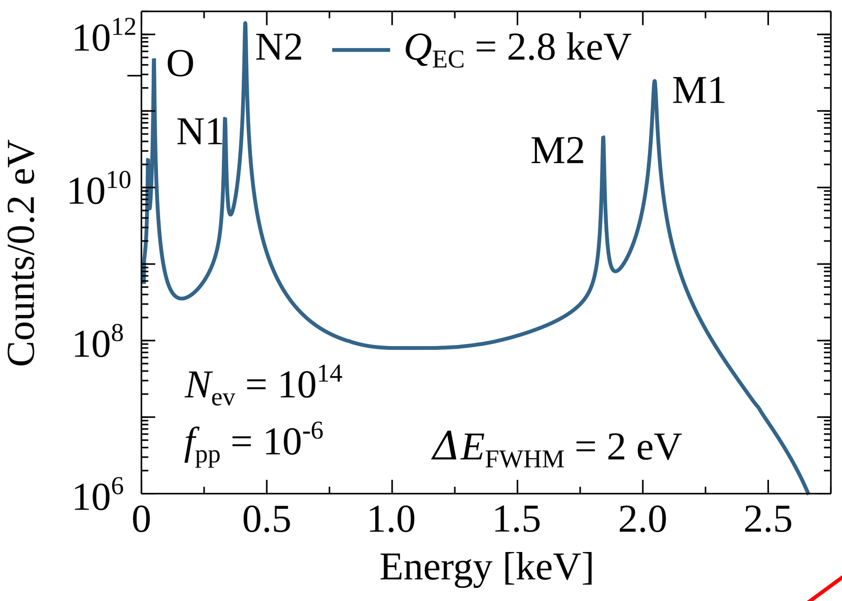
Overview

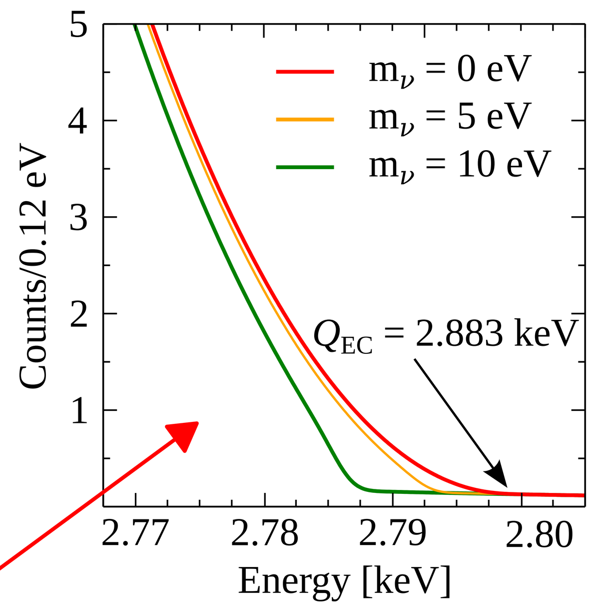
HOLMES is an experiment with the aim to directly measure the neutrino mass. HOLMES will perform a calorimetric measurement of the energy released in the Electron Capture decay of the artificial isotope ^{163}Ho. The most suitable detectors for this type of measurement are low temperature thermal detectors. HOLMES will deploy 1000 detectors of low temperature microcalorimeters with implanted ^{163}Ho nuclei with the aim to extract information on neutrino mass with a sensitivity below 2 eV. As soon as the embedding technique will be optimized the first sub-arrays will provide useful data about the EC decay of ^{163}Ho together with a first limit on neutrino mass.

B. Alpert et al. Eur. Phys. J. C75 (2015) 112

^{163}Ho Electron Capture Decay

- **Electron capture from shell ≥ M1** ⟶ $^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e(E_c)$
- Calorimetric measurement of Dy atomic de-excitations ⇒ measurement of the entire energy released except the ν energy; *A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429.*
- Rate at end-point and ν mass sensitivity depend on Q_{EC} ⇒ Measured with Penning trap: Q_{EC} = 2.833 keV; *S. Eliseev et al, Phys. Rev. Lett. 115 (2015) 062501*
- High specific activity ⇒ $\tau_{1/2}$ = 4570 years





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

Statistical sensitivity Σ(m_ν) from MC simulations

A. Nucciotti, Eur. Phys. J. C 74 (2014) 3161

- Strong on statistic

$$N_{ev} = A_{EC} \cdot N_{det} \cdot T_M \Rightarrow \Sigma(m_\nu) \propto N_{ev}^{1/4}$$

T_M: Measurement live time; N_{det}: Number of detectors; A_{EC}: Single pixel activity

- Strong on rise time pile-up

Probability ⇒ $f_{pp} \simeq A_{EC} \cdot \tau_r$ (τ_r: Detector time resolution)

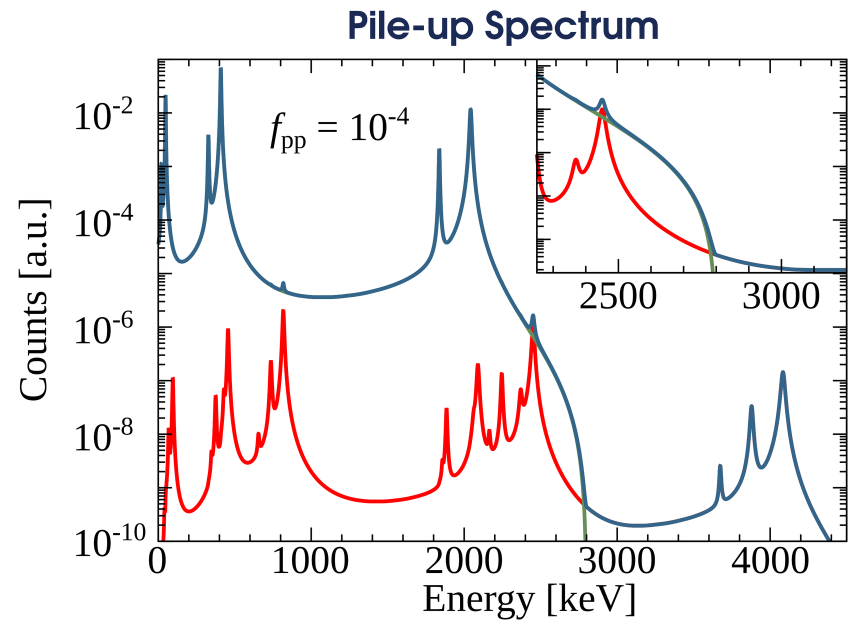
- Weak on energy resolution ΔE

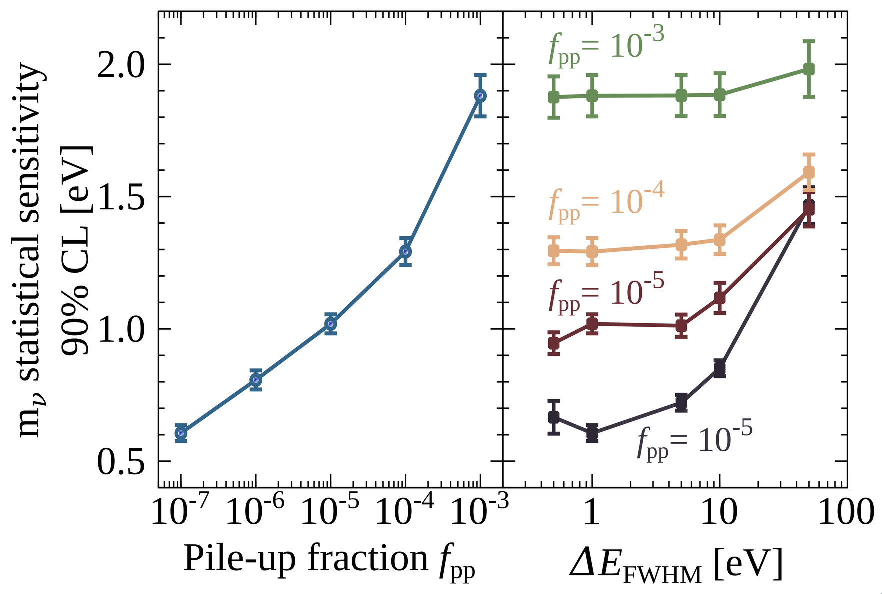
HOLMES target

- Microcalorimeters base on Transition Edge Sensors with ^{163}Ho implanted Au absorber
- Pixel activity of A_{EC} ~ 300 Bq/det
- Energy resolution: O(eV)
  Time resolution : τ_r ~ 1 μs
- 1000 channels for 3 x 10^{13} events collected in T_M = 3 years

Expected Sensitivity $m_\nu \leq 2\,\mathrm{eV}$

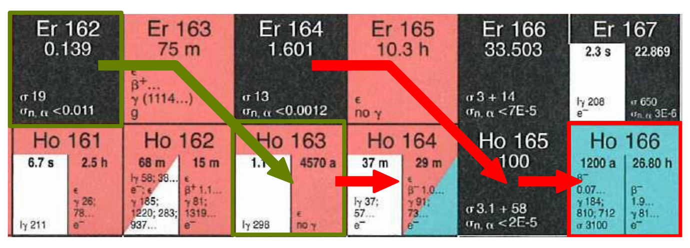
Pile-up Spectrum





^{163}Ho production and embedding

Production by neutron activation of enriched ^{162}Er



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

- Irradiation at the ILL reactor in Grenoble with a high thermal flux

$$\Phi_n = 1.3 \cdot 10^{15}\ n/\mathrm{cm}^2/2$$

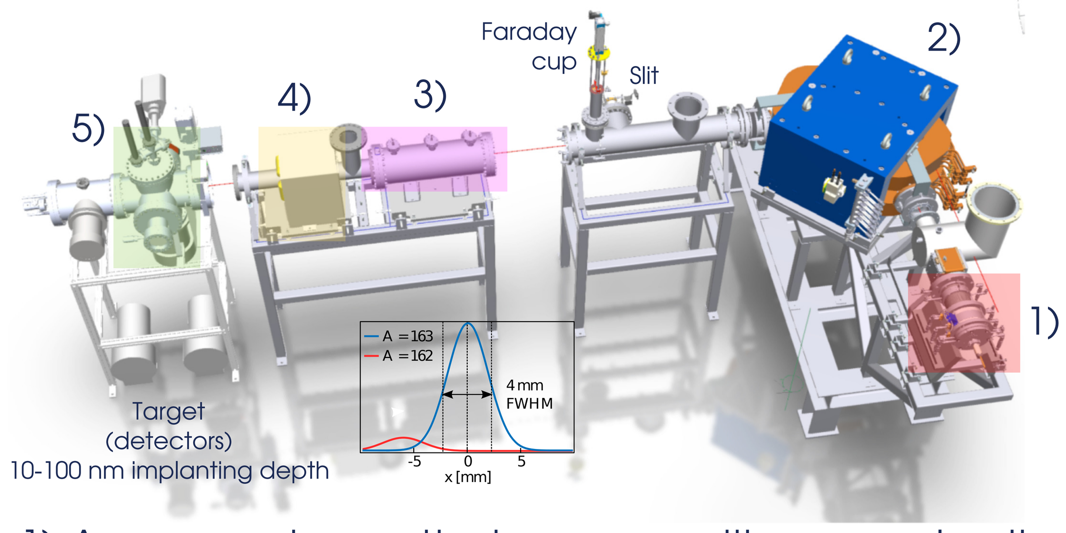
- Cross section burn up $^{163}\mathrm{Ho}(n,\gamma)^{164}\mathrm{Ho}$ not negligible (~200 b)
- Unavoidable $^{165}\mathrm{Ho}(n,\gamma)^{166m}\mathrm{Ho}$ (mostly from $^{164}\mathrm{Er}(n,\gamma)^{165}\mathrm{Er}$)

$$\Rightarrow \beta^- : \tau_{1/2} = 1200\,\mathrm{y},\ Q = 5.97\,\mathrm{keV}$$
$$\Rightarrow A(^{163}\mathrm{Ho})/A(^{166m}\mathrm{Ho}) = (100 - 1000)$$

- Chemical pre-purification and post-separation at PSI (based on ion exchange chromatography) leaves a 166:163 ratio better than 1:1000
- Thermoreduction to obtain the metallic Ho target for implantation

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

Mass separation based on ion implanter



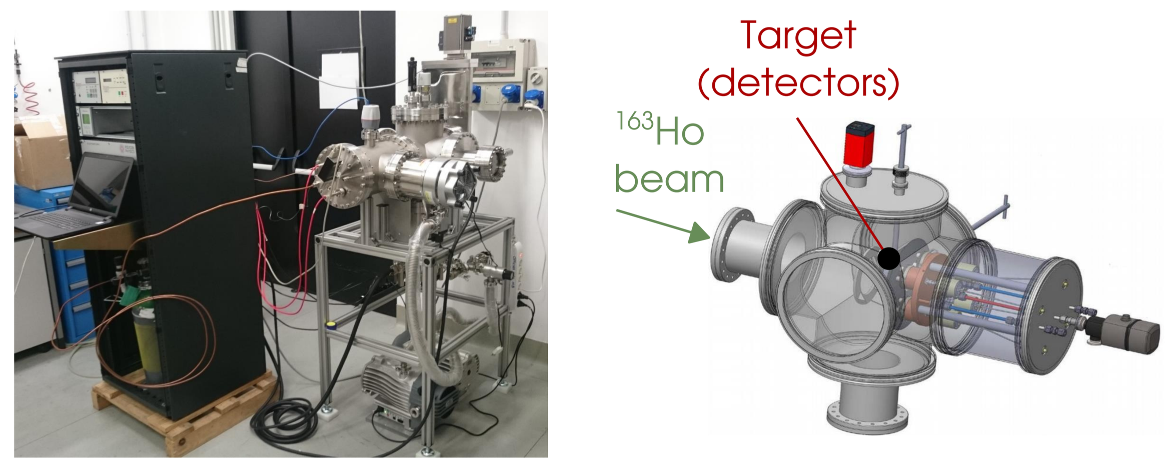
1) Argon penning sputter ion source with an acceleration section allowing to reach a maximum energy of 50 KeV
2) Magnetic dipole mass analyzer with magnetic field up to 1.1 Tesla;
3) Focusing electrostatic triplet;
4) Magnetic scanning stage;
5) Deposition and target Chamber

Currently under comissioning @INFN Genova

From MC simulations ⇒ beam spot ~4 mm FWHM at the target chamber.

Expected 163/166m separation ≥ 5σ.

Deposition and target Chamber



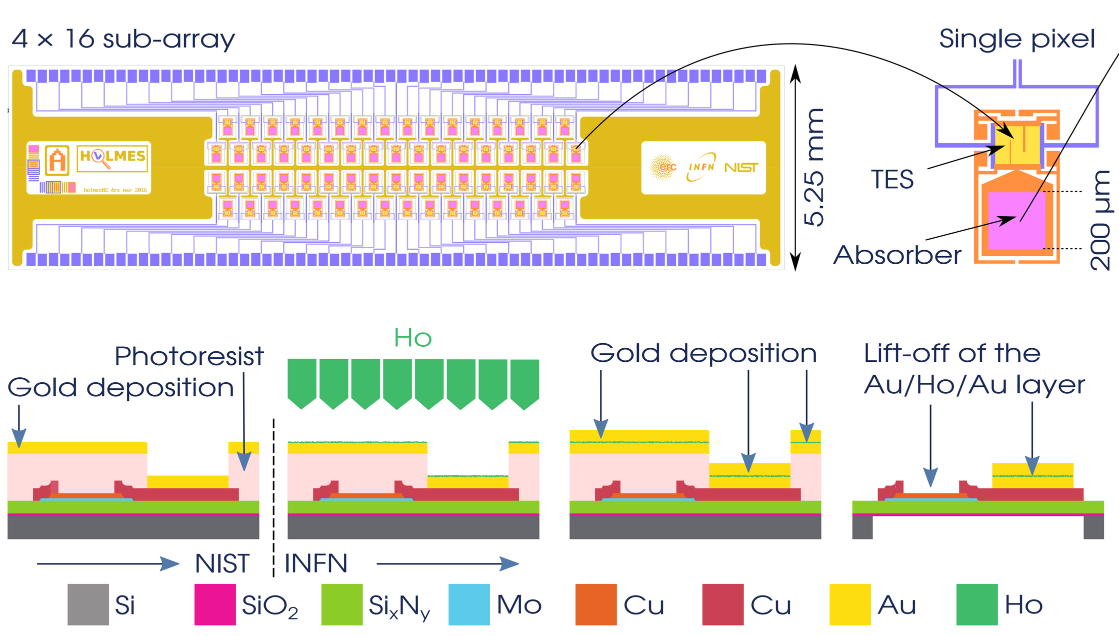
- To obtaion A_{EC} ~ 300 Bq/det, the ^{163}Ho concentration in absorbers saturate because ^{163}Ho sputters off Au from absorber
- Effect compensated by Au co-evaporation during the implantation procedure
- Absorbers finalization with 1 μm Au layer deposited in situ to avoid oxidation
- Au deposition rate ~100 nm/hour (tunable with RF power or with Ar energy)

Currently under comissioning @University of Milano-Bicocca

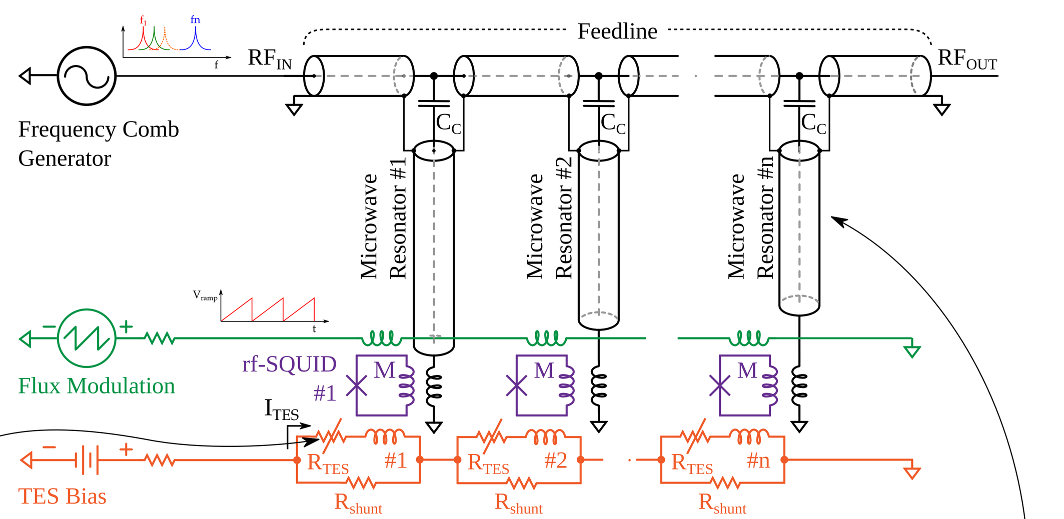
Detectors and Read-out

Low Temperature microcalorimeters

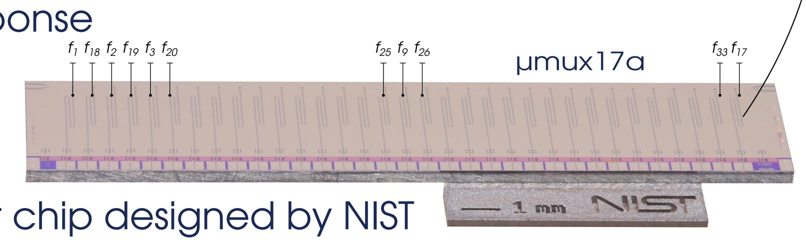
- Sensor: TES Mo/Au bilayers, critical temperature T_c = 100 mK
- Absorber: Gold, 2 μm thick for full e⁻/γ absorption (sidecar design)
- Produced @ NIST (Boulder, CO, USA)
- ^{163}Ho implanting and absorber finalization @ INFN-GE (Italy)
- 4 × 16 linear sub-array designed for high implant efficiency



Microwave rf-SQUID multiplexing read-out



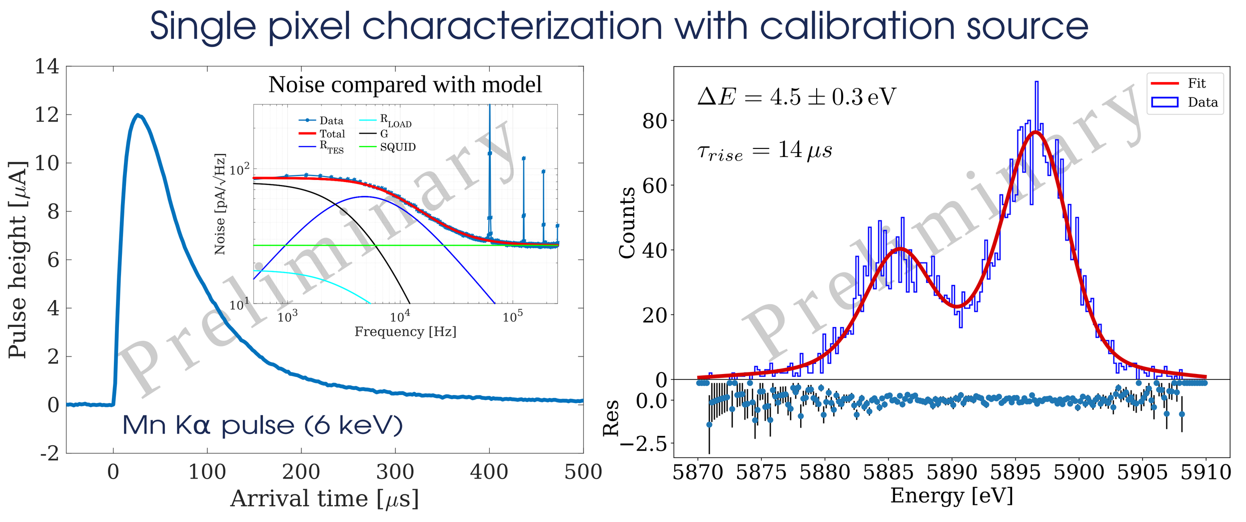
- SQUID coupled with DC biased TES and a λ/4-wave resonant circuit
- Readout with flux ramp demodulation to linearize the SQUID response



- Multiplexer chip designed by NIST
- 33 resonances packed in 500 Hz
- 2 MHz BW per resonance (for a time resolution ~1 μs)
- Resonators spacing ~14 MHz (to avoid crosstalk)

Detector performances

Single pixel characterization with calibration source



- ROACH2-based read-out system: demodulation and triggering in real time performed by FPGA Virtex-6
- A rise time of 15 μs and a sampling frequency of f_s = 500 kHz allow an effective time resolution of 3 μs by Wiener filtering and Singular Value Decomposition-based algorithms
- The development of a 64-channel read-out and multiplexing system is currently in progress
- This setup will be fundamental to acquire the data from the first two microcalorimeter 4 × 16 sub-arrays with ^{163}Ho nuclei implanted starting from 2019

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