Direct neutrino mass measurement with low-temperature microcalorimeters in HOLMES experiment

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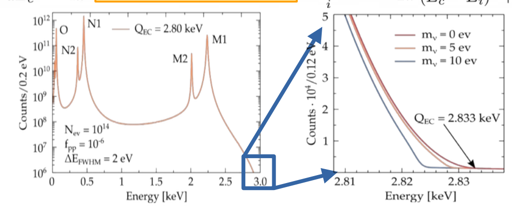
The HOLMES experiment

$$^{163}\mathrm{Ho} + e^- \to {}^{163}\mathrm{Dy}^* + \nu_e \to {}^{163}\mathrm{Dy} + E_c + \nu_e$$

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



Use of Transition edge sensor (TES) based micro-calorimeters with ^{163}Ho implanted in Au absorber:

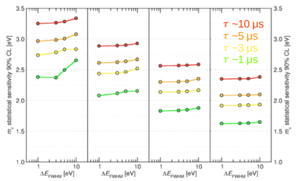
- Resolution ΔE $\mathcal{O}$(eV), Δτ ~ $\mathcal{O}$(μs);
- 6.5 x 10^{13} nuclei/det, A(EC) ~ 300 Bq/det.

Two-step approach to prove technique potential and scalability:

- mid-term prototype: 64 channels, 1 month, m_ν sensitivity 10 eV;
- full scale: 1000 channels, $\mathcal{O}(10^{13})$ events / year, 3 years;
- Pile-up fraction $f_{pp} \approx A \times \Delta t = 3\times10^{-4}$.

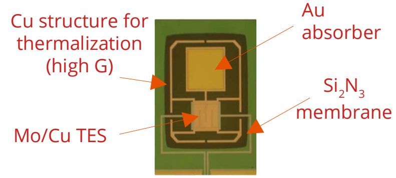
Calorimetric measurement of Dy atomic de-excitation in ^{163}Ho electron capture (EC) from ≥M1 shell:

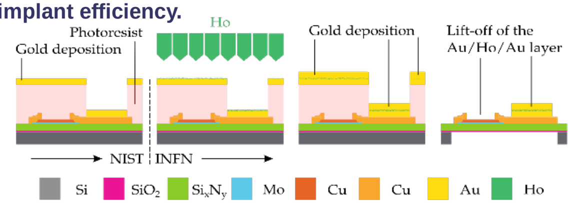
- Few nuclei for sufficient statistics: τ ≈ 4570 years → 2×10^{11} Ho nuclei ↔ 1 Bq;
- Enhance of m_ν statistical sensitivity by low Q-value (≈ 2.83 keV) & proximity of M1 peak: ~$1/(Q-E_{M1})^3$;
- Self-calibrating.

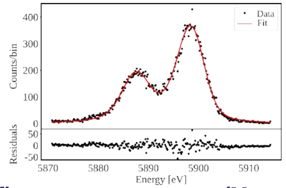


TES design and fabrication

- Mo/Cu (T_c ~ 100 mK) thermometer coupled to 2 μs Au absorber ("sidecar" configuration) to avoid TES proximization;
- ^{163}Ho sandwiched between two 1 μm thick Au layers for a total electron containment;
- 4x16 linear array for low parasitic L and high implant efficiency.

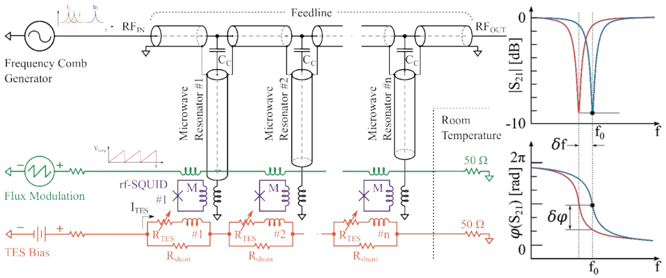






- Several geometries were tested using ^{55}Fe (5.9 keV) and fluorescence sources (Mn – 5.9 keV, Ca – 3.7 keV, Cl – 2.6 keV, Al – 1.5 keV). A 4 to 6 eV energy resolution has been evaluated on those lines with the rise time of ~20 μs, compatible with experimental requirements.

Microwave multiplexing readout



- Each sensor inductively coupled to an rf-SQUID part of a λ/4 resonator;
- A comb of signals probe the resonators at their characteristic resonant frequency

$$E \to \delta T_{TES} \to \delta I_{TES} \to \delta\phi_{SQUID} \to \delta f_{resonator};$$

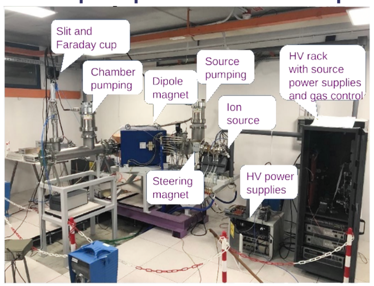
- Flux ramp SQUIDs modulation to linearize the response;
- Real-time pulse reconstruction with ROACH2 (ADC BW 550 MHz);
- Tested resonators spacing (14 MHz), bandwidth (2 MHz), and depth (29 dB) match HOLMES specifications;
- At the moment readout available for 64 channels.

Ho production and embedding

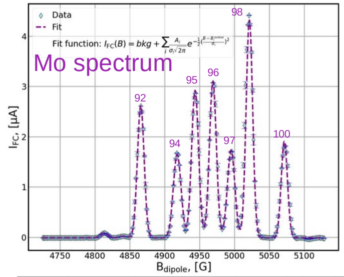
- ^{163}Ho produced by neutron irradiation of Er_2O_3 enriched (30%) in ^{162}Er at the Institut Laue-Langevin (ILL, Grenoble, France). Thermal neutron flux at ILL: 1.3×10^{15} n/cm²/s.

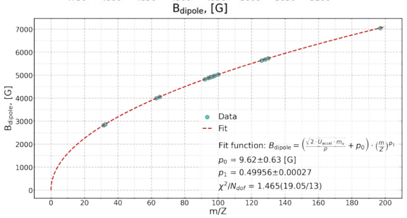
^{162}Er(n,γ)^{163}Er ($\sigma_{thermal}$ ~ 20 b),
^{163}Er + e^- → ^{163}Ho + ν_e ($\tau_{1/2}$ ~ 75min).

- Contaminants:
1. Other elements (residual Er, rare earth contaminants, decay product, etc…)
   → chemical purification;
2. Holmium isotopes, in particular
   ^{166m}Ho (β^-, Q = 1856 keV, $\tau_{1/2}$ ~ 1200 y)
   A(^{163}Ho)/A(^{166m}Ho)=100-1000
   → isotope separation with ion implanter.



- Ion implanter equipped with Ar sputter ion source and magnetic dipole + electrostatic quadrupole (later) for a ^{163}Ho beam with 4 mm FWHM spot and mass separation 163/166 better than 5σ.





- Reduced beamline commissioned, showed a good performance for different elements extraction;
- Calibration procedure established, effect of misalignment and beam spot assessment understood, more detailed investigations are ongoing;
- Tests with different natural ^{165}Ho-containing targets (molecular plating on bulk Cu, on-demand inkjet printing, Ti-Ni-Sn-Ho sinter) show clear peak, $\mathcal{O}$(10 nA - 100 nA), at 165 a.m.u.;
- Best current-stability, $\mathcal{O}$(200 nA) over ~15 h, with $Ho(NO_3)_3$ on Zr-Y sinter target; coupled reduction of Ho on Pd substrate to be tested;
- Next milestone: implant of first 64-TES array with low dose ^{163}Ho (≈ 1 Bq) without focusing.