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Probing the absolute neutrino mass scale with ^{163}Ho: the HOLMES project.

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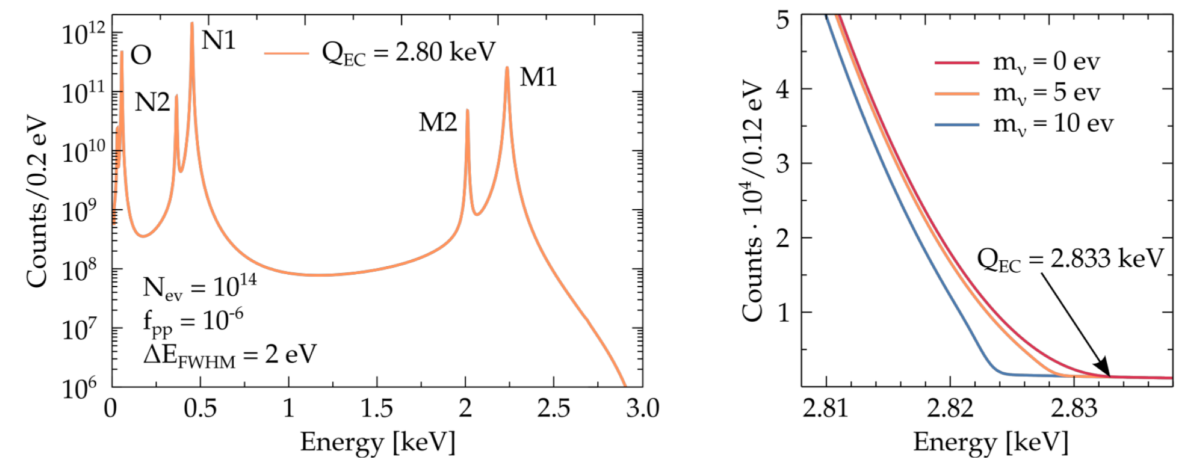
The HOLMES project aims to directly measure the neutrino mass using the e^- capture decay (EC) of ^{163}Ho down to the eV scale. It will perform a precise measurement of the end-point of the Ho calorimetric energy spectrum to search for the deformation caused by a finite electron neutrino mass. The choice of ^{163}Ho as source is driven by the very low Q-value vof the EC reaction, which allows for high sensitivity with low activities (O(10^2)Hz/detector), thus reducing the pile-up probability. A large array made by thousands of TES based micro-calorimeters will be used. The calorimetric approach eliminates systematic uncertainties arising from the use of an external beta-source, and minimizes the effect of the atomic de-excitation process. The commissioning of the first implanted sub-array is scheduled for the end of 2018. It will provide useful data about the EC decay of ^{163}Ho together with a first limit on neutrino mass. In this presentation the current status of the main tasks will be summarized: the TES array design and engineering, the isotope preparation and embedding, and the development of a high speed multiplexed SQUID read-out system for the DAQ.

^{163}Ho decay via electron capture from shell ≥ M1, with Q_{EC} ~ 2.8 keV [1]:

$$^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy}^* + \nu_e$$

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

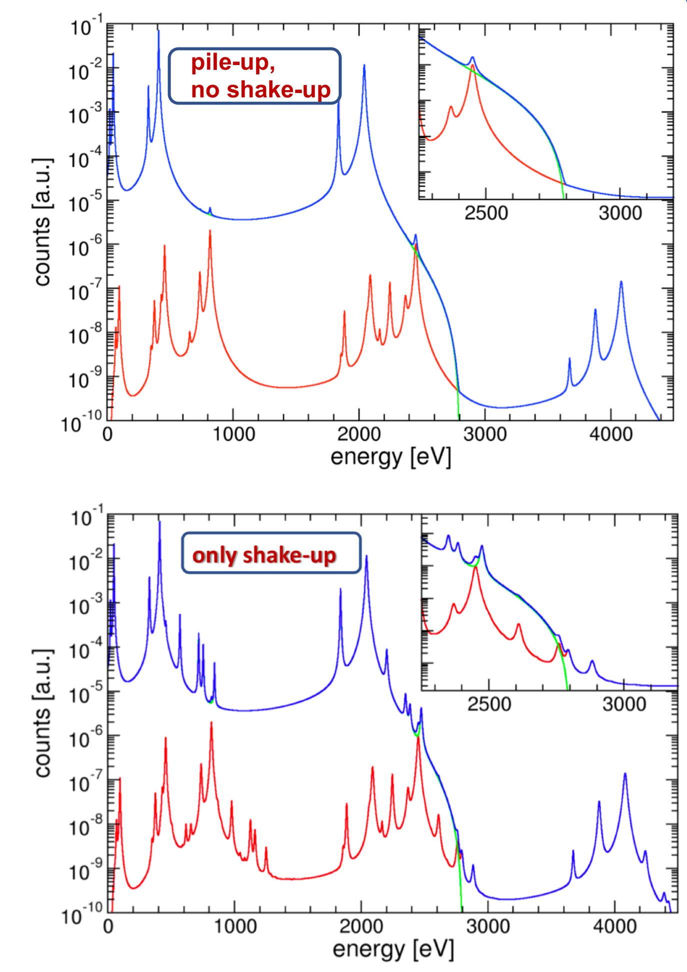
- **Calorimetric measurement** of Dy* de-excitation energy E_c
- **m_ν sensitivity depends on Q-value and capture peak position** (roughly ~$1/(Q-E_{M1})^3$)
- τ ~ 4570y: few active nuclei needed to obtain reasonable activity (1 Bq = 2 x 10^{11} nuclei)



simulation with single hole excitation

Complex pile-up spectrum:
$N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$
with $f_{pp} = A_{EC} \times \tau_r$

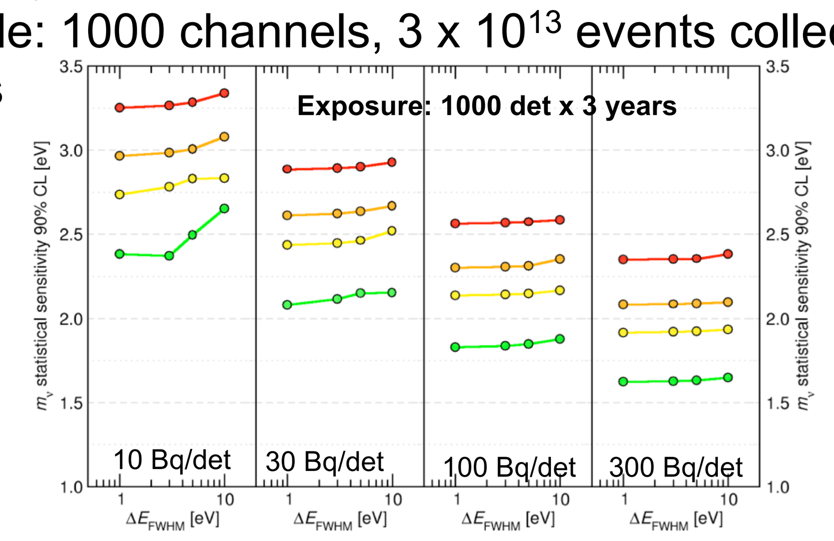
Shake-up and shake-off process due to 2-holes excitation are possible:
- n holes excitations have much lower probability;
- energy and probabilities are still uncertain;
- Spectrum could be even more complicated.



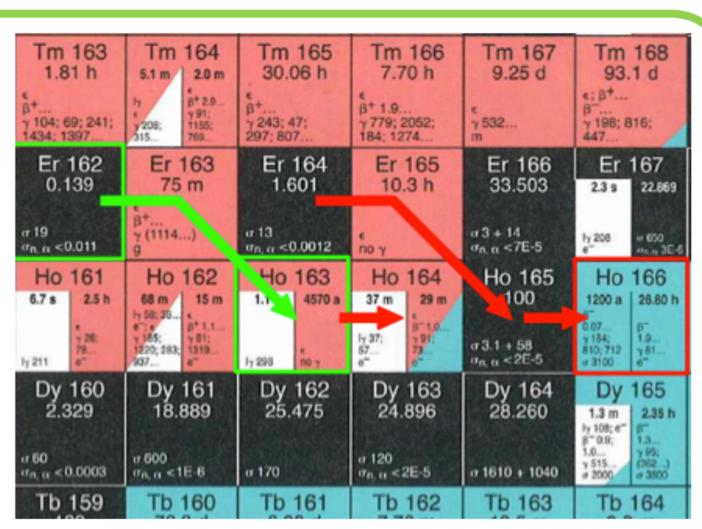
Pile-up implies:
- tradeoff between detector activity and statistics;
- needs of detector with fast resolving time
- dedicated resolving algorithm.

Direct m_ν measurement with statistical sensitivity around 1 eV **using Transition Edge Sensors based microcalorimeters** with **^{163}Ho implanted Au absorber [2]**:
- 6.5 x 10^{13} nuclei/det, A_{EC} ~ 300 Bq/det
- Energy resolution O(eV), τ ~ 1µs
- 1000 channels array → 6.5 x 10^{16} total nuclei

Should prove the tecnique potential and scalability by: assessing EC spectral shape and systematic errors.
Two steps approach:
- 64 channels mid-term prototype, t_M = 1 month, m_ν sensitivity ~ 10 eV
- full scale: 1000 channels, 3 x 10^{13} events collected in 3 years

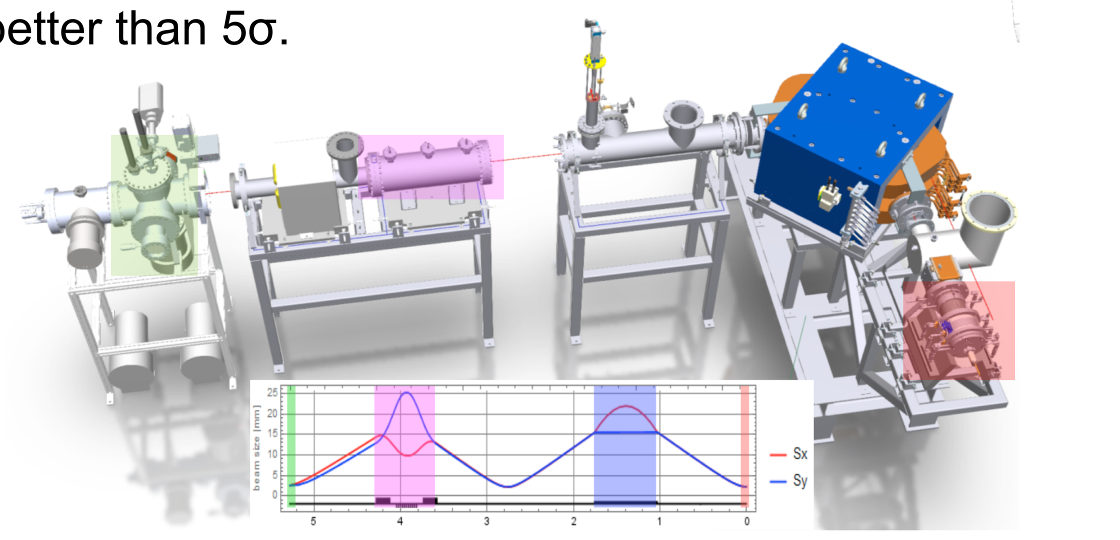


Holmium production and embedding chain:
^{163}Ho is produced by n-activation of ^{162}Er sample:
- ^{162}Er(n,γ)^{163}Er, ^{163}Er + e^- → ^{163}Ho + ν_e ($\tau_{1/2}$ ~ 75min)
- High yield (σ_{th}~ 20b), but contaminations from other species:
- ^{165}Ho(n,γ)^{166m}Ho (β, $\tau_{1/2}$ ~ 1200y)
- ^{166m}Ho is the main source of background.
- Could come from Ho contaminations or ^{164}Er(n,γ)
- 2 steps purification procedure has been developed:

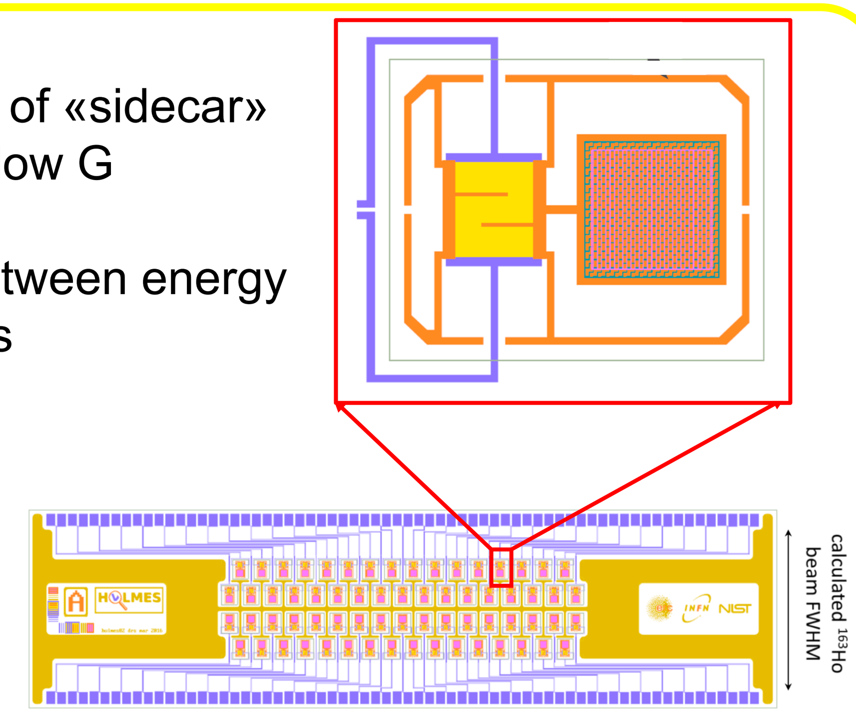


1) **Radiochemical purification pre and post irradiation**, based on ion exchange chromatography: eliminates all species other than Ho, leaves a 166:163 ratio better than 1:1000

2) **Mass separation based on ion implanter** (E = 30 – 50 keV) **equipped with magnetic dipole + electrostatic quadrupole** produces a 163Ho beam with 4mm FWHM spot and mass separation 163/166 better than 5σ.

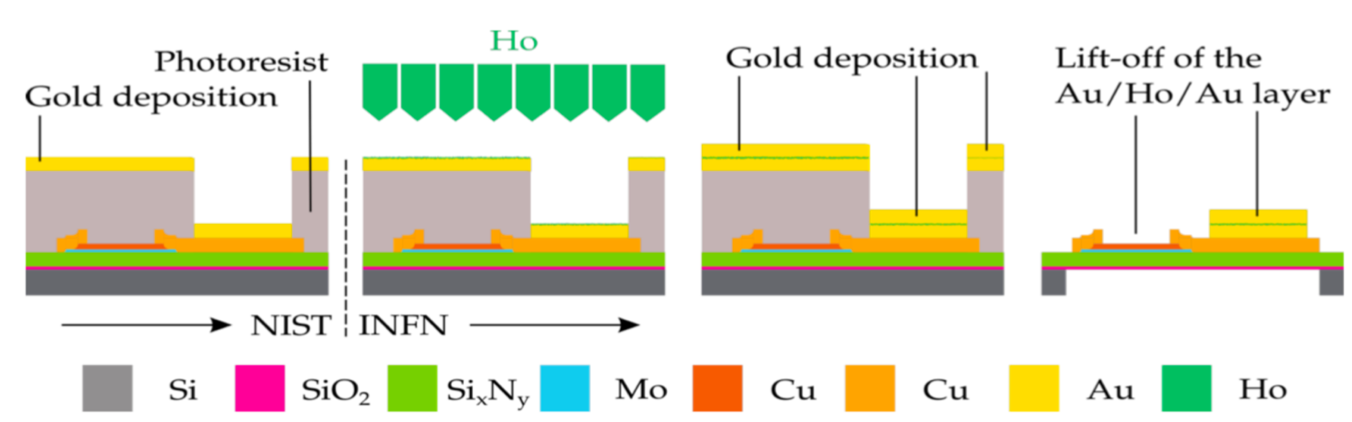


TES design and production:
2 µm Au absorber for full e^-/γ absorption, usage of «sidecar» configuration to avoid TES proximization and allow G engineering for τ control.
Desing optimized to obtain best compromise between energy resolution and time response: ΔE O(eV), τ ~ 1µs



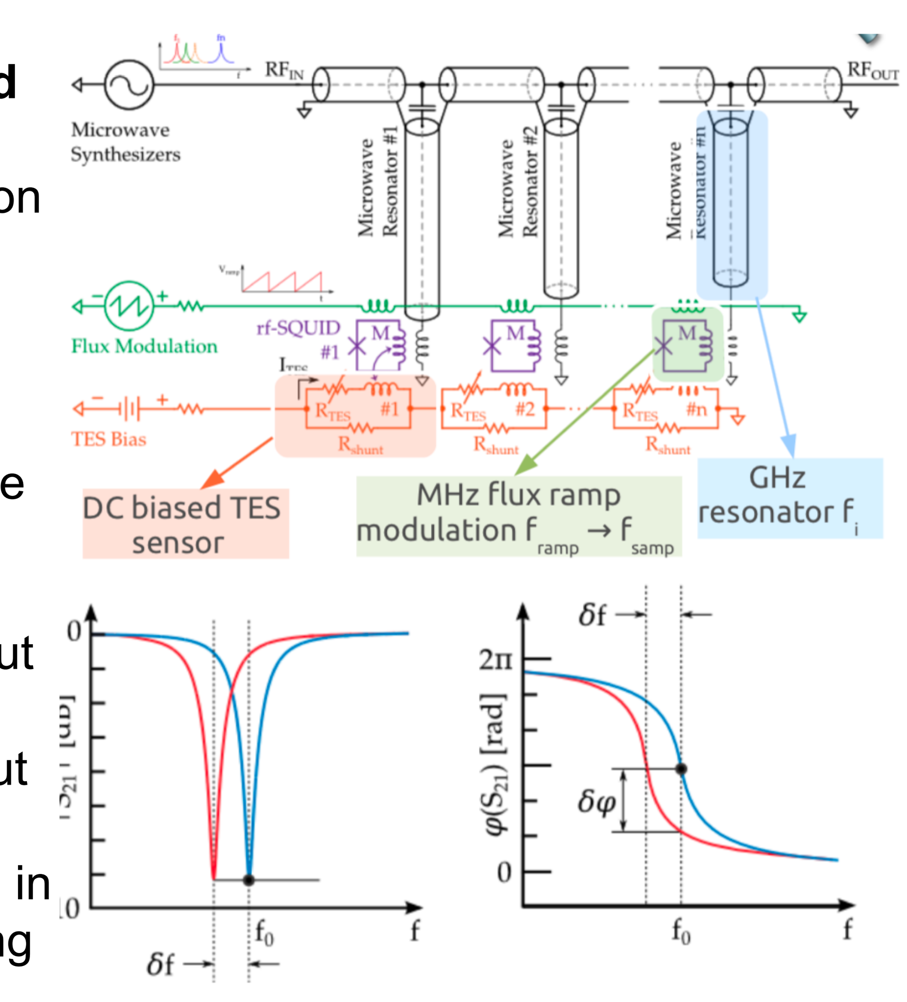
Multistep production:
1. TES array is produced up to first 1µm Au layer;
2. ^{163}Ho implantation
3. 1µm Au final layer deposition
4. Membrane release with KOH or DRIE process.

- 4 x 16 linear array for low parasitic L and high implant efficiency



RF SQUID readout with microwave multiplexing: SQUID coupled with DC biased TES and a λ/4-wave resonant circuit:
- readout with flux ramp demodulation (common flux line inductively coupled to all SQUIDs);
- signal reconstructed by Software defined Radio Technique (ROACH2, ADC bandwidth 550MHz).

1. Energy deposit in the absorber increases the temperature and therefore the TES resistance.
2. Change in TES current ⇒ change in the input flux to the SQUID;
3. The RF-SQUID transduces a change in input flux into a variation of resonant frequency;
4. The ramp induces a controlled flux variation in the RF-SQUID, which is crucial for linearizing the response.

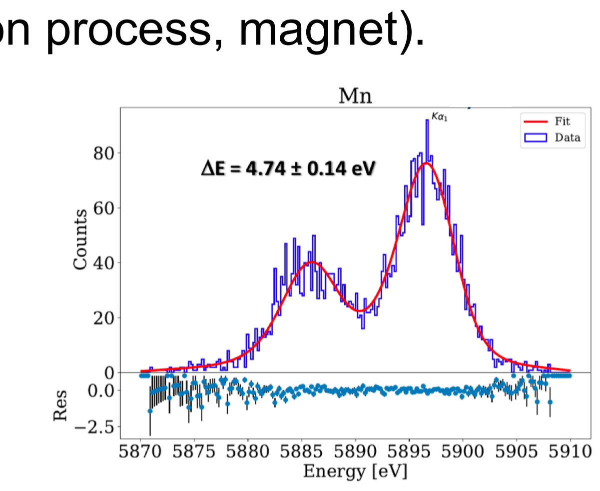


Status and perspectives:

Source production: 3 batches have been already irradiated at ILL (Grenoble, FR), for a total of 140MBq of ^{163}Ho. The radiochemical separation process has been prvoed to work with an efficiency ≥ 79%

Ion implanter: the setup of the machine is on going in Genova's INFN laboratory. All devices have been separately tested (source, acceleration process, magnet).

Microcalorimeter test: several geometries were tested using ^{55}Fe (5.9 keV) and fluorescence source (Mn - 5.9 keV, Ca - 3.7 keV, Cl – 2.6 keV, Al – 1.7 keV). A 3.5 to 5 eV energy resolution have been evaluated on those lines.



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[2] B. Alpert et al., Eur. Phys. J. C (2015) 75:112