The CROSS demonstrator: structure, performance and physics reach

Mariia Buchynska on behalf of the CROSS Collaboration[1]
mariia.buchynska@ijclab.in2p3.fr

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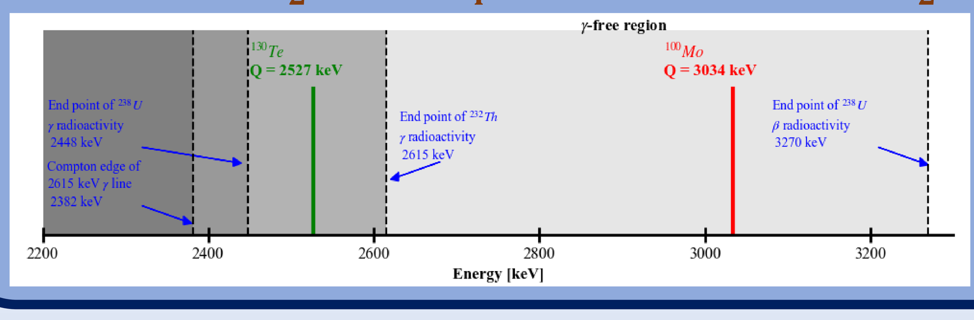
1. CROSS experiment

CROSS (Cryogenic Rare-event Observatory with Surface Sensitivity) is a project aiming at the development of a new bolometric technique to search for $0\nu\beta\beta$ decay in ^{100}Mo and ^{130}Te nuclei.

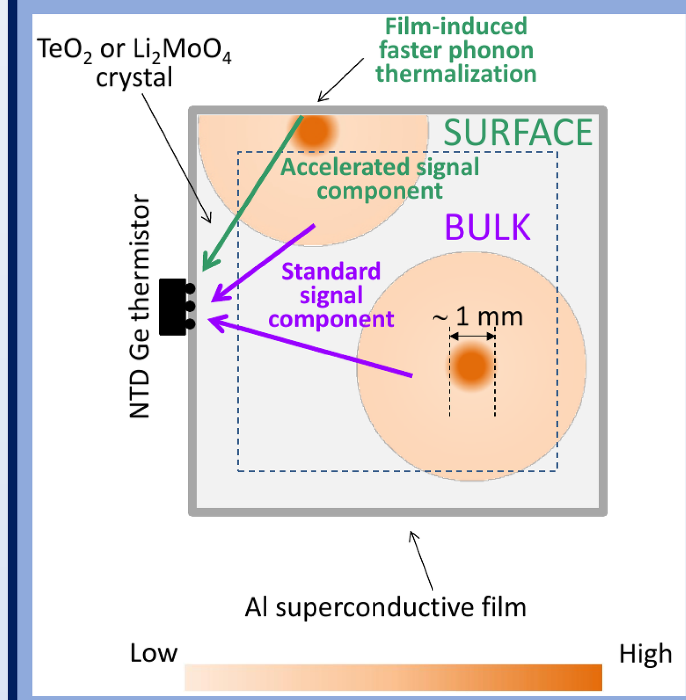
$^{100}Mo \Rightarrow Li_2{}^{100}MoO_4$ $\quad$ $^{130}Te \Rightarrow {}^{130}TeO_2$

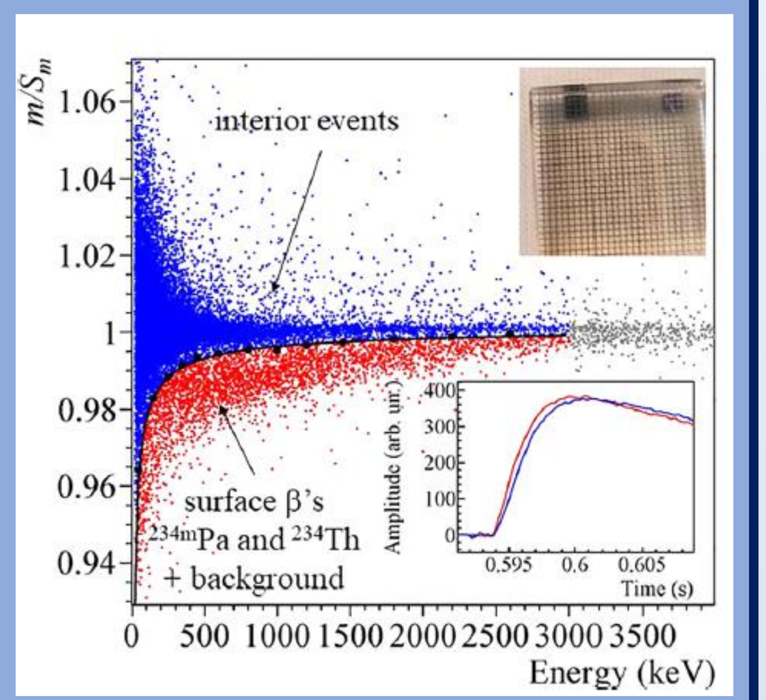


2. CROSS in a nutshell

- **Particle ID: Bulk / Surface**
  - R&D on metal-coated bolometers for discrimination between bulk and near surface interactions
- **Development of $^{130}TeO_2$**
  - protocol for the production of radiopure ^{130}Te-enriched TeO_2 bolometers
- **Production and use of $Li_2{}^{100}MoO_4$ crystals**
- **Competitive experiment on the ^{100}Mo $0\nu\beta\beta$**
- **Development of fully equipped underground facility (LSC, Canfranc, Spain) to test advanced bolometers**

3. Evolution of the experiment

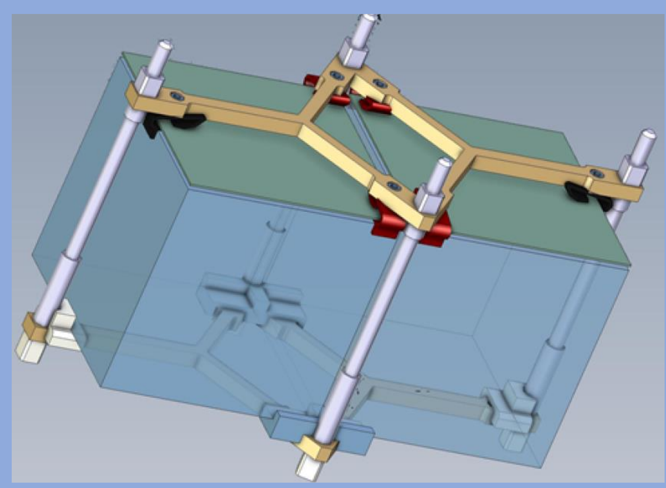




[2] JHEP 01 (2020) 018 $\quad$ [3] Appl. Phys. Lett. 118, 184105 (2021)

- **Discrimination between bulk / near surface α and β interactions [3]:**
  - coatings with Al, Pd, and Al-Pd are studied
  - works for small samples, e.g. $2 \times 2 \times 1$ cm^3 Li_2MoO_4 crystal with Al-Pd grid
  - discrimination power of surface α-s: DP $\geq 4.5\sigma$
  - β surface events selection efficiency (with Al-Pd): ~93%
  - baseline resolution is not affected and remains at keV level (with Al-Pd)
  - at the moment, there are difficulties in reproducing these results with larger samples
- **Light channel is exploited via Neganov-Trofimov-Luke light detectors (NTL-LDs)**
  - α discrimination due to lower light yield for alpha particles
  - to improve substantially pile-up (coincidence of two $2\nu\beta\beta$ events) rejection

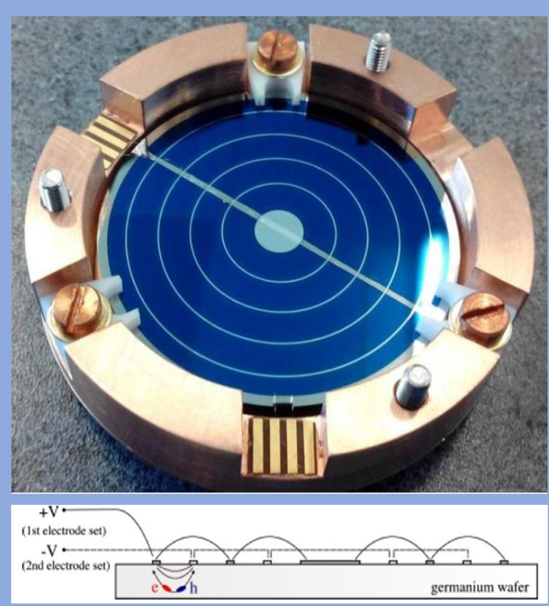
4. CROSS detector structure [4]



- Cubic $Li_2{}^{100}MoO_4$ (LMO) and $^{130}TeO_2$ crystals ($45 \times 45 \times 45$ mm^3) and square Ge wafers ($45 \times 45 \times 0.3$ mm^3)
- Temperature sensors: neutron transmutation doped (NTD) Ge thermistors glued at crystals and Ge wafers with bi-component epoxy or UV-cured glue
- Each crystal has a direct heat sinking through supporting elements made of polytetrafluoroethylene (PTFE) or other plastic material
- Light detectors are kept with 3D-printed polylactic acid (PLA) clamps on the crystal
- Cu-to-LMO mass ratio is minimized to 6% to decrease radioactivity from surface of close elements

[4] arXiv:2405.18980 (2024)

5. Neganov-Trofimov-Luke light detectors [5]



- Electronic grade purity Ge wafer with SiO anti-reflective coating (enhances light collection by ~30%)
- Al electrodes are deposited and connected with Al bonding wires
- NTD is electrically connected to Au-coated copper pads on Kapton through gold bonding wire
- Amplification effect due to extra heat produced by charged carriers drifted by an electric field. Total heat: $\boldsymbol{E_{tot} = E_0 \cdot G_{NTL}}$; $\boldsymbol{G_{NTL} \propto V_{NTL}}$

Essential NTL LD parameters

- $\sigma_{baseline}$ – baseline noise RMS after applying Gatti-Manfredi optimum filtering. When expressed in energy units represents also the signal-to-noise ratio for the LD. Important for $\alpha/\beta(\gamma)$ discrimination and pile-up events rejection. Can be improved by a factor 10 thanks to the NTL effect
- rise time – crucial for pile-up events rejection [6]. Can be kept below 0.5 ms at a proper operation point

[5] NIMA 940 (2019) 320 $\quad$ [6] EPJC 83 (2023) 373 $\quad$ see poster №474 by Antoine Armatol

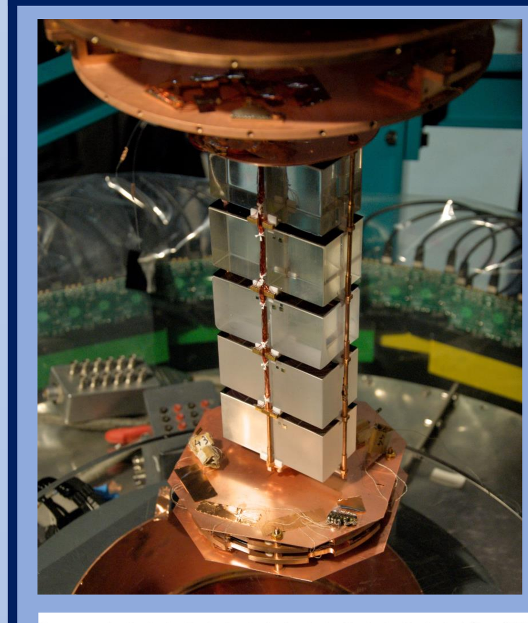
6. CUPID and CROSS interplay [7]

The CROSS cryogenic facility[8] is exploited to:

- **test performance of CUPID crystals**
  - crystals resolution and sensitivity
- **test NTL-LDs**
  - leakage current and sensitivity checks
  - search for optimal geometry of electrodes
  - studies on pile-ups rejection efficiency
- **probe assembly structures**

[7] JINST 18 (2023) P06018 $\quad$ [8] JINST 18 (2023) P12004

7. Recent results in Canfranc



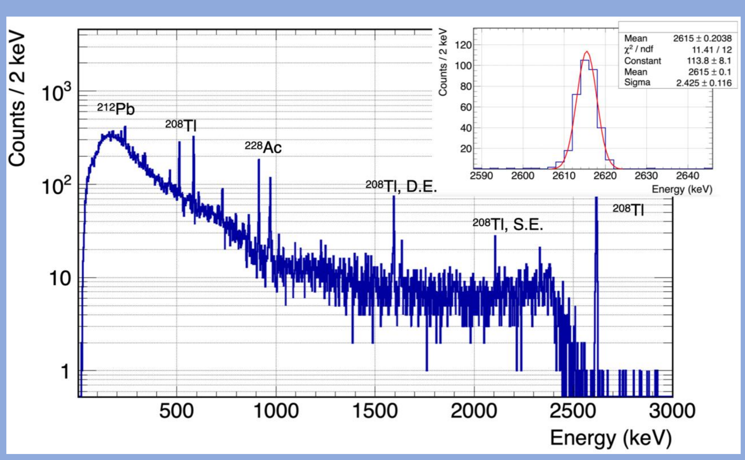
10-crystal structure:

- 6 Li_2MoO_4 crystals (2 reference high purity $Li_2{}^{100}MoO_4$ crystals and 4 natural crystals from a US company that are under investigation)
- 2 bare $^{130}TeO_2$ crystals
- 2 $^{130}TeO_2$ crystals with thin metallic coating (Al for one and Al-Pd for other)
- 10 NTL light detectors with circular electrodes geometry

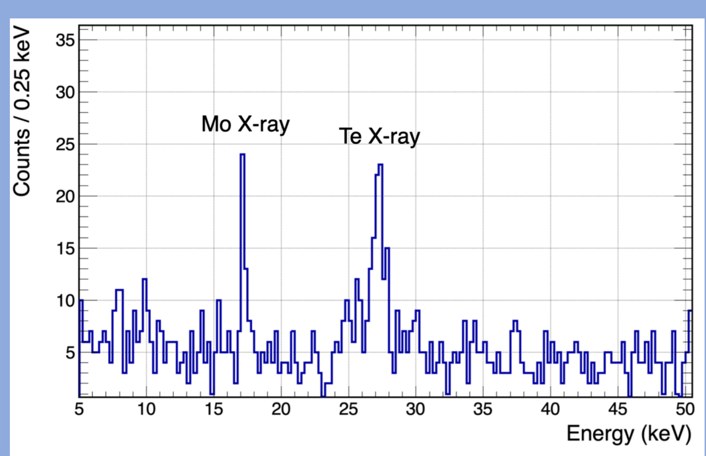
Operation temperatures: 17–27 mK

Measurements:

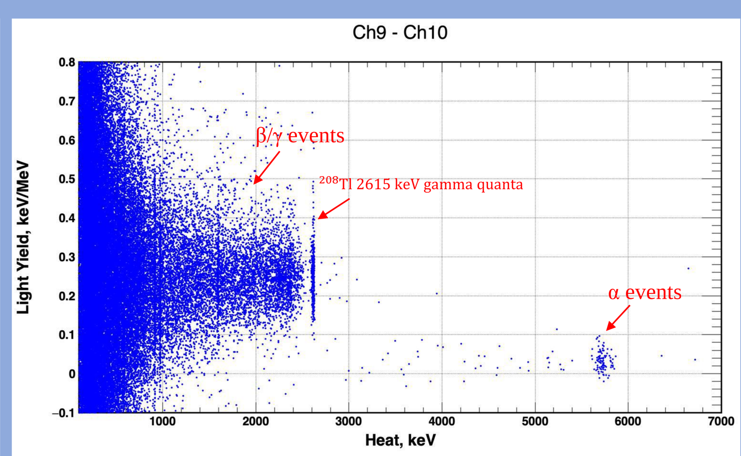
- Calibration measurements with ^{232}Th source
- Background measurements
- Tests on pile-up rejection capability



Th calibration for one of the reference detectors $Li_2{}^{100}MoO_4$. Energy resolution @ 2615 keV ^{208}Tl line is (5.7 ± 0.3) keV



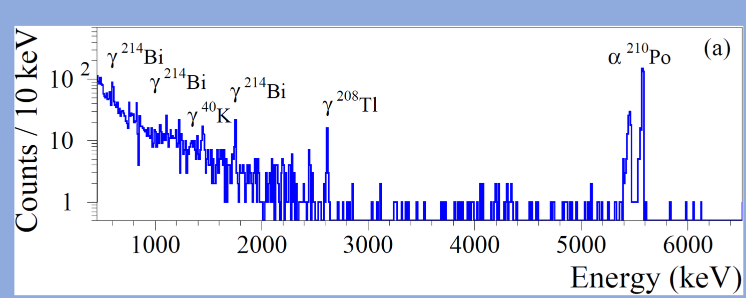
Mo and Te X-rays in the LD used for calibration



α/β(γ) events discrimination at 0 V bias

Results:

- **$^{130}TeO_2$ crystal performance [9]:** confirmation of the radiopurity of the crystals (~1 mBq/kg activity of ^{210}Po) by bolometric measurements together with excellent energy resolution

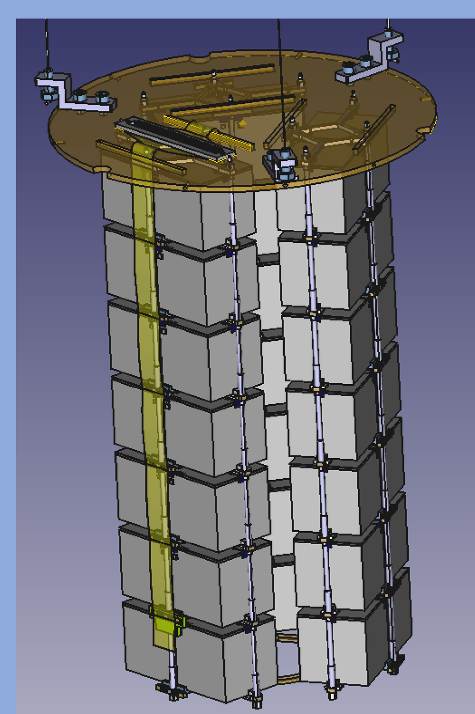


Background spectrum measured by a 0.55 kg $^{130}TeO_2$ bolometer (116 h at 27 mK)

- **NTL LD performance:**
  - **0V bias performance:** all LD have $\sigma_{baseline} < 150$ eV which means 99.9 % α rejection factor (mean value of $\sigma_{baseline} < 85$ eV)
  - **Leakage current:** all NTL LD where able to stand 50 V across the electrodes without developing leakage current and 8/9 were able to stand more than 90 V
  - **80V bias performance:**
    - mean value of $\sigma_{baseline}$ is (12 ± 4) eV (G_{NTL}~11) and SNR = 89. Taking into account that only 56% of surface area is covered by the electrodes, we expect $\sigma_{baseline}$= 6.8 eV and SNR = 152 for the full surface coverage
    - working at ~1 MOhm resistances of LD NTDs we reached rise-times 0.42–0.74 ms with a mean value (0.55 ± 0.11) ms. Together with achieved SNR, these results are important for pile-up rejection
    - higher gain is obtained when light impinges on the electrode side of the Ge wafer (factor 2.5 difference)

[9] arXiv:2406.01444 (2024)

8. CROSS demonstrator



Structure

- 3 towers with 7 floors each
- Each floor has 2 crystal + 2 NTL-LD
- Top floor consists of TeO_2 crystals, that will work also as shielding to others crystals due to higher density

In total: 36 $Li_2{}^{100}MoO_4$ (32 ^{100}Mo-enriched) and 6 TeO_2 (all ^{130}Te-enriched)

Total mass of ^{100}Mo: 4.7 kg

Installation envisaged within the end of 2024
Commissioning in early 2025

9. Sensitivity

According to current estimations (see poster №343 by David Cintas) background index in the CROSS demonstrator can be estimated as:

- **10^{-2} counts/keV/kg/yr** in the worst case scenario
- **10^{-3} counts/keV/kg/yr** in the best case scenario

Assuming 2 years live time, the CROSS experiment will be able to set a limit (at 90% confidence level) on the ^{100}Mo 0νββ decay:

- half-life $\mathbf{T^{0\nu}_{1/2} > 8.5 \cdot 10^{24}}$ **yr** and $\langle m_{\beta\beta} \rangle <$ **(0.131–0.221) eV** in the worst case scenario
- half-life $\mathbf{T^{0\nu}_{1/2} > 1.2 \cdot 10^{25}}$ **yr** and $\langle m_{\beta\beta} \rangle <$ **(0.110–0.186) eV** in the best case scenario

Even in the worst case scenario, the CROSS demonstrator will have higher sensitivity on the ^{100}Mo 0νββ than the best current limits established by CUPID-Mo [10] and AMoRE-I [11] experiments.

[10] Eur.Phys.J.C 82 (2022) 11, 1033
[11] H.B. Kim. 2023. Result of AMoRE-I Experiment. TAUP, 30 August, Vienna