CUPID-Mo first sensitivity estimates to $2\nu\beta\beta(0\nu\beta\beta)$ to excited states

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Double Beta Decay

- **Double beta decay ($2\nu\beta\beta$)** - a rare standard model process ($T_{1/2} \sim 10^{18} - 10^{21}\ yrs$) - has been observed in a number of isotopes including ^{100}Mo.
- As neutral leptons, neutrinos could be Majorana or Dirac particles. As Majorana particles, neutrinos could induce an additional decay mode ($0\nu\beta\beta$) which would violate lepton number conservation.
- The transition mechanism is presently subject to considerable nuclear theory uncertainties.
- The half-lives are related to nuclear physics by the equations below where G is the phase space, M the nuclear matrix element and $m_{\beta\beta}$ the effective Majorana mass

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}\,|M_{0\nu}|^2\,\frac{m_{\beta\beta}^2}{m_e^2} \qquad \frac{1}{T_{1/2}^{2\nu}} = G_{2\nu}\,|M_{2\nu}|^2 \tag{1}$$

- Precision measurement of $\boldsymbol{2\nu\beta\beta}$ to excited states helps constrain the nuclear models used to compute the nuclear matrix elements for both the $\boldsymbol{2\nu\beta\beta}$ and $\boldsymbol{0\nu\beta\beta}$.

The CUPID-Mo Experiment

CUPID-Mo, a demonstrator experiment for **CUPID** [1], consists of an array of 20 $\sim$ 0.2 kg enriched $Li_2^{100}MoO_4$ scintillating cryogenic calorimeters with 20 Ge wafer light detectors for particle discrimination, each instrumented with NTD's. CUPID-Mo has demonstrated excellent: (see [2], poster #404 by D.Poda)

- Energy resolution ($\sim$ 7 keV at 2615 keV)
- Radiopurity (LMO ^{232}Th, ^{238}U $\leq 3\,\mu$Bq/kg)
- α/β particle discrimination ($> 99.9\%$)

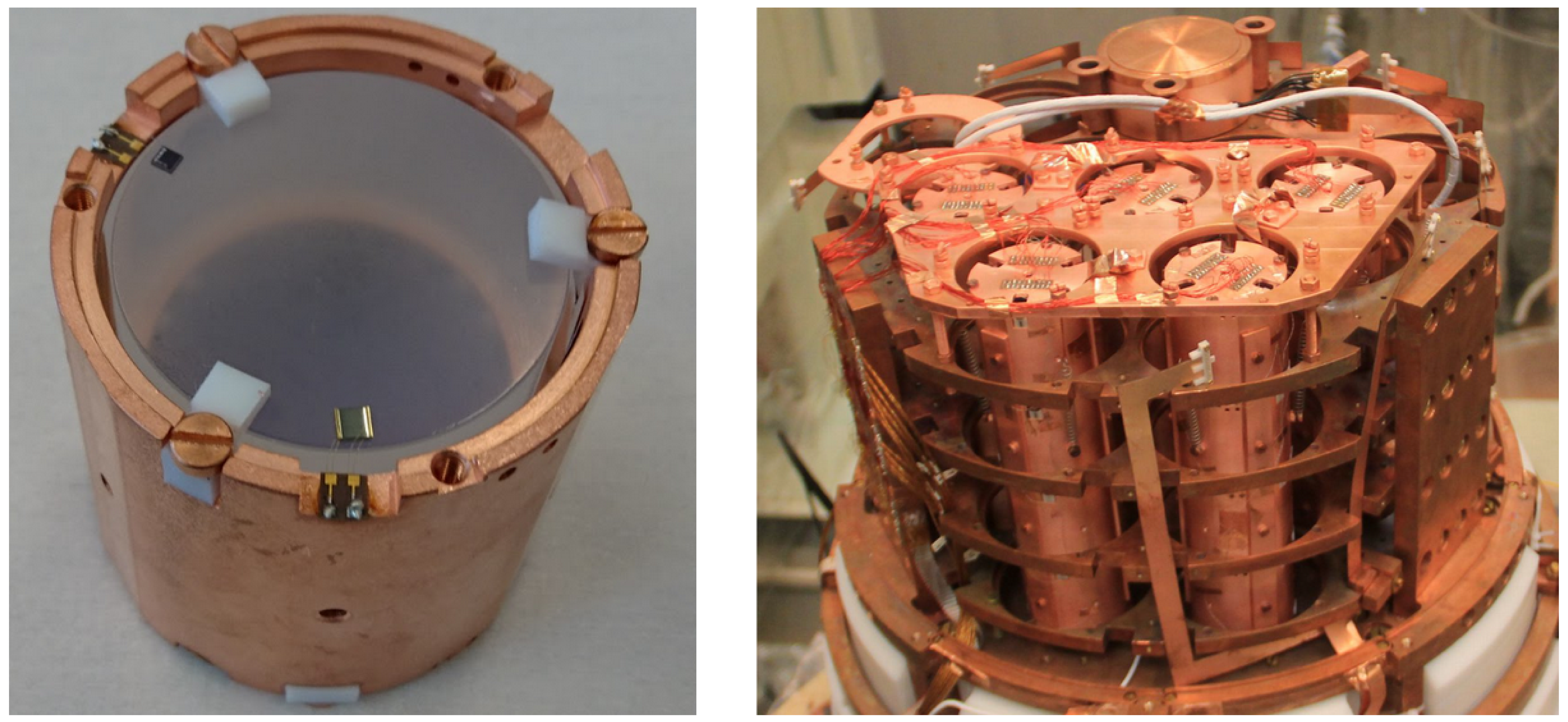

Figure 1: Left: An individual CUPID-Mo bolometer. Right: The CUPID-Mo setup in the EDELWEISS cryostat.

Decays of ^{100}Mo

- We consider ^{100}Mo decays to both the 0_1^+, 2_1^+ excited states of ^{100}Ru, where the two electrons are accompanied by one or two de-excitation γ's

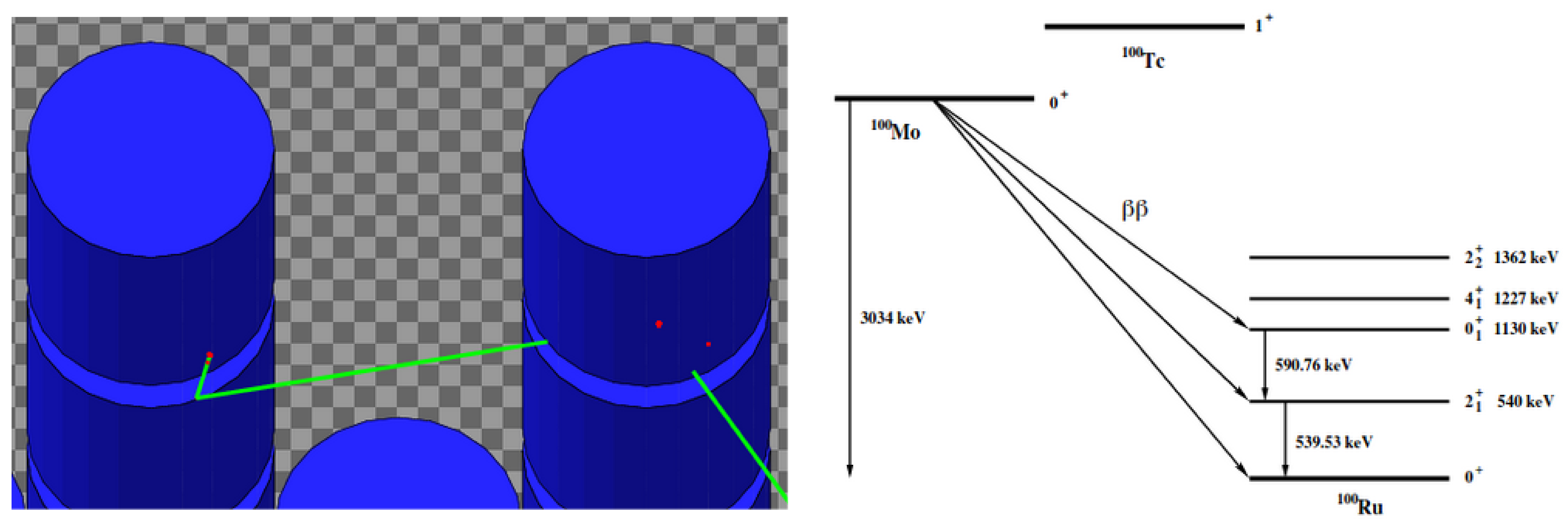

Figure 2: Left: Simulated $2\nu\beta\beta$ decay to 0_1^+ state; we see the two γ's, the electrons are contained in the crystal. Right: Decay scheme of $2(0)\nu\beta\beta$ to excited states [3]

$0\nu\beta\beta/2\nu\beta\beta$ Signatures in CUPID-Mo

- We simulate signatures for $\boldsymbol{0\nu\beta\beta(2\nu\beta\beta)}$ - decay to the 0_1^+, 2_1^+ excited states of ^{100}Ru in a detailed Geant4 MC simulation using the Decay0 event generator [4].
- We classify signatures into three sets, those involving 1, 2, 3 crystals.
- For a preliminary sensitivity estimate we focus on the first two sets.
- For $\boldsymbol{0\nu\beta\beta}$ we look for peaks in the summed energy distribution of events depositing energy in two crystals (M2).
- For $\boldsymbol{2\nu\beta\beta}$ the electrons can carry a variable amount of energy and we restrict ourselves to candidates with a photopeak of one of the gammas in the secondary crystal.

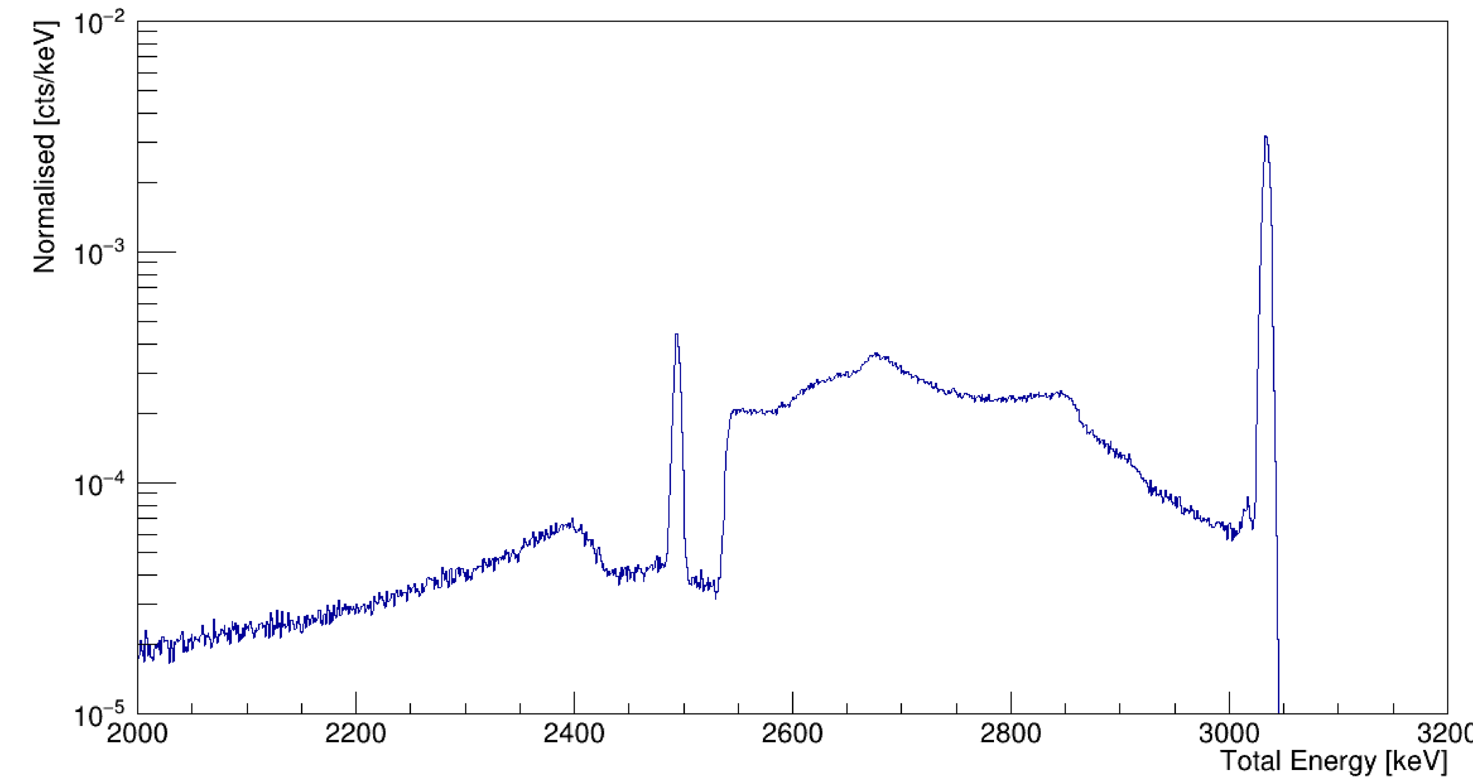

Figure 3: MC simulation of total energy M2 Spectrum of $0\nu\beta\beta$ to 2_1^+, the two peaks are at 3034 keV, 2494 keV.

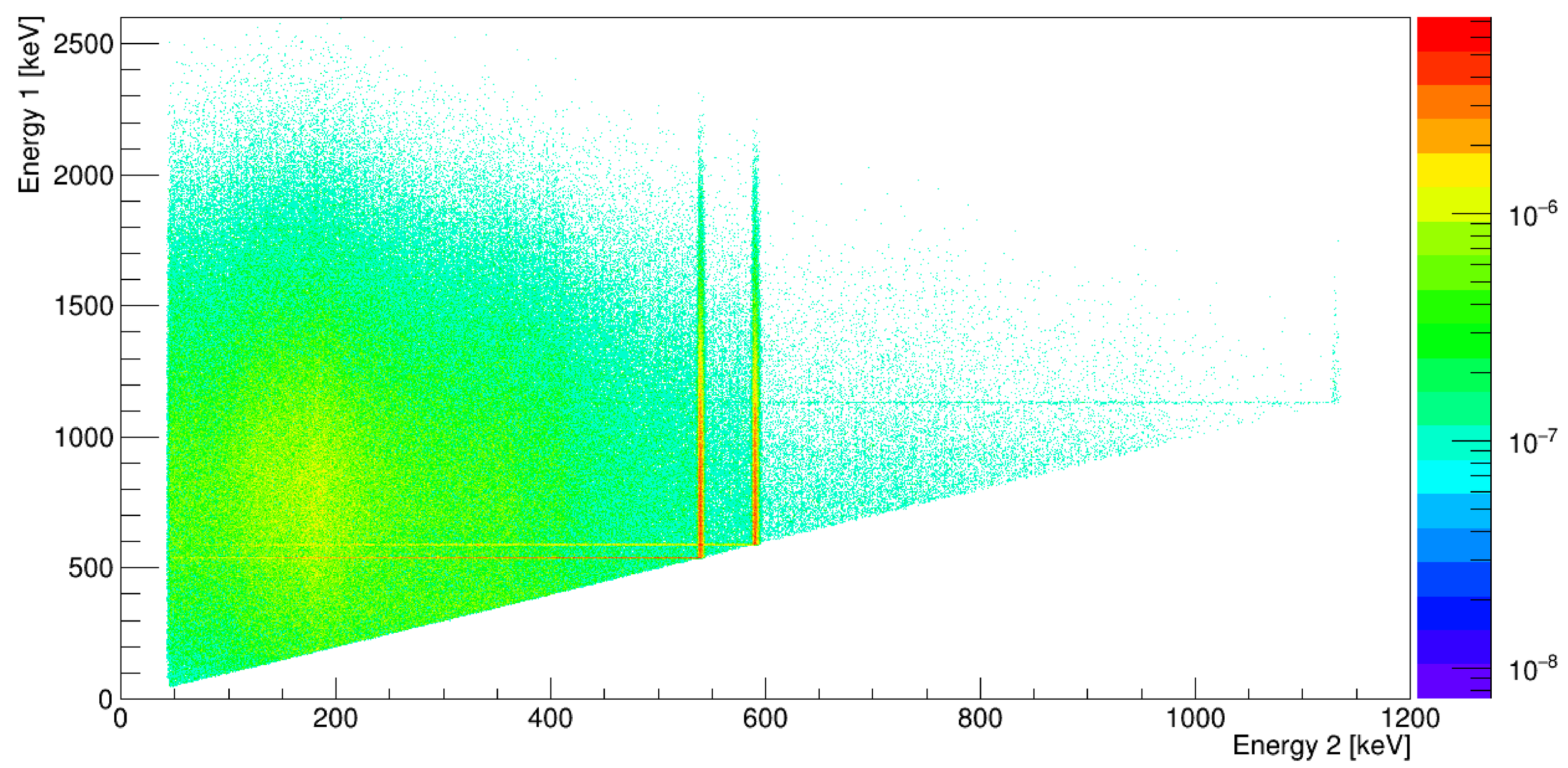

Figure 4: Normalised MC simulation of M2 Spectrum of $2\nu\beta\beta$ to 0_1^+, the 540 and 590 keV gammas are visible as vertical and horizontal lines.

References

[1] The CUPID Interest Group CUPID pre-CDR `arXiv:1907.09376`
[2] Armengaud, et al., The CUPID-Mo experiment for neutrinoless double-beta decay: performance and prospects. Eur. Phys. J. C 80, 44 (2020)
[3] R.Arnold, et al., Measurement of double beta decay of ^{100}Mo to excited states in the NEMO 3 experiment, Nucl. Phys. A 781, 209, (2007)
[4] O.A Ponkratenko et al., Phys. Atom. Nucl. 63, 1282 (2000)
[5] F.Alessandria et al., Sensitivity and Discovery Potential of CUORE to Neutrinoless Double-Beta Decay `arXiv:1109.04`
[6] R. Arnold, et al., Investigation of double beta decay of ^{100}Mo to excited states of ^{100}Ru, Nucl. Phys. A, 925, 25 (2014)
[7] A. S. Barabash, Double beta decay to the excited states: Review, AIP Conf. Proc. 1894, 020002 (2017)

Signal containment and Background

- We evaluate the signal containment efficiencies (ε) for various signatures using an energy dependent window of $\pm$ FWHM/2 ($\Delta E/2$) and an analysis efficiency of 0.9^m where m is the multiplicity
- Use a preliminary background model (see poster by P. Loaiza # 418) to make prediction for each ROI
- For the $\boldsymbol{2\nu\beta\beta}$ to 0_1^+ state we compute S, B (expected number of signal and background counts) using the measured half-life from the NEMO-3 collaboration [3] and thus the significance $S/\sqrt{S+B}$

Decay	Energy 1 [keV]	Energy 2 [keV]	ε [%]	b [ckky]	ΔE [keV]	$\hat{T}_{1/2}$ [yrs]	$S/\sqrt{S+B}$
$\boldsymbol{2\nu\beta\beta\ \ 0^+ \to 0_1^+}$	$535 - 2494$	540	0.69	10	3.6	-	4.6
$\boldsymbol{2\nu\beta\beta\ \ 0^+ \to 0_1^+}$	$585 - 2444$	590	0.50	10	3.7	-	3.5
$\boldsymbol{2\nu\beta\beta\ \ 0^+ \to 2_1^+}$	$0 - 2494$	540	1.0	15	3.6	2.4E21	-

Table 1: Efficiencies, backgrounds and 90% CL sensitivities for $2\nu\beta\beta$ to excited states, predicted significance is given for the decay to 0_1^+ state.

Decay	Energy 1 +Energy 2 [keV]	ε [%]	b [ckky]	ΔE [keV]	$\hat{T}_{1/2}$ [yrs]
$\boldsymbol{0\nu\beta\beta\ \ 0^+ \to 2_1^+}$	3034	1.9	0.1	7.7	1.1E22
$\boldsymbol{0\nu\beta\beta\ \ 0^+ \to 0_1^+}$	3034	0.36	0.1	7.7	2.1E21
$\boldsymbol{0\nu\beta\beta\ \ 0^+ \to 0_1^+}$	2444	1.2	1	6.9	8.3E21
$\boldsymbol{0\nu\beta\beta\ \ 0^+ \to 0_1^+}$	2494	1.1	1	7.0	7.6E21

Table 2: Efficiencies, backgrounds and 90% CL sensitivities for $\boldsymbol{0\nu\beta\beta}$ to excited states.

Decay	M1 Energy [keV]	ε [%]	b [ckky]	ΔE [keV]	$\hat{T}_{1/2}$ [yrs]
$\boldsymbol{0\nu\beta\beta\ \ 0^+ \to 2_1^+}$	3034	5.9	1E-2	7.7	8.6E22
$\boldsymbol{0\nu\beta\beta\ \ 0^+ \to 2_1^+}$	2494	32.7	5.5	7.0	1.1E23

Table 3: Efficiencies, backgrounds and 90% CL sensitivities for M1 signatures for $\boldsymbol{0\nu\beta\beta}$ to excited states

Predicted Sensitivities

- We expect to be able to make a measurement of $\boldsymbol{2\nu\beta\beta \to 0_1^+}$ with $> 5\sigma$ significance.
- We can use these results to predict conservative experimental 90% exclusion sensitivities for the other decays, after final exposure of $\sim 2.5\,\mathrm{kg\cdot yr}$
- We use the background dominated formula from [5] (Gaussian stat) for $\boldsymbol{2\nu\beta\beta}$ and take a numerical approach to estimate sensitivity for $\boldsymbol{0\nu\beta\beta}$ (Poisson stat)
- Where we have multiple signatures we add them in quadrature.

Decay	Predicted 90% CL sensitivity [yrs]	Current leading 90% CL limit [yrs]
$\boldsymbol{0\nu\beta\beta \to 2_1^+}$	$1.4 \cdot 10^{23}$	$1.6 \cdot 10^{23}$ [3]
$\boldsymbol{0\nu\beta\beta \to 0_1^+}$	$1.1 \cdot 10^{22}$	$8.9 \cdot 10^{22}$ [3]
$\boldsymbol{2\nu\beta\beta \to 2_1^+}$	$2.4 \cdot 10^{21}$	$2.5 \cdot 10^{21}$ [6]

Table 4: Predicted CUPID-Mo Sensitivity and current leading limits

Outlook for CUPID-Mo/CUPID

- **CUPID-Mo** will be able to detect $\boldsymbol{2\nu\beta\beta \to 0_1^+}$ and this will be a new independent measurement of this decay.
- The other results are competitive with the current limits [3,6] motivating a more dedicated analysis.
- Plan to optimize analysis in terms of gamma selection window, inclusion of higher multiplicity events and use of the spectral shape.
- Potential to explore new parameter space for these decays with **CUPID-Mo** and excellent discovery potential for **CUPID** with more than $\times 100$ in mass and a minimization of passive material between detectors.