Precise measurement of two-neutrino double-beta decay of ^{100}Mo with Li_2MoO_4 low temperature detectors: preliminary results

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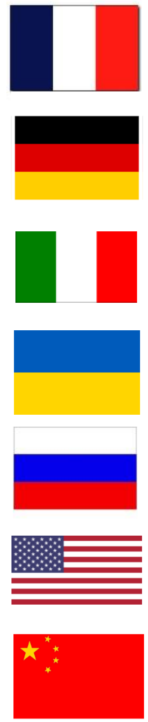
***** The data here reported belong to the CUPID-Mo collaboration. However, the $2\nu2\beta$ analysis has not been finalized at the collaboration level yet, therefore all the $2\nu2\beta$ results have to be considered as a personal elaboration of the speaker

CUPID-Mo collaboration

CSNSM, France
CEA/DRF, France
IPNL, France
LAL, France
KIT, Germany
INFN, LNGS, Italy
KINR, Ukraine
JINR, Russia
ITEP, Russia
NIIC, Russia
MIT, US
UCB/LBNL, US
CUPID-China, P.R. China



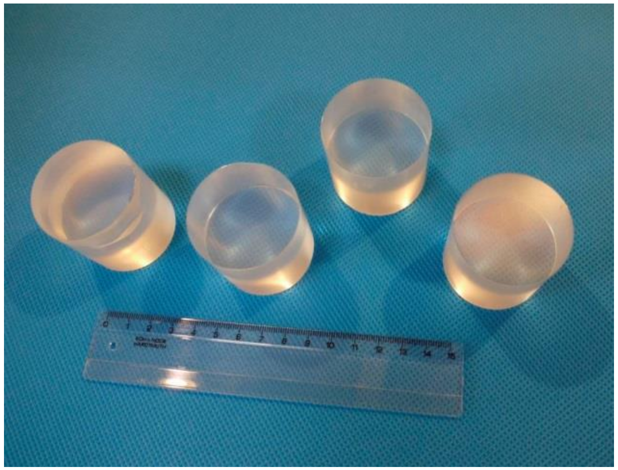
Léon Perrault (1832–1908)
Les flèches de Cupidon *)

CUPID-Mo is an important milestone in the framework of the CUPID R&D activities and will provide essential elements for the choice of the CUPID technique, by clarifying the merits and the drawbacks of the ^{100}Mo option. A final goal is $0\nu2\beta$ decay of ^{100}Mo.

*) Disclaimer: It is neither an official CUPID nor CUPID-Mo logo, I just like this painting…

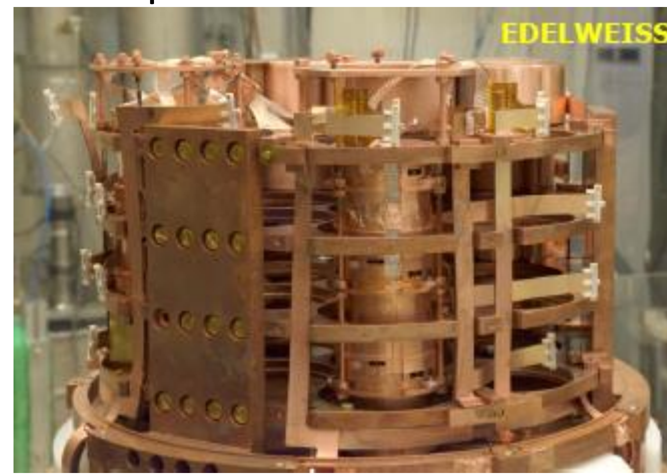
Experiment

$Li_2{}^{100}MoO_4$ scintillators



Detectors assembling

EDELWEISS-III set-up at the Modane Underground Laboratory, 4800 m of water equivalent

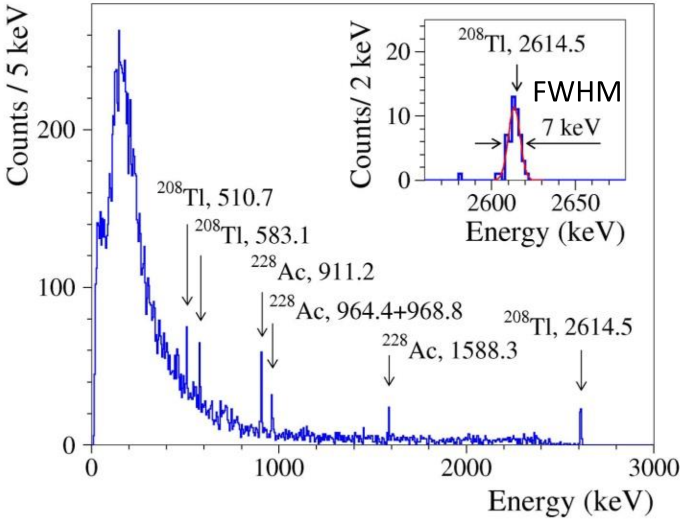


$Li_2{}^{100}MoO_4$ crystal scintillators used in the experiment (enrichment 96.9 ± 0.2 %)

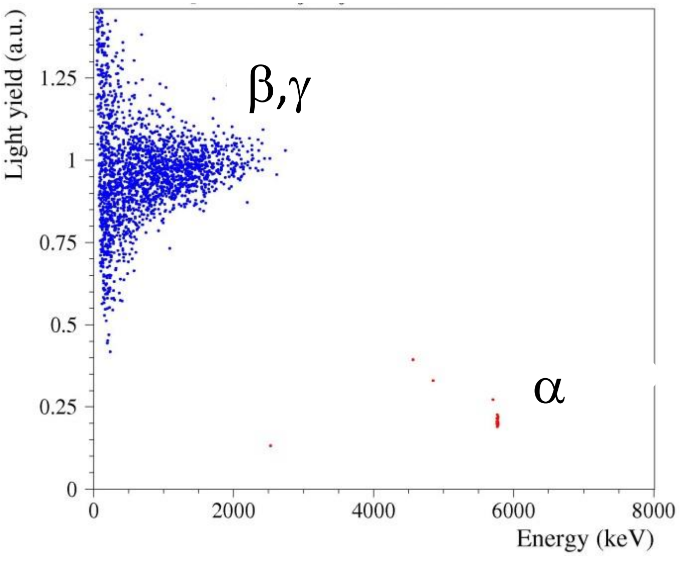
Crystal mass (g), size (mm)	Number of ^{100}Mo nuclei	Live time (h)	
		Set-up 1	Set-up 2
185.86, ∅43.6×40.0	6.103×10^{23}	1331.03	1000.58
203.72, ∅43.6×44.2	6.689×10^{23}		997.64
212.61, ∅43.9×45.6	6.981×10^{23}		1037.92
206.68, ∅43.9×44.5	6.787×10^{23}		756.59

$Li_2{}^{100}MoO_4$ detectors performance

Li_2MoO_4 scintillation bolometers were first proposed in [1] and developed by the LUMINEU project [2]



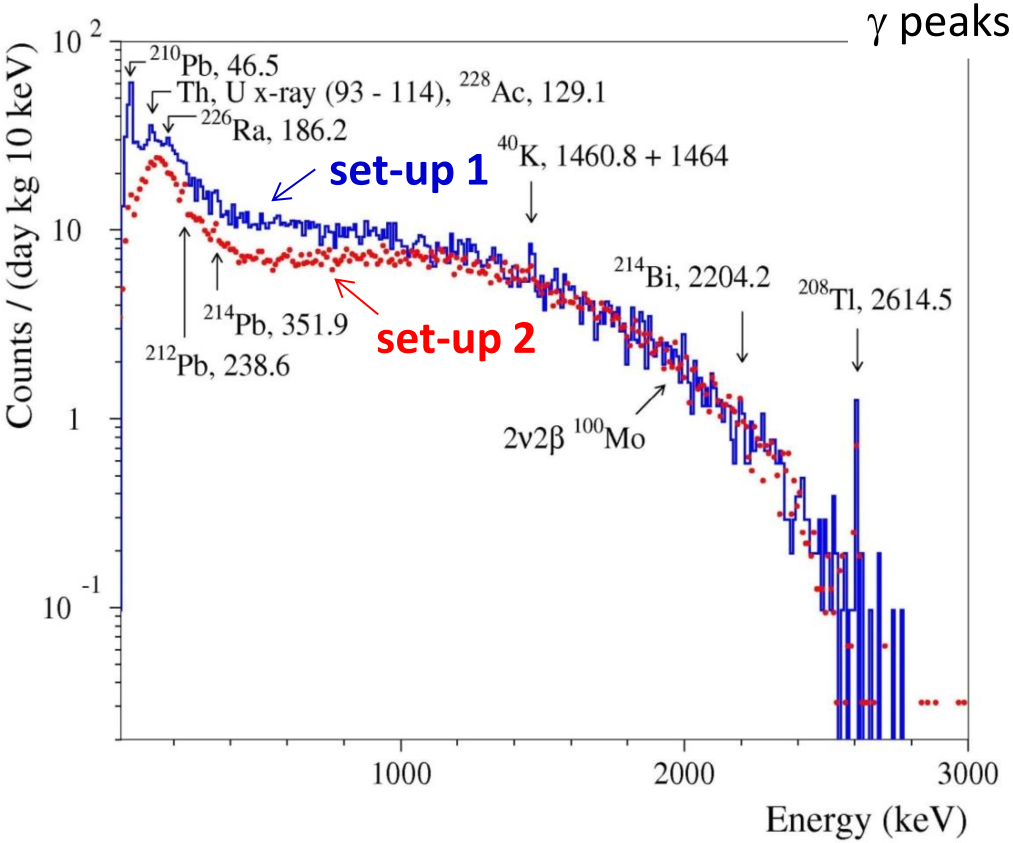
- High energy resolution 5-7 keV at 2615 keV



- Excellent particle discrimination ($DP_{\alpha/\beta}$ ~ 9 - 18)
- High radio-purity (< 3 μBq/kg of ^{228}Th and ^{226}Ra, <5 μBq/kg of ^{238}U) [3]
- The established technology of $Li_2{}^{100}MoO_4$ crystal growth (high yield of crystal boule: > 80%, low irrecoverable losses: ~2-3%, recovery of ^{100}Mo)

[1] O.Barinova et al., NIMA 613 (2010) 54
[2] http://lumineu.in2p3.fr/.
[3] R&D and performance of Li_2MoO_4 detectors: E. Armengaud et al., Eur. Phys. J. C 77 (2017) 785

Experimental energy spectra

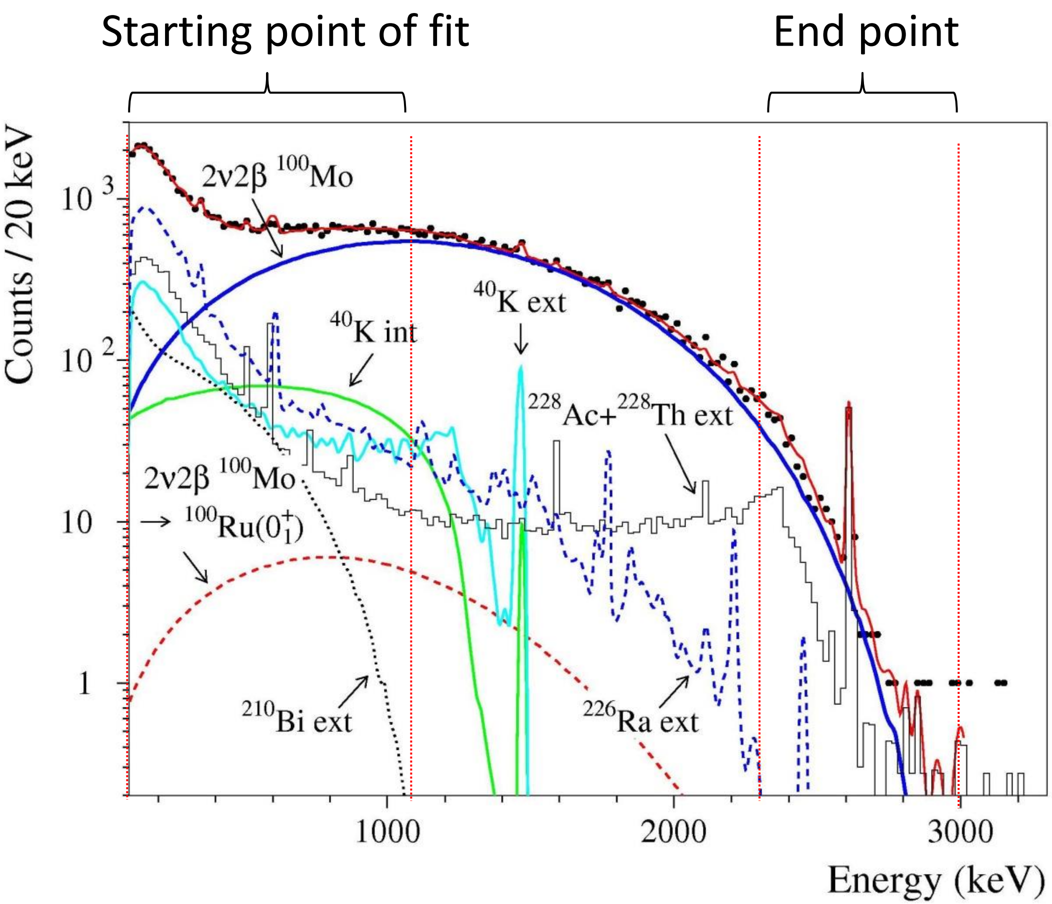


γ peaks in the sum energy spectrum (1013.64 kg×h)

Peak energy (keV)	Peak area (counts)	Nuclide	Energy of γ quanta (keV)
47.4(4)	1026(110)	^{210}Pb	46.5
239.7(8)	170(34)	^{212}Pb	238.6
351.3(18)	109(28)	^{214}Pb	351.9
1462.8(21)	134(34)	^{40}K	1460.8
2204.4(13)	21(8)	^{214}Bi	2204.2
2614.3(16)	33(6)	^{208}Tl	2614.5

- The contributions of external γ from ^{226}Ra and ^{228}Th can be estimated from γ peaks of ^{212}Pb, ^{214}Pb, ^{214}Bi, ^{208}Tl
- The 1462.8 keV peak is due to potassium in the crystals and in the set-up (since the peak is widened)

Background model



The sum 1013.64 kg×h energy spectrum was fitted in (100-1100) keV – (2300-3000) keV by the following model:

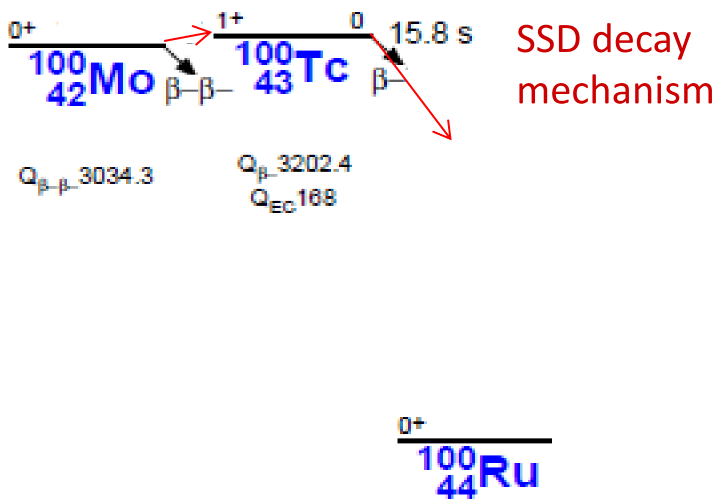
- $2\nu2\beta$ decay to the ground state
- $2\nu2\beta$ decay to the first 0^+ excited level of ^{100}Ru

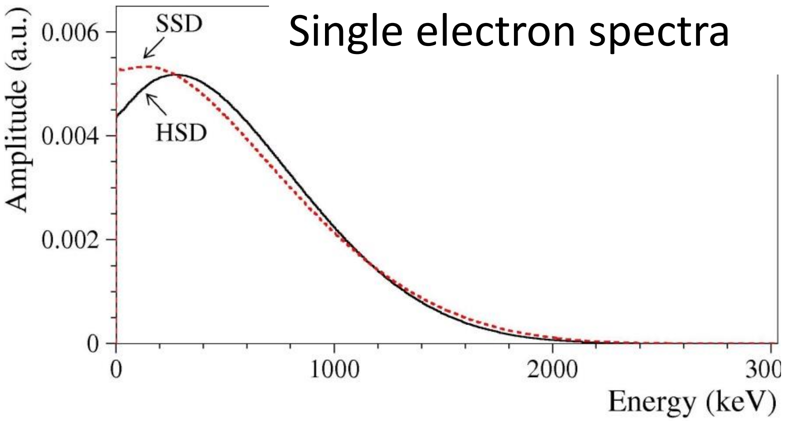
  $T_{\frac{1}{2}}^{2\nu2\beta}(0_1) = (7.5 \pm 0.8) \times 10^{20}$ yr [1]
- Internal ^{40}K, ^{90}Sr – ^{90}Y, ^{87}Rb
- External ^{40}K, ^{228}Ra, ^{228}Th, ^{226}Ra, ^{210}Pb

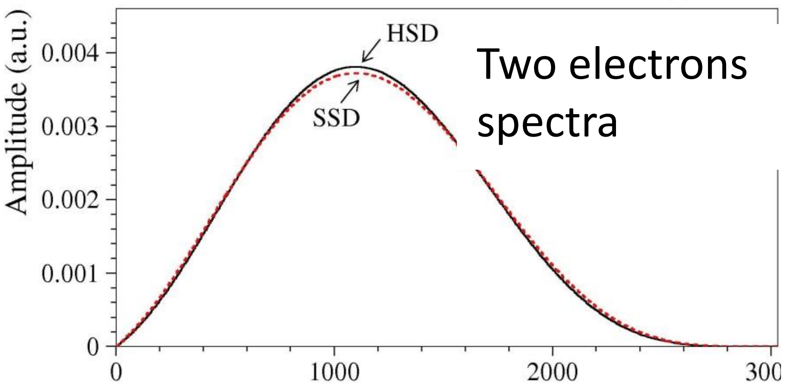
The model describes the experimental data with χ^2/n.d.f. = 0.79 – 1.17

[1] R. Arnold et al., NPA 925 (2014) 25

The mechanism of the decay: SSD or HSD ?



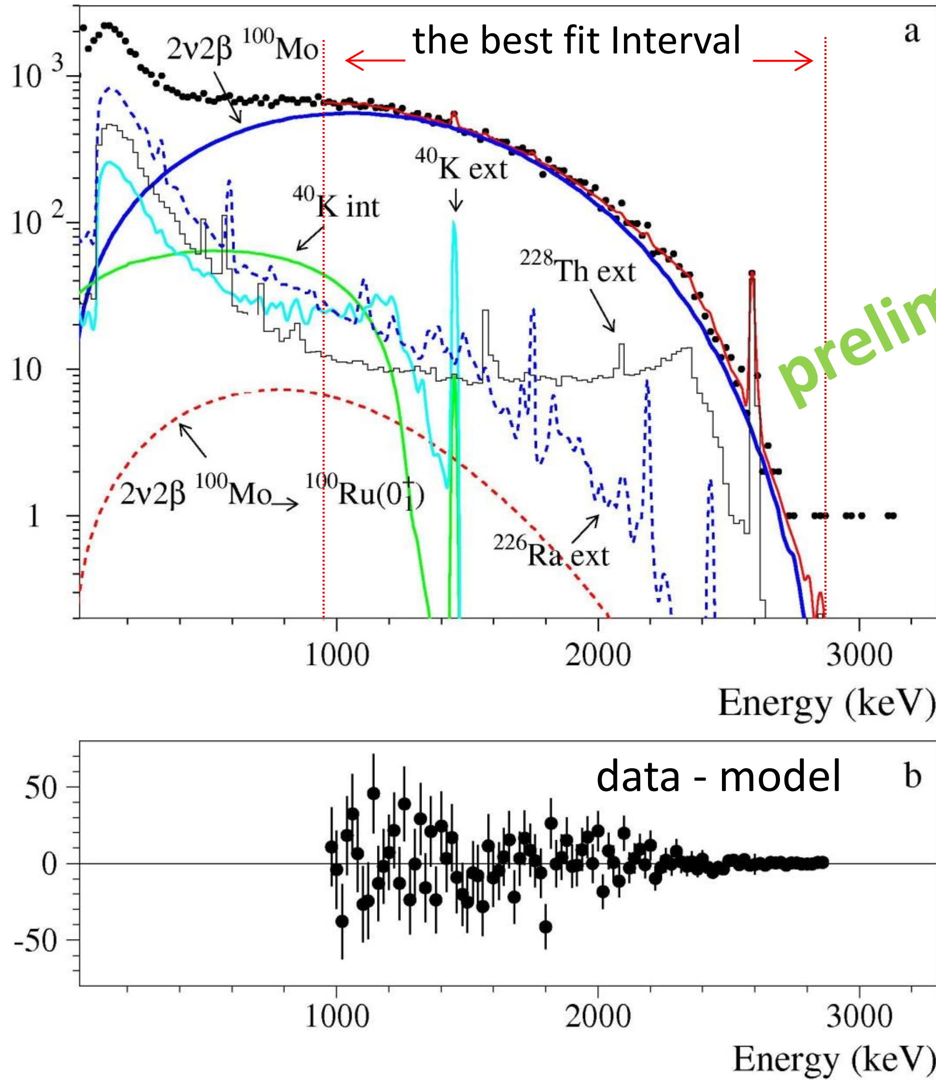




- As it was proposed in [1] in some nuclei the lowest 1^+ intermediate state dominates the $2\nu2\beta$-decay. This is so called the single-state dominance hypothesis (SSD), in contrast to the high-state dominance (HSD) [2]. "^{100}Mo is one of the few cases where the SSD may have some merit" [3]
- The HSD model is excluded with high confidence by the NEMO-3, while the SSD model is consistent with the data [4]
- We have used SSD spectrum to estimate the $T_{1/2}$

[1] J. Abad et al., Ann. Fis. A 80 (1984) 9
[2] P. Domin et al., Nucl. Phys. A 735 (2005) 337
[3] F. Iachello, private communication
[4] R. Arnold et al., Eur. Phys. J. C 79 (2019) 440

The half-life



The best fit (χ^2/n.d.f. = 0.79) achieved in the 940 – 2860 keV interval,
the signal / background = 8.4

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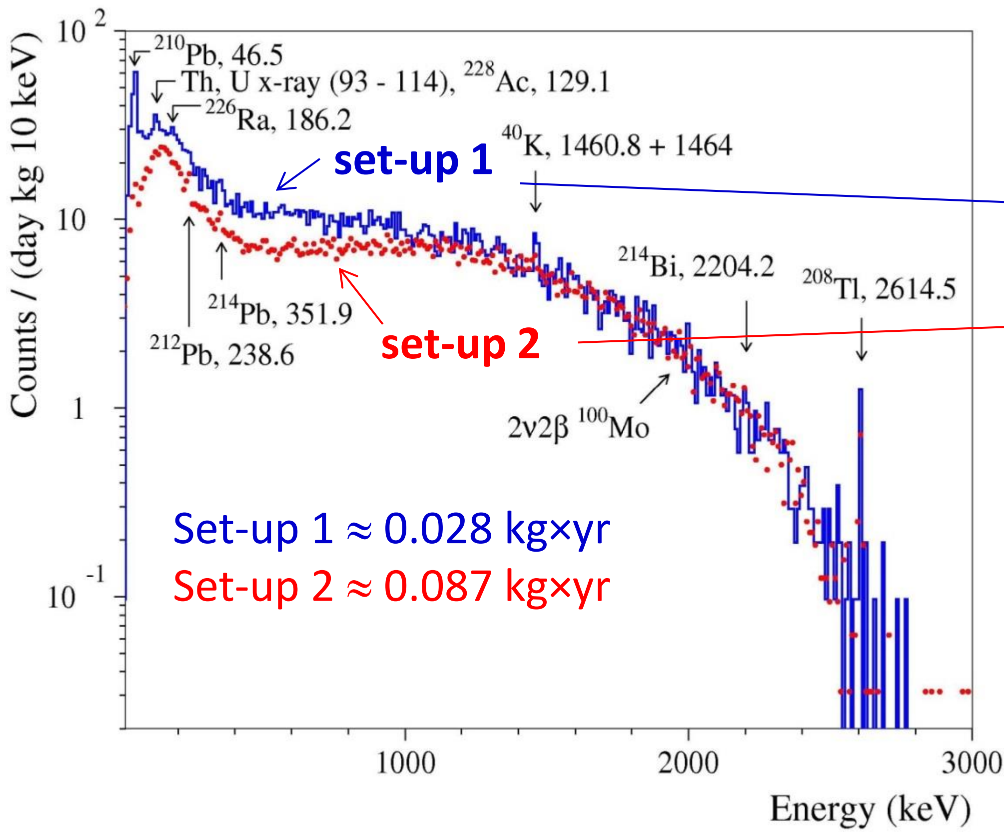
$$T_{1/2}^{2\nu2\beta} = [6.988 \pm 0.074(\mathrm{stat})]\times10^{18}\ \mathrm{yr}$$

The statistical error includes the background model uncertainty

Estimation of the background model error by using the experimental data



$T_{1/2}$=6.92±0.11 ×10^{18} yr

$T_{1/2}$=7.04±0.06 ×10^{18} yr

$\Delta T_{1/2}$= 0.12 ×10^{18} yr (1.7%)

The difference between the $T_{1/2}$ from the data of the set-up 1 and 2 is 0.12×10^{18} yr, consistent with the error 0.086×10^{18} yr obtained from the fit of the sum spectrum

Estimated systematic uncertainties (%)

Number of ^{100}Mo nuclei	±0.2
Live time	±0.22
Pulse-shape discrimination cut to accept β events	±0.60
Localization of radioactivity in the set-up	±0.85
Interval of fit	$^{+0.80}_{-0.86}$
Monte Carlo simulated models statistic	±1
Energy scale instability	±0.46
2ν2β spectral shape	±1
Mechanism of decay (HSD instead of SSD)	$+0.14$
Total systematic error	$^{+2.01}_{-2.03}$
Statistical error	**±1.05**
Total error	$^{+2.27}_{-2.29}$

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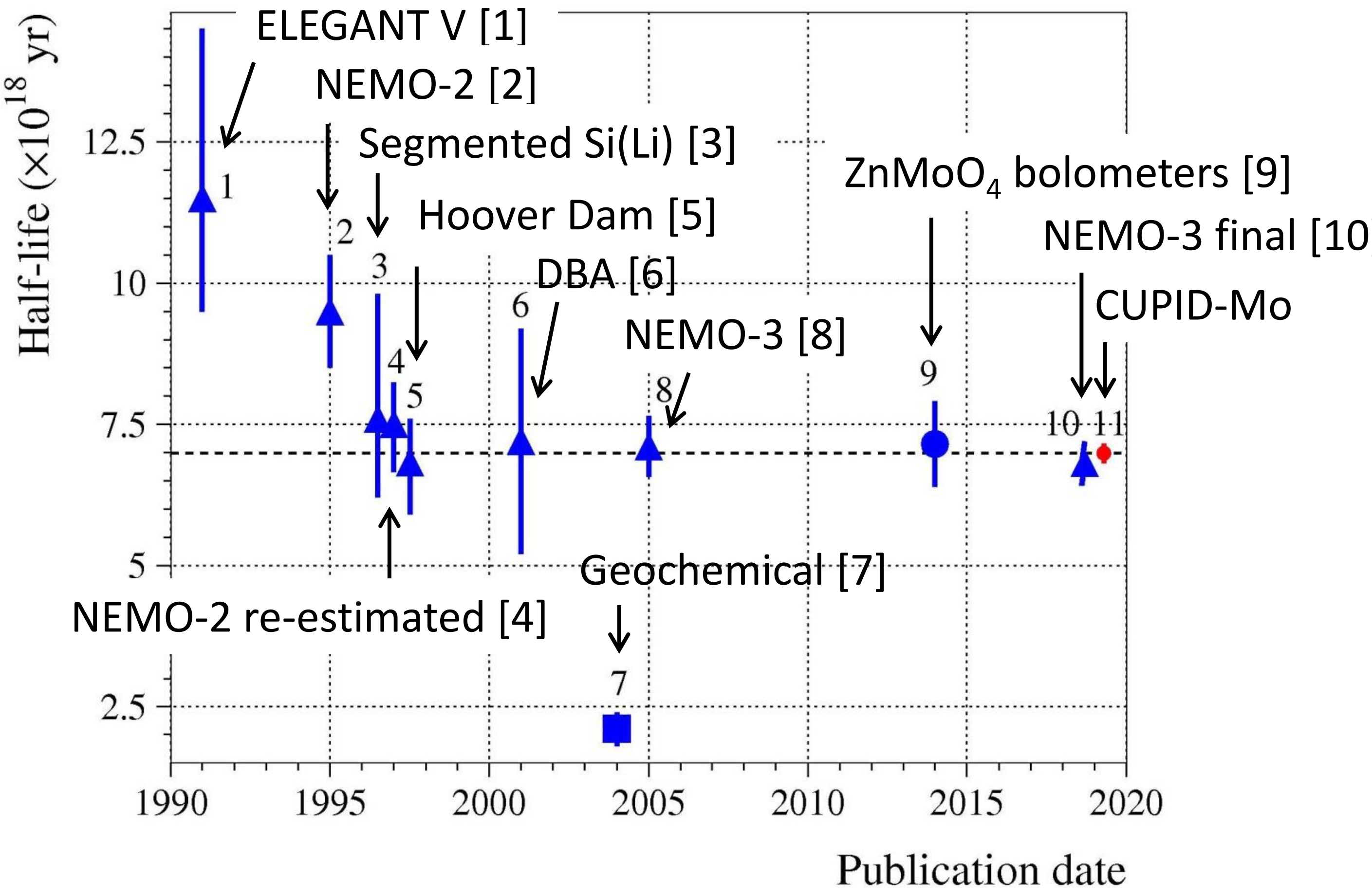
$$T_{1/2}^{2\nu2\beta} = [6.988 \pm 0.074(\mathrm{stat})\ ^{+0.141}_{-0.142}(\mathrm{syst})] \times 10^{18}\ \mathrm{yr}$$

$$\boldsymbol{T_{1/2}^{2\nu2\beta} = (6.99 \pm 0.16) \times 10^{18}\ \mathrm{yr}}$$

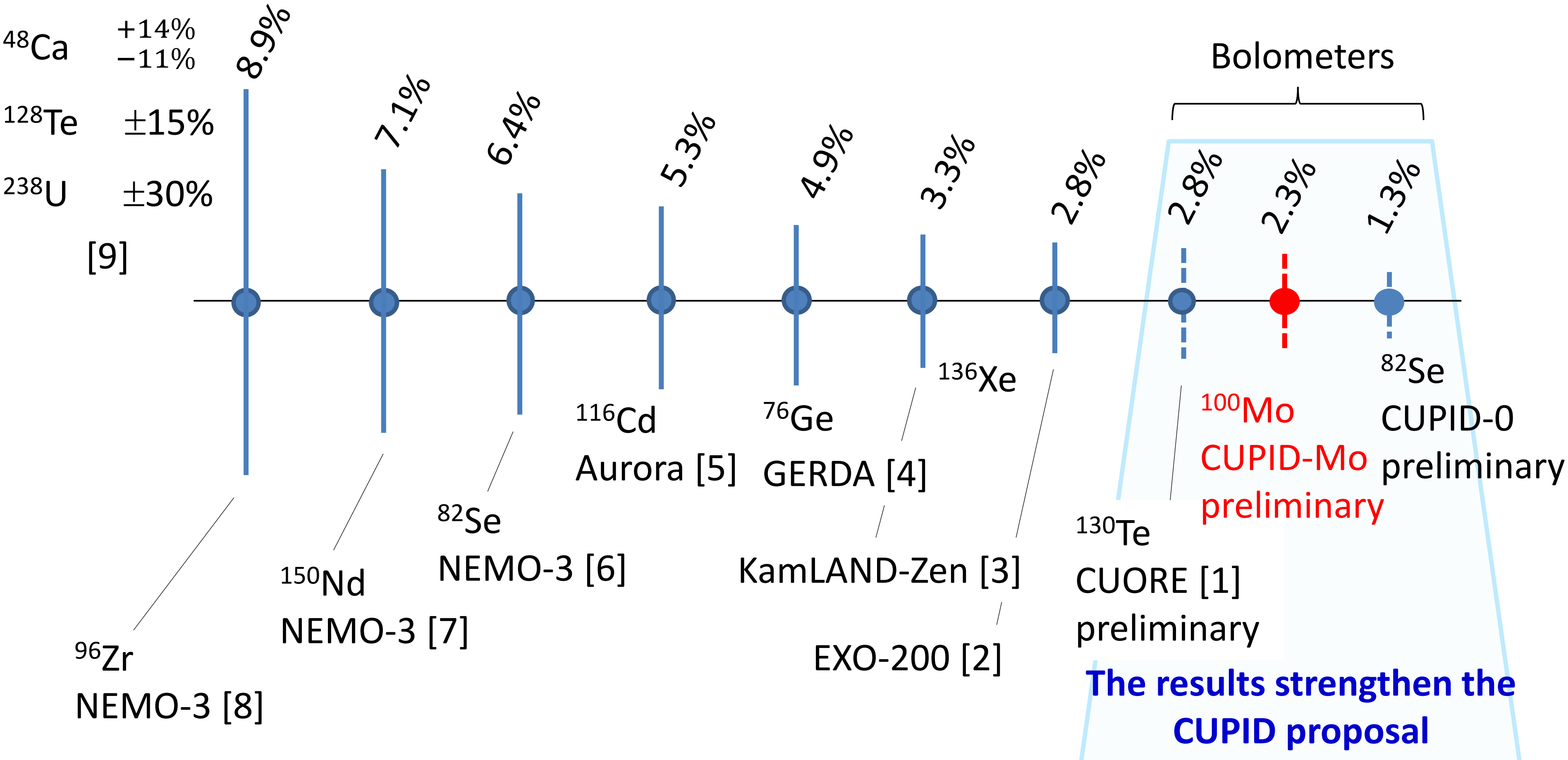
Comparison with other ^{100}Mo experiments



[1] H. Ejiri et al., Phys. Lett. B 258 (1991) 17
[2] D. Dassié et al., Phys. Rev. D 51 (1995) 2090
[3] M. Alston-Garnjost et al., Phys. Rev. C 55 (1997) 474
[4] A. Vareille, PhD thesis, 1997
[5] A. De Silva et al., Phys. Rev. C 56 (1997) 2451

[6] V.D. Ashitkov et al., JETP Lett. 74 (2001) 529
[7] H. Hidaka et al., Phys. Rev. C 70 (2004) 025501
[8] R. Arnold et al., Phys. Rev. Lett. 95 (2005) 182302
[9] L. Cardani et al., J. Phys. G 41 (2014) 075204
[10] R. Arnold et al., Eur. Phys. J. C 79 (2019) 440

Comparison with $T_{1/2}$ for other $2\beta^-$ nuclei



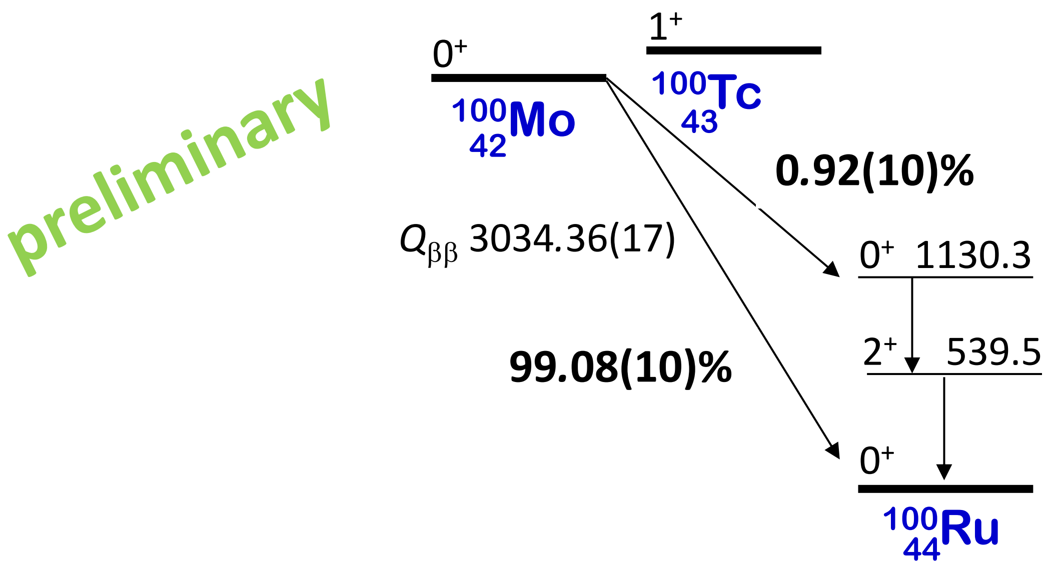
[1] A. Caminata et al., Universe 5 (2019) 10 (Conf. Proc.)
[2] J.B. Albert et al., Phys. Rev. C 89 (2014) 015502
[3] A. Gando et al., Phys. Rev. Lett. 117 (2016) 082503
[4] M. Agostini et al., Eur. Phys. J. C 75 (2015) 416
[5] A.S. Barabash et al., Phys. Rev. D 98 (2018) 092007
[6] R. Arnold et al., Eur. Phys. J. C 78 (2018) 821
[7] R. Arnold et al., Phys. Rev. D 94 (2016) 072003
[8] J. Argyriades et al., Nucl. Phys. A 847 (2010) 168
[9] A.S. Barabash et al., Nucl. Phys. A 935 (2015) 52

The actual half-life of ^{100}Mo

Taking into account that ^{100}Mo nuclei decay by the two modes: to the ground state and to the first 0^+ excited level of ^{100}Ru, the actual half-life of ^{100}Mo (using the most accurate measurement of the decay of ^{100}Mo to the first 0^+ 1130.3 keV excited level of ^{100}Ru [1]) is:

$$T_{1/2} = (6.92 \pm 0.16) \times 10^{18}\ \text{yr}$$

In other words, the branching ratio is 99.08(10)% for the $2\nu2\beta$ decay of ^{100}Mo to the ground state, and 0.92(10)% for decay to the first 0^+ 1130.3 keV excited level of ^{100}Ru



Scheme of 2β decay of ^{100}Mo

[1] R. Arnold et al., NPA 925 (2014) 25

An effective nuclear matrix element for 2ν2β decay of ^{100}Mo

An effective nuclear matrix element for 2ν2β decay of ^{100}Mo to the ground state of ^{100}Ru, assuming the SSD mechanism, by using the phase-space factor 4134×10^{-21} yr^{-1} calculated in [1]:

preliminary

$$\left| M^{\mathrm{eff}}_{2\nu} \right| = 0.1860 \pm 0.0021$$

The effective nuclear matrix element can be written as a product $\left| M^{\mathrm{eff}}_{2\nu} \right| = g_A^2 \times M_{2\nu}$, where g_A is axial vector coupling constant, $M_{2\nu}$ is nuclear matrix element, that is almost independent on the g_A and can be calculated with a reasonable accuracy.

[1] J. Kotila, F. Iachello, Phys. Rev. C 85 (2012) 034316

Summary and Prospects

- The half-life of ^{100}Mo relatively to the 2ν2β decay to the ground state of ^{100}Ru is measured with a highest accuracy (≈2.3%) :

$$T_{1/2}^{2\nu2\beta} = (6.99 \pm 0.16) \times 10^{18}\ \mathrm{yr}$$

- The accuracy was achieved with only ≈ 0.12 kg × yr exposure thanks to utilization of enriched detectors with high energy resolution (provided an accurate background reconstruction), negligible internal contamination and low external background, precisely defined detection efficiency (no problem with fiducial volume, etc), high signal/background ratio

- The accuracy can be further improved in the CUPID-Mo with 20 detectors in progress: higher statistics, a more precise background model

- Depleted in ^{100}Mo $Li_2{}^{100depl}MoO_4$ crystals (0.007% of ^{100}Mo) are already produced to investigate the 2ν2β spectrum shape (mechanism of decay: SSD vs HSD, hypothetical decays, etc.)

Thanks organizers for invitation and kind support!