Measurement of the $2\nu2\beta$ decay of ^{100}Mo with CUPID-Mo precursors

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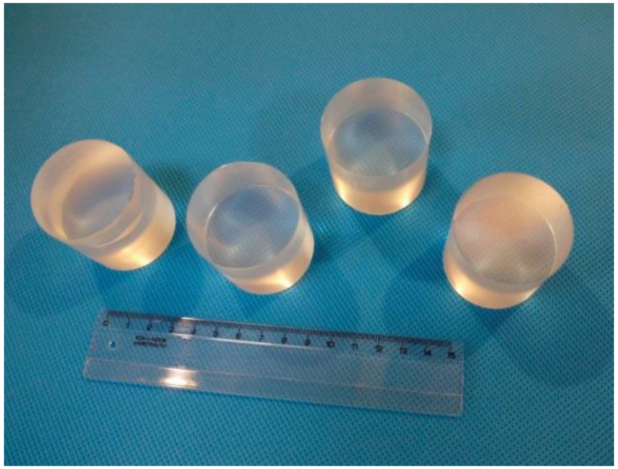
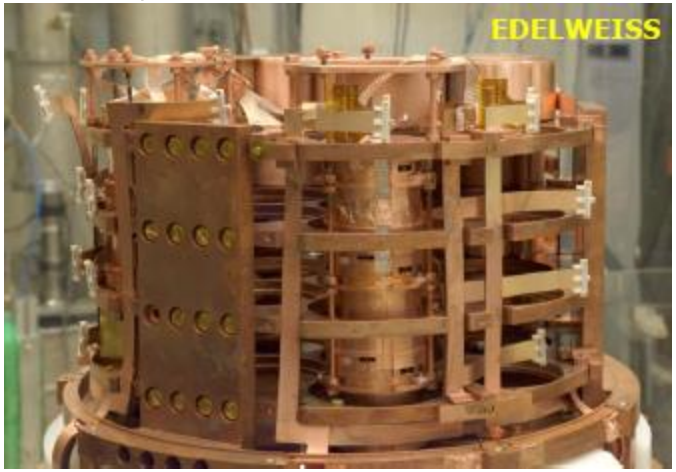
Experiment

$Li_2{}^{100}MoO_4$ scintillators



Detectors assembling

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

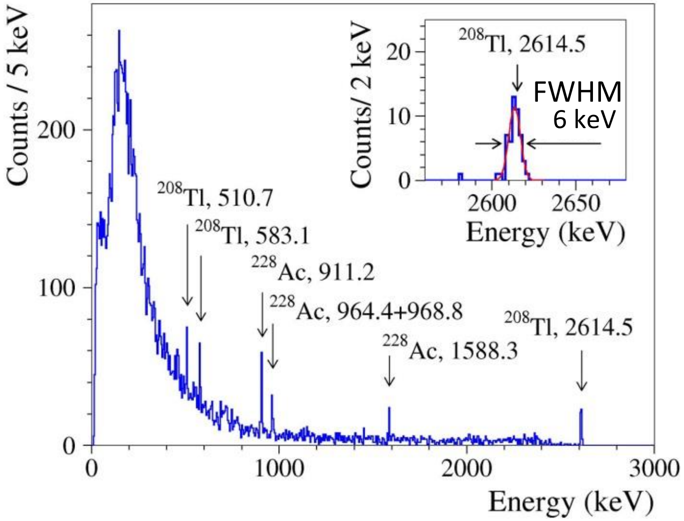


$Li_2{}^{100}MoO_4$ crystal scintillators used in the experiment

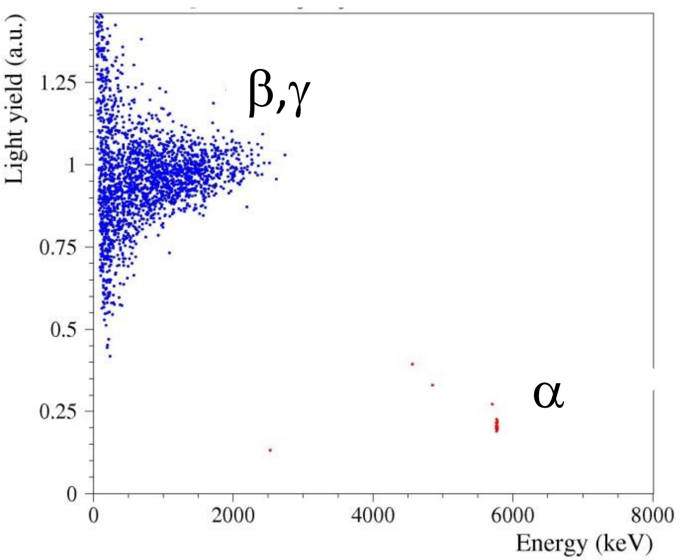
Crystal number, mass (g), size (mm)	^{100}Mo isotopic concentration (%)	Number of ^{100}Mo nuclei	Live time (h)	
			Setup 1	Setup 2
#1, 185.86, ∅43.6×40.0	96.93(7)	$6.105(9)\times10^{23}$	1331.03	1000.58
#2, 203.72, ∅43.6×44.2	96.93(7)	$6.692(10)\times10^{23}$		997.64
#3, 212.61, ∅43.9×45.6		$6.981(16)\times10^{23}$		1037.92
#4, 206.68, ∅43.9×44.5		$6.786(15)\times10^{23}$		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

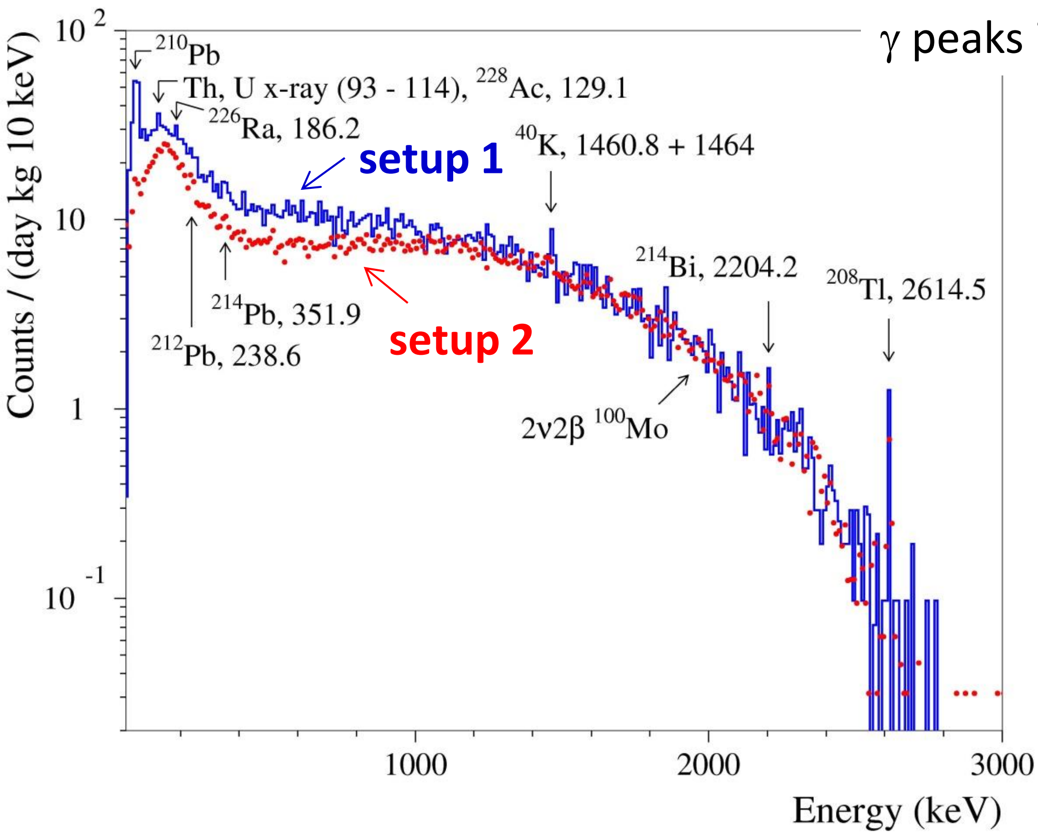


- Excellent particle discrimination ($DP_{\alpha/\beta}$ ~ 9 - 18)
- High radio-purity (< 3 μBq/kg of ^{228}Th and ^{226}Ra, <5 μBq/kg of ^{238}U) [3]

- The established technology of $Li_2{}^{100}MoO_4$ crystal growth (high yield of crystal boule: > 80%, low irrecoverable losses: ~2-3%, recovery procedure for ^{100}Mo is developed)

[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

The experiment was realized in two steps: "setup 1" and "setup 2"



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

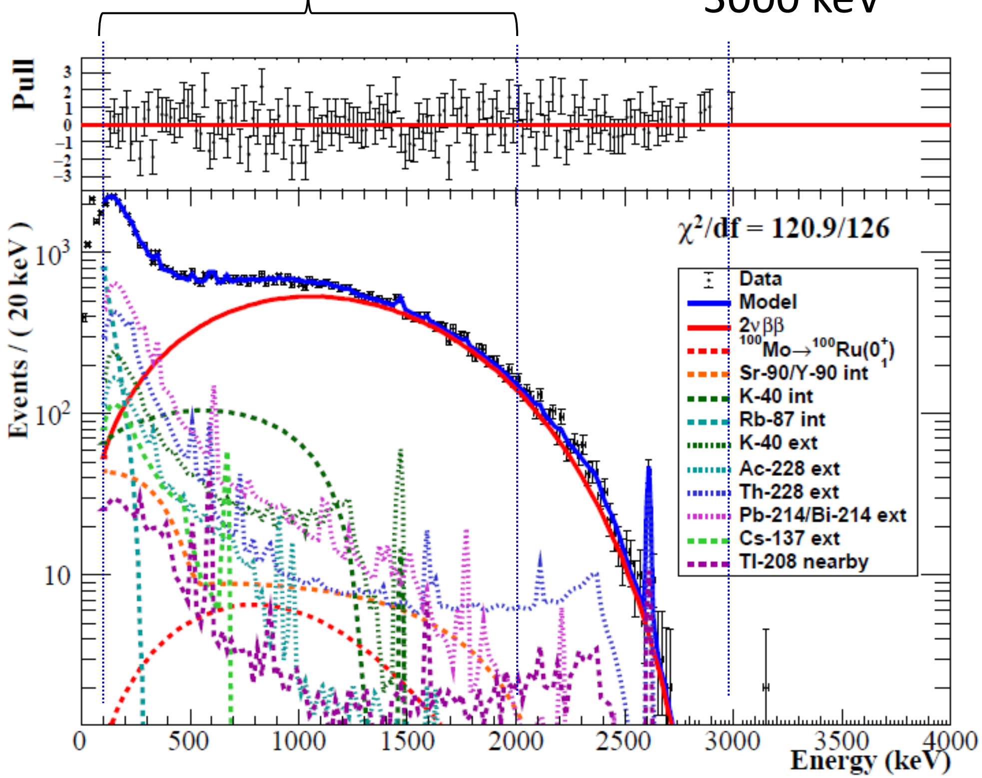
Peak energy (keV)	Peak area (counts)	Nuclide	Energy of γ quanta (keV)
239.7(8)	174(40)	^{212}Pb	238.6
351.3(18)	151(46)	^{214}Pb	351.9
1462.8(21)	134(34)	^{40}K	1460.8
2204.4(13)	22(9)	^{214}Bi	2204.2
2614.3(16)	33(6)	^{208}Tl	2614.5

- 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

Model of background

Starting point,
120 – 2000 keV

Final point,
3000 keV



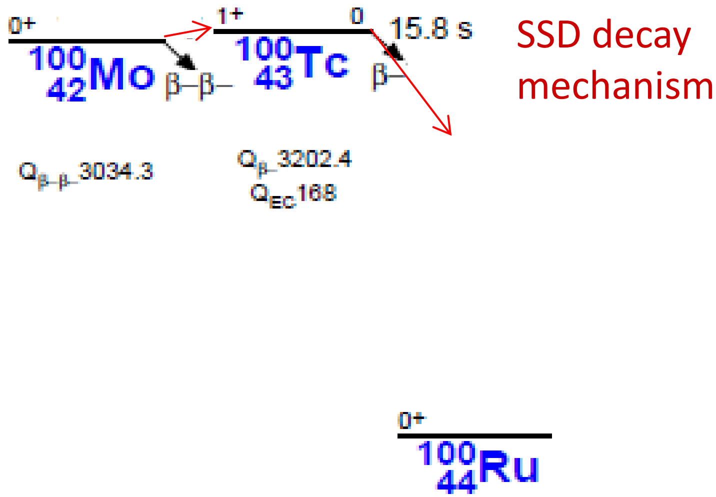
The sum 42.235 kg×d energy spectrum was fitted in (120-2000) keV –3000 keV by the following model:

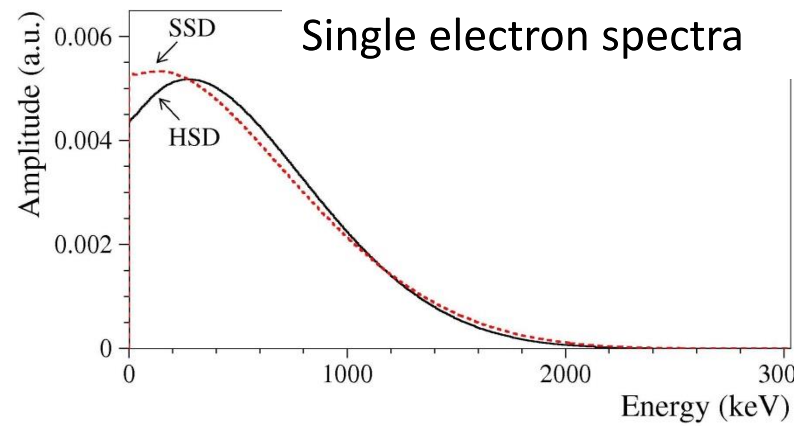
- $2\nu2\beta$ decay to the ground state
- $2\nu2\beta$ decay to the first 0^+ excited level of ^{100}Ru
  $T_{\frac{1}{2}}^{2\nu2\beta}(0_1) = (7.5 \pm 0.8)\times 10^{20}$ yr [1]
- Internal ^{40}K, ^{90}Sr – ^{90}Y, ^{87}Rb, ^{210}Pb-^{210}Bi
- External ^{40}K, ^{137}Cs, ^{228}Ra, ^{228}Th, ^{226}Ra, ^{210}Pb

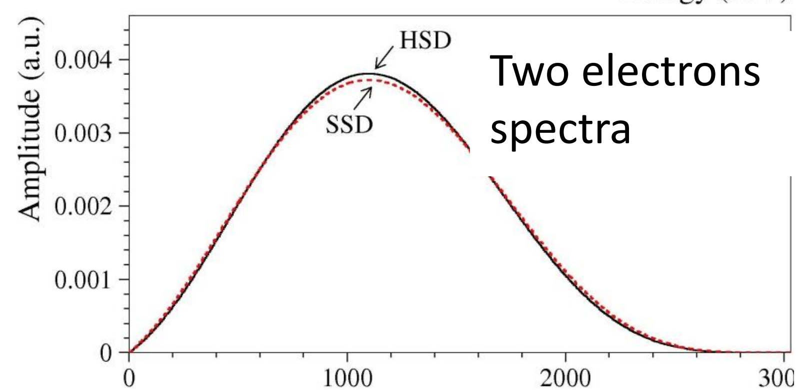
The model describes the experimental data very well with χ^2/n.d.f. = 120.9/126

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

The mechanism of the decay: SSD or HSD ?







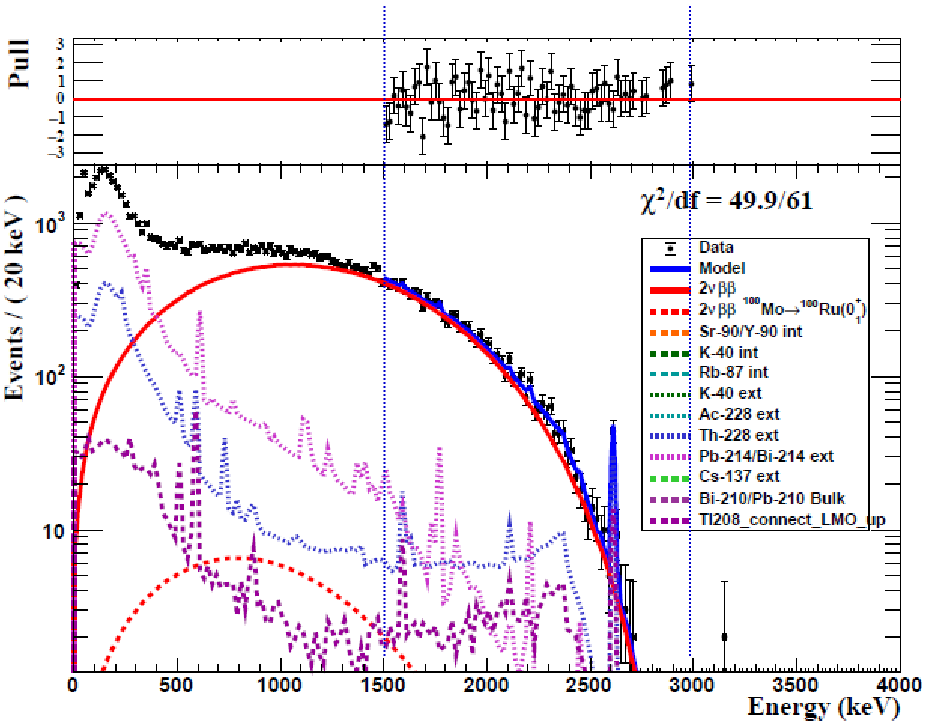
- As it was proposed in [1] in some nuclei the lowest 1^+ intermediate state dominates the $2\nu2\beta$-decay. This is so called the single-state dominance hypothesis (SSD), in contrast to the high-state dominance (HSD) [2]. "^{100}Mo is one of the few cases where the SSD may have some merit" [3]
- The 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 of ^{100}Mo

The interval of fit 1500 – 3000 keV



The fit (χ^2/n.d.f. = 0.82) in the 1500 – 3000 keV interval returns 8370^{+639}_{-912} events (the interval contains 23% of the whole 2ν2β-distribution)

$$T_{1/2}^{2\nu2\beta} = [7.12\,^{+0.18}_{-0.14}(\mathrm{stat})]\times10^{18}\ \mathrm{yr}$$

The signal / background ≈ 10

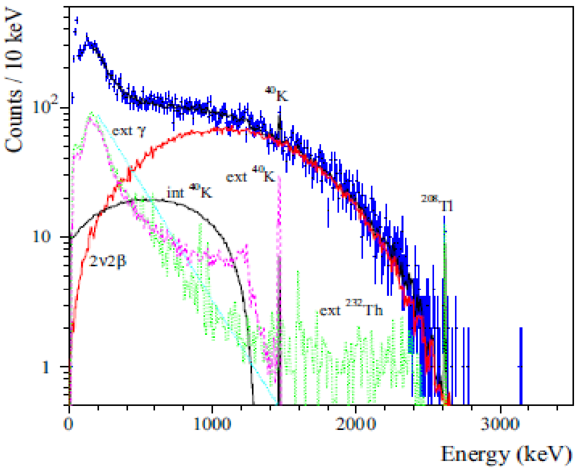
Estimated systematic uncertainties (%)

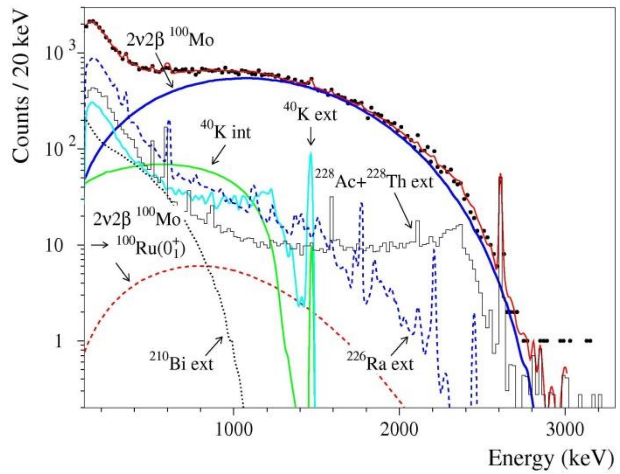
Binning of the energy spectrum	±0.8
Localization of radioactive sources	±0.8
Selection efficiency to accept β events	±0.6
2ν2β spectral shape	±0.4
Monte Carlo simulated models statistic	±0.4
Background composition	±0.3
Exposure of ^{100}Mo	±0.2
Energy scale	±0.2
$T_{1/2}^{2\nu2\beta}$ $^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Ru}(0^+_1)$	±0.1
Total systematic error	**±1.4**

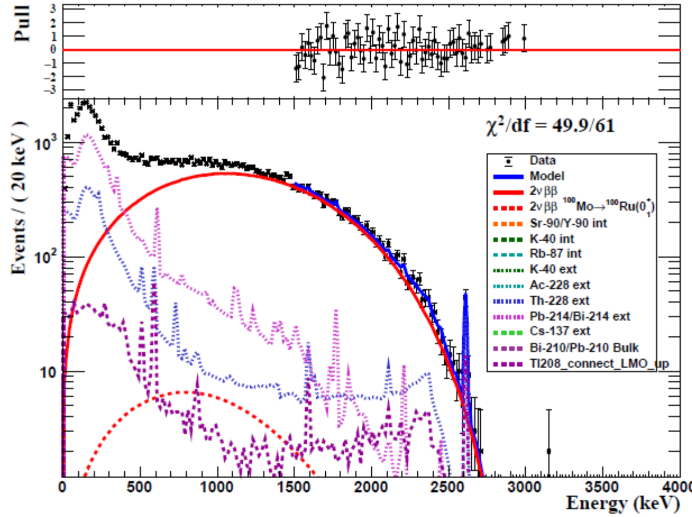
$$T_{1/2}^{2\nu2\beta} = [7.12\,^{+0.18}_{-0.14}(\mathrm{stat}) \pm 0.10\,(\mathrm{syst})] \times 10^{18}\ \mathrm{yr}$$

$$\boldsymbol{T_{1/2}^{2\nu2\beta} = (7.12\,^{+0.21}_{-0.17}) \times 10^{18}\ \mathrm{yr}}$$

History of the ^{100}Mo $T_{1/2}$ ($\times 10^{18}$ yr) from the $Li_2{}^{100}MoO_4$ data



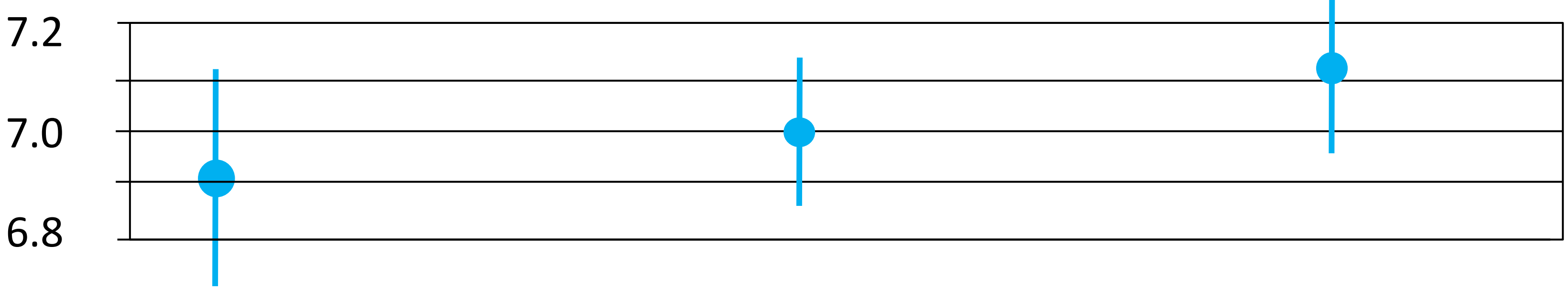




6.90 ± 0.15(stat) ± 0.37(syst) [1]

$[6.99 \pm 0.15]$ [2]

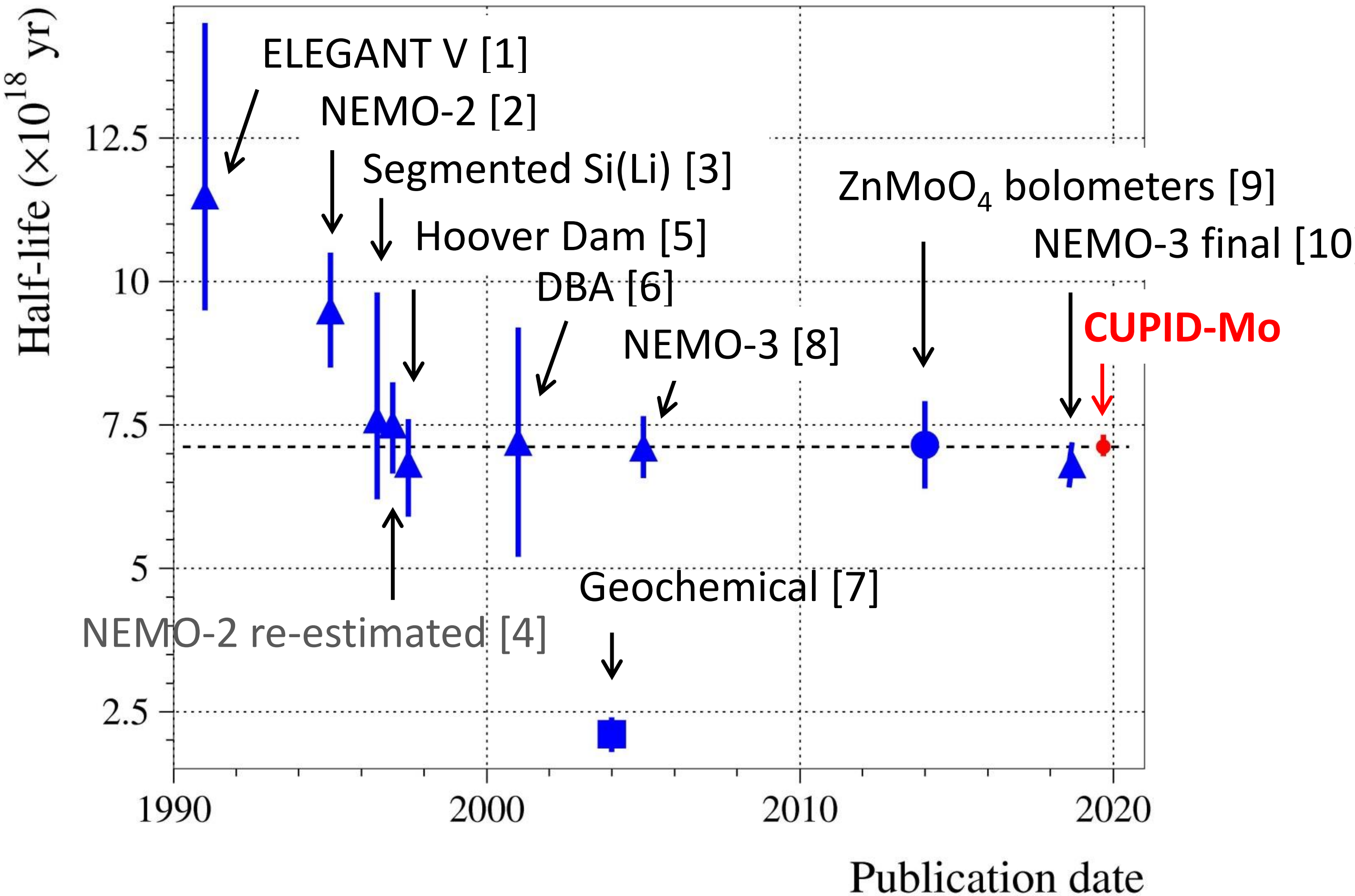
$[7.12^{+0.18}_{-0.14}(\text{stat}) \pm 0.10(\text{syst})]$ [3]



Conclusion: The half-life is proportional to the time spent for and number of people involved in the data analysis…

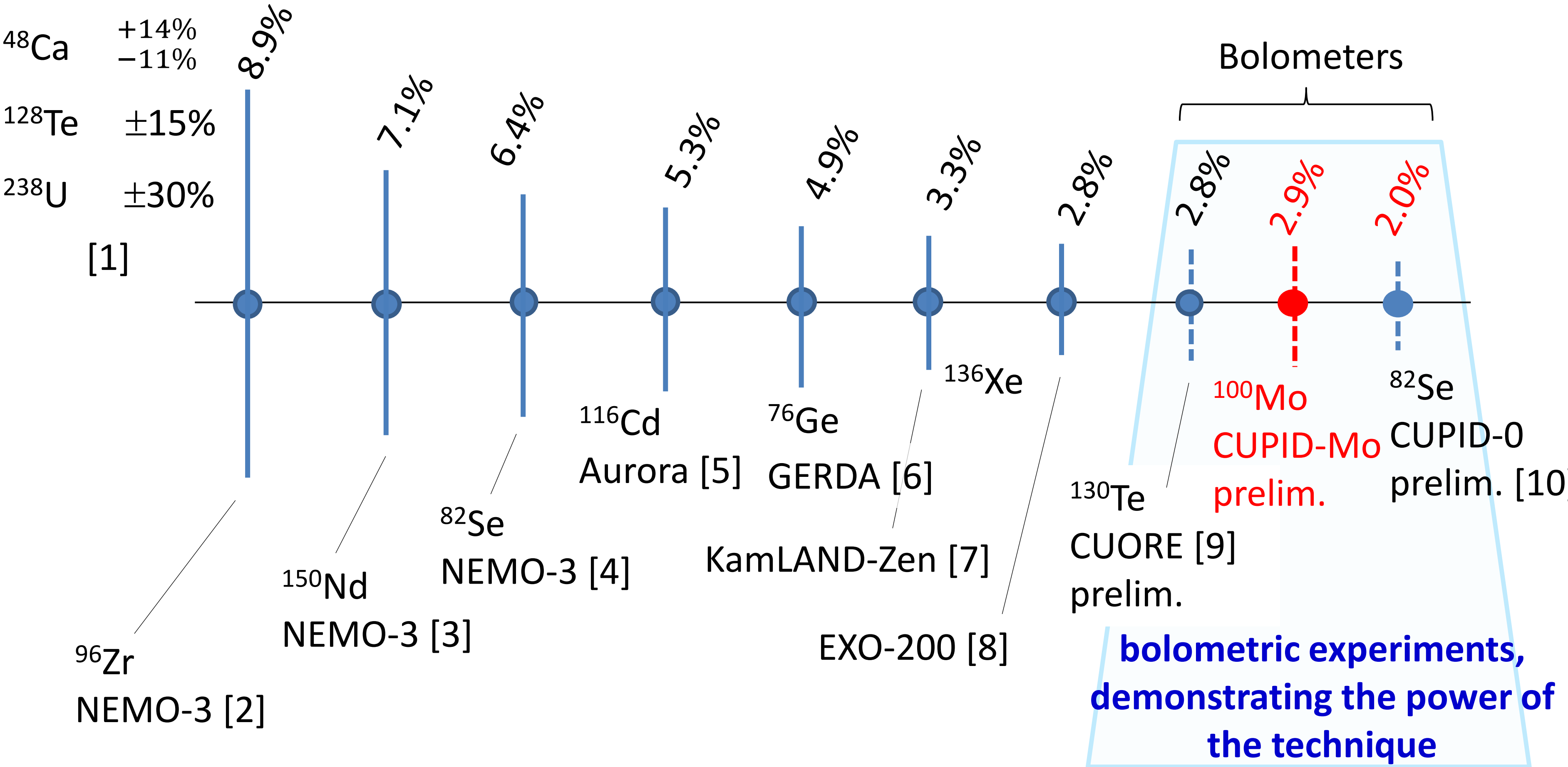
[1] E. Armengaud et al., Eur. Phys. J. C 77 (2017) 785
[2] E. Armengaud et al., AIP Conf. Proc. **2165** (2019) 020005
[3] E. Armengaud et al., in preparation (2020)

CUPID-Mo and 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



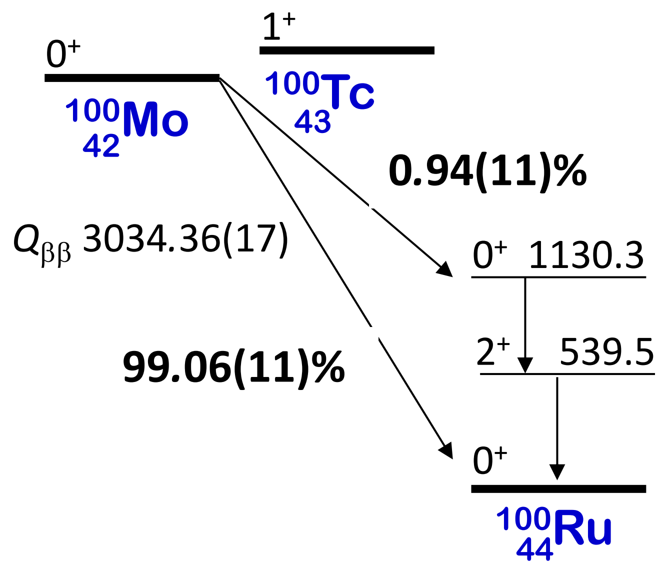
[1] A.S. Barabash et al., Nucl. Phys. A 935 (2015) 52
[2] J. Argyriades et al., Nucl. Phys. A 847 (2010) 168
[3] R. Arnold et al., Phys. Rev. D 94 (2016) 072003
[4] R. Arnold et al., Eur. Phys. J. C 78 (2018) 821
[5] A.S. Barabash et al., Phys. Rev. D 98 (2018) 092007
[6] M. Agostini et al., Eur. Phys. J. C 75 (2015) 416
[7] A. Gando et al., Phys. Rev. Lett. 117 (2016) 082503
[8] J.B. Albert et al., Phys. Rev. C 89 (2014) 015502
[9] A. Caminata et al., Universe 5 (2019) 10 (Conf. Proc.)
[10] O. Azzolini et al. arXiv:1909.03397

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:

$$\mathbf{T_{1/2} = (7.05\,^{+0.21}_{+0.17}) \times 10^{18}\ yr}$$

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]:

$$\left| M^{\mathrm{eff}}_{2\nu} \right| = 0.184 ^{+0.002}_{-0.003}$$

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 (2.9%) :

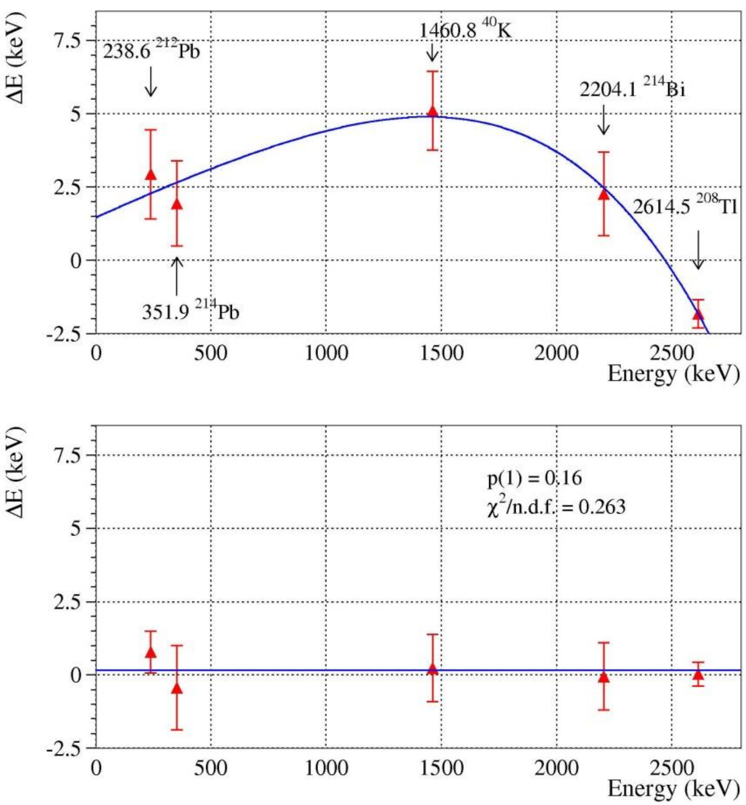
$$T_{1/2}^{2\nu2\beta} = [7.12\ ^{+0.18}_{-0.14}(\mathrm{stat}) \pm 0.10\ (\mathrm{syst})] \times 10^{18}\ \mathrm{yr}$$

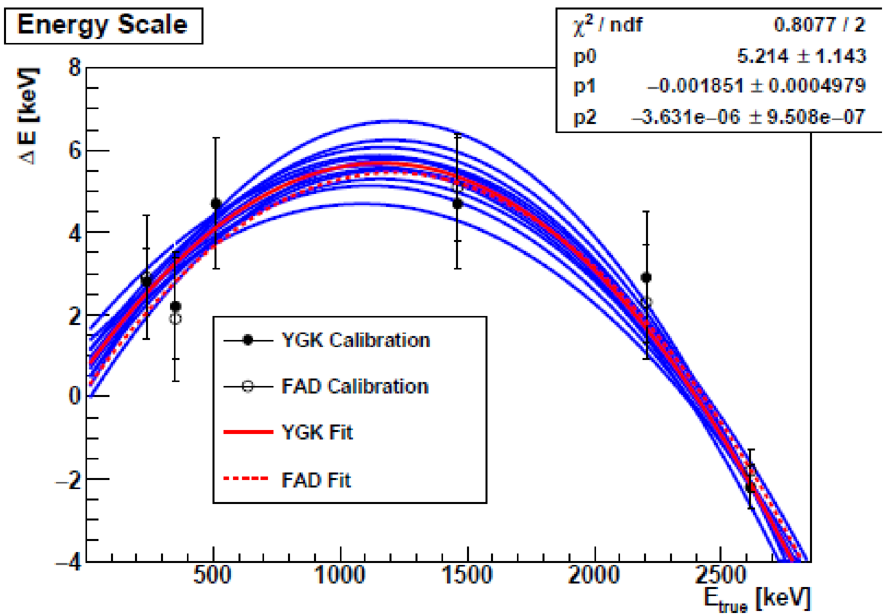
- The accuracy was achieved with only ≈ 0.12 kg × yr exposure thanks to:
  - utilization of enriched detectors
  - negligible radioactive contamination and low background
  - high energy resolution o
  - clearly defined detection efficiency

- The accuracy can be further improved in the CUPID-Mo with 20 detectors in progress

- 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.), and to improve background understanding

Bias in the energy spectrum

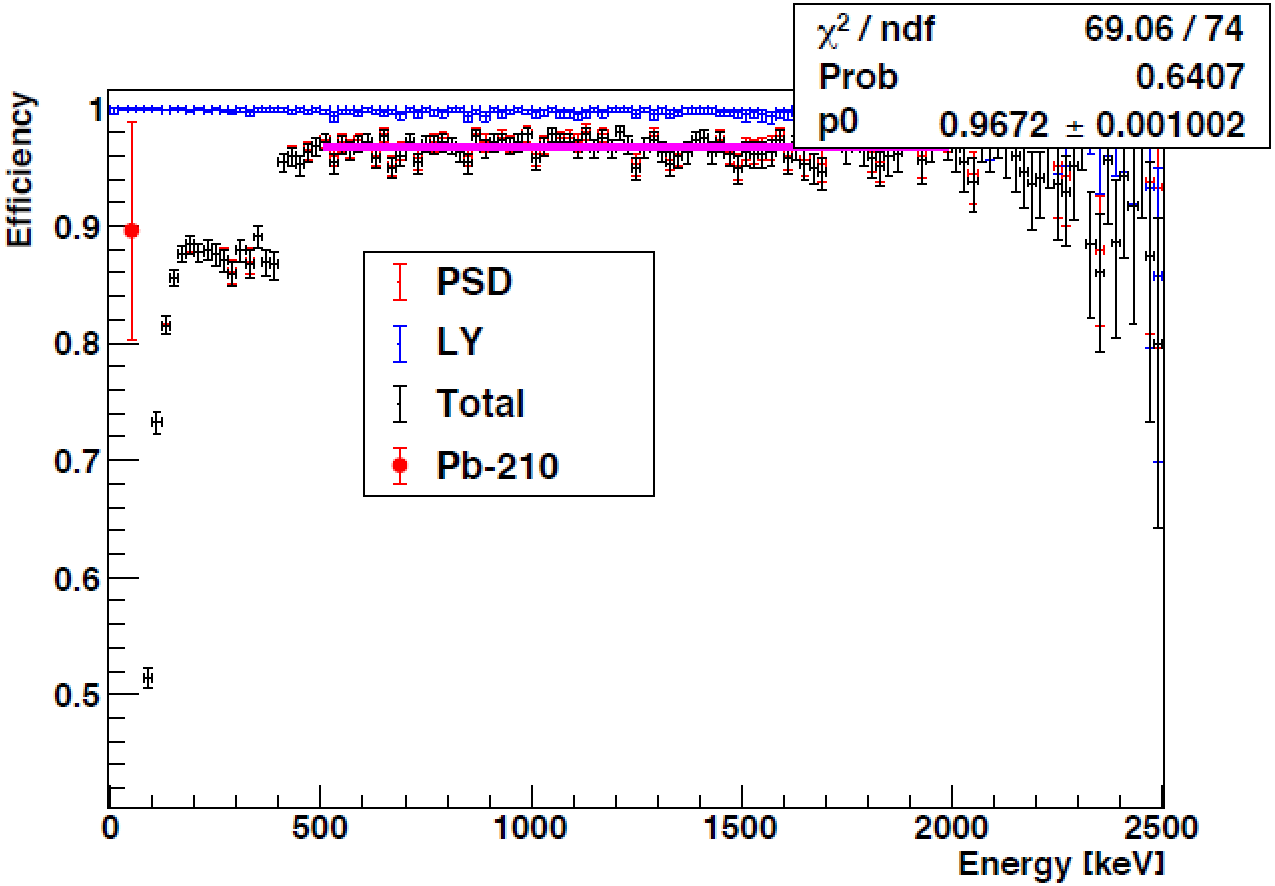




Fit of energy shift vs true energy of the gamma peaks (by Vivek and Yury).

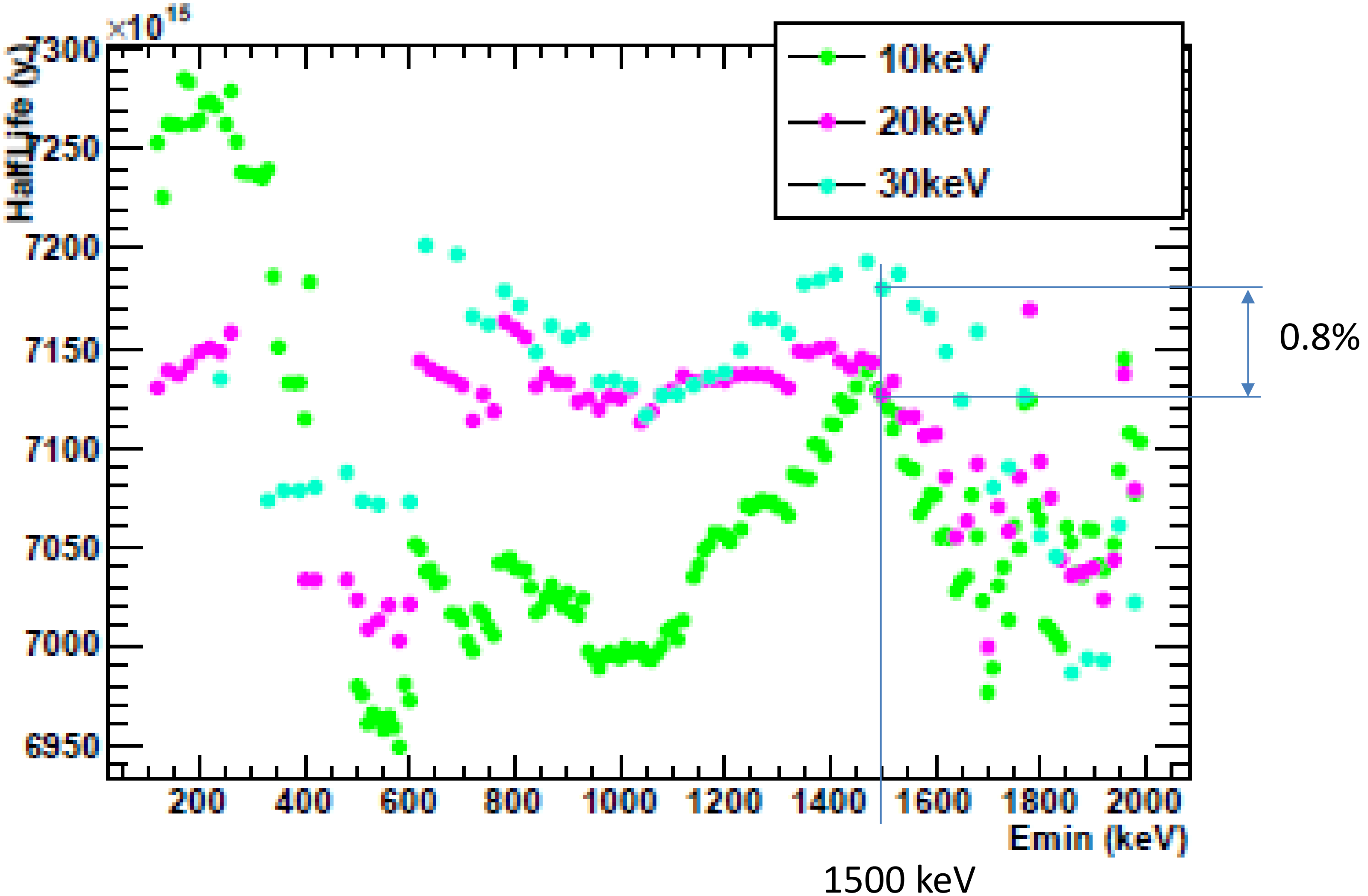
Shift of peaks positions before (upper panel) and after (lower panel) the energy scale correction (by Fedor).

Events selection efficiency

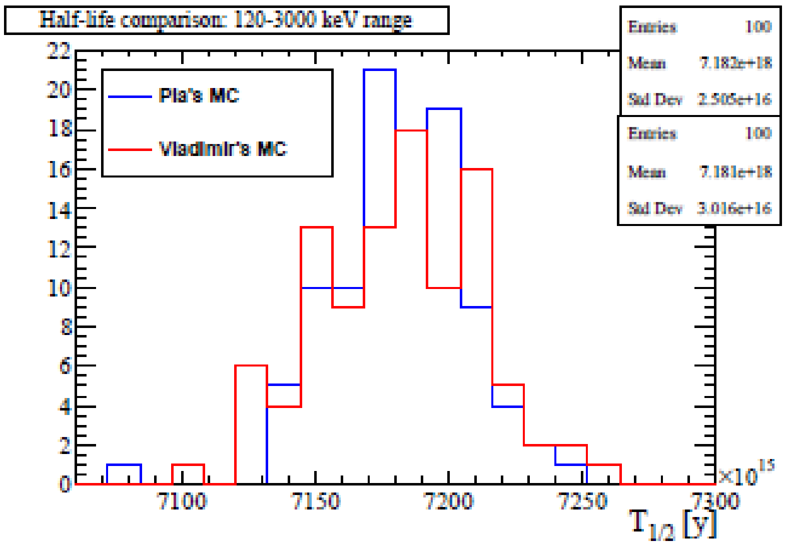


The efficiency is known reliable after 500 keV

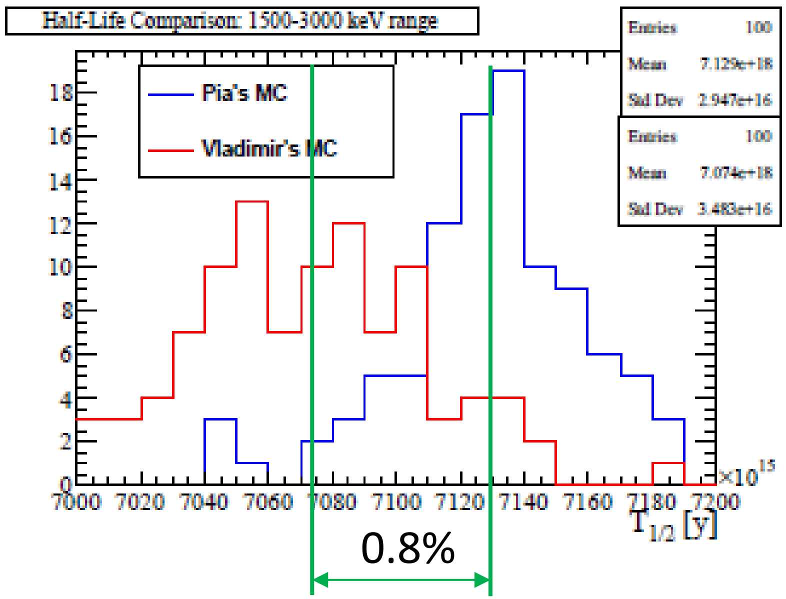
Binning of the energy spectrum



Localization of radioactivity in the set-up



Fit in 120 - 3000 keV



Fit in 1500 - 3000 keV

$\Delta\chi^2 = f(E_1)$ for SSD and HSD