Aurora experiment: Final results of studies of ^{116}Cd 2β decay with enriched ^{116}CdWO$_4$ crystal scintillators

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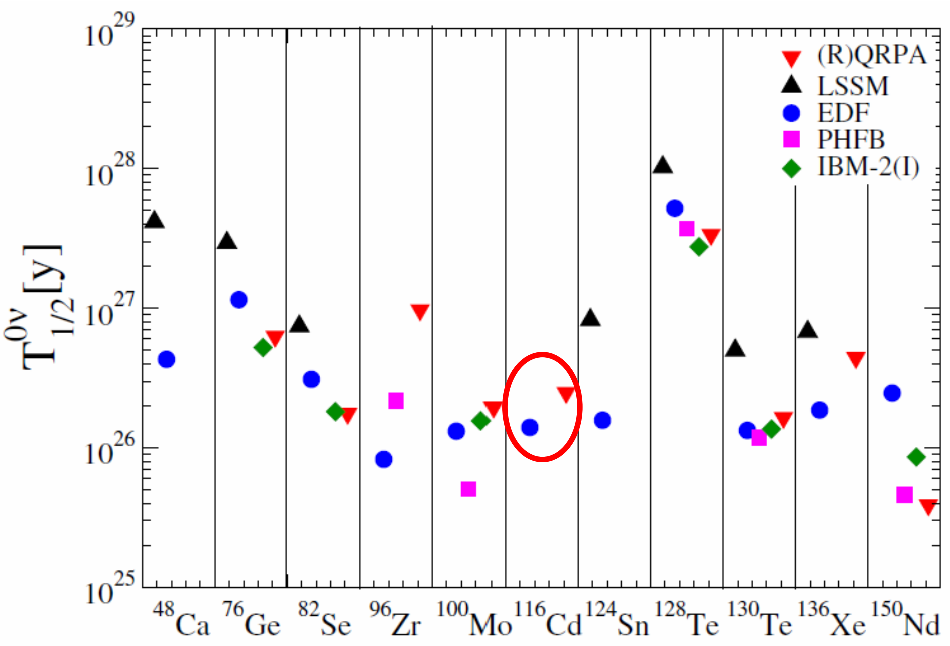
Introduction

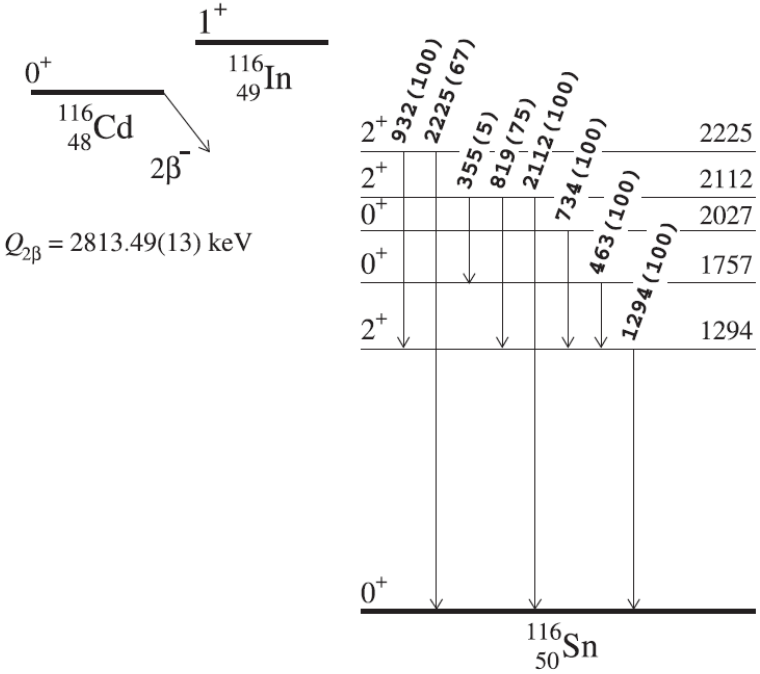
^{116}Cd is one of the best isotopes to search for $2\beta0\nu$ decay:

(1) $Q_{2\beta}$ = 2813.49(13) keV:
(a) exp. point of view: > 2615 keV of ^{208}Tl;
(b) th. point of view: $\Gamma(2\beta2\nu) \sim Q_{2\beta}^{11}$, $\Gamma(2\beta0\nu) \sim Q_{2\beta}^{5}$;
(2) favorable th. estimations of NMEs for $2\beta0\nu$;
(3) quite high isotopic abundance δ = 7.512(54)% and availability of enrichment by centrifugation (cheap) in large amounts;
(4) possibility to use "source = detector" approach with $CdWO_4$ / CdTe / … which ensures high (close to 1) efficiency.

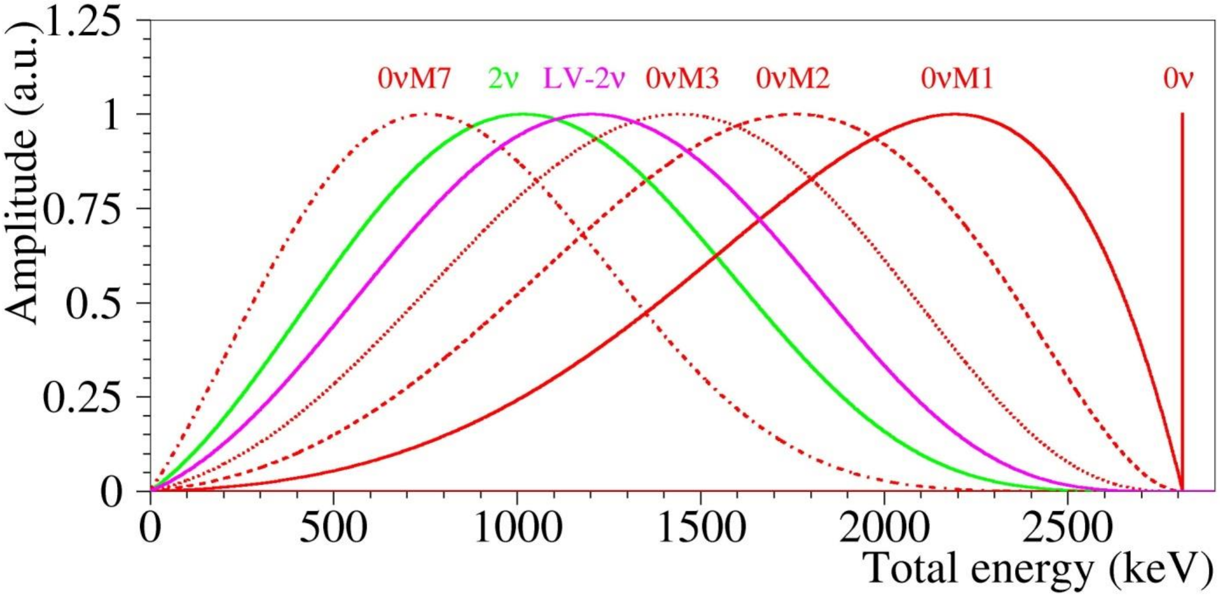


$1/T_{1/2}(2\beta0\nu) = \eta^2\, |NME^{0\nu}|^2\, G^{0\nu}(Q_{2\beta},Z)$
$\eta = m_\nu/m_e$ for light ν mass mechanism

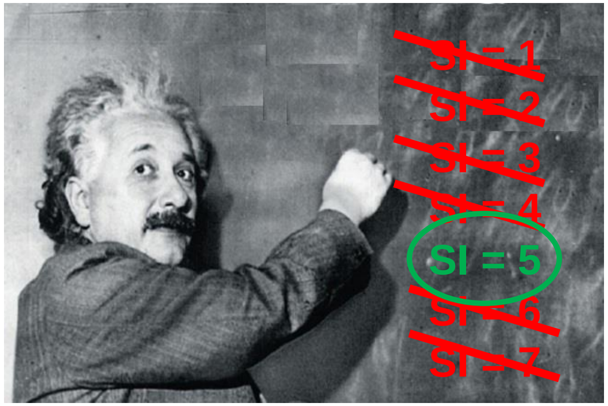
J.D. Vergados et al., RPP 75 (2012) 106301
(m_ν = 50 meV, g_A = 1.25)



Scheme of 2β decay ^{116}Cd → ^{116}Sn



Energy spectra (E_1+E_2) for different 2β modes



The most stringent previous limits (90% C.L.) for ^{116}Cd 2β0ν:

$T_{1/2} > 1.7\times10^{23}$ yr (Solotvina, F.A. Danevich et al., PRC 68 (2003) 035501)
$T_{1/2} > 1.0\times10^{23}$ yr (NEMO-3, R. Arnold et al., PRD 95 (2017) 012007)

Positive observations of 2β2ν:

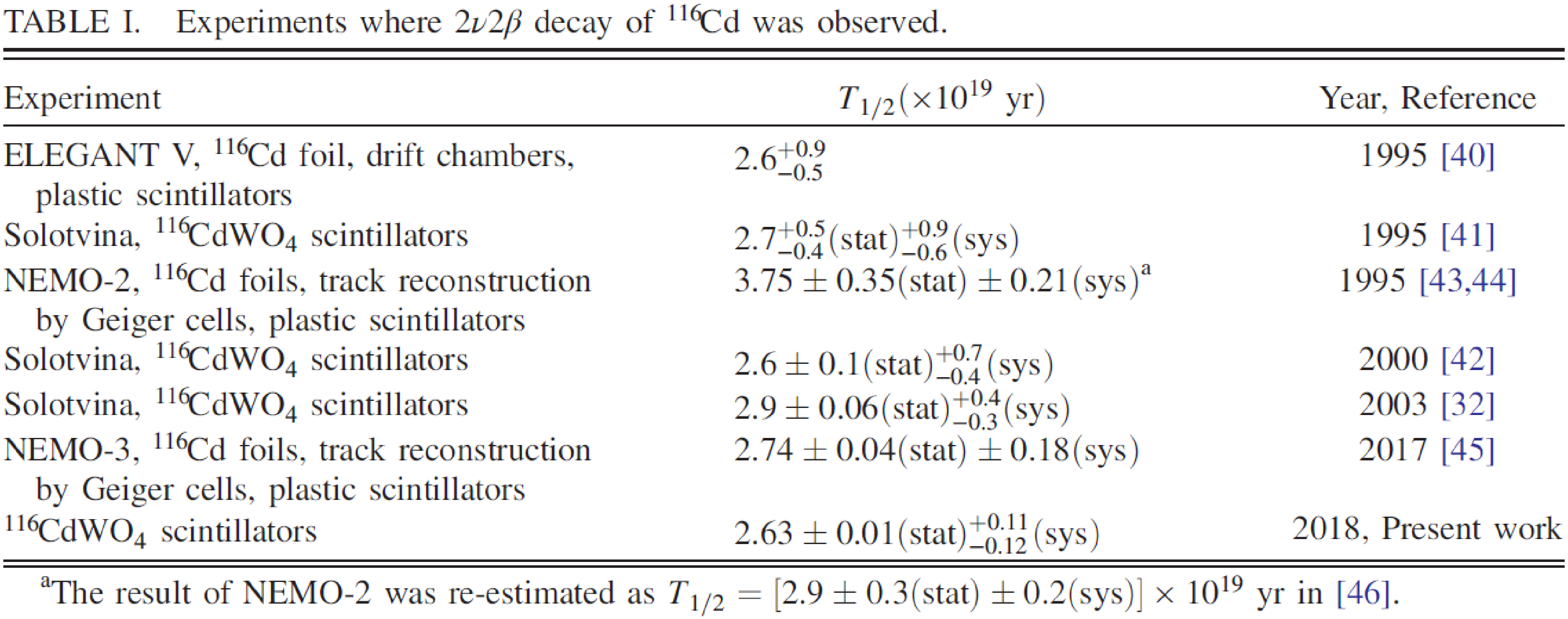
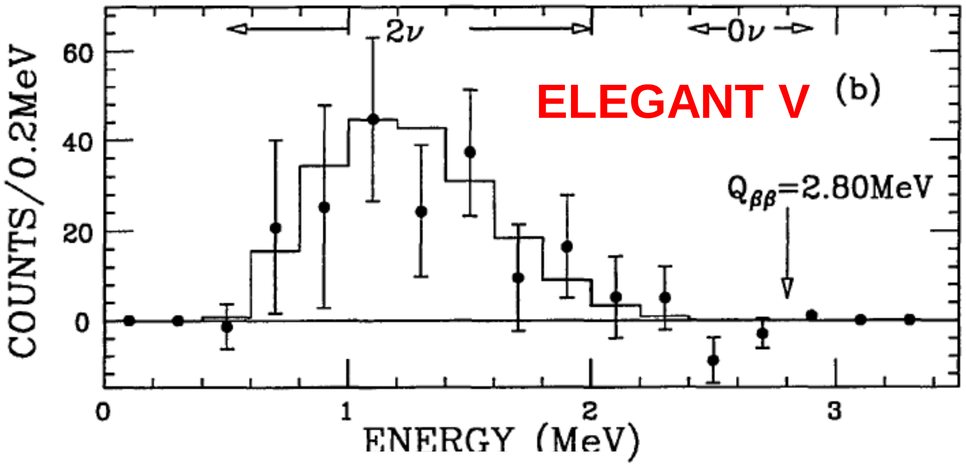


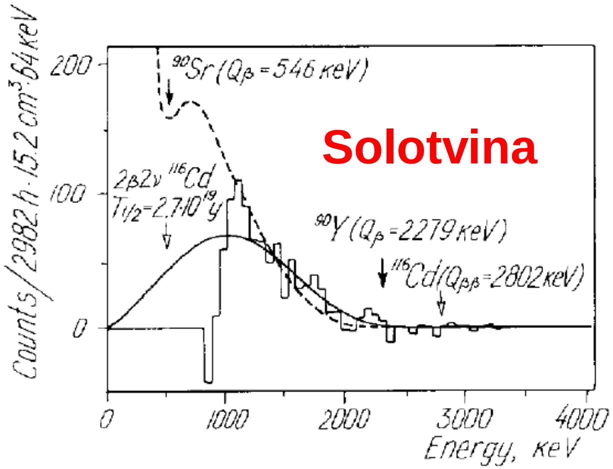
TABLE I. Experiments where $2\nu2\beta$ decay of ^{116}Cd was observed.

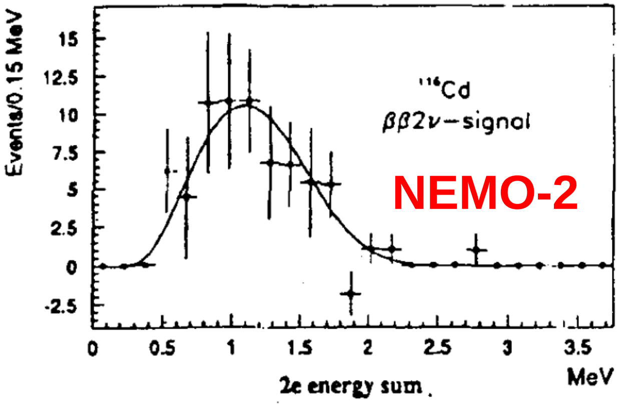
Experiment	$T_{1/2}(\times10^{19}$ yr)	Year, Reference
ELEGANT V, ^{116}Cd foil, drift chambers, plastic scintillators	$2.6^{+0.9}_{-0.5}$	1995 [40]
Solotvina, ^{116}CdWO$_4$ scintillators	$2.7^{+0.5}_{-0.4}$(stat)$^{+0.9}_{-0.6}$(sys)	1995 [41]
NEMO-2, ^{116}Cd foils, track reconstruction by Geiger cells, plastic scintillators	3.75 ± 0.35(stat) ± 0.21(sys)[a]	1995 [43,44]
Solotvina, ^{116}CdWO$_4$ scintillators	2.6 ± 0.1(stat)$^{+0.7}_{-0.4}$(sys)	2000 [42]
Solotvina, ^{116}CdWO$_4$ scintillators	2.9 ± 0.06(stat)$^{+0.4}_{-0.3}$(sys)	2003 [32]
NEMO-3, ^{116}Cd foils, track reconstruction by Geiger cells, plastic scintillators	2.74 ± 0.04(stat) ± 0.18(sys)	2017 [45]
^{116}CdWO$_4$ scintillators	2.63 ± 0.01(stat)$^{+0.11}_{-0.12}$(sys)	2018, Present work

[a] The result of NEMO-2 was re-estimated as $T_{1/2} = [2.9 \pm 0.3(\text{stat}) \pm 0.2(\text{sys})] \times 10^{19}$ yr in [46].

First observations (1995) of $2\beta2\nu$ decay in ^{116}Cd







ELEGANT V: H.Ejiri et al., J. Phys. Soc. Japan 64 (1995) 339:
foil ^{116}Cd (90.7%), 33 μm, 91 g, 1875 h, ~200 events

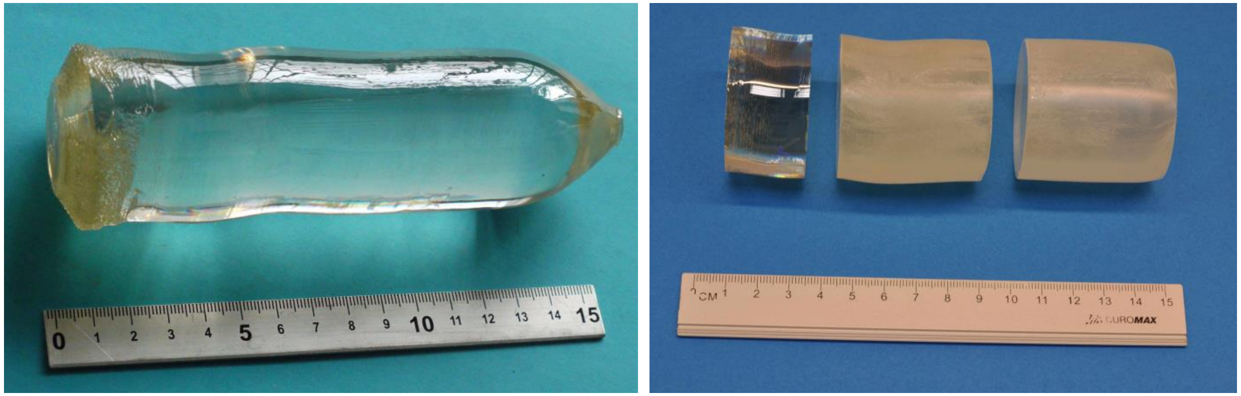
Solotvina: F.A. Danevich et al., PLB 344 (1995) 72:
$^{116}CdWO_4$ 19 cm^3 (83%), 2982 h, ~600 events

NEMO-2: R. Arnold et al., JETP Lett. 61 (1995) 170:
foil ^{116}Cd (93.2%), 40 μm, 152 g, 2460 h, 69 events

(Aurora experiment: 92,923 events observed)

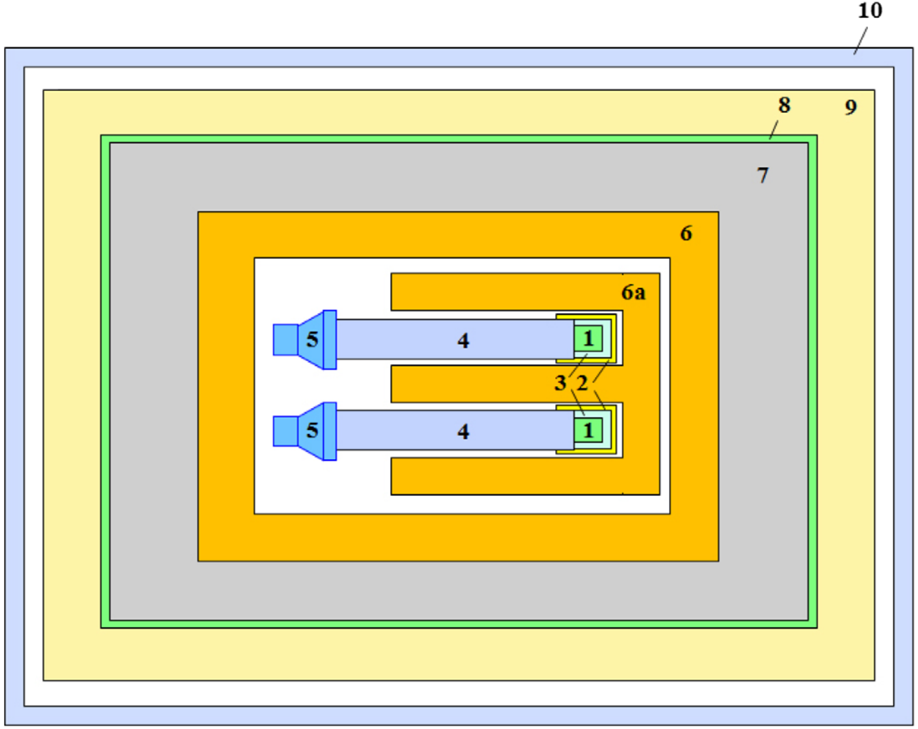
Experiment

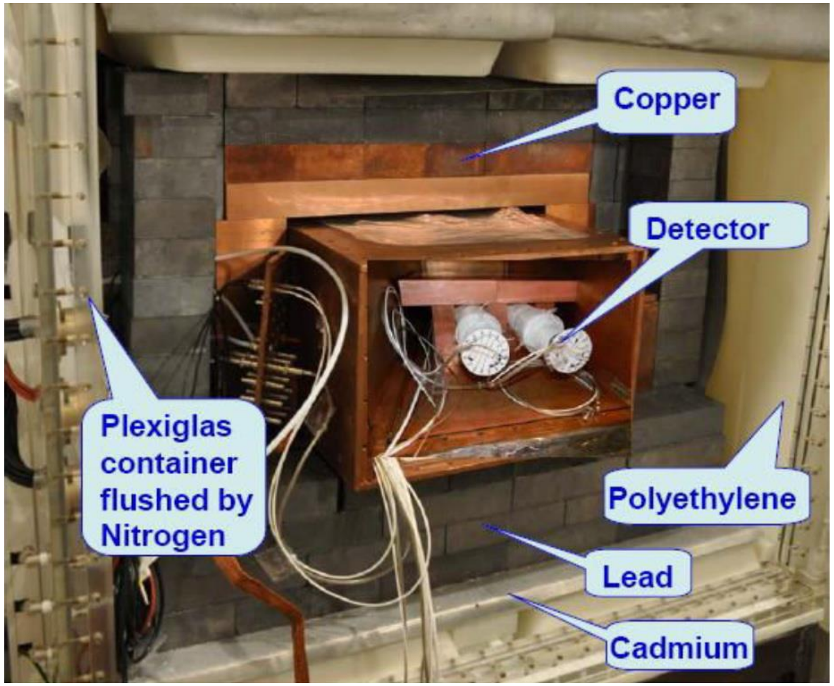
Two enriched $CdWO_4$ scintillating crystals (580 and 582 g), 82% of ^{116}Cd, produced by low-thermal-gradient Czochralski crystal growth technique from highly purified Cd



Crystal boule 1868 g and scintillating elements (326, 582 and 586 g, JINST 06 (2011) P08011)

LNGS (3600 m w.e.), DAMA/R&D low background set-up





Few upgrades. Final stage (since March 2014):
(1)^{116}CdWO$_4$ crystal scintillators
(2) teflon containers
(3) liquid scintillator
(4) quartz light guides (∅7×40 cm)
(5) photomultipliers (3” Hamamatsu R6233MOD)
(6) high-purity copper (10 cm)
(7) low radioactive lead (15 cm)
(8) cadmium (1.5 mm)
(9) polyethylene/paraffin (4 to 10 cm)
(10) plexiglas box (flushed by HP N$_2$)

DAQ:
amplitude
arrival time
pulse shape
(50 μs with 20 ns bin)

Calibration:
^{22}Na, ^{60}Co, ^{133}Ba,
^{137}Cs, ^{228}Th

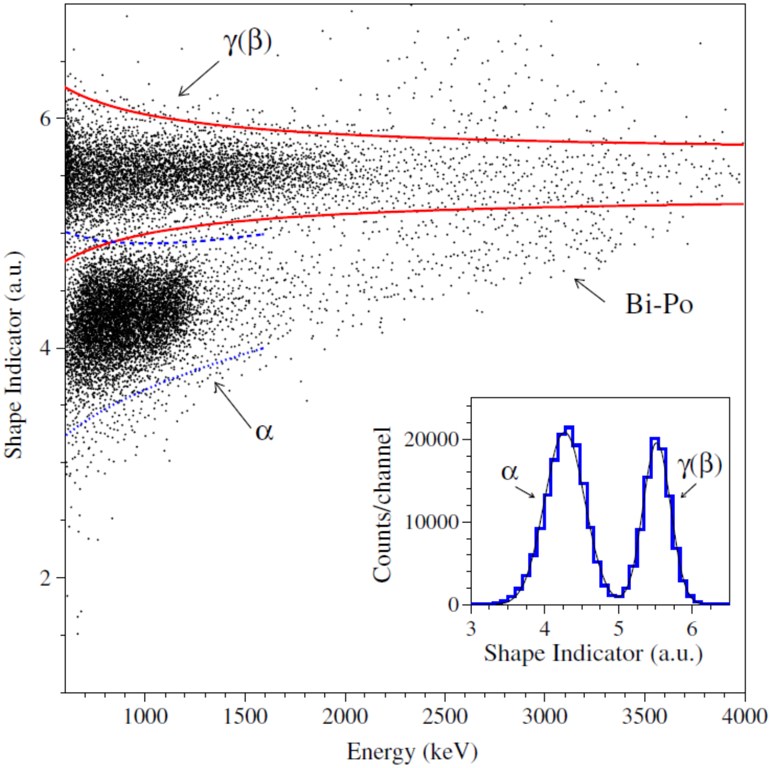
$\mathrm{FWHM}_\gamma = (10.2E_\gamma)^{1/2}$

Data analysis

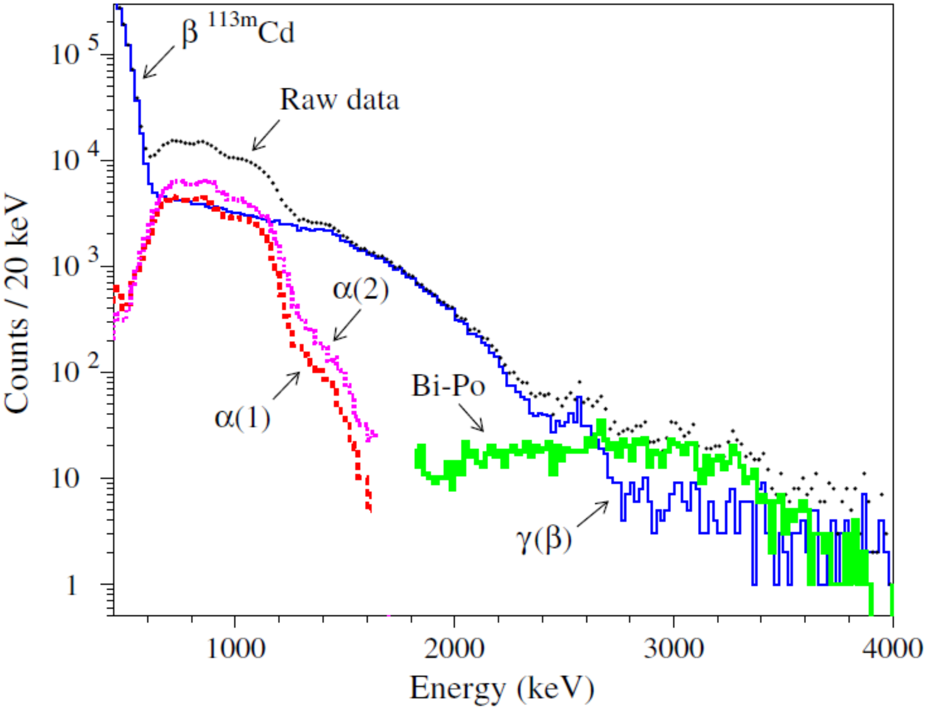
1. Pulse-shape discrimination

For each signal f(t), shape indicator (SI) is calculated:

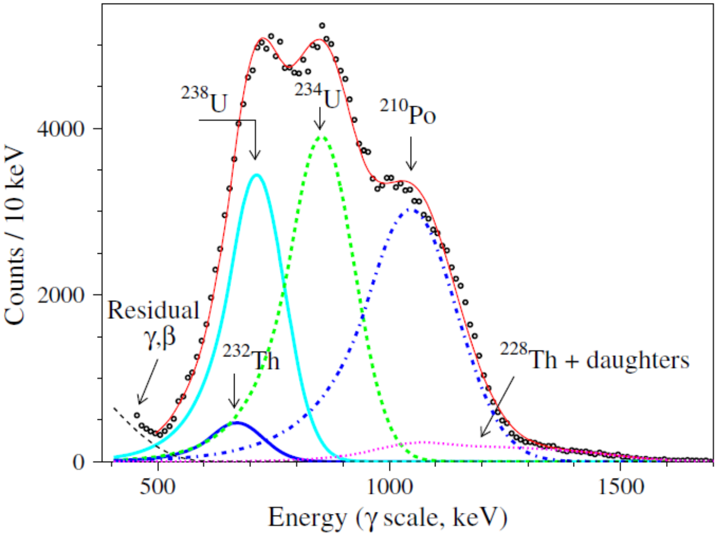
$$SI = \sum f(t_k) \times P(t_k) / \sum f(t_k) \qquad P(t) = |f_\alpha(t) - f_\gamma(t)| / |f_\alpha(t) + f_\gamma(t)|$$



^{116}CdWO$_4$ detector #2, 26831 h. Good discrimination ability.



^{116}CdWO$_4$ detectors #1+2, 26831 h. Raw data, γ(β) and α components (in CWO-1 and CWO-2), 212Bi-Po events



Spectrum of α events (26831 h, CWO-1 and CWO-2) and its individual components

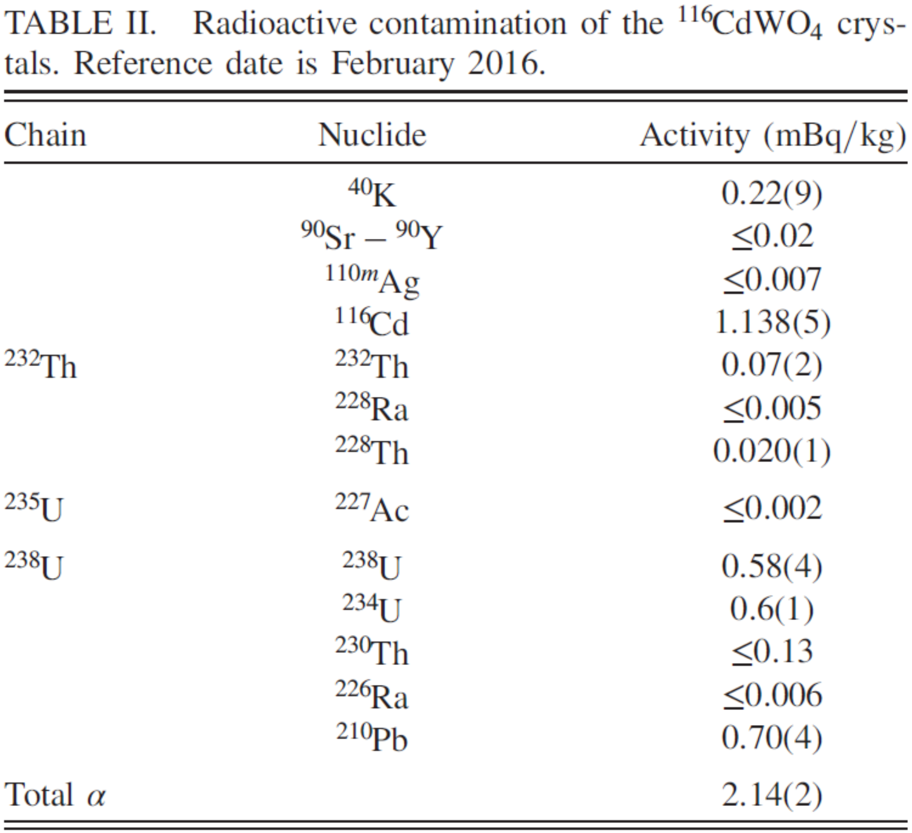


TABLE II. Radioactive contamination of the ^{116}CdWO$_4$ crystals. Reference date is February 2016.

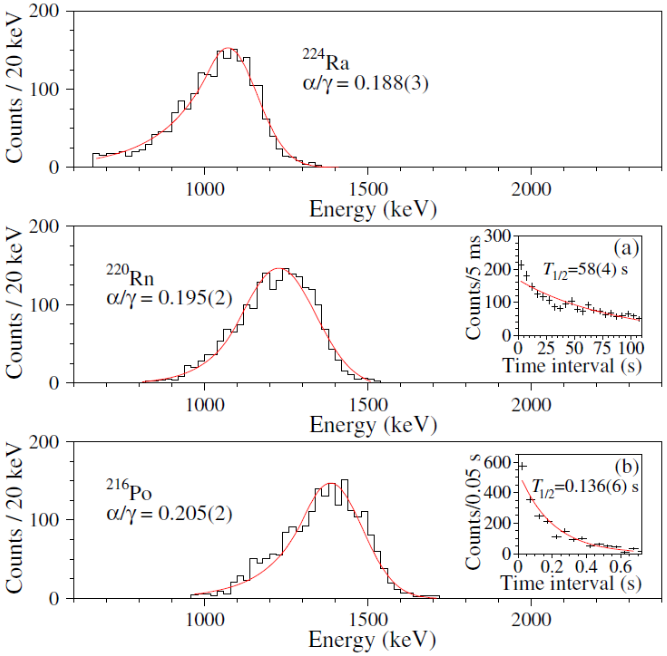
Chain	Nuclide	Activity (mBq/kg)
	^{40}K	0.22(9)
	^{90}Sr – ^{90}Y	≤0.02
	^{110m}Ag	≤0.007
	^{116}Cd	1.138(5)
^{232}Th	^{232}Th	0.07(2)
	^{228}Ra	≤0.005
	^{228}Th	0.020(1)
^{235}U	^{227}Ac	≤0.002
^{238}U	^{238}U	0.58(4)
	^{234}U	0.6(1)
	^{230}Th	≤0.13
	^{226}Ra	≤0.006
	^{210}Pb	0.70(4)
Total α		2.14(2)

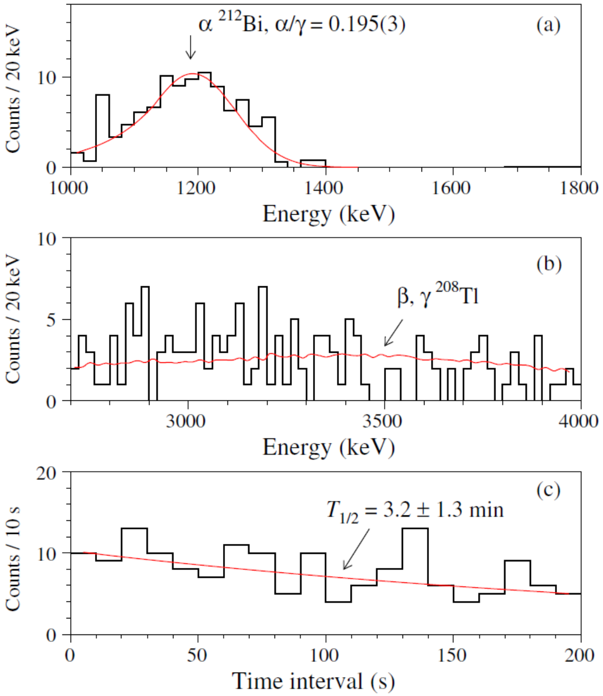
2. Time-amplitude analysis of fast subchains

Selection of subchains: events with known energies and time differences

$$^{224}\mathrm{Ra}(Q_\alpha = 5789\ \mathrm{keV}; T_{1/2} = 3.632\ \mathrm{d}) \rightarrow {}^{220}\mathrm{Rn}(Q_\alpha = 6405\ \mathrm{keV}; T_{1/2} = 55.6\ \mathrm{s}) \rightarrow {}^{216}\mathrm{Po}\ (Q_\alpha = 6906\ \mathrm{keV}; T_{1/2} = 0.145\ \mathrm{s}) \rightarrow {}^{212}\mathrm{Pb}.$$

$$^{212}\mathrm{Bi}(Q_\alpha = 6207\ \mathrm{keV}) \rightarrow {}^{208}\mathrm{Tl}(Q_\beta = 4999\ \mathrm{keV}, T_{1/2} = 3.053\ \mathrm{min}) \rightarrow {}^{208}\mathrm{Pb}$$





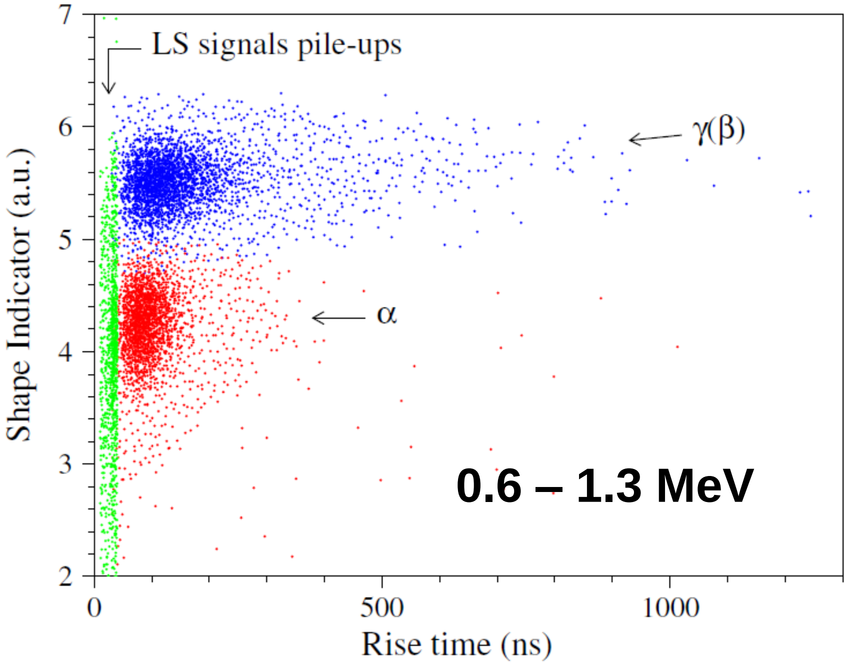
α peaks of ^{224}Ra, ^{220}Rn, ^{216}Po. $T_{1/2}$: ^{220}Rn = 58(4) s; ^{216}Po = 0.136(6) s

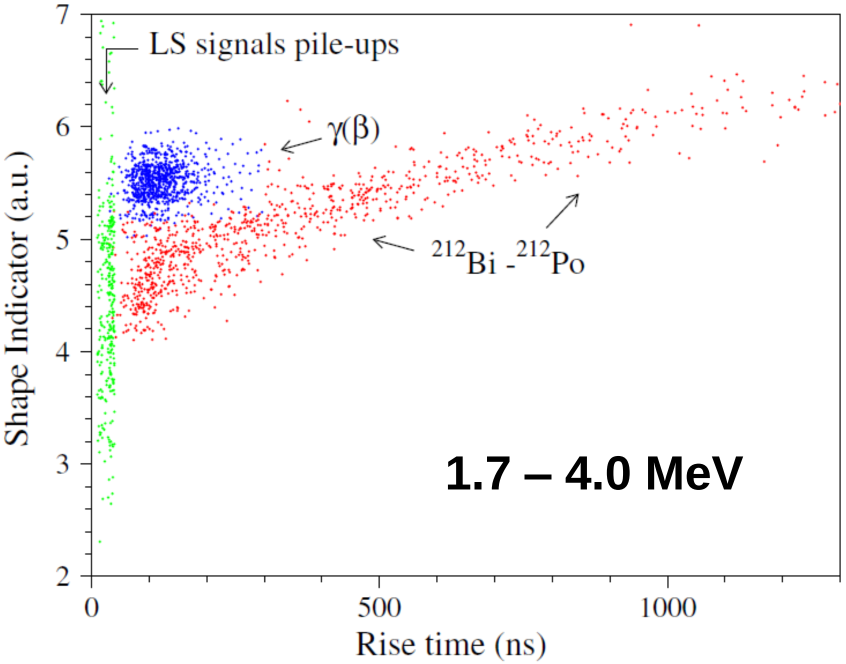
α peak of ^{212}Bi and β distribution of ^{208}Tl

α/β ratio = 0.114(7) + 0.0133(12)E_α

3. Front-edge analysis

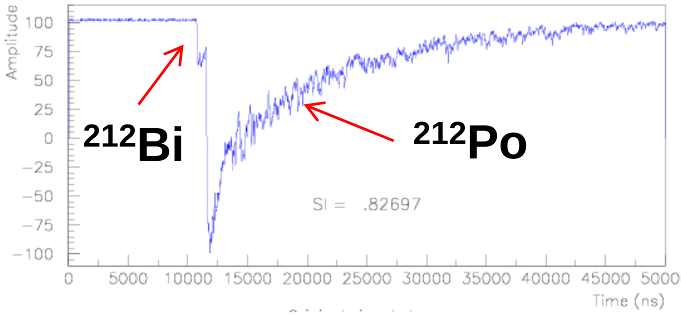
Front-edge parameter (rise time) = time between the signal origin and time of 0.7 of max value





In this way ^{212}Bi-^{212}Po events are selected

$$^{212}\mathrm{Bi}(Q_\beta = 2252\ \mathrm{keV}; T_{1/2} = 60.55\ \mathrm{m})$$
$$\rightarrow {}^{212}\mathrm{Po}(Q_\alpha = 8954\ \mathrm{keV}; T_{1/2} = 0.299\ \mu\mathrm{s}) \rightarrow {}^{208}\mathrm{Pb}$$

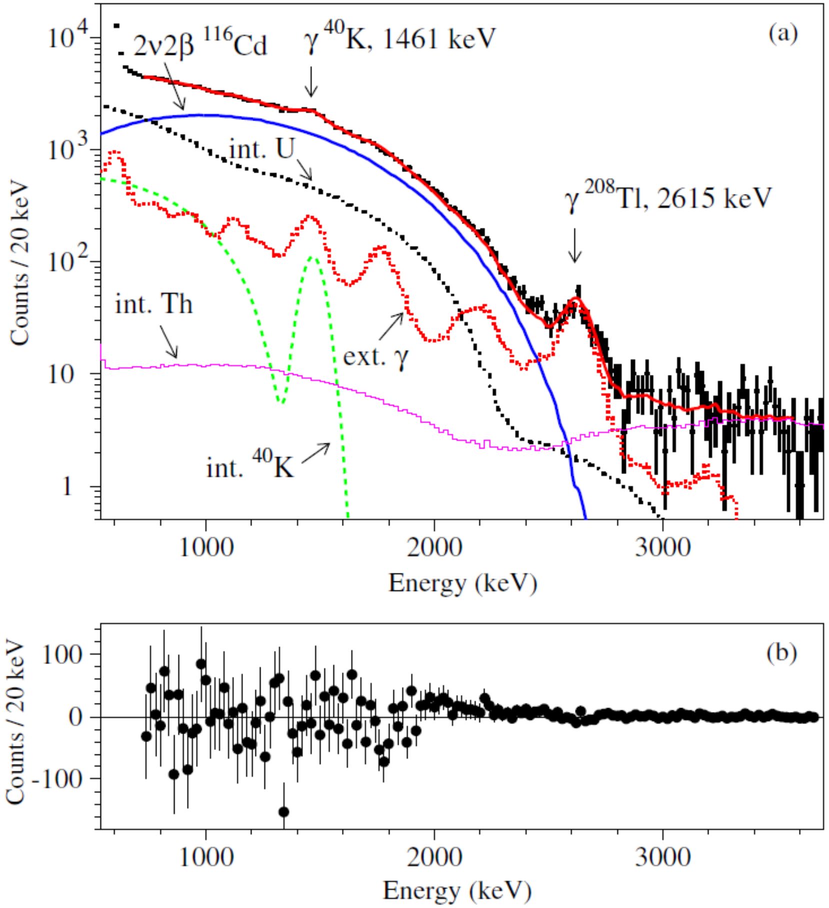


(also pile-ups of CWOs with LS)

Results

1. $2\beta2\nu$ decay of ^{116}Cd (g.s. to g.s.)

Selection of events: PSD and FE



$\gamma(\beta)$ energy spectrum, CWO-1 and CWO-2, 26831 h together with the main components

Background model:

(1) internal contaminations of CWOs by ^{40}K, ^{90}Sr/^{90}Y, ^{110m}Ag, ^{232}Th, ^{238}U

(2) external γ's from Cu shield, PMTs, quartz light-guides (^{40}K, Th/U)

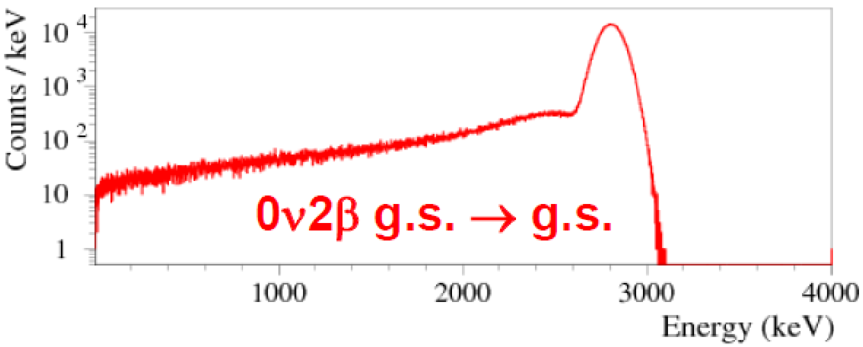
Initial kinematics: DECAY0 generator
Simulations: EGS4

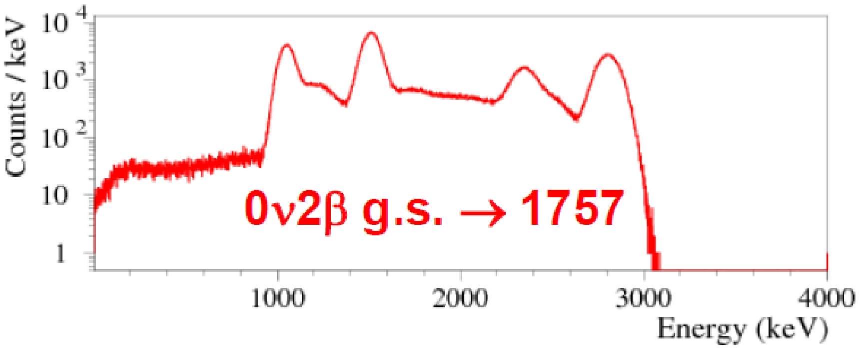
Starting point: 640–1600 keV (20 keV step)
Final point: 2800–3600 keV
χ^2/ndf = 1.15 – 1.75
Best fit (720 – 3560 keV, χ^2/ndf = 1.15): 92923±388 $2\beta2\nu$ events (126341±527 in the whole spectrum)

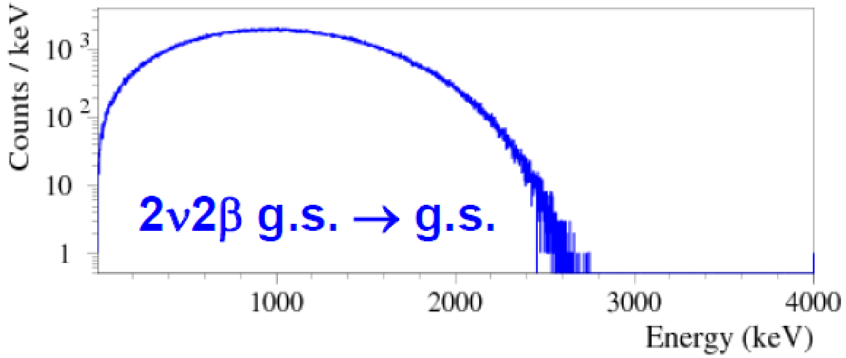
$T_{1/2}(2\beta2\nu) = (2.630 \pm 0.011(\text{stat}))\times10^{19}$ yr

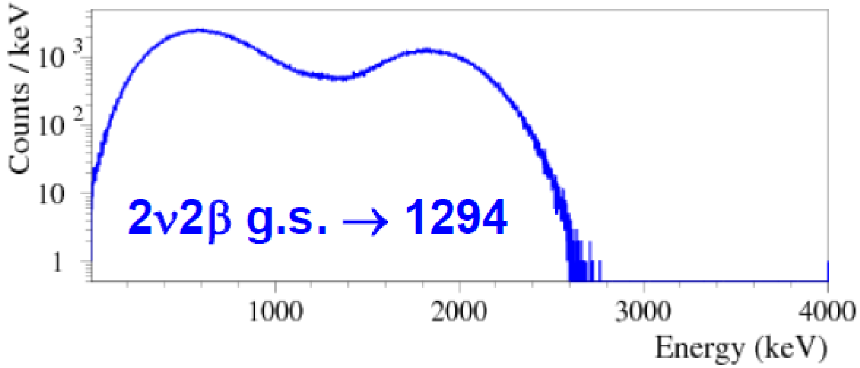
Examples of simulations of 2β processes

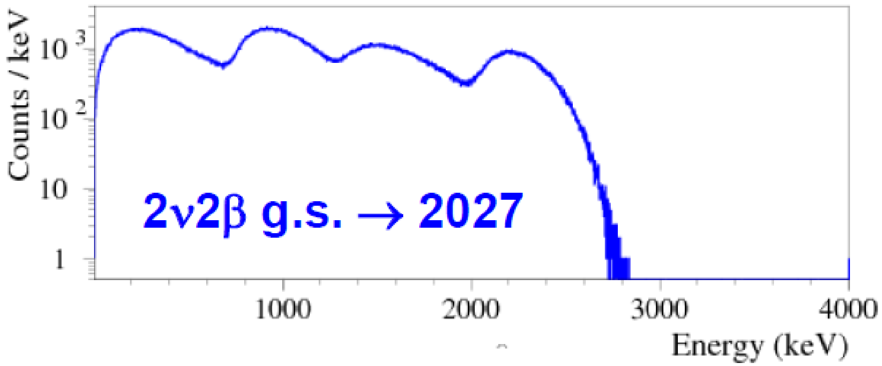
$^{116}CdWO_4$ response to 2β processes in ^{116}Cd (EGS4 + DECAY0)











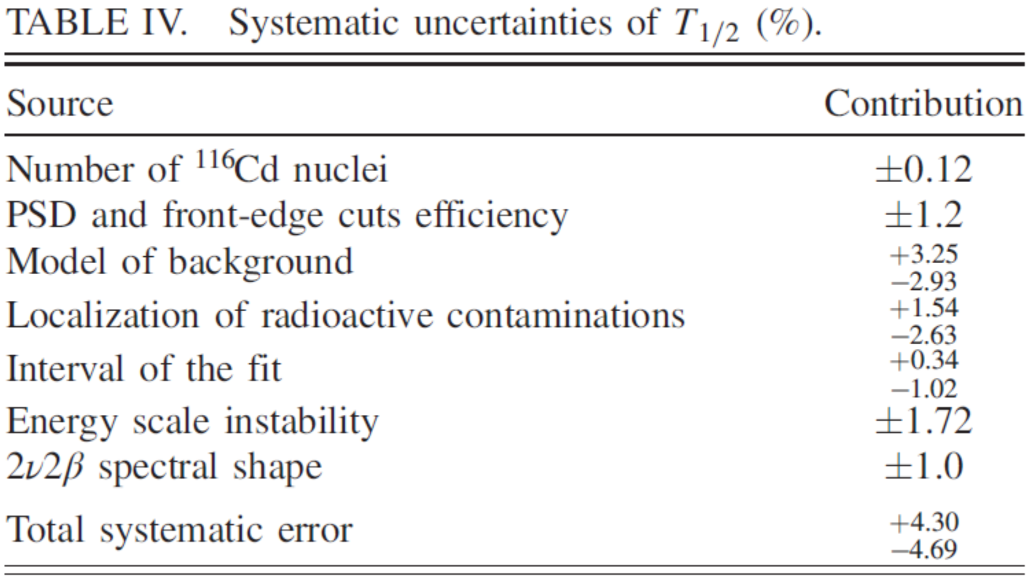
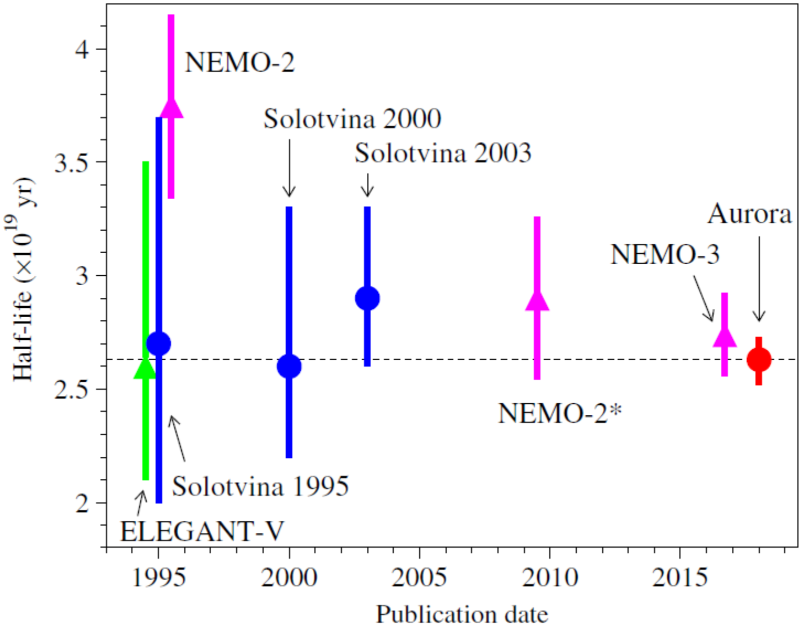


TABLE IV. Systematic uncertainties of $T_{1/2}$ (%).

Source	Contribution
Number of ^{116}Cd nuclei	± 0.12
PSD and front-edge cuts efficiency	± 1.2
Model of background	$^{+3.25}_{-2.93}$
Localization of radioactive contaminations	$^{+1.54}_{-2.63}$
Interval of the fit	$^{+0.34}_{-1.02}$
Energy scale instability	± 1.72
$2\nu2\beta$ spectral shape	± 1.0
Total systematic error	$^{+4.30}_{-4.69}$

$T_{1/2}(2\beta2\nu) = (2.630 \pm 0.011(\mathrm{stat})^{+0.113}_{-0.123}(\mathrm{sys}))\times10^{19}$ yr



$\mathrm{NME_{eff}} = 1/(G_{2\nu}\times T_{1/2})^{1/2}$

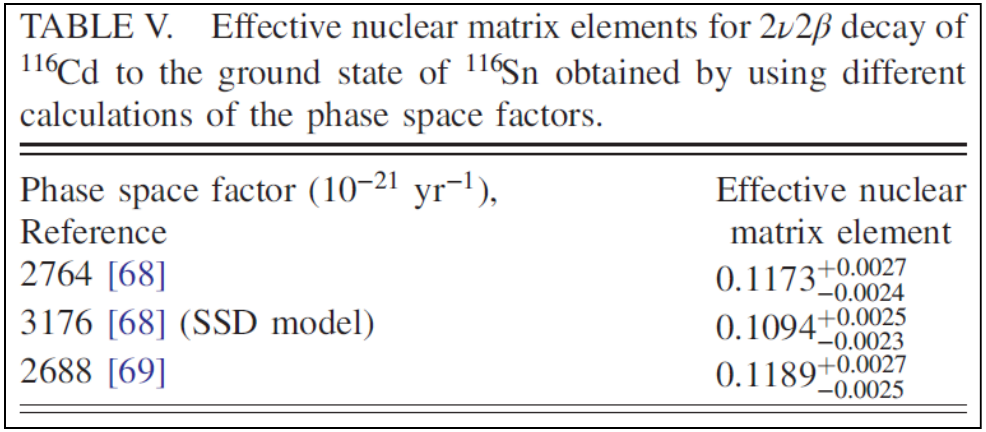


TABLE V. Effective nuclear matrix elements for $2\nu2\beta$ decay of ^{116}Cd to the ground state of ^{116}Sn obtained by using different calculations of the phase space factors.

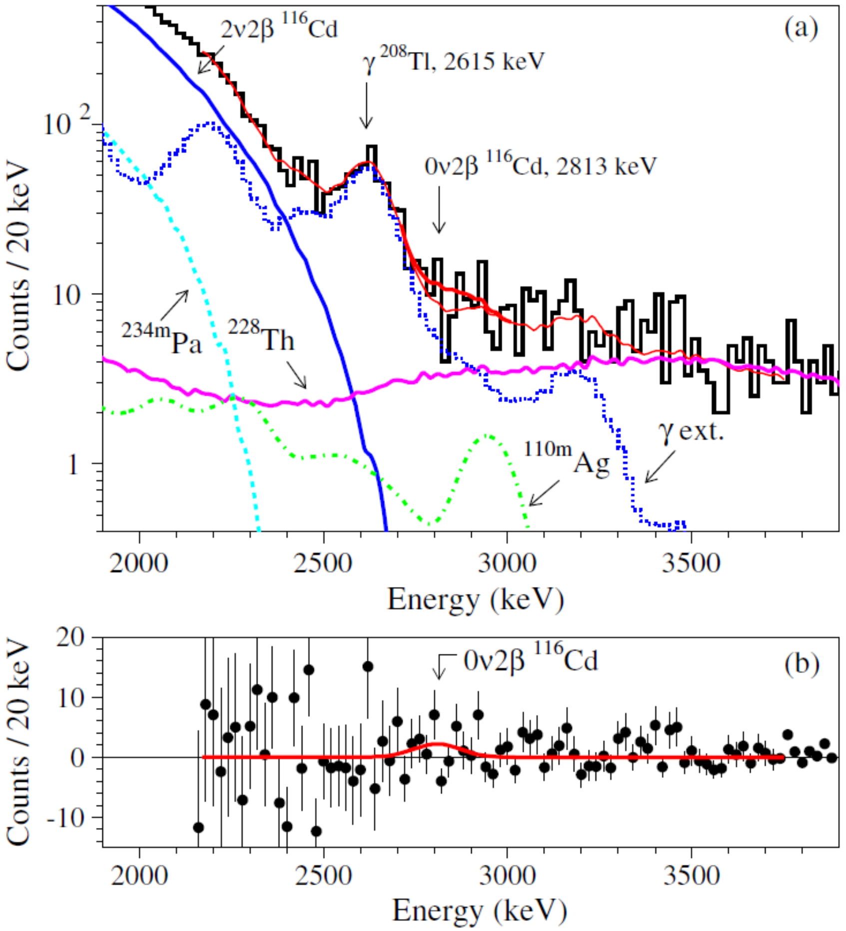
Phase space factor (10^{-21} yr^{-1}), Reference	Effective nuclear matrix element
2764 [68]	$0.1173^{+0.0027}_{-0.0024}$
3176 [68] (SSD model)	$0.1094^{+0.0025}_{-0.0023}$
2688 [69]	$0.1189^{+0.0027}_{-0.0025}$

[68] J. Kotila and F. Iachello, PRC 85 (2012) 034316

[69] M. Mirea et al., Rom. Rep. Phys. 67 (2015) 872

2. 2β0ν decay of ^{116}Cd (g.s. to g.s.)

26831 h + 8493 h from previous stage with background rate ~0.1 counts/(keV kg yr) at 2.7–2.9 MeV = 35324 h

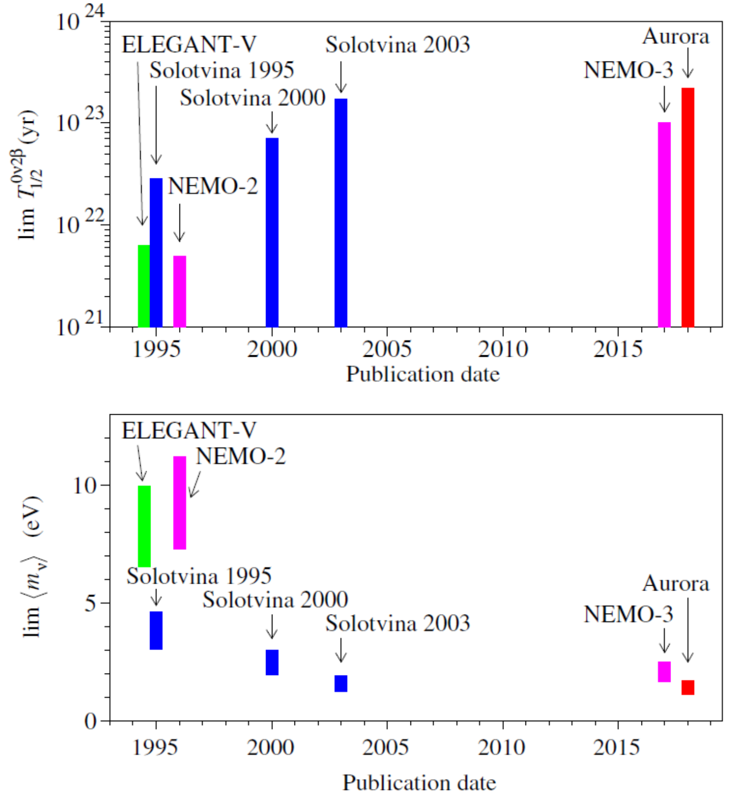


γ(β) energy spectrum, CWO-1 and CWO-2, 35324 h together with the main components

Best fit: 2160–3740 keV, χ^2/ndf = 1.01

S = –4.5 ±14.2 → S < 19.1 counts

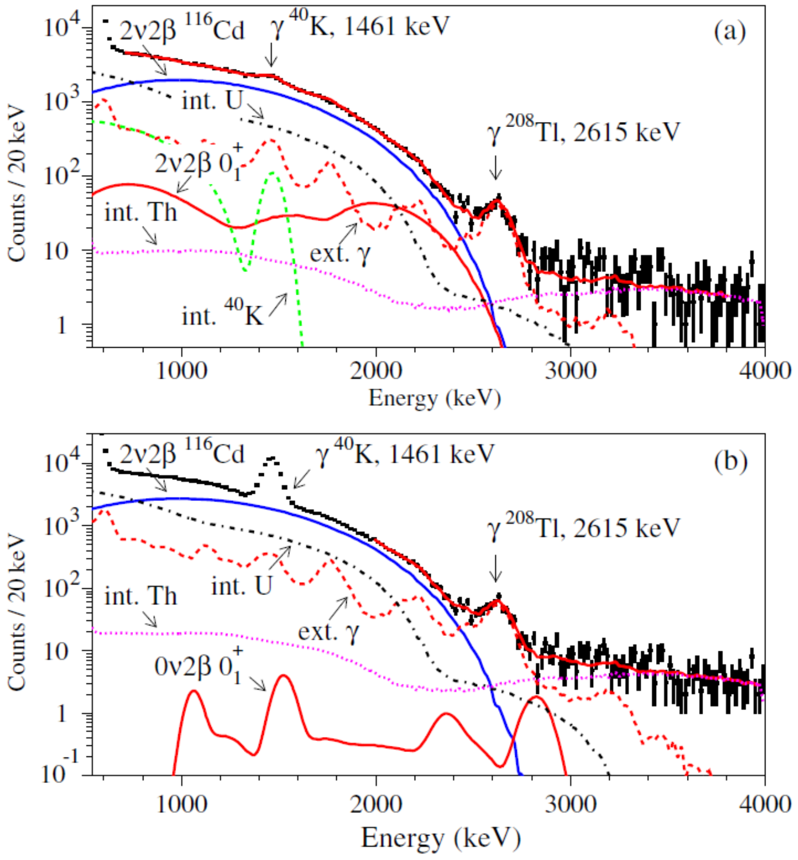
$T_{1/2}(2\beta0\nu) > 2.2\times10^{23}$ yr 90% C.L.



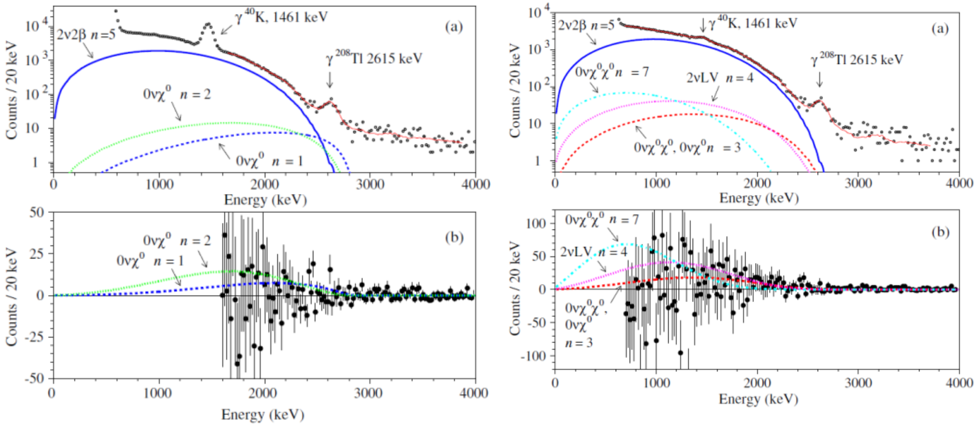
m_ν-λ-η ellipsoid: limits on m_ν, λ, η

3. 2β decays to excited levels, 2β0ν decays with majoron(s) emission, Lorentz violating 2β2ν decay

Fit of experimental spectrum by background model + 2β2ν distribution + additional distribution for transition to excited state

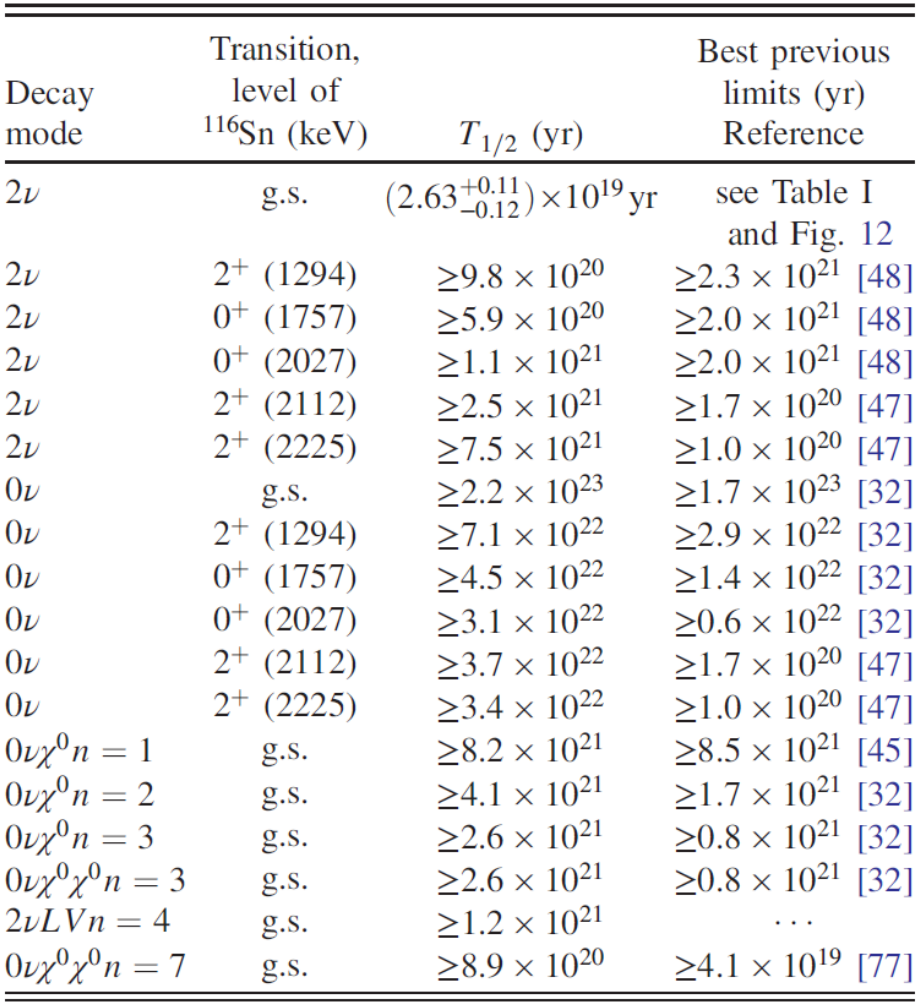


Fit for 2β2ν and 2β0ν decays to the first 0_1^+ level of ^{116}Sn (1757 keV)



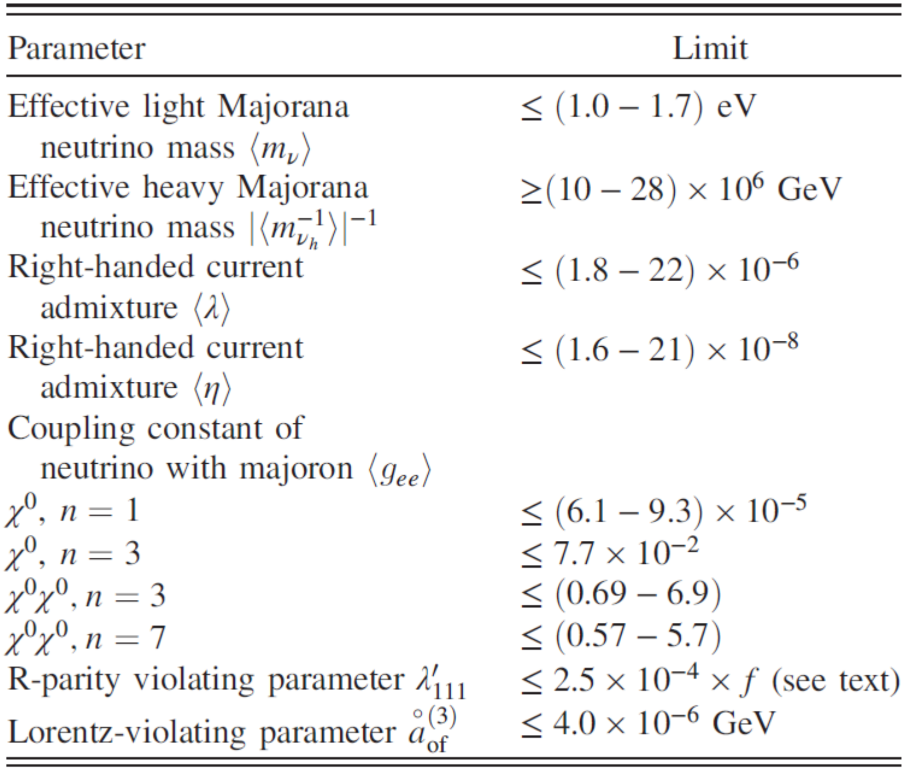
Fits for majorons with spectral index SI = 1, 2 (at higher energies) and SI = 3, 4, 7 (at lower energies)

TABLE VI. Summary of the obtained results on 2β processes in ^{116}Cd. The limits are given at 90% C.L., except of the results of [47], obtained at 68% C.L.



Decay mode	Transition, level of ^{116}Sn (keV)	$T_{1/2}$ (yr)	Best previous limits (yr) Reference
2ν	g.s.	$(2.63^{+0.11}_{-0.12})\times10^{19}$ yr	see Table I and Fig. 12
2ν	2^+ (1294)	$\geq 9.8\times10^{20}$	$\geq 2.3\times10^{21}$ [48]
2ν	0^+ (1757)	$\geq 5.9\times10^{20}$	$\geq 2.0\times10^{21}$ [48]
2ν	0^+ (2027)	$\geq 1.1\times10^{21}$	$\geq 2.0\times10^{21}$ [48]
2ν	2^+ (2112)	$\geq 2.5\times10^{21}$	$\geq 1.7\times10^{20}$ [47]
2ν	2^+ (2225)	$\geq 7.5\times10^{21}$	$\geq 1.0\times10^{20}$ [47]
0ν	g.s.	$\geq 2.2\times10^{23}$	$\geq 1.7\times10^{23}$ [32]
0ν	2^+ (1294)	$\geq 7.1\times10^{22}$	$\geq 2.9\times10^{22}$ [32]
0ν	0^+ (1757)	$\geq 4.5\times10^{22}$	$\geq 1.4\times10^{22}$ [32]
0ν	0^+ (2027)	$\geq 3.1\times10^{22}$	$\geq 0.6\times10^{22}$ [32]
0ν	2^+ (2112)	$\geq 3.7\times10^{22}$	$\geq 1.7\times10^{20}$ [47]
0ν	2^+ (2225)	$\geq 3.4\times10^{22}$	$\geq 1.0\times10^{20}$ [47]
$0\nu\chi^0 n=1$	g.s.	$\geq 8.2\times10^{21}$	$\geq 8.5\times10^{21}$ [45]
$0\nu\chi^0 n=2$	g.s.	$\geq 4.1\times10^{21}$	$\geq 1.7\times10^{21}$ [32]
$0\nu\chi^0 n=3$	g.s.	$\geq 2.6\times10^{21}$	$\geq 0.8\times10^{21}$ [32]
$0\nu\chi^0\chi^0 n=3$	g.s.	$\geq 2.6\times10^{21}$	$\geq 0.8\times10^{21}$ [32]
$2\nu LV n=4$	g.s.	$\geq 1.2\times10^{21}$	...
$0\nu\chi^0\chi^0 n=7$	g.s.	$\geq 8.9\times10^{20}$	$\geq 4.1\times10^{19}$ [77]

TABLE VII. Limits on lepton-number violating parameters. The limits are given at 90% C.L.



Parameter	Limit
Effective light Majorana neutrino mass $\langle m_\nu \rangle$	$\leq (1.0-1.7)$ eV
Effective heavy Majorana neutrino mass $\lvert\langle m_{\nu_h}^{-1}\rangle\rvert^{-1}$	$\geq(10-28)\times10^6$ GeV
Right-handed current admixture $\langle\lambda\rangle$	$\leq (1.8-22)\times10^{-6}$
Right-handed current admixture $\langle\eta\rangle$	$\leq (1.6-21)\times10^{-8}$
Coupling constant of neutrino with majoron $\langle g_{ee}\rangle$	
χ^0, $n=1$	$\leq (6.1-9.3)\times10^{-5}$
χ^0, $n=3$	$\leq 7.7\times10^{-2}$
$\chi^0\chi^0, n=3$	$\leq (0.69-6.9)$
$\chi^0\chi^0, n=7$	$\leq (0.57-5.7)$
R-parity violating parameter λ'_{111}	$\leq 2.5\times10^{-4}\times f$ (see text)
Lorentz-violating parameter $\mathring{a}^{(3)}_{\rm of}$	$\leq 4.0\times10^{-6}$ GeV

NME for m_ν:
J. Barea et al., PRC 91 (2015 034304 (IBM)
F. Simkovic et al., PRC 87 (2013) 045501 (QRPA)
N.L. Vaquero et al., PRL 111 (2013) 142501 (EDFT)
J. Hyvärinen et al., PRC 91 (2015) 024613 (pnQRPA)
L.S. Song et al., PRC 95 (2017) 024305 (EDFT)

PSF:
J. Kotila, F. Iachello, PRC 85 (2012) 034316

Conclusions

After near 5 yr of data taking at LNGS (3600 m w.e.), the Aurora experiment to investigate 2β processes in ^{116}Cd with 1.162 kg of enriched (82%) $^{116}CdWO_4$ scintillators is finished

$T_{1/2}$ for 2β2ν is precisely measured: $T_{1/2}(2\beta2\nu) = 2.63^{+0.11}_{-0.12} \times 10^{19}$ yr

The most stringent limit for 2β0ν is obtained: $T_{1/2}(2\beta0\nu) > 2.2 \times 10^{23}$ yr, equivalent to Majorana ν mass limits: $m_\nu < 1.0 - 1.7$ eV (depending on NME)

Limits on 2β2ν and 2β0ν decays to excited levels: $T_{1/2} > 10^{20} - 10^{22}$ yr

Limits on 2β0ν decays with different majorons: $T_{1/2} > 10^{21} - 10^{22}$ yr

Limits on right-handed admixtures in weak interaction, heavy ν mass, majoron-neutrino coupling constants, Lorentz-violating 2β2ν decay

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Děkuji za pozornost!

P.S. Lorentz-violating 2β2ν decay

$$d\Gamma/dt_1 dt_2 = C \cdot e_1 p_1 F(t_1, Z) \cdot e_2 p_2 F(t_2, Z) \cdot [(t_0 - t_1 - t_2)^5 + 10\mathring{a}^{(3)}_{\text{of}}(t_0 - t_1 - t_2)^4]$$

$$\Gamma = \Gamma_{2\nu} + \Gamma_{2\nu\text{LV}}$$

$$\Gamma_{2\nu} = CI_5, \qquad \Gamma_{2\nu\text{LV}} = 10\mathring{a}^{(3)}_{\text{of}} \cdot CI_4$$

$$I_5 = \int_0^{t_0} dt_1 e_1 p_1 F(t_1, Z) \times \int_0^{t_0 - t_1} dt_2 e_2 p_2 F(t_2, Z)(t_0 - t_1 - t_2)^5$$

$$I_4 = \int_0^{t_0} dt_1 e_1 p_1 F(t_1, Z) \times \int_0^{t_0 - t_1} dt_2 e_2 p_2 F(t_2, Z)(t_0 - t_1 - t_2)^4$$

$$10\mathring{a}^{(3)}_{\text{of}} = \frac{\Gamma_{2\nu\text{LV}}}{\Gamma_{2\nu}} \cdot \frac{I_5}{I_4} = \frac{T^{2\nu}_{1/2}}{T^{2\nu\text{LV}}_{1/2}} \cdot \frac{I_5}{I_4}$$

In the Primakoff-Rosen approximation F(t,Z) ~ e/p

$$I_5 = t_0^7(t_0^4 + 22t_0^3 + 220t_0^2 + 990t_0 + 1980)/83160$$

$$I_4 = t_0^6(t_0^4 + 20t_0^3 + 180t_0^2 + 360t_0 + 1260)/37800$$

Monument in Kyiv to Vitaly Primakov (revolutioner), grand-uncle of Henry Primakoff

Henry Primakoff

Primakoff-Rosen approximation