Search for double beta decay of ^{116}Cd with enriched $^{116}CdWO_4$ crystal scintillators
(Aurora experiment)

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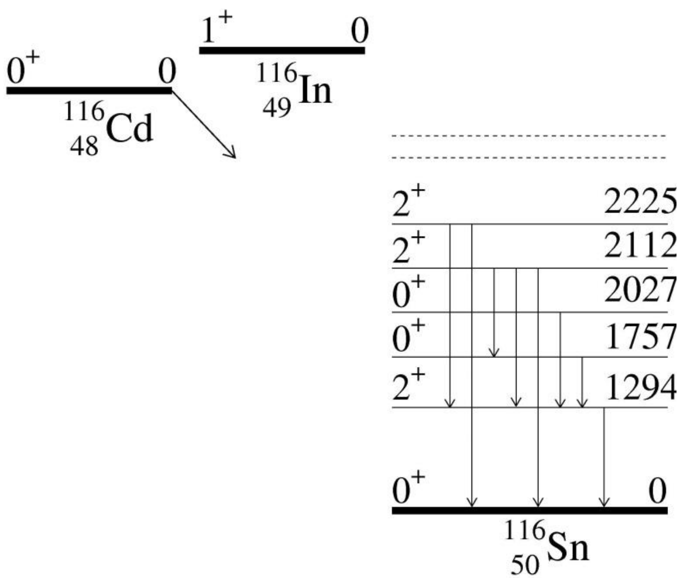
[+] deceased

Puech Denys (1854 -1942)
Aurora, Museum D'Orsay

In this presentation

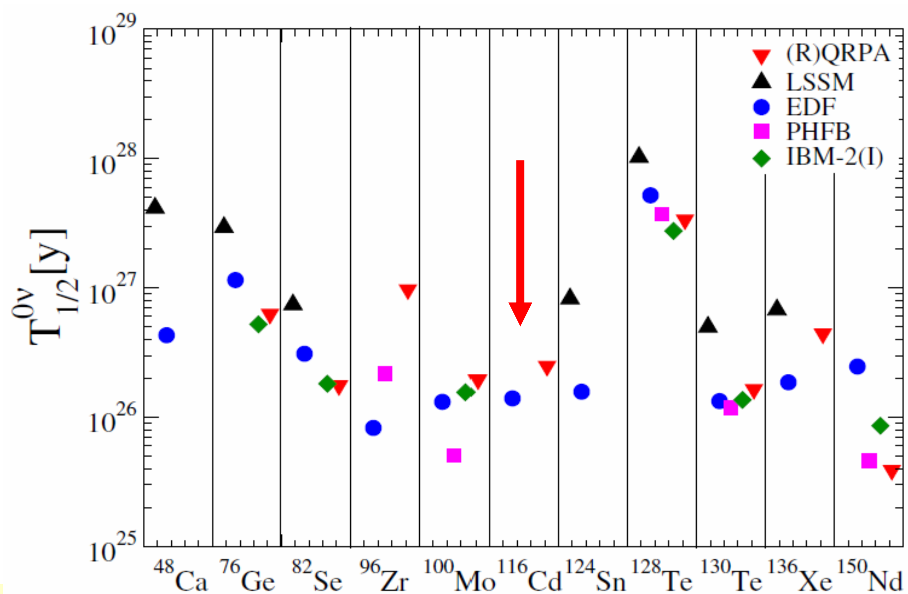
- Introduction
- Aurora experiment
  - R&D of $^{116}CdWO_4$ crystal scintillators
  - Low background set-up
  - Data analysis
- Results and discussion
- Conclusions

^{116}Cd is promising 2β candidate



Advantages of ^{116}Cd

- Large energy of decay $Q_{2\beta}$= 2813.44(13) keV [1]
- Large isotopic abundance δ = 7.49(18)% [2] and possibility of enrichment by centrifugation
- Promising theoretical estimations of decay probability (see, e.g. [3, 4])

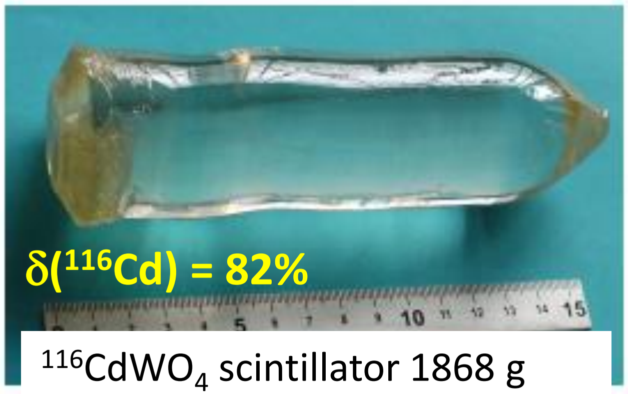


Availability of cadmium tungstate crystal scintillators ($CdWO_4$) as detectors for 2β experiment with ^{116}Cd

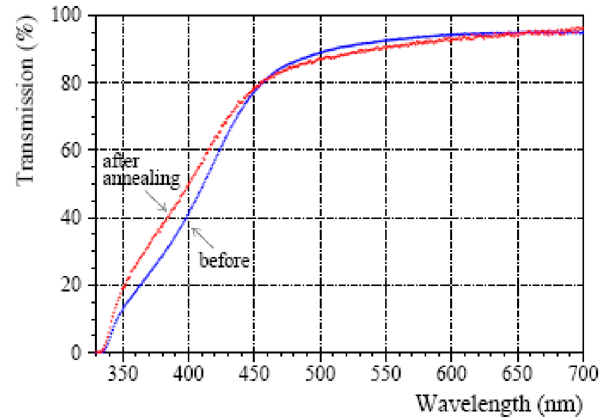
[1] S. Rahaman et al., Phys. Lett. B 703 (2011) 412
[2] M. Berglund and M.E. Wieser, Pure Appl. Chem. 83 (2011) 397
[3] J.D.Vergados, H.Ejiri, F.Simkovic, Rep. Prog. Phys. 75 (2012) 106301
[4] J. Barea, J. Kotila, and F. Iachello Phys. Rev. Lett. 109 (2012) 042501

- *Experiment*

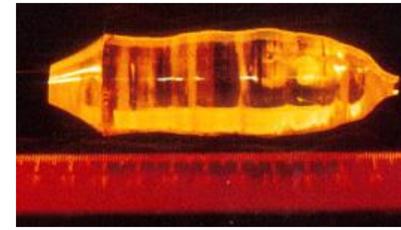
R&D of enriched $^{116}CdWO_4$ crystal scintillators



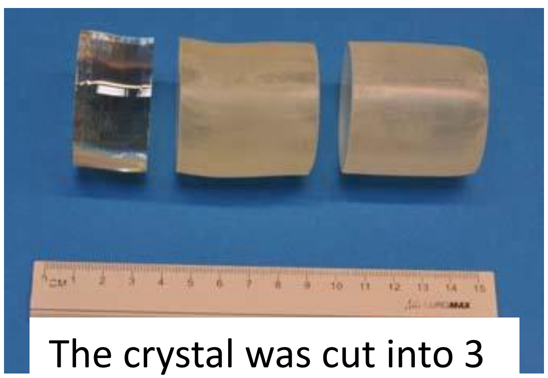
$^{116}CdWO_4$ scintillator 1868 g
Yield of crystal 87%
Losses of ^{116}Cd ≈ 2%



Optical transmission curve of $^{116}CdWO_4$ crystal before and after annealing

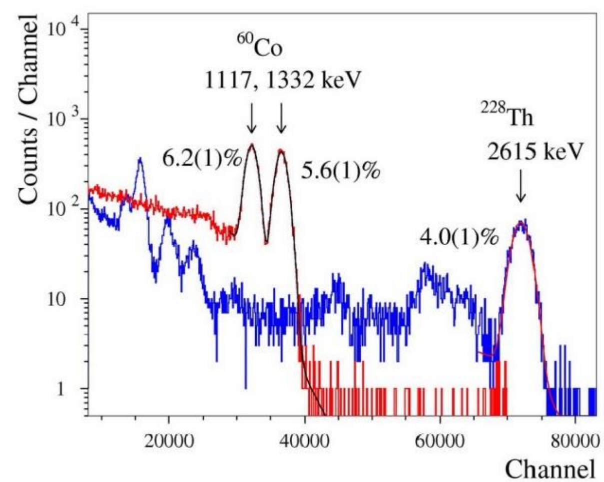


$^{116}CdWO_4$ crystal (510 g) grown in 1986 for the Solotvina experiment [2]



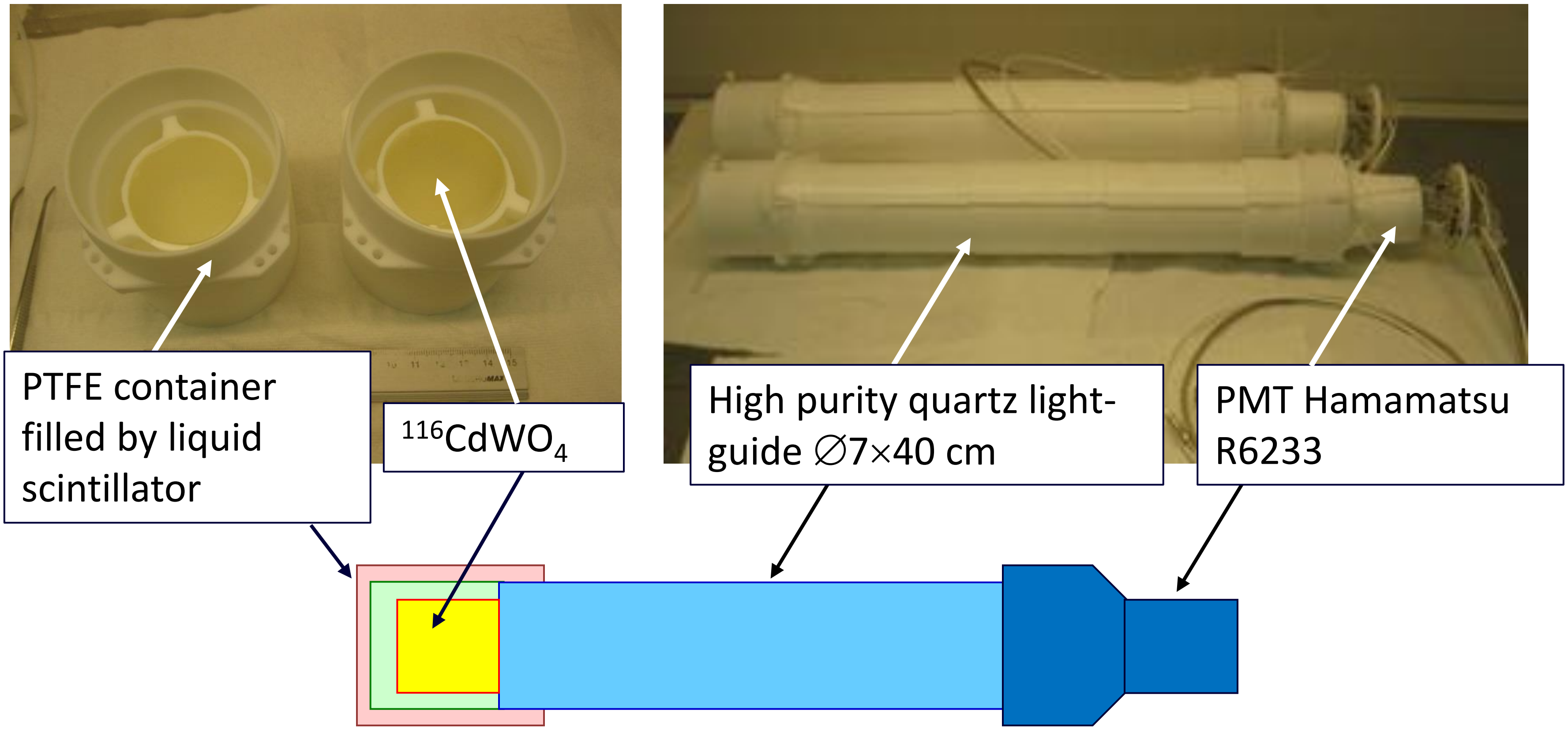
The crystal was cut into 3 scintillation elements

The excellent optical and scintillation properties of the crystal were obtained thanks to the deep purification of ^{116}Cd and W, and the advantage of the low-thermal-gradient Czochralski technique to grow the crystal [1]



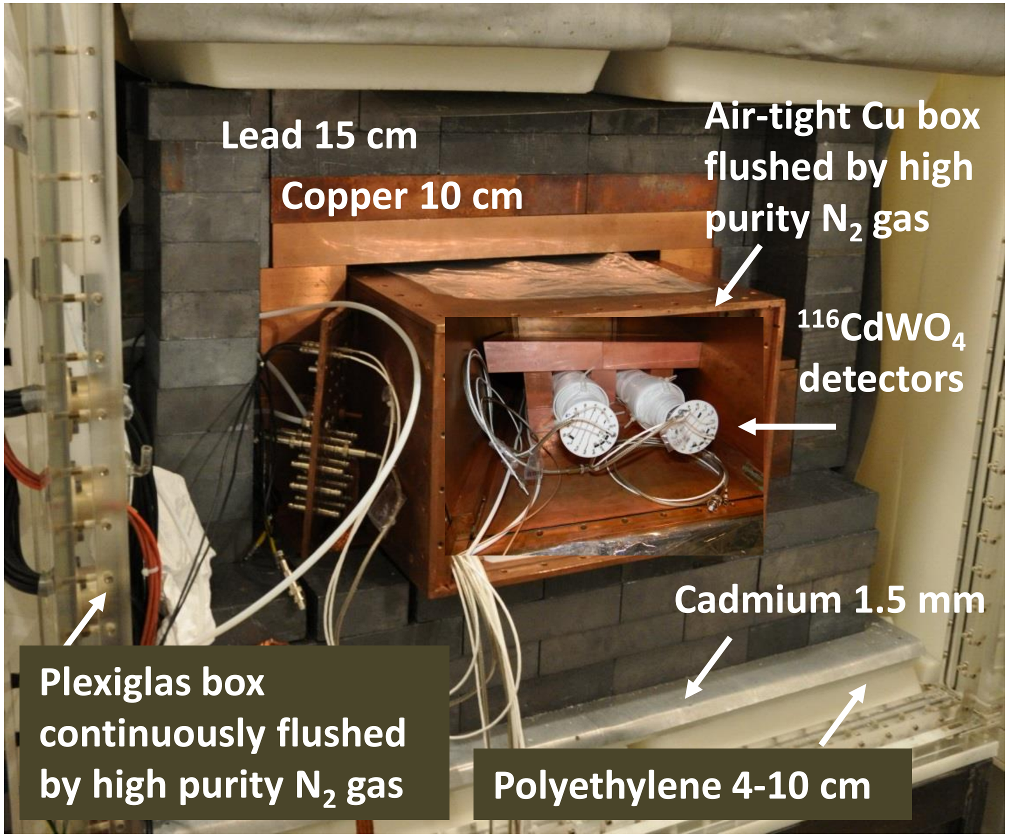
[1] A.S. Barabash et al., JINST 06(2011) p08011
[2] F.A.Danevich et al., JETP Lettt. 49 (1989) 476

$^{116}CdWO_4$ scintillation detector



FWHM ≈ 5% at 2615 keV

Low background DAMA R&D set-up at LNGS

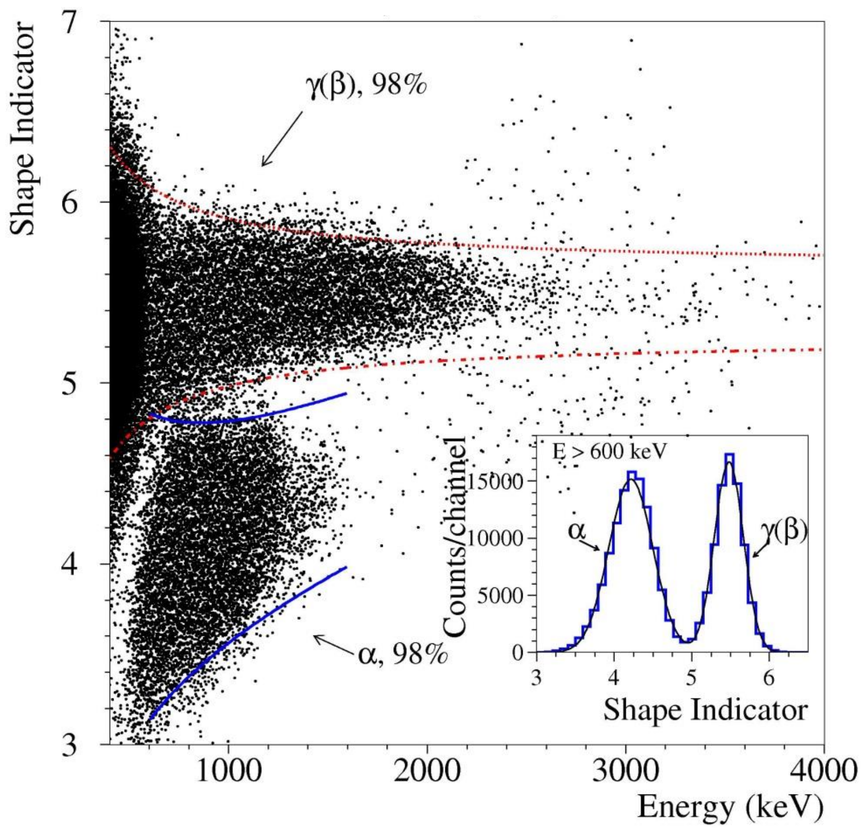


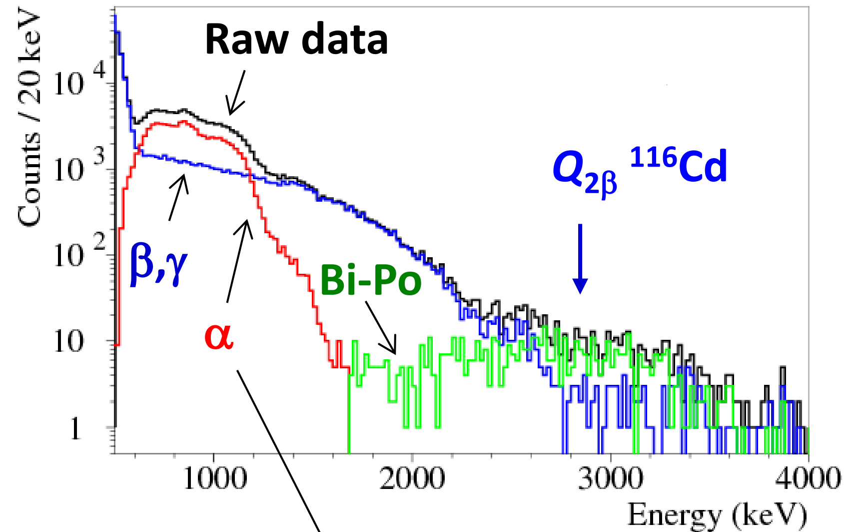
An event-by-event data acquisition system based on a 1 GS/s 8 bit transient digitizer (operated at 50 MS/s) records the time of each event and the pulse shape over a time window of ≈100 μs from the $^{116}CdWO_4$ detectors

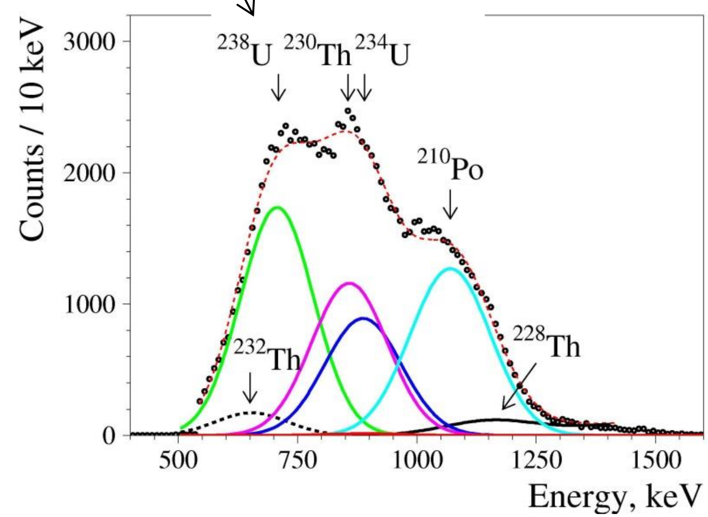
The background rate in the region of interest 2.7 – 2.9 MeV (after pulse-shape discrimination) is on the level of ≈ 0.12 counts/(yr keV kg)

Data analysis

pulse-shape discrimination (12 015 h)





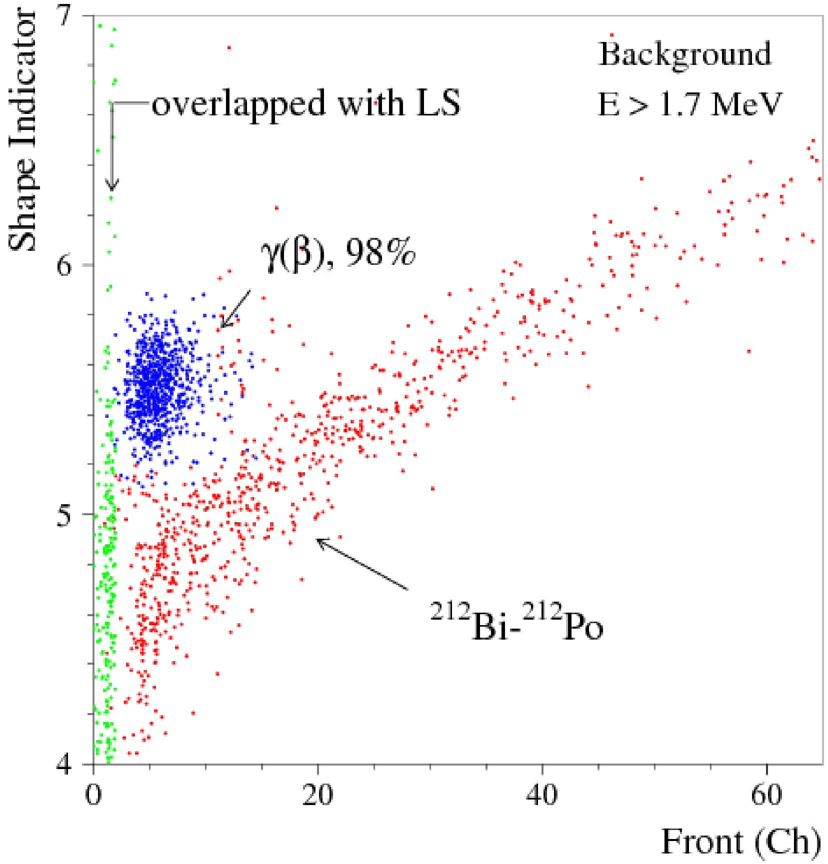


Activity of ^{238}U: 0.69(2) mBq/kg
^{210}Po: 0.57(3) mBq/kg ⇐

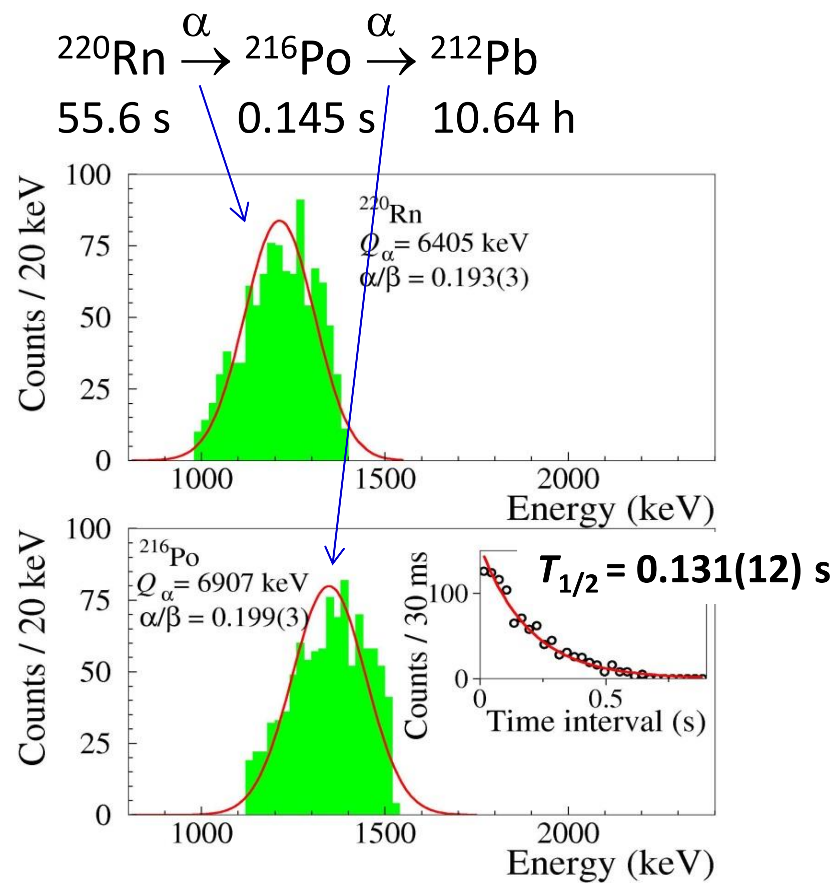
- *Experiment*

Data analysis

front edge and time-amplitude analyses (12 015 h)



Activity ^{228}Th: 0.027(3) mBq/kg*



Activity of ^{228}Th: 0.027(4) mBq/kg*

*Reference date: November 2014

Radioactive contamination of $^{116}CdWO_4$

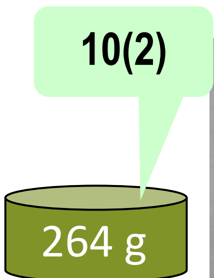
Chain	Nuclide	Activity (mBq/kg)
^{232}Th	^{232}Th	$\leq$ 0.07
	^{228}Th	0.027(4)*
^{238}U	^{238}U	0.69(2)
	^{226}Ra	$\leq$ 0.005
	^{210}Po	0.57(3)
Total α		2.25(7)
	^{40}K	$\leq$ 0.9

*Reference date: November 2014

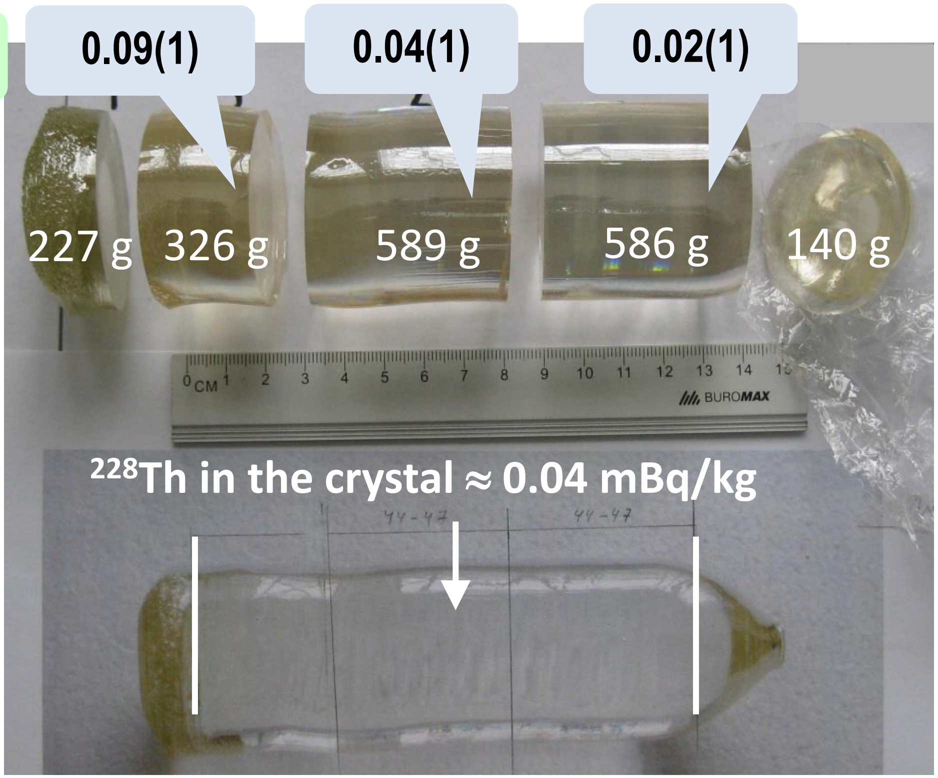
- *Experiment*

Segregation of Th, Ra and K in $CdWO_4$

Activity of ^{228}Th (mBq/kg)*



Rest of the melt after the crystal growth



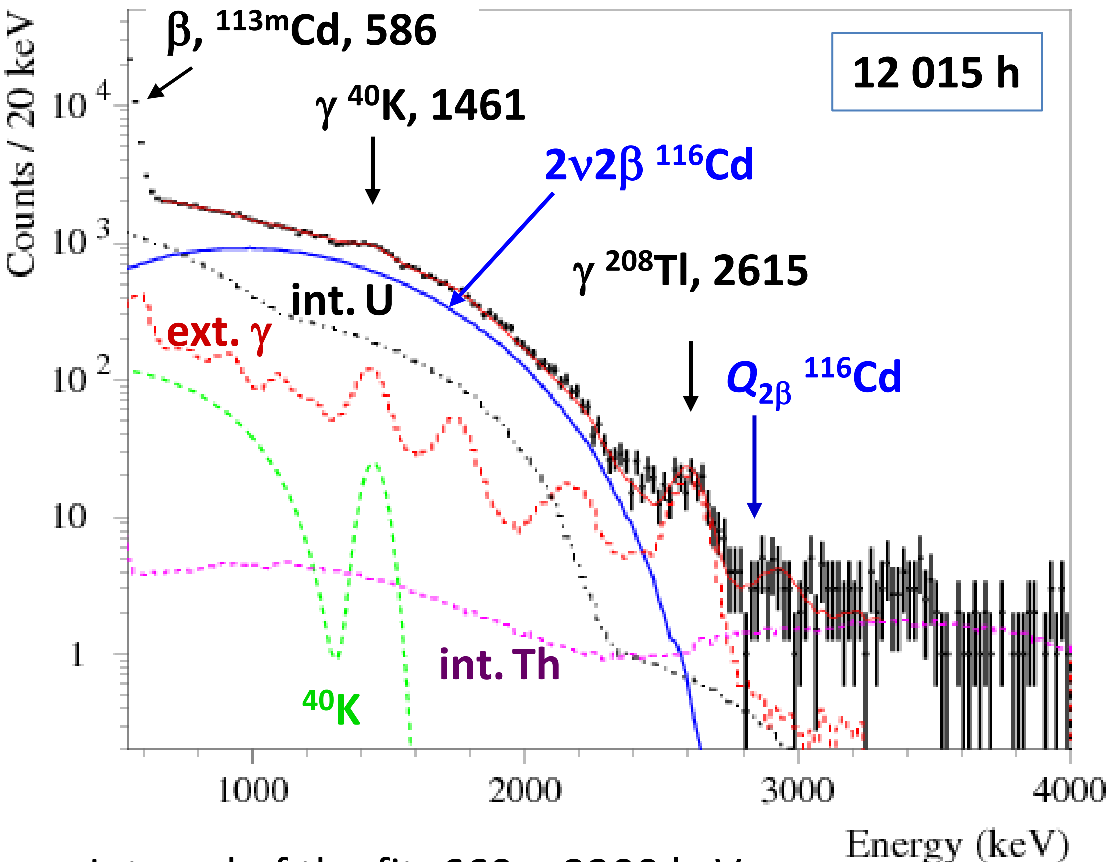
Nuclide	Crystal	Rest of melt
^{40}K	< 0.9	27(11)
^{226}Ra	< 0.005	64(4)
^{228}Th	0.04*	10(2)*

*Reference date: May 2014

^{228}Th in the initial powder / crystal ≈ 1.4 mBq/kg / 0.04 mBq/kg ≈ 35

Thorium expected to be reduced by re-crystallization → ~ 1 μBq/kg

Two neutrino 2β decay of ^{116}Cd



Interval of the fit: 660 – 3300 keV

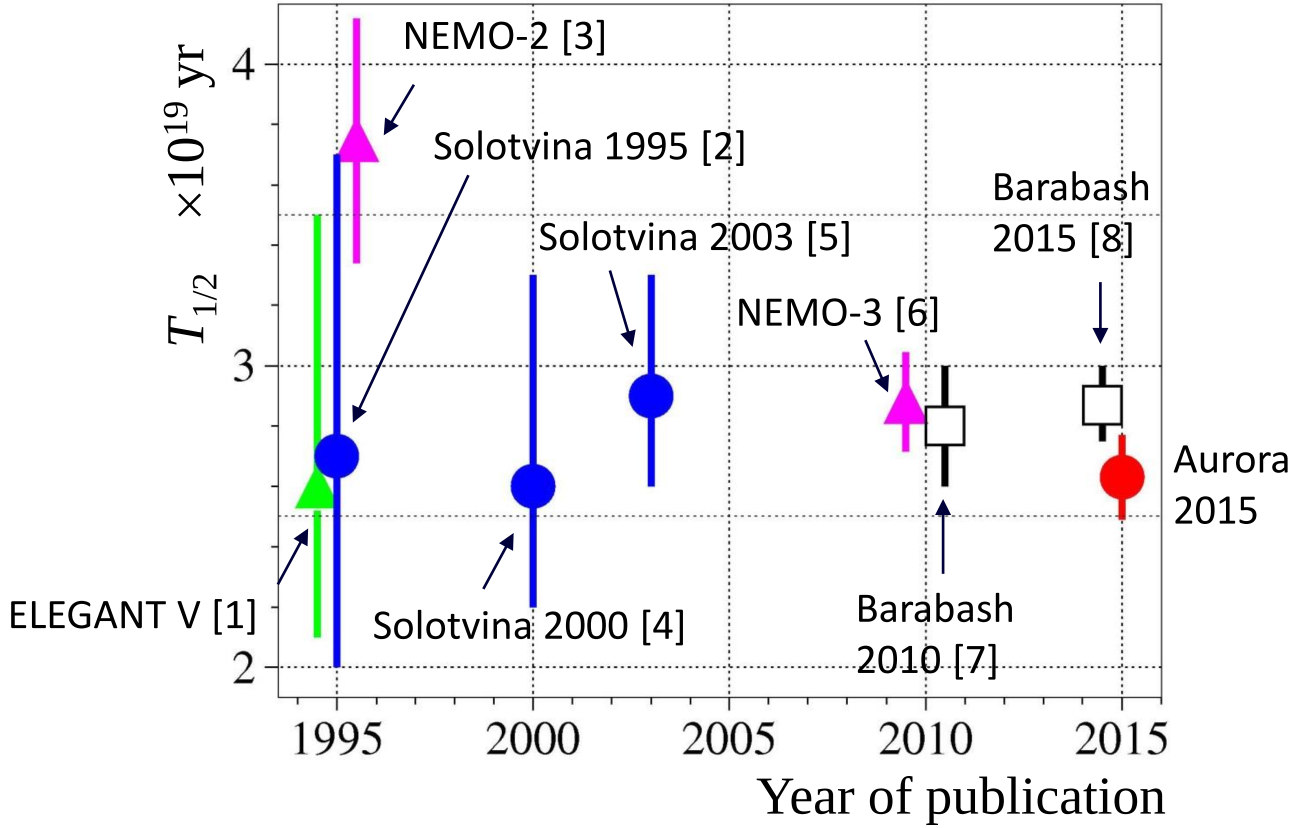
Sources of the systematic error

Source	Contribution $\times 10^{19}$ yr
Number of nuclei	0.002
Live time	≤ 0.002
Efficiency of PSD	0.012
Model of background, interval of fit	0.1
Simulation	0.025

$$T_{1/2}^{2\nu} = [2.62 \pm 0.02(stat.) \pm 0.14(syst.)] \times 10^{19} \text{ yr}$$

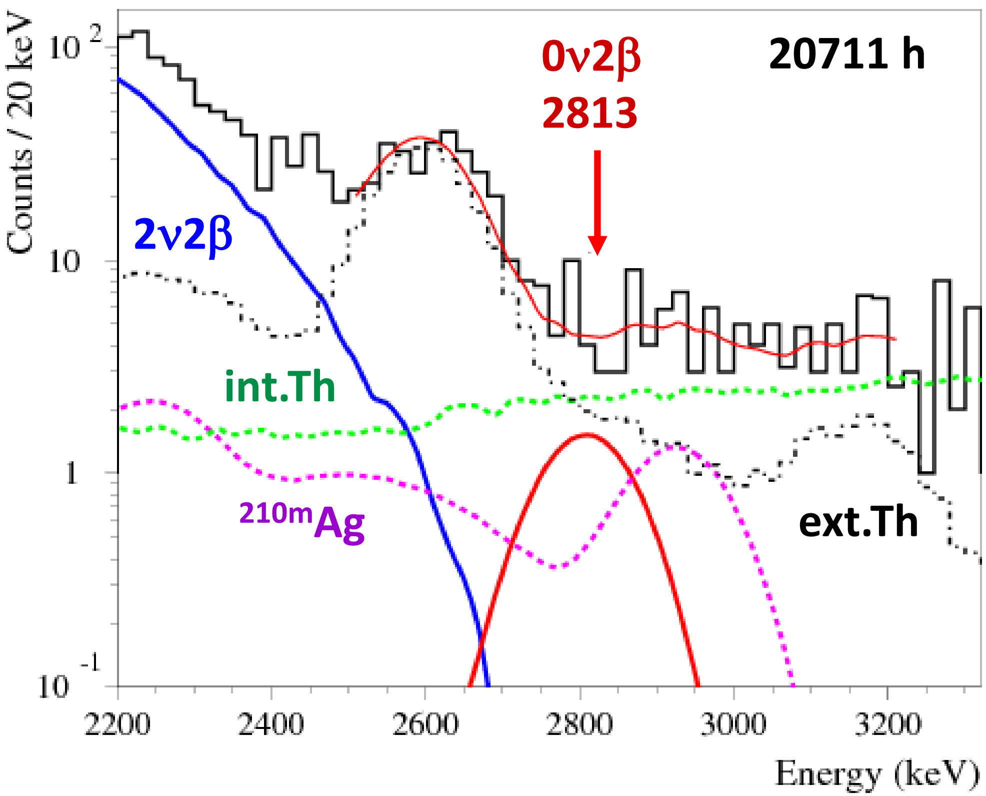
- *Results and discussion*

Comparison with other experiments and averaged values



[1] H. Ejiri et al., J. Phys. Soc. Japan 64 (1995) 339; [2] F.A. Danevich et al., Phys. Lett. B 344 (1995) 72; [3]R.Arnold et al., Z. Phys. C 72 (1996) 239; [4] F.A.Danevich et al., PRC 62 (2000) 045501; [5] F.A.Danevich et al., PRC 68 (2003) 035501; [6] V.I. Tretyak et al., AIP Conf. Proc. 1572 (2013) 110; [7] A.S. Barabash, PRC 81 (2010) 035501; [8] A.S. Barabash, NPA 935 (2015) 52

Limit on 0ν2β decay of ^{116}Cd



Sum of two runs with the background counting rate ≈0.1 cnt/(yr keV kg) in the energy interval 2.7-2.9 MeV

Fit in 2.5 – 3.2 MeV gives area of the effect *S* = -3.7 ± 10.2 counts

lim*S* = 13.3 counts at 90% CL [1]

$$T_{1/2}^{0\nu} \geq 1.9\times10^{23}\ \text{yr}$$

Effective Majorana neutrino mass limits:

$\langle m_\nu \rangle \leq$ 1.6 eV [2]

$\langle m_\nu \rangle \leq$ (1.3– 1.7) eV [3]

[1] G.J. Feldman and R. D. Cousins, Phys. Rev. D 57 (1998) 3873
[2] J. Barea, J. Kotila, and F. Iachello Phys. Rev. Lett. 109 (2012) 042501
[3] J.D. Vergados, H.Ejiri and F.Simkovic Rep. Prog. Phys. 75 (2012) 106301

Results

Decay mode	Transition, level of ^{116}Sn	lim$T_{1/2}$ (yr) 90% CL	Best previous limit 90% CL
0ν	g.s.	**$\geq 1.9 \times 10^{23}$**	$\geq 1.7 \times 10^{23}$ [1]
0ν	2_1^+ (1294 keV)	**$\geq 6.2 \times 10^{22}$**	$\geq 2.9 \times 10^{22}$ [1]
0ν	0_1^+ (1757 keV)	**$\geq 6.3 \times 10^{22}$**	$\geq 1.4 \times 10^{22}$ [1]
0ν	0_2^+ (2027 keV)	**$\geq 4.5 \times 10^{22}$**	$\geq 0.6 \times 10^{22}$ [1]
0ν	2_2^+ (2112 keV)	**$\geq 3.6 \times 10^{22}$**	$\geq 1.7 \times 10^{20}$ [2] (at 68% CL)
0ν	2_3^+ (2225 keV)	**$\geq 4.1 \times 10^{22}$**	$\geq 1.0 \times 10^{20}$ [2] (at 68% CL)
0νM1	g.s.	**$\geq 1.1 \times 10^{22}$**	$\geq 0.8 \times 10^{22}$ [1]
0νM2	g.s.	**$\geq 0.9 \times 10^{21}$**	$\geq 0.8 \times 10^{21}$ [1]
0νM^{bulk}	g.s.	**$\geq 2.1 \times 10^{21}$**	$\geq 1.7 \times 10^{21}$ [1]
2ν	g.s.	**$= 2.62 \times 10^{19}$**	see slide 12
2ν	2_1^+ (1294 keV)	$\geq 0.9 \times 10^{21}$	$\geq 2.3 \times 10^{21}$ [3]
2ν	0_1^+ (1757 keV)	$\geq 1.0 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [3]
2ν	0_2^+ (2027 keV)	$\geq 1.1 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [3]
2ν	2_2^+ (2112 keV)	**$\geq 2.3 \times 10^{21}$**	$\geq 1.7 \times 10^{20}$ [2] (at 68% CL)
2ν	2_3^+ (2225 keV)	**$\geq 2.5 \times 10^{21}$**	$\geq 1.0 \times 10^{20}$ [2] (at 68% CL)

[1] F.A. Danevich et al., Phys. Rev. C 68 (2003) 035501
[2] A.S. Barabash, A.V. Kopylov, V.I. Cherehovsky, Phys. Lett. B 249 (1990)186
[3] A.Piepke et al. Nucl. Phys. A 577 (1994) 493

Conclusions

- The Aurora experiment to search for 2β decay processes in ^{116}Cd with the help of enriched radiopure $^{116}CdWO_4$ scintillators is running at the Gran Sasso underground laboratory

- The most precise measurement of $2\nu2\beta$ decay of ^{116}Cd:

$$\boldsymbol{T_{1/2} = [2.62 \pm 0.02(\mathrm{stat.}) \pm 0.14(\mathrm{syst.})]\times 10^{19}\ \mathrm{yr}}$$

- The new limit is set for the $0\nu2\beta$ decay as

$$\boldsymbol{T_{1/2} \geq 1.9 \times 10^{23}\ \mathrm{yr}}$$

which corresponds to $\langle m_\nu \rangle \leq$ **(1.3 – 1.7) eV**

- New improved limits are obtained for 2β decay of ^{116}Cd with emission of majorons and to the exited levels of ^{116}Sn: $\boldsymbol{T_{1/2} \geq 10^{21} - 10^{22}\ \mathrm{yr}}$

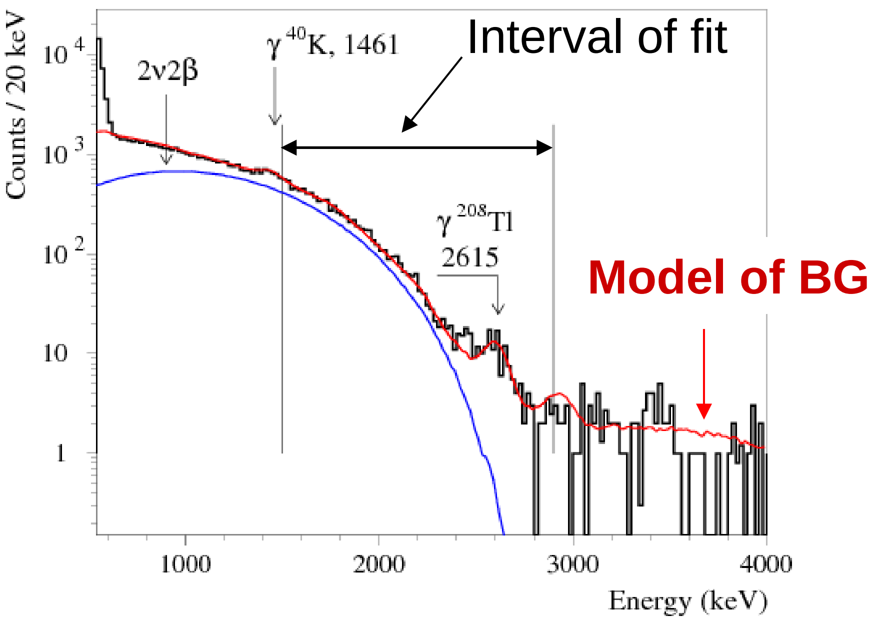
- The experiment is in progress

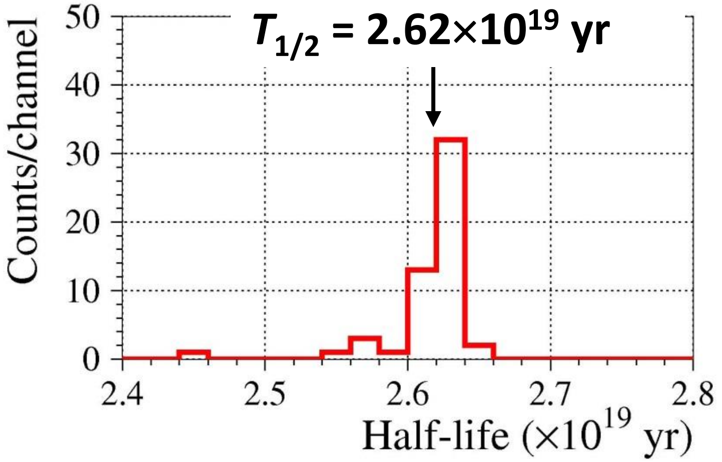
Backup slides

Estimation of systematic errors

Conditions of the Fit:

- Variation of bounds for rad. contaminations
- Model of background
- Interval of fit
- Quenching for β (non proportional light response) [1,2]



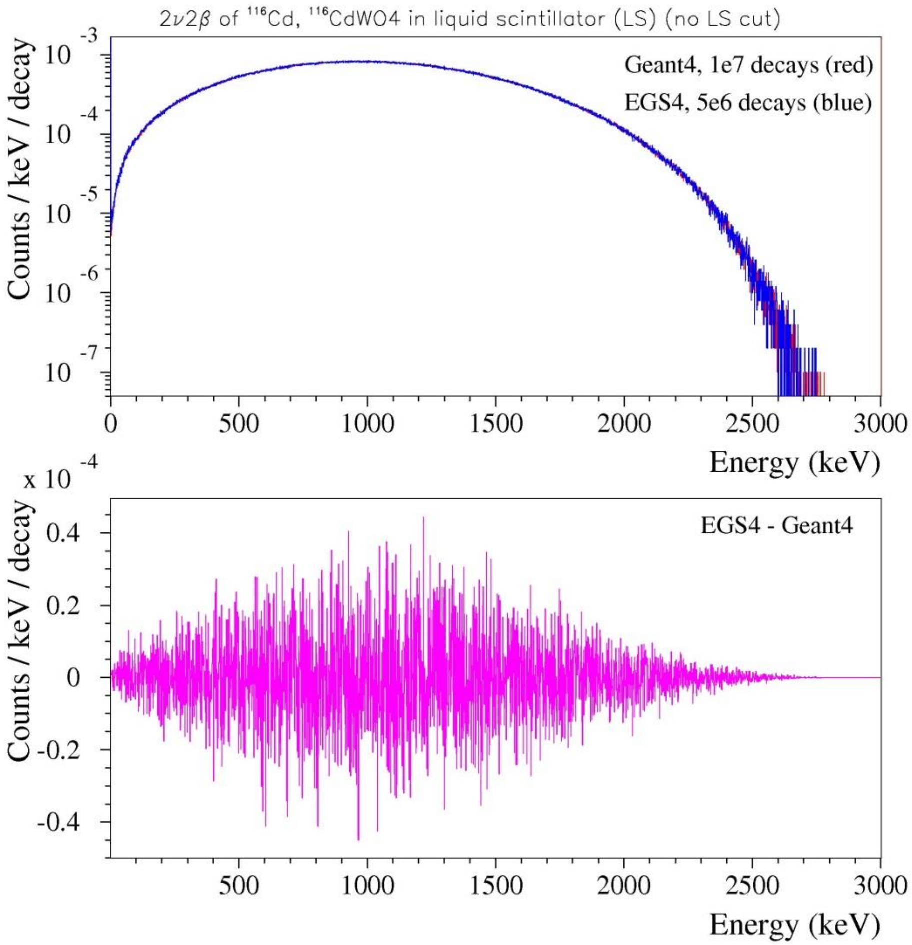


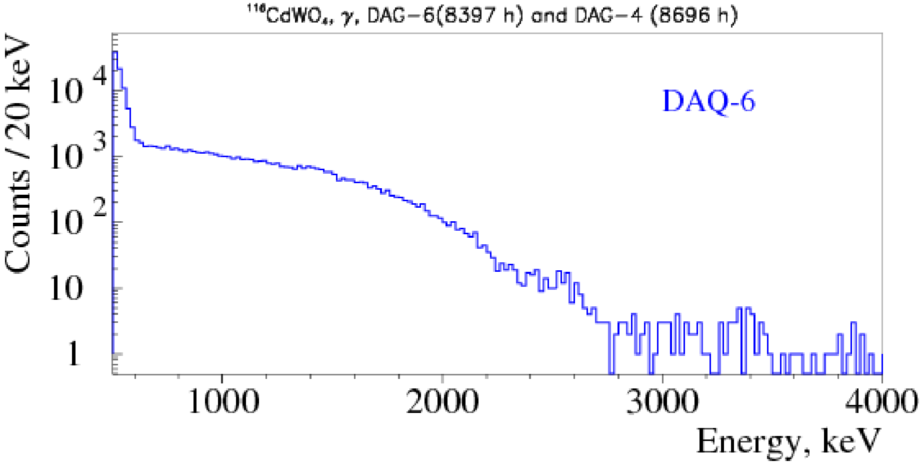
53 fits in (640-1700) - (2300-3900) keV

Source	Contribution $\times 10^{19}$ yr
Number of nuclei	0.002
Live time	$\leq$ 0.002
Efficiency of PSD	0.012
Model of background, interval of fit	0.1
Simulation	0.025

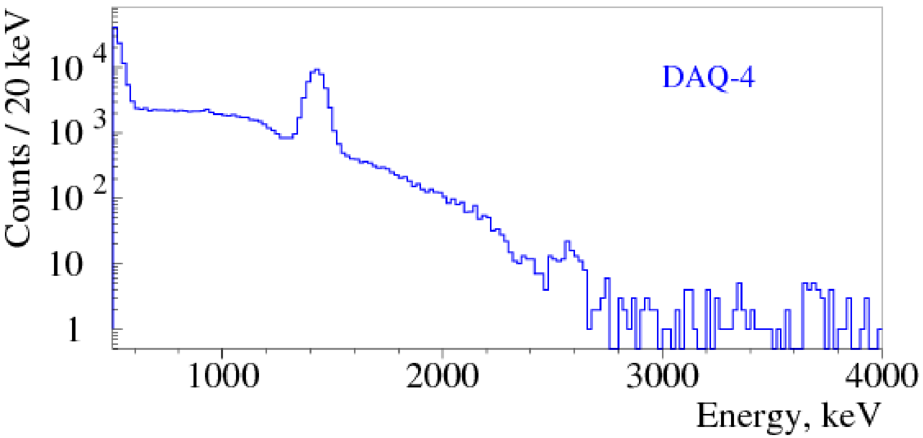
[1] PRC 76(2007)064603 [2] NIMA 696(2012)144

Estimation of systematic error: Monte Carlo simulation

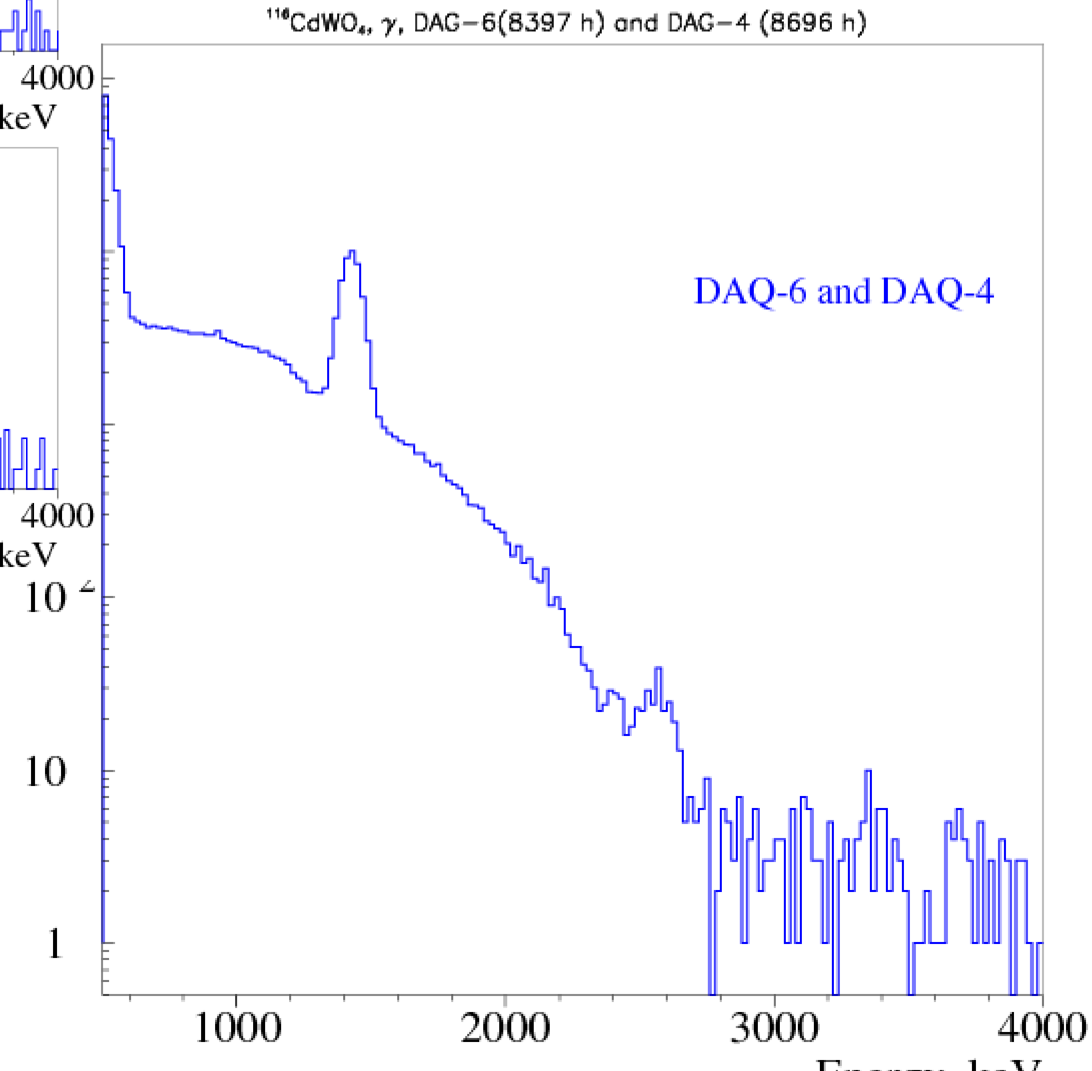




^{116}CdWO$_4$, γ, DAG-6(8397 h) and DAG-4 (8696 h)
DAQ-6
Counts / 20 keV
Energy, keV



DAQ-4
Counts / 20 keV
Energy, keV



^{116}CdWO$_4$, γ, DAG-6(8397 h) and DAG-4 (8696 h)
DAQ-6 and DAQ-4
Energy, keV

Response of the $^{116}CdWO_4$ detector to 2β processes in ^{116}Cd simulated by EGS4