Investigation of 2β decay of ^{116}Cd with the help of enriched $^{116}CdWO_4$ crystal scintillators

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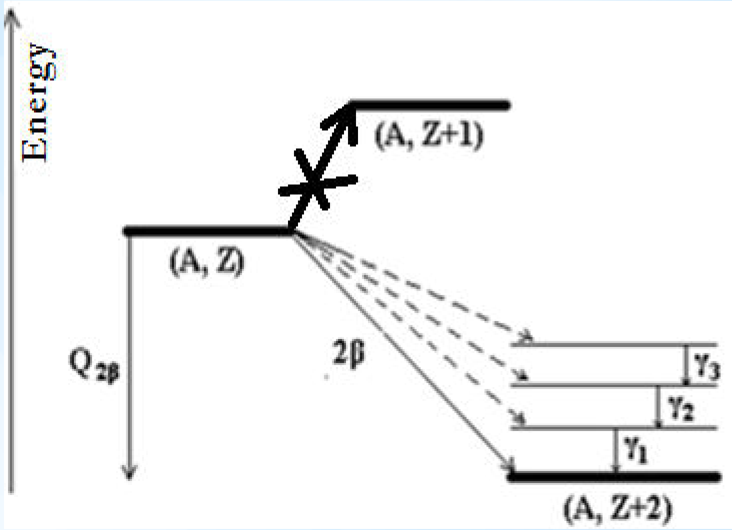
2β processes

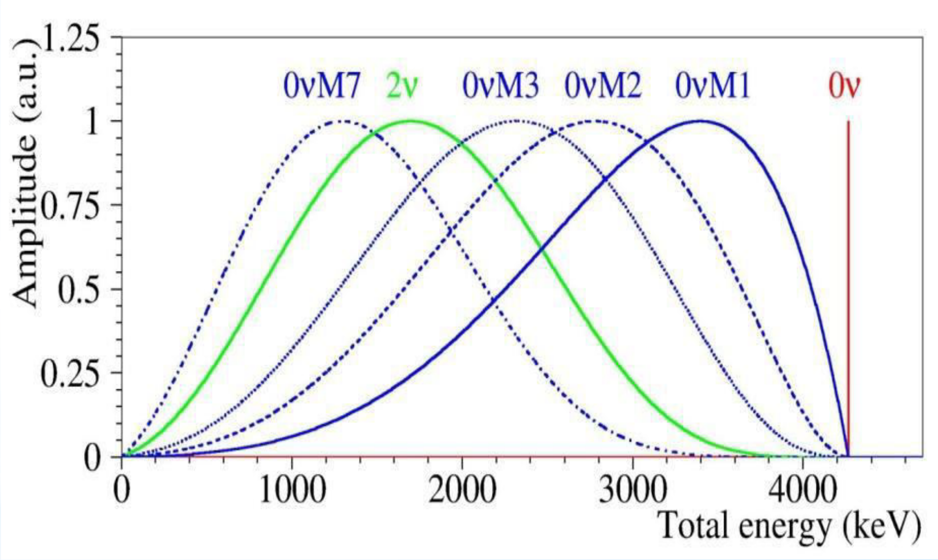
2ν2β (A, Z) → (A, Z + 2) + 2e⁻ + 2$\tilde{\nu}$ (allowed in SM)
0ν2β (A, Z) → (A, Z + 2) + 2e⁻ (forbidden in SM, ΔL=2)



Detection of 0ν2β decay allows to test:
- nature of neutrino (**Dirac** or **Majorana** particle);
- existence of right-handed currents in the weak interaction;
- scale of the neutrino mass and hierarchy, conservation of lepton charge;
- existence of Majorons;
- theory of supersymmetry

Over 75 years of experimental searches 2ν2β decay was observed only for 11 nuclei in the direct, geochemical and radiochemical experiments (^{48}**Ca**, ^{76}**Ge**, ^{82}**Se**, ^{96}**Zr**, ^{100}**Mo**, ^{116}**Cd**, ^{128}**Te**, ^{130}**Ba**, ^{130}**Te**, ^{150}**Nd**, ^{136}**Xe and** ^{238}**U**) with half-lives in the range ~ **10^{18}–10^{24} years**

2β decay processes with decreasing nuclear charge and 0ν2β decay (*) has not been observed yet (^{130}Ba - geochemical and ^{78}Kr - indication in laboratory experiment)



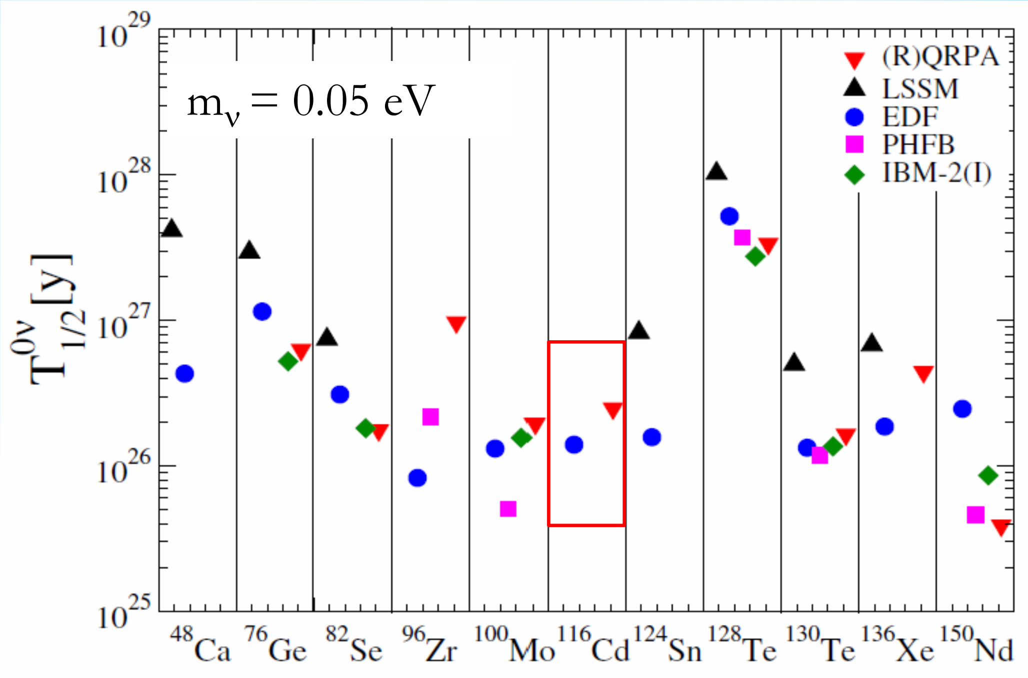
e_1+e_2 energy spectra for different 2β modes

- **One positive claim on observation of 0ν2β in ^{76}Ge by HM ($T_{1/2}$ = 2.2×10^{25} yr),**
- **GERDA - >5.2×10^{25} yr [M. Agostini talk at NEUTRINO'2016]**

^{116}Cd

One of the most promising isotopes to search for 0ν2β decay

- $Q_{2\beta}$ = 2813.44(13) keV
- δ = 7.5%
- promising theoretical calculation
- possible isotopic enrichment in large amount



J.D. Vergados et al., RPP 75(2012)106301

$CdWO_4$ crystals

- good scintillation properties
- source = detector approach
- low levels of internal contamination
- particle discrimination ability (↓ background)

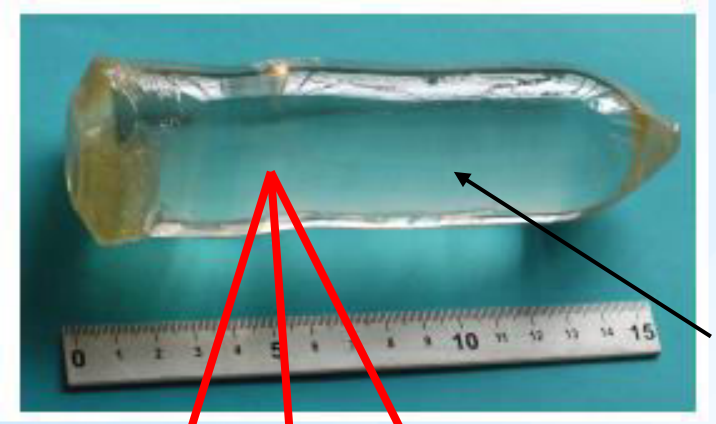
$CdWO_4$ were successfully used in low-background experiments on search for 2β decay of Cd and W [1], as well as for the study of rare α [2] and β [3] decays

The most sensitive 0ν2β experiments (90% C.L.):

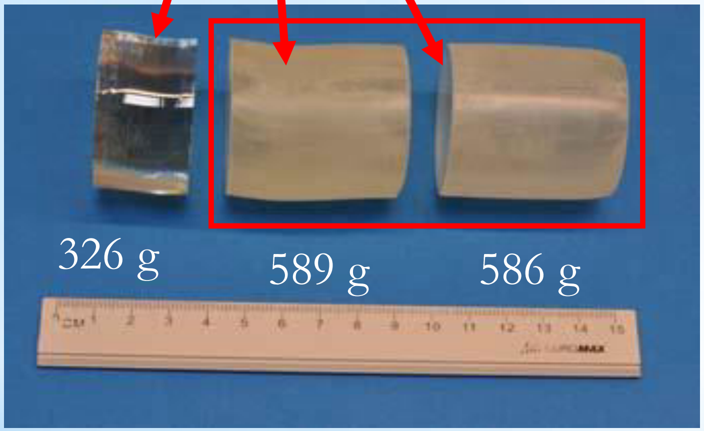
- Solotvina, F.A. Danevich et al., PRC 68 (2003) 035501 – $T_{1/2}$ > 1.7×10^{23} yr
- NEMO-3, D. Waters, talk at Neutrino'2016 – $T_{1/2}$ > 1.0×10^{23} yr

[1] ZPA 355(1996)433, EPJA 36(2008)167, PRC 93(2016)045502;
[2] PRC 67(2003)014310;
[3] PAN 59(1996)1, PRC 76(2007)064603

$^{116}CdWO_4$ crystal scintillator



Good 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]

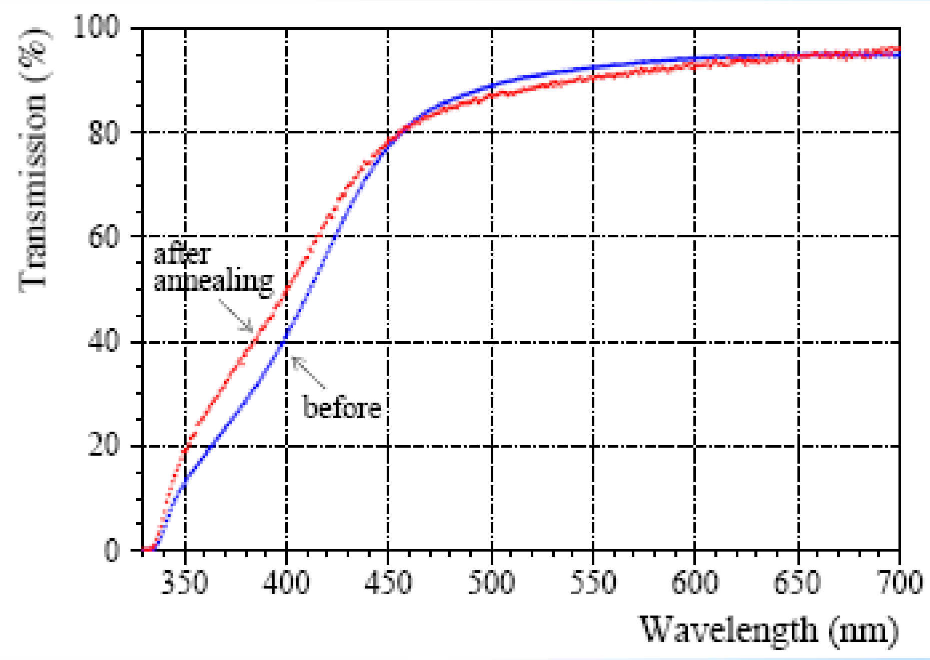


Boule of enriched $^{116}CdWO_4$ crystal (82% of ^{116}Cd).

Yield of the crystal boule is 87% of the initial powder

Losses (the total production cycle) < 3%

[1] JINST 6(2011)P08011



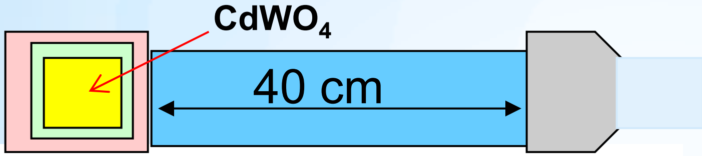
The optical transmission curve of $^{116}CdWO_4$ before and after annealing
Attenuation length is 60 cm

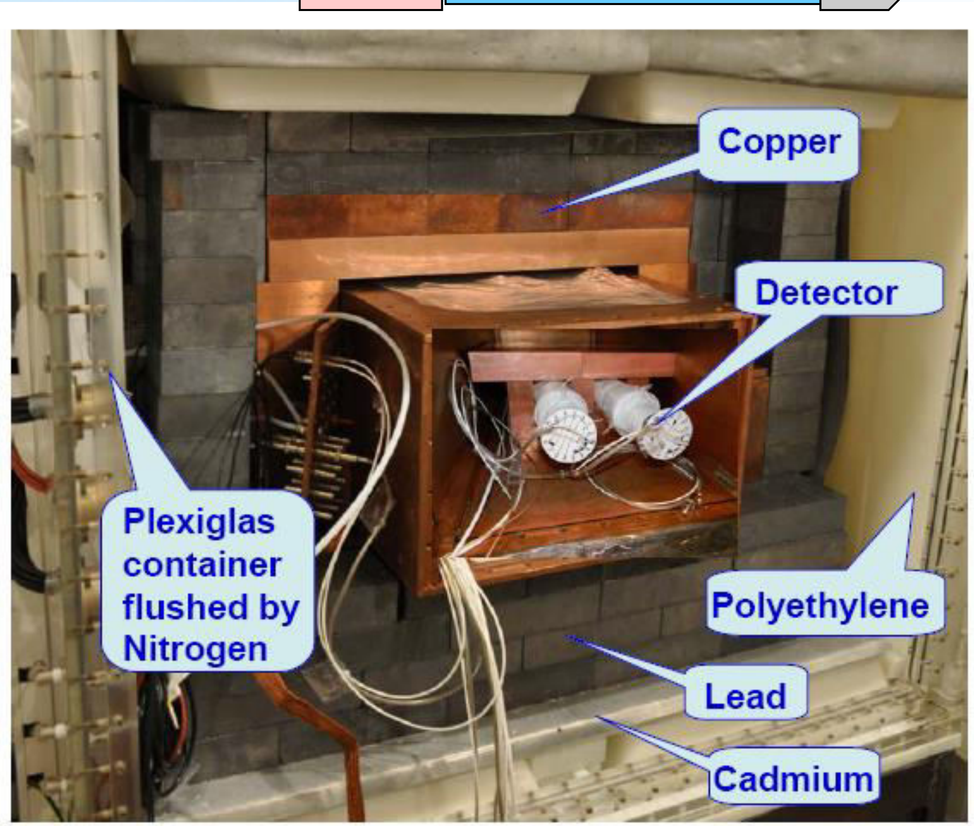
Experiment AURORA

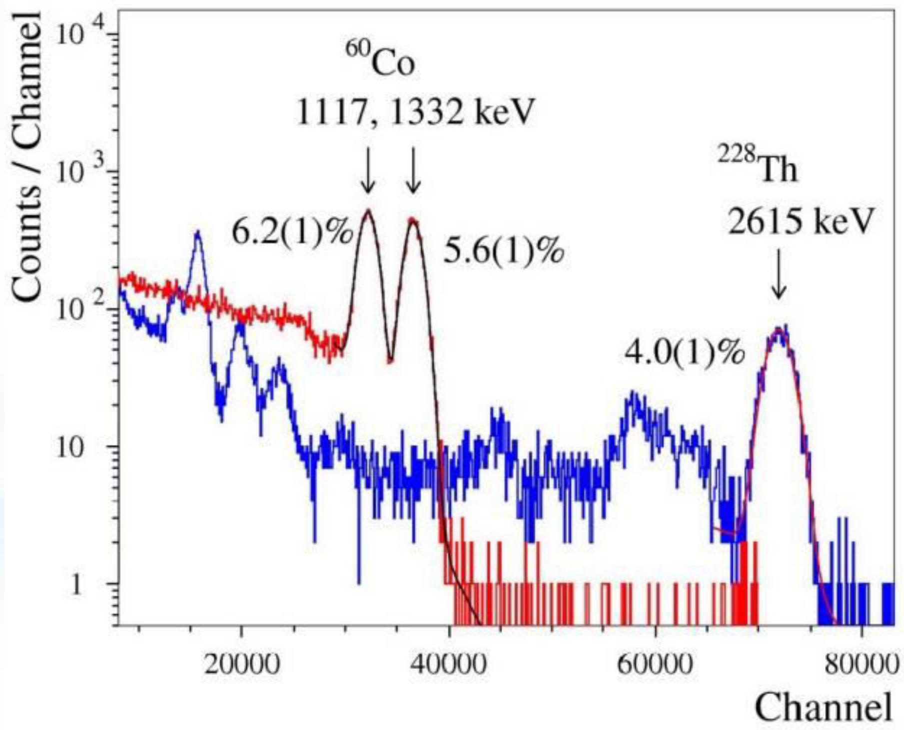
Experiment started in 2011

2 crystals of $^{116}CdWO_4$, 1.162 kg in DAMA/R&D (external shielding – Cu, Pb, polyethylene, Cd, air-tight with N_2 flashing)

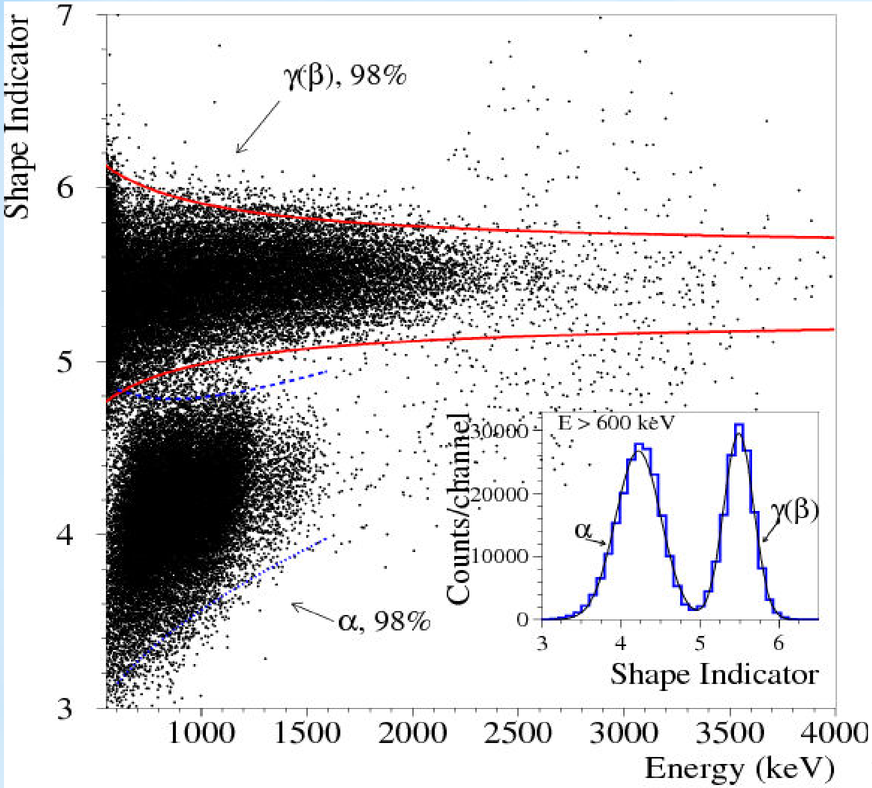
Upgrade - March 2014 → Bg ↓ to ≈ 0.1 counts/(yr×kg×keV) at 2.7−2.9 MeV







Pulse shape discrimination (PSD), 21470 h



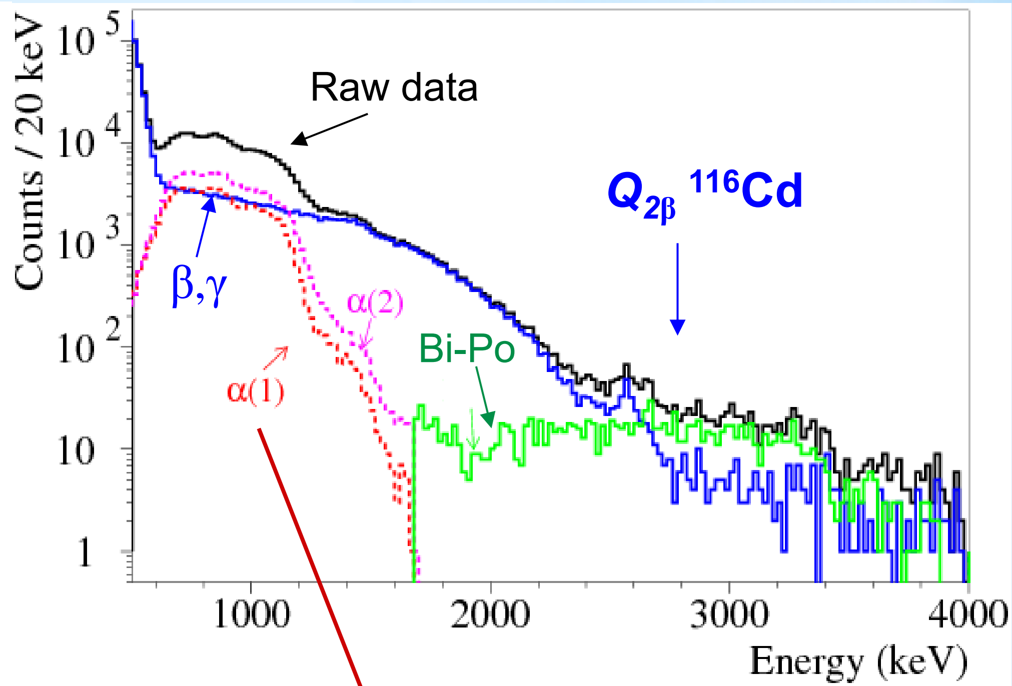
Shape indicator (SI) versus energy for the background exposure (21470 h × 1.162 kg)

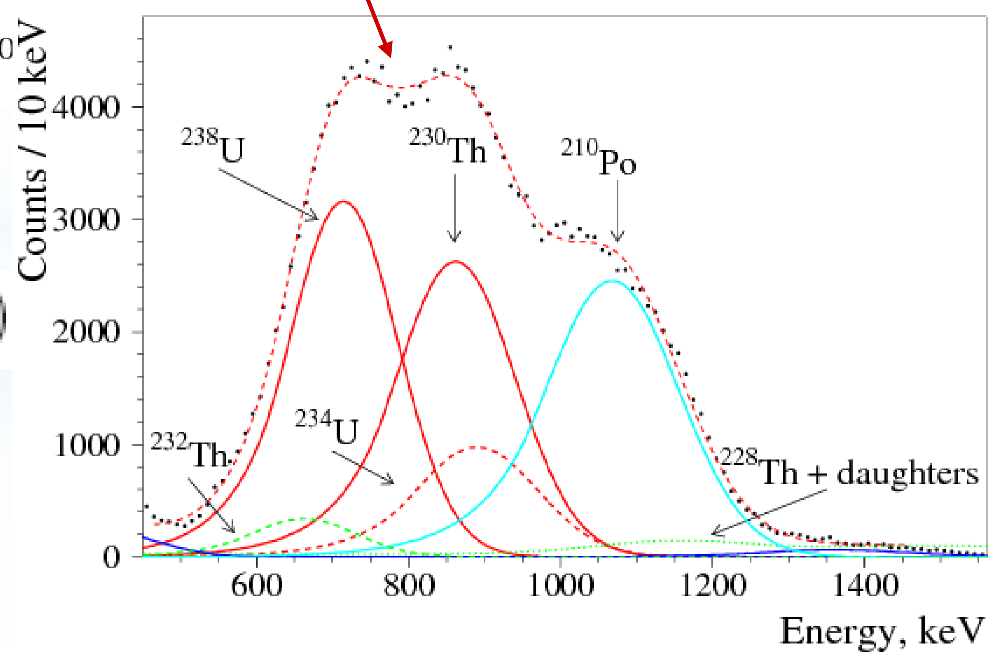
$$SI = \sum f(t_k) \times P(t_k) / \sum f(t_k)$$

$P(t) = [f\alpha(t) - f\gamma(t)] / [f\ \alpha(t) + f\gamma(t)]$

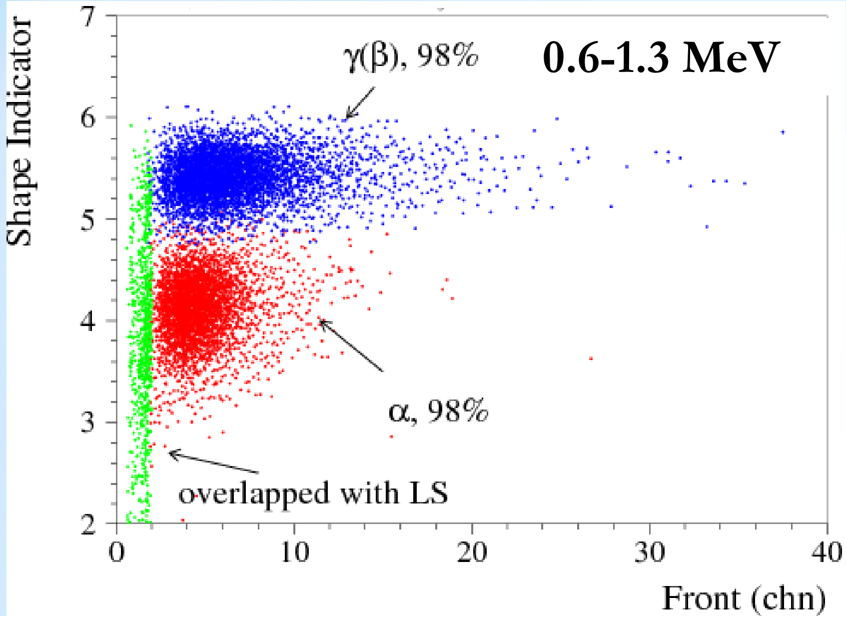
$f(t_k)$ - digitized amplitude

$f_\alpha(t), f_\gamma(t)$ - reference pulse shapes for α and γ

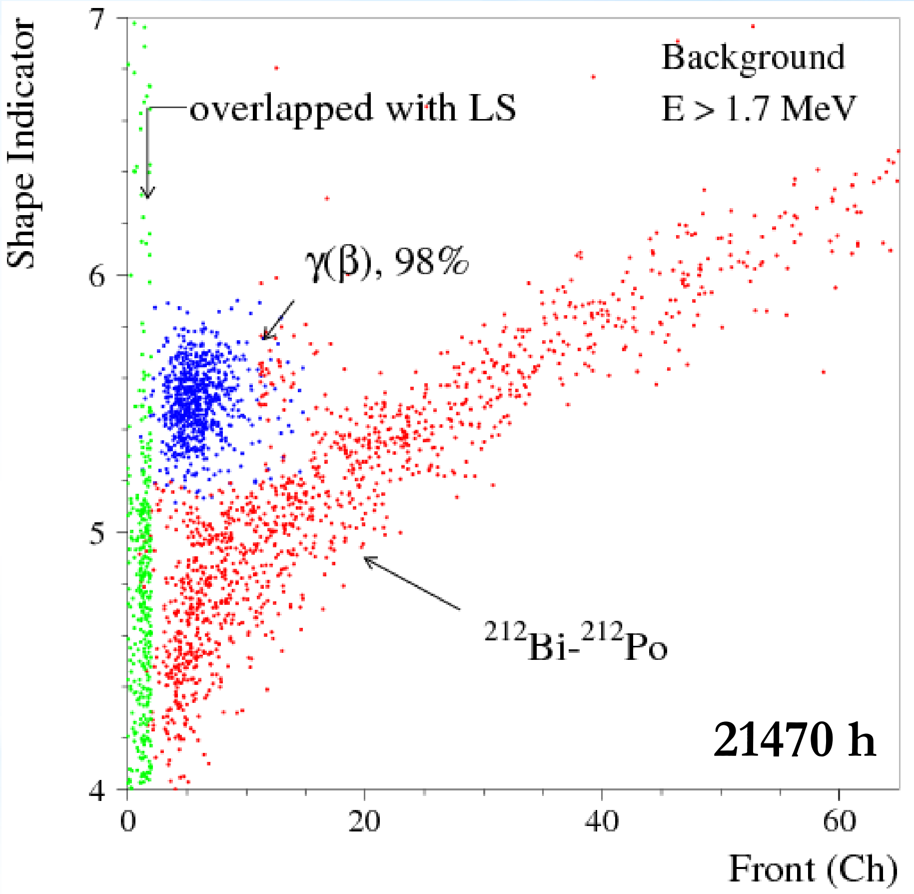




Selection of ^{212}Bi-^{212}Po events by front-edge analysis



2D histogram: shape indicator versus front edge for the background measurements



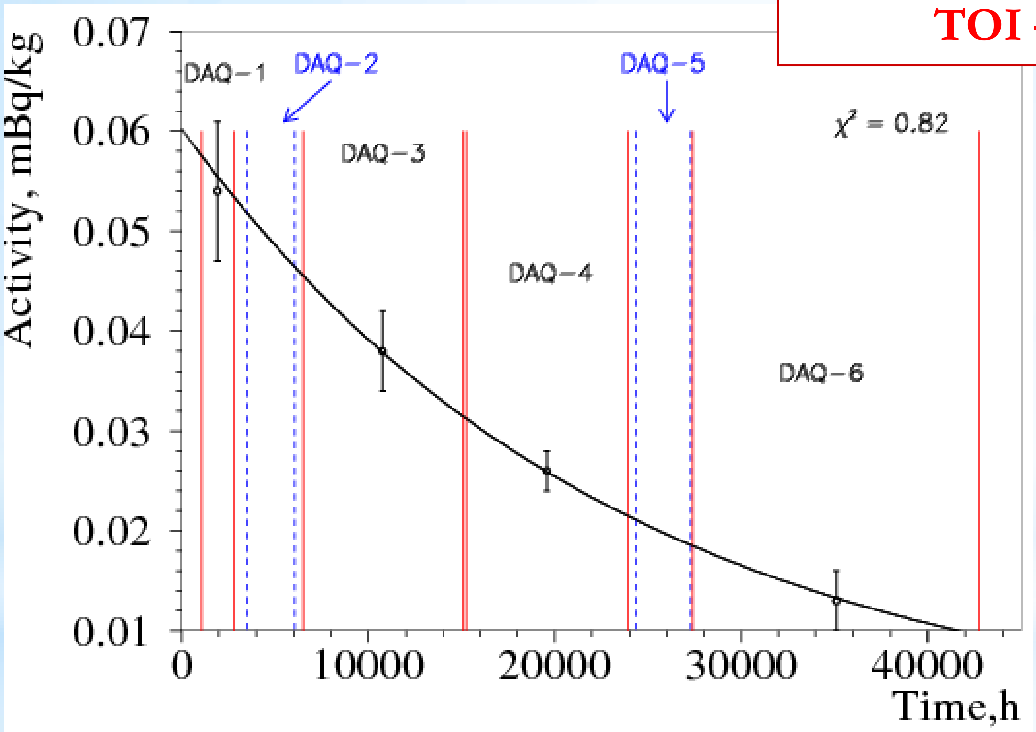
Important information from PSD and front-edge analysis:

1) **Activity of ^{228}Th (in μBq/kg), 21470 h**

Crystal 1 18(2)

Crystal 2 27(3)

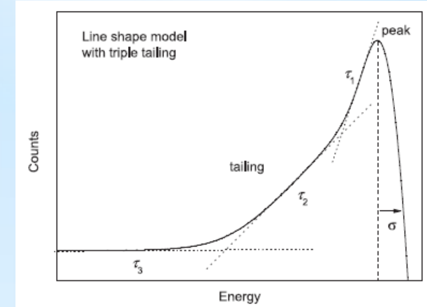
2) **Change of ^{228}Th in time**

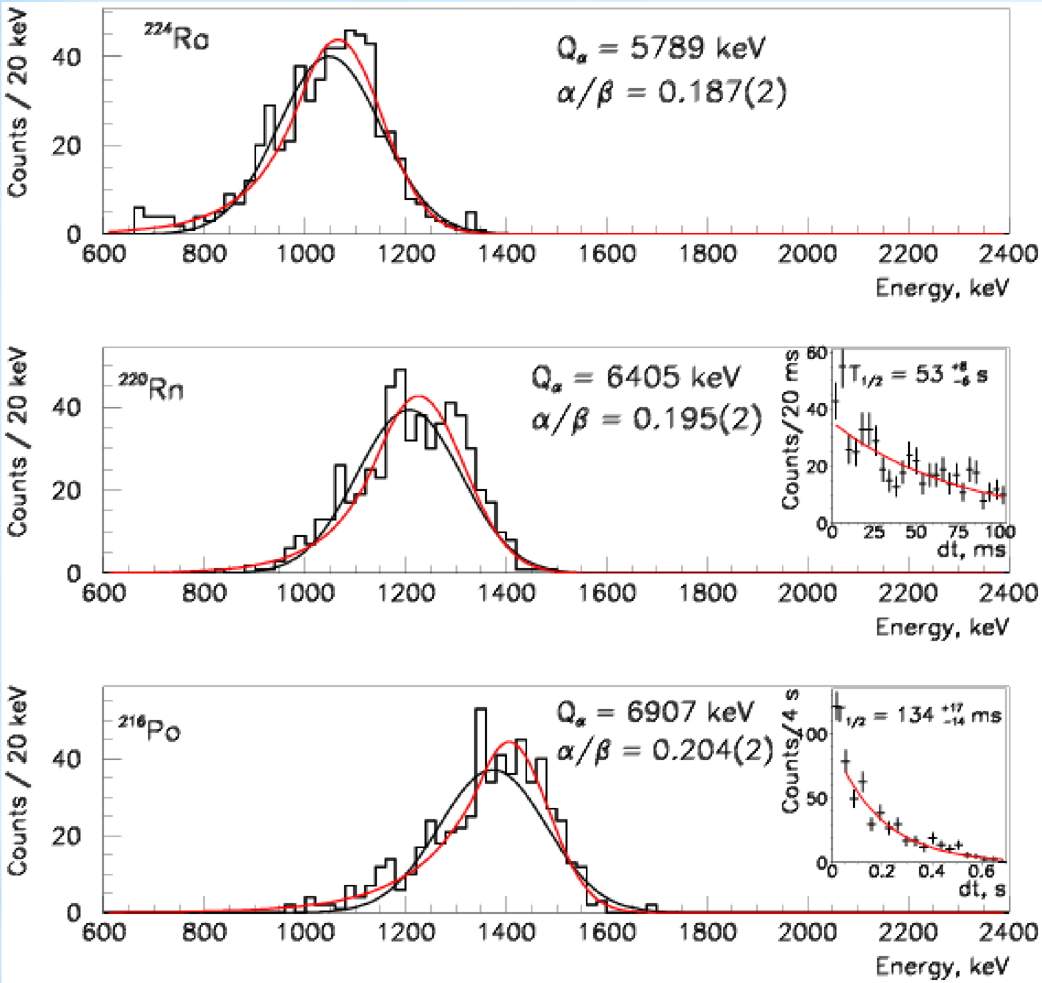


Decay of ^{228}Th ($T_{1/2} \approx 1.9(1)$ yr)
TOI – 1.9116(16) yr

3) **Rate @ 2.7–2.9 MeV: 0.11(2) cnts/(keV×kg×yr)**

Time-amplitude analysis





M.J. Koskelo et al., Radioact. Radiochem. 7(1996)18

$$f(u) = \begin{cases} A \exp\left[-\frac{(u-\mu)^2}{2\sigma^2}\right], & \text{if } u \geq \mu - T \\ A \exp\left[\frac{T(2u - 2\mu + T)}{2\sigma^2}\right], & \text{if } u < \mu - T \end{cases},$$

A – amplitude of Gauss
μ – center of Gauss
σ – standard deviation
T determines both the characteristics of the tailing and its joining point with the Gaussian

Alpha peaks of ^{224}Ra, ^{220}Rn and ^{216}Po selected by the time-amplitude analysis from the data accumulated during 21470 h with the $^{116}CdWO_4$ detector No. 1. The obtained half-lives of **^{220}Rn (53^{+8}_{-6} s)** and **^{216}Po ($0.134^{+0.017}_{-0.014}$ s)** are in agreement with the table values (**55.6 s** and **0.145 s**, respectively [TOI]).

Activity of ^{228}Th, μBq/kg

	PSD+FA	T-A
Crystal 1	**18(2)**	**18(1)**
Crystal 2	**27(3)**	**28(1)**

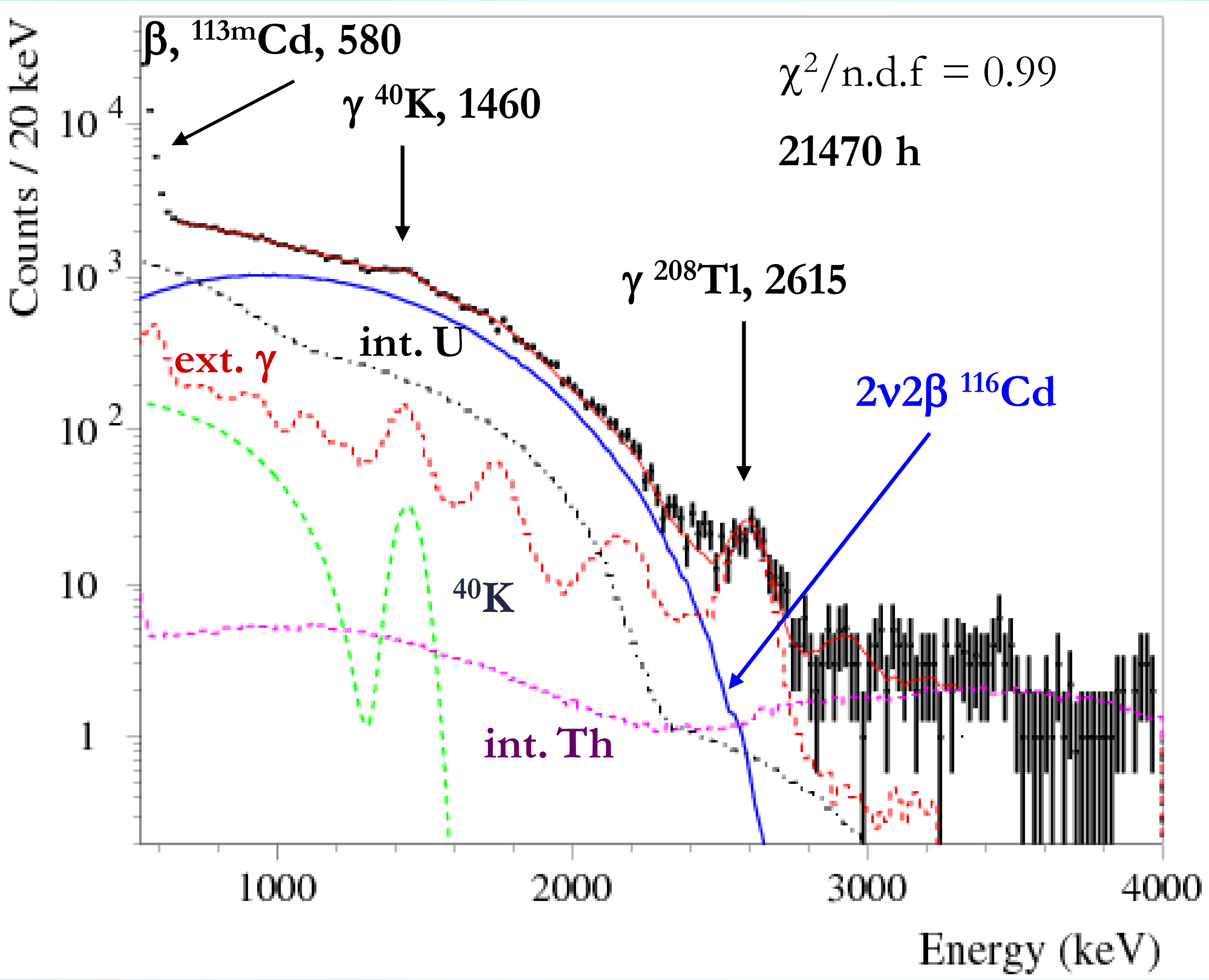
Radioactive contaminations of $^{116}CdWO_4$ crystal scintillators (and elements of the set-up)

Chain	Nuclide	Activity, mBq/kg
^{232}Th	^{232}Th	0.66(9)
	^{228}Th	0.22(4)
^{238}U	^{238}U	0.64(3)
	^{234}Th	0.24(3)
	^{230}Th	0.56(4)
	^{226}Ra	≤ 0.005
	^{210}Pb	0.6(1)
	^{40}K	≤ 0.9
	^{110m}Ag	≤ 0.02

Total α activity of two crystals = 2.27 mBq/kg

	Nuclide	Activity, mBq/kg
PMT	^{226}Ra	543(226)
	^{228}Ra	80(40)
	^{228}Th	116(55)
	^{40}K	<830
Copper	^{238}U	0.11(1)
	228Th	0.05(4)
	^{40}K	0.3(1)
Light quides	^{238}U	<23
	^{228}Th	0.1(1)
	^{40}K	1.2(9)

Two neutrino double beta decay of ^{116}Cd



Simulations (EGS4 + DECAY0 generator)

Signal to bg ratio
= 2.6 in [1.1–2.8] MeV

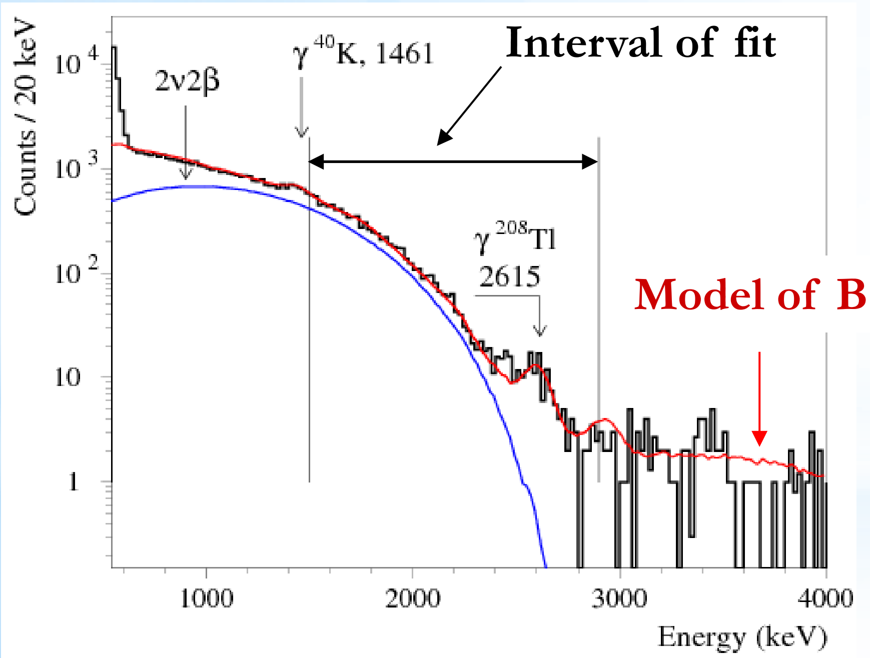
Index of Bg
= 0.11(2) in [2.7-2.9] MeV

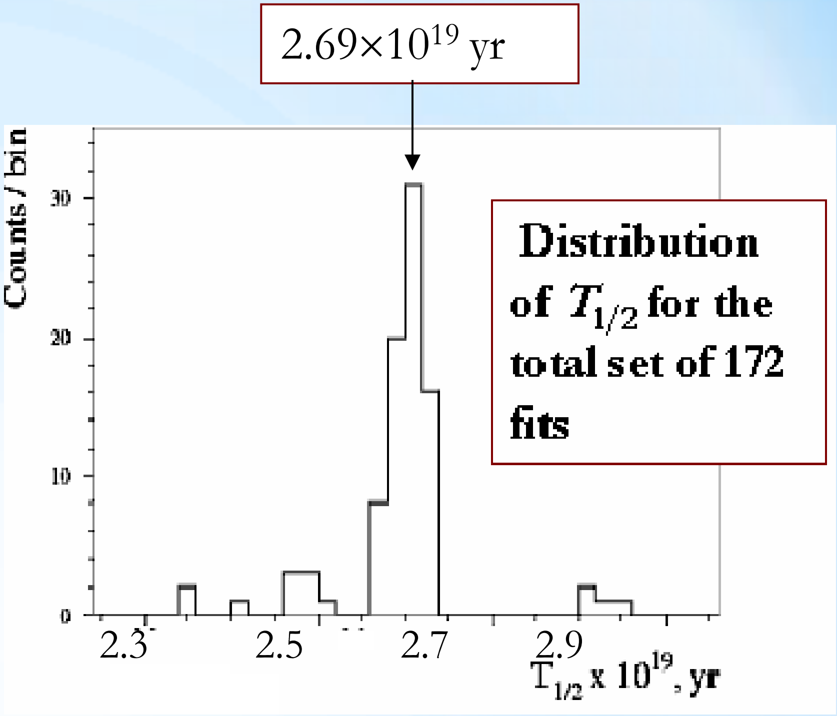
$T_{1/2}$ = [2.69 ± 0.14(syst.) ± 0.02(stat.)] × 10^{19} yr

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]



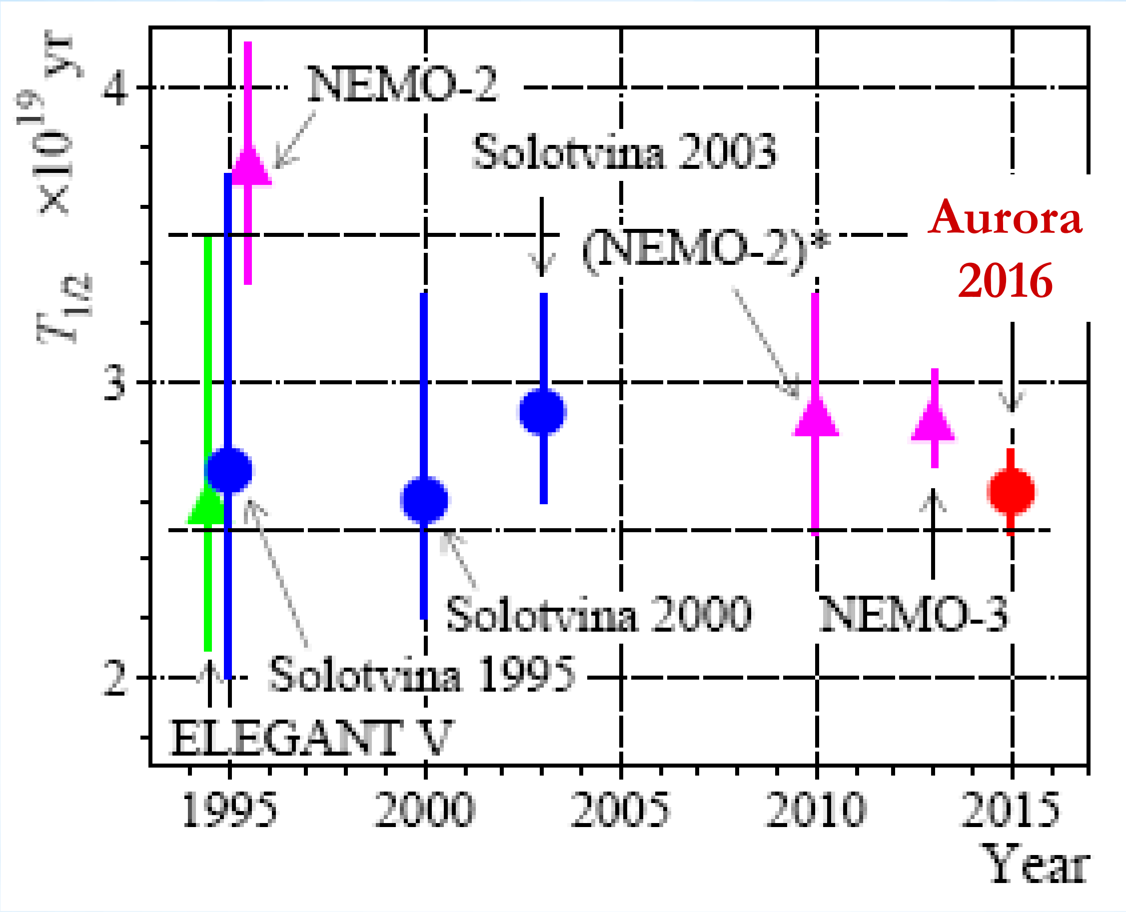


Systematic errors

Source	Contribution,%
Number of nuclei	0.1
Live time	<0.1
Efficiency of PSD	0.5
Fit	5
Simulation	?

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

Summary of the $T_{1/2}(2\nu 2\beta)$ results ^{116}Cd

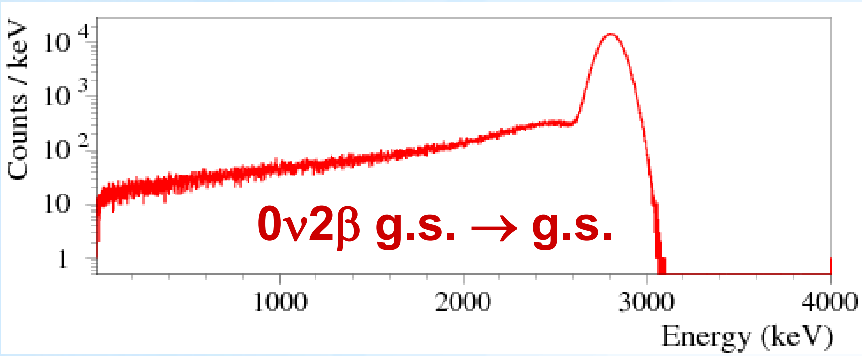


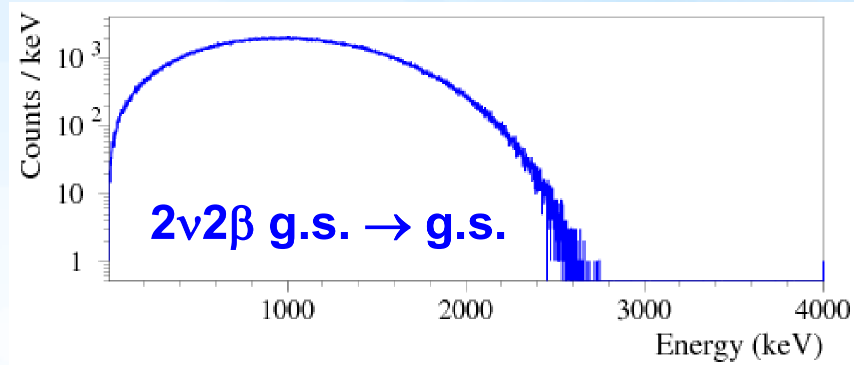
+NEMO-3 eprint 2016 2.74×10^{19}

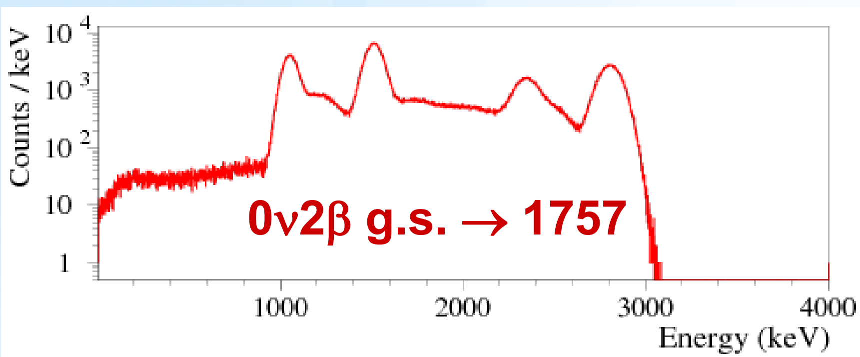
Comparison of the ^{116}Cd $2\nu2\beta$ half-life obtained in the Aurora experiment with other experiments: ELEGANT V, Solotvina, NEMO-2 and NEMO-3. A reevaluated NEMO-2 value is labelled as (NEMO-2)*.

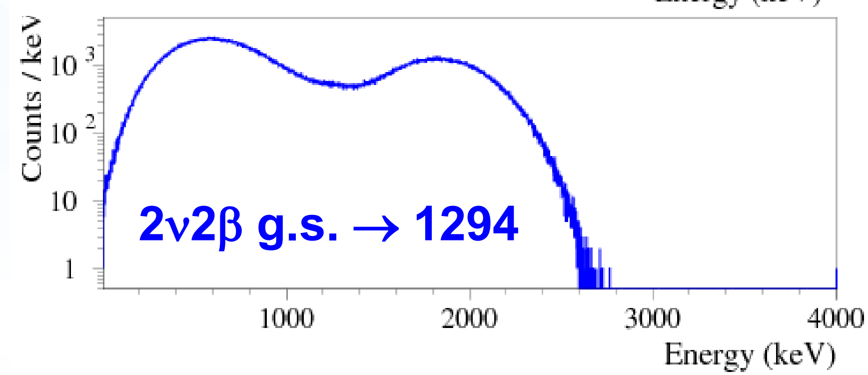
PRC 81(2010)035501 with corrected value for NEMO-2 – $(2.8 \pm 0.4)\times10^{19}$ yr

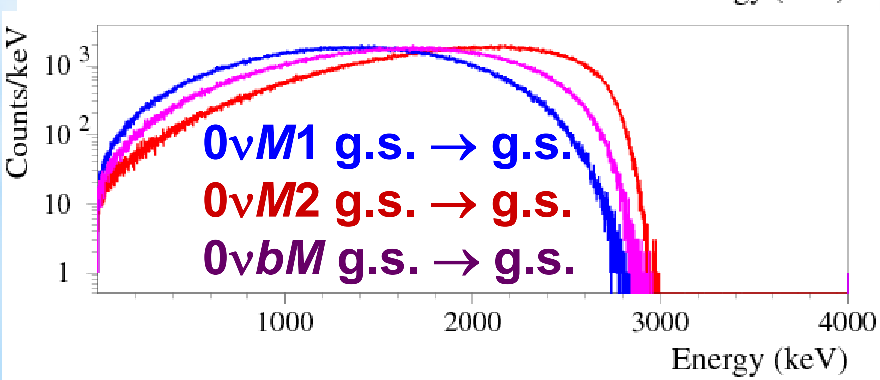
Response of the $^{116}CdWO_4$ detector to 2β processes in ^{116}Cd simulated by EGS4

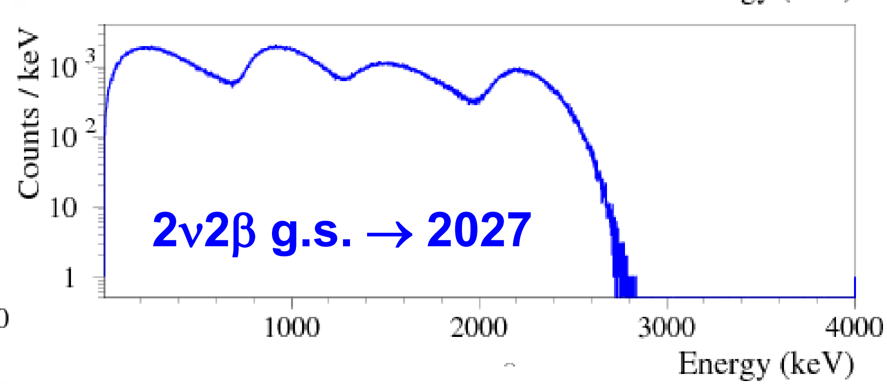




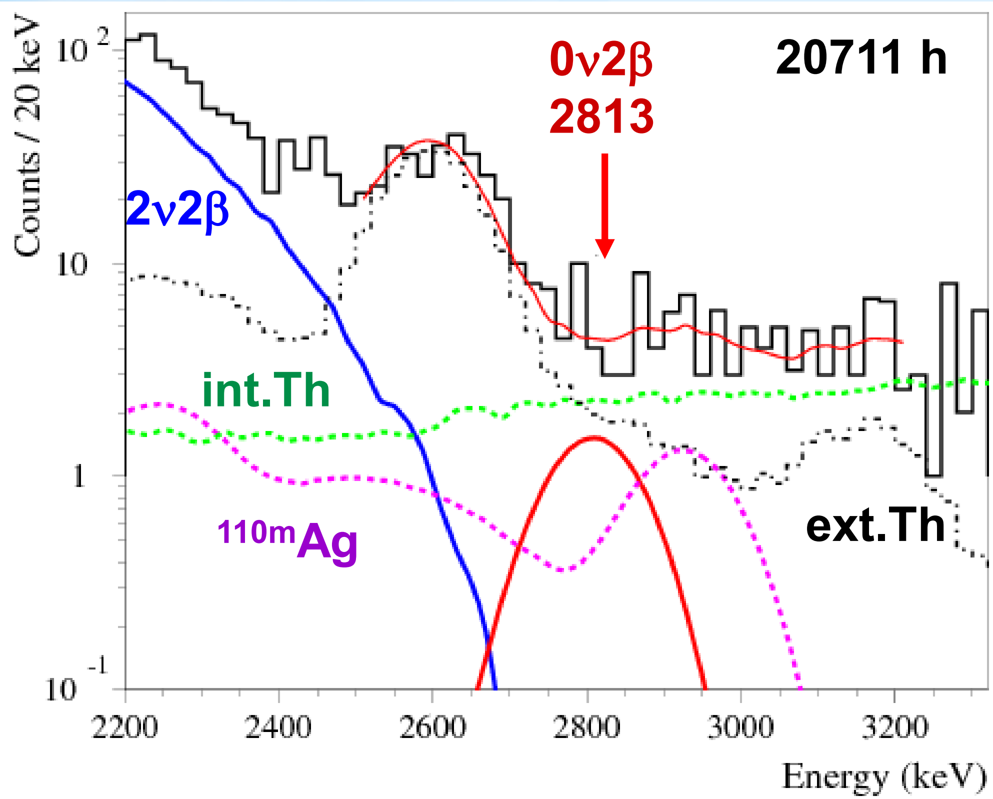








Limit on 0ν2β decay of ^{116}Cd to g.s. of ^{116}Sn



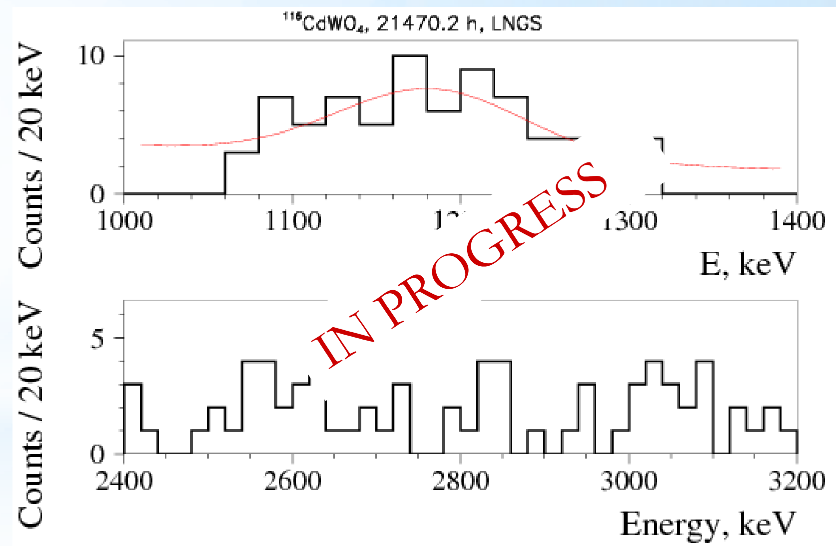
There is no such peculiarity in the spectrum, therefore only lower half-life limit on the process can be set

Fit in 2.5–3.1 MeV with χ^2/n.d.f. = 1.13

S = -3.1 ± 14.1

lim*S* = 20.1 counts @ 90% C.L. by [1]

$T_{1/2} > 1.9 \times 10^{23}$ yr



Effective Majorana neutrino mass

$\langle m_\nu \rangle$ ~ 1.7 eV [2]

$\langle m_\nu \rangle$ ~ 1.2 – 1.8 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

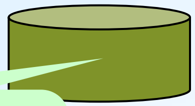
Results

Decay mode	Transition	$T_{1/2}$, yr , present results	$T_{1/2}$, yr at 90% C.L.
0ν	g.s.- g.s.	$\geq 1.9 \times 10^{23}$	$\geq 1.7 \times 10^{23}$ [1]
0ν	g.s.- 2_1^+(1294 keV)	$\geq 6.2 \times 10^{22}$	$\geq 2.9 \times 10^{22}$ [1]
0ν	g.s.- 0_1^+(1757 keV)	$\geq 6.3 \times 10^{22}$	$\geq 1.4 \times 10^{22}$ [1]
0ν	g.s.- 0_2^+(2027 keV)	$\geq 4.5 \times 10^{22}$	$\geq 0.6 \times 10^{22}$ [1]
0ν	g.s.- 2_2^+ (2112 keV)	$\geq 3.6 \times 10^{22}$	$\geq 1.7 \times 10^{20}$[2] (at 68% CL)
0ν	g.s.- 2_3^+ (2225 keV)	$\geq 4.1 \times 10^{22}$	$\geq 1.0 \times 10^{20}$[2] (at 68% CL)
$0\nu M1$	g.s.- g.s.	$\geq 1.1 \times 10^{22}$	$\geq 0.8 \times 10^{22}$ [1]
$0\nu M2$	g.s.- g.s.	$\geq 0.9 \times 10^{21}$	$\geq 0.8 \times 10^{21}$ [1]
$0\nu bM$	g.s.- g.s.	$\geq 2.1 \times 10^{21}$	$\geq 1.7 \times 10^{21}$ [1]
2ν	g.s.- g.s.	$[2.69 \pm 0.14(\text{syst.}) \pm 0.02(\text{stat.})] \times 10^{19}$	See slide 13
2ν	g.s.- 2_1^+(1294 keV)	$\geq 0.9 \times 10^{21}$	$\geq 2.3 \times 10^{21}$ [3]
2ν	g.s.- 0_1^+(1757 keV)	$\geq 1.0 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [3]
2ν	g.s.- 0_2^+(2027 keV)	$\geq 1.1 \times 10^{21}$	$\geq 2.0 \times 10^{21}$ [3]
2ν	g.s.- 2_2^+ (2112 keV)	$\geq 2.3 \times 10^{21}$	$\geq 1.7 \times 10^{20\,*}$ [2] (at 68% CL)
2ν	g.s.- 2_3^+ (2225 keV)	$\geq 2.5 \times 10^{21}$	$\geq 1.0 \times 10^{20\,*}$ [2] (at 68% CL)

[1] PRC 68(2003)035501 **[2]** Phys.Lett.B 249(1990)186 *68% C.L. **[3]** NPA 577(1994)493

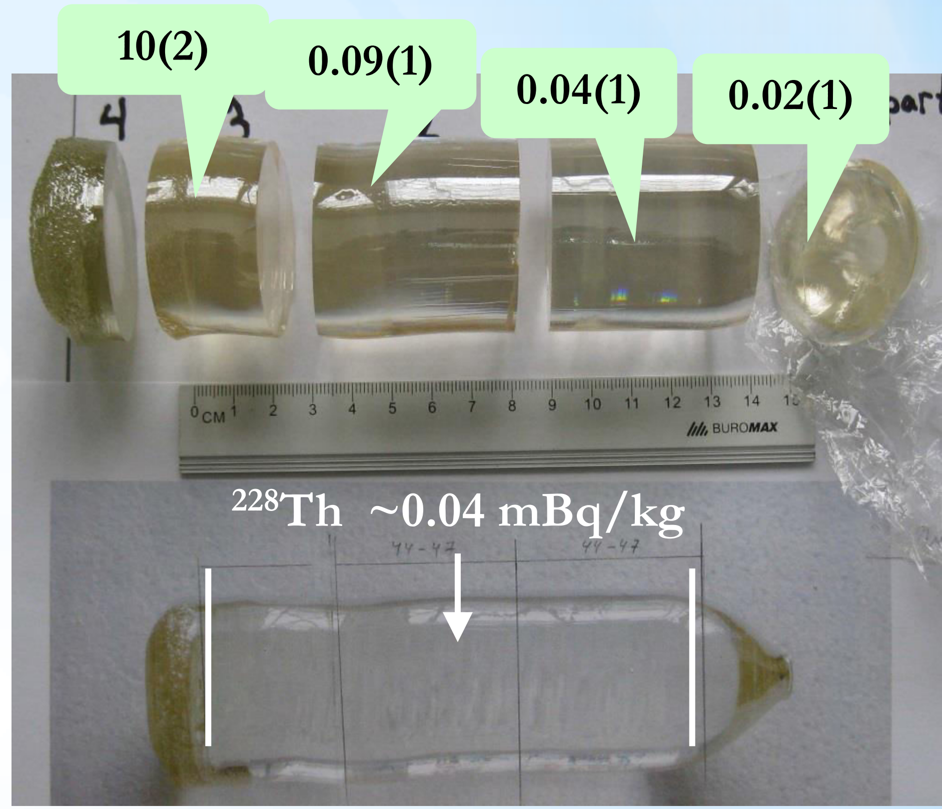
Possibility to improve the radiopurity of $^{116}CdWO_4$ by re-crystallization

Activity of ^{228}Th



rest of the melt after the crystal growth

Nuclide	Crystal	Rest of melt
^{40}K	<1	27(11)
^{226}Ra	<0.005	64(4)
^{228}Th	0.02 – 0.09	10(2)



^{228}Th in the initial $^{116}CdWO_4$ powder ~1.4 mBq/kg

Thorium expected to be reduced by a factor ~35 → 1 μBq/kg

We expect to reduce K, Th, U and Ra contamination by re-crystallization ⇒ reduction of the background by a factor 4 ⇒ advancement of the sensitivity up to ~ 5×10^{23} yr [1]

[1] NIMA 833(2016)77

$^{116}CdWO_4$ after re-crystallization

Re-crystallized by the low-thermal-gradient Czochralski technique in a platinum crucible with 99.93% Pt purity level

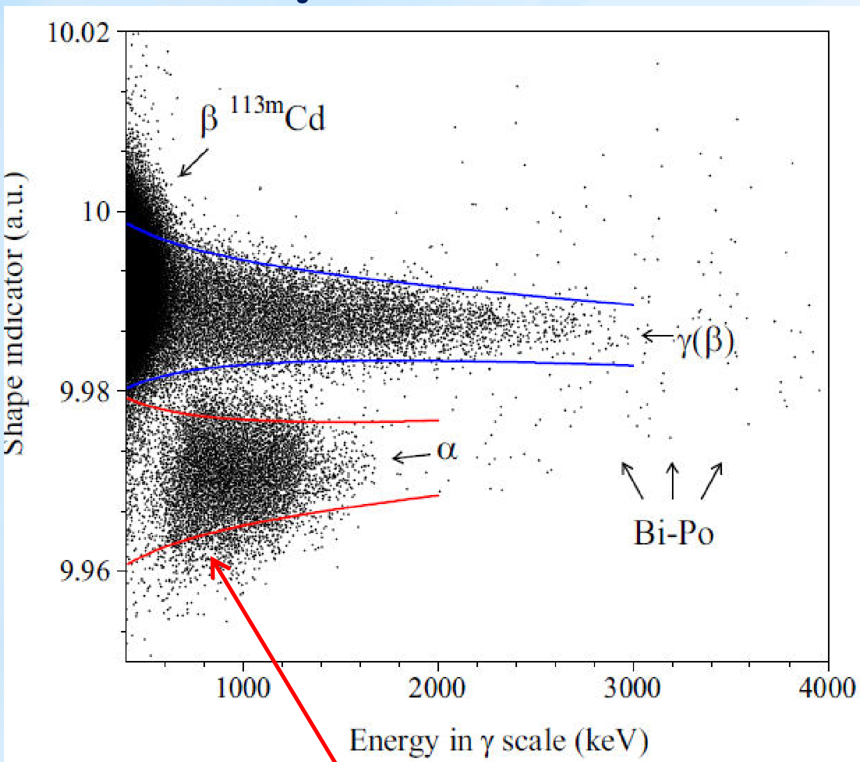
286 g (88% of sample after re-crystallization)

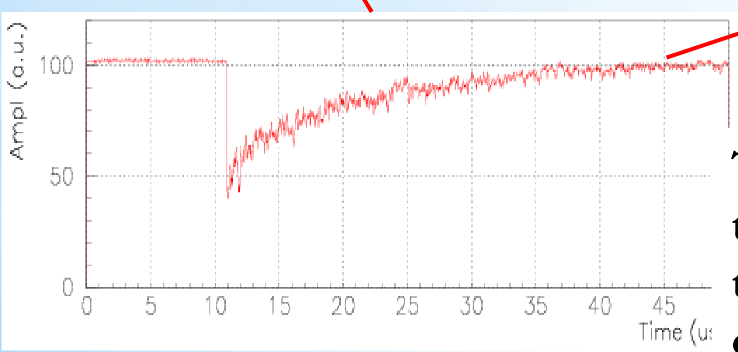
195 g (60% of sample after re-crystallization) The side surface of the sample was made opaque by grinding paper to improve light collection.

DAMA/Crys

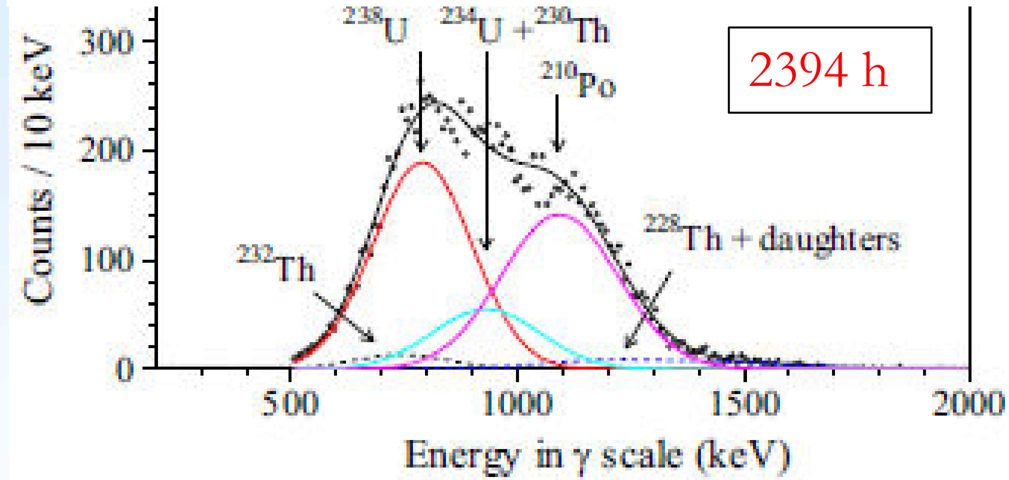
The passive shield of the DAMA/Crys set-up is made of high purity materials: copper (11cm), lead (10cm), cadmium (2mm), polyethylene (10cm)

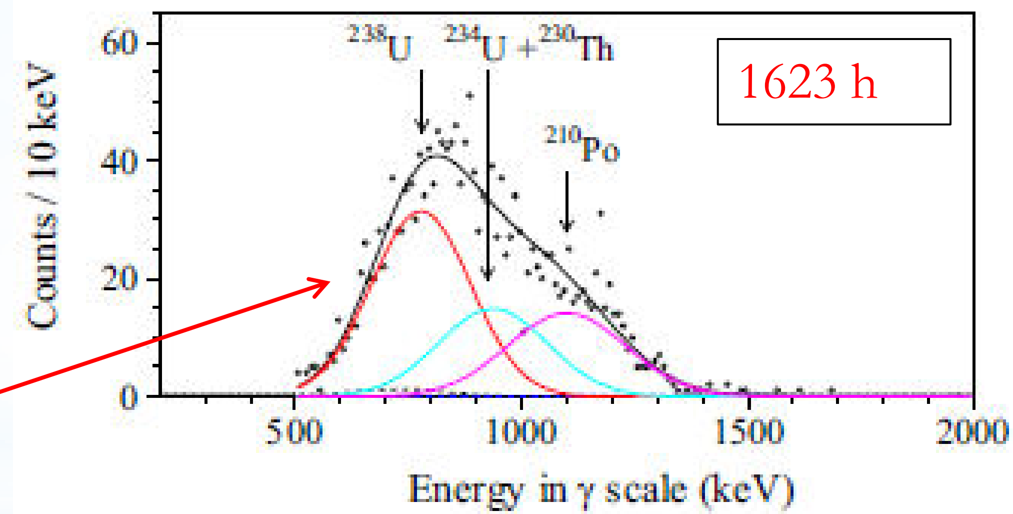
$^{116}CdWO_4$ after re-crystallization





α spectra before and after re-crystallization





The specific activity of ^{228}Th decreased by ≈10 times to the level of 0.010(3) mBq/kg, which is the result of the strong segregation of thorium in the $CdWO_4$ crystal growth process.

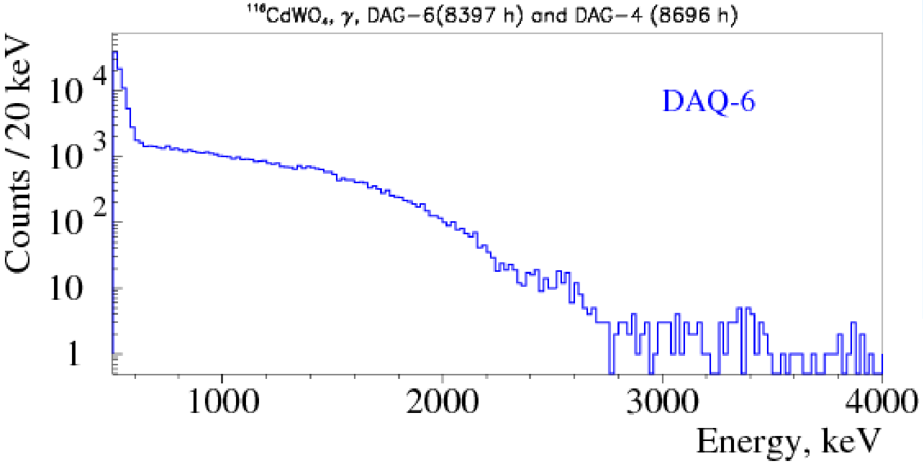
Total α activity ↓ ~3 times (4.44(4) → 1.62(4)mBq/kg)

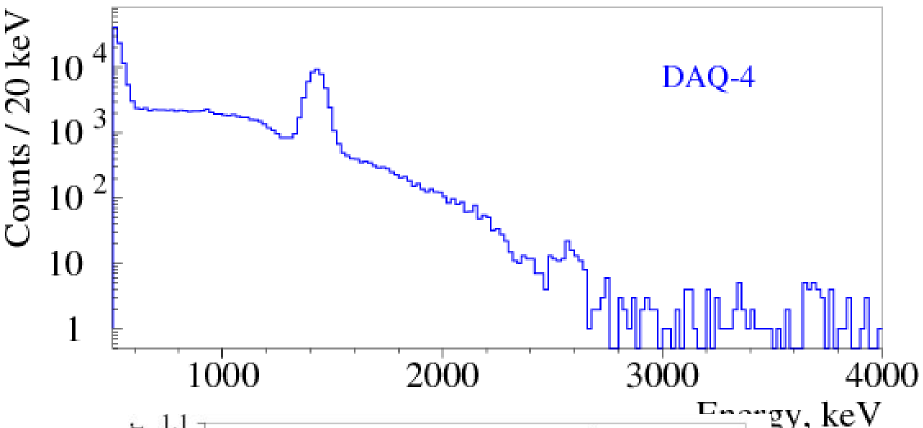
Conclusions

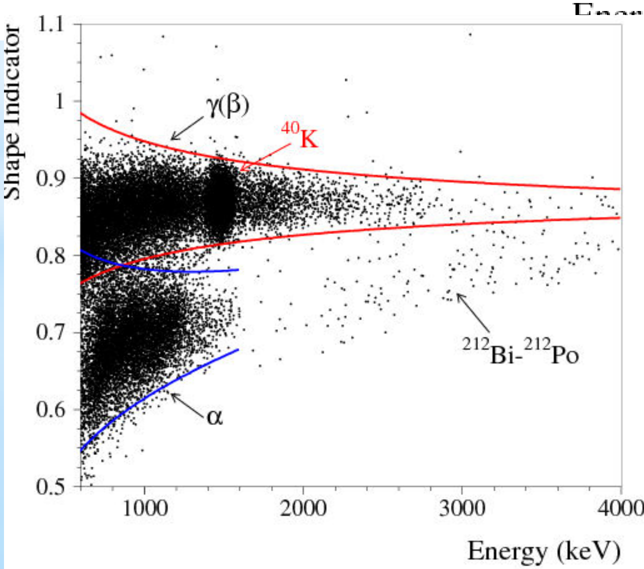
* Experiment to search for double beta decay processes in ^{116}Cd with the help of enriched in ^{116}Cd (to 82%) low background $^{116}CdWO_4$ scintillation detectors (1.16 kg) is in progress at the Gran Sasso underground laboratory of INFN (Italy).
* The $2\nu2\beta$ half-life is $\boldsymbol{T_{1/2}(2\nu2\beta) = [2.69 \pm 0.14(\text{syst.}) \pm 0.02(\text{stat.})] \times 10^{19}}$ **yr** (in agreement with previous measurements)
* $\boldsymbol{T_{1/2}(0\nu2\beta) \geq 1.9 \times 10^{23}}$ **yr** (is on the level of the Solotvina (1.7×10^{23} yr) and NEMO-3 (1.0×10^{23} yr)) $\rightarrow$ $\boldsymbol{\langle m_\nu \rangle < (1.4 - 1.8)}$ **eV**
* New improved limits are obtained for $0\nu2\beta$ decay of ^{116}Cd to excited levels of ^{116}Sn: **lim** $\boldsymbol{T_{1/2} \sim (2.9\text{–}7.8) \times 10^{22}}$ **yr**

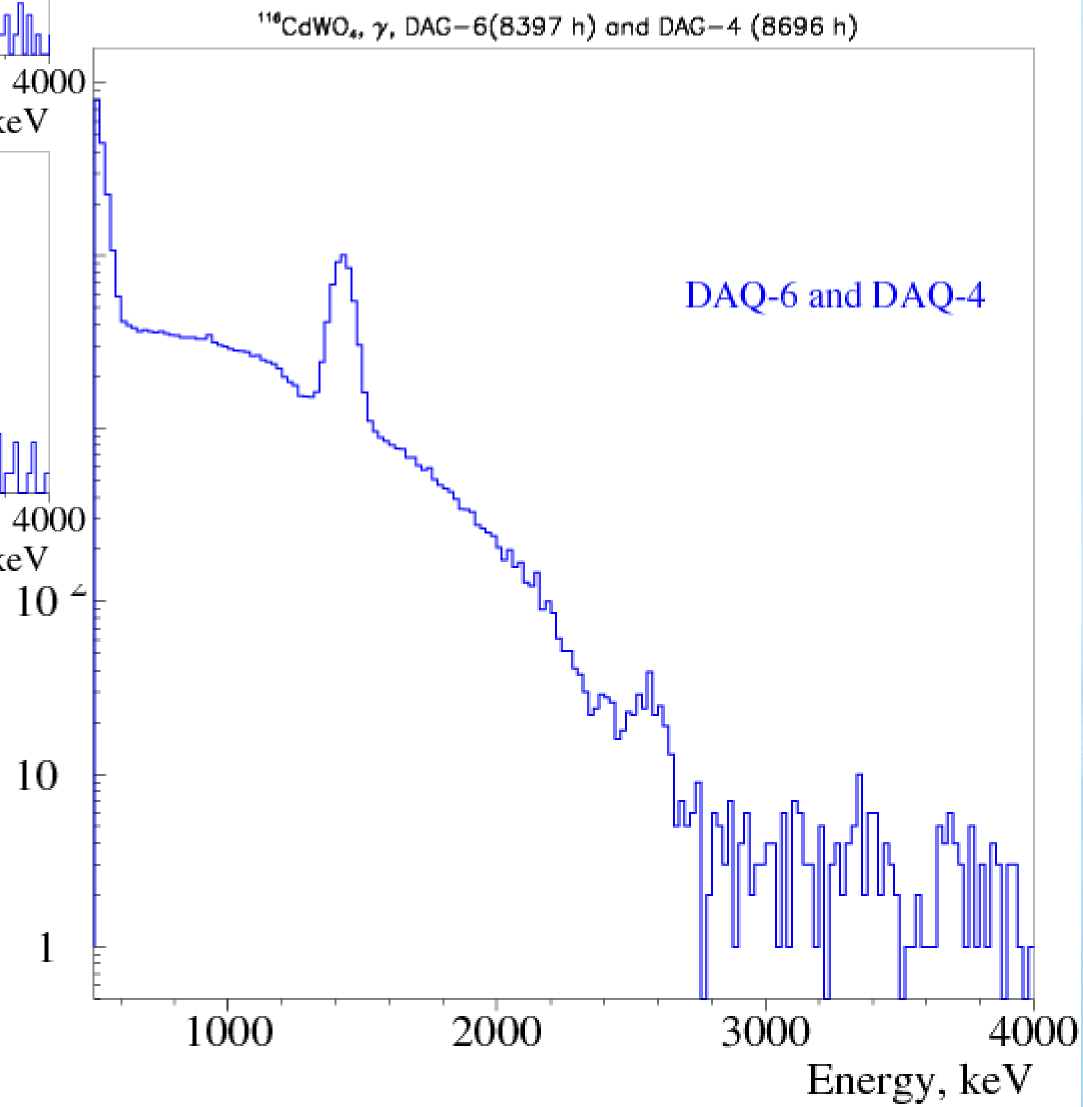
The main background component, internal ^{228}Th, can be reduced by 35 times by re-crystallization $\rightarrow$ sensitivity of the experiment $T_{1/2} \geq 5 \times 10^{23}$ yr

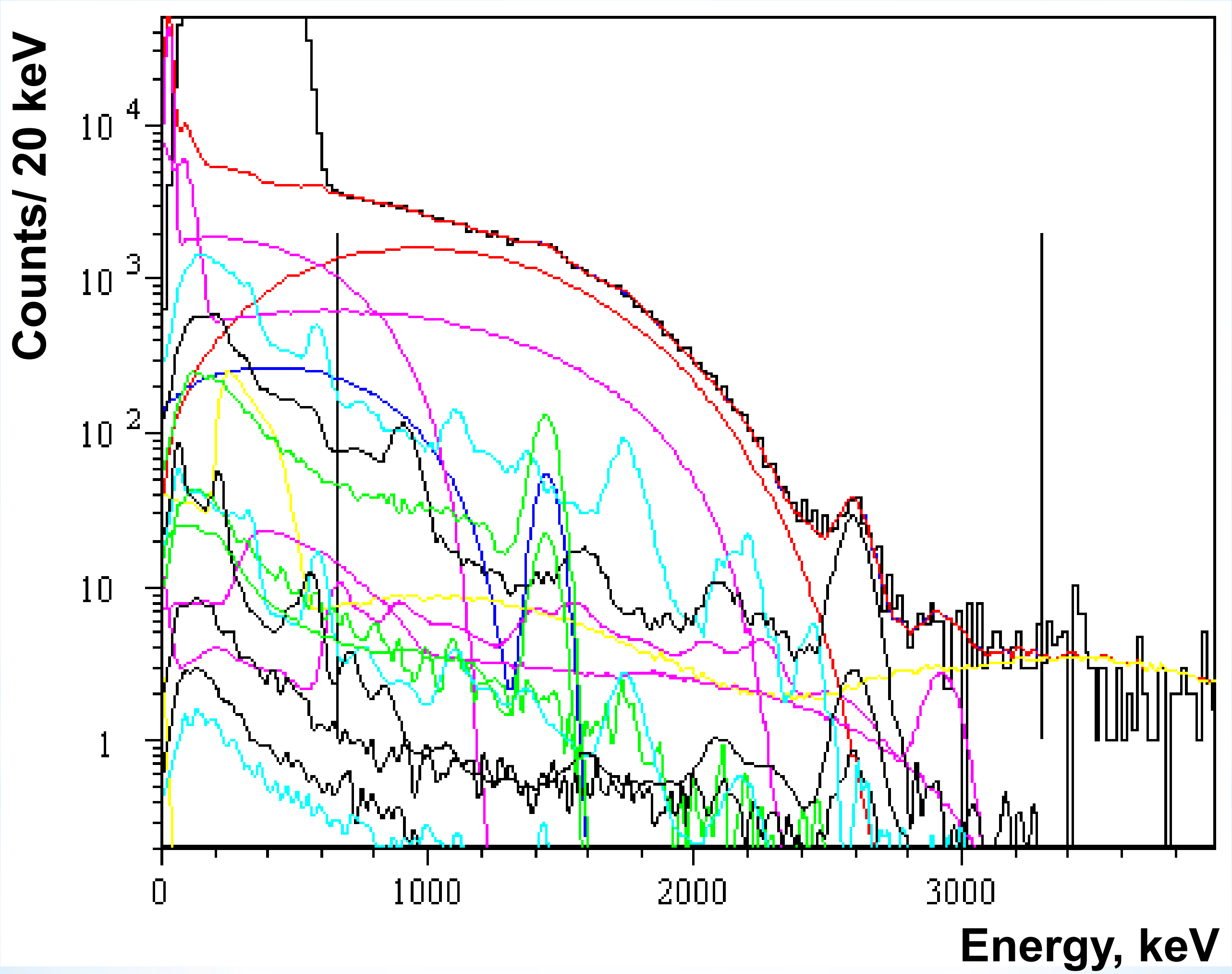
Thank you for attention!


116CdWO4, γ, DAG−6(8397 h) and DAG−4 (8696 h)
DAQ-6
Counts / 20 keV
Energy, keV

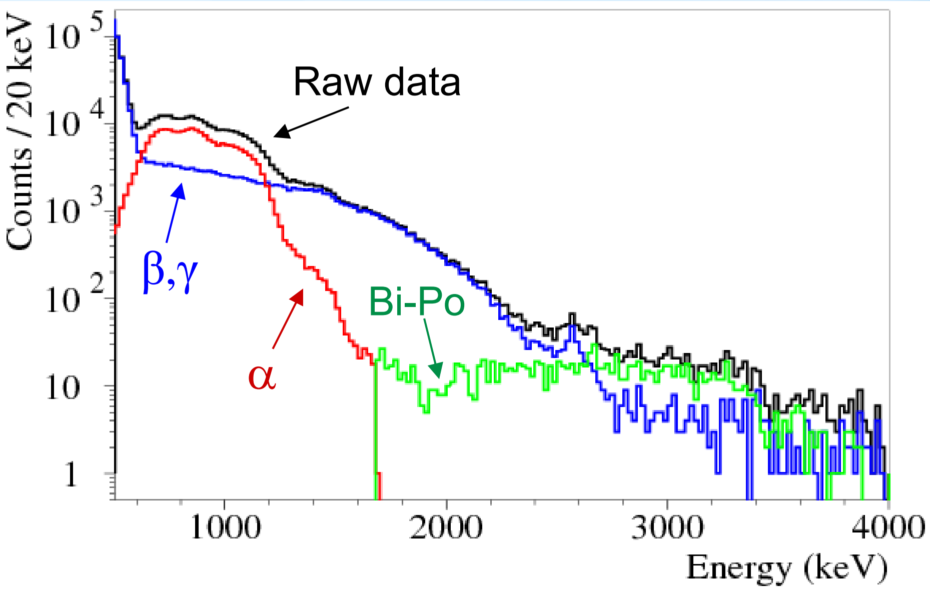

DAQ-4
Counts / 20 keV
Energy, keV

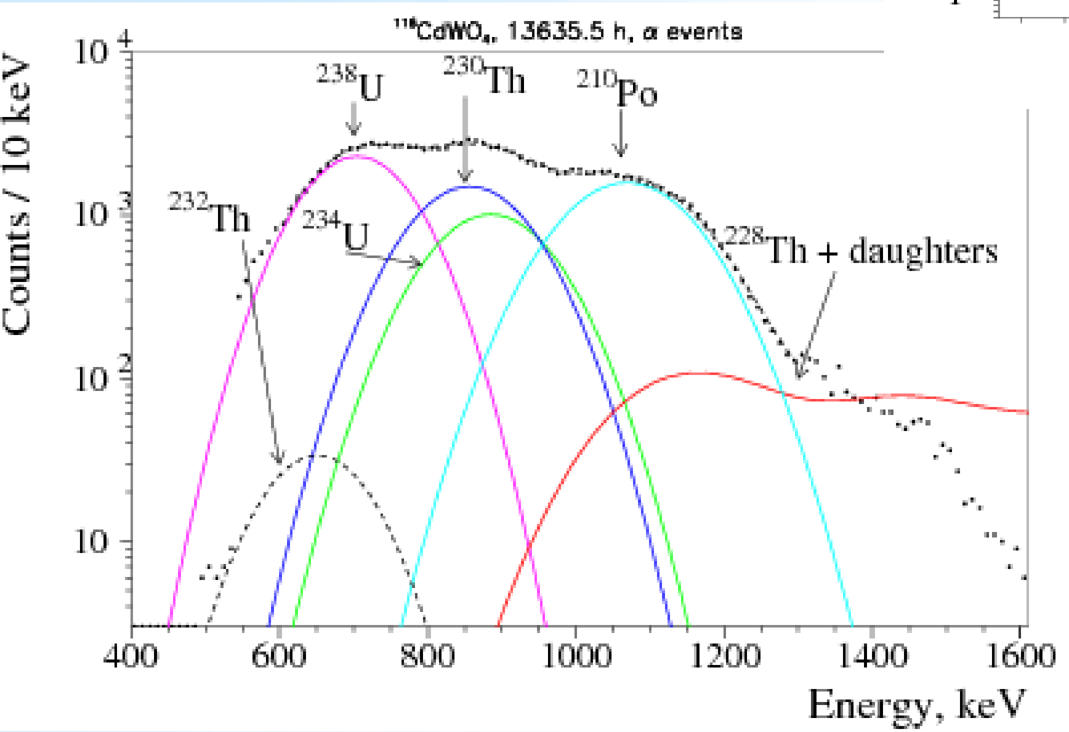

Shape Indicator
γ(β)
40K
212Bi-212Po
α
Energy (keV)


116CdWO4, γ, DAG−6(8397 h) and DAG−4 (8696 h)
DAQ-6 and DAQ-4
Energy, keV

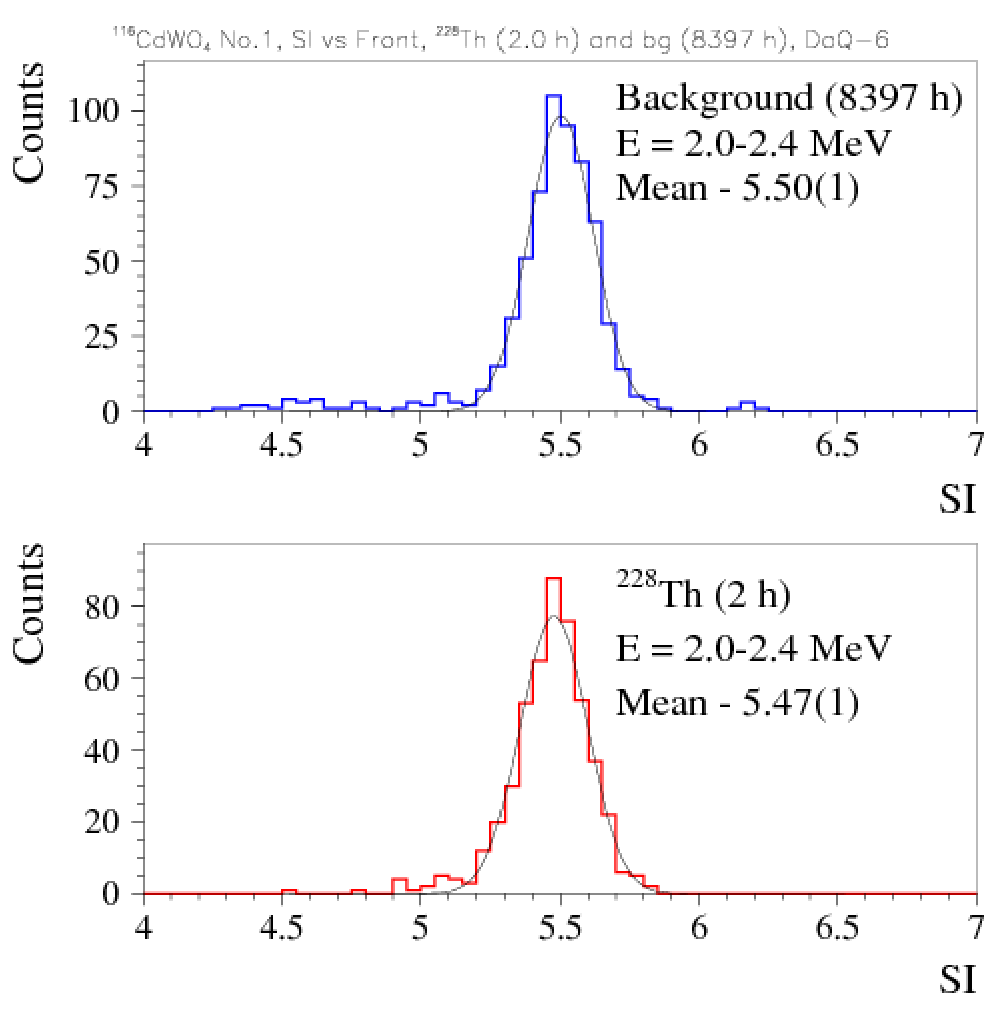


Counts/ 20 keV
10 4
10 3
10 2
10
1
0
1000
2000
3000
Energy, keV

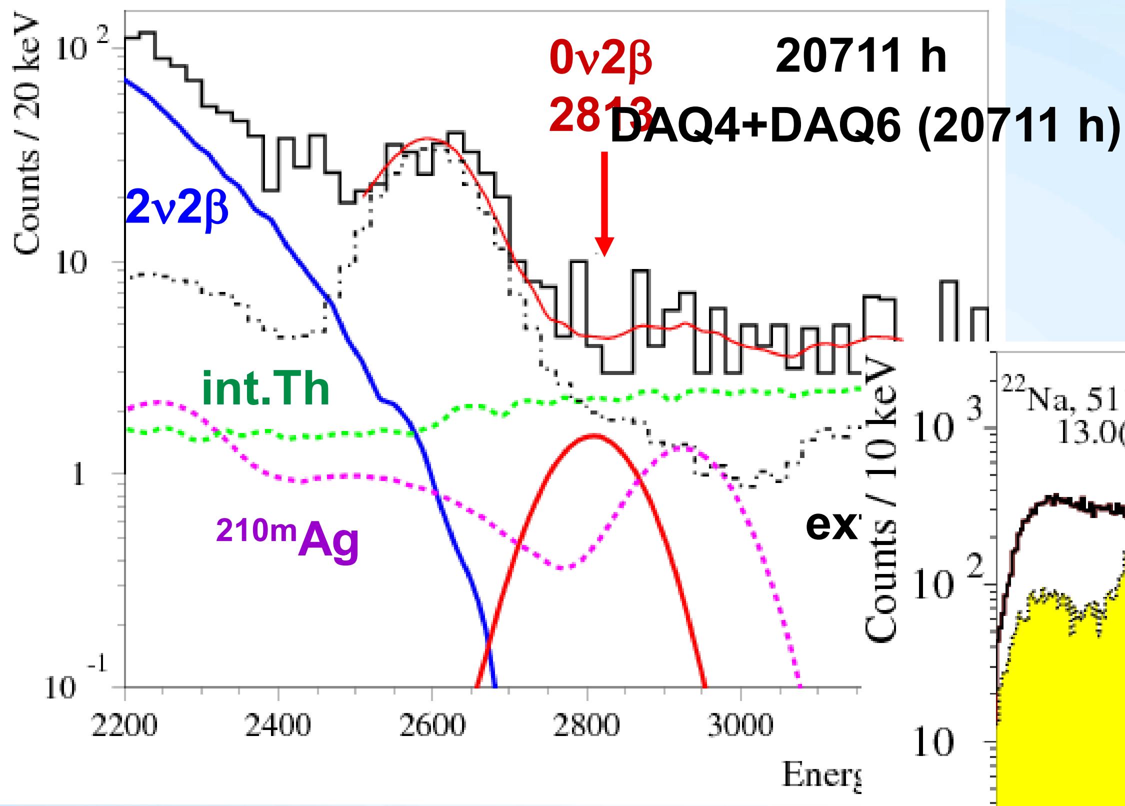


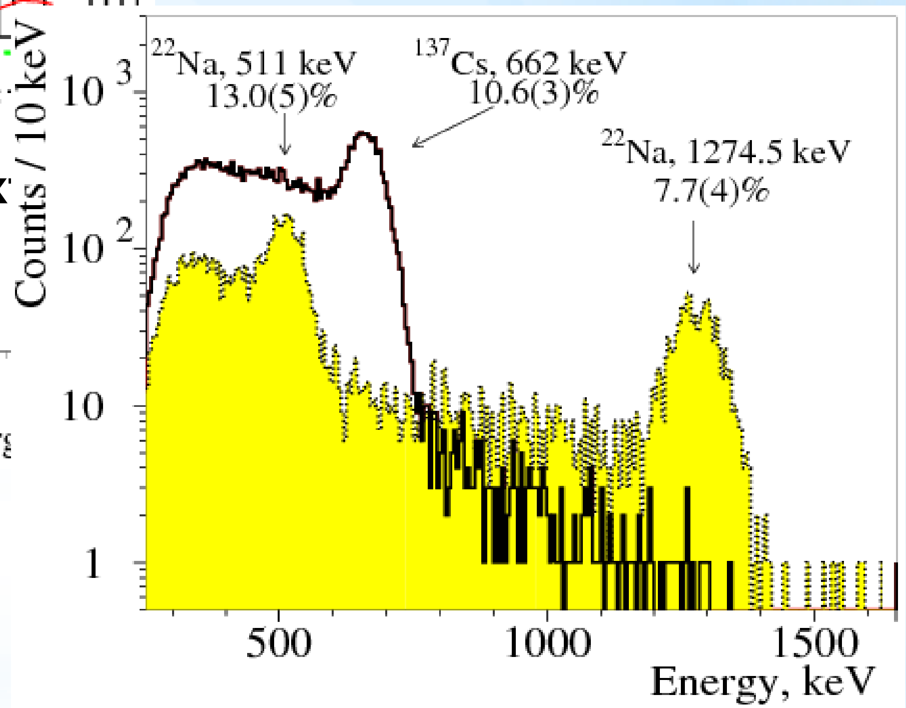


M.J. Koskelo, W.C.Burnett, P.H.Cable, Anadvanced analysis program for alpha-particle spectrometry, Radioact. Radiochem. 7(1996)18–27.



116CdWO4 No.1, SI vs Front, 228Th (2.0 h) and bg (8397 h), DaQ−6
Background (8397 h)
E = 2.0-2.4 MeV
Mean - 5.50(1)
Counts
SI
228Th (2 h)
E = 2.0-2.4 MeV
Mean - 5.47(1)
Counts
SI





Fit in 2.5 – 3.16 MeV gives area of the effect
S = -3.7 ± 10.2 counts -> $T_{1/2}$ > 1.9e23 yr