Investigation of double β decay of cadmium by using isotopically enriched cadmium tungstate crystal scintillators $^{106}CdWO_4$ and $^{116}CdWO_4$

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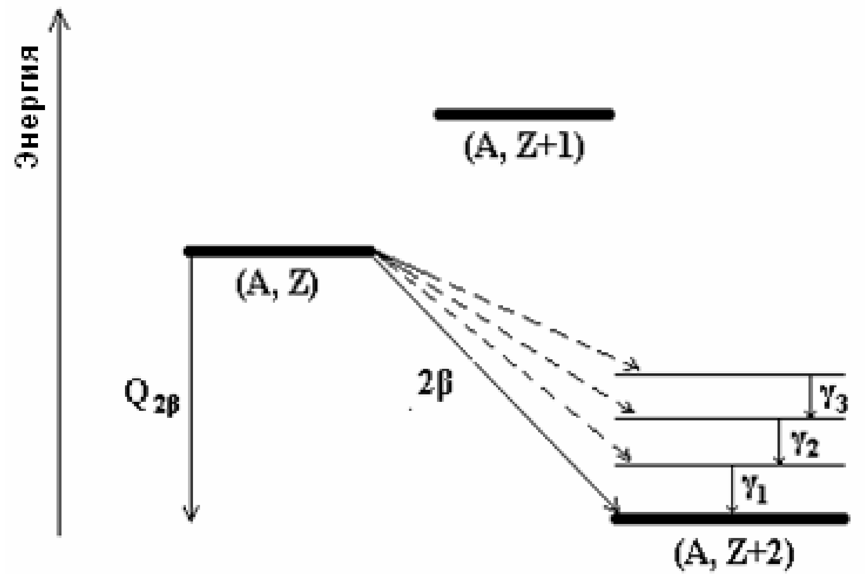
Basics of the theory



2ν2β $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\tilde{\nu}$

0ν2β $(A, Z) \rightarrow (A, Z+2) + 2e^-$

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}Te, ^{150}Nd, ^{136}Xe and ^{238}U**) with half-lives in the range ~ **10^{18}–10^{24} years**

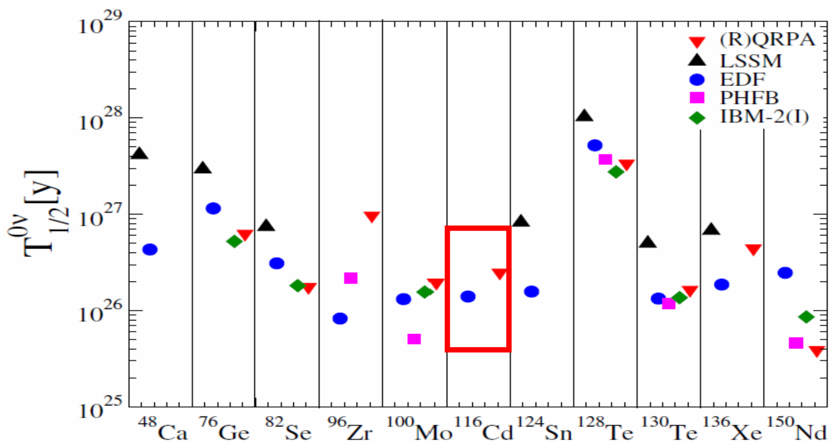
2β decay processes with decreasing nuclear charge and neutrinoless 2β decay has not yet been observed

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

^{116}Cd

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

- $Q_{2\beta}$ = 2813 keV, δ = 7.5%
- promising theoretical calculation
- the possibility of isotopic enrichment in large amount

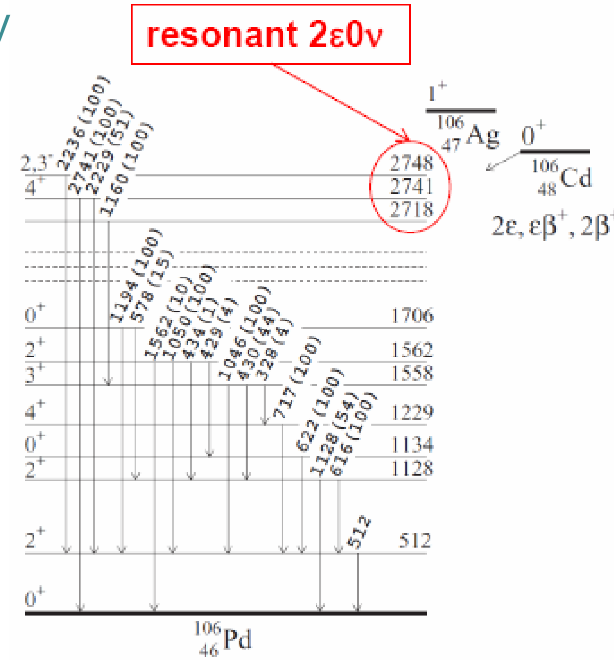


^{106}Cd

The one among six 2β⁺ isotopes (2ε, εβ⁺, 2β⁺)

- $Q_{2\beta}$ = 2775 keV, δ = 1.3%
- theoretical calculation (10^{20} – 10^{22} yr) [1]
- resonant 2ε0ν decay on the exited levels of ^{106}Pd

[1] EPJA 17(2003)529, PRC 86(2012)024301



$CdWO_4$

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

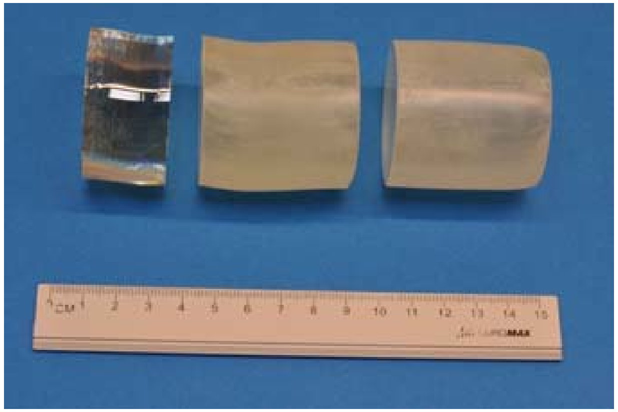
$CdWO_4$ were successfully used in low-energy experiments on search for 2β decay of Cd and W [2], as well as for the study of rare α [3] and β [4] decays

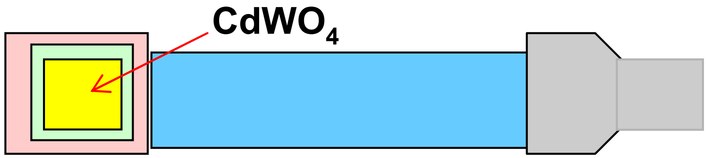
[2] PRC 68 (2003) 035501, EPJA 36 (2008) 167, ZPA 355 (1996) 433
[3] PRC 67 (2003) 014310
[4] PAN 59 (1996) 1, PRC 76 (2007) 064603

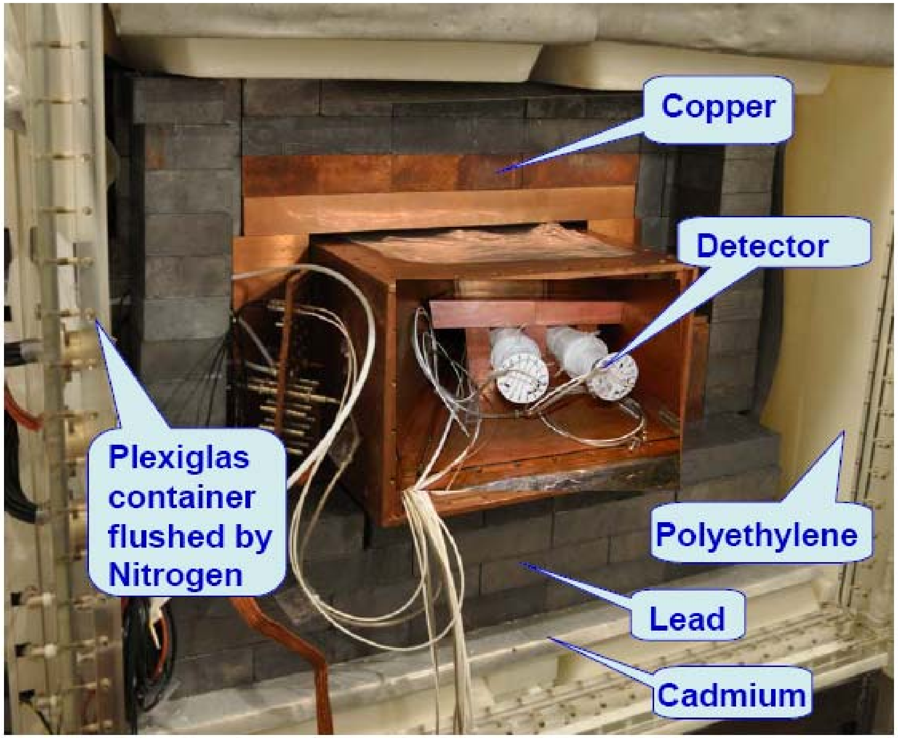
^{116}Cd, new stage of measurements

2 crystals of $^{116}CdWO_4$, (82% of ^{116}Cd), m_{tot}=1175 g in DAMA R&D

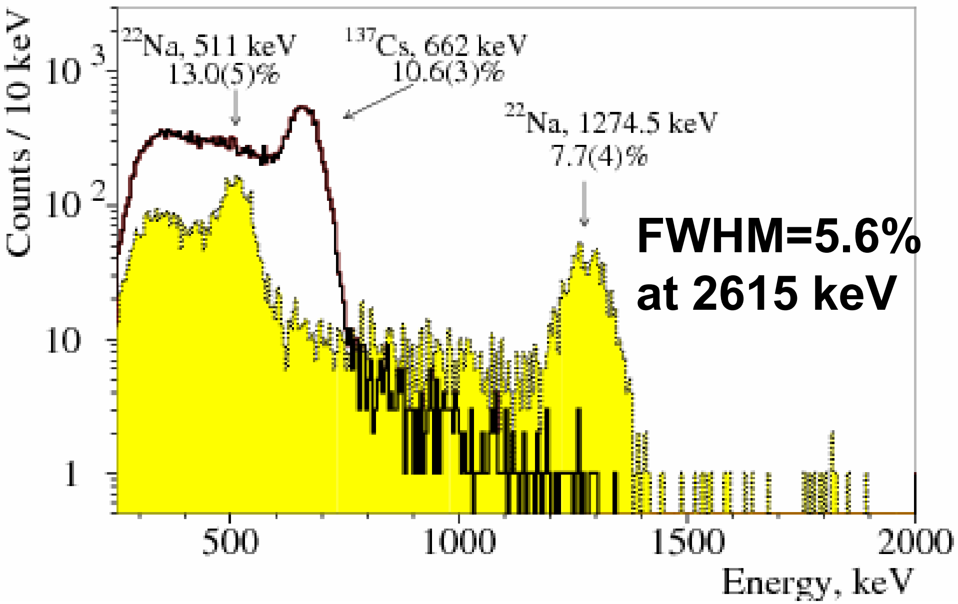
Time of measurements ~ 2744 h (the last stage of the experiment started from 2011)





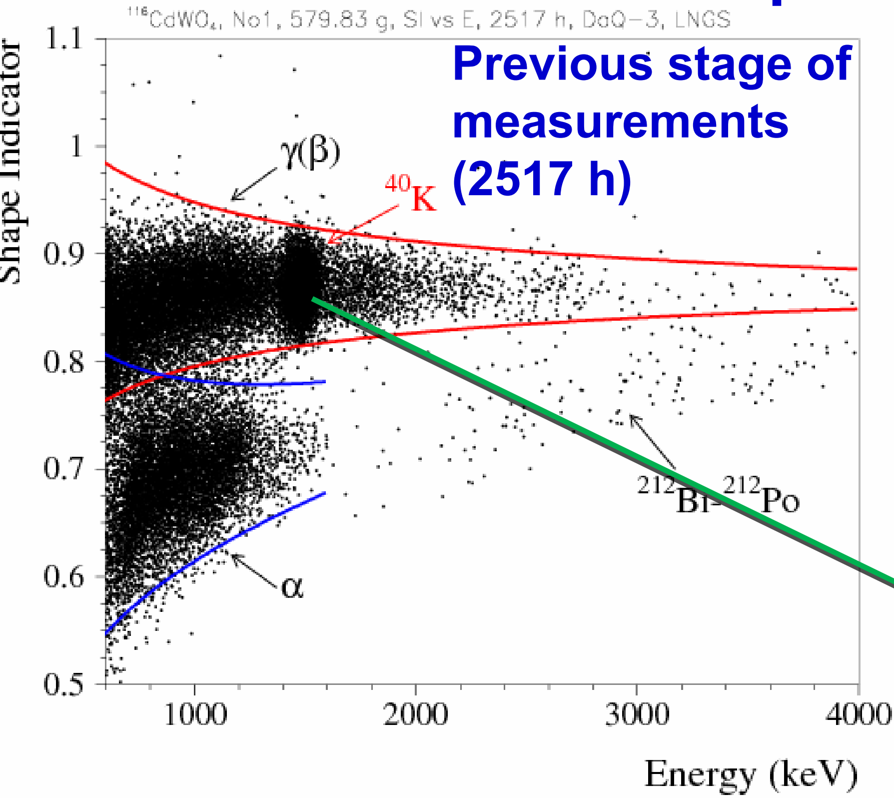


Upgrade of the set-up have been made in March 2014. As a result radioactive background reduced to ≈ 0.12 counts/ (yr×kg×keV) within region of interest 2.7−2.9 MeV

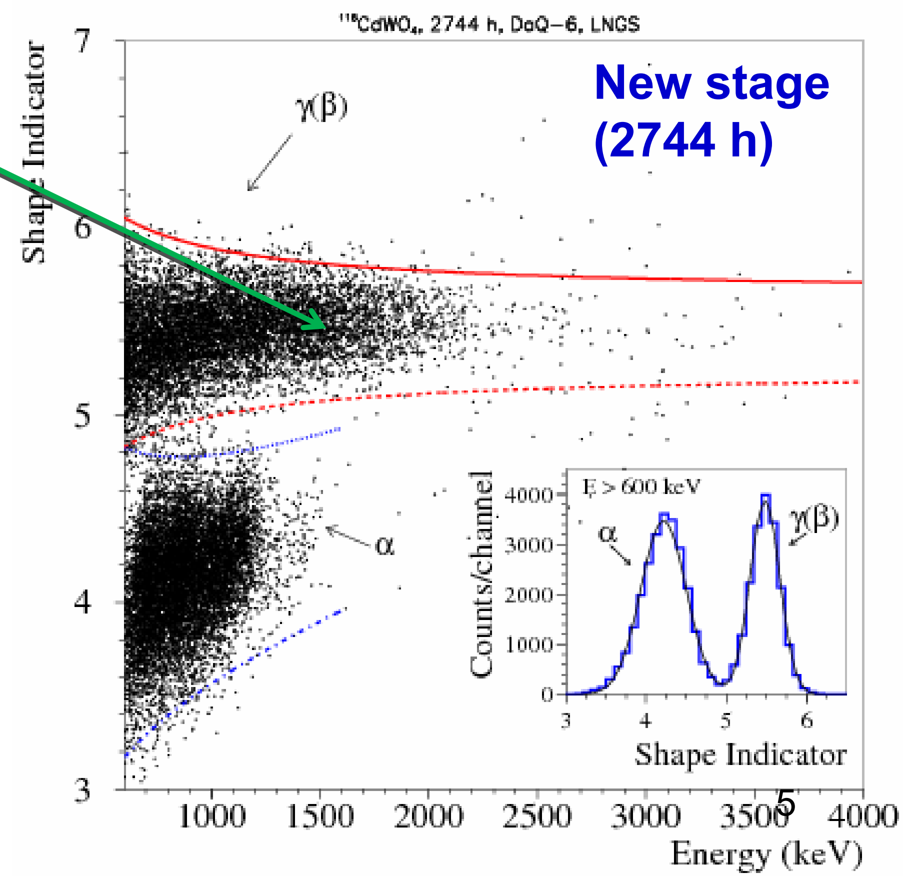


FWHM=5.6% at 2615 keV

Pulse shape discrimination (PSD)

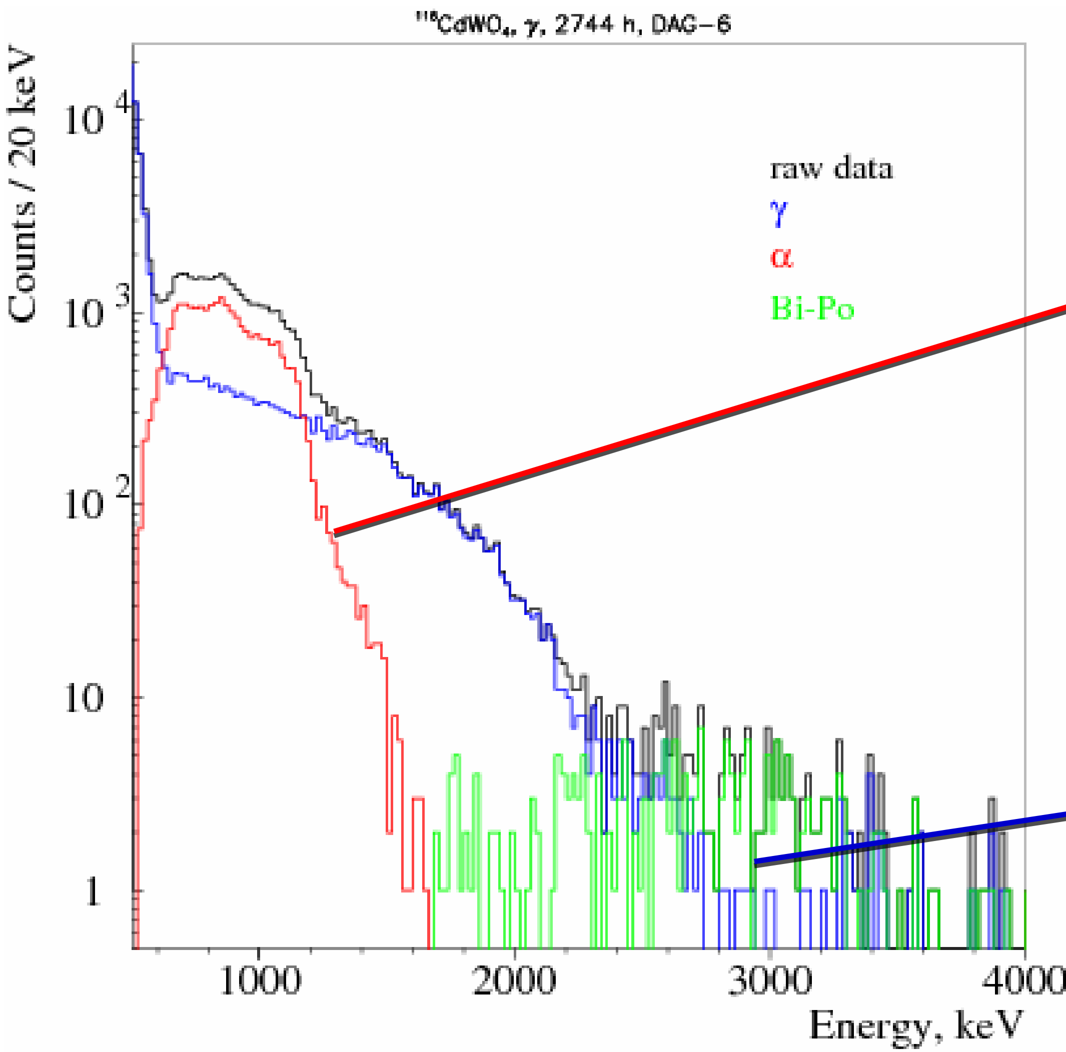


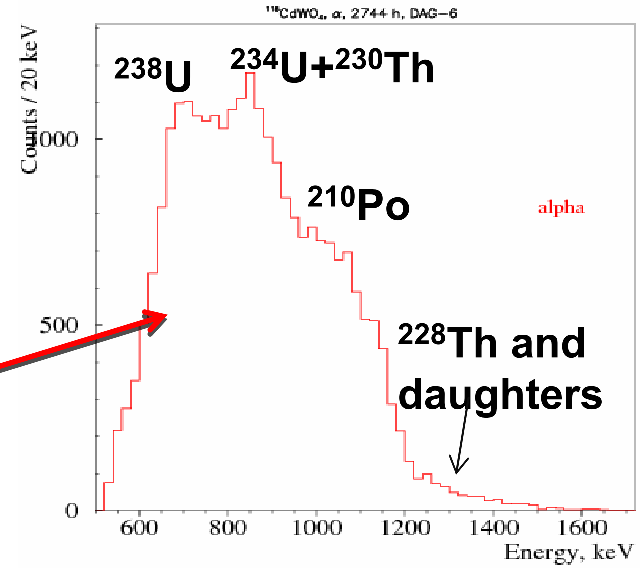
good particle discrimination ability between β(γ) and α

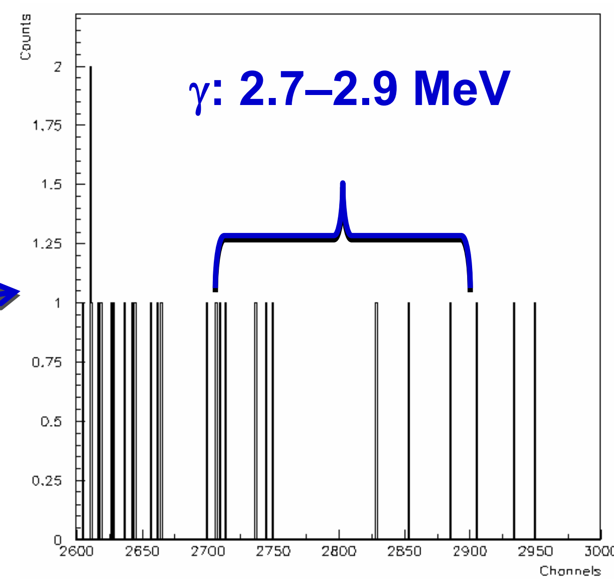


Two dimensional histogram presents shape indicator (SI) versus energy for the background measurements

Energy spectra of γ(β) events over 2744 h

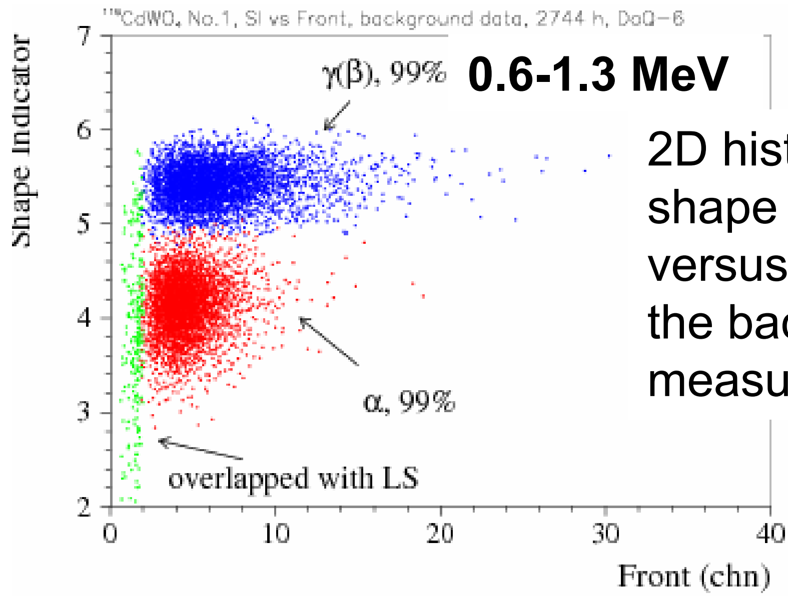




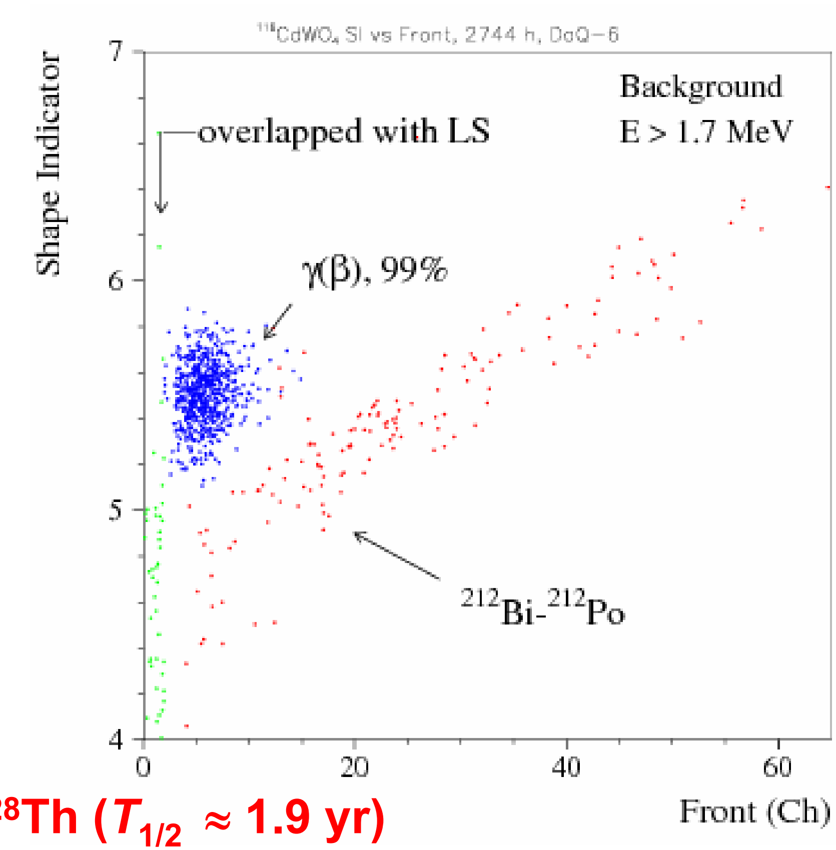


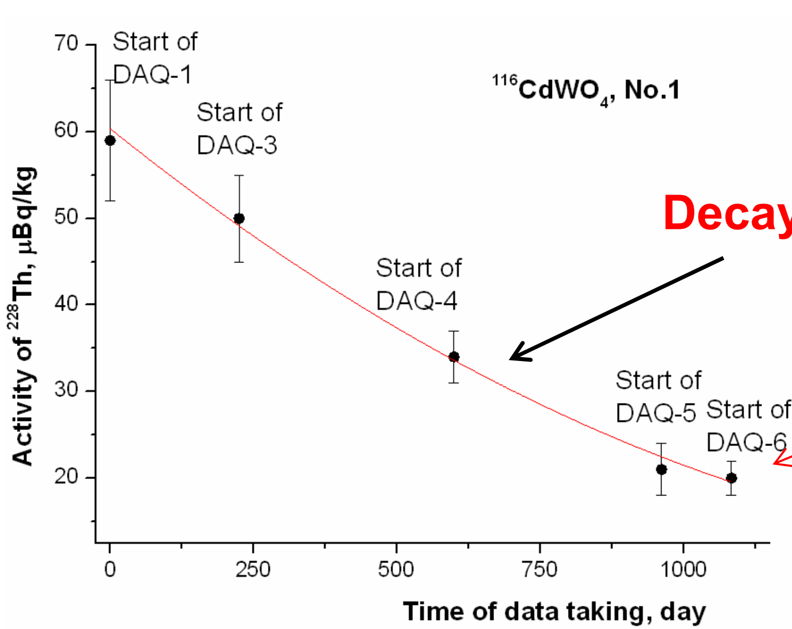
Rate @ 2.7–2.9 MeV:
0.12(3) cnts/(keV×kg×yr)

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



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



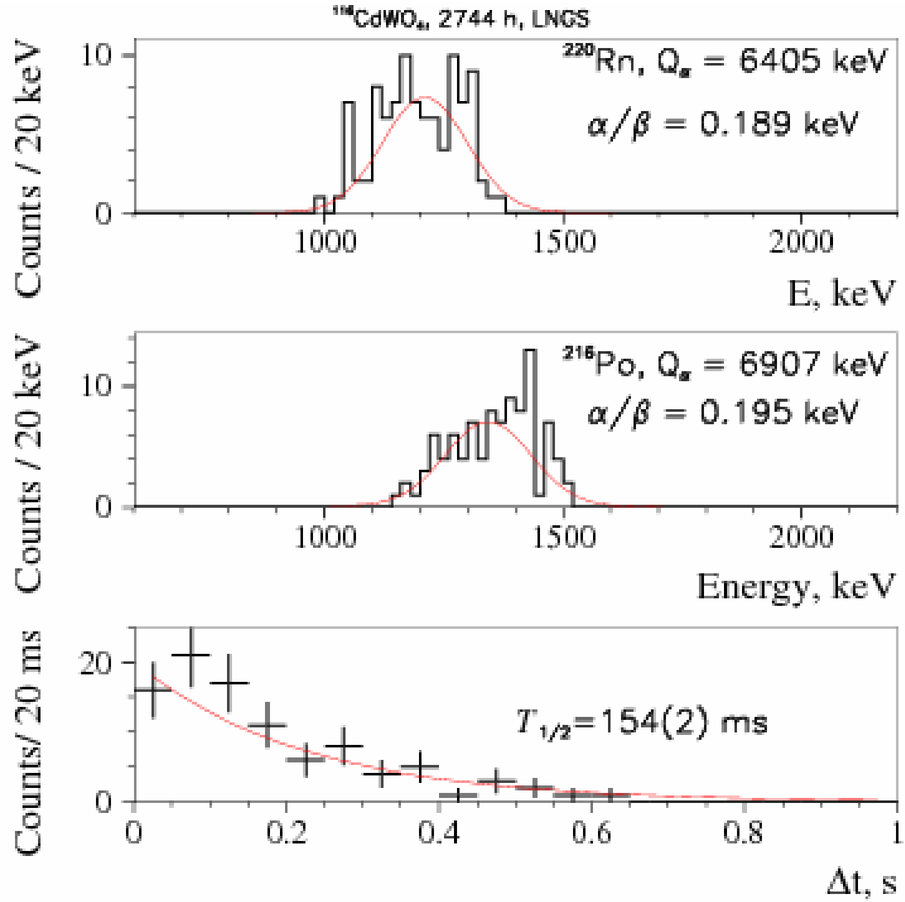


Decay of ^{228}Th ($T_{1/2}$ ≈ 1.9 yr)

Activity of ^{228}Th (in μBq/kg)

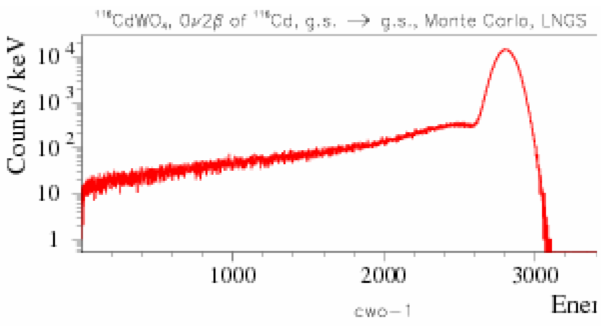
No.1	**20(2)**
No.2	**39(3)**

Time-amplitude analysis

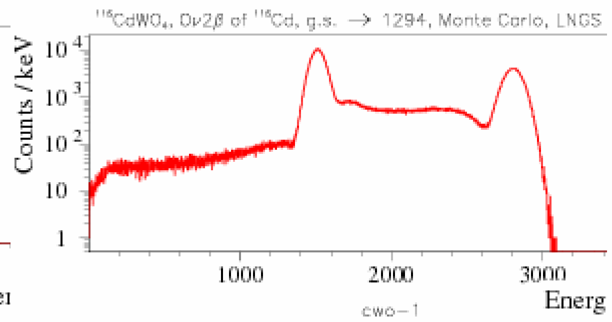


$^{116}CdWO_4$	Activity ^{228}Th, μBq/kg
No.1	17(3)
No.2	36(5)

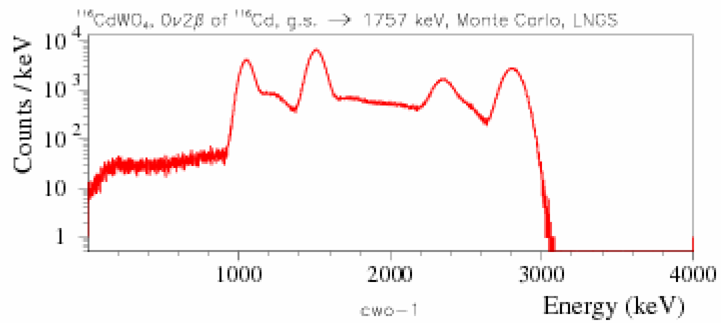
Response of the $^{116}CdWO_4$ detector to 2β processes in ^{116}Cd simulated by EGS4



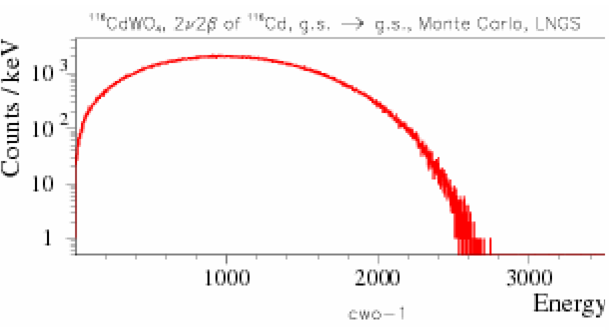
0γ2β g.s. → g.s.



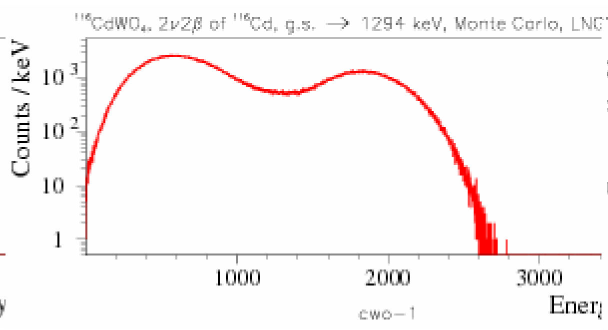
0γ2β g.s. → 1294



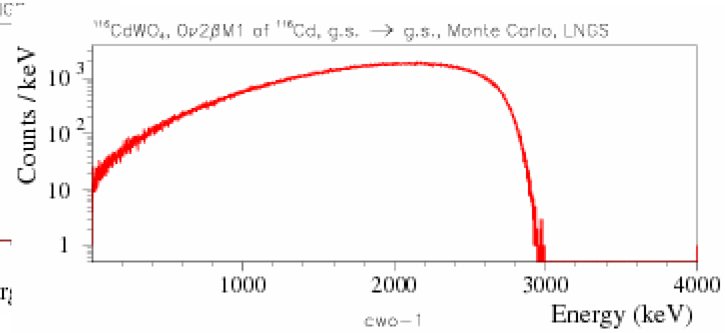
0γ2β g.s. → 1757



2γ2β g.s. → g.s.



2γ2β g.s. → 1294

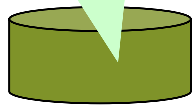


0γ2M1 g.s. → g.s

Possibility to improve the radiopurity of $^{116}CdWO_4$ by recrystallization

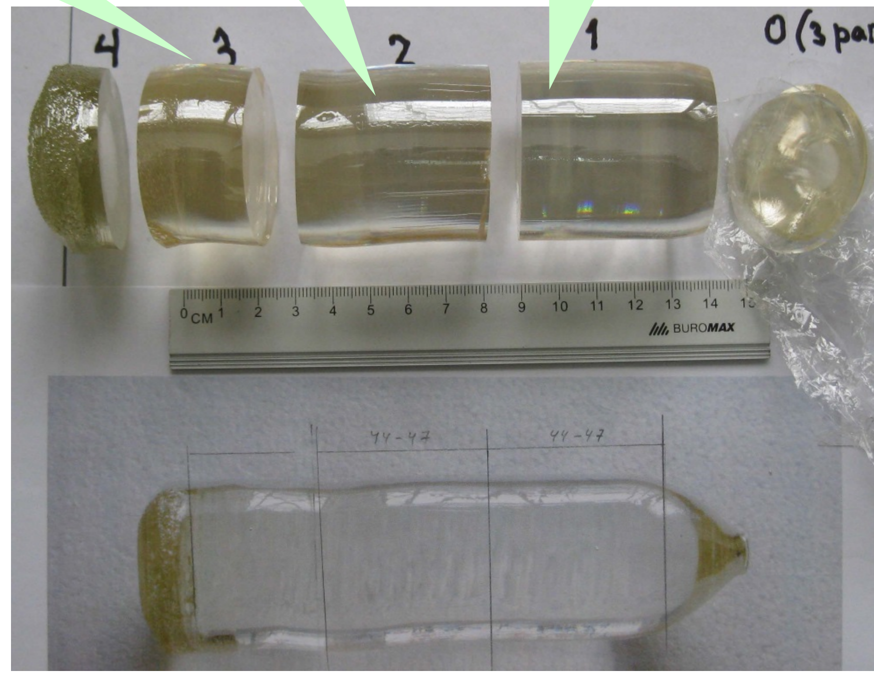
Activity of ^{228}Th

10(2)



rest of the melt after the crystal growth

0.09(1)* 0.04(1) 0.02(1)



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

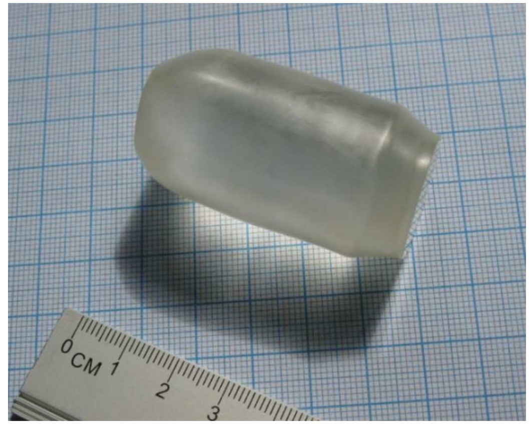
*) Measured recently in the DAMA-Crys R&D set-up

We expect to reduce K, Th, U and Ra contamination by recrystallization ⇒ reduction of the background by a factor 2-5 ⇒ advancement the sensitivity up to ~ 10^{24} yr

$^{106}CdWO_4$ and $^{arch}PbWO_4$

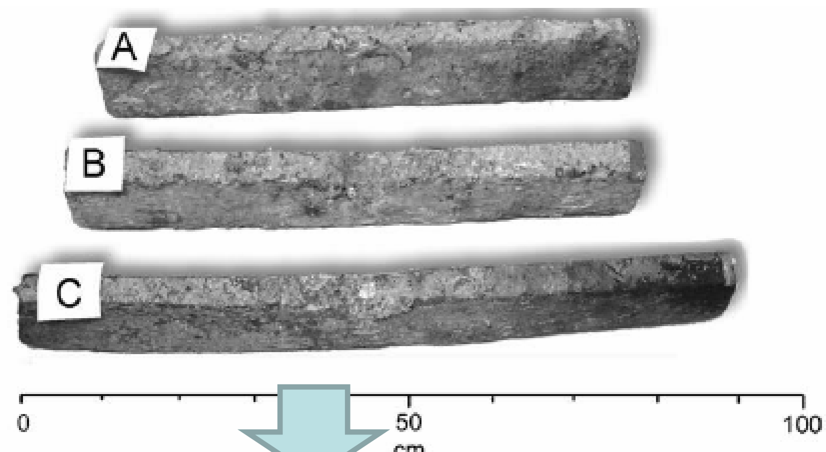
Purification ^{106}Cd: Institute of Physics and Technology (Kharkiv)
Crystal growth: NIIC Novosibirsk

$^{106}CdWO_4$ 231 g 66%

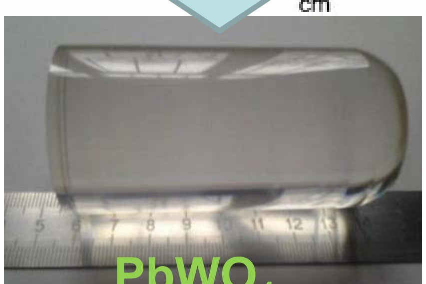


$^{106}CdWO_4$,215 g [1]

Isotope	Before, ppm	After, ppm
K	11	0.04
Ni	0.6	<0.2
Cu	5	0.5
Fe	1.3	0.4
Mg	12	<0.05
Mn	0.1	0.1
Cr	9	<0.1
Pb	270	<0.3



To suppress the radioactive components from the photomultiplier, $PbWO_4$ light-guide (from archaeological lead A (^{210}Pb) <0.3 mBq/kg [2]) were used



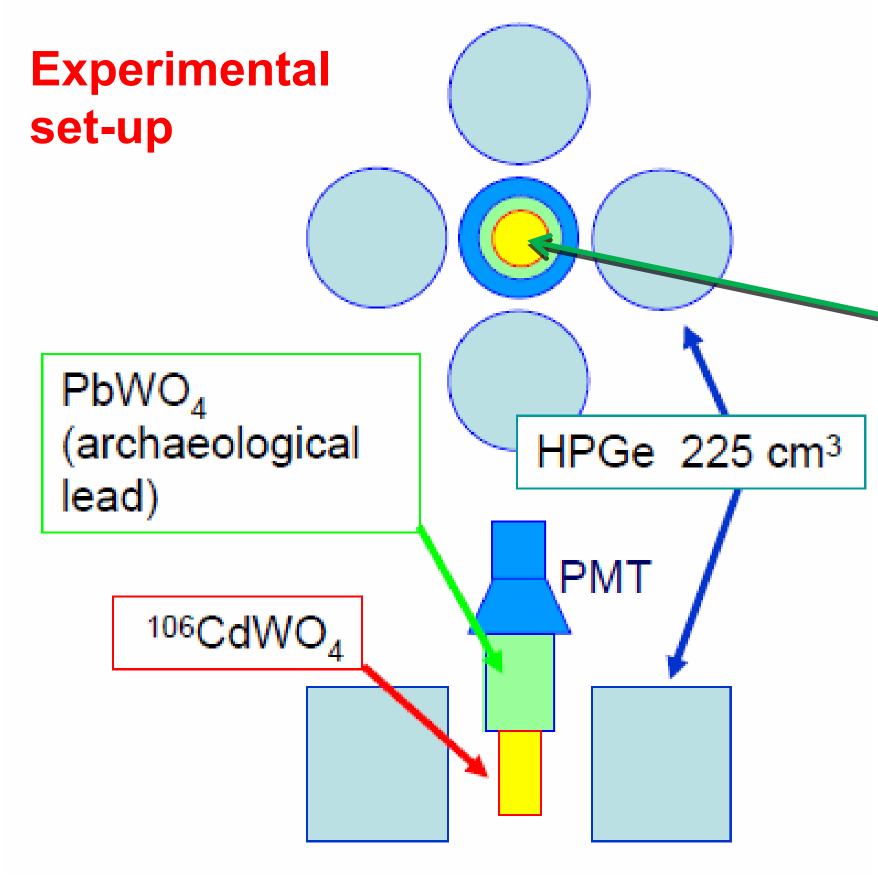
Purification Pb: Institute of Physics and Technology (Kharkiv)
Crystal growth: Institute of Scintillation Materials (Kharkiv)

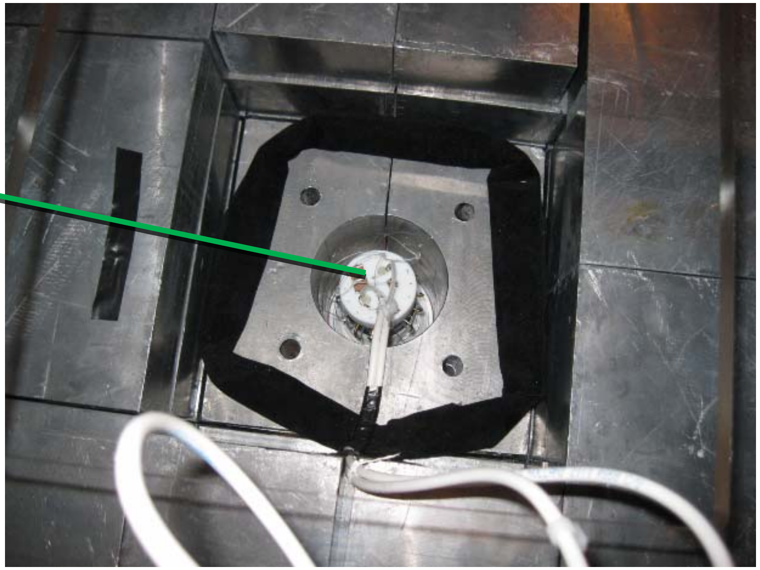
[1] P. Belli et al., *PRC 85 (2012) 044610*
[2] NIMA 603 (2009) 328; Inorganic Mater. 47 (2011) 645.

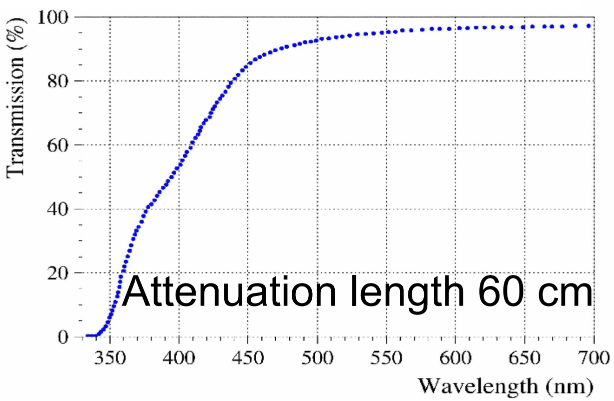
$^{106}CdWO_4$ in GeMulti set-up

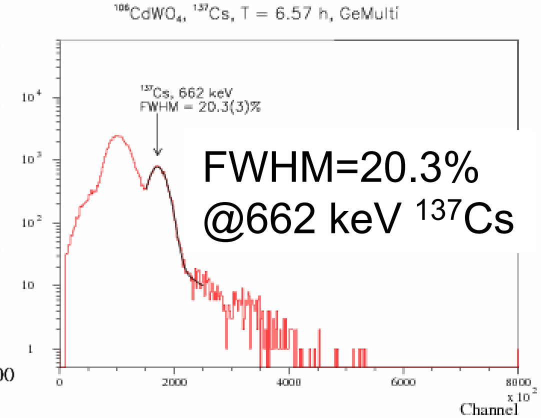
$^{106}CdWO_4$ crystal (215 g, 66% ^{106}Cd) is viewed by low background photomultiplier through a $PbWO_4$ crystal light-guide made from deeply purified archaeological lead. The detector operates in coincidence with the 4 low background HPGe detectors

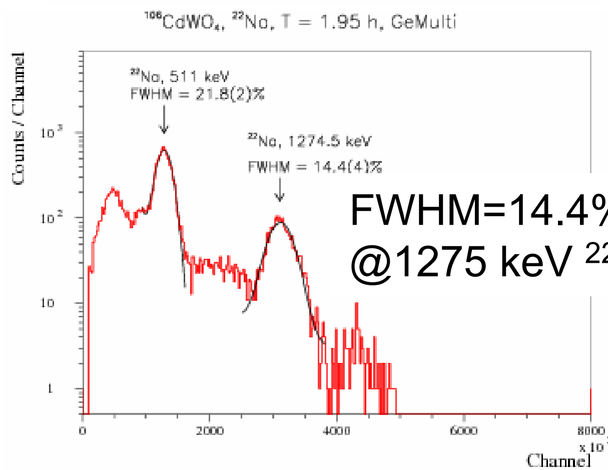
Time of measurements > 10 000 h

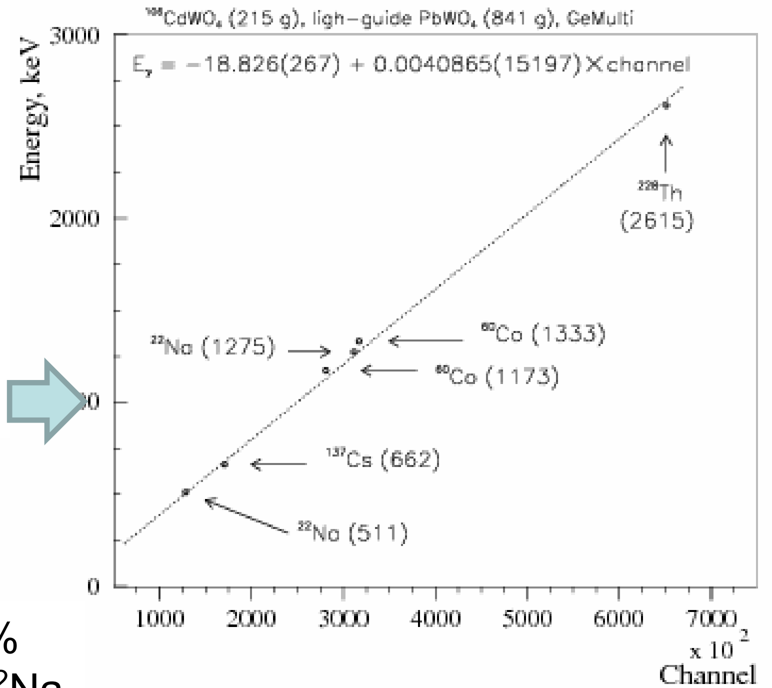


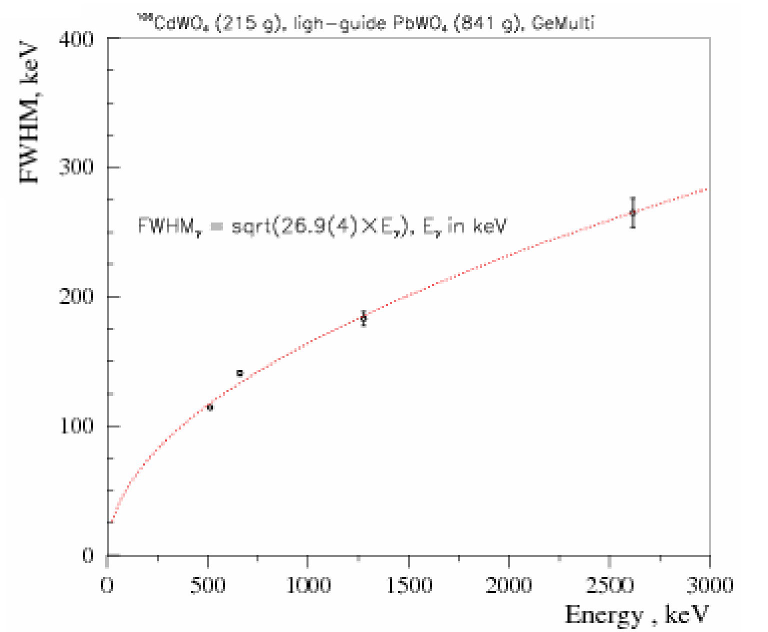






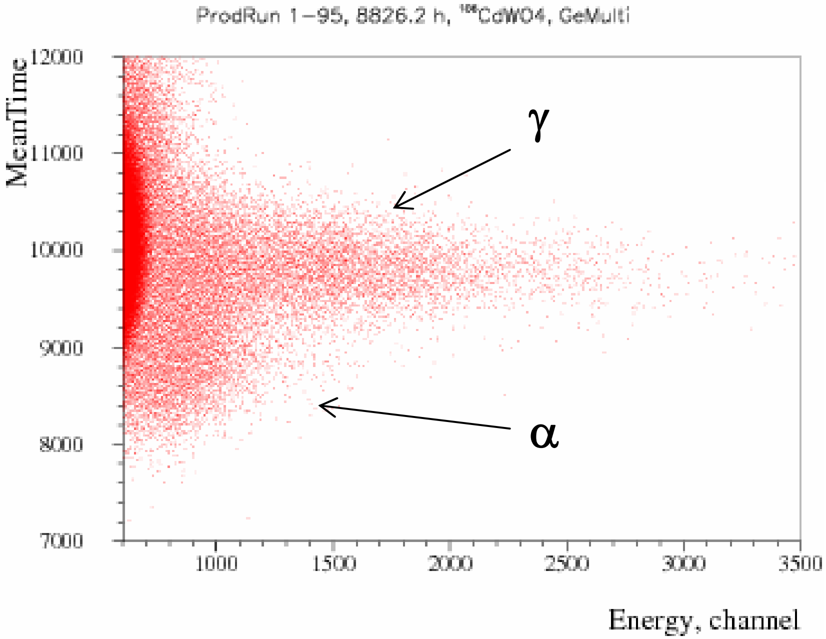






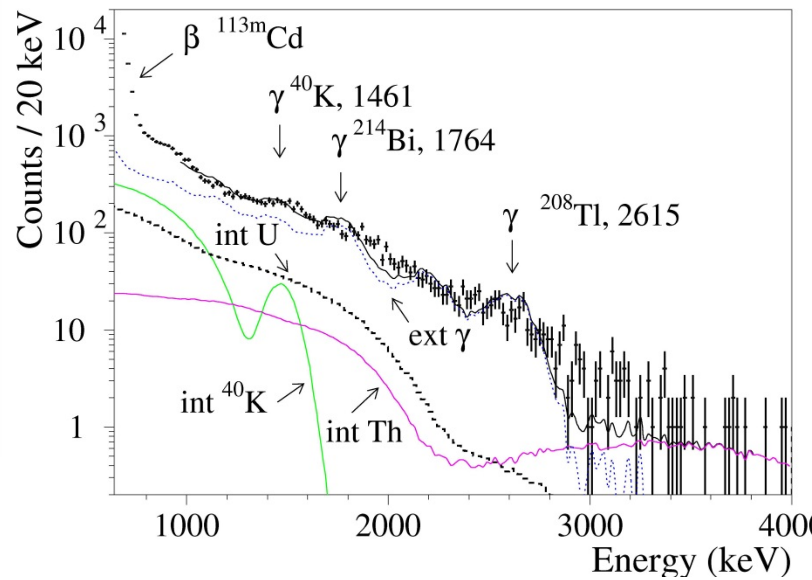
Excellent optical and luminescence properties were reached thanks to a special R&D (deep purification of raw materials and low-gradient crystal growth by the Czochralski method)

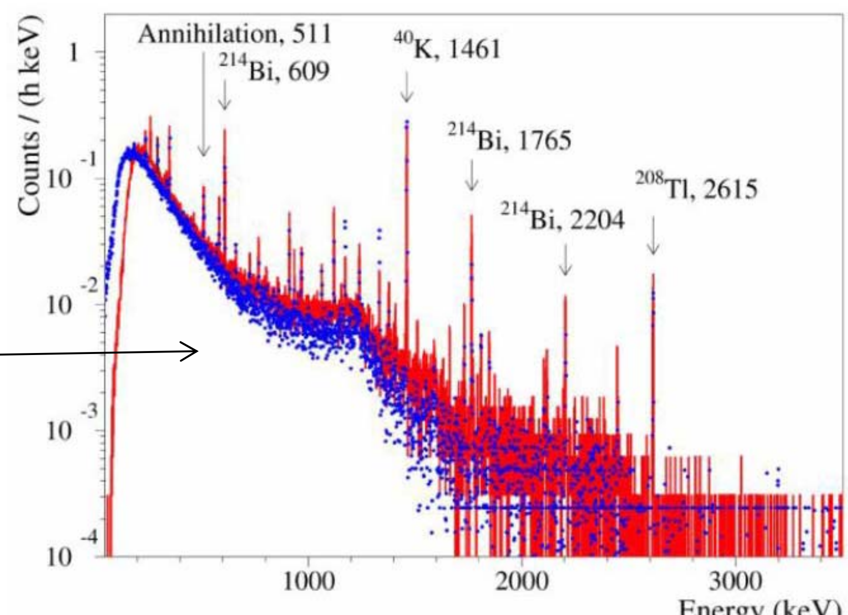
Source	Energy, keV	Energy resolution, %
^{60}Co	1173	9.9(6)
	1333	7.6(8)
^{137}Cs	662	20.3(3)
^{22}Na	511	21.8(5)
	1275	14.4(4)
^{228}Th	2615	10.0(4)



Two-dimensional spectrum of the signals mean-time versus energy

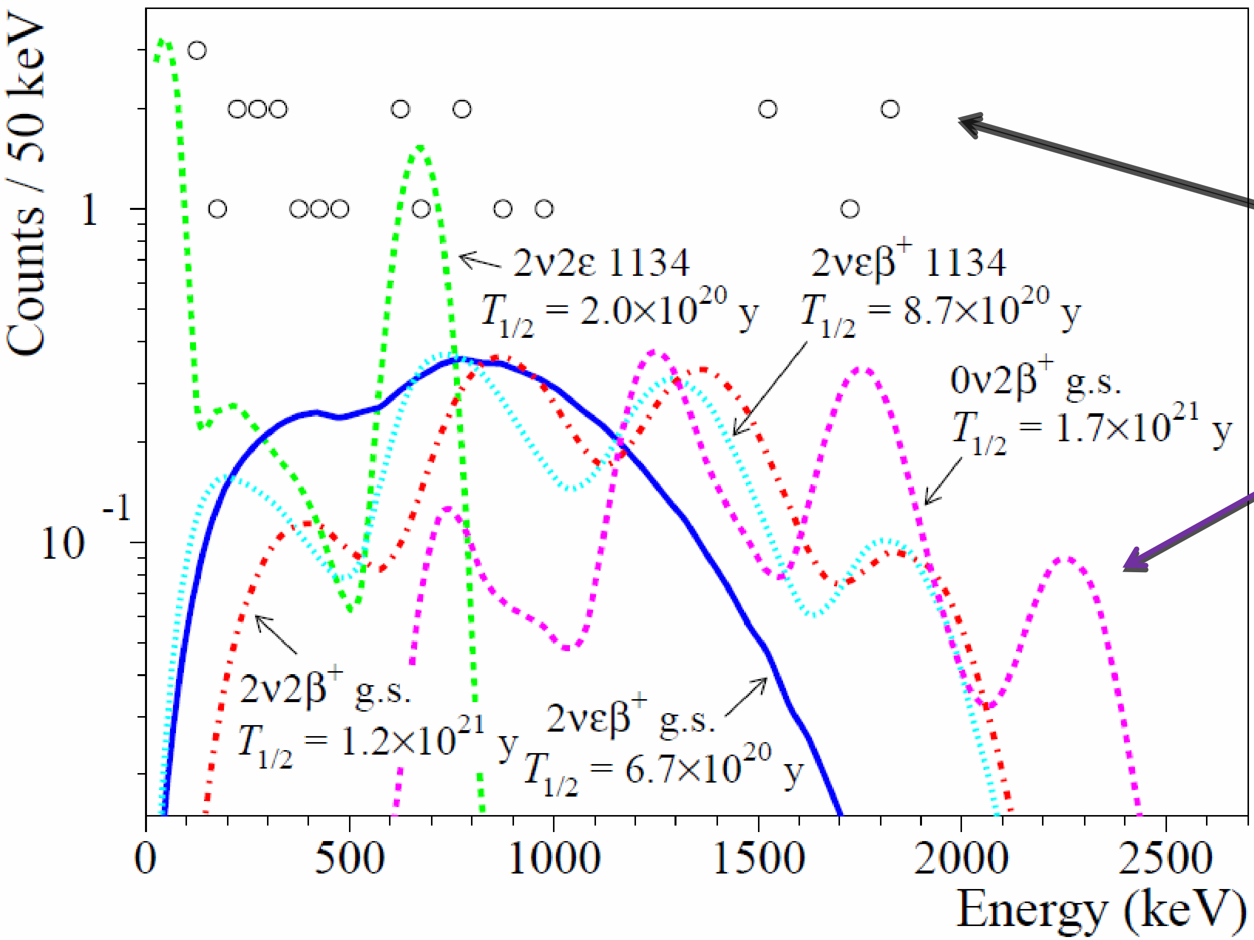
Background energy spectrum with $^{106}CdWO_4$ over 10513 h





Energy spectrum of germanium spectrometer (with and without $^{106}CdWO_4$)

$T_{1/2}$ limits on 2β processes in ^{106}Cd



Experimental spectrum $^{106}CdWO_4$ in coincidence with 511 keV in HPGe

Excluded distributions for different 2β processes 90% CL
(EGS4 + DECAY0)

Background energy spectrum of the $^{106}CdWO_4$ detector in coincidence with 511 keV annihilation γ quanta in the HPGe detectors accumulated over 3233 h (circles) together with the simulated distributions of double beta processes in ^{106}Cd excluded at 90% C.L.

New **$T_{1/2}$ limits for different modes: 10^{20}-10^{21} yr**

Conclusions

- Experiments to search for double beta decay processes in $^{106,116}Cd$ with the help of enriched in $^{106,116}Cd$ (to 66% and 82%, respectively) low background $^{106,116}CdWO_4$ scintillation detectors are in progress at the Gran Sasso underground laboratory of INFN (Italy).
- Spectrometric properties of detectors (energy and time resolution), the methods of separation of signals from the α-particles and γ quanta (β-particles) were developed
- Sensitivity of the experiment for different channels of 2β decay for ^{116}Cd is 10^{20}-10^{23} years. It is expected that the 2ν-mode of 2β decay of ^{116}Cd will be measured with an accuracy better than 10%.
- $^{106}CdWO_4$ scintillator was successfully cleaned from different impurities (including ^{207}Bi). The detector is running in coincidence with four HPGe detectors to search for 2β processes in ^{106}Cd.
- Deeply purified lead tungstate ($PbWO_4$) crystal light-guide from low-radioactive archaeological lead (that is free from ^{210}Pb) with good optical properties is used as light-guide to supress gamma quanta from contamination of the PMT.
- Sensitivity of the experiment for different channels of 2β decay for ^{106}Cd is on the level of 10^{20}-10^{21} years.
- Data taking and analysis of both experiments are in progress.

Plans

- Recrystallization of the crystals would reduce contamination of $CdWO_4$ from Th, U, Ra, K (due to the very strong segregation of these elements)
- Production of $^{106}CdWO_4$ depleted with ^{113}Cd to remove ^{113m}Cd

Thank you for attention!