New limit on two neutrino electron capture with positron emission in ^{106}Cd

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2β processes

$2\nu2\beta$ $(A, Z) \rightarrow (A, Z + 2) + 2\beta^- + 2\bar{\nu}$ (allowed in SM)

$0\nu2\beta$ $(A, Z) \rightarrow (A, Z + 2) + 2\beta^-$ (forbidden in SM, $\Delta L=2$)

Detection of $0\nu2\beta$ 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 number;
- existence of Majorons
- theory of supersymmetry and many other effects beynd the Standard Model

Over 75 years of experimental searches $2\nu2\beta^-$ 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** and 2β processes with decreasing nuclear charge – in ^{78}Kr, ^{124}Xe, ^{130}Ba ($T_{1/2}$ ~ **10^{21}–10^{22} yr**).
Neutrinoless 2β decay has not yet been observed (*)

Investigation of $0\nu\varepsilon\beta^+$ and $0\nu2\beta^+$ is a way to refine the mechanism of the decay due to the light ν mass or due to the right-handed currents [1]

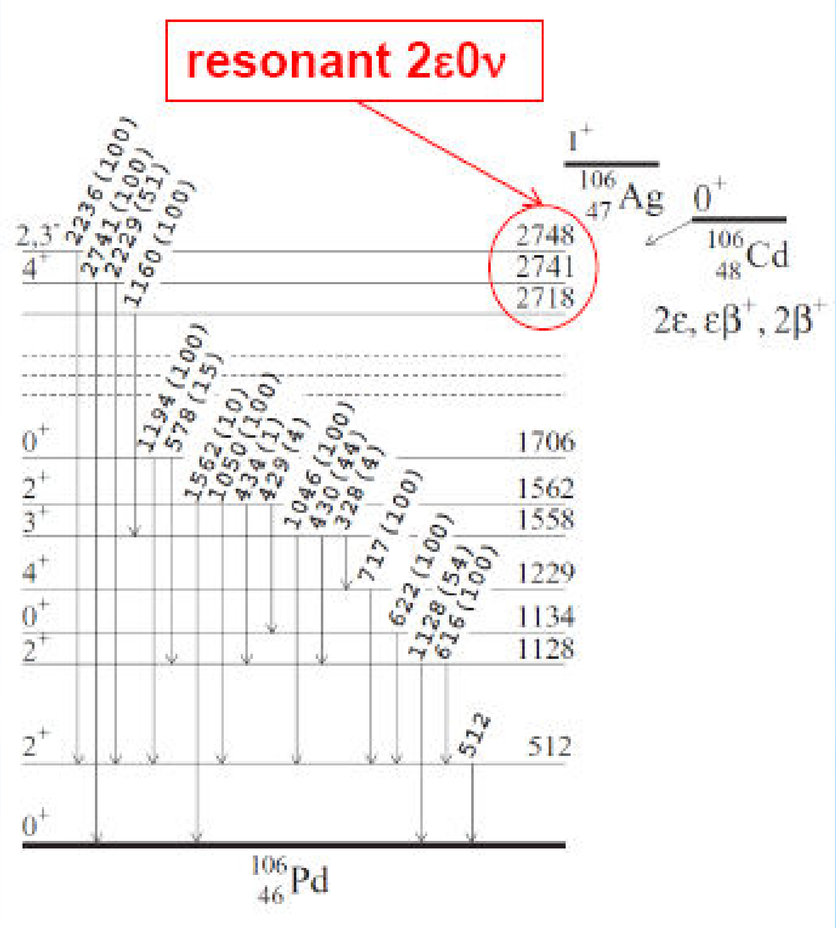
[1] M.Hirsch et al., Nuclear structure calculation of $\beta\beta$, β/EC, and EC/EC decay matrix elements, Z. Phys. A 347, 151 (1994)

* One positive claim on observation of $0\nu2\beta$ in ^{76}Ge by part of HM ($T_{1/2}$ = 2.2×10^{25} yr), excluded by the last GERDA results (8.0×10^{25} yr) [PRL 120(2018)132503]

^{106}Cd is a promising candidate to search for 2EC, ECβ^+, 2β^+

- ✓ One of the six isotopes candidates for 2β^+ decay;
- ✓ **$Q_{2\beta}$= 2775.39(10) keV $\rightarrow$ 2β^+, $\varepsilon\beta^+$** and **2ε** decay modes possible;
- ✓ High natural abundance δ=**1.245(22)** + possible enrichment up to 100% by centrifugation;
- ✓ Possible near **resonant 2ε0ν captures** to excited level of ^{106}Pd (**2718** keV – 2K0ν, **2741** keV – $KL_1 0\nu$, **2748** keV – $KL_3 0\nu$)
- ✓ **Theoretical $T_{1/2}$ favorable for some modes (10^{20} – 10^{22} yr)**, thus reachable by modern low-counting techniques;
- ✓ **Source = detector → high efficiency**

Decay scheme



2β decay modes of ^{106}Cd

2ε $2e^- + (A, Z) \rightarrow (A, Z - 2) + (2\nu) + (\gamma)$

→ $2K_{x\text{-rays}}(^{106}Pd)$ (~20 keV) + γ for excited states

εβ⁺ $2e^- + (A, Z) \rightarrow (A, Z - 2) + e^+ + (2\nu) + (\gamma)$

→ positron + 2γ 511 keV + γ for excited states

2β⁺ $(A, Z) \rightarrow (A, Z - 2) + 2e^+ + (2\nu) + (\gamma)$

→ 2 positrons + 4γ 511 keV + γ for excited states

Degeneracy of the energies of the parent (A,Z) and the daughter atom $(A,Z - 2)^*$ gives rise to resonant enhancement of the decay, with a decay rate highly enhanced (up to 10^6)

Recent experimental result on 2β decay of ^{106}Cd

Experiment	$\lim T_{1/2}$, yr at 90% C.L.	Reference, Year
TGV-2, 32 planar type HPGe (~400 cm^2), 16 foils of ^{106}Cd (99.57%), m=23.2 g, Modane (France)	(2νEC/EC) > 3.7×10^{20} (KL, 2741 keV) > 0.9×10^{20} (KK, 2718 keV) > 1.4×10^{20}	J. Phys.: Conf. Ser. 718 (2016) 062049
COBRA: 32/64 semiconductors CdZnTe 1 cm^3 each (monolithic, calorimetric detectors in a coplanar grid (CPG) design), LNGS (Italy)	For dif. modes ~ 10^{18}	Prog. Part. Nucl. Phys. 64 (2010) 267 + Annual report LNGS (2016)
$^{106}CdWO_4$, 215 g (66%) scint.crystal, LNGS (Italy)	For dif. modes ~ 10^{19} - 10^{21}	PRC 85 (2012) 044610
$^{106}CdWO_4$, 215 g (66%) scint.crystal, in coinc. with 4HPGe (225 cm^3), LNGS (Italy)	For dif. modes ~ 10^{20} - 10^{21}	PRC 93 (2016) 045502

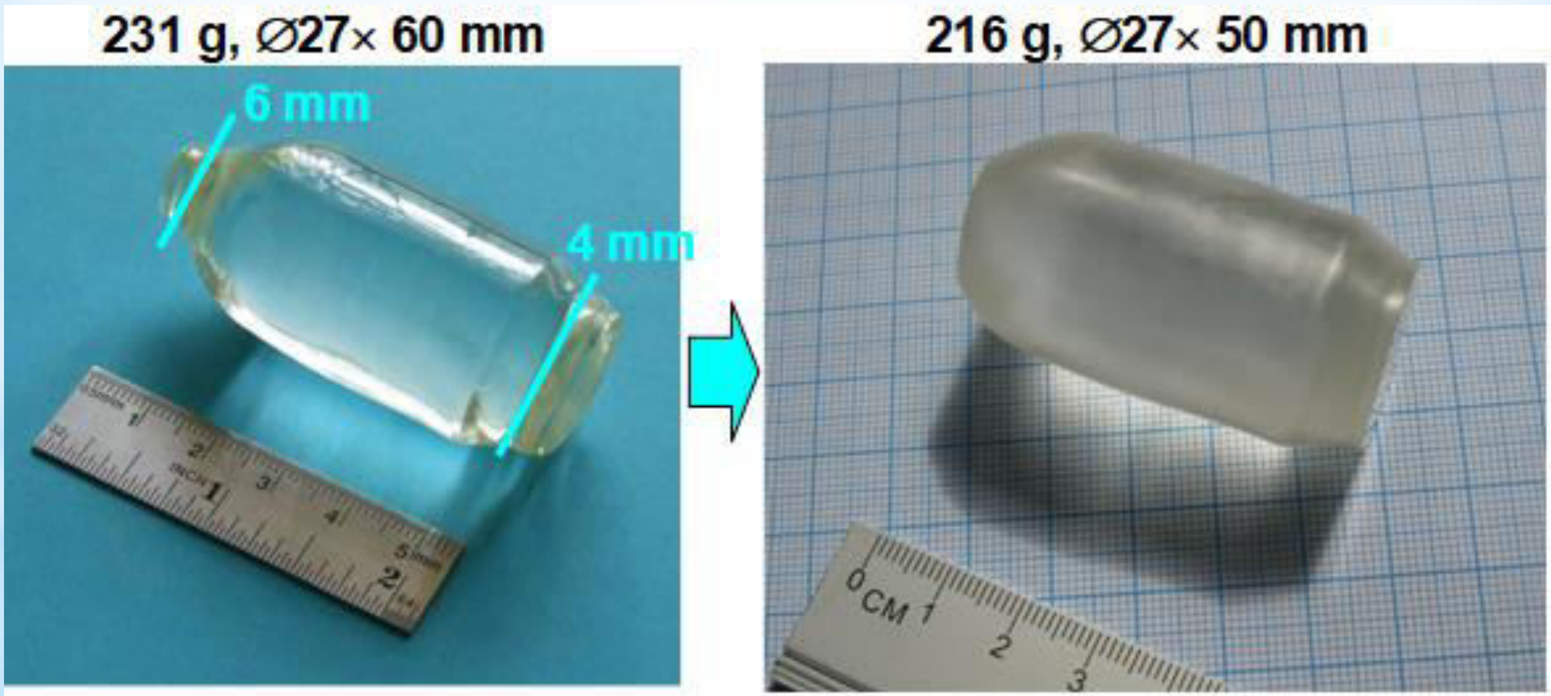
$CdWO_4$ crystal scintillator as a 2β detector

- ✓ Source = detector → high efficiency
- ✓ Good scintillation properties
- ✓ Low levels of internal contamination in U, Th and K
- ✓ α/β discrimination capability

F.A. Danevich et al., PRC 68 (2003) 035501;
P. Belli et al, NIMA 615 (2010) 301-306
P. Belli et al., PRC 85 (2012) 044610;
F.A. Danevich et al., NIMA 741 (2014) 41
P. Belli et al., PRC € 93 (2016) 045502

$^{106}CdWO_4$ (enriched to 66%) crystal scintillator

- Samples with enriched ^{106}Cd were purified by vacuum distillation and the cadmium tungstate compound was synthesized from solutions
- Crystal boule with mass 231 g was grown by the low-thermal-gradient Czochralski technique
- Isotopic composition was measured precisely by thermal ionization mass-spectrometry



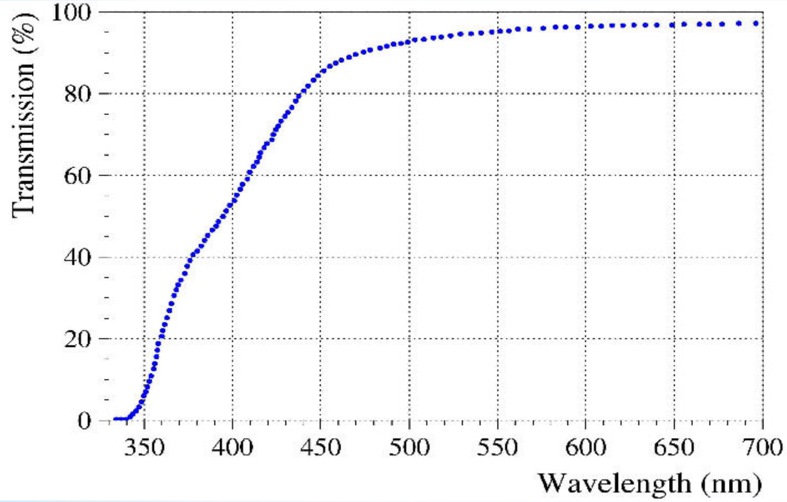
Crystal surface has been diffused to improve light collection

NIMA 615(2010)301

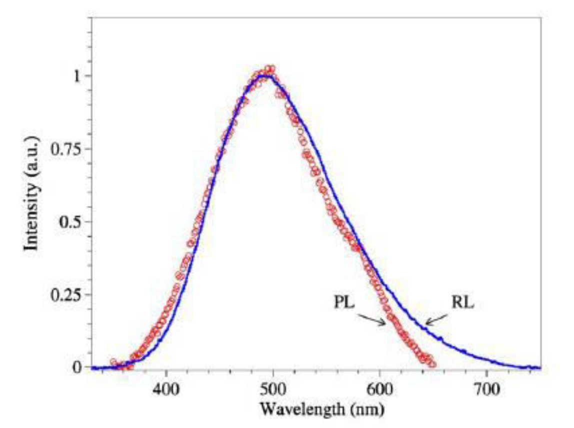
$^{106}CdWO_4$ (unprecedently high quality of material)

Excellent optical and luminescence properties were obtained thanks to the deep purification of raw materials and utilization of the low-thermal gradient Czochralski method for the crystal growth.

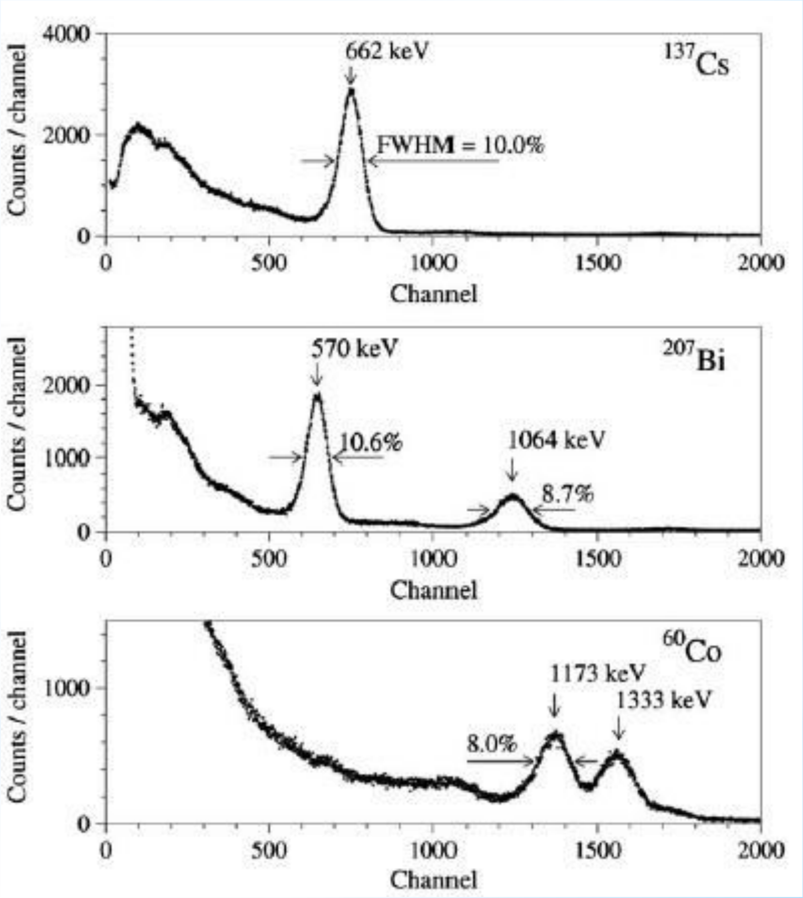
Optical transmission



Emission spectra of $^{106}CdWO_4$ crystal under ultraviolet and X-ray excitation

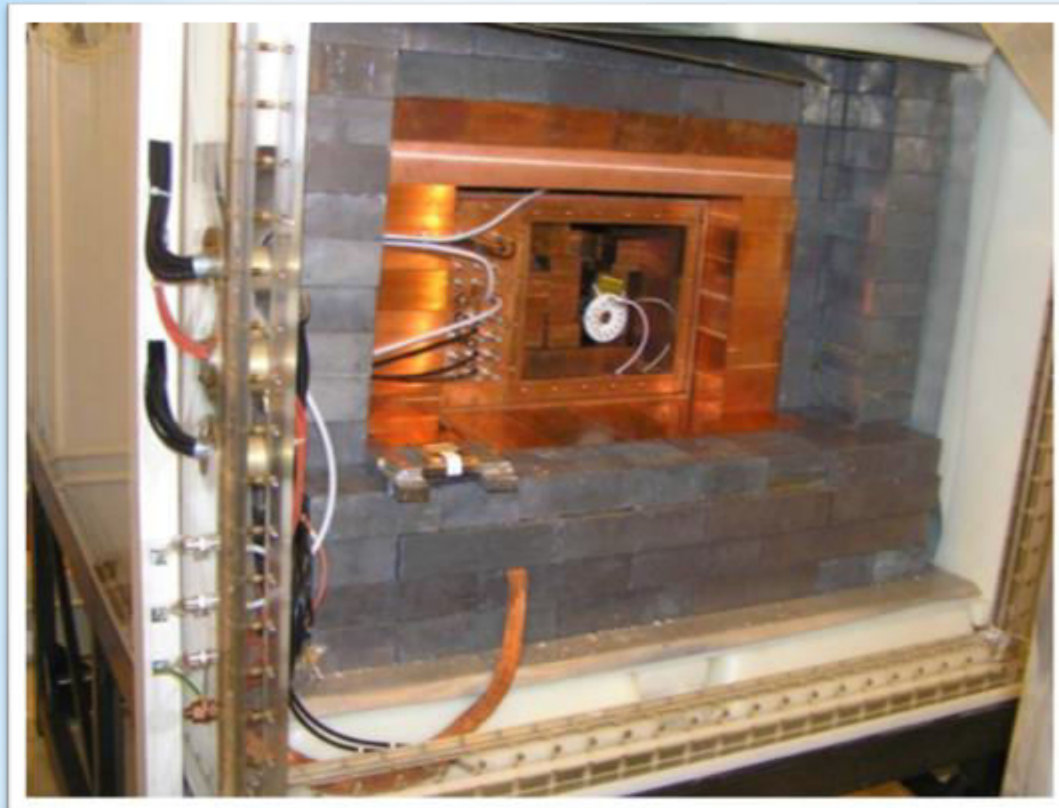


Response of the detector to γ quanta

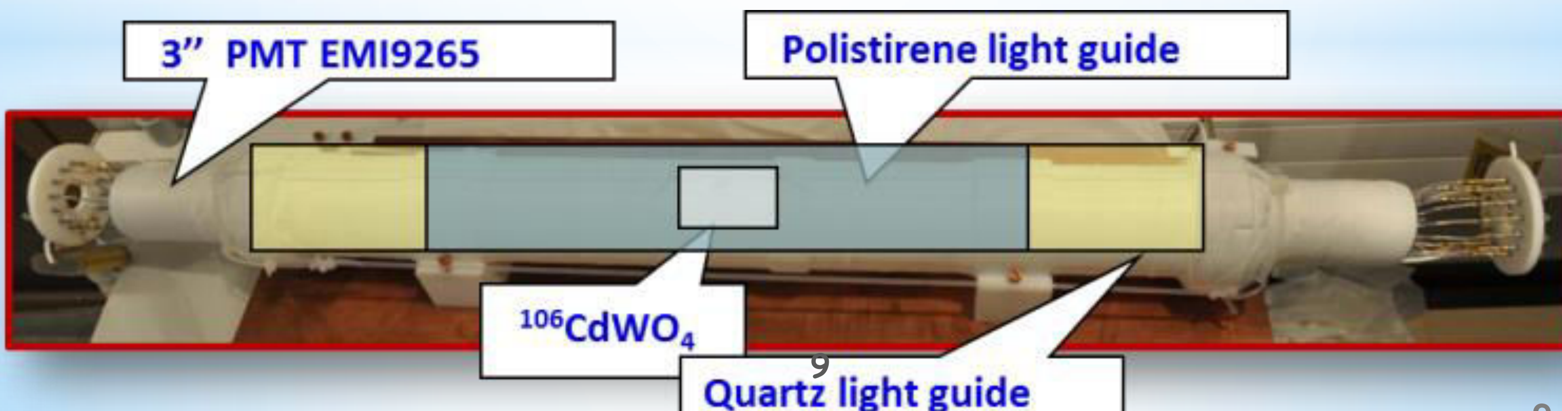


FWHM = 10% @ 662 keV (not optimized light collection)

1st stage of the experiment: experimental set-up



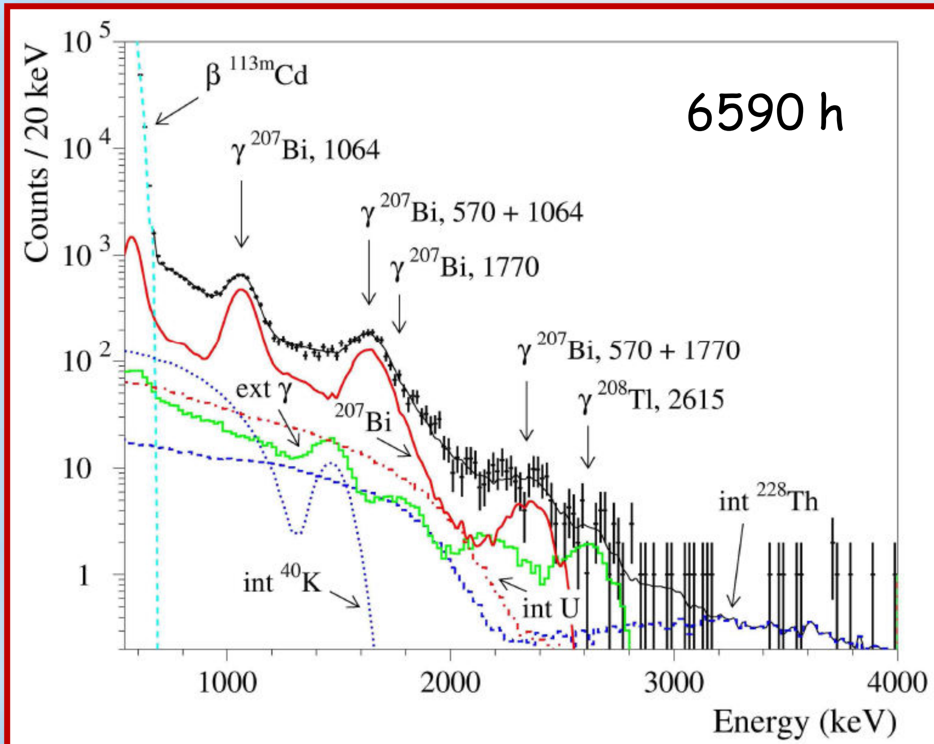
DAMA R&D set-up at the Gran Sasso Underground Laboratory



PRC85(2012)044610

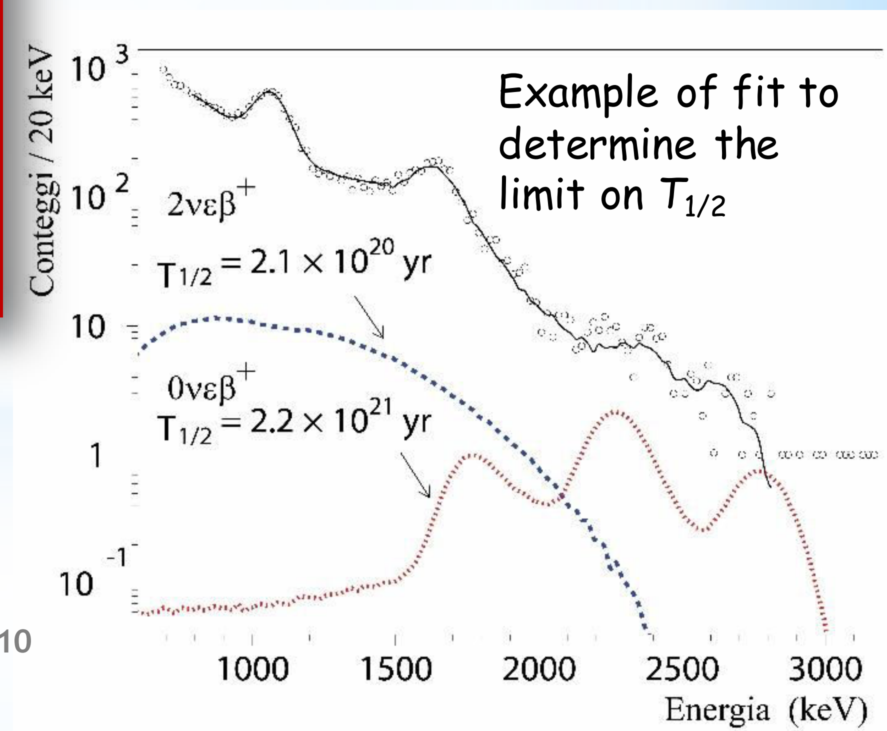
1st stage of the experiment: results

Distribution of the γ/β events selected by pulse-shape discrimination



Contamination level in $^{106}CdWO_4$ (mBq/Kg)

^{207}Bi	<0.7
^{113m}Cd	116 ·10^3
^{232}Th	<0.07
^{228}Th	0.042(4)
^{238}U	<0.6
^{226}Ra	0.012(3)
^{40}K	<1.4
^{207}Bi on surface	0.06



Results:

$T_{1/2}$ (^{106}Cd→ ^{106}Pd) ≥ 10^{19-21} yr

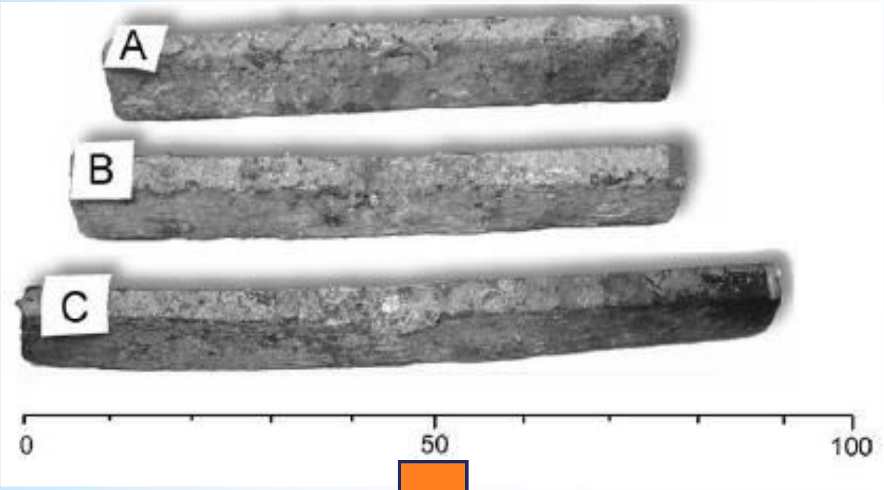
27 new results for 2β ^{106}Cd
9 of them – for the first time

Phys. Rev. C 85 (2012) 044610

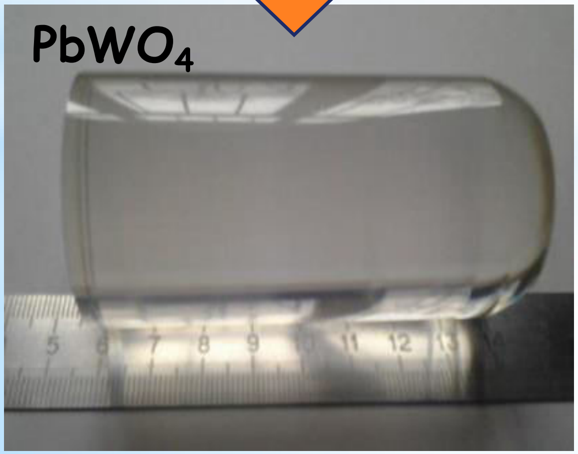
2nd stage of the experiment: R&D of PbWO4 light-guide from archaeological lead

A $PbWO_4$ light-guide was developed from archaeological lead to suppress γ quanta from the PMT

Archaeological lead found in Ukraine: A (^{210}Pb) <0.3 mBq/kg [1]



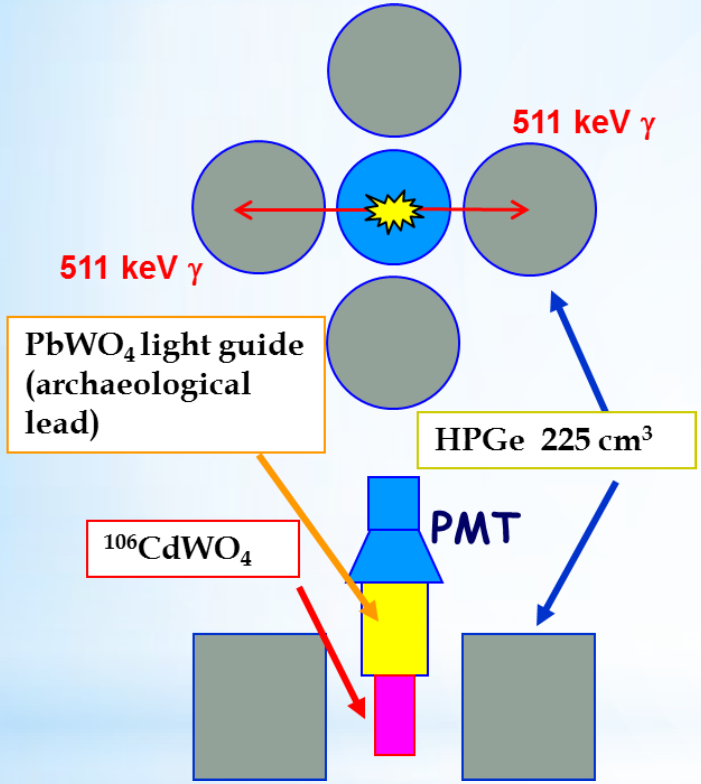
- Deep purification of lead sample by vacuum distillation
- Crystal growth by Czochralski process

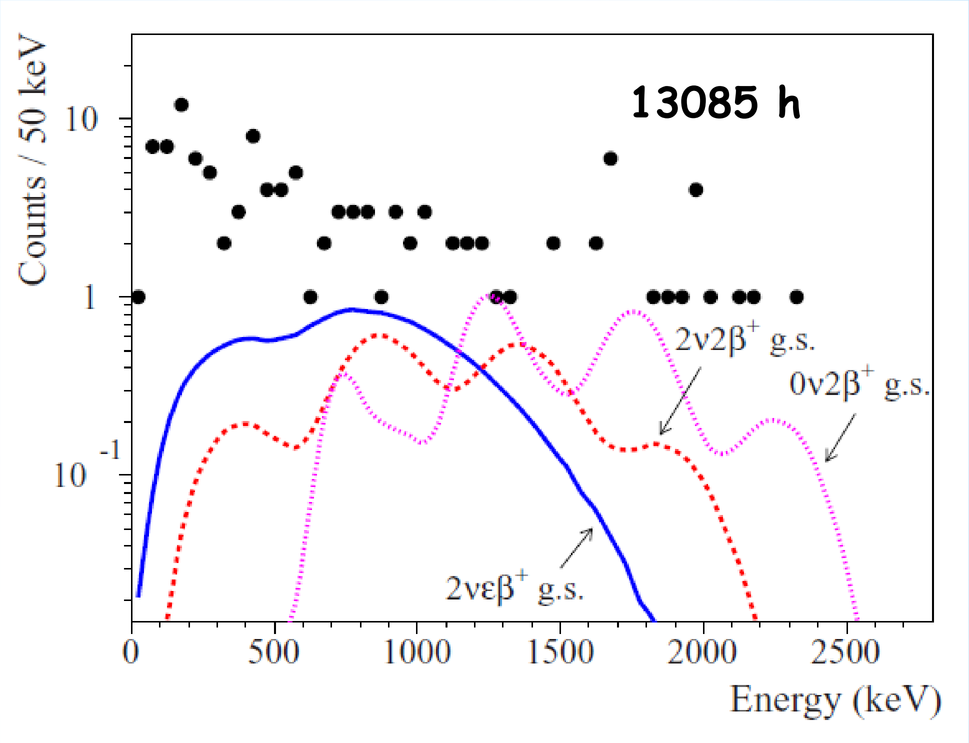


[1] NIMA 603 (2009) 328; Inorganic Mater. 47 (2011) 645.

2nd stage of the experiment: the set-up and results

- $^{106}CdWO_4$ in coincidence / anticoincidence with 4 HPGe detectors
- Registration efficiency ~ **(3–8)%**



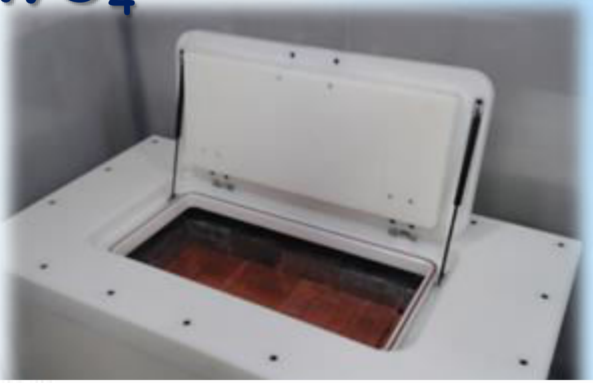


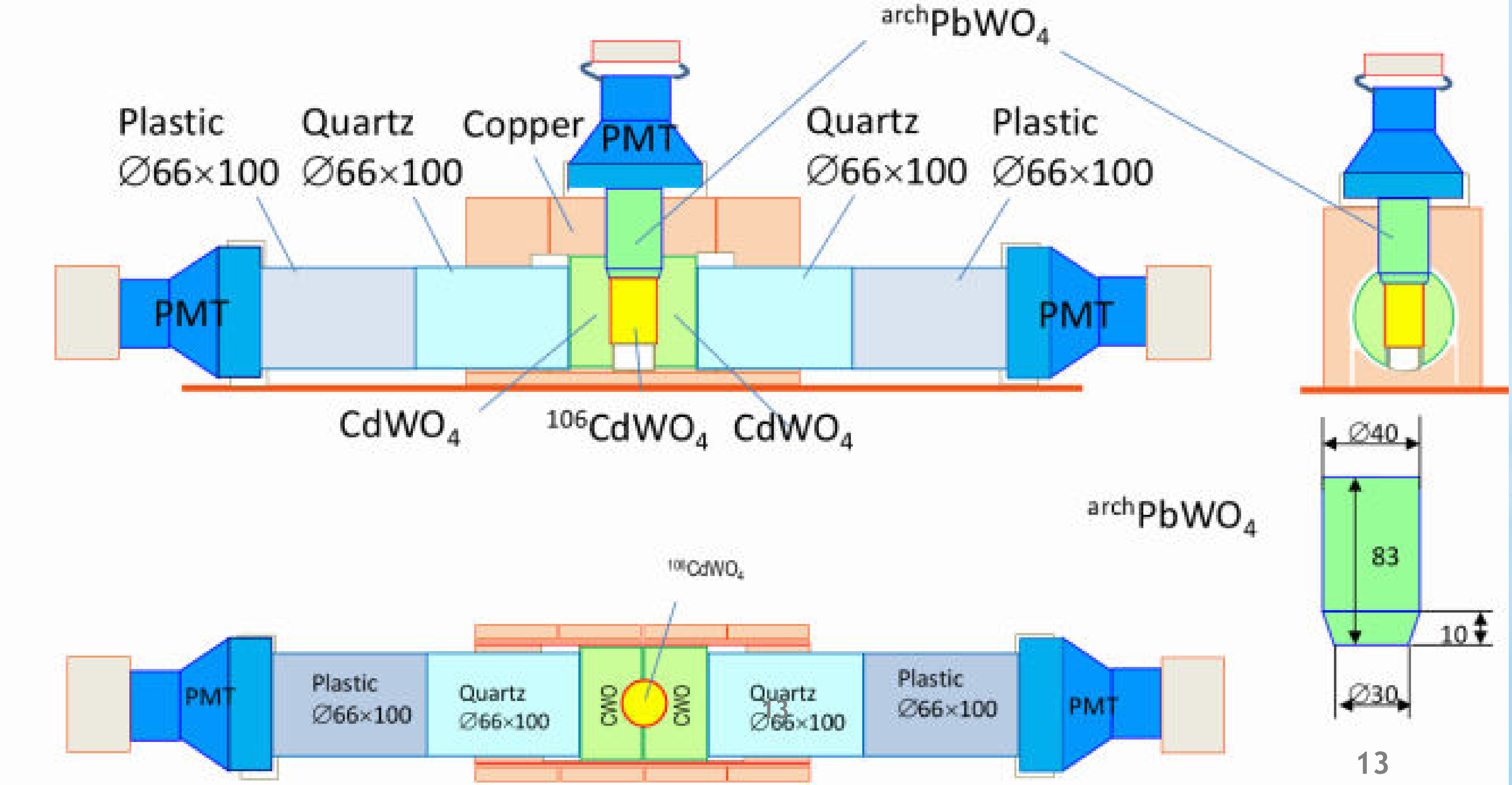
Energy spectrum of $^{106}CdWO_4$ detector in coincidence with 511 keV in HPGe (circles). Monte Carlo simulated distributions of 2β decay of ^{106}Cd excluded at 90% CL.

- New limits on 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes on the level of $T_{1/2} > 10^{20}$ -10^{21} yr
- The half-life limit on the **$2\nu\varepsilon\beta^+$ decay $T_{1/2}$ > 1.1 × 10^{21} yr** reached the region of theoretical predictions -> $M_{eff}(2\nu\varepsilon\beta^+) \leq 1.1$ [PRC 93(2016)045502]
- For $0\nu2\varepsilon$ resonant captures: $T_{1/2} > (8.5 \times 10^{20} – 1.4 \times 10^{21})$ yr

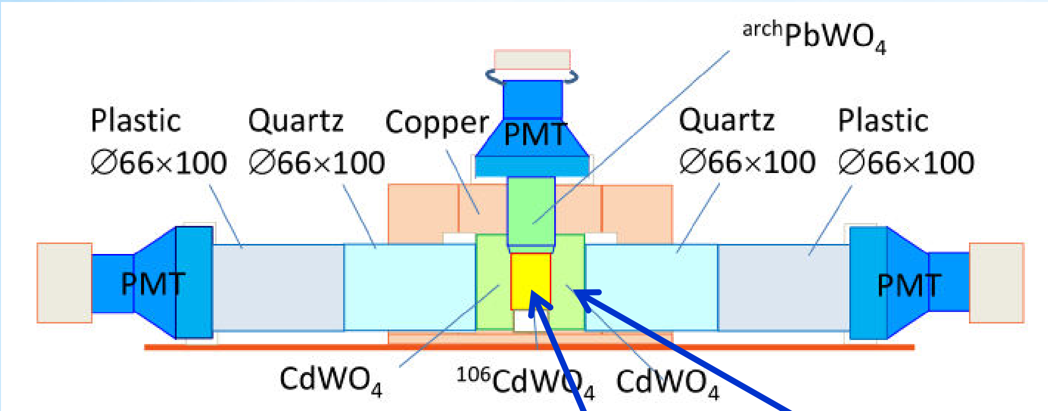
$^{106}CdWO_4$ in coincidence with two $CdWO_4$

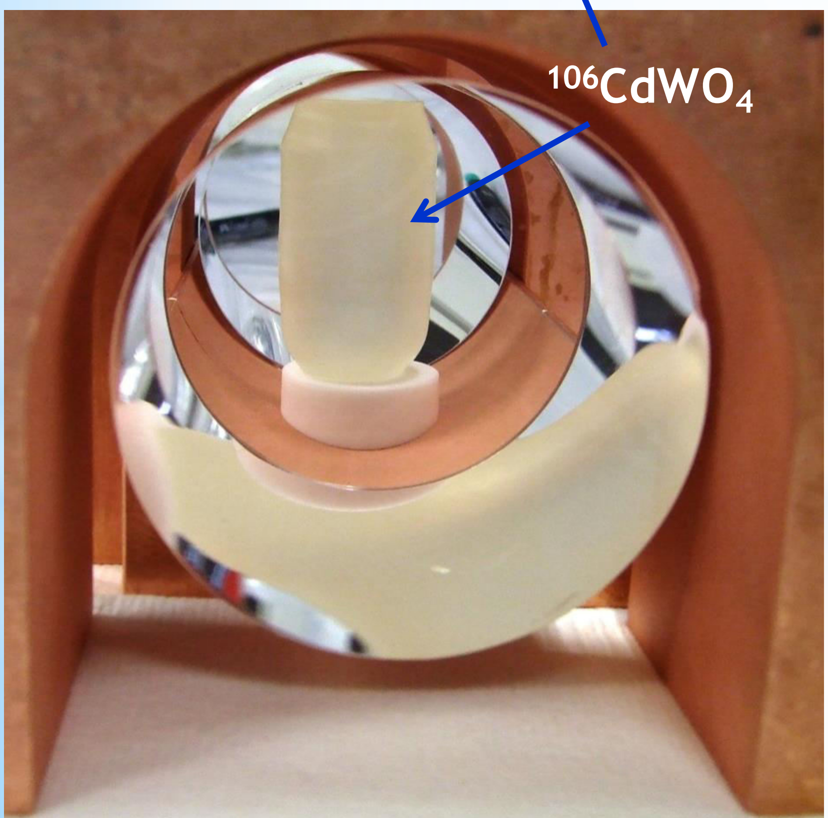
1) $^{106}CdWO_4$ in (anti)coincidence with two large $CdWO_4$ scintillators in close geometry mounted in DAMA/Crys set-up at LNGS
2) Higher efficiency
3) Experiment in data taking since May 2016



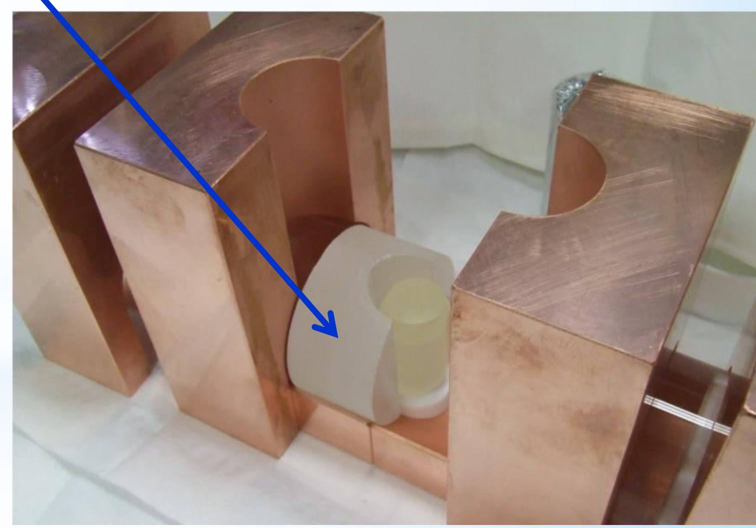


$^{106}CdWO_4$ in the DAMA/Crys set-up

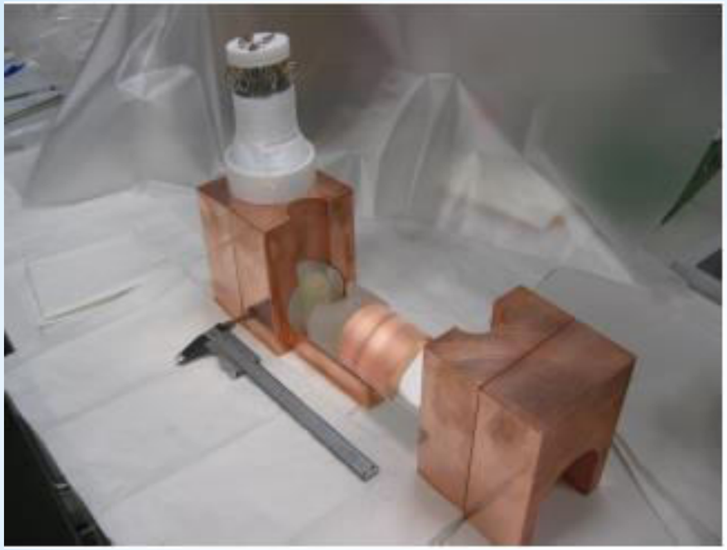


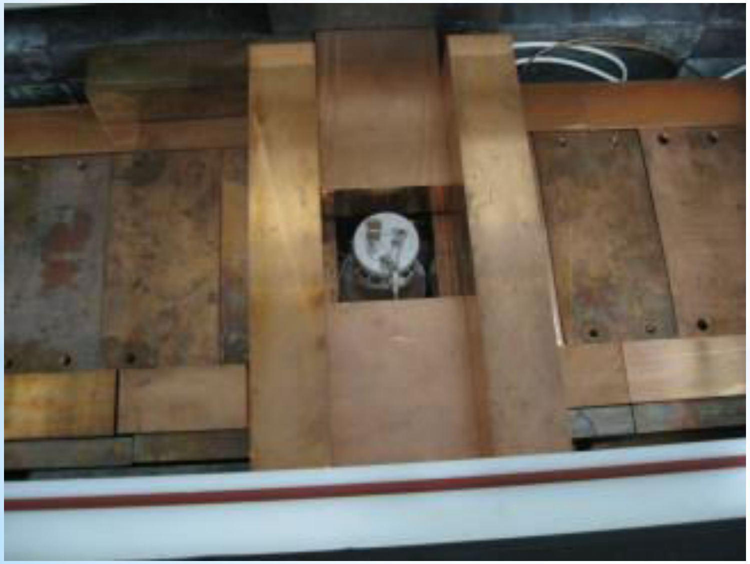
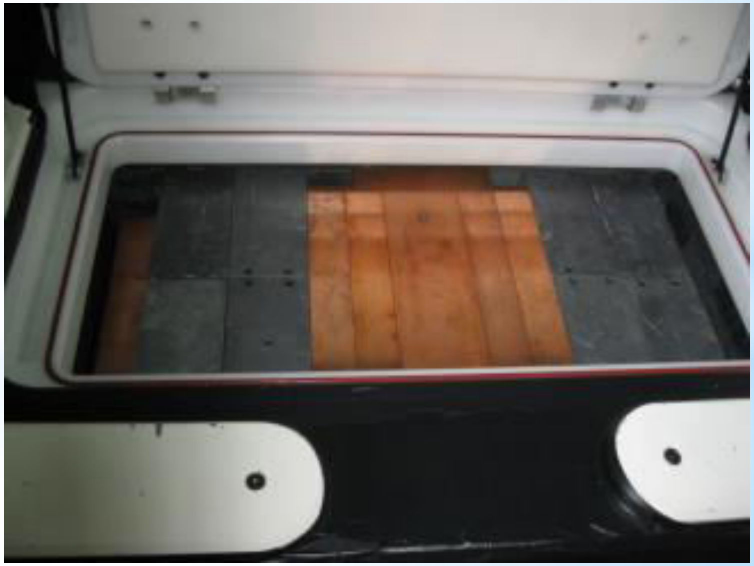


$^{106}CdWO_4$



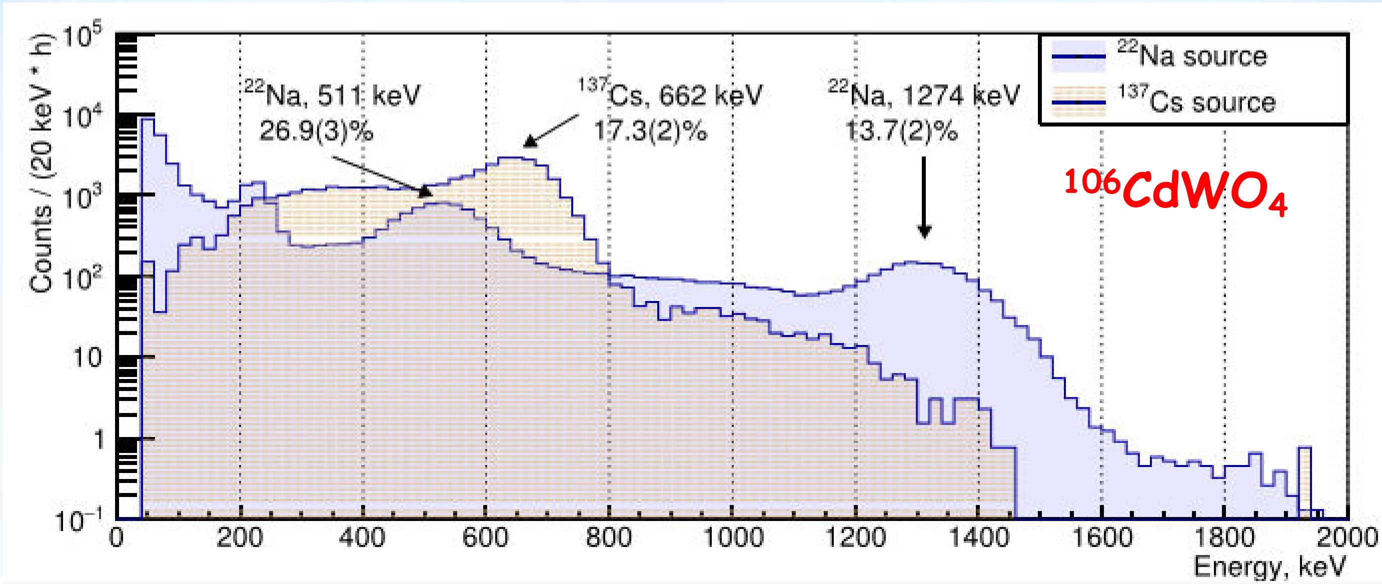
$^{106}CdWO_4$ detector assembling in the DAMA/Crys set-up

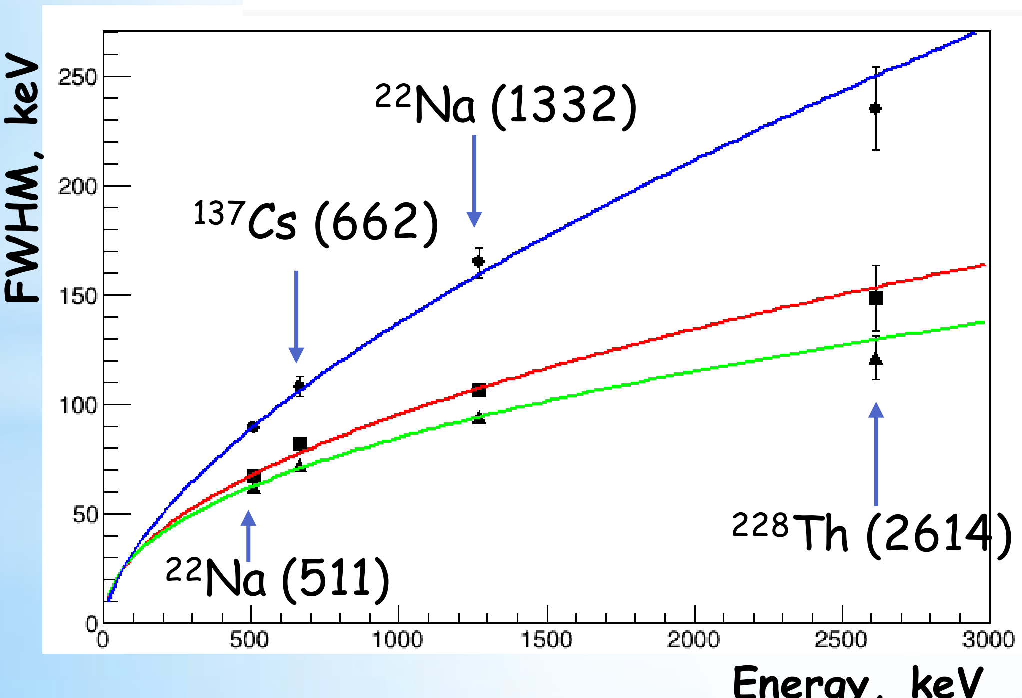


15

Energy resolutions for $^{106}CdWO_4$ and $CdWO_4$

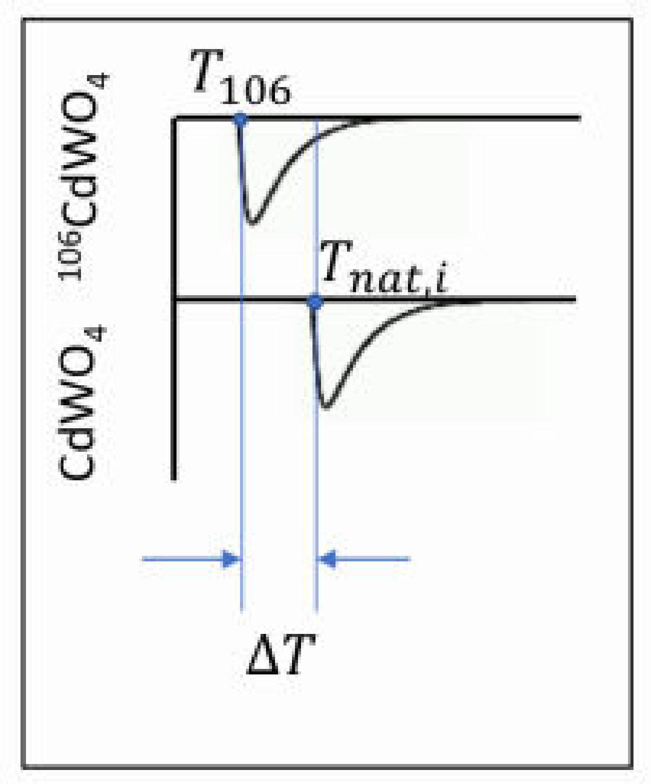


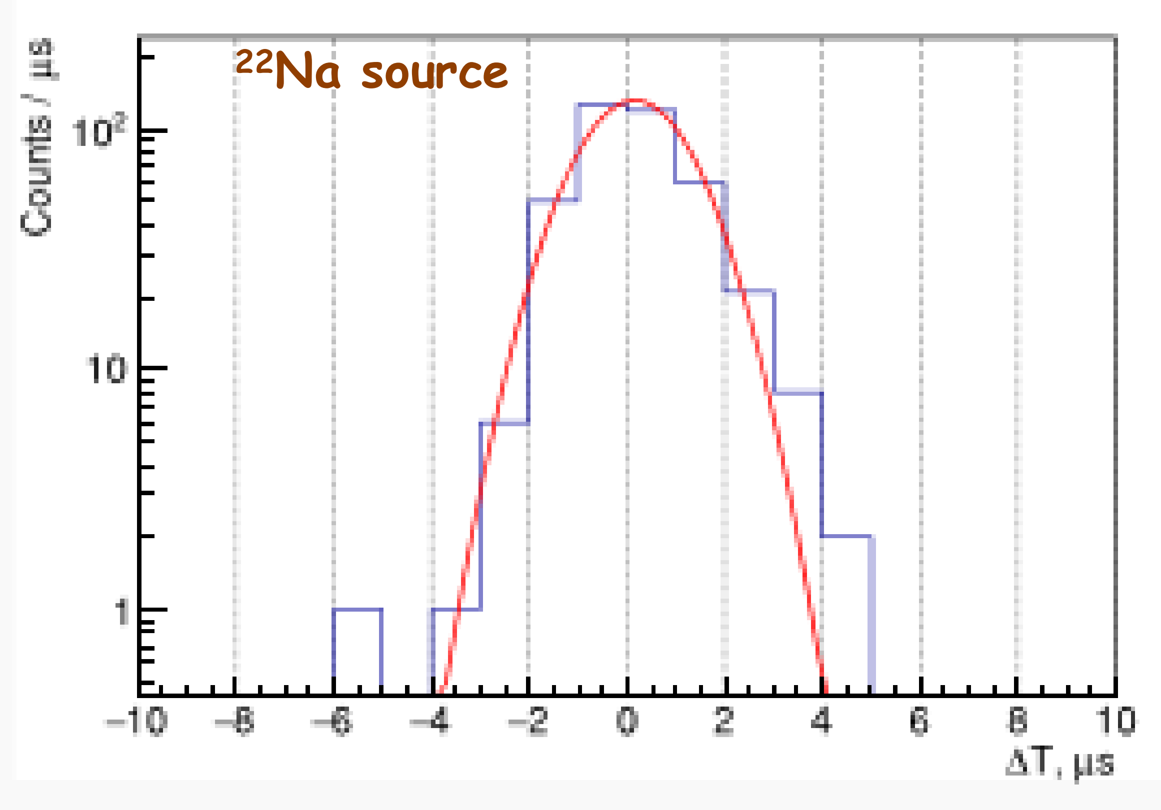


Unfortunately, the $PbWO_4$ light-guide is not transparent enough

Detector performances

$^{106}CdWO_4$ detector pulses start positions relatively to the $^{nat}CdWO_4$ signals



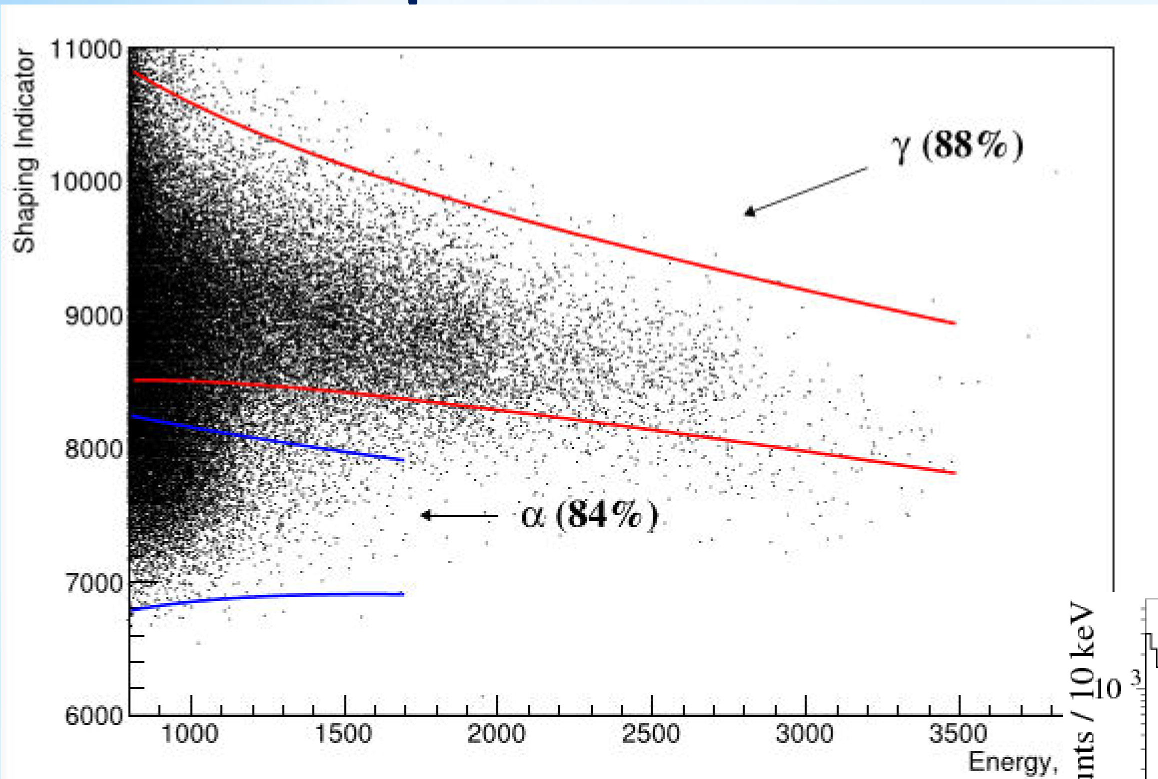


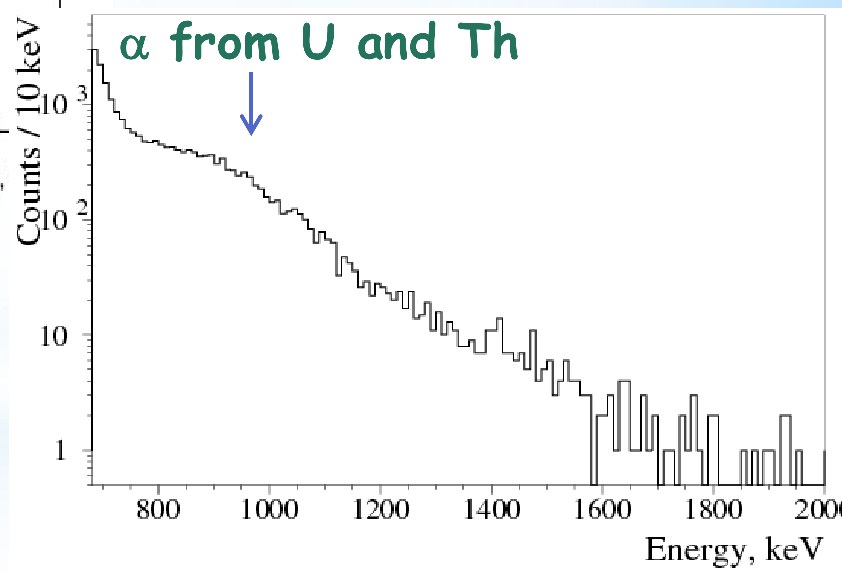
$$\Delta T = T_{nat,i} - T_{106}$$

$T_{nat,i}$ – start of the signal in detector $CdWO_4$, i = 1,2

T_{106} – start of the signal in $^{106}CdWO_4$

Pulse shape discrimination between β(γ) and α (PSD)





$$SI = \frac{\sum f(t_k) \times P(t_k)}{\sum f(t_k)}$$

$$P(t) = \frac{f_\alpha(t) - f_\beta(t)}{f_\alpha(t) + f_\beta(t)}$$

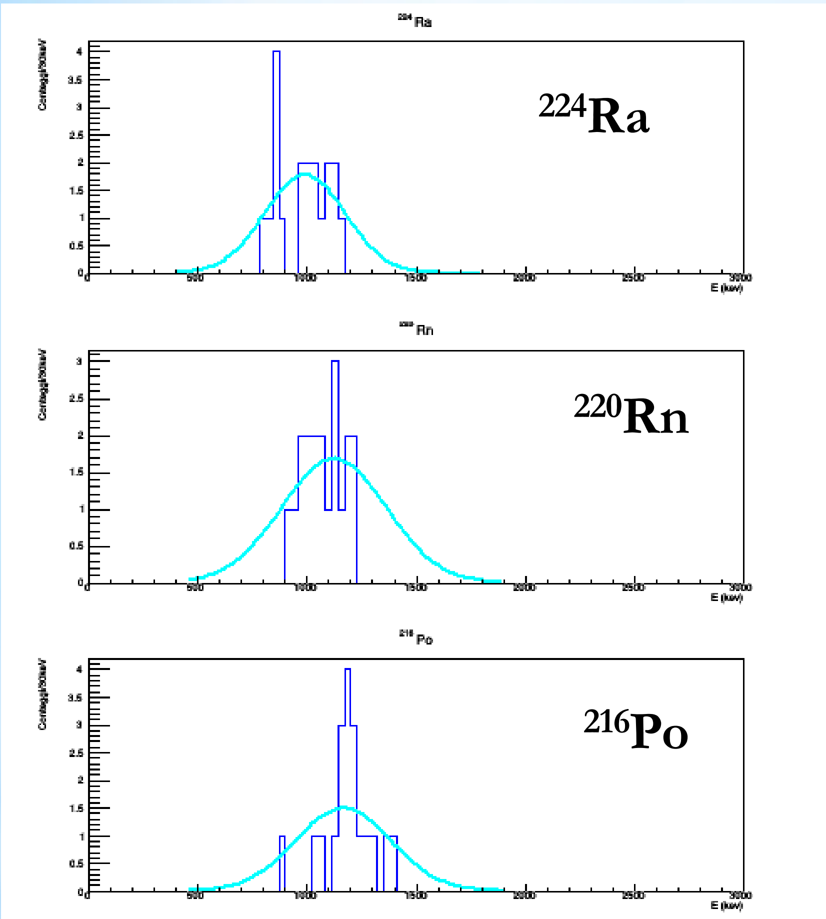
$f_\alpha(t), f_\beta(t)$- reference pulse shapes

$f(t_k)$ – amplitude at t_k
$P(t_k)$ – weight function

Total α activity = 2.1(2) mBq/kg

Time-Amplitude Analysis of ^{228}Th daughters

T = 6935 h



Activity of ^{228}Th:

The arrival time, the energy and the pulse shape of each event were used to select the fast decay chain in the ^{228}Th sub-chain of the ^{232}Th family:

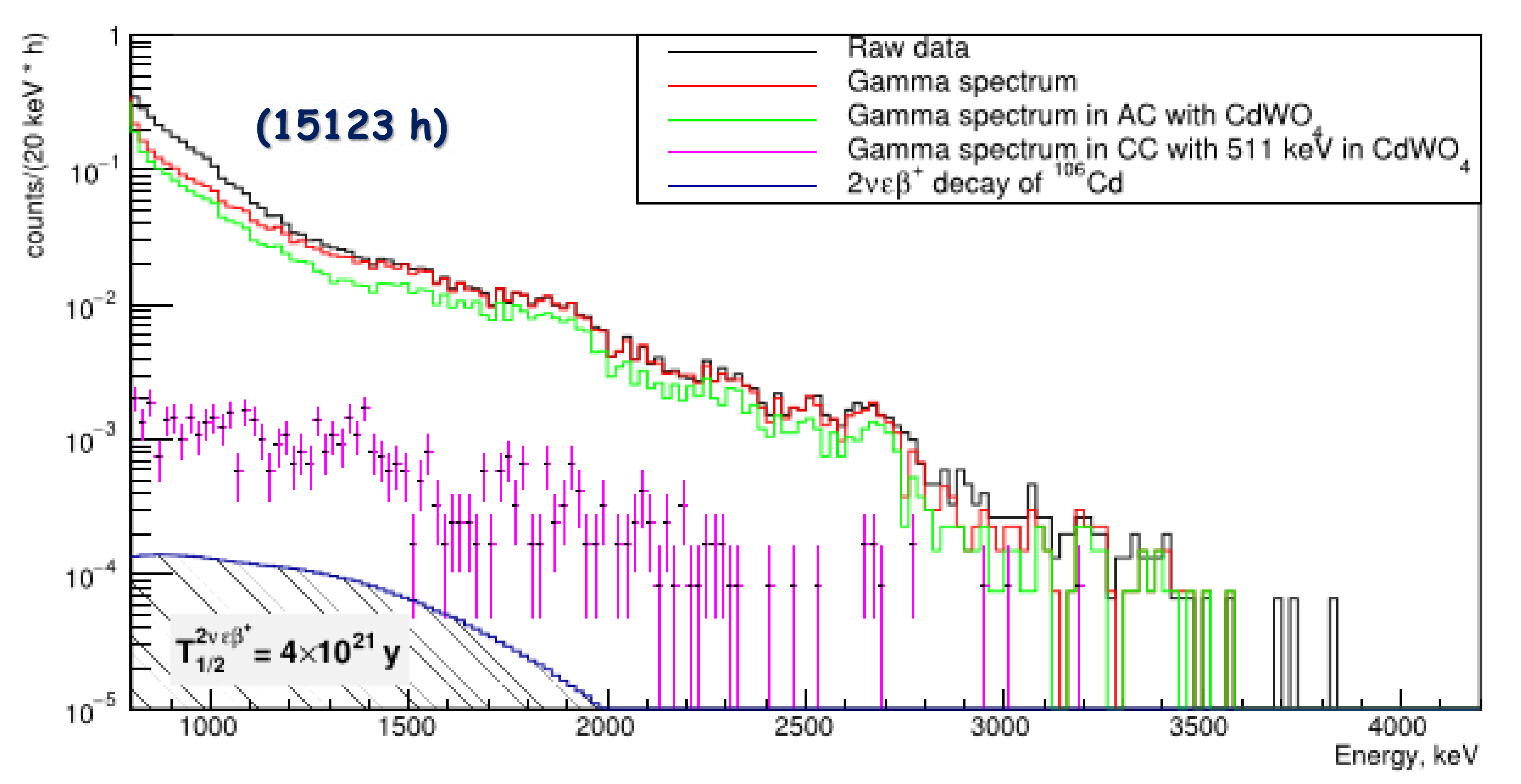
^{224}**Ra** (Q = 5.789 MeV, $T_{1/2}$ = 3.66 d)
↓
^{220}**Rn** (Q = 6.405 MeV, $T_{1/2}$ = 55.6 s)
↓
^{216}**Po** (Q = 6.906 MeV, $T_{1/2}$ = 0.145 s)
↓
^{212}Pb

Activity of ^{228}Th in $^{106}CdWO_4$ crystal was estimated as: **5(1) μBq/kg**
Also α/γ ratio and energy resolution for alpha-particles were estimated

Radioactive contamination of the $^{106}CdWO_4$ crystal

Chain	Nuclide	Activity, mBq/kg
^{232}Th	^{232}Th	< 0.07
	^{228}Th + daughters	0.005(1)
^{238}U	^{238}U	< 0.6
	^{230}Th	< 0.4
	^{226}Ra	0.012(3)
	^{210}Po	< 0.2
Total α activity		**2.1(2)**
	^{40}K	< 1.4
	^{90}Sr-^{90}Y	< 0.3
	^{106}Ru	< 0.02
	^{113m}Cd	116×10^3
	^{110m}Ag	< 0.06

Energy spectra of $^{106}CdWO_4$ in CC and AC with $CdWO_4$



Sensitivity:

$T_{1/2}(2\nu\varepsilon\beta^+)$ > 4 × 10^{21} yr at 90% C.L.

lim NME ($2\nu\varepsilon\beta^+$) = 0.6748 [1]
0.5967 [2]
0.5559 [3]

[1] Mirea et al., RRP 67(2015)872
[2] Kotila et al., PRC 87(2013)024313
[3] Suhonen, Civitarese 300(1998)123

Conclusions

- Experiments to search for 2β processes in ^{106}Cd are in progress with the help of enriched $^{106}CdWO_4$.scintillator. At the present stage the detector is running in coincidence with two $^{nat}CdWO_4$ detectors in close geometry.

- $PbWO_4$ crystal from deeply purified low-radioactive archaeological lead is used **as light-guide to suppress** γ **quanta** from contamination of the PMT **(the new cleaner $PbWO_4$ will be installed soon → better energy resolution for ^{106}Cd).**
- Selection of the events in the $^{106}CdWO_4$ detector in CC with $^{nat}CdWO_4$ reduces background to search for $EC\beta^+$ and other process in ^{106}Cd with emission of γ quanta.

- The experiment sensitivity $T_{1/2}(2\nu\varepsilon\beta^+)$ **> 4 × 10^{21} yr at 90% C.L.** is near the theoretical predictions 10^{21}-10^{22} yr.

- Sensitivity of the experiment for different channels of 2β decay for ^{106}Cd is on the level of 10^{20}-10^{21} years.