Search for double beta processes in ^{106}Cd and ^{116}Cd with enriched $^{106}CdWO_4$ and $^{116}CdWO_4$ crystal scintillators

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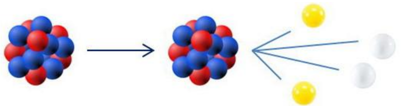
Contents:

Double beta decay: (A,Z) → (A,Z±2)

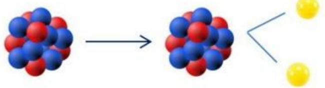
Allowed in SM:

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ – two-neutrino $2\beta^-$ decay



Forbidden in SM, $\Delta L=2$:

$(A,Z) \rightarrow (A,Z+2) + 2e^-$ – neutrinoless $2\beta^-$ decay

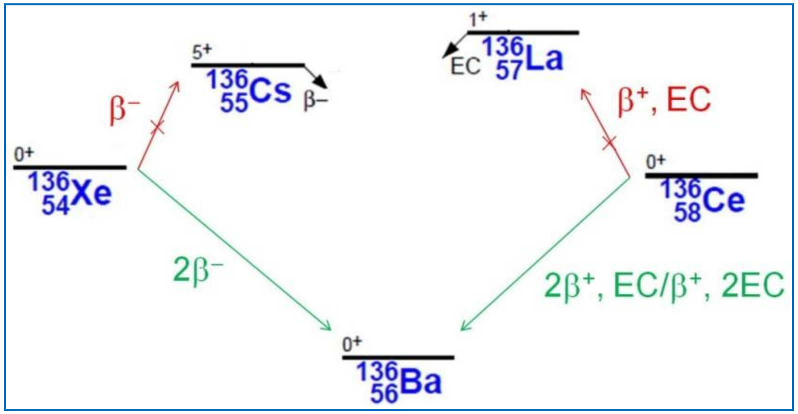


$(A,Z) \rightarrow (A,Z+2) + 2e^- + M$ – $2\beta^-0\nu$ decay with Majoron emission

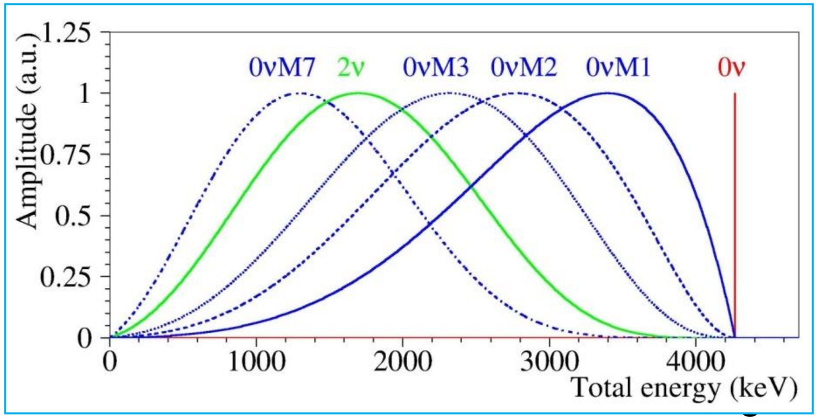
$2\beta^+/\ \varepsilon\beta^+/2\varepsilon$ processes, decays to excited states, different Majorons …

$2\beta0\nu$ requires: $\nu_e = -\nu_e$ (Majorana particle)
$m(\nu_e) \neq 0$ (or right-handed admixtures, …)

Many extensions of the SM predict $m(\nu_e) \neq 0$ and, as a result, $2\beta0\nu$ processes. Experimental observation of this exotic phenomenon would be an unambiguous signal of new physics which lies beyond the SM.



β^-, β^+ energetically forbidden $2\beta^-$, $2\beta^+$ allowed



e_1+e_2 energy spectra in different 2β modes

Status of experimental investigations of 2β decay

$2\beta^-$	$2\beta^+/\varepsilon\beta^+/2\varepsilon$
35 candidates	34 candidates
Nat. abundances $\delta \sim (5\text{-}10\text{-}100)\%$	Typical $\delta < 1\%$ with few exclusions
$Q_{2\beta}$ up to 4.3 MeV	$Q_{2\beta} > 2$ MeV only for 6 nuclides
$2\beta2\nu$ is registered for 11 nuclei (^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U) with $T_{1/2} = 10^{18} – 10^{24}$ yr	$2\varepsilon2\nu$ - ^{130}Ba ? ($T_{1/2} \sim 10^{21}$ yr) - ^{78}Kr ? ($T_{1/2} \sim 10^{22}$ yr)
Sensitivity to $2\beta0\nu$ up to 10^{25} yr	Sensitivity to 0ν up to 10^{21} yr

One positive claim on observation of $2\beta^-0\nu$ in ^{76}Ge by part of HM ($T_{1/2} = 2.2\times10^{25}$ yr), on the edge of current sensitivity of GERDA (2.1×10^{25} yr)

$2\beta^+/\varepsilon\beta^+/2\varepsilon$ studies are less popular but nevertheless:
Information from $2\beta^+/\varepsilon\beta^+/2\varepsilon$ is supplementary to $2\beta^-$
(possible contributions of right-handed currents to 0ν,
M. Hirsch et al., ZPA 347 (1994) 151)

^{106}Cd is attractive because of:

(1) $Q_{2\beta}$ = 2775.39±0.10 keV – one of only six $2\beta^+$ nuclides

(2) Quite high natural abundance δ = 1.25%

(3) Possibility of resonant $2\varepsilon0\nu$ captures to excited levels of daughter ^{106}Pd (2718 keV – $2K0\nu$, 2741 keV – $KL_1 0\nu$, 2748 keV – $KL_3 0\nu$)

(4) Theoretical $T_{1/2}$ are quite optimistic for some modes (g.s.→g.s.):

$2\varepsilon2\nu$ - $(2.0\text{-}2.6)\times10^{20}$ yr [1],

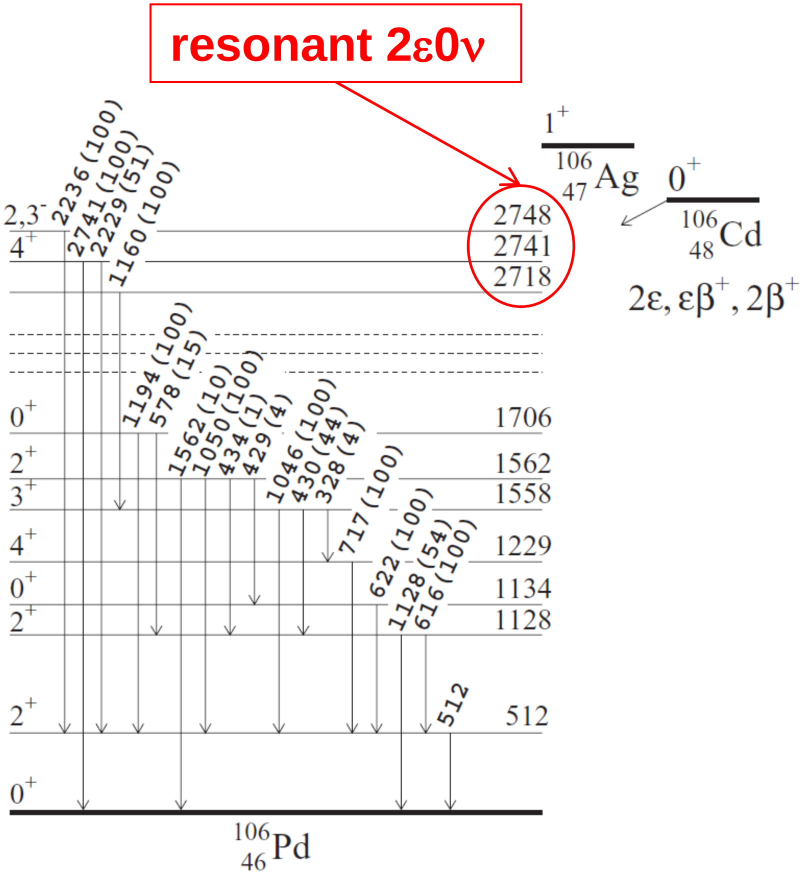
- 4.8×10^{21} yr [2],

$\varepsilon\beta^+2\nu$ - $(1.4\text{-}1.6)\times10^{21}$ yr [1],

- 2.9×10^{22} yr [2]

[1] S. Stoica et al., EPJA 17 (2003) 529

[2] J. Suhonen, PRC 86 (2012) 024301



resonant $2\varepsilon0\nu$

Decay scheme of ^{106}Cd

Current experiments to search for 2β processes in ^{106}Cd

(1) TGV-2: 32 planar HPGe + 16 foils of ^{106}Cd (δ=75%), LSM (France)
$T_{1/2}$ limits for different modes: ~ 10^{20} yr
[N.I. Rukhadze et al., NPA 852 (2011) 197, BRASP 75 (2011) 879]

(2) COBRA: 32/64 semiconductors CdZnTe 1 cm^3 each, LNGS (Italy)
$T_{1/2}$ limits for different modes: ~ 10^{18} yr
[K. Zuber, Prog. Part. Nucl. Phys. 64 (2010) 267]

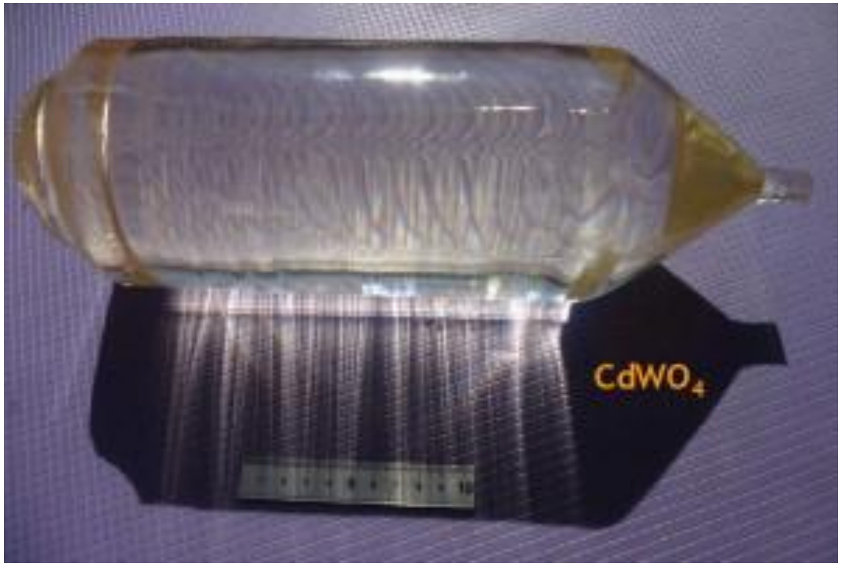
(3) First stage of our measurements with ^{106}CdWO$_4$ crystal scintillator (without HPGe), LNGS (Italy)
$T_{1/2}$ limits for different modes: ~ 10^{20}–10^{21} yr (mostly the best limits)
[P. Belli et al., PRC 85 (2012) 044610]

R&D for $^{106}CdWO_4$

Purification of enriched ^{nat}Cd & ^{106}Cd by vacuum distillation (~ 0.1 ppm; Kharkiv Phys. Techn. Institute, Kharkiv, Ukraine); Synthesis of $CdWO_4$ & $^{106}CdWO_4$ powders; Growth of $^{nat}CdWO_4$ of improved quality (Czochralski method). [R. Bernabey et al., Metallofiz. Nov. Tekhn. 30 (2008) 477]

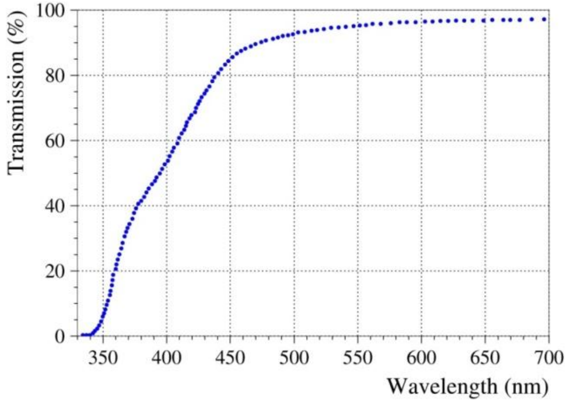
Growth of $^{106}CdWO_4$ crystals by Low-Thermal-Gradient Czochralski technique (Nikolaev Institute of Inorg. Chem., Novosibirsk, Russia): output ~90%, loss of powder <0.3%, better quality and radiopurity [P. Belli et al., NIMA 615 (2010) 301]

Example of $CdWO_4$ grown by the LTG Cz technique (20 kg) [V.V. Atuchin et al., J. Solid State Chem., in press]

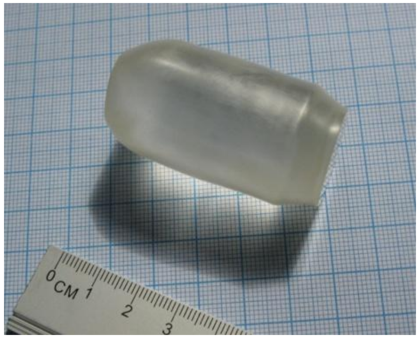


$^{106}CdWO_4$ crystal scintillators (^{106}Cd enrichment – 66%)

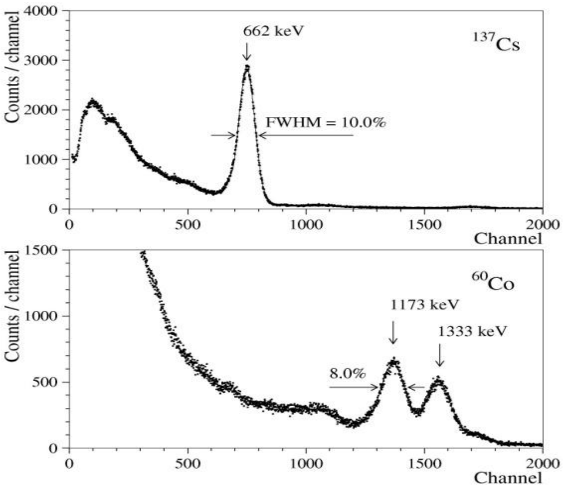
Attenuation length 60 cm
(the best reported for $CdWO_4$)



$^{106}CdWO_4$ boule 231 g (87.2% of initial charge)
Total irrecoverable losses of ^{106}Cd = 2.3%



FWHM=10% at 662 keV

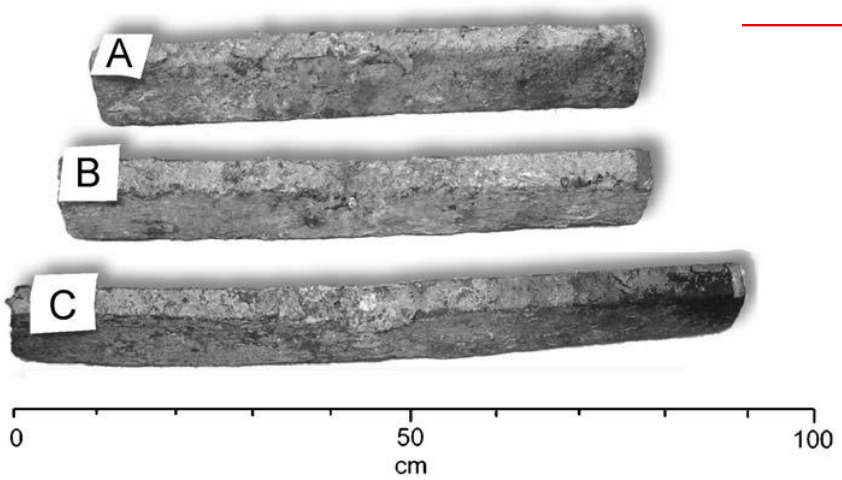


$^{106}CdWO_4$ scintillator 215 g

Excellent optical and scintillation properties thanks to special R&D to purify raw materials and Low-Thermal-Gradient Czochralski technique to grow the crystal [P. Belli et al., NIMA 615 (2010) 301]

1st stage: $^{106}CdWO_4$ scintillator in low background DAMA/R&D set-up
2nd stage: $^{106}CdWO_4$ in coinc./anticoincidence with 4 HPGe detectors

To suppress radioactivity from PMT, $PbWO_4$ light-guide is used.
It is grown from archeological lead: $A(^{210}Pb) < 0.3$ mBq/kg
[F.A. Danevich et al., NIMA 603 (2009) 328]



Samples of archeological lead (1st cent. BC, Black Sea, Ukraine)

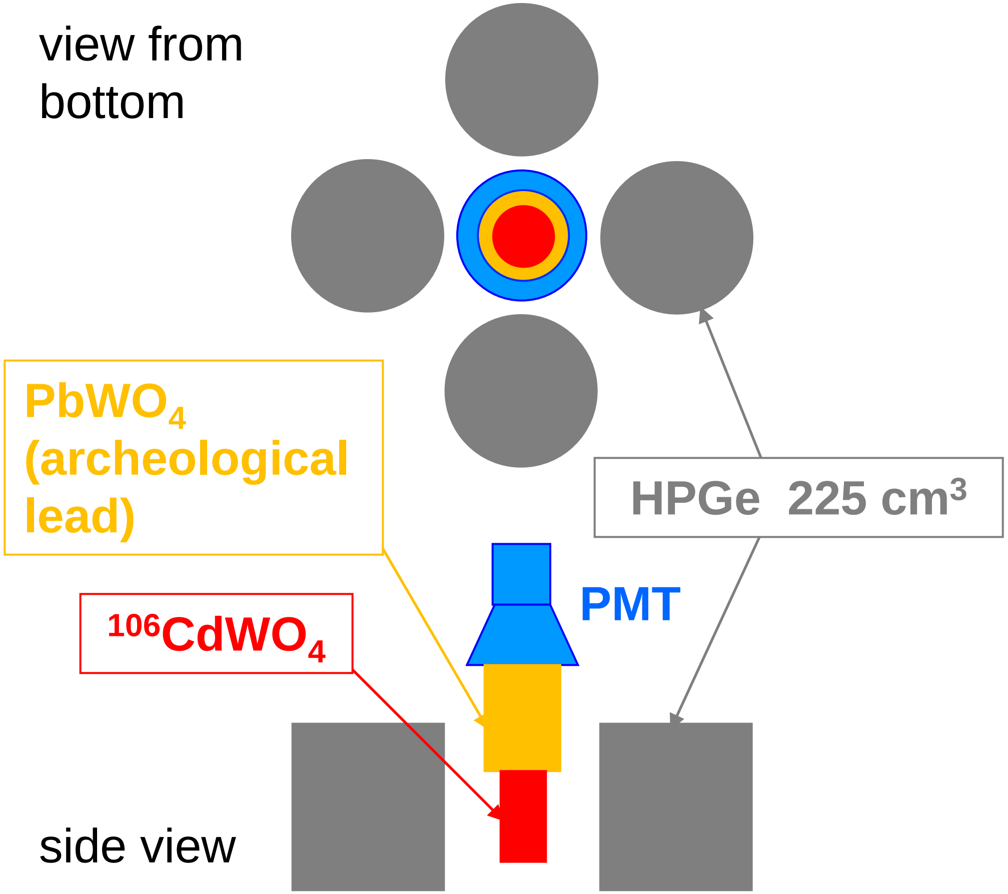
Pb was purified by vacuum distillation [R.S. Boiko et al., Inorganic Mater. 47 (2011) 645]

Initial $PbWO_4$

After mechanical treatment (daylight exposure?)

After annealing (24 h, 750° C) optical properties were restored

$^{106}CdWO_4$ in the GeMulti setup with 4 HPGe detectors (in one cryostat)



4 HPGe, ~ 225 cm^3 each, in one cryostat

$^{106}CdWO_4$ in coincidence/ anticoincidence with HPGe

Detection efficiency ~ 5 – 7%

External shield: radiopure Cu + Pb, sealed in PMMA air-tight box flushed by nitrogen

Laboratori Nazionali del Gran Sasso 3600 m w.e.

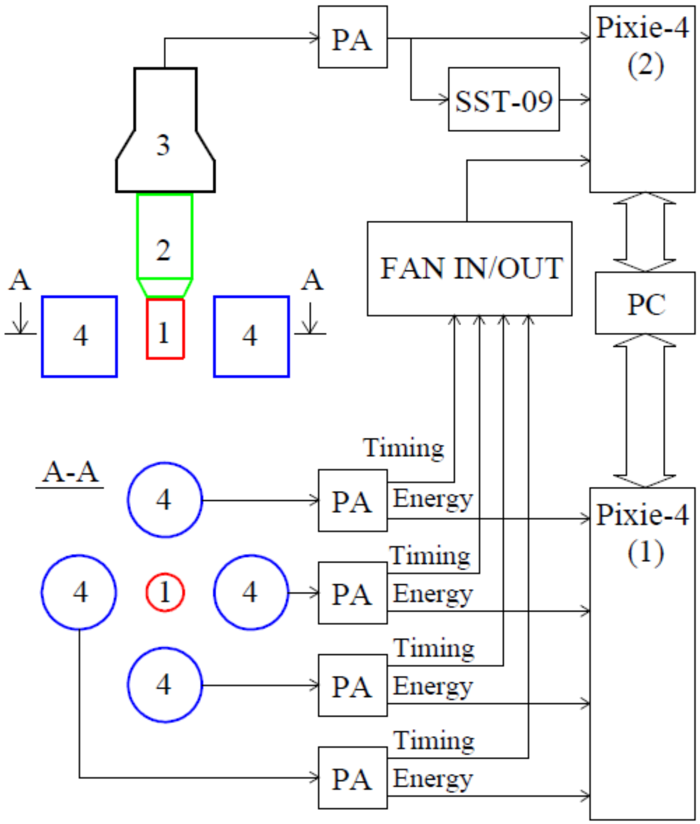
Background expected to be several events during year

Estimated sensitivity to two neutrino $\varepsilon\beta^+$ and $2\beta^+$ in ^{106}Cd:

$T_{1/2} \sim 10^{20} – 10^{21}$ yr

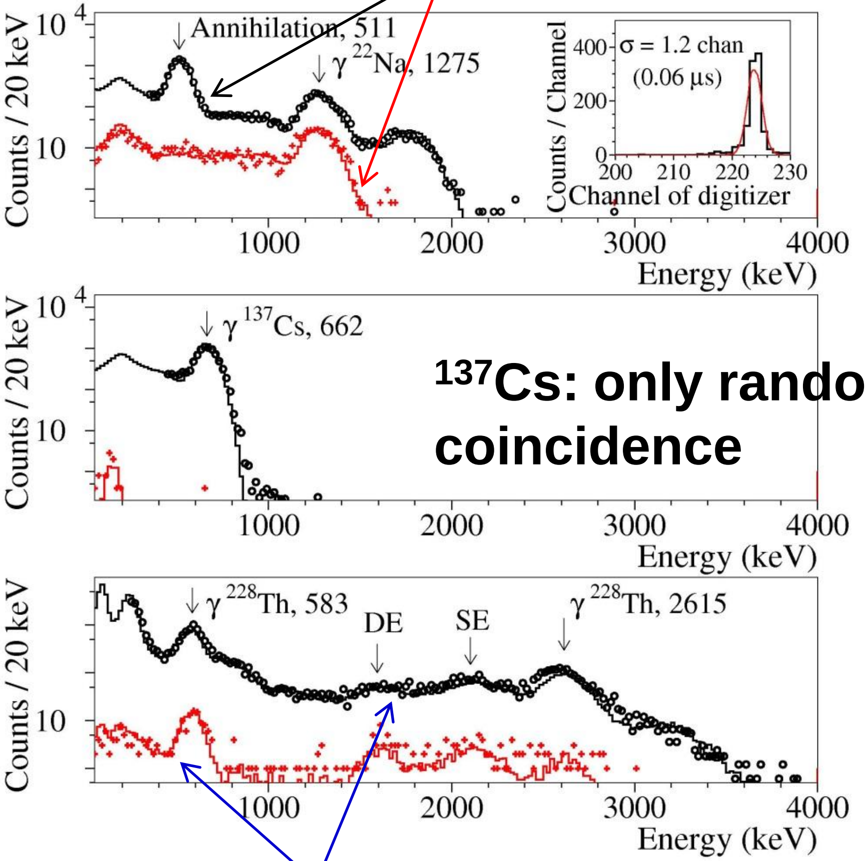
Theory: $2\nu 2K$ $10^{20} – 5\times10^{21}$ yr $2\nu\varepsilon\beta^+$ $8\times10^{20} – 4\times10^{22}$ yr

DAQ:
time and energy for each HPGe;
shape of signal (in time) for $^{106}CdWO_4$ (>580 keV);
different triggers (c/ac)



Calibration: ^{22}Na, ^{60}Co, ^{137}Cs, ^{228}Th
$^{106}CdWO_4$ – FWHM$_\gamma$ = $(20.4\times E_\gamma)^{1/2}$

^{22}Na:
no coincidence with HPGe and
coincidence with 511 keV in HPGe

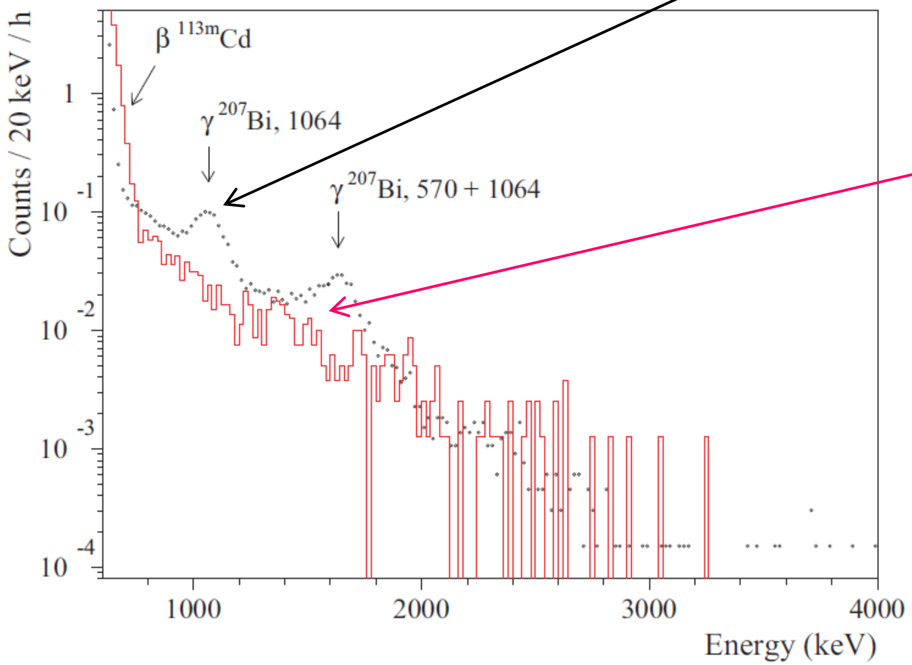


^{137}Cs: only random coincidence

Nice agreement with EGS4 simulations (solid lines)

Results

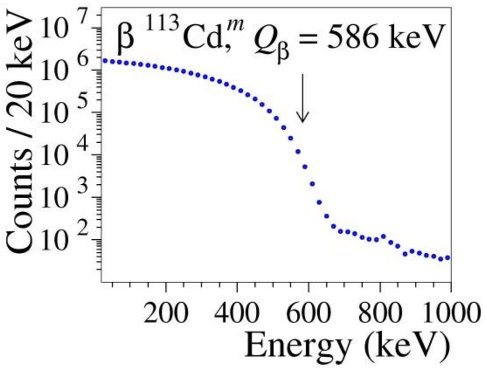
Previous measurements
PRC 85 (2012) 044610



Current measurements (^{207}Bi disappeared thanks to cleaning of $^{106}CdWO_4$ by ultra-pure nitric acid + K-free detergent)

Spectrum of $^{106}CdWO_4$ (β/γ events) measured during 6590 h (anticoincidence with HPGe) [F.A. Danevich et al., AIP CP 1549 (2013) 201]

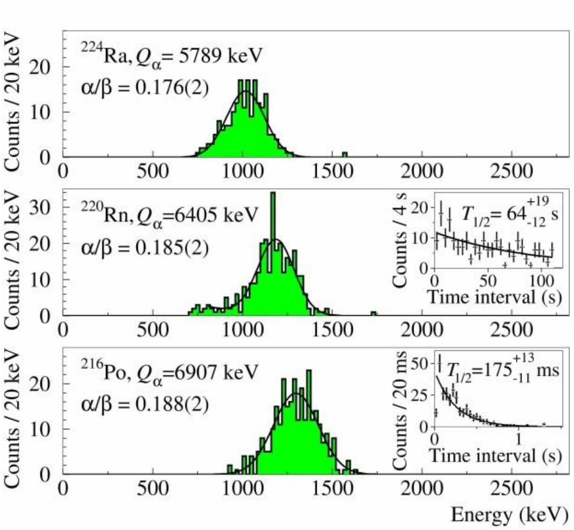
Internal contamination of $^{106}CdWO_4$



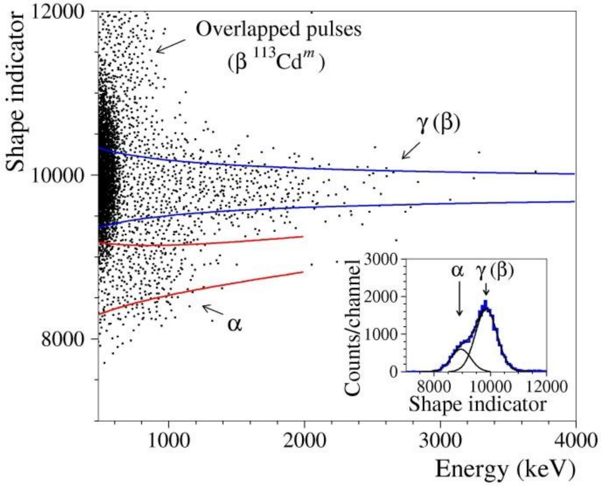
^{113m}Cd activity

116(4) Bq/kg

(it seems that before enrichment, Cd was used as a shielding somewhere at reactor)



Time-amplitude analysis:
^{228}Th 0.042(2) mBq/kg

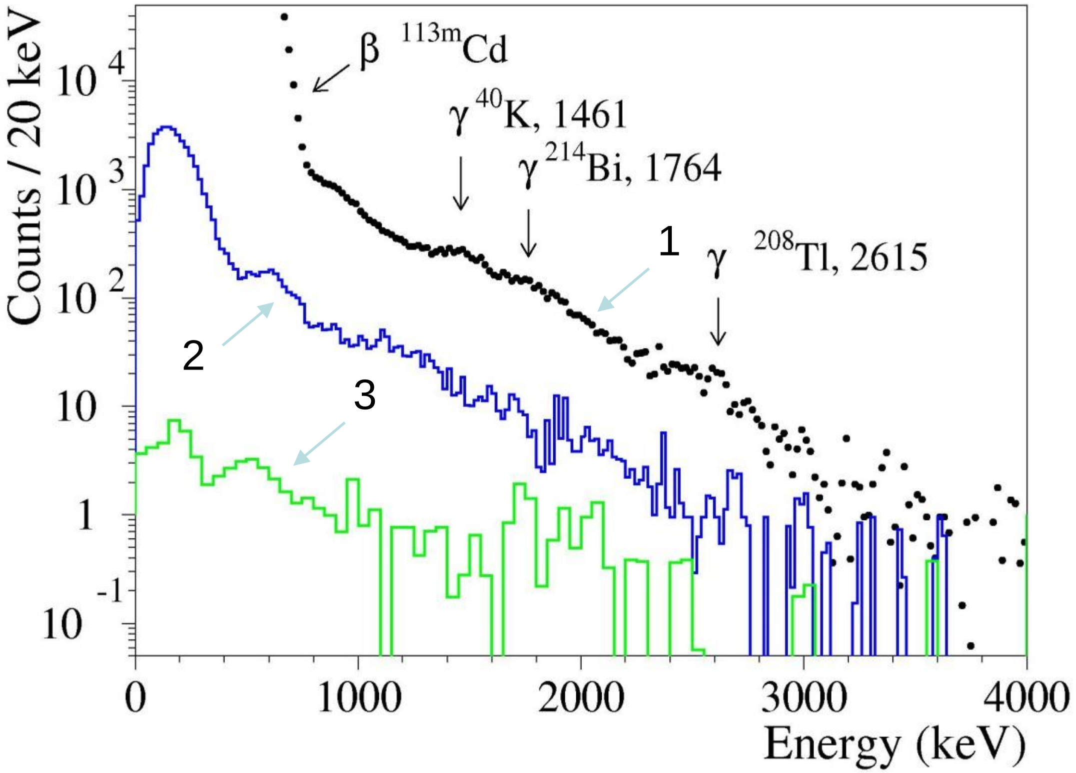


Pulse-shape discrimination:
total α activity 2.1(2) mBq/kg

Chain	Nuclide	Activity (mBq/kg)
^{232}Th	^{232}Th	≤ 0.07
	^{228}Th	0.042(4)
^{238}U	^{238}U	≤ 0.6
	^{226}Ra	0.012(3)
	^{40}K	≤ 1.4
	^{113m}Cd	116(4) × 10^3

[F.A. Danevich et al., AIP CP 1549 (2013) 201]

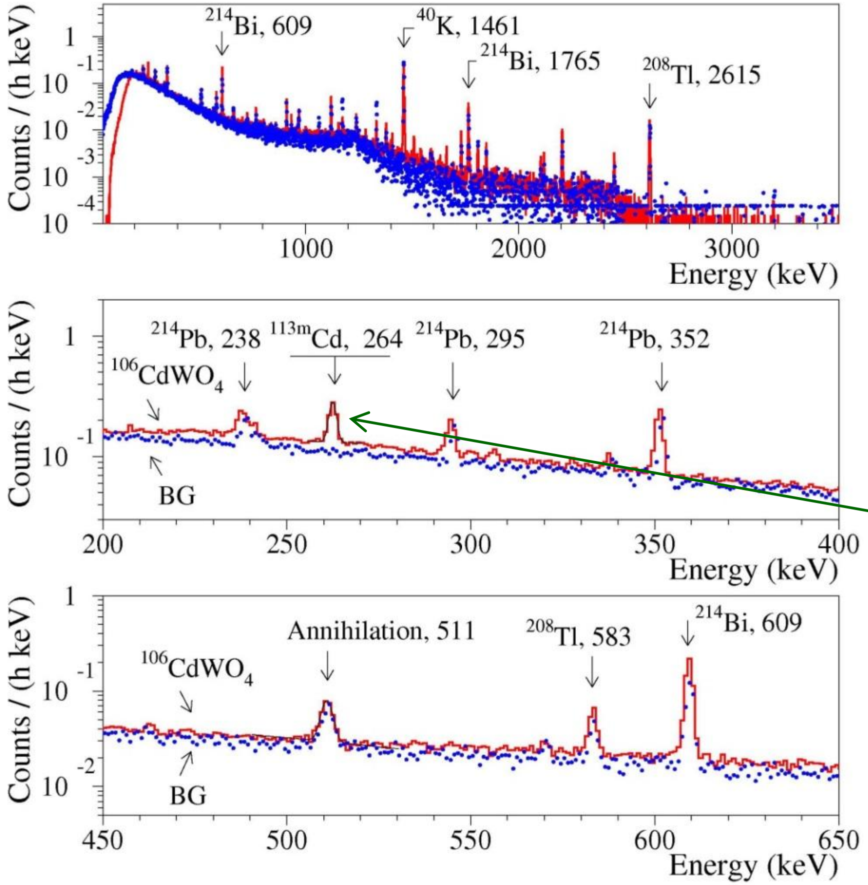
$^{106}CdWO_4$ energy spectra measured during 13085 h



1. **In anticoincidence with the HPGe detectors (AC);**
2. **In coincidence with HPGe when energy release in at least one HPGe detector is E(HPGe) > 50 keV (CC >50);**
3. **In coincidence with E(HPGe) = 511 keV (CC 511)**

All the spectra contain 95% of γ(β) events selected by PSD

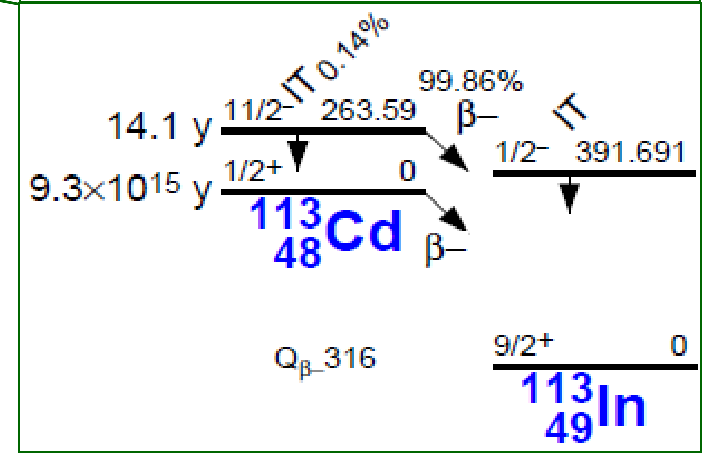
HPGe energy spectra (sum of 4 detectors) over 13085 h



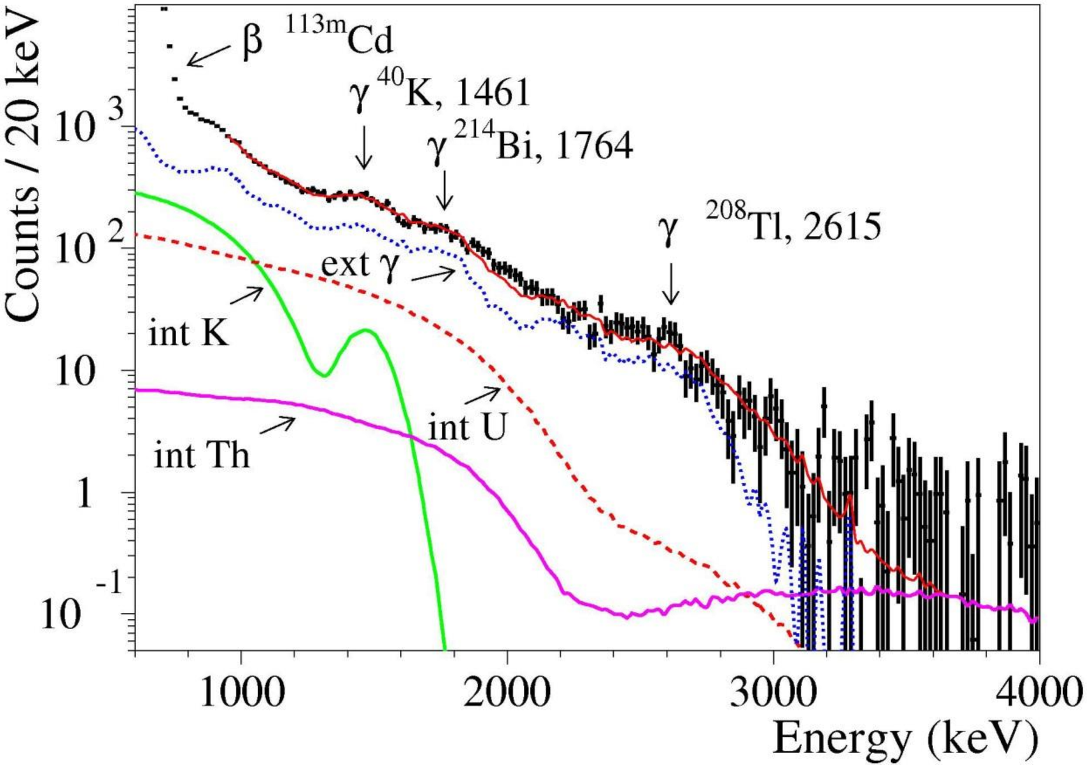
HPGe spectra without and with ^{106}CdWO$_4$ crystal

Some excess of ^{226}Ra daughters (PMT ?)

Peak 263.5 keV of ^{113m}Cd isomeric transition



$^{106}CdWO_4$ in anticoincidence with HPGe



Simulations (EGS4 + DECAY0 event generator):

$^{106}CdWO_4$ contaminations

PMT

$PbWO_4$

Cu shield

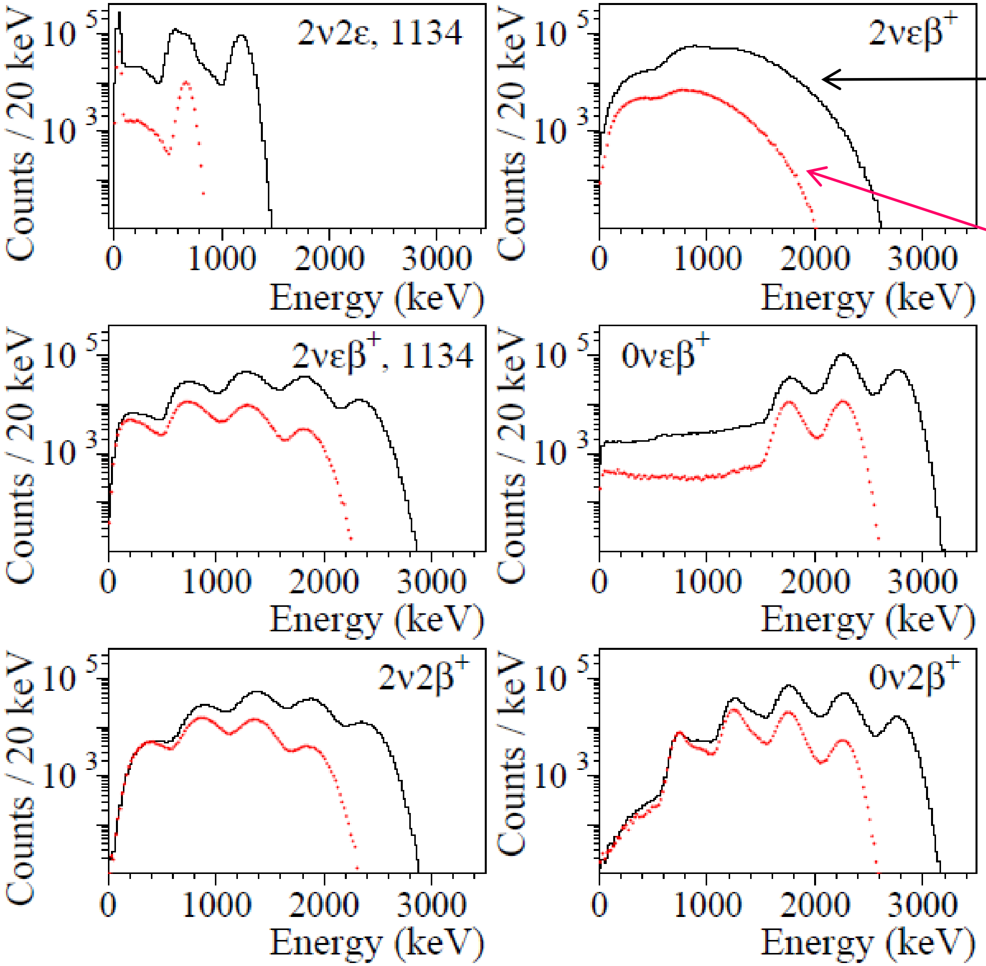
Al cryostat

…

Energy spectrum of γ(β) events in $^{106}CdWO_4$ accumulated over 13085 h (points) in anticoincidence with HPGe together with the background model (red continuous line).

Main components of the background are shown: internal K, Th and U; external γ from K, U and Th contamination of the set-up in

Simulation of 2β processes in ^{106}Cd: EGS4 + DECAY0 event generator

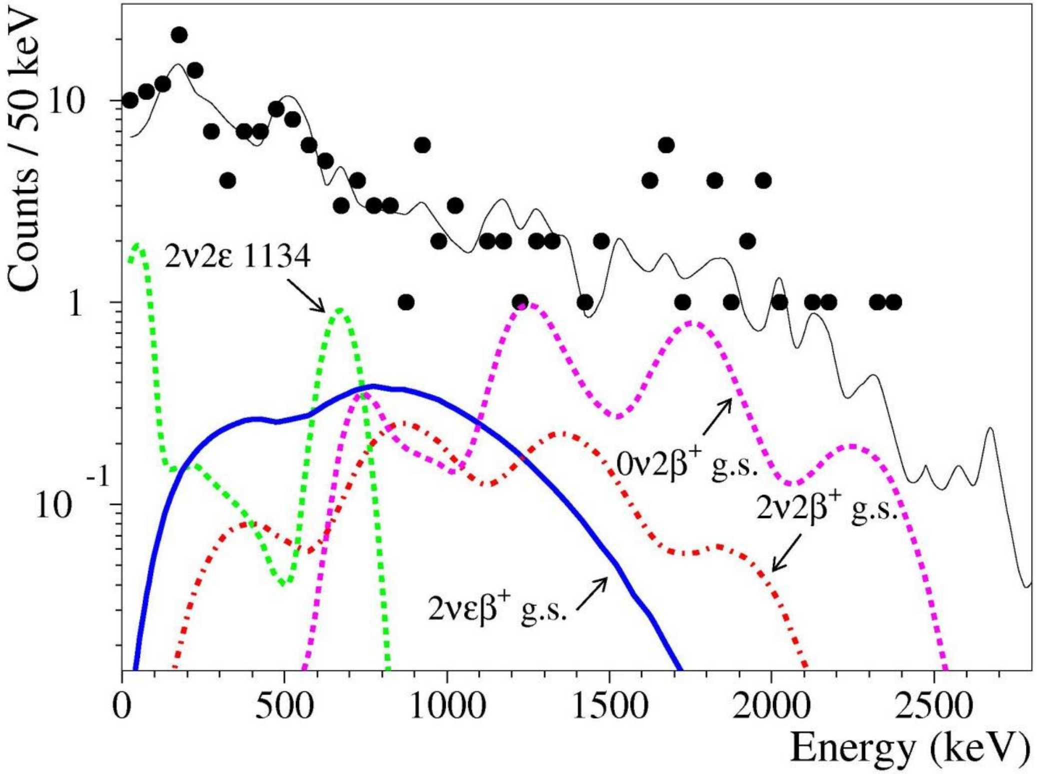


Anticoincidence
^{106}CdWO$_4$ + HPGe

Coincidence
^{106}CdWO$_4$ + HPGe 511 keV

DECAY0: O.A. Ponkratenko et al., Phys. At. Nucl. 63 (2000) 1282

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



Energy spectrum of the $^{106}CdWO_4$ detector accumulated over 13085 h in coincidence with 511 keV annihilation γ quanta at least in one of the HPGe detectors (circles).

The Monte Carlo simulated distributions for different modes of 2ν and 0ν 2ε, $\varepsilon\beta^+$ $2\beta^+$ decays are shown.

Limits (preliminary) on 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes in ^{106}Cd

Decay, level of ^{106}Pd (keV)	$T_{1/2}$ (yr) at 90% C.L.		
	Present work		Previous limit
$2\nu2\varepsilon$, 0_1^+ 1134	$\geq 9.0\times10^{20}$	(AC)	$\geq 1.7\times10^{20}$ [1]
$0\nu2\varepsilon$, g.s.	$\geq 2.7\times10^{20}$	(AC)	$\geq 1.0\times10^{21}$ [1]
$2\nu\varepsilon\beta^+$, g.s.	$\geq 1.9\times10^{21}$	(CC 511)	$\geq 4.1\times10^{20}$ [2]
$2\nu\varepsilon\beta^+$, 0_1^+ 1134	$\geq 1.4\times10^{21}$	(CC 511)	$\geq 3.7\times10^{20}$ [1]
$0\nu\varepsilon\beta^+$, g.s.	$\geq 1.6\times10^{21}$	(CC >50)	$\geq 2.2\times10^{21}$ [1]
$2\nu2\beta^+$, g.s.	$\geq 5.5\times10^{21}$	(CC 511)	$\geq 4.3\times10^{20}$ [1]
$0\nu2\beta^+$, g.s.	$\geq 2.2\times10^{21}$	(CC 511)	$\geq 1.2\times10^{21}$ [1]
$0\nu2K$, 2718	$\geq 8.3\times10^{20}$	(CC 511)	$\geq 4.3\times10^{20}$ [1]
$0\nu KL_1$, 4^+ 2741	$\geq 5.0\times10^{20}$	(HPGe)	$\geq 9.5\times10^{20}$ [1]
$0\nu KL_3$, $2,3^-$ 2748	$\geq 8.7\times10^{20}$	(HPGe)	$\geq 4.3\times10^{20}$ [1]

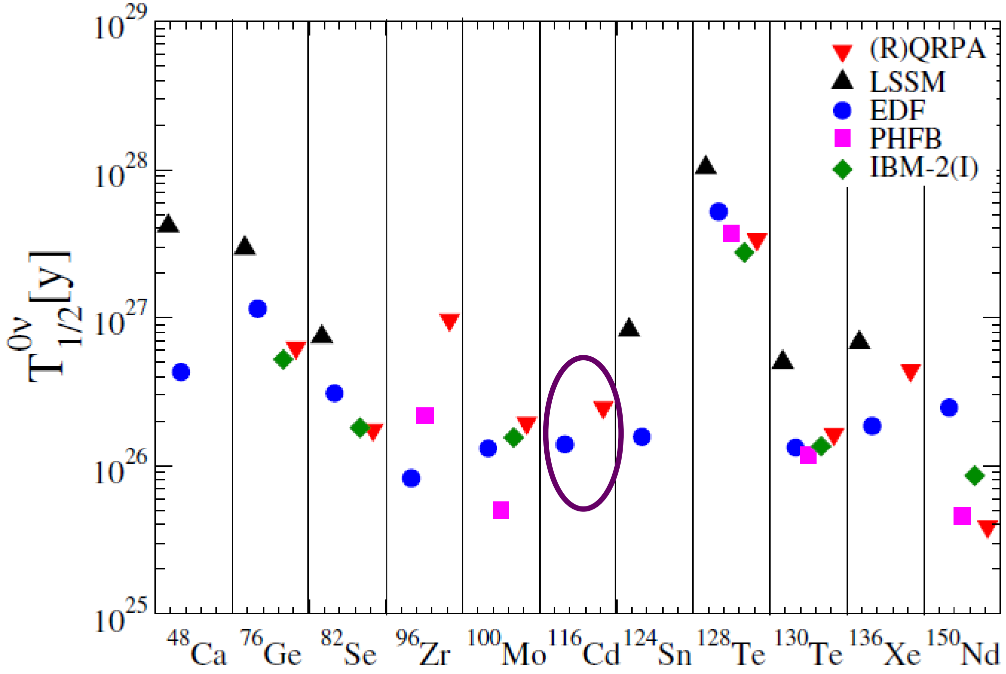
[1] P. Belli et al., PRC 85 (2012) 044610
[2] P. Belli et al., APP 10 (1999) 115

Also limits for 2β processes to other excited levels of ^{106}Pd (512, 1128, 1134, 1562, 1706, 2001, 2278 keV) were set on the level of $T_{1/2}$~10^{19}-10^{21} yr

2β physics with enriched ^{116}CdWO$_4$ crystal scintillators

^{116}Cd – one of the best candidates to search for 2β0ν decay:

- $Q_{2\beta}$ = 2813.5(13) keV
- δ = 7.5%
- promising theoretical calculation
- isotopic enrichment in large amount by cheap centrifugation method

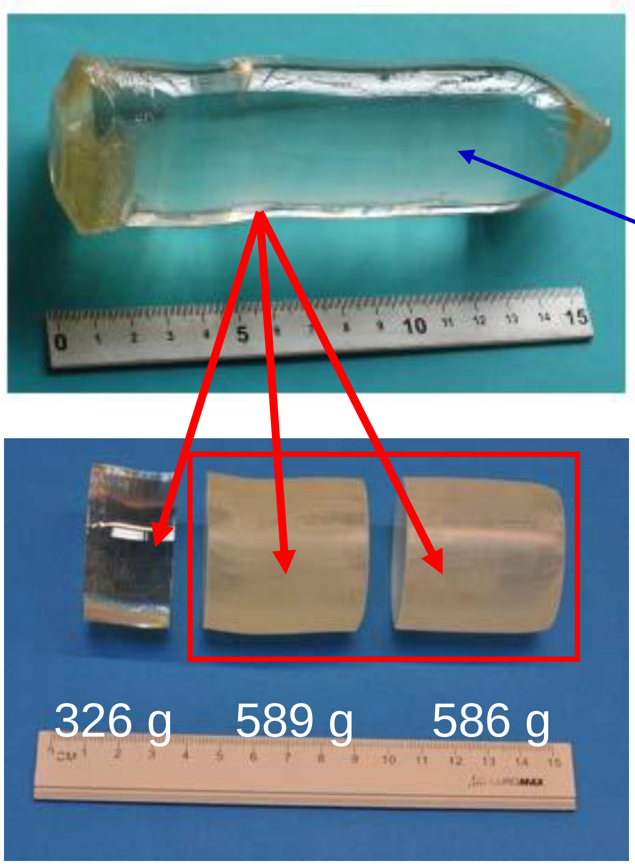


J.D. Vergados, H. Ejiri, F. Simkovic, RPP 75 (2012) 106301 – m_ν = 50 meV

The most sensitive 2β0ν experiments (90% C.L.):

- Solotvina, F.A. Danevich et al., PRC 68 (2003) 035501 – $T_{1/2}$ > 1.7e23 yr
- NEMO-3, R.B. Pahlka et al., Phys. Proc. 37 (2012) 1241 – $T_{1/2}$ > 1.3e23 yr

$^{116}CdWO_4$ crystal scintillator

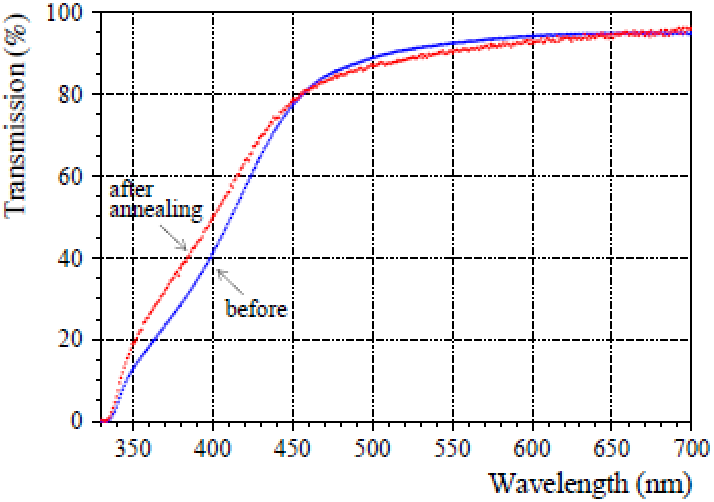


Deep purification of ^{116}Cd and W
LTG Cz technique to grow the crystal
Good optical and scintillation properties

Initial boule, 1868 g (87% of initial charge)

Enrichment in ^{116}Cd – 82%

Irrecoverable ^{116}Cd losses <3%

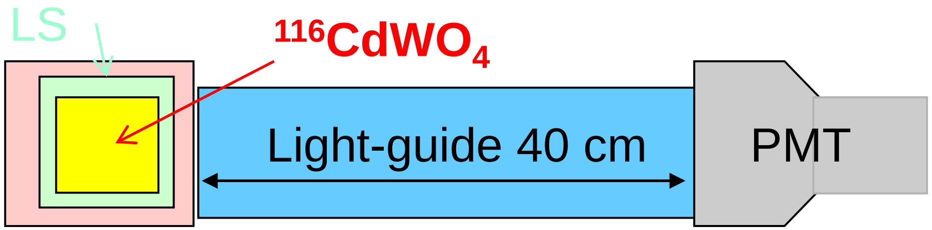


A.S. Barabash et al., JINST 6 (2011) P08011

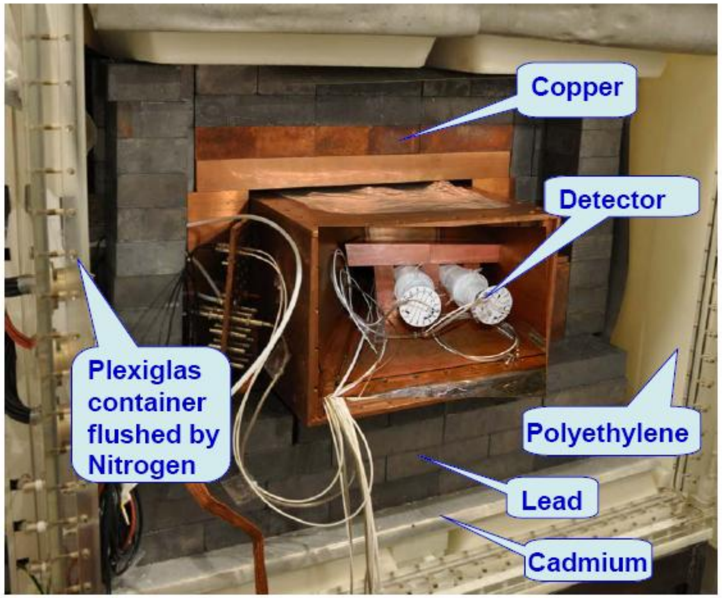
The optical transmission curve of $^{116}CdWO_4$ before and after annealing

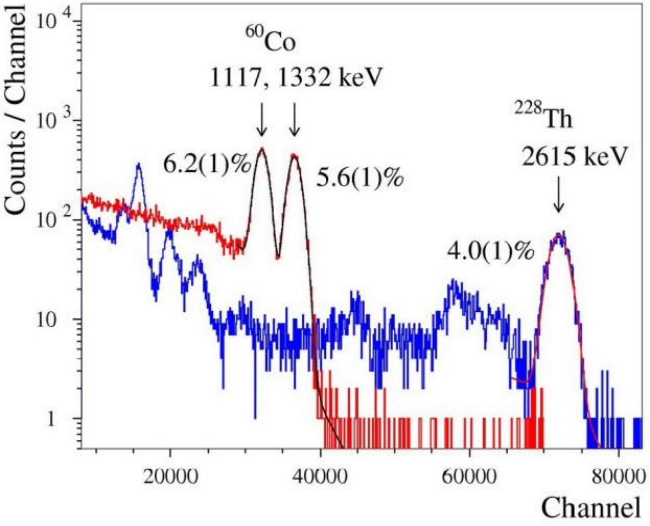
Attenuation length is 60 cm

Experimental set-up with $^{116}CdWO_4$ scintillator



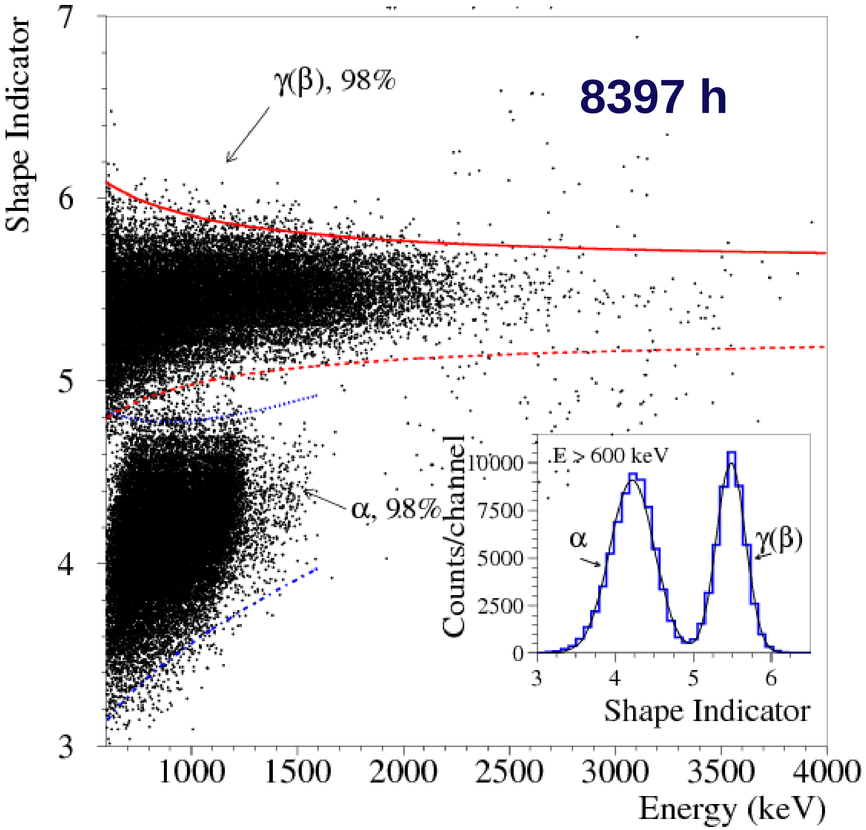
Two $^{116}CdWO_4$ crystals, m_{tot} = 1.162 kg
DAMA/R&D low-background set-up
External shielding – Cu, Pb, polyethylene, Cd, air-tight with N_2 flashing
Laboratori Nazionali del Gran Saso, 3600 m w.e.
Start of experiment – 2011
Last upgrade – March 2014. Bkg at 2.7−2.9 MeV ~0.1 c/(yr×kg×keV)



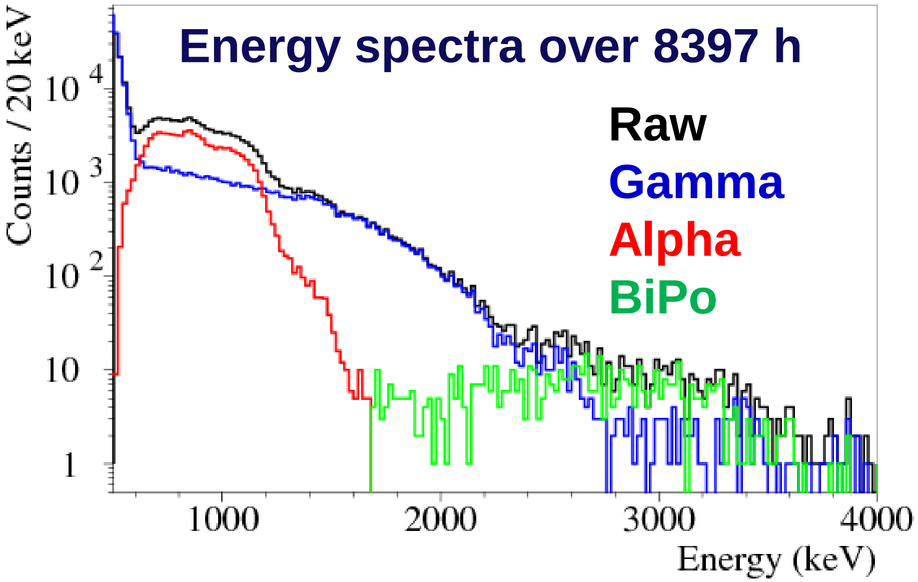


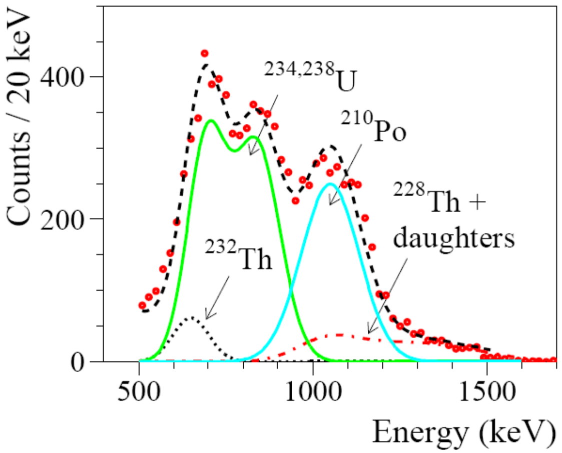
FWHM = 4% at 2615 keV

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



Shape indicator (SI) versus energy for the background exposure (8397 h × 1.162 kg)

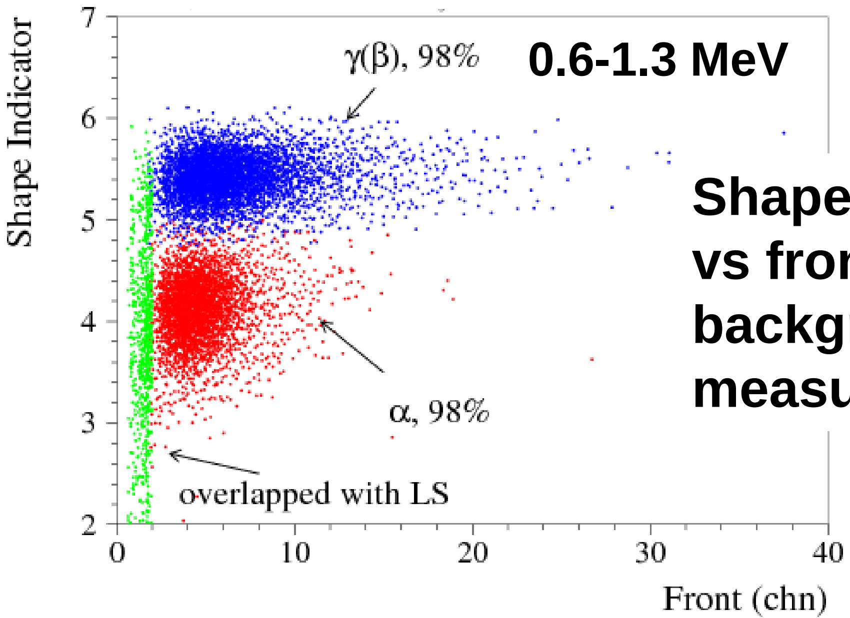




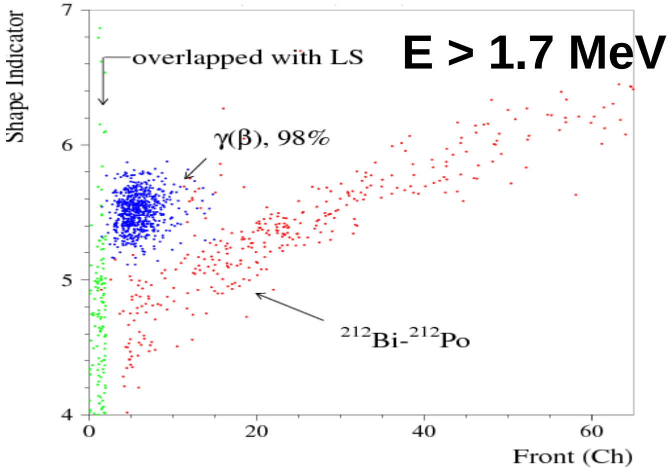
α spectrum (1724 h)

O.G. Polischuk, talk at MEDEX’15

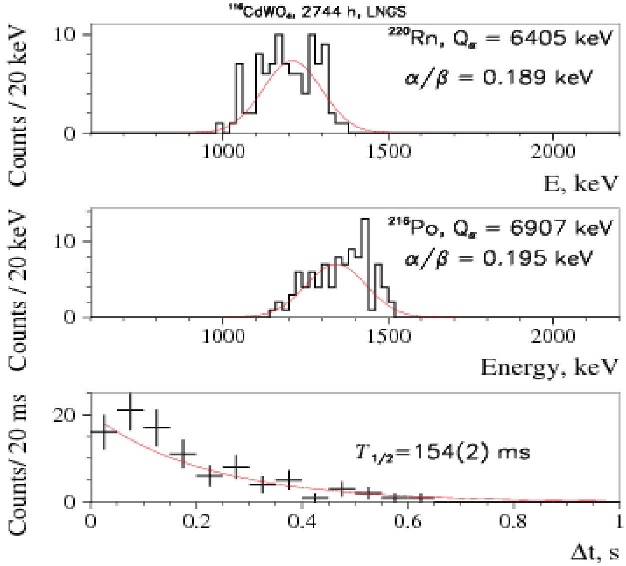
Front-edge analysis (FEA) to select ^{212}Bi-^{212}Po events



Shape indicator vs front edge for background measurements



Time-amplitude analysis



^{116}CdWO$_4$ contaminations

Chain	Nuclide	Activity, mBq/kg
^{232}Th	^{232}Th	≤ 0.07
	^{228}Th	0.036(2)
^{238}U	^{238}U-^{234}Th	0.4(2)
	^{226}Ra	≤ 0.009
	^{210}Pb	0.5(2)
	^{40}K	≤ 0.2
	^{110m}Ag	≤ 0.02

O.G. Polischuk, talk at MEDEX’15

Two neutrino double beta decay of ^{116}Cd

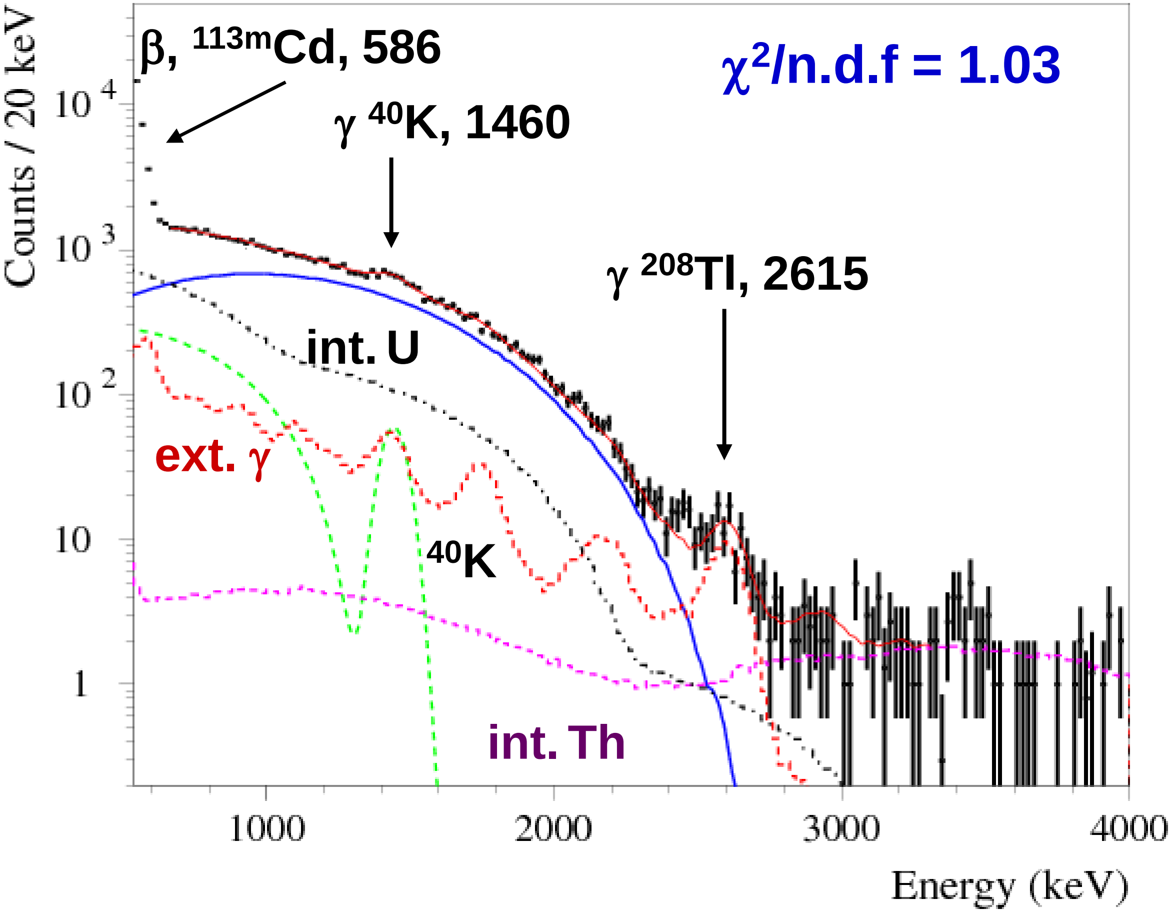
Simulations (EGS4 + DECAY0 generator):

^{116}CdWO$_4$ contaminations

PMT

Cu shield

…

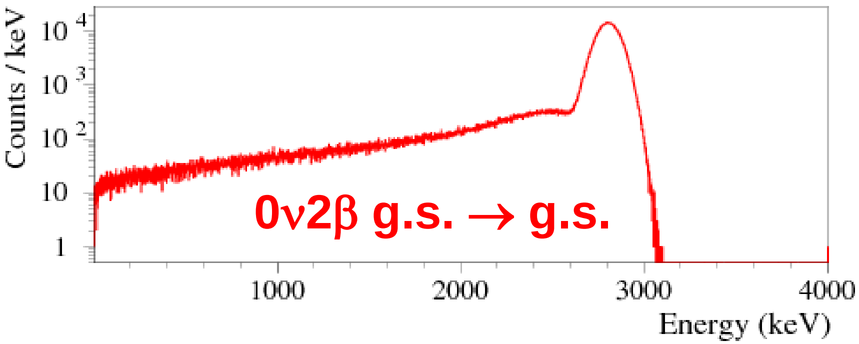


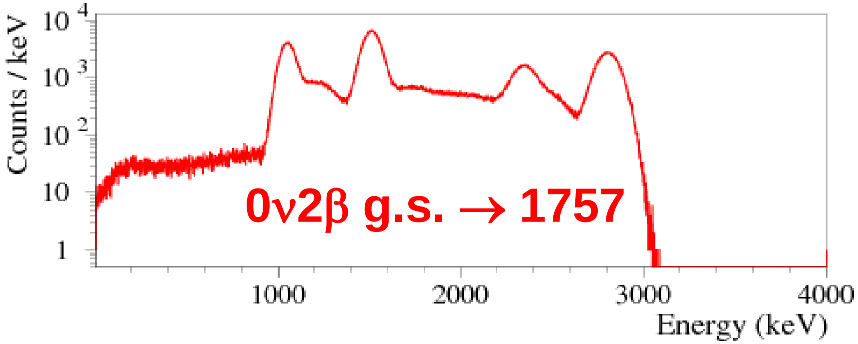
$T_{1/2}$ = [2.51 ± 0.02(stat.) ± 0.14(syst.)] × 10^{19} yr

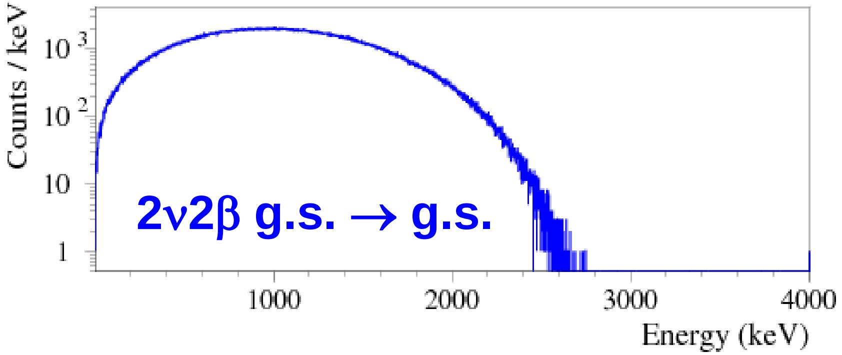
S/B ratio = 2.6 in 1.1–2.8 MeV interval

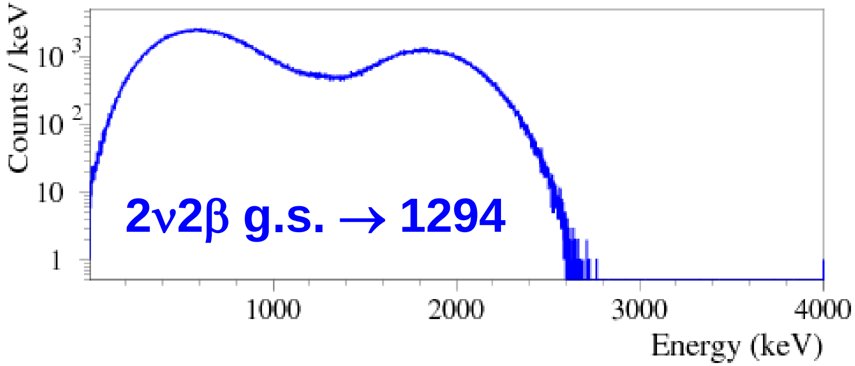
O.G. Polischuk, talk at MEDEX’15

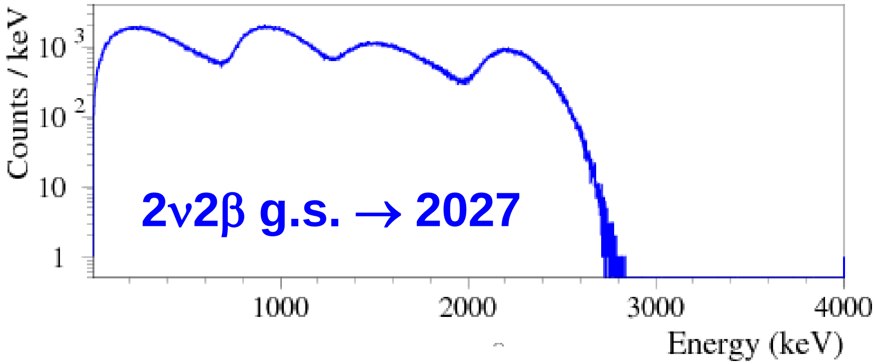
$^{116}CdWO_4$ response to 2β processes in ^{116}Cd (EGS4 + DECAY0)



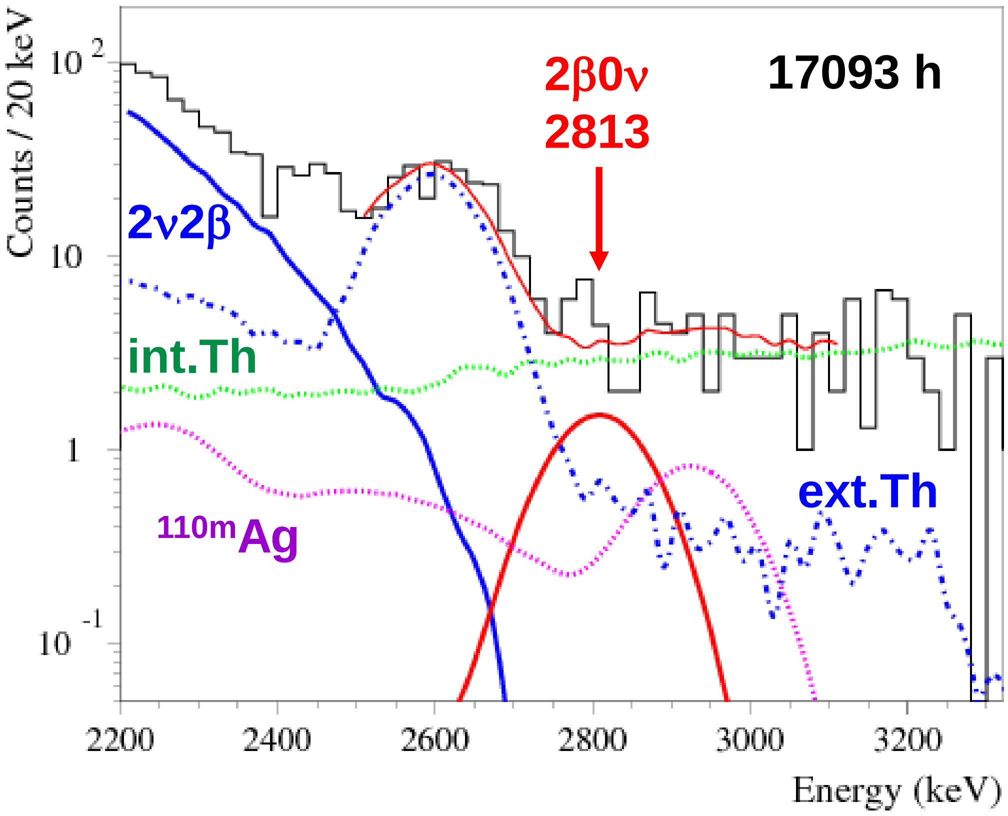








Limit on 2β0ν decay of ^{116}Cd to g.s. of ^{116}Sn



Fit in 2.5–3.1 MeV χ^2/n.d.f.=1.13
S = 2.1 ± 6.8 counts
lim S = 13.3 counts 90% C.L. FC
$T_{1/2} > 1.6\times10^{23}$ yr

(Simple square root estimation:
$T_{1/2} \geq 1.5\times10^{23}$ yr 90% C.L.)

On the level of Solotvina ($T_{1/2} > 1.7\times10^{23}$ yr) and NEMO-3 ($T_{1/2} > 1.6\times10^{23}$ yr) results

Effective Majorana neutrino mass:
$\langle m_\nu \rangle$ ~ 1.7 eV J. Barea et al., PRL 109 (2012) 042501
$\langle m_\nu \rangle$ ~ 1.4 – 1.8 eV J.D. Vergados et al., RPP 75 (2012) 106301

Results for ^{116}Cd 2β decay (preliminary, data taking is in progress)

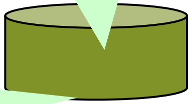
Decay mode	Transition	$T_{1/2}$, yr [present results]	$T_{1/2}$, yr [1]
0ν	g.s.- g.s.	$\geq 1.6\times10^{23}$	$\geq 1.7\times10^{23}$
0ν	g.s.- 2^+ (1294 keV)	$\geq 5.8\times10^{22}$	$\geq 2.9\times10^{22}$
0ν	g.s.- 0^+ (1757 keV)	$\geq 7.8\times10^{22}$	$\geq 1.4\times10^{22}$
0ν	g.s.- 0^+ (2027 keV)	$\geq 4.5\times10^{22}$	$\geq 0.6\times10^{22}$
0ν	g.s.- 2^+ (2112 keV)	$\geq 2.9\times10^{22}$	
0ν	g.s.- 2^+ (2225 keV)	$\geq 4.0\times10^{22}$	
0νM1	g.s.- g.s.	$\geq 0.2\times10^{22}$	$\geq 0.8\times10^{22}$
0νM2	g.s.- g.s.	$\geq 0.9\times10^{21}$	$\geq 0.8\times10^{21}$
0νbM	g.s.- g.s.	$\geq 0.8\times10^{21}$	$\geq 1.7\times10^{21}$
2ν	g.s.- g.s.	$[2.51\pm0.14(\text{syst.})\pm0.02(\text{stat.})]\times10^{19}$	$2.9^{+0.4}_{-0.3}\times10^{19}$
2ν	g.s.- 2^+ (1294 keV)	$\geq 0.5\times10^{21}$	$\geq 2.3\times10^{21}$ [2]
2ν	g.s.- 0^+ (1757 keV)	$\geq 1.1\times10^{21}$	$\geq 2.0\times10^{21}$ [2]
2ν	g.s.- 0^+ (2027 keV)	$\geq 0.9\times10^{21}$	$\geq 2.0\times10^{21}$ [2]
2ν	g.s.- 2^+ (2112 keV)	$\geq 1.7\times10^{21}$	
2ν	g.s.- 2^+ (2225 keV)	$\geq 1.6\times10^{21}$	

[1] F.A. Danevich et al., PRC 68 (2003) 035501 [2] A. Piepke et al., NPA 577 (1994) 493

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

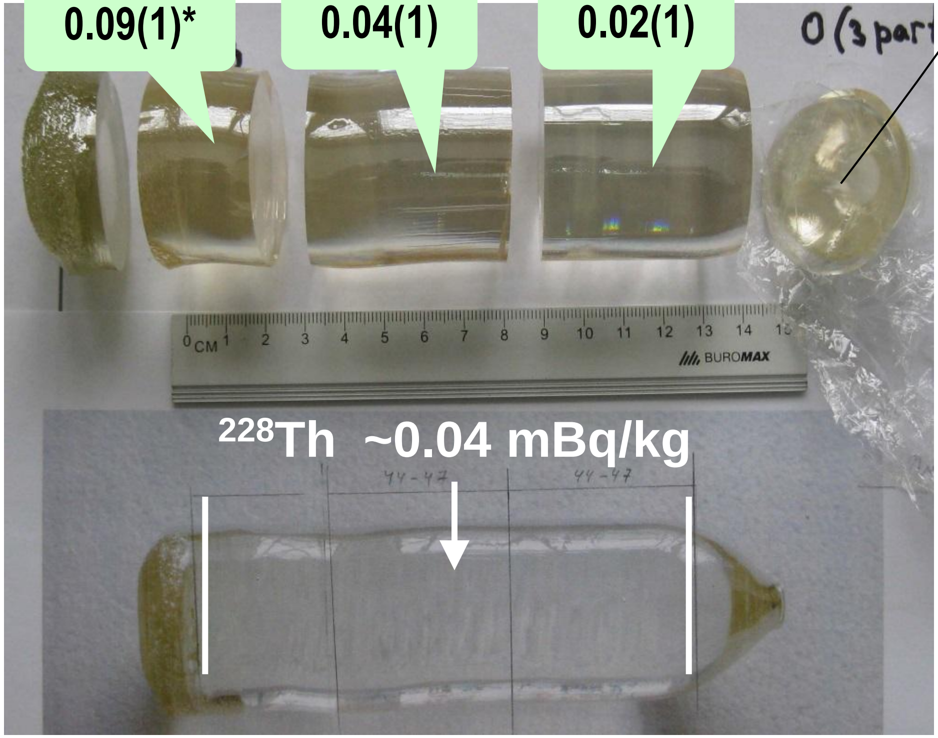
Activity of ^{228}Th

10(2)



rest of the melt after the crystal growth

Beginning of the crystal



0.09(1)*

0.04(1)

0.02(1)

^{228}Th ~0.04 mBq/kg

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 recrystallization

⇒ reduction of the background by a factor 4

⇒ advancing the $2\beta0\nu$ sensitivity to ~ 5×10^{23} yr

Conclusions

1. **Two unique radiopure high quality $CdWO_4$ crystal scintillators were developed: with enriched ^{106}Cd (66%, mass of 215 g) and enriched ^{116}Cd (82%, mass of 1162 g);**
2. **Measurements at LNGS: $^{106}CdWO_4$ – 13085 h (finished); $^{116}CdWO_4$ – 8397 h in the last modification (data taking, bkg at 2.7−2.9 MeV ~0.1 c/(yr×kg×keV);**
3. **$\varepsilon\beta^+0\nu/2\beta^+0\nu$ processes in ^{106}Cd are sensitive to $2\beta0\nu$ mechanism (mass or right-handed currents). New limits on 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes in ^{106}Cd to g.s. and excited levels were set on the level of $T_{1/2} > 10^{20} – 10^{21}$ yr. Half-life limit $T_{1/2}(\varepsilon\beta^+2\nu) > 1.9\times10^{21}$ yr reached the region of theoretical predictions;**
4. **For ^{116}Cd, $2\beta2\nu$ half-life is measured as $T_{1/2}(2\nu2\beta) = [2.51 \pm 0.02(\text{stat.}) \pm 0.14(\text{syst.})]\times10^{19}$ yr (in agreement with previous measurements). For $2\beta0\nu$, $T_{1/2}(0\nu2\beta) \geq 1.6\times10^{23}$ yr at 90% C.L. is on the level of the Solotvina (1.7×10^{23} yr) and NEMO-3 (1.3×10^{23} yr) results ($\langle m_\nu\rangle < 1.4 – 1.8$ eV). New improved limits for $2\beta0\nu$ decays to excited levels ($\lim T_{1/2} \sim (2.9–7.8)\times10^{22}$ yr);**
5. **Possibility to increase experimental sensitivity: in $^{106}CdWO_4$ experiment – change of HPGe to close high efficiency $CdWO_4$ scintillation counters; in $^{116}CdWO_4$ – re-crystallization of the crystal.**

Thanks for your attention!

Current experiments to search for 2β processes in ^{106}Cd

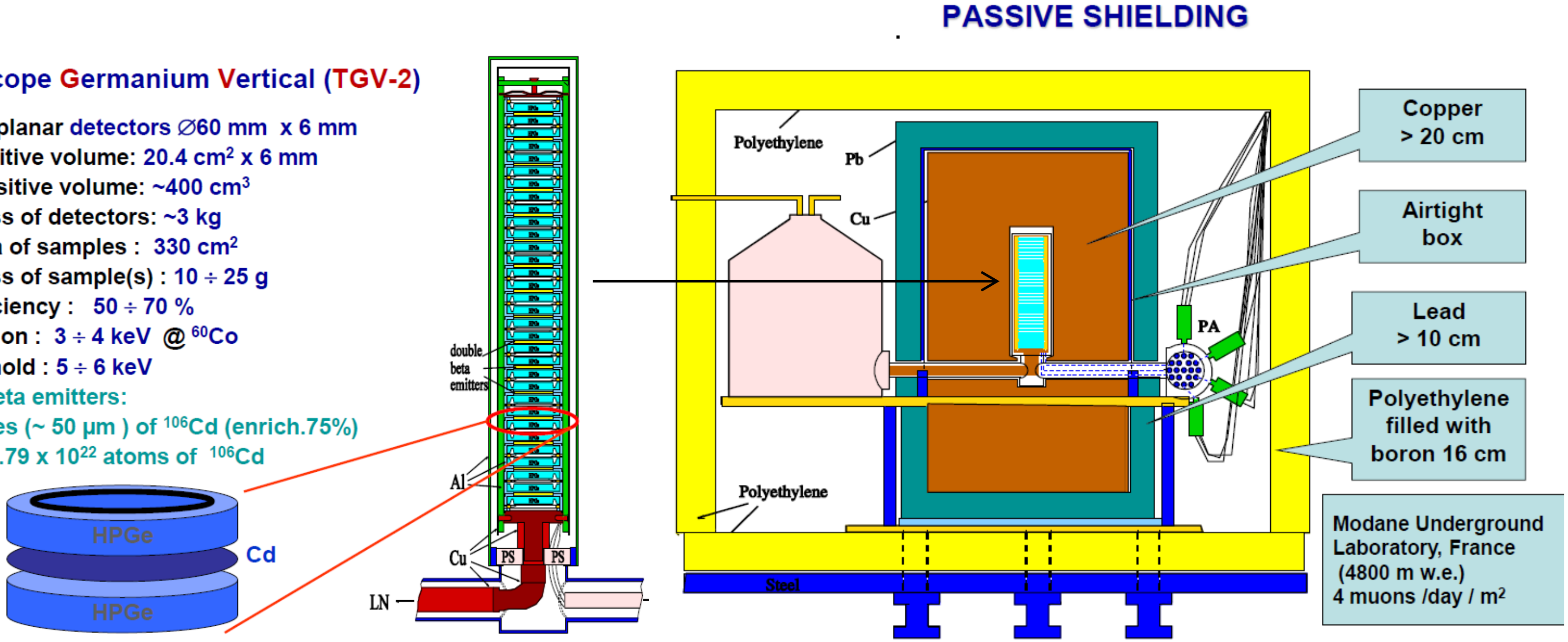
(1) TGV-2: 32 planar HPGe + 16 foils of ^{106}Cd (δ=75%), LSM (France)

$T_{1/2}$ limits for different modes: ~ 10^{20} yr

N.I. Rukhadze et al., NPA 852 (2011) 197, BRASP 75 (2011) 879

Telescope Germanium Vertical (TGV-2)

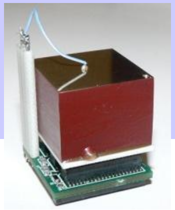
32 HPGe planar detectors ∅60 mm x 6 mm
with sensitive volume: 20.4 cm^2 x 6 mm
Total sensitive volume: ~400 cm^3
Total mass of detectors: ~3 kg
Total area of samples : 330 cm^2
Total mass of sample(s) : 10 ÷ 25 g
Total efficiency : 50 ÷ 70 %
E-resolution : 3 ÷ 4 keV @ ^{60}Co
LE-threshold : 5 ÷ 6 keV
Double beta emitters:
16 samples (~ 50 μm) of ^{106}Cd (enrich.75%)
13.6 g ~ 5.79 x 10^{22} atoms of ^{106}Cd



(2) COBRA: 32 semiconductors CdZnTe 1 cm^3 each, LNGS (Italy)

$T_{1/2}$ limits for different modes: ~ 10^{18} yr

K. Zuber, Prog. Part. Nucl. Phys. 64 (2010) 267



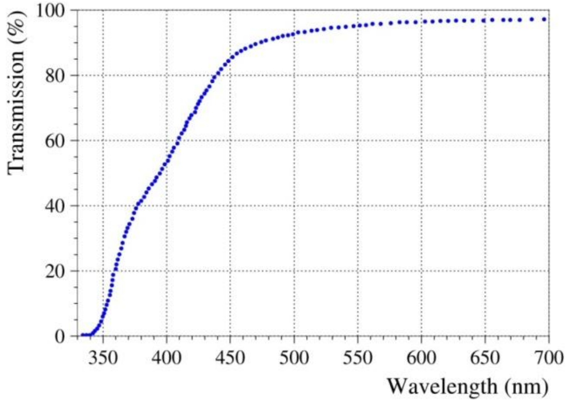
(3) Our previous measurements with $^{106}CdWO_4$ crystal scintillator, LNGS (Italy)
$T_{1/2}$ limits for different modes: ~ 10^{20}–10^{21} yr (mostly the best limits)
P. Belli et al., PRC 85 (2012) 044610

R&D: Purification of enriched ^{nat}Cd & ^{106}Cd by vacuum distillation (~ 0.1 ppm; Kharkiv Phys. Techn. Institute, Kharkiv, Ukraine);
Synthesis of $CdWO_4$ & $^{106}CdWO_4$ powders;
Growth of $^{nat}CdWO_4$ of improved quality (Czochralski method).
R. Bernabey et al., Metallofiz. Nov. Tekhn. 30 (2008) 477

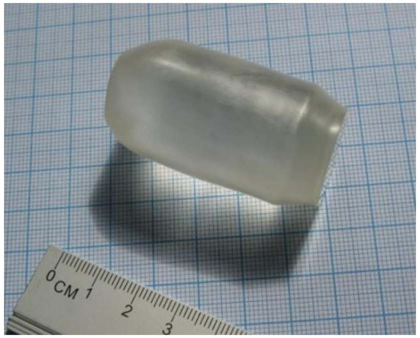
Growth of $^{106}CdWO_4$ crystals by Low-Thermal-Gradient Czochralski technique (Nikolaev Institute of Inorg. Chem., Novosibirsk, Russia): output ~90%, loss of powder <0.3%, better quality and radiopurity
P. Belli et al., NIMA 615 (2010) 301

$^{106}CdWO_4$ crystal scintillators (^{106}Cd enrichment – 66%)

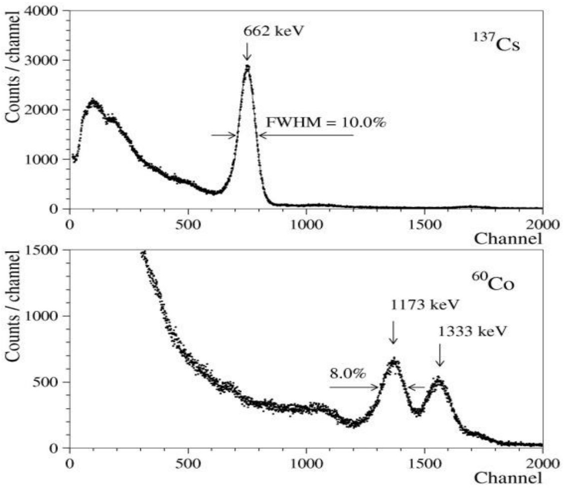
Attenuation length 60 cm
(the best reported for $CdWO_4$)



$^{106}CdWO_4$ boule 231 g (87.2%)
Total losses of ^{106}Cd = 2.3%



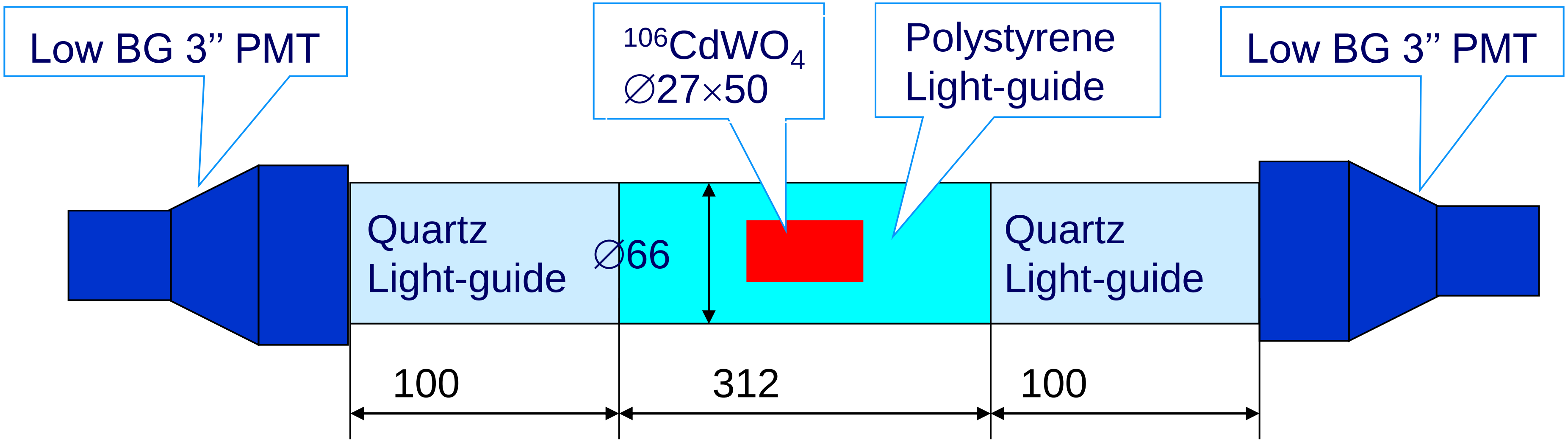
FWHM=10% at 662 keV

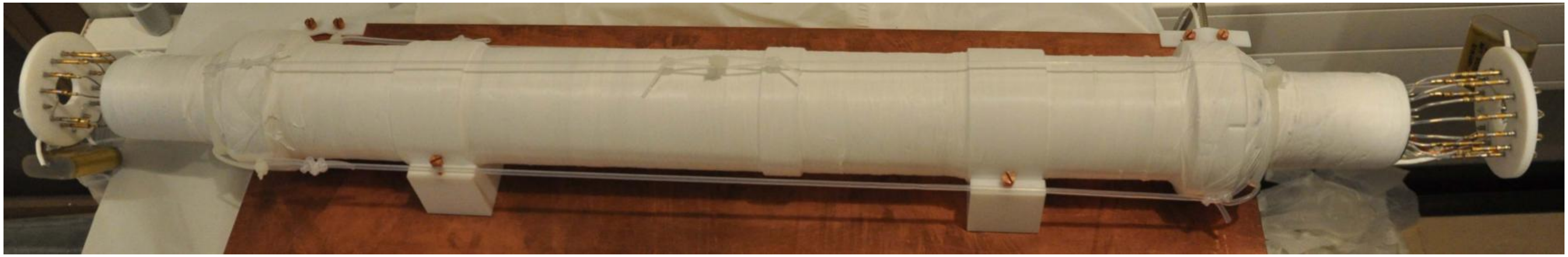


$^{106}CdWO_4$ scintillator 215 g

Excellent optical and scintillation properties thanks to special R&D to purify raw materials and Low-Thermal-Gradient Czochralski technique to grow the crystal [P. Belli et al., NIMA 615 (2010) 301]

Low background scintillation detector with $^{106}CdWO_4$ crystal scintillator





Low background scintillation set-up DAMA/R&D

LNGS (Italy), 3600 m w.e.