New limits on 2β processes in ^{106}Cd

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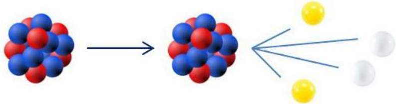
Double beta decay: (A,Z) $\rightarrow$ (A,Z$\pm$2)

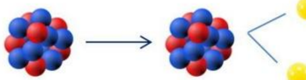
Allowed in SM:

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



Forbidden in SM, ΔL=2:

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

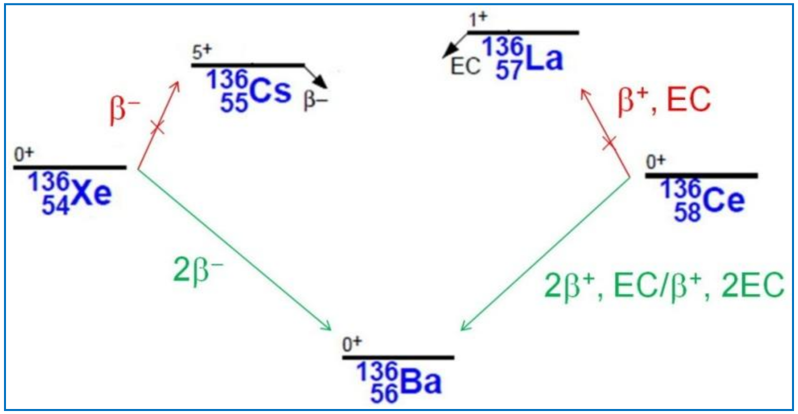


(A,Z) $\rightarrow$ (A,Z+2) + 2e$^-$ + M – 2β^-0ν decay with Majoron emission

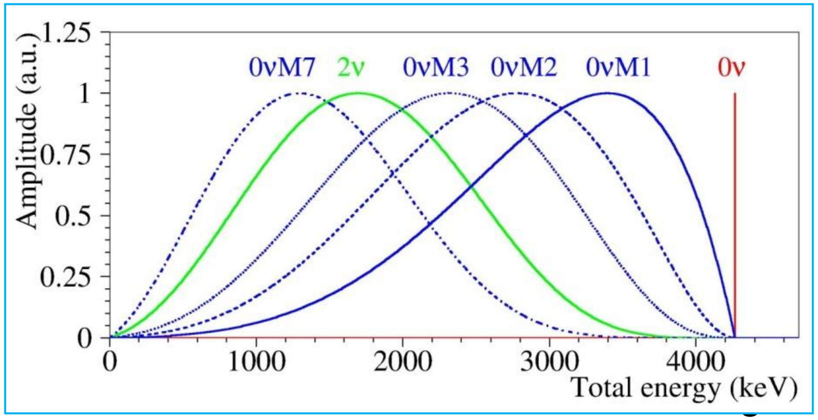
2β^+/ $\varepsilon\beta^+$/2ε processes, decays to excited states, different Majorons …

2β0ν requires: $\nu_e=\tilde{\nu}_e$ (Majorana particle)
m(ν_e)$\neq$0 (or right-handed admixtures, …)

Many extensions of the SM predict m(ν_e)$\neq$0 and, as a result, 2β0ν processes. Experimental observation of this exotic phenomenon would be an unambiguous signal of new physics which lies beyond the SM.



β^-, β^+ energetically forbidden 2β^-, 2β^+ 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:

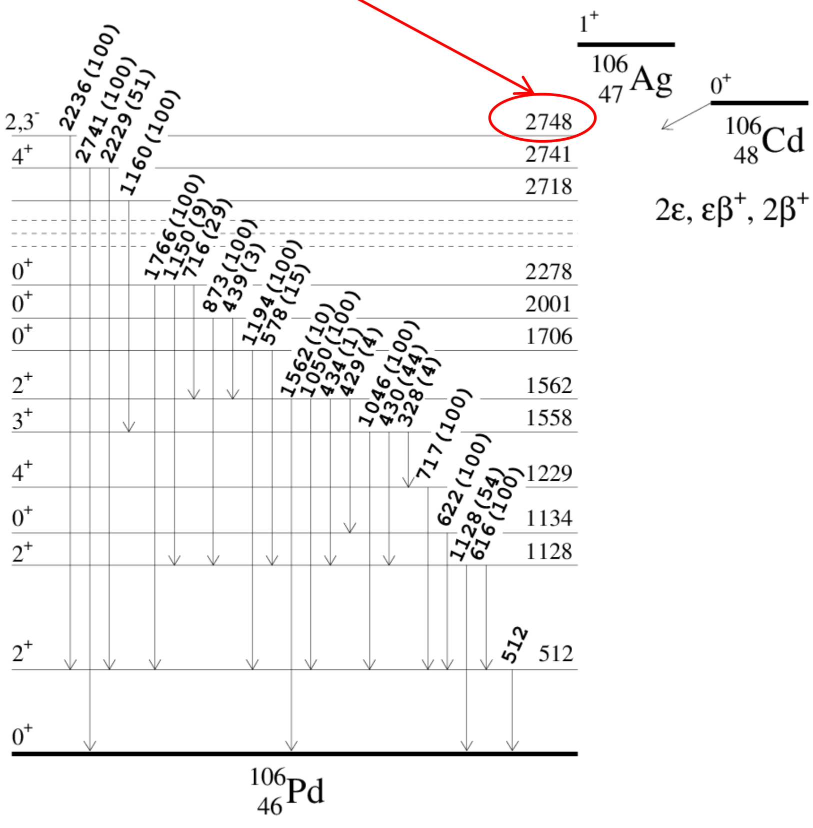
Information from $2\beta^+/\varepsilon\beta^+/2\varepsilon$ is supplementary to $2\beta^-$ (possible contributions of right-handed currents to 0ν, [M. Hirsch et al., ZPA 347 (1994) 151])

^{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±0.06 %
(3) Possibility of resonant $2\varepsilon0\nu$ captures to excited levels of daughter ^{106}Pd ($KL_3 0\nu$ to E_{exc} = 2748.2(4) keV, $Q - E_{exc}$ = –0.33±0.41 keV)
(4) Theoretical $T_{1/2}$ are quite optimistic for some modes (g.s.→g.s.):
$2\varepsilon2\nu$ - (2.0–2.6)×10^{20} yr [1],
– 4.8×10^{21} yr [2],
$\varepsilon\beta^+2\nu$ - (1.4–1.6)×10^{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 2ε0ν



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]

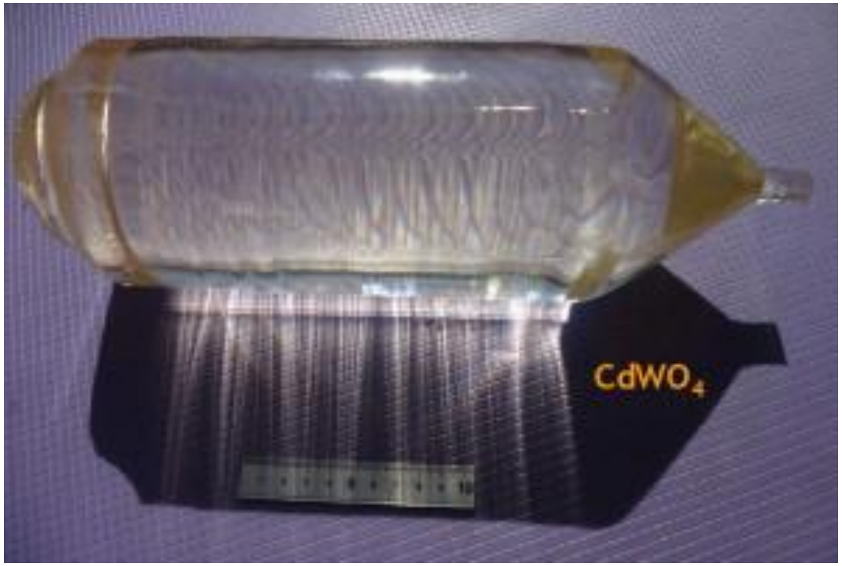
(3) First stage of our measurements with $^{106}CdWO_4$ crystal scintillator (without HPGe), LNGS (Italy)
$T_{1/2}$ limits for different modes: ~ 10^{20}–10^{21} yr (mostly the best limits)
[P. Belli et al., PRC 85 (2012) 044610]

R&D of $^{106}CdWO_4$

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]

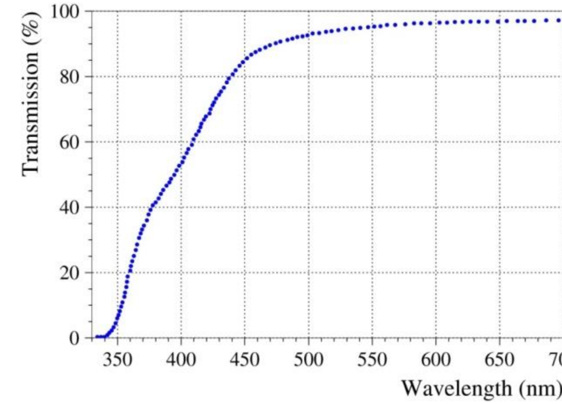
Growth of $^{106}CdWO_4$ crystal by Low-Thermal-Gradient Czochralski technique (Nikolaev Institute of Inorg. Chem., Novosibirsk, Russia): output ~90%, loss of powder <0.3%, better quality and radiopurity
[P. Belli et al., NIMA 615 (2010) 301]

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

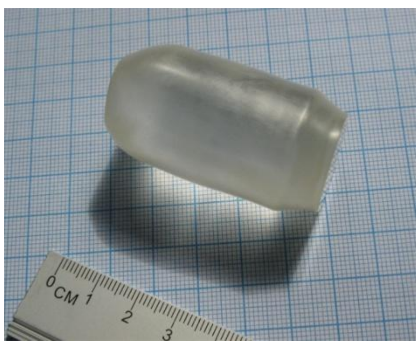


$^{106}CdWO_4$ crystal scintillator (^{106}Cd enrichment – 66%)

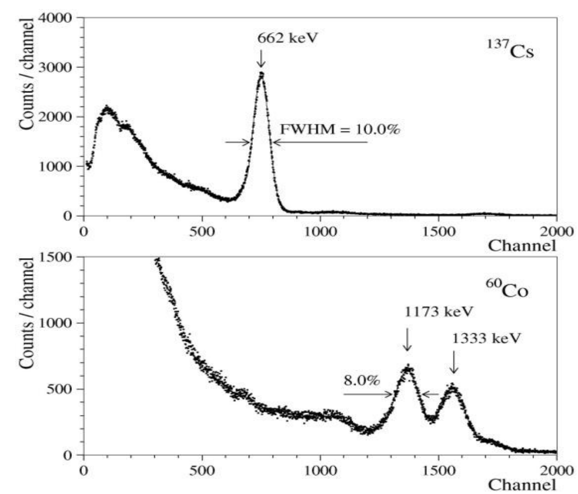
Attenuation length 60 cm (the best reported for $CdWO_4$)



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



FWHM=10% at 662 keV

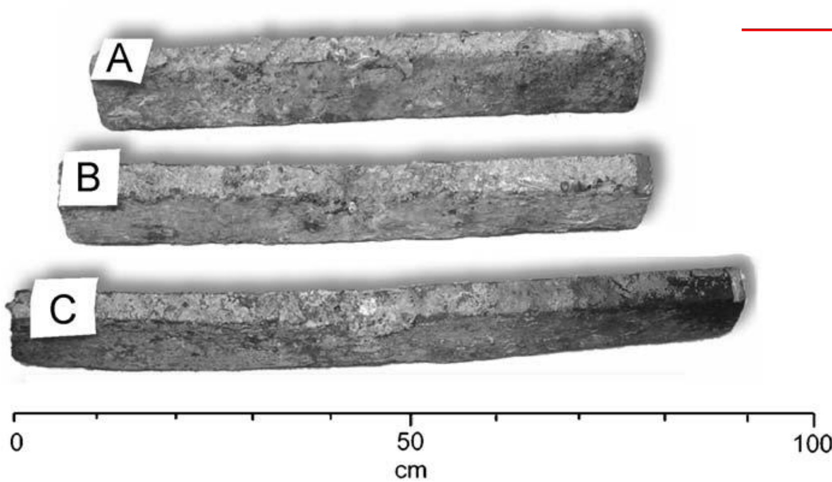


$^{106}CdWO_4$ scintillator 215 g

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

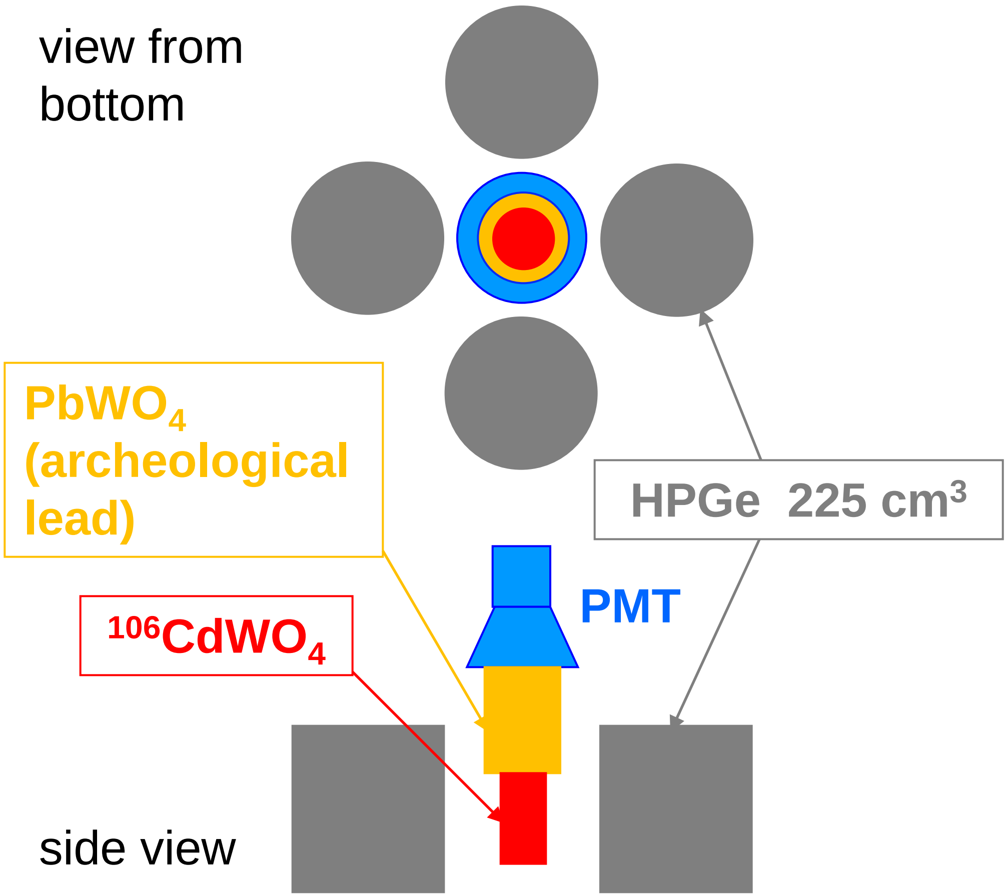
Pb was purified by vacuum distillation [R.S. Boiko et al., Inorganic Mater. 47 (2011) 645]

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%

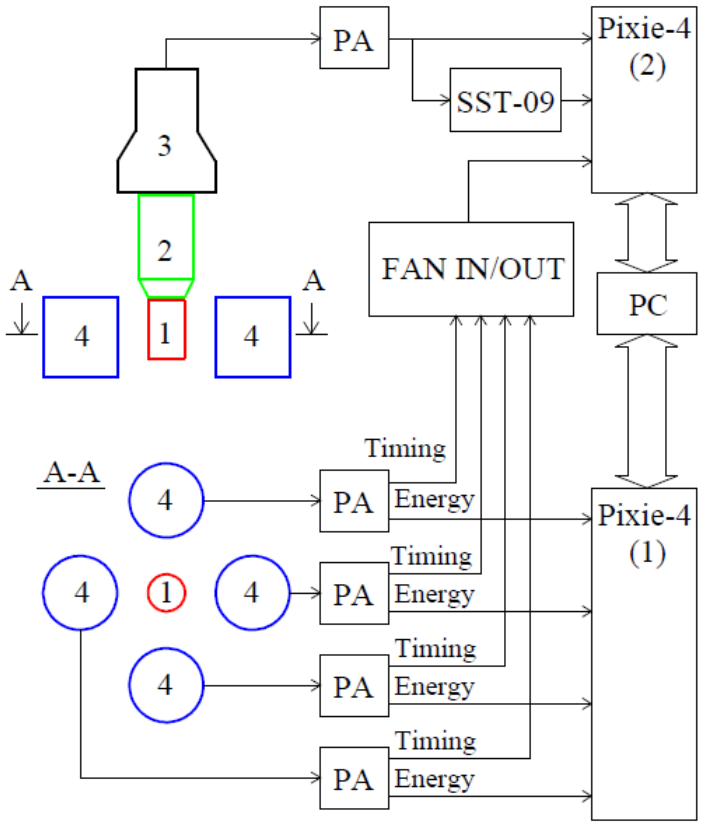
External shield: radiopure Cu + Pb, sealed in PMMA air-tight box flushed by nitrogen

Laboratori Nazionali del Gran Sasso 3600 m w.e.

Estimated sensitivity to two neutrino $\varepsilon\beta^+$ and $2\beta^+$ in ^{106}Cd:
$T_{1/2} \sim 10^{20} – 10^{21}$ yr

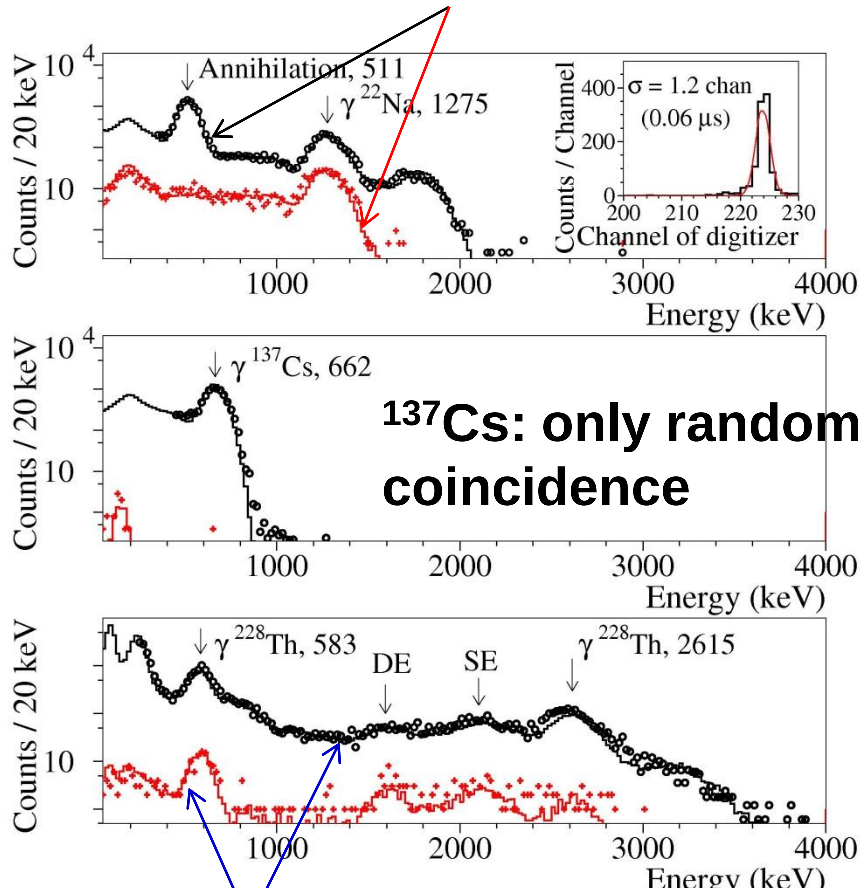
Theory: 2ν2K $10^{20} – 5\times10^{21}$ yr 2νεβ$^+$ $8\times10^{20} – 4\times10^{22}$ yr

DAQ:
- time and energy for each HPGe;
- shape of $^{106}CdWO_4$ signal (>580 keV);
- $^{106}CdWO_4$ and HPGe signals were recorded to find c/ac offline



Calibration: ^{22}Na, ^{60}Co, ^{137}Cs, ^{228}Th
$^{106}CdWO_4$ – $FWHM_\gamma = (21.7 \times E_\gamma)^{1/2}$

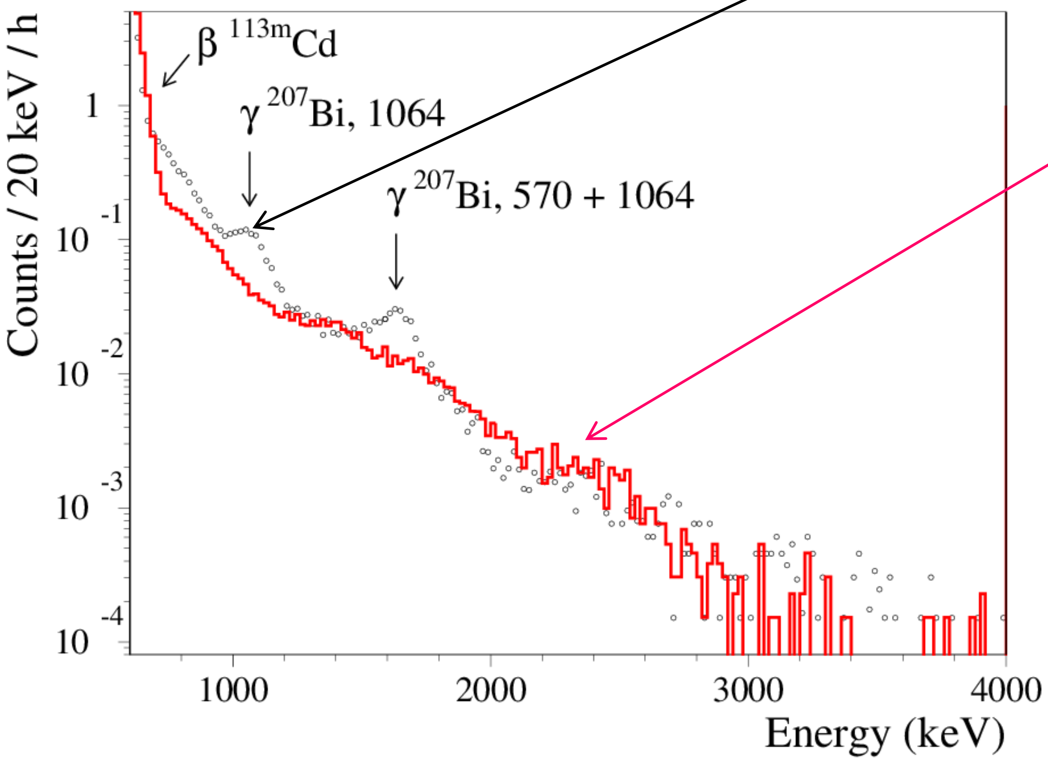
^{22}Na:
no coincidence with HPGe and
coincidence with 511 keV in HPGe



Good agreement with EGS4 simulations (solid lines)

Results

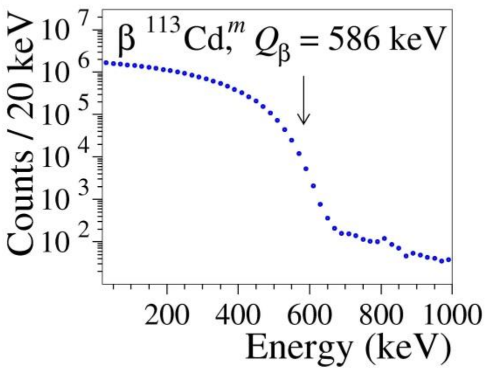
Previous measurements
PRC 85 (2012) 044610



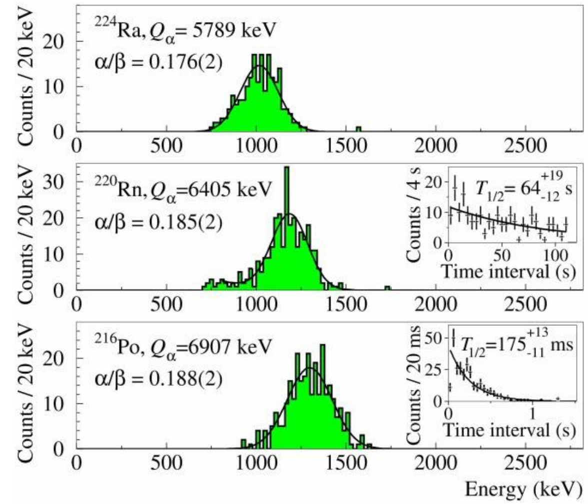
Current measurements (^{207}Bi disappeared thanks to cleaning of $^{106}CdWO_4$ by ultra-pure nitric acid + K-free detergent)

Spectrum of $^{106}CdWO_4$ (β/γ events) measured during 13085 h (anticoincidence with HPGe) [F.A. Danevich et al., AIP CP 1549 (2013) 201]

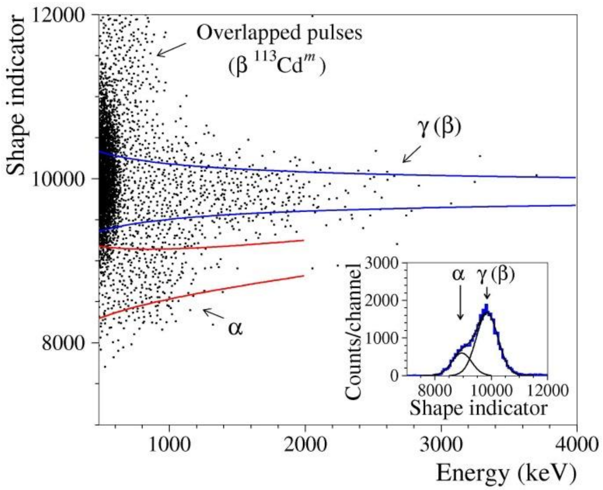
Internal contamination of $^{106}CdWO_4$



^{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

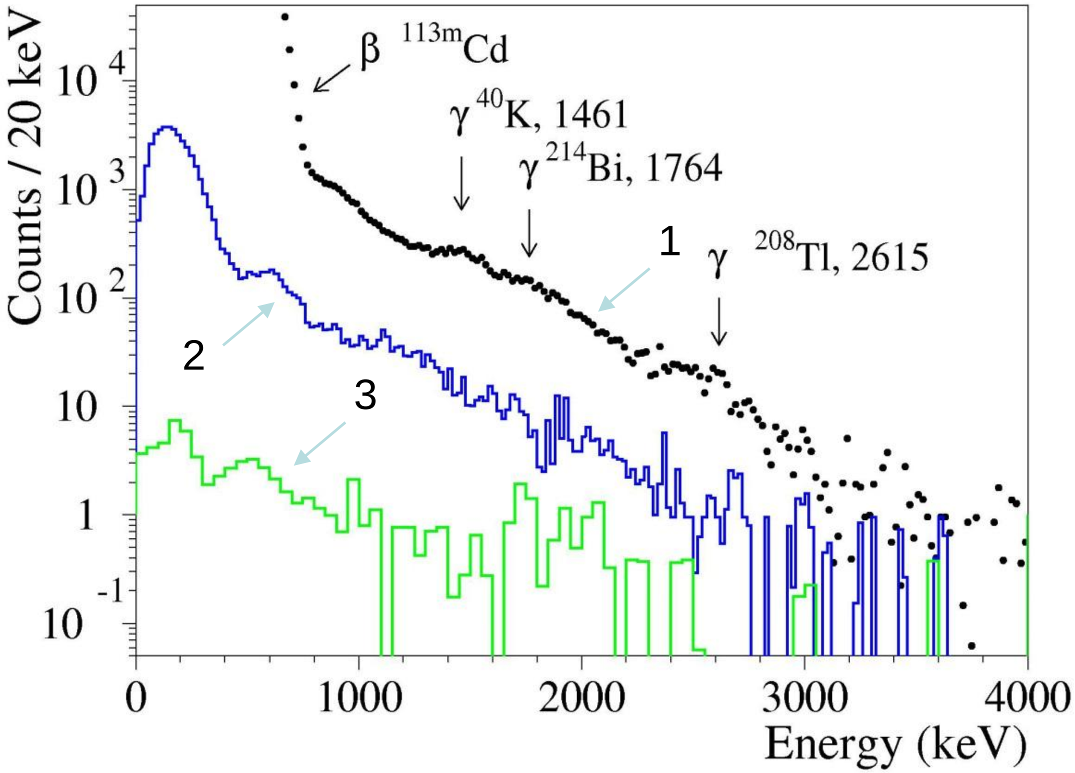


Pulse-shape discrimination:
total α activity 2.1(2) mBq/kg

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



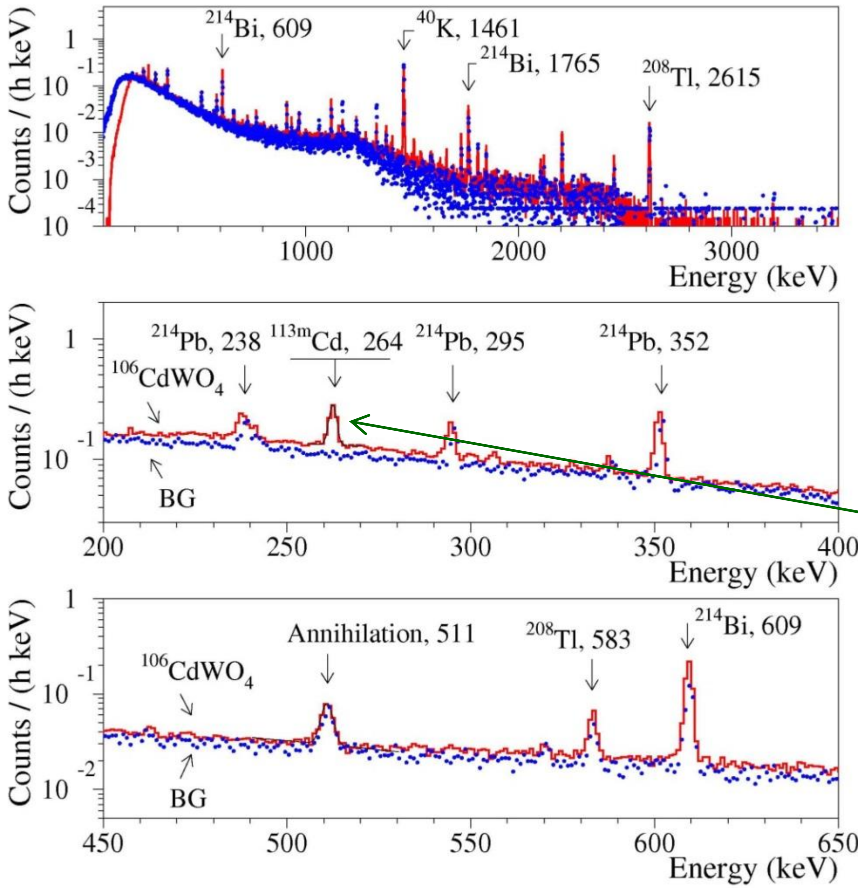
1 - In anticoincidence with the HPGe detectors (AC);

2 - In coincidence with HPGe when energy release in at least one HPGe detector is E(HPGe) > 200 keV (CC >200);

3 - In coincidence with E(HPGe) = 511 keV (CC 511)

AC and CC>200 spectra contain 95.5% of γ(β) events selected by PSD; CC=511 – 99.7% events

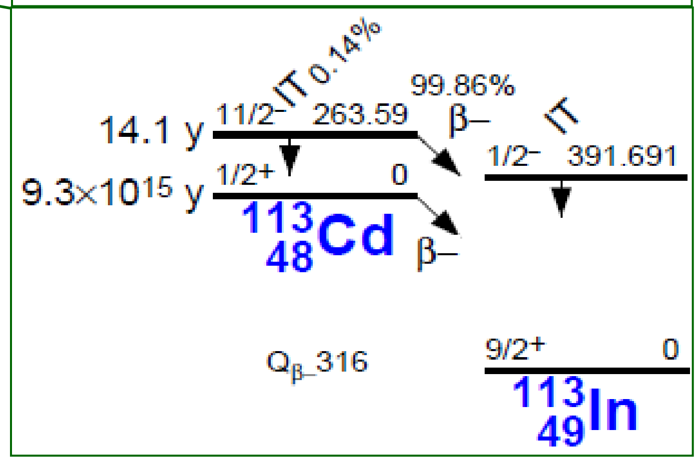
HPGe energy spectra (sum of 4 detectors) over 13085 h



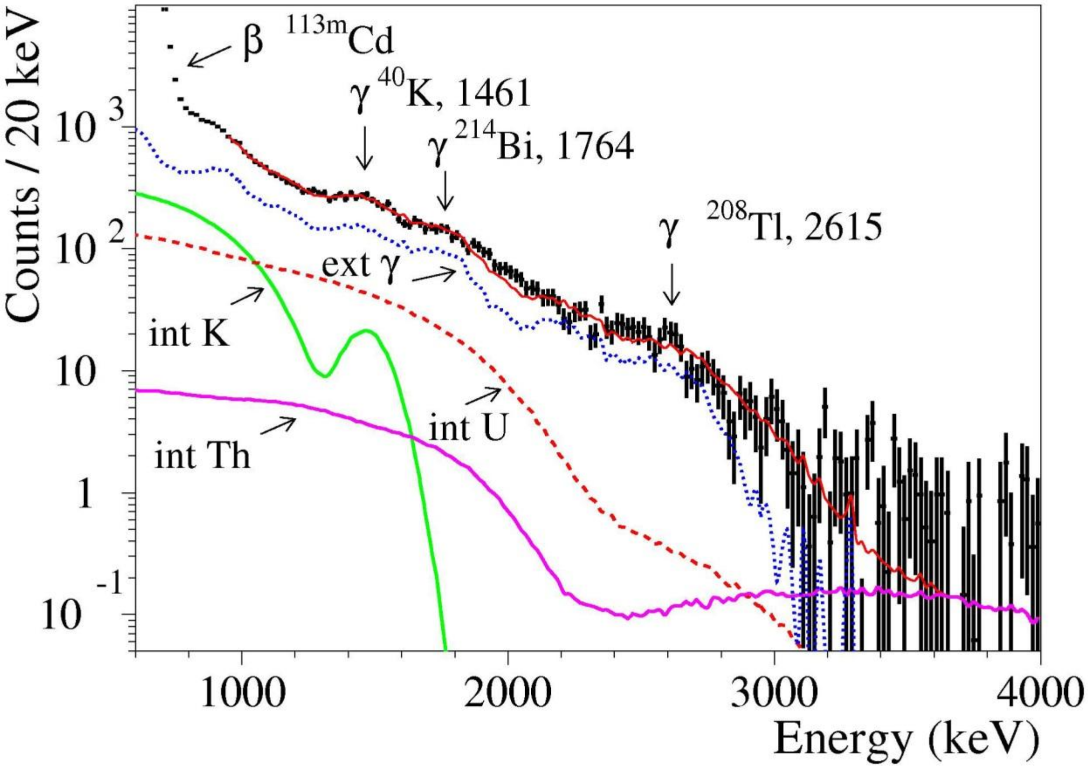
HPGe spectra without and with $^{106}CdWO_4$ crystal

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

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



$^{106}CdWO_4$ in anticoincidence with HPGe



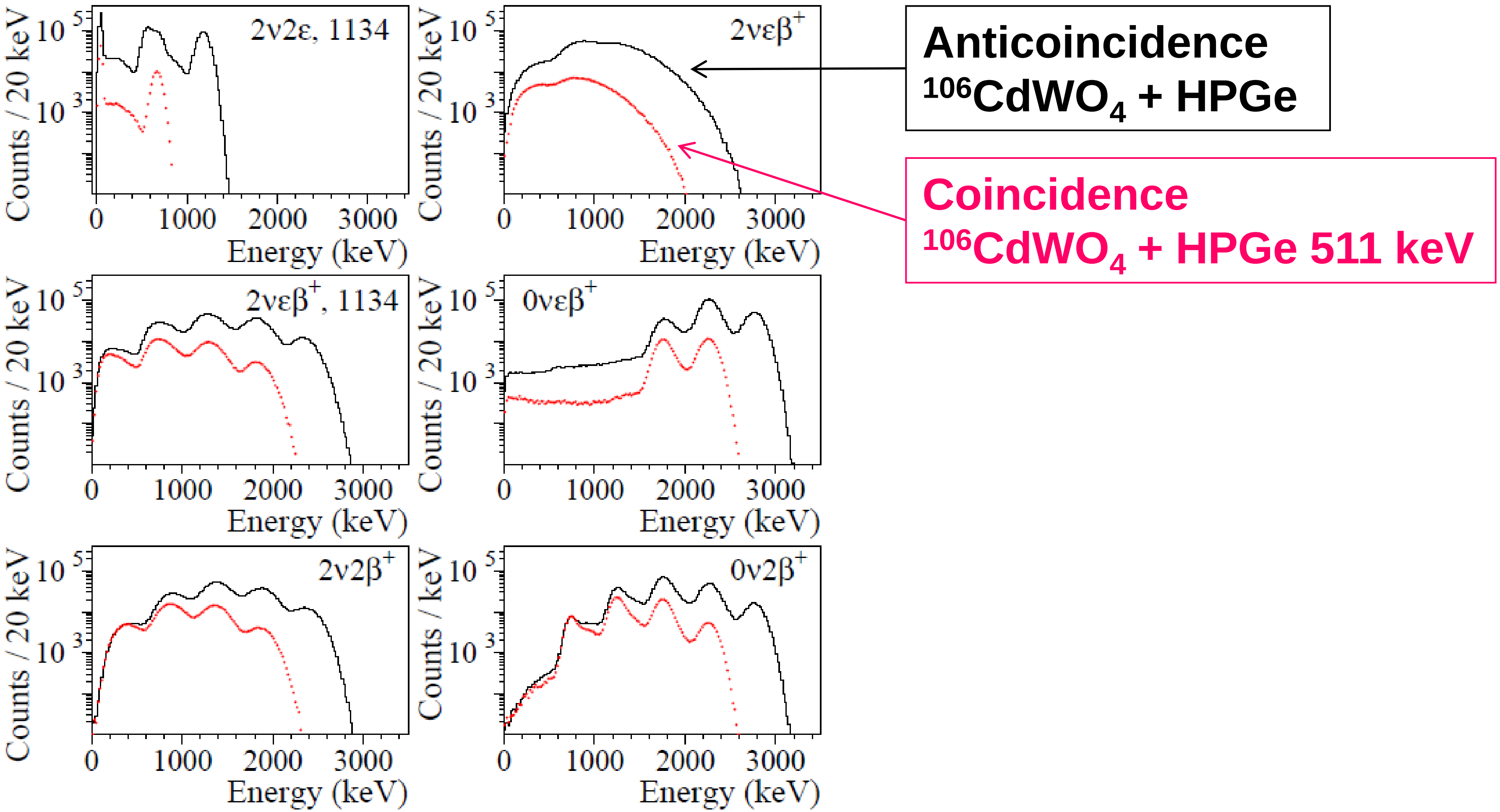
Simulations (EGS4 + DECAY0 event generator):

$^{106}CdWO_4$ contaminations
PMT
$PbWO_4$
Cu shield
Cryostat
^{116}Cd $2\beta2\nu$ decay
…

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).

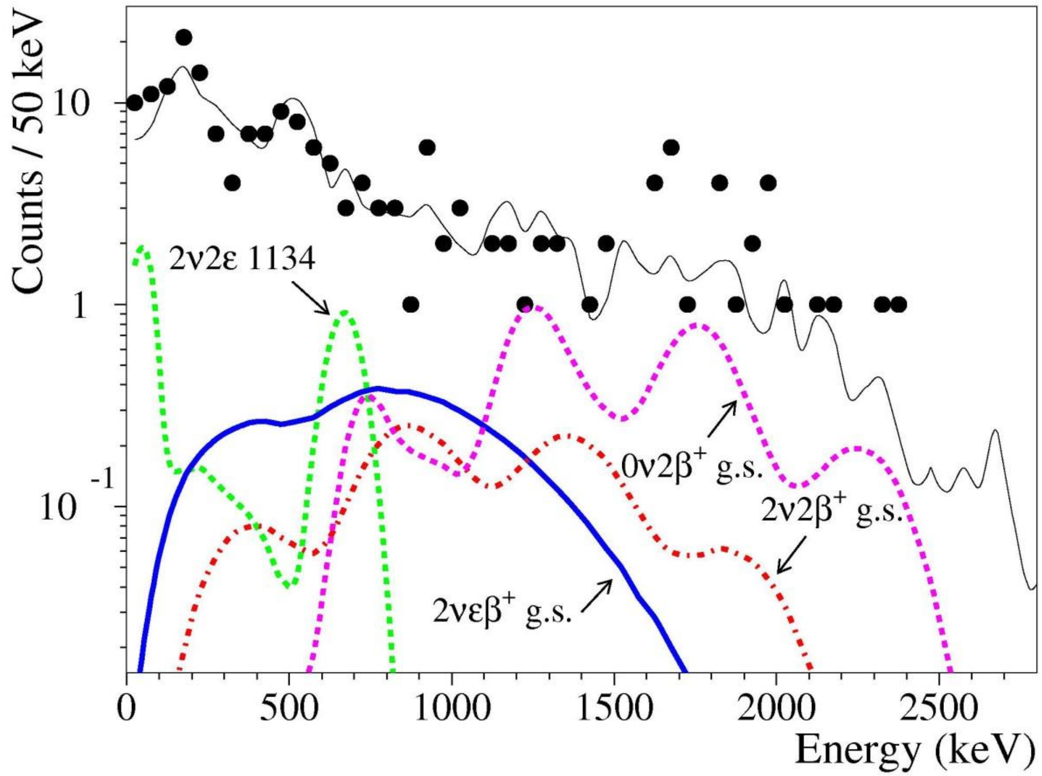
Main components of the background are shown: internal K, Th and U; external γ from K, U and Th contamination of the set-up

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



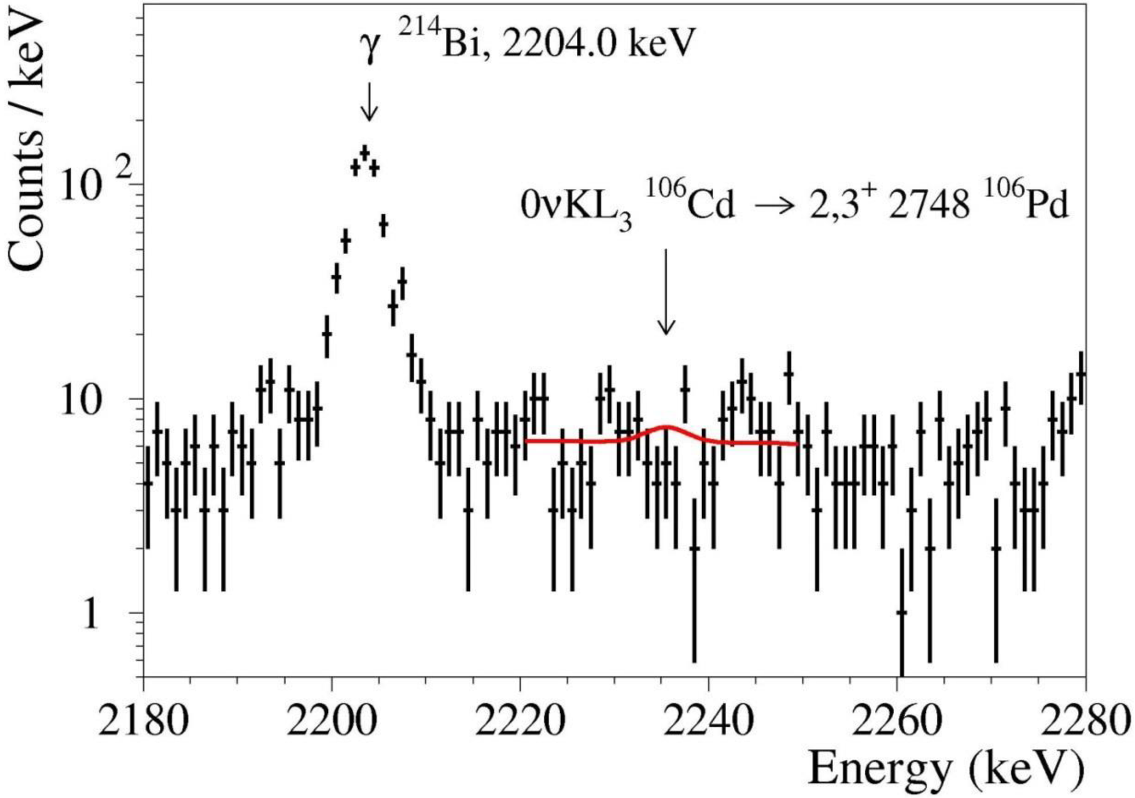
DECAY0: O.A. Ponkratenko et al., Phys. At. Nucl. 63 (2000) 1282

$^{106}CdWO_4$ 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, εβ$^+$ 2β$^+$ decays are shown (excluded at 90% C.L.).

HPGe data



Sum energy spectrum of four HPGe detectors accumulated over 13085 h in region where the 2236 keV peak from deexcitation of 2748 keV excited level of ^{106}Pd is expected (possible resonant 0νKL$_3$ electron capture). $T_{1/2} \geq 8.7\times10^{20}$ yr at 90% C.L.

Limits (preliminary) on 2ε, $\varepsilon\beta^+$, 2β^+ 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	$\geq 3.1\times10^{20}$	(AC)	$\geq 1.7\times10^{20}$ [1]
$0\nu2\varepsilon$, g.s.	$\geq 2.6\times10^{20}$	(AC)	$\geq 1.0\times10^{21}$ [1]
$2\nu\varepsilon\beta^+$, g.s.	$\geq 1.8\times10^{21}$	(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 >200)	$\geq 2.2\times10^{21}$ [1]
$2\nu2\beta^+$, g.s.	$\geq 4.7\times10^{21}$	(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	$\geq 6.3\times10^{20}$	(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

Conclusions

1. The unique radiopure high quality $CdWO_4$ crystal scintillator was developed with enriched ^{106}Cd (66%, mass of 215 g);
2. Measurements at LNGS with $^{106}CdWO_4$ in low background set up with light guide from archeological lead and four HPGe detectors were performed during 13085 h (finished);
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, $\varepsilon\beta^+$, $2\beta^+$ proce-sses 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 $T_{1/2}(\varepsilon\beta^+2\nu) > 1.8\times10^{21}$ yr reached the region of theoretical predictions;
4. There is a possibility to increase experimental sensitivity in the $^{106}CdWO_4$ experiment – to change HPGe detectors to close (almost ~4π) $CdWO_4$ scintillators: (1) higher efficiency and (2) lower background.

Thanks for your attention!