Search for double beta processes in ^{106}Cd with enriched ^{106}CdWO$_4$ crystal scintillator in coincidence with four crystals HPGe detector

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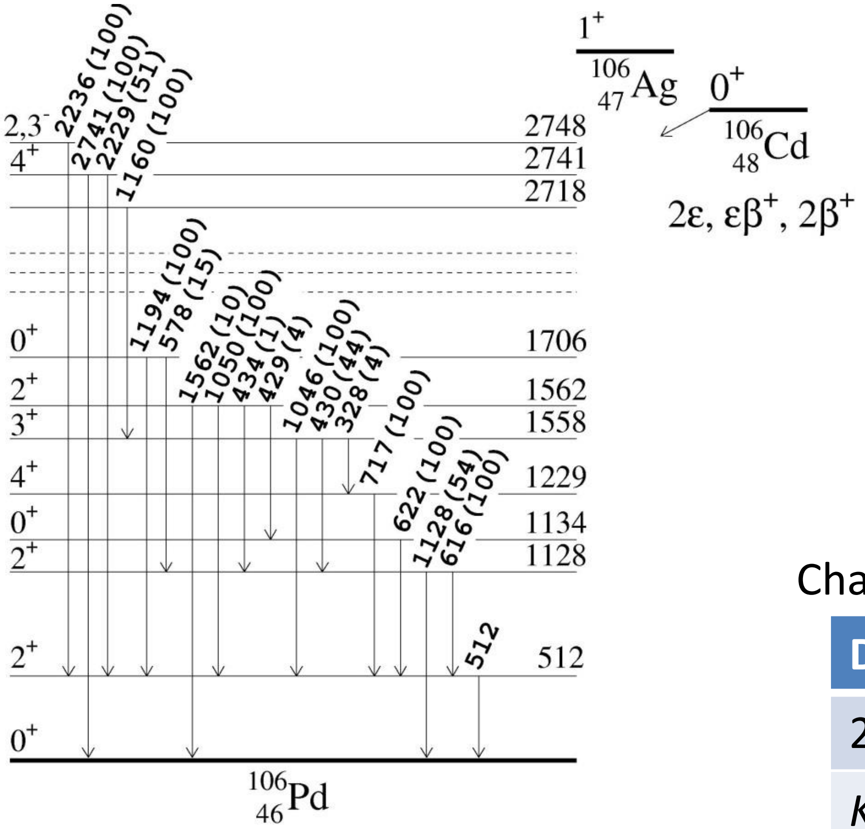
Double beta decay of ^{106}Cd



$Q_{2\beta}$= 2775.39(10) keV [1]
δ = 1.25(6)% [2]

- Possibility to refine mechanism of $0\nu2\beta^-$ decay (neutrino mass or right handed currents contribution). Enhancement of $0\nu\varepsilon\beta^+$ mode is expected for the right handed current mechanism of decay [3]
- Resonant $0\nu2\varepsilon$ transitions

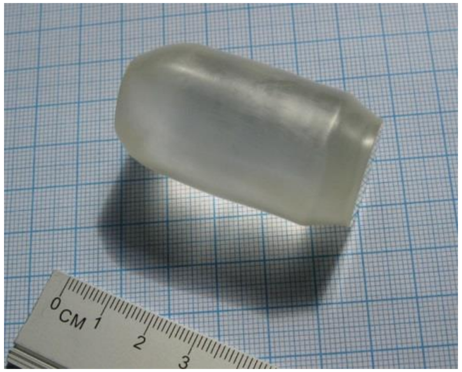
Characteristics of possible resonant $0\nu2\varepsilon$ in ^{106}Cd

Decay, level E_{exc} (keV)	**$\Delta(Q\text{-}E_{exc})$ (keV)**
$2K \rightarrow$ 2717.59(21)	9.1 ± 0.2
$KL_1 \rightarrow 4^+$ 2741.0(5)	6.4 ± 0.5
$KL_3 \rightarrow 2,3^-$ 2748.2(4)	-0.3 ± 0.4

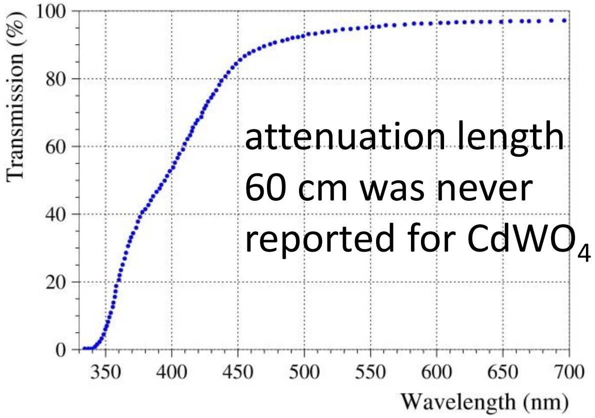
[1] M. Wang et al., The AME2012 atomic mass evaluation, Chin. Phys. C 36 (2012) 1603
[2] M. Berglund, M.E. Wieser, Isotopic compositions of the elements 2009 (IUPAC Technical Report), Pure Appl. Chem. 83 (2011) 397
[3] M. Hirsch et al., Nuclear structure calculation of $\beta^+\beta^+$, β^+EC and EC/EC decay matrix elements, Z. Phys. A 347 (1994) 151

$^{106}CdWO_4$ crystal scintillator

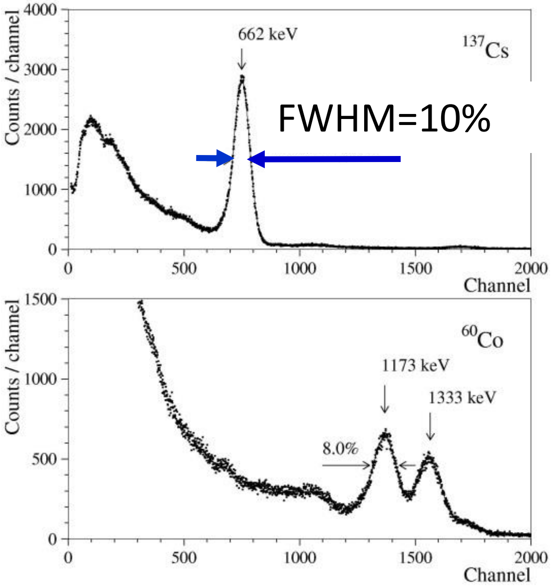
$^{106}CdWO_4$ crystal 231 g
$\delta(^{106}Cd)$ = 66%
yield of crystal = 87%



$^{106}CdWO_4$ scintillator 216 g
The total irrecoverable losses of $^{106}Cd \approx 2\%$



attenuation length 60 cm was never reported for $CdWO_4$

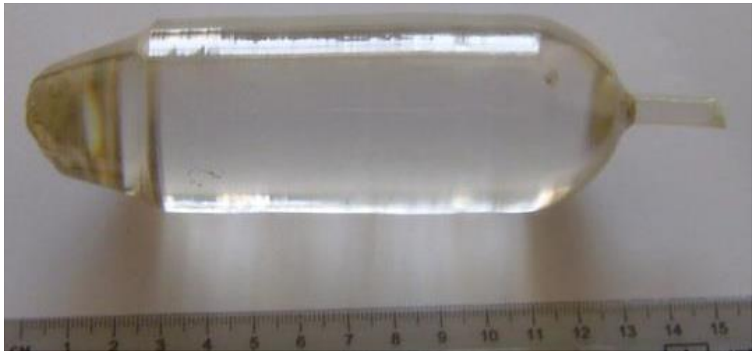


FWHM=10%

The excellent optical and scintillation properties of the crystal were obtained thanks to the deep purification of ^{106}Cd and W, and the advantage of the low-thermal-gradient Czochralski technique to grow the crystal

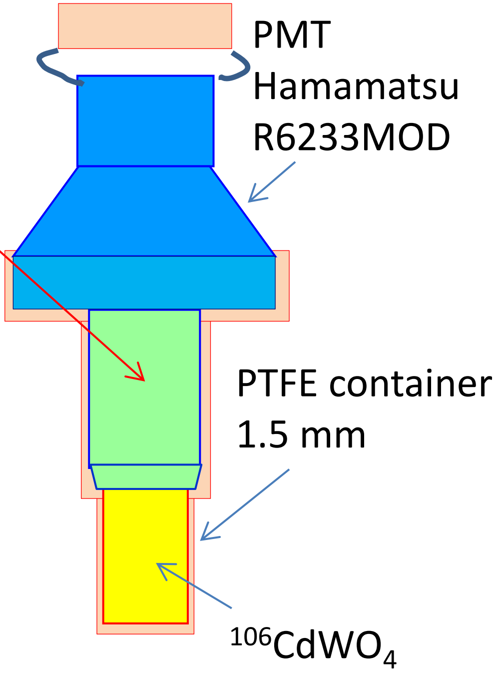
[1] P. Belli et al., Development of enriched $^{106}CdWO_4$ crystal scintillators to search for double β decay processes in ^{106}Cd, NIMA 615 (2010) 301

$PbWO_4$ light guide from archaeological lead



PbWO4 crystal boule from archaeological lead

$PbWO_4$ light guide ∅40×83 mm

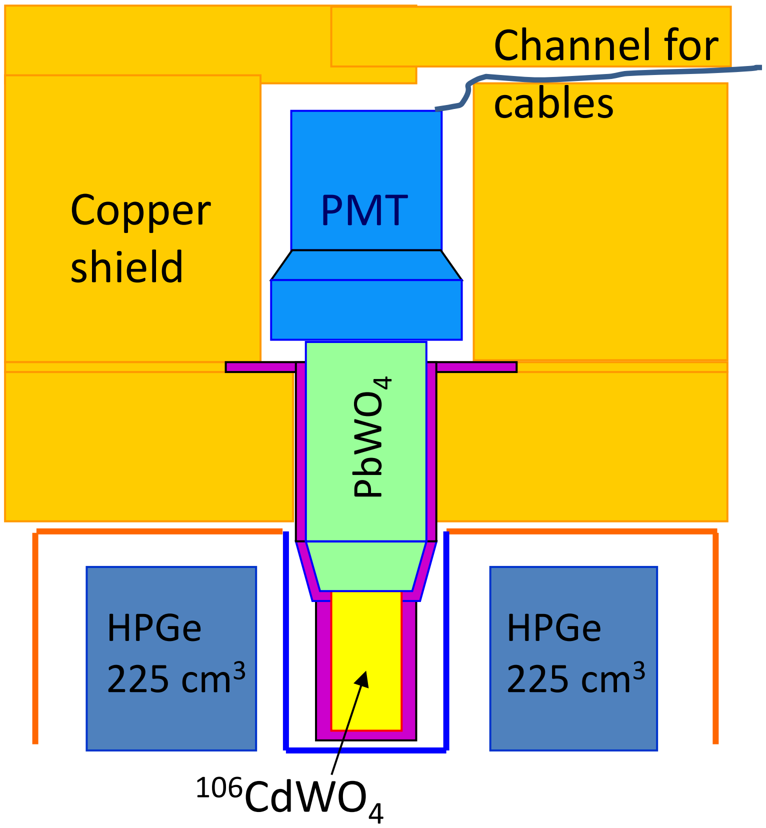


$^{106}CdWO_4$ detector

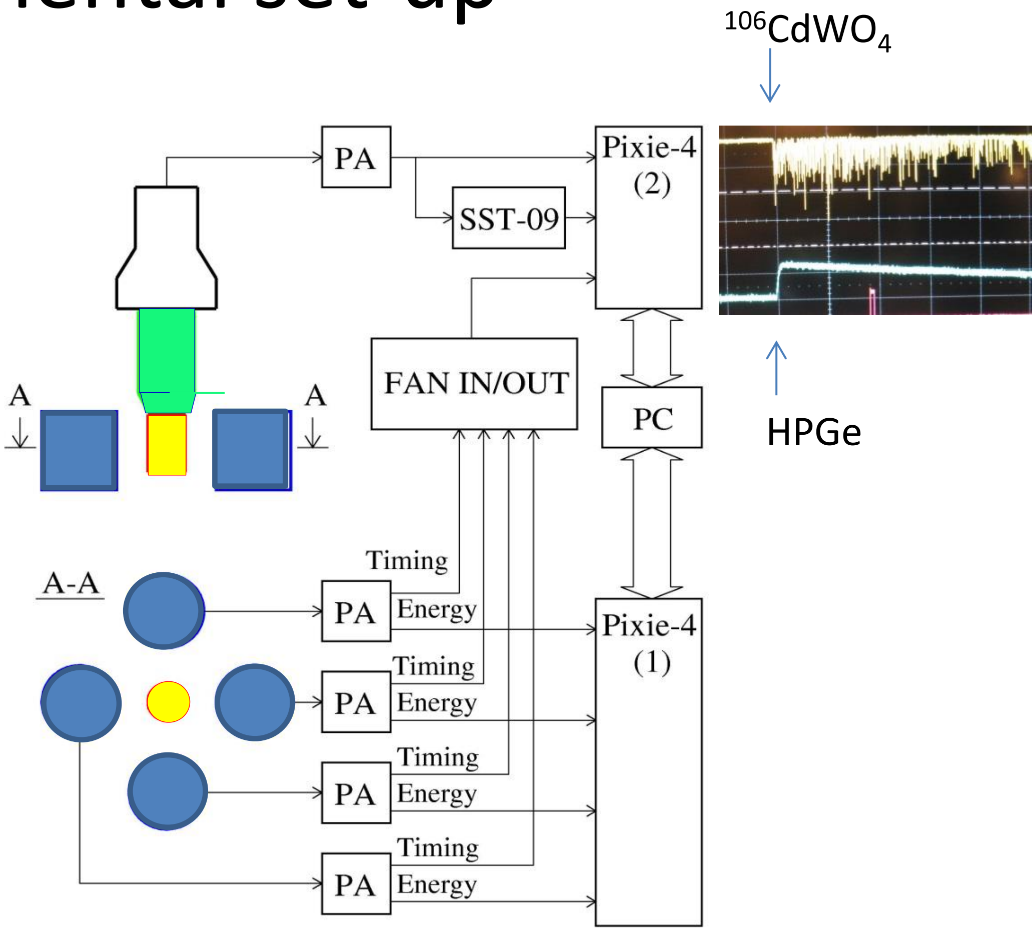
Light-guide for the experiment was made from archaeological lead [1] deeply purified by vacuum distillation [2]. The light guide provides reasonable scintillation light collection (65% in comparison to the geometry without light guide) [3]

[1] F.A. Danevich et al., Ancient Greek lead findings in Ukraine, NIMA 603 (2009) 328
[2] R. S. Boiko et al., Ultrapurification of Archaeological Lead, Inorganic Materials 47 (2011) 645
[3] G.P. Kovtun et al., Development and properties of cadmium and lead tungstate low-background scintillators for double beta decay experiments, Nucl. Phys. Atom. Energy 15 (2014) 92

Experimental set-up



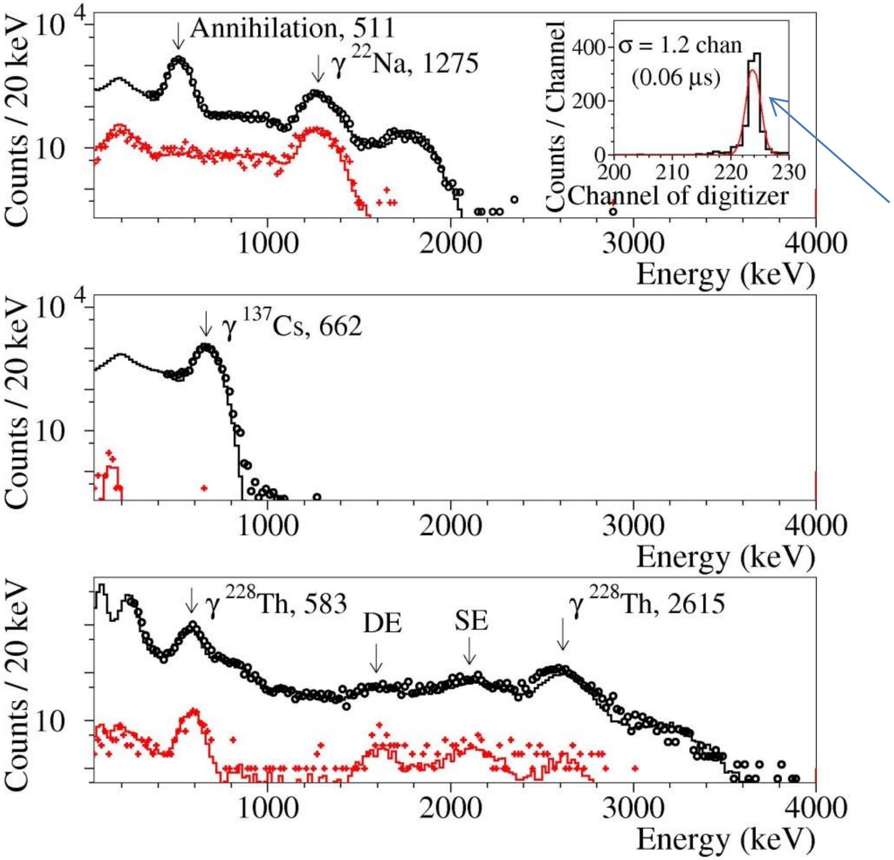
Experimental set-up. The detector was surrounded by layers of radiopure copper, lead, sealed in PMMA air tight box flushed by nitrogen to remove radon



Scheme of the electronic chain: (PA) preamplifiers; (FAN IN/OUT) linear FAN-IN/FAN-OUT; (SST-09) triggers unit for cadmium tungstate scintillation signals; (Pixie-4) four-channel all digital spectrometers; (PC) computer.

Calibration and Monte Carlo simulation

γ sources



The energy scale, energy and time resolution were measured with ^{22}Na, ^{60}Co, ^{137}Cs and ^{228}Th γ sources

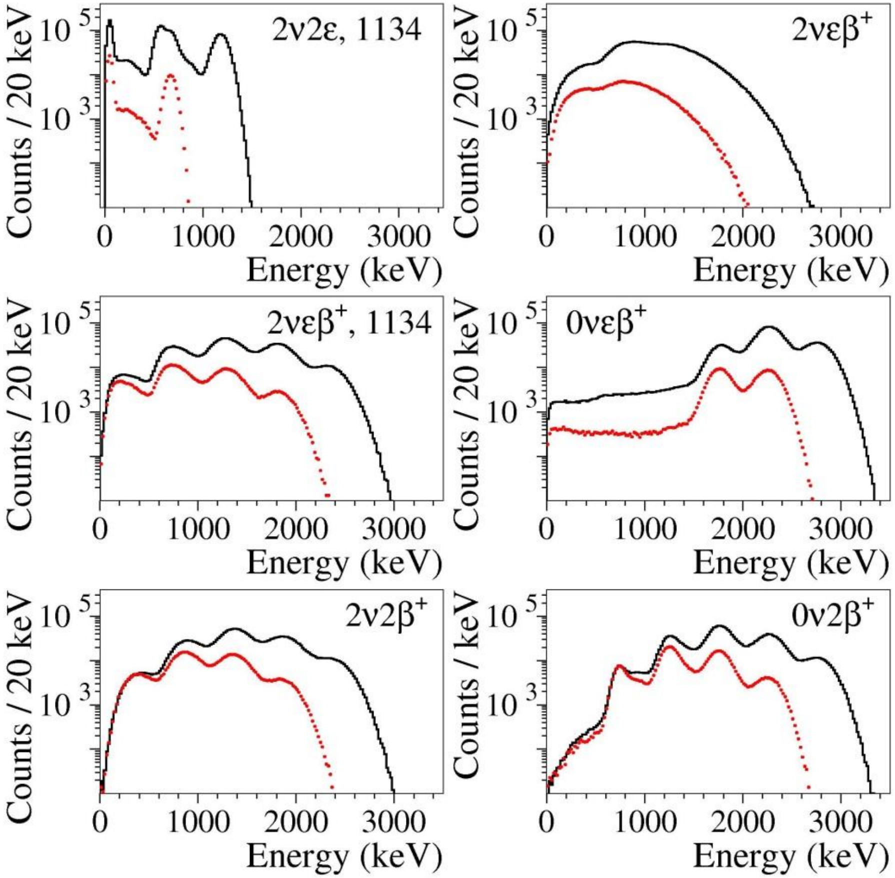
Distribution of the ^{106}CdWO$_4$ detector pulses start positions relative to the HPGe signals with the energy 511 keV accumulated with ^{22}Na source

Energy spectra of ^{22}Na, ^{137}Cs and ^{228}Th γ sources: with no coincidence (black), and in coincidence with energy 511 keV in the HPGe detector (red). The data simulated using the EGS4 Monte Carlo code are drawn by solid lines.

FWHM = $\sqrt{(20.4 \times E_\gamma)}$ where FWHM and E_γ are given in keV

Monte Carlo simulation

2ε, $\varepsilon\beta^+$, $2\beta^+$ processes in ^{106}Cd



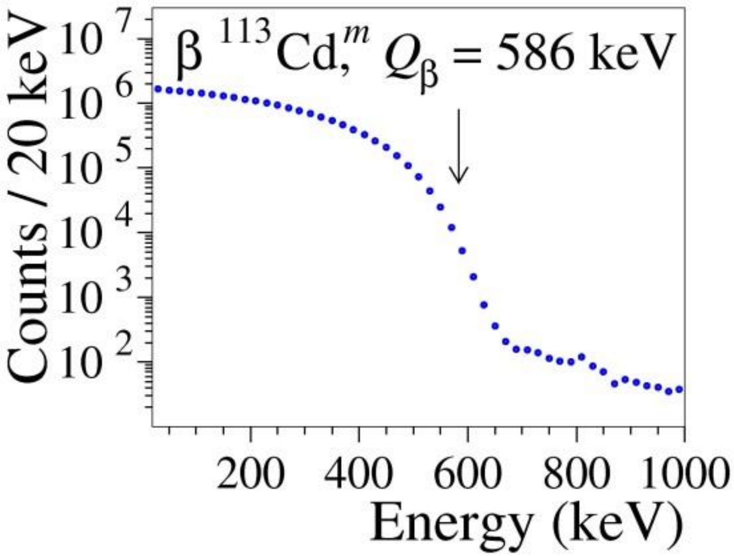
The response functions of the ^{106}CdWO$_4$ detector to the 2β processes in ^{106}Cd were simulated with the help of the EGS4 code

Simulated response functions of ^{106}CdWO$_4$ detector to 2ε, $\varepsilon\beta^+$, and $2\beta^+$ processes in ^{106}Cd without coincidence (black) and in coincidence with annihilation γ quanta in the HPGe detector (red).

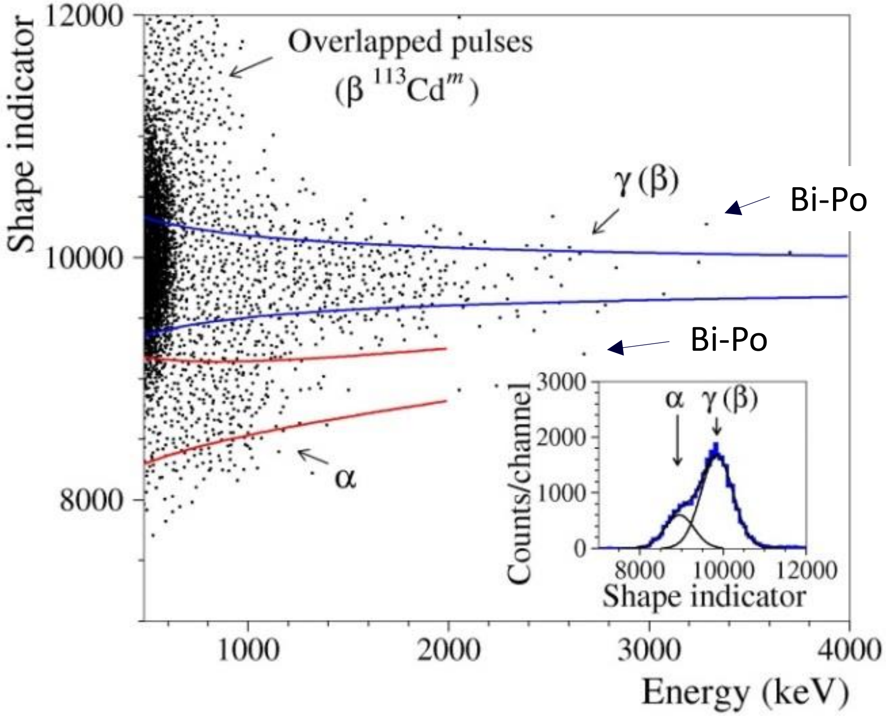
With ^{106}CdWO$_4$ crystal scintillator one can distinguish the neutrinoless and two neutrino modes of the 2ε, $\varepsilon\beta^+$ and $2\beta^+$ processes

Internal contamination of ^{106}CdWO$_4$

energy spectra and pulse-shape discrimination



Energy spectrum measured with the ^{106}CdWO$_4$ scintillator over 283 h in the low-background setup [1]. Beta active ^{113m}Cd with activity 116(4) Bq/kg dominates at an energy of < 0.65 MeV

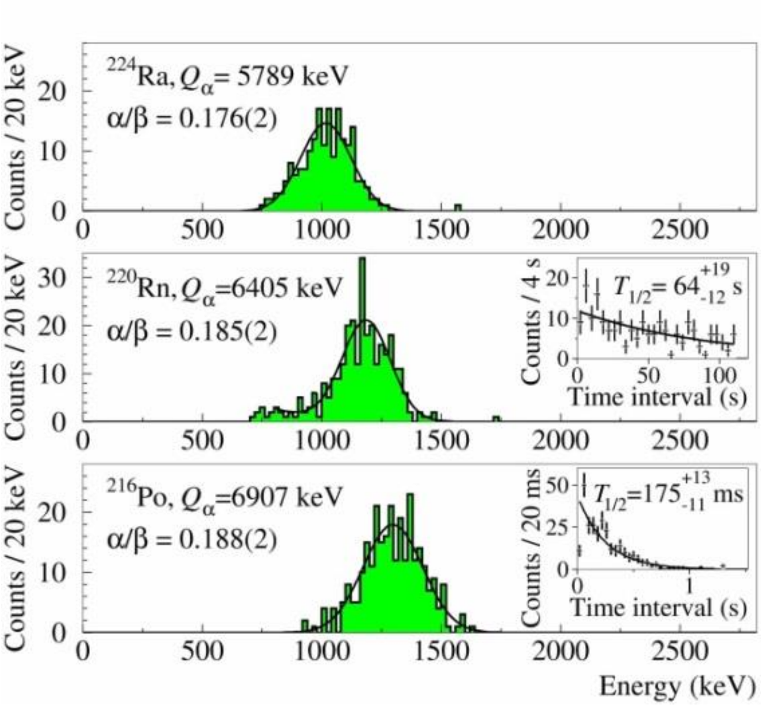


Mean time versus the energy accumulated over 571 h. The total α activity of U/Th in ^{106}CdWO$_4$ crystal is 2.1(2) mBq/kg.

[1] P. Belli et al., Search for double-*β* decay processes in ^{106}Cd with the help of a ^{106}CdWO$_4$ crystal scintillator, PRC 85 (2012) 044610

Internal contamination of $^{106}CdWO_4$

time-amplitude analysis



Energy and time spectra of ^{228}Th daughters decays selected by time-amplitude analysis. ^{228}Th activity is 0.042(2) mBq/kg

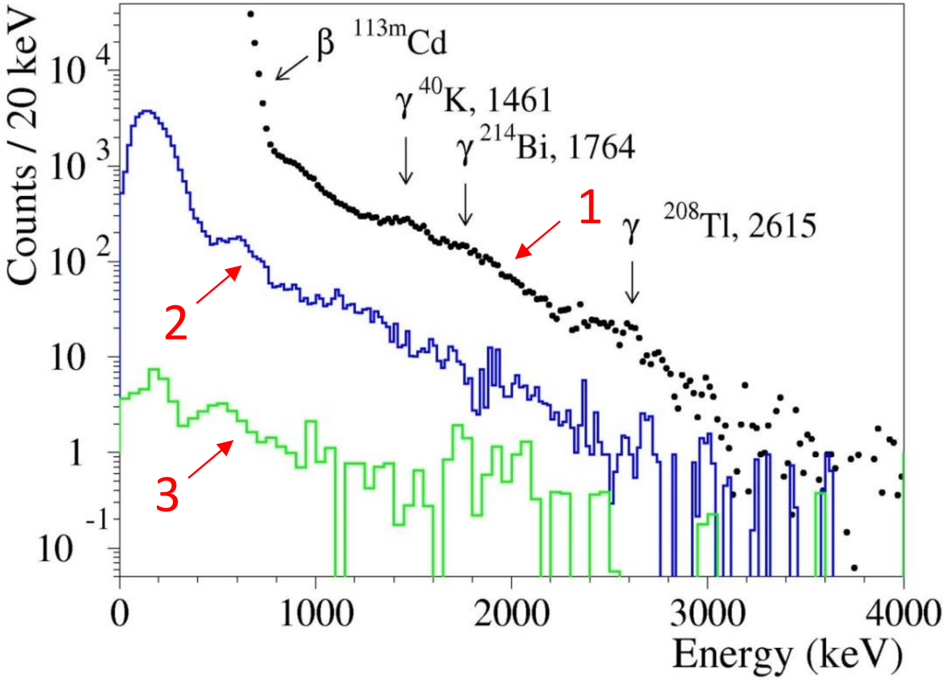
Radioactive contamination of $^{106}CdWO_4$ crystal scintillator [1, 2]

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	$116(4) \times 10^3$

*Reference date: November 2009

[1] D.V. Poda et al., $CdWO_4$ crystal scintillators from enriched isotopes for double betadecay experiments, Radiation Measurements 56 (2013) 66
[2] F.A.Danevich et al., Development of radiopure cadmium tungstate crystal scintillators from enriched ^{106}Cd and ^{116}Cd to search for double beta decay, AIP Conf. Proc. 1549 (2013) 201

^{106}CdWO$_4$ energy spectra in (anti) coincidence with HPGe detectors



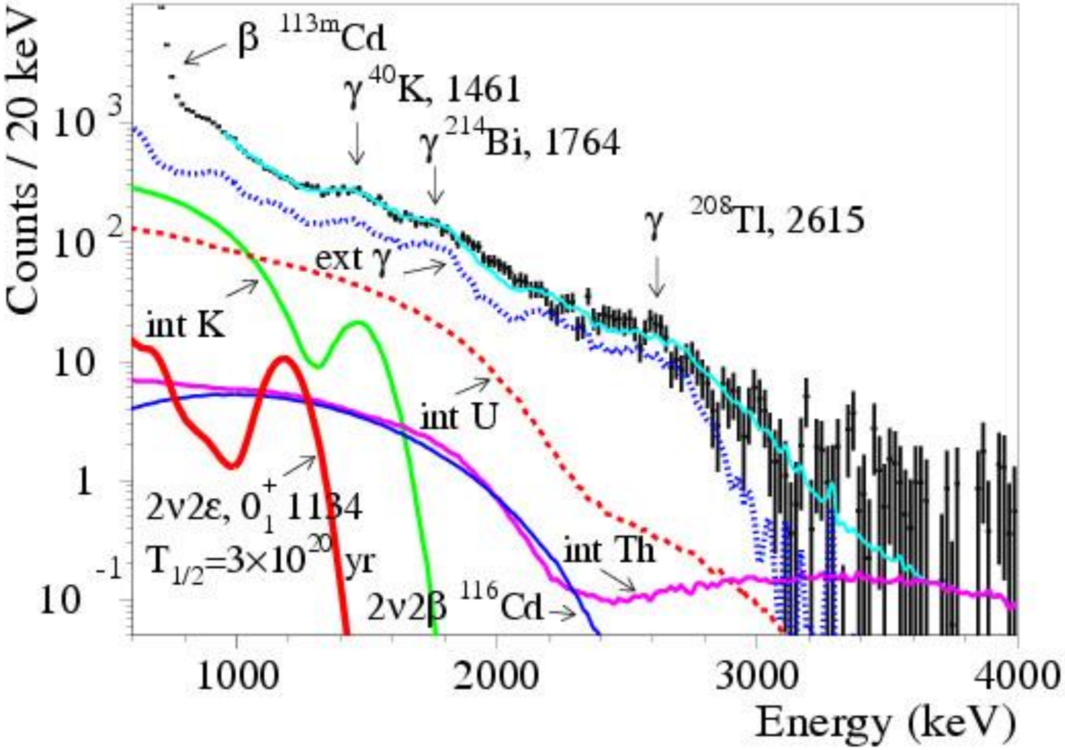
Energy spectra measured over 13085 h by ^{106}CdWO$_4$ detectors:

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

All the spectra content 95% of $\gamma(\beta)$ events selected by the pulse-shape analysis

No effect of 2β decay of ^{106}Cd observed. Limits on half-lives were set by choosing the data with a higher ratio of the detection efficiency to the background counting rate (in some cases also HPGe spectra were used)

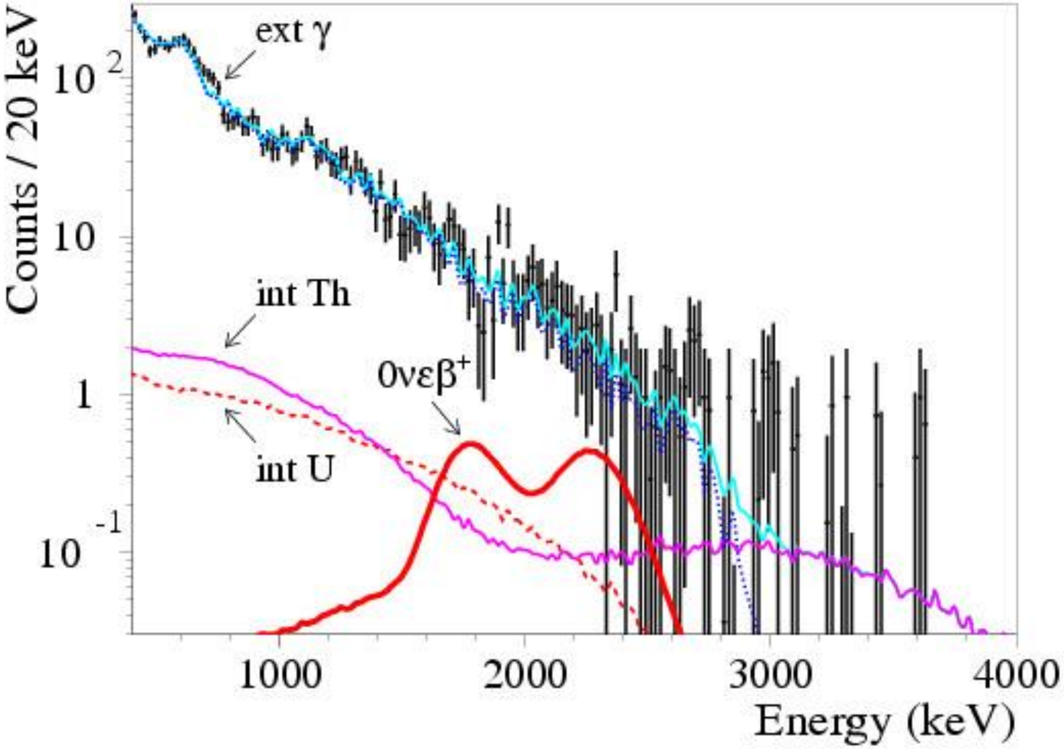
$^{106}CdWO_4$ in anticoincidence with HPGe



Energy spectrum of 95% of γ(β) events selected from the data accumulated over 13085 h (points) in anticoincidence with HPGe together with the background model (blue continuous line). The main components of the background are shown: the distributions of internal K, Th and U, 2ν2β decay of ^{116}Cd and the contribution from the external γ quanta from K, U and Th contamination of the set-up in these experimental conditions. The energy spectrum of the 2ν2ε decay of ^{106}Cd to the 0_1^+ 1134 keV level of ^{106}Pd excluded at 90% CL is shown by red solid histogram.

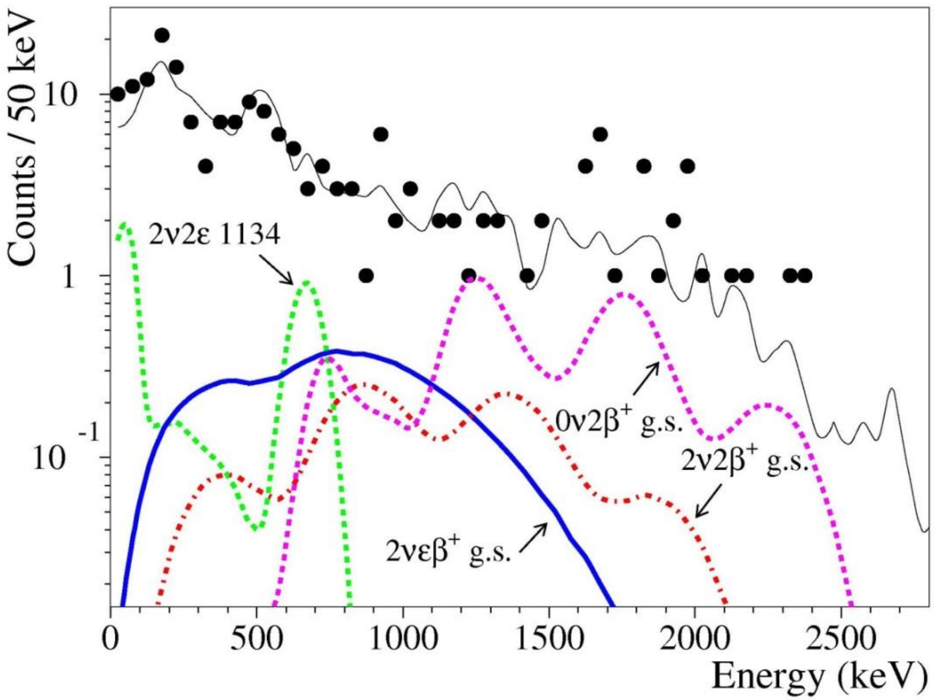
$^{106}CdWO_4$ in coincidence with

E(HPGe) > 50 keV



Energy spectrum of 95% of γ(β) events selected from the data accumulated over 13085 h (points) in coincidence with event(s) in at least one of the HPGe detectors with energy > 50 keV. The background model is shown by the blue continuous line. The background is mainly due to the external γ quanta of the K, U and Th contamination of the set-up. The energy spectrum of the $0\nu\varepsilon\beta^+$ decay of ^{106}Cd to the ground level of ^{106}Pd with the half-life 2.2×10^{21} yr excluded at 90% CL is shown by red solid histogram.

^{106}CdWO$_4$ in coincidence with 511 keV in HPGe



Measured background in the energy interval 0 - 4 MeV is 176 counts.

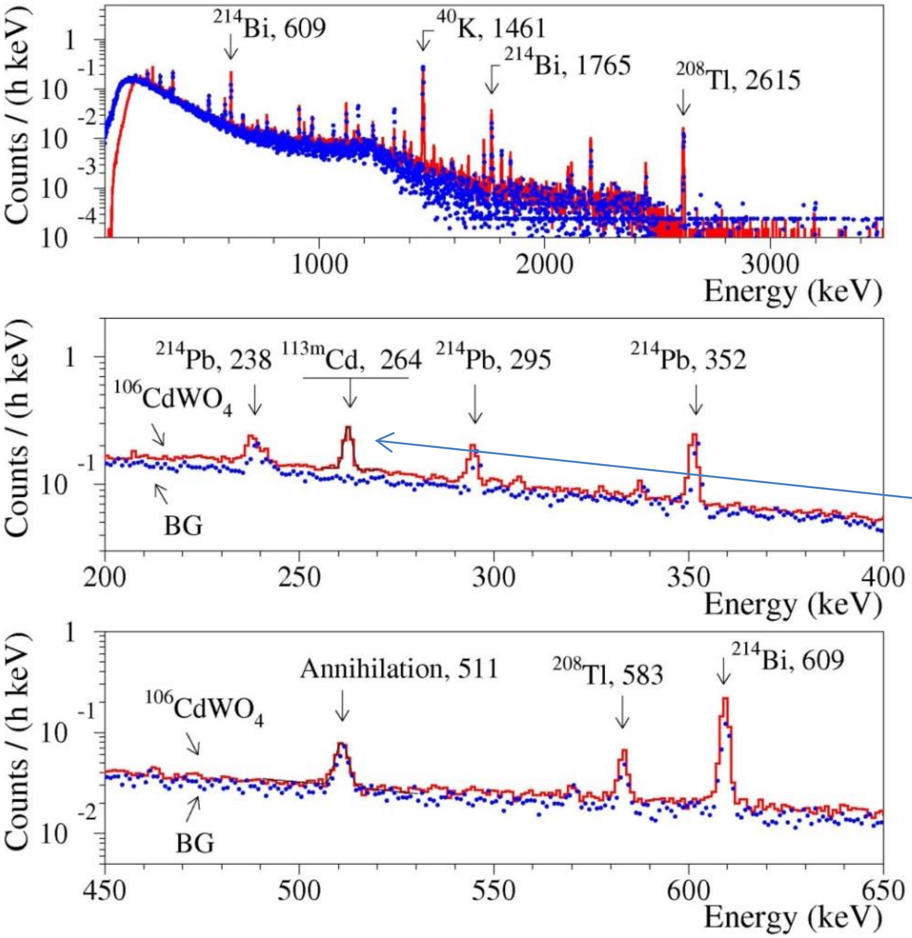
Model of background built from the fit of the anticoincidence spectra gives 170 counts.

For example, 51 counts in the energy interval 550-1300 keV (68% of the 2νεβ$^+$ spectra, detection efficiency is 7.59%). Model of BG gives 58.3 counts $\Rightarrow$ lim*S* = 6.4 counts [1] $\Rightarrow T_{1/2} > 1.9\times10^{21}$ yr

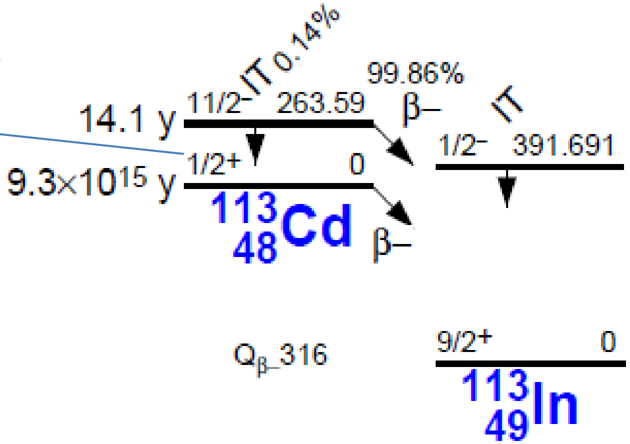
The energy spectrum of the ^{106}CdWO$_4$ detector accumulated over 13085 h in coincidence with 511 keV annihilation γ quanta in at least one of the HPGe detectors (circles). The Monte Carlo simulated distributions for different modes of 2ν and 0ν 2ε, εβ$^+$ 2β$^+$ decays excluded at 90% CL are shown.

[1] G.J. Feldman, R.D. Cousins, Unified approach to the classical statistical analysis of small signals, Phys. Rev. D 57 (1998) 3873

HPGe spectrum



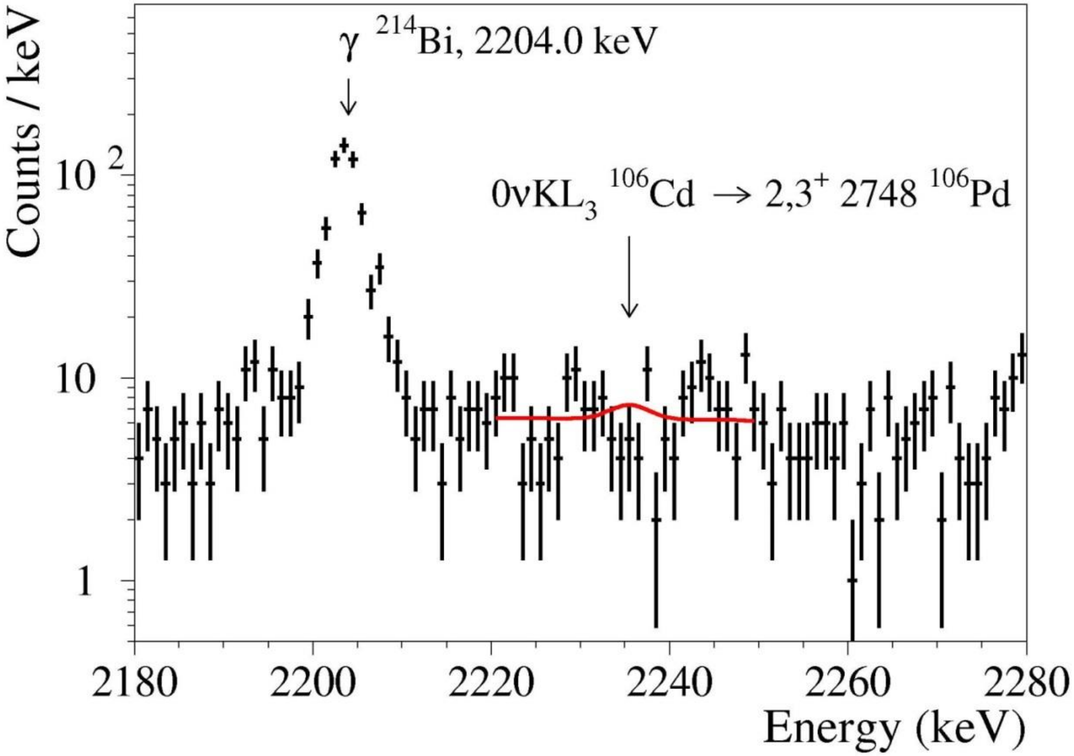
- Some excess of ^{226}Ra daughters (^{214}Bi, ^{214}Pb). It may be due to PMT + radon from the PMT + reduced overall passive shield due to the ^{106}CdWO$_4$ detector installation (e.g., ~0.2 counts/h in 609 keV ^{214}Bi peak)
- Peak 263.5 keV of ^{113m}Cd isomeric transition



Energy spectrum measured over 13085 h by the four HPGe detectors with the ^{106}CdWO$_4$ detector installed (red histogram) together with background accumulated over 4102 h (blue) (the energies of the γ quanta are in keV)

Using the HPGe data to search for 2β decay of ^{106}Cd

resonant KL_3 $0\nu2\varepsilon$ transition to $2,3^+$ 2748 keV excited level of ^{106}Pd



Sum energy spectrum accumulated over 13085 h by the four HPGe detectors. The expected 2236 keV peak of the resonant $0\nu KL_3$ capture of ^{106}Cd to the $2,3^+$ 2748 keV excited level of ^{106}Pd with the half-life 2.5×10^{20} yr (excluded at 90% CL, lim$S$ = 6 counts) is shown by the red solid histogram.

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

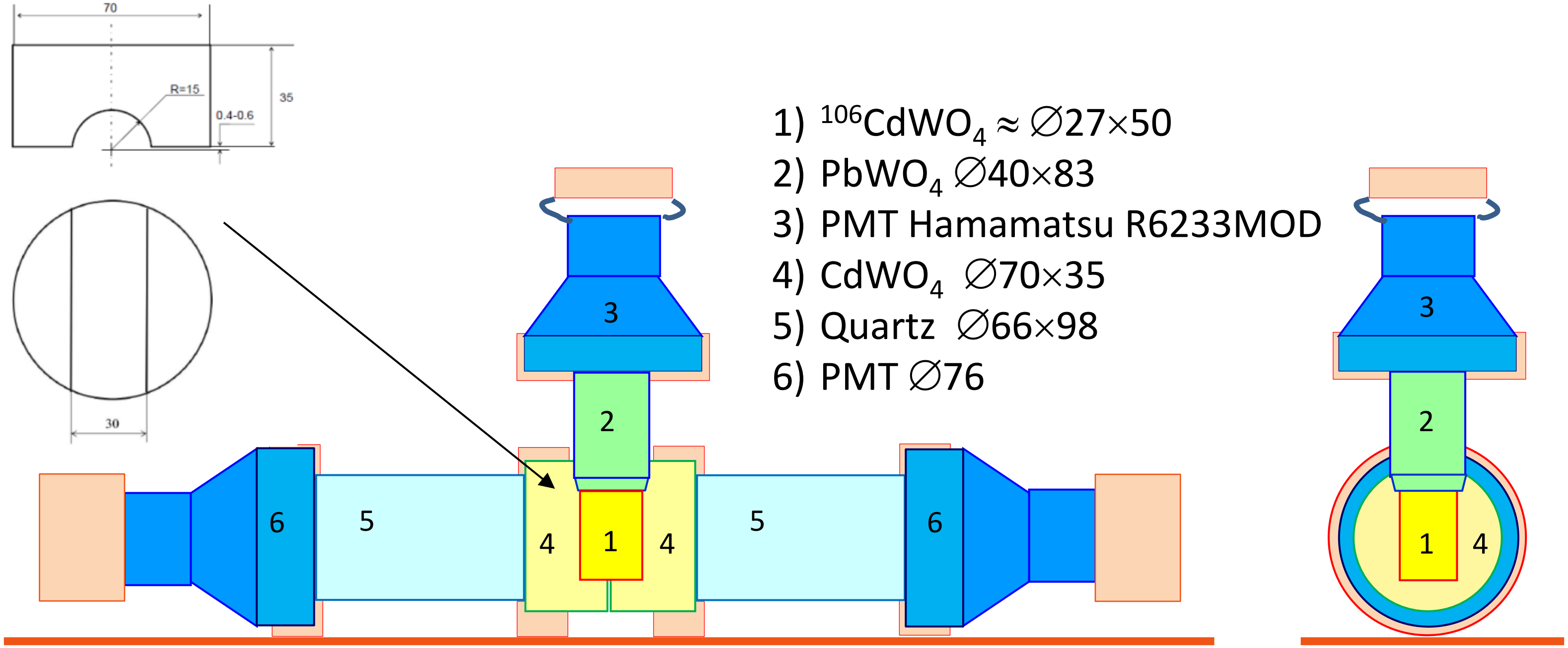
Decay, level of ^{106}Pd (keV)	**$T_{1/2}$ (yr) at 90% C.L.**	
	Present work	**Previous limit**
$2\nu 2\varepsilon$, 0^+_1 1134	**$\geq 3.0\times10^{20}$** (AC)	$\geq 1.7\times10^{20}$ [1]
$0\nu 2\varepsilon$, g.s.	$\geq 2.7\times10^{20}$ (AC)	$\geq 1.0\times10^{21}$ [1]
$2\nu\varepsilon\beta^+$, g.s.	**$\geq 1.9\times10^{21}$** (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 $E\gamma$>50 keV)	$\geq 2.2\times10^{21}$ [1]
$2\nu 2\beta^+$, g.s.	**$\geq 5.5\times10^{21}$** (CC 511)	$\geq 4.3\times10^{20}$ [1]
$0\nu 2\beta^+$, g.s.	**$\geq 2.2\times10^{21}$** (CC 511)	$\geq 1.2\times10^{21}$ [1]
$0\nu 2K$, 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]

Limits on the level of $T_{1/2}\sim10^{19}$-10^{21} yr were also set on the 2β processes to the excited levels 512, 1128, 1134, 1562, 1706, 2001, 2278 keV of ^{106}Pd

[1] P. Belli et al., Search for double-β decay processes in ^{106}Cd with the help of a ^{106}CdWO$_4$ crystal scintillator, Phys. Rev. C 85, 044610 (2012)
[2] P. Belli et al., New limits on $2\beta^+$ decay processes in ^{106}Cd, Astropart. Phys. 10 (1999) 115

Plans to improve the sensitivity

coincidence with two $CdWO_4$ detectors in close geometry



1) $^{106}CdWO_4 \approx \varnothing 27\times 50$
2) $PbWO_4$ $\varnothing 40\times 83$
3) PMT Hamamatsu R6233MOD
4) $CdWO_4$ $\varnothing 70\times 35$
5) Quartz $\varnothing 66\times 98$
6) PMT $\varnothing 76$

Event of the $2\nu\varepsilon\beta^+$ decay	Efficiency	Background 200-1100 keV over 1 yr	Ratio efficiency/ sqrt(BG)
$^{106}CdWO_4$ & 511 in at least on of the four HPGe	**6.00%**	**76 counts**	**0.69**
$^{106}CdWO_4$ & CWO1 (511) & CWO2 (511)	**3.52%**	**15.7 counts**	**0.89**

Conclusions

1. ^{106}Cd is one of the most promising isotopes to search for double beta plus processes. In addition:
    - possibility to decide whether the $0\nu2\beta^-$ decay (if observed) is dominated by the mass mechanism or by right-handed current interaction
    - possible resonant $0\nu2\varepsilon$ transitions
2. Enriched ^{106}CdWO$_4$ crystal scintillator has been developed: excellent quality, high crystal yield and low losses, high radiopurity (only problem is ^{113m}Cd due to contamination of the isotopically enriched ^{106}Cd)
3. Use of PbWO$_4$ light guide from archaeological lead allows constructing a small size low background scintillation detector to be installed inside the four crystal HPGe set-up
4. Detector based on ^{106}CdWO$_4$ crystal scintillator distinguishes the 0ν and 2ν modes of the 2ε, $\varepsilon\beta^+$ and $2\beta^+$ processes
5. New limits on 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes in ^{106}Cd were set on the level of $T_{1/2}>10^{20}$ - 10^{21} yr
6. The half-life limit on the two neutrino electron capture with positron emission, $\lim T_{1/2}^{2\nu\varepsilon\beta^+} = 1.9\times10^{21}$ yr, reached the region of theoretical predictions
7. Advancement of the experimental sensitivity is in progress using two CdWO$_4$ scintillation detectors in close geometry