Search for 2β decay of ^{116}Cd with the help of enriched $^{116}CdWO_4$ crystal scintillators

D.V.Poda[1], A.S.Barabash[2], P.Belli[3], R.Bernabei[3,4], F.Cappella[5,6], V.Caracciolo[7], S.Castellano[7], R.Cerulli[7], D.M.Chernyak[1], F.A.Danevich[1], E.N.Galashov[8], A.Incicchitti[5,6], V.V.Kobychev[1], S.I.Konovalov[2], M.Laubenstein[7], R.B.Podviyanuk[1], O.G.Polischuk[1,5], V.N.Shlegel[8], V.I.Tretyak[1], V.I.Umatov[2], Ya.V.Vasiliev[8]

[1] Institute for Nuclear Research, Kyiv, Ukraine
[2] Institute of Theoretical and Experimental Physics, Moscow, Russia
[3] INFN, Section of Rome "Tor Vergata", Rome, Italy
[4] Department of Physics, University of Rome "Tor Vergata", Rome, Italy
[5] INFN, Section of Rome "La Sapienza", Rome, Italy
[6] Department of Physics, University of Rome "La Sapienza", Rome, Italy
[7] INFN, Gran Sasso National Laboratories, Assergi (Aq), Italy
[8] Nikolaev Institute of Inorganic Chemistry, Novosibirsk, Russia

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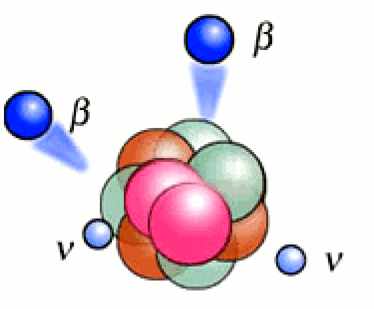
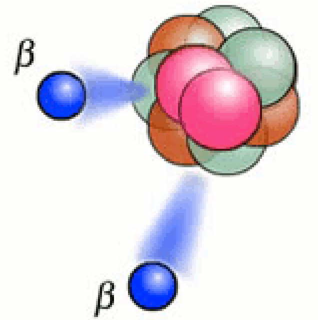
Double beta (2β) decay

- **Nuclear transformations when the charge of nuclei changes by two units: (A, Z) → (A, $Z \pm 2$)**



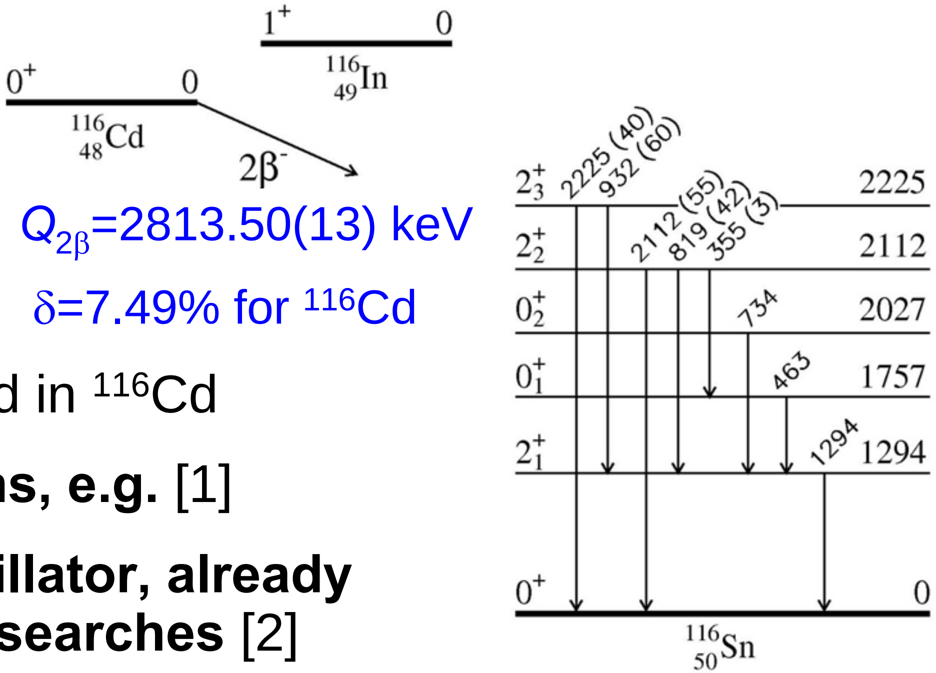
- **The rarest nuclear decay (2ν2β) ever observed**
 (registered for 12 nuclides; half-lives $T_{1/2} \sim 10^{18}$–10^{24} yr)

- **Observation of 0ν2β decay could help to clarify the fundamental problems in particle physics:**
  Lepton number non-conservation
  Nature of neutrino (Dirac or Majorana particle)
  Hierarchy of neutrino mass
  Absolute scale of neutrino mass



[1] see J.D. Vergatos et al., Rep. Prog. Phys. 75 (2012) 106301 and Refs. there in.

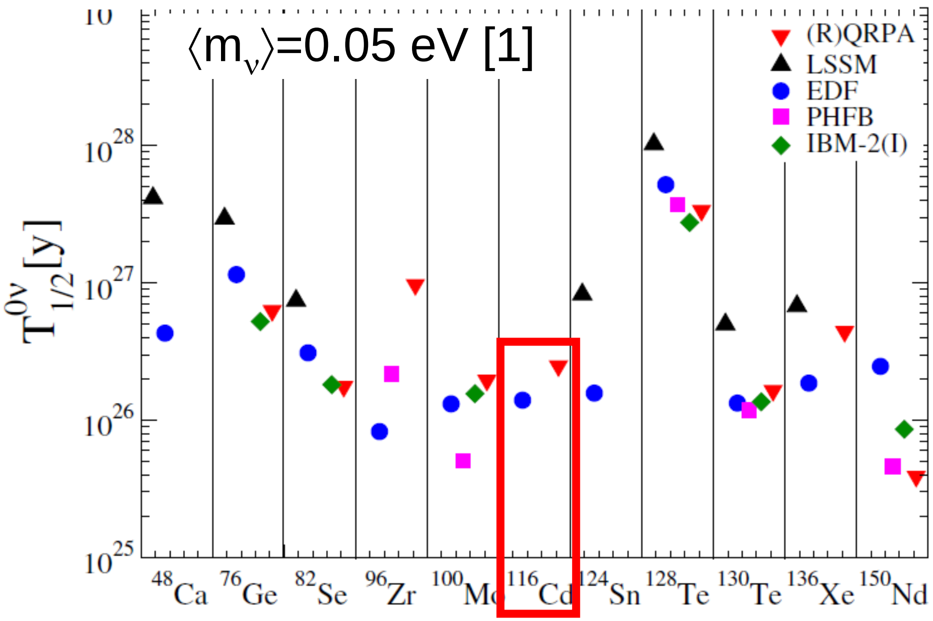
2β decay of ^{116}Cd



$Q_{2\beta}$=2813.50(13) keV

δ=7.49% for ^{116}Cd

- **One of the highest energy of 2β decay**
- **Large isotopic abundance**
  Availability of raw material enriched in ^{116}Cd
- **Promising theoretical estimations, e.g.** [1]
- **Excellent detector, $CdWO_4$ scintillator, already used for rare α, β, and 2β decay searches** [2]
  "source = detector" experiment
  low level of intrinsic radioactivity
  good scintillation properties
  particle identification ability
  relatively low cost
  stability for long term operation

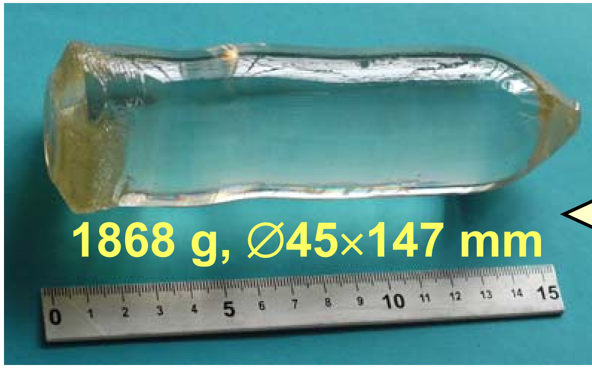


[1] J.D.Vergatos et al., RPP 75(2012)106301.

[2] ZPA 355 (1996) 433; PAN 59 (1996) 1; PRC 67 (2003) 014310; PRC 68 (2003) 035501; PRC 76 (2007) 064603; EPJA 36 (2008) 167; PRC 85 (2012) 044610.

R&D of enriched $^{116}CdWO_4$ scintillators

- **Deep purification of raw materials**
- **Low-thermal-gradient Czochralski technique**

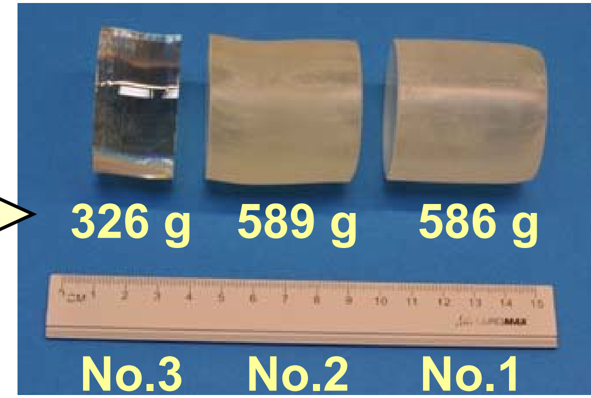


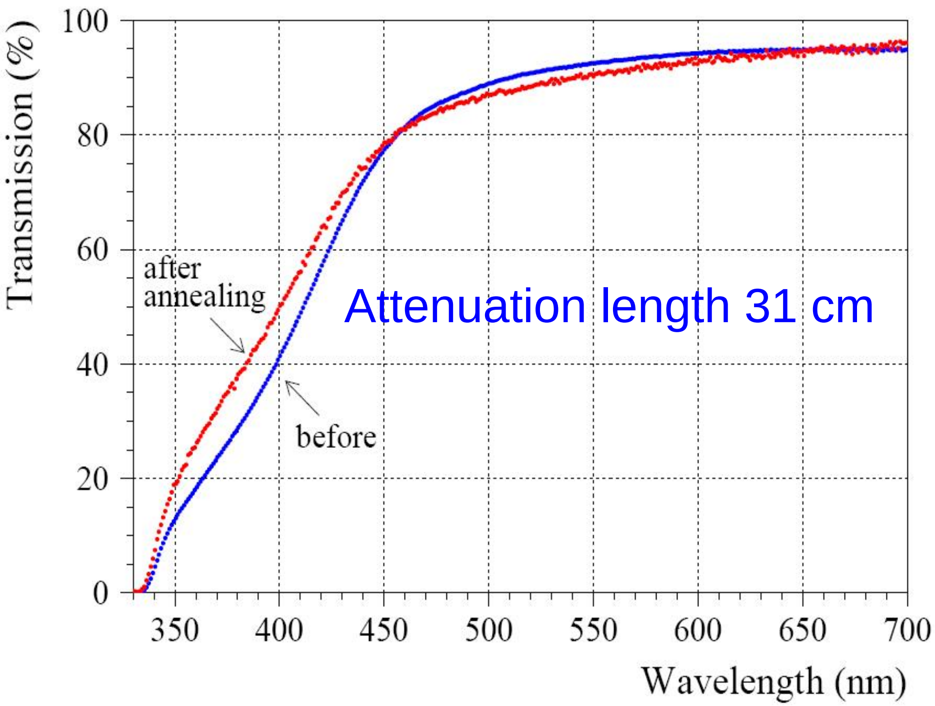
^{116}Cd enrichment ≈ 82%

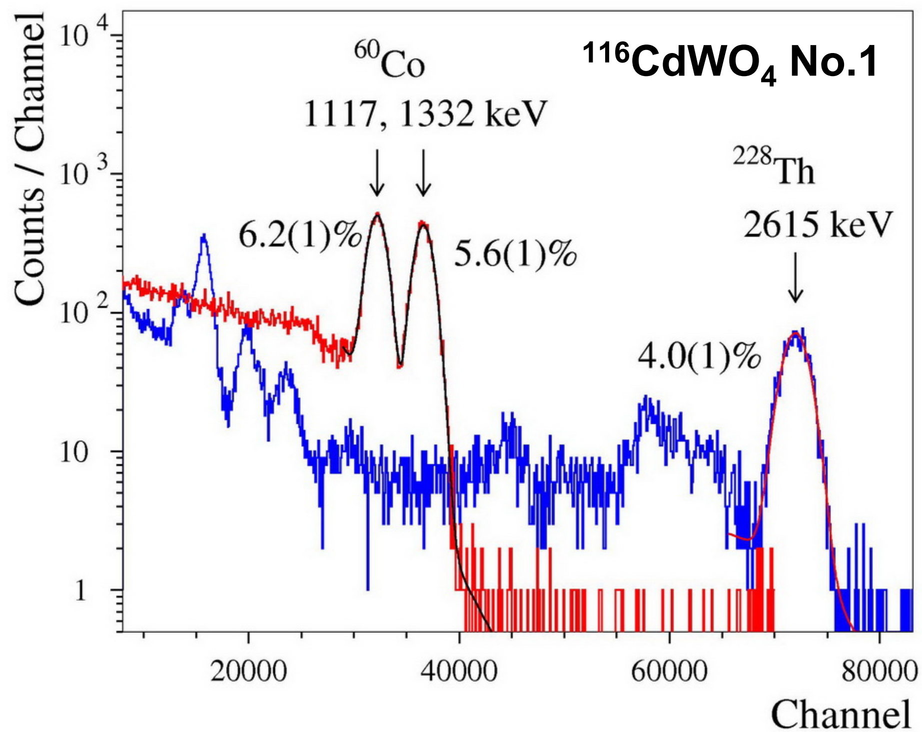
of initial charge

87% ⟷ **70%**

2% of irrecoverable losses



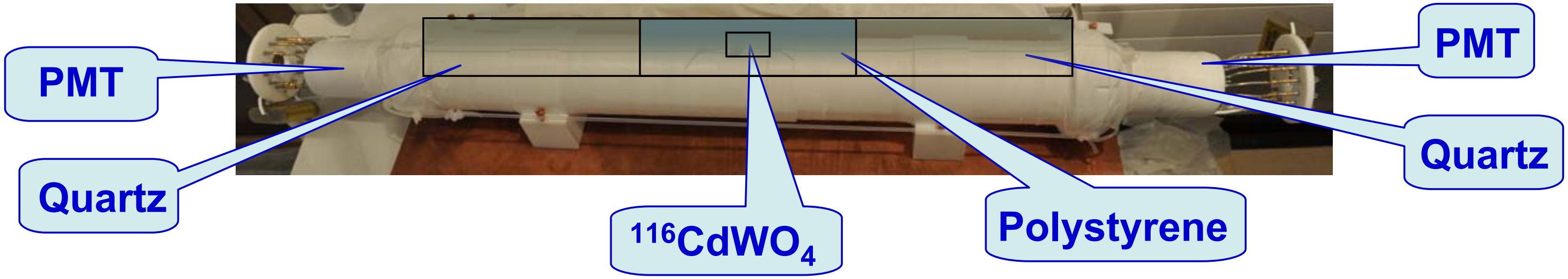




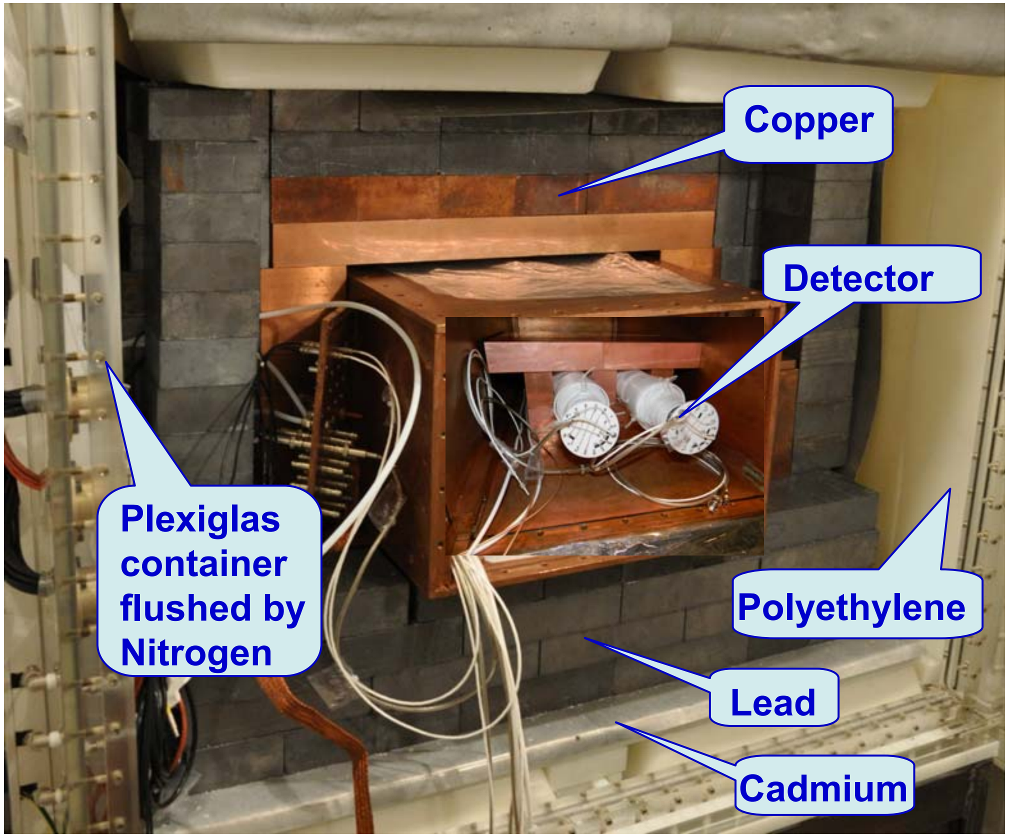
A.S. Barabash et al., JINST 06 (2011) P08011.

$^{116}CdWO_4$ scintillation detector

DAMA/R&D set-up, Laboratori Nazionali del Gran Sasso (Italy)



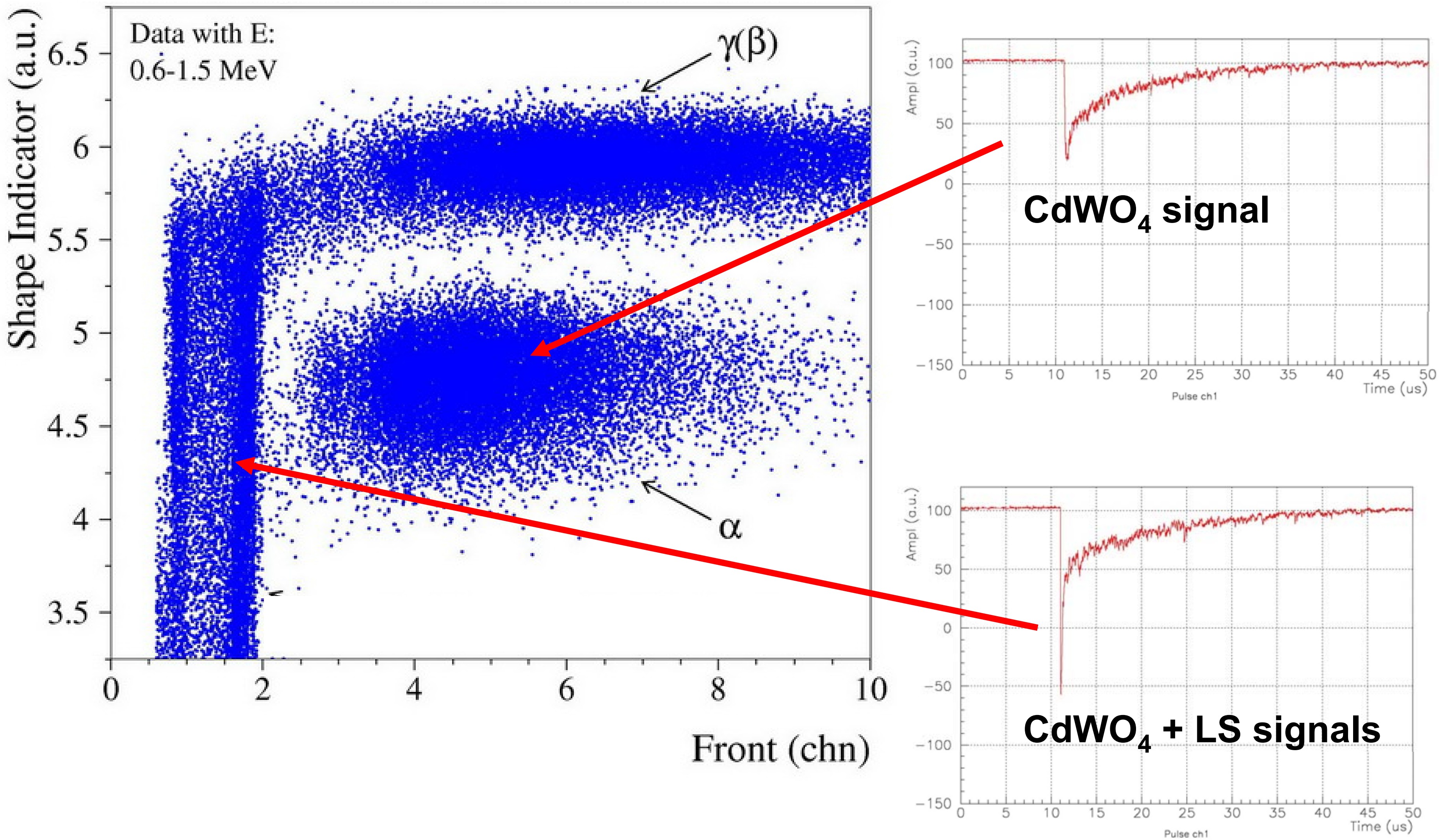
- **Two $^{116}CdWO_4$ crystals**
  ∅45×50 mm, ≈ 0.6 kg
- **Light guide**
  ∅70×194 mm, UPS923A
  ∅70×200 mm, quartz
- **Ultima Gold liquid scintillator**
- **Four low background 3″ PMTs**
  Hamamatsu R6233MOD
- **Transient digitizer**
  1 GS/s 8 bit Acqiris DC270
  50 MS/s, 50 μs pulse profile



A.S. Barabash et al., JINST 06 (2011) P08011.

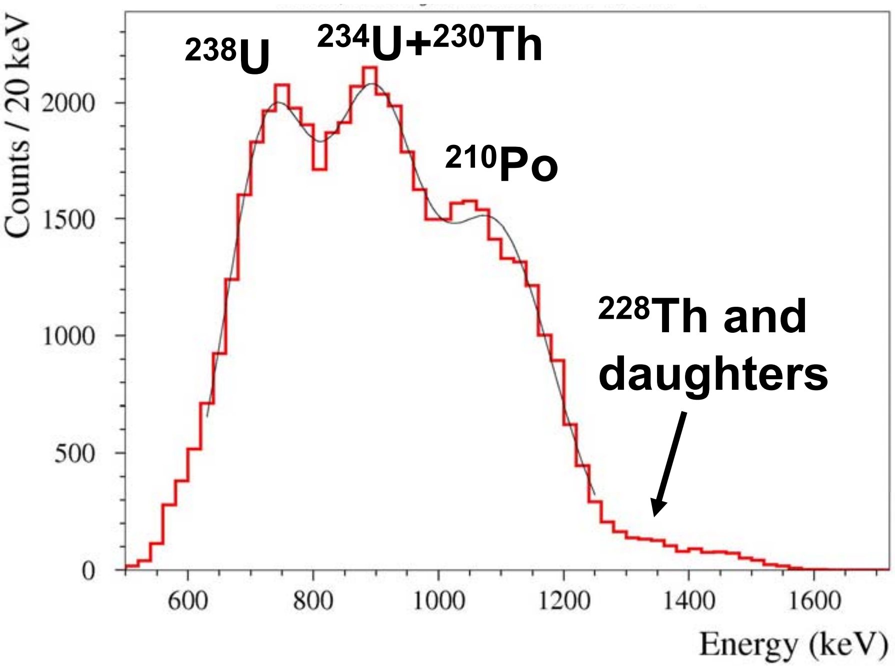
Particle identification ability

Pulse-shape analysis



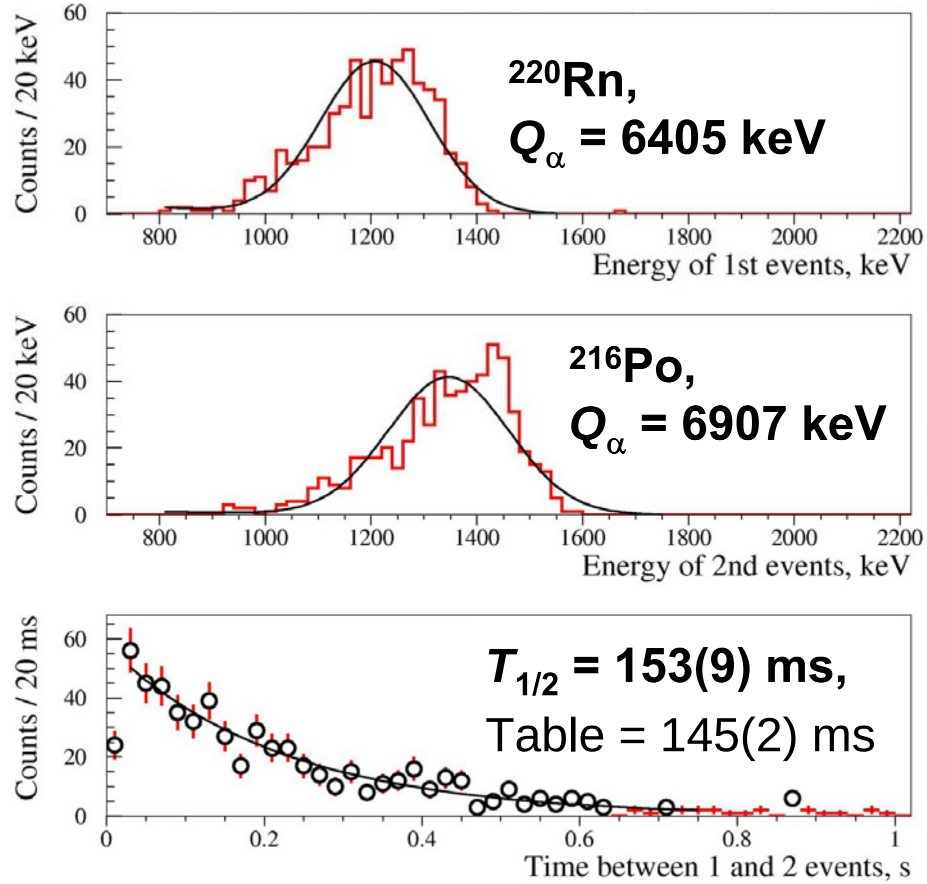
Activity of U/Th in the $^{116}CdWO_4$ crystals

Pulse-shape discrimination



Only limits on the ^{238,234}U, ^{230}Th, ^{210}Po activity were derived in [1]

Time-amplitude method



$^{116}CdWO_4$	Activity, mBq/kg					
	^{232}Th	^{228}Th	^{238}U	^{234}U+ ^{230}Th	^{210}Po	Total α
No.1	≤ 0.1	0.031(3)	0.5(2)	0.6(2)	0.6(2)	1.8(1)
No.2	≤ 0.1	0.054(5)	0.7(2)	0.8(2)	0.8(2)	2.6(1)

[1] A.S. Barabash et al., JINST 06 (2011) P08011.

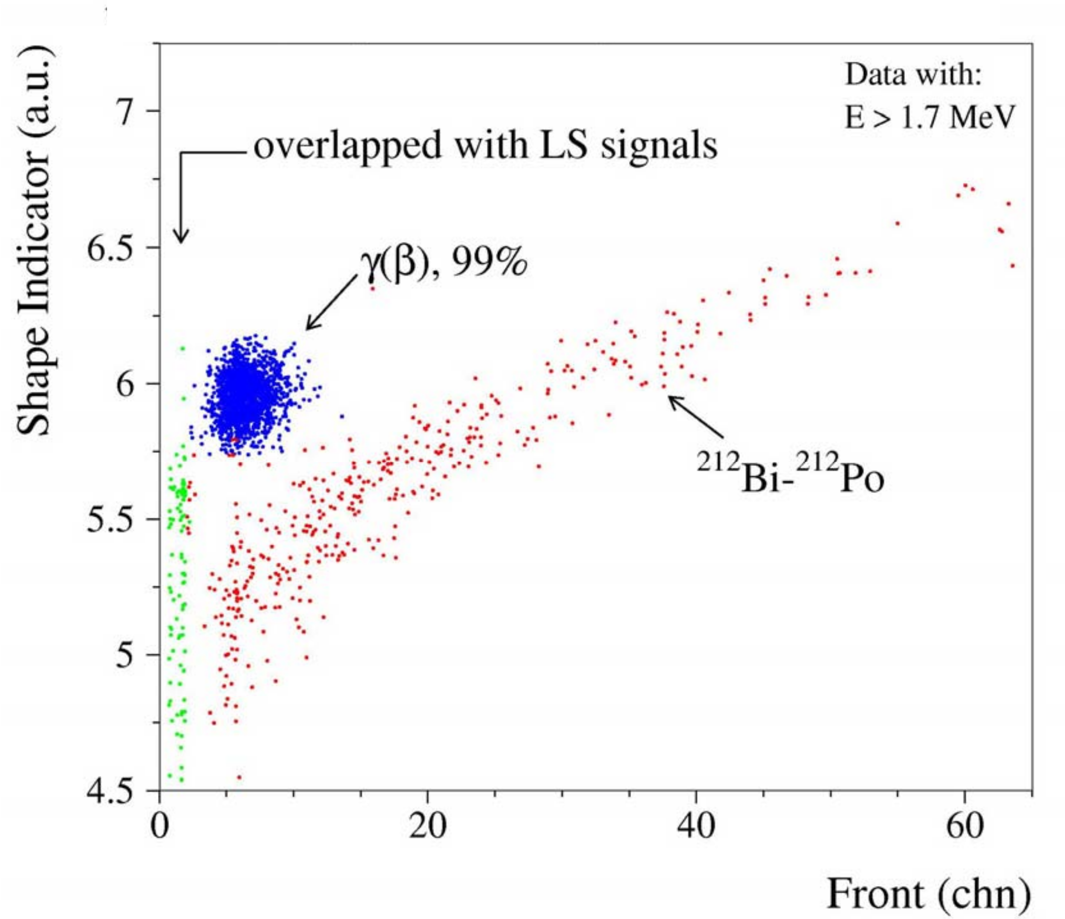
Selection of ^{212}Bi-^{212}Po events

^{212}Bi ($T_{1/2}$ = 60.55 s) → 64%, Q_β = 2254 keV → ^{212}Po ($T_{1/2}$ = 0.299 μs)

^{212}Bi → 36%, Q_α = 8954 keV → ^{208}Tl ($T_{1/2}$ = 3.053 m)

^{212}Po → Q_α = 8954 keV → ^{208}Pb (stable; ^{232}Th family)

^{208}Tl ($T_{1/2}$ = 3.053 m) → Q_β = 5001 keV → ^{208}Pb (stable; ^{232}Th family)



^{116}CdWO$_4$	Activity of ^{228}Th (in μBq/kg)	
	BiPo	t-A
No.1	32(2)	31(3)
No.2	51(3)	54(5)

Radiopurity of $^{116}CdWO_4$ crystals

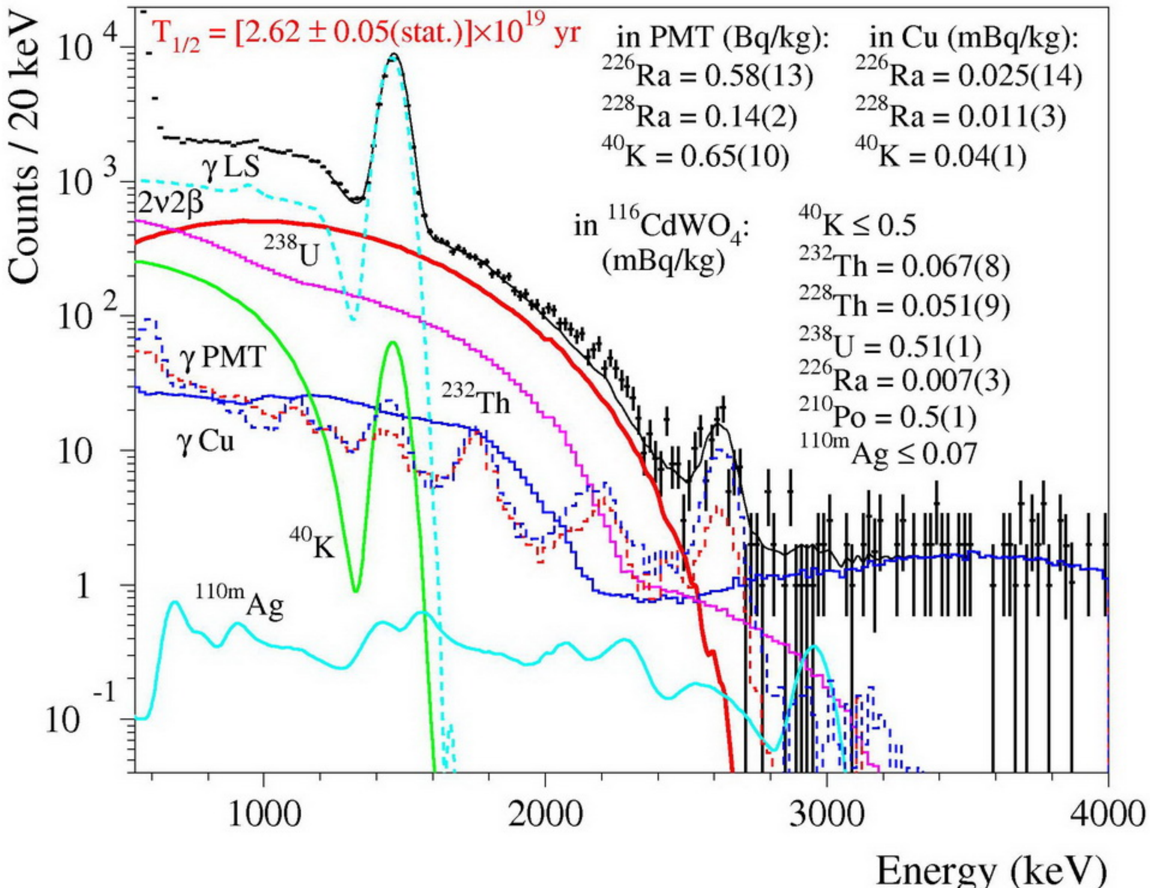
Source	Activity, mBq/kg			
	^{116}CWO [1]	Scraps [1]	^{116}CWO [2]	^{106}CWO [3]
^{232}Th	≤ 0.08	–	0.053(9)	≤ 0.07
^{228}Ra	≤ 0.2	9(2)	≤ 0.004	–
^{228}Th	0.031(3) – 0.054(5)	10(2)	0.039(2)	0.042(4)
^{227}Ac	≤ 0.002	–	0.0014(9)	–
^{238}U	0.5(2) – 0.7(2)	–	≤ 0.6	≤ 0.6
^{234}U	0.6(2) – 0.8(2)	–	≤ 0.5	≤ 0.4
^{226}Ra	≤ 0.005	64(4)	≤ 0.004	0.012(3)
^{210}Po	0.6(2) – 0.8(2)	–	≤ 0.4	≤ 0.2
$\Sigma\ \alpha$	1.8(1) – 2.6(1)	–	1.4(1)	2.1(2)
^{40}K	≤ 0.5	≤ 38	0.3(1)	≤ 1.4
^{90}Sr-^{90}Y	≤ 0.1	–	≤ 0.2	≤ 0.3
^{110m}Ag	≤ 0.07	–	–	≤ 0.06
^{113}Cd	100(10)	–	91(5)	182
^{113m}Cd	460(20)	–	1.1(1)	$116(4)\times10^3$
^{137}Cs	≤ 0.3	≤ 2.1	0.43(6)	–

[1] 10.1016/j.radmeas.2013.02.017; AIPCP1549(2013)201. [2] PRC68(2003)035501. [3] PRC85(2012)044610.

Fit of the $^{116}CdWO_4$ background

- Monte Carlo models by using EGS4 [1] & Decay0 [2]
- U/Th in $^{116}CdWO_4$ were bounded according to PSD and t-A results
- U/Th in PMTs from [3]
- Radiopurity of Cu is comparable with results in [4]
- Fit gives $N_{2\beta}$ = (4019 ± 63) events of 2ν2β decay of ^{116}Cd above 1.6 MeV
- Signal/BG ratio is ≈ 2.3

$^{116}CdWO_4$ 1.16 kg, 7832 h, PSD γ(β)=92%



$T_{1/2}$ (2ν2β, ^{116}Cd) = [2.6 ± 0.05(stat.) ± 0.3(syst.)] × 10^{19} yr

[1] W.R. Nelson et al., SLAC-Report-265 (1985).
[2] O.A. Ponkratenko et al., PAN 1282 (2000) 63; V.I. Tretyak, to be published.
[3] R. Bernabei et al., JINST 7 (2012) P03009.
[4] G. Heusser et al., Radionuclides in the Environment 8 (2006) 495.

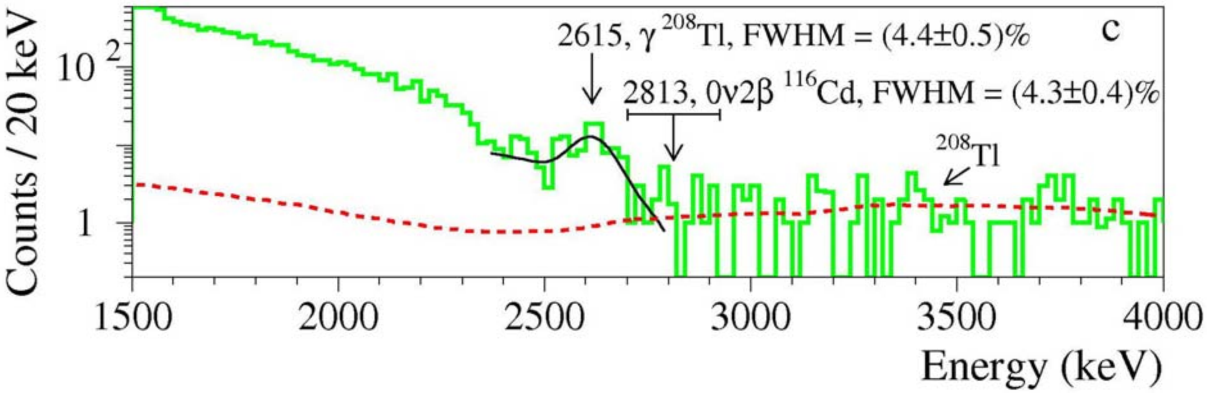
Half-live on $2\nu2\beta$ decay of ^{116}Cd (g.s→g.s.)

Experimental $T_{1/2}$, 10^{19} yr		
Present work	**Previous results**	
2.5 ± 0.5 [1]	**2.6** $^{+0.9}_{-0.5}$	[2]
2.6 ± 0.05(stat.) ± 0.3(syst.)	**2.9 ± 0.06**(stat.) $^{+0.4}_{-0.3}$(syst.)	[3]
	3.75 ± 0.35(stat.) ± **0.21**(syst.)	[4]
	2.88 ± 0.04(stat.) ± **0.16**(syst.)	[5]
	2.8 ± 0.2 [world average value]	[6]
	2.85± 0.15 [world average value]	[7]

[1] A.S. Barabash et al., Proc. NPAE-2012, Kyiv, 2013, pp. 353-356.
[2] H. Ejiri et al., J. Phys. Soc. Japan 64 (1995) 339.
[3] F.A. Danevich et al., Phys. Lett. B 344 (1995) 72; Phys. Rev. C 68 (2003) 035501.
[4] R. Arnold et al., JETP Lett. 61 (1995) 170; Z. Phys. C 72 (1996) 239.
[5] V.I. Tretyak on behalf of the NEMO-3 collaboration, AIP Conf. Proc. 1417 (2011) 125.
[6] A.S. Barabash, Phys. Rev. C 81 (2010) 035501.
[7] A.S. Barabash, talk at MEDEX'13, Prague, 2013.

Background in 0ν2β region of ^{116}Cd

$^{116}CdWO_4$, 1.04 kg×yr, LNGS (Italy)



Rate @ 2.7–2.9 MeV: 0.14(3) cnts/(keV×kg×yr)

Main contribution ^{208}Tl: int. (CWO), ext. (PMT+Cu)

Experimental $T_{1/2}$ (90% C.L.) on 0ν2β decay of ^{116}Cd				
Present work	Previous experiments			
5.7 × 10^{22}	**1.7 × 10^{23}**	$^{116}CdWO_4$	0.53 kg×yr	Solotvina experiment [1]
	1.3 × 10^{23}	^{116}Cd foil	1.95 kg×yr	NEMO-3 [2]
	9.4 × 10^{19}	CdZnTe	0.05 kg×yr	COBRA [3]

Reducing BG by a factor 2–20 ⇒ Sensitivity over 5 yr of measurements

$T_{1/2}$ ~ (0.5–1.5)×10^{24} yr
$\langle m_\nu \rangle$ ~ (0.4–1.4) eV

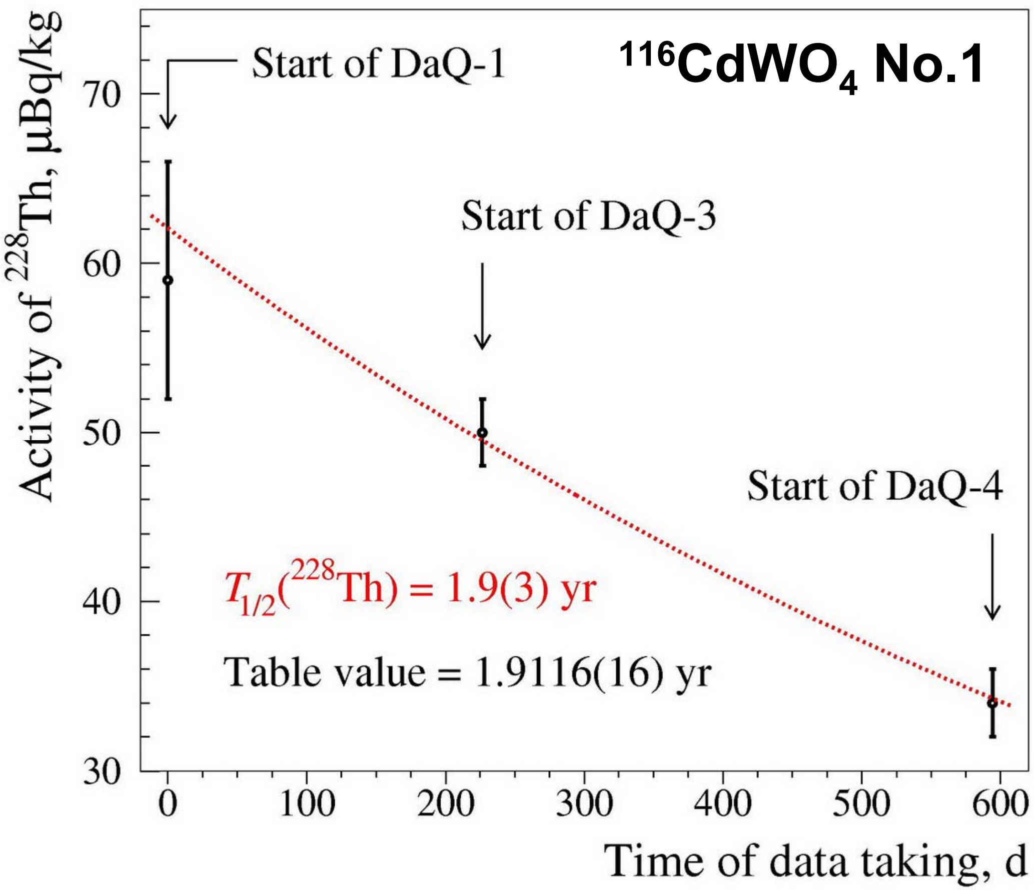
[1] F.A. Danevich et al., Phys. Rev. C 68 (2003) 035501.
[2] R.B. Pahlka et al., Phys. Procedia 37 (2012) 1241; R.B. Pahlka, Ph.D. thesis, 2010.
[3] J.V. Dawson et al., Phys. Rev. C 80 (2009) 025502.

How to decrease BG in $0\nu2\beta$ region of ^{116}Cd?

- **Internal BG decreases in time**
  ^{228}Th in ≈2 and ^{110m}Ag in ≈3

- **Removing of one LowBg PMT**
  \+ replacing by UltaLowBg PMT

PMT Hamamatsu	Activity, mBq/PMT	
	^{228}Ra	^{226}Ra
R6233MOD	18(3)	65(9)
R11065SEL	2.3	3.3



- **Adding of quartz light guide**
  or made from $PbWO_4$ scintillator

- **Recrystallization of $^{116}CdWO_4$**
  to remove Th/U thanks to observed low segregation

Summary

- **An experiment using $^{116}CdWO_4$ crystal scintillator (1.16 kg, enrichment is 82%) to search for 2β decay of ^{116}Cd is in progress at the Laboratori Nazionali del Gran Sasso (Italy)**

- **The $^{116}CdWO_4$ scintillators exhibit excellent optical and scintillation properties, and low level of radioactive contamination** (^{228}Th = (0.03–0.05) mBq/kg, $^{226}Ra \leq 0.005$ mBq/kg, total α activity ≈ (2–3) mBq/kg)

- **Low segregation of Th and Ra by $CdWO_4$ was observed**

- **After ≈1.0 kg×yr of data taking the 2ν2β decay of ^{116}Cd was measured with the half-life [2.6 ± 0.05(stat.) ± 0.3(syst.)] × 10^{19} yr**

- **R&D to improve the background (caused mainly by 2615 keV γ quanta) is in progress. Assuming factor 2–20 of BG suppression the expected sensitivity of a 5 yr experiment is**

  $T_{1/2}$ (0ν2β, ^{116}Cd) ~ (0.5–1.5) × 10^{24} yr ⇒ $\langle m_\nu \rangle$ ~ (0.4–1.4) eV