Cryogenic search for neutrinoless double beta decay of cadmium (CYGNUS project)

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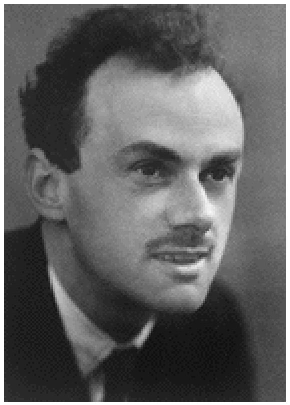
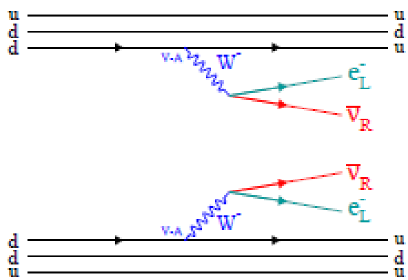
- Choice of ^{116}Cd
- 2β of ^{116}Cd with conventional scintillation detectors
- CYGNUS: low temperature breakthrough
- Conclusions and Prospects

Double beta (2β) decay

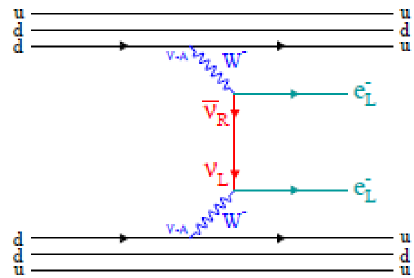
and particle physics



Paul Adrien Maurice Dirac



2ν2β decay



0ν2β decay

Ettore Majorana

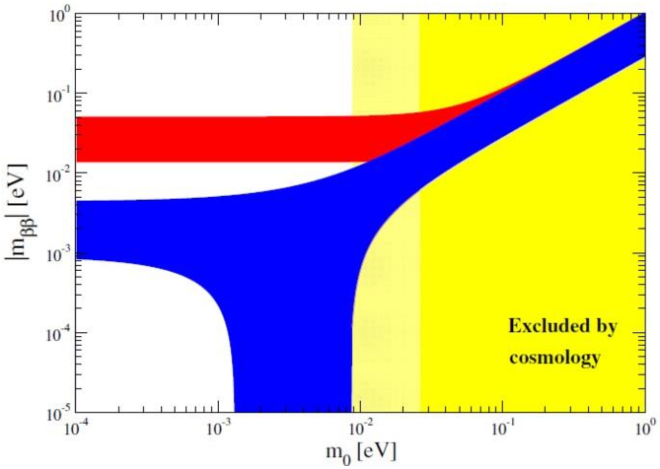
The 2ν2β decay is allowed in the Standard Model, observed in 11 nuclei with $T_{1/2}$~10^{19}-10^{24} yr

0ν2β decay **breaks the Lepton number** and is possible if the neutrino is a Majorana particle

- Sensitive to the absolute value of the neutrino mass, the neutrino mass hierarchy, the Majorana CP phases
- The 0ν2β decay can be mediated by presence of right handed currents in weak interactions, massless (or very light) Nambu-Goldstone bosons (majorons), and many other effects beyond the Standard Model

Status of 0ν2β decay experiments

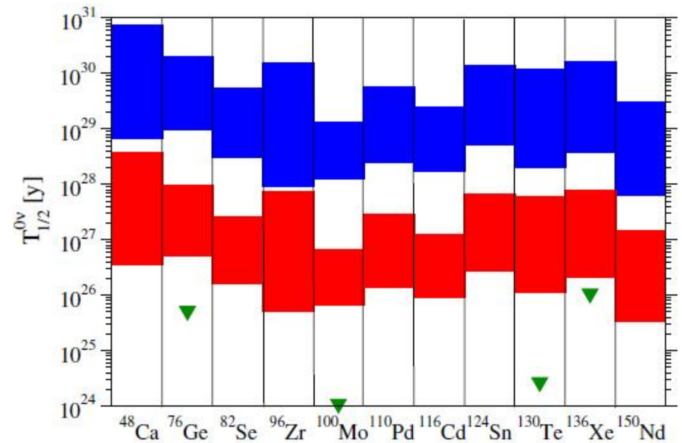
- The 0ν2β is not observed, the best limits: lim$T_{1/2}$~10^{24}-10^{26} yr → ⟨m_ν⟩~0.1-1 eV
- The experimental sensitivity should be advanced to explore the inverted hierarchy of the neutrino mass ⟨m_ν⟩ ~ 0.02-0.05 eV, $T_{1/2}$~10^{26} - 10^{27} yr



Normal Hierarchy

?

Inverted Hierarchy



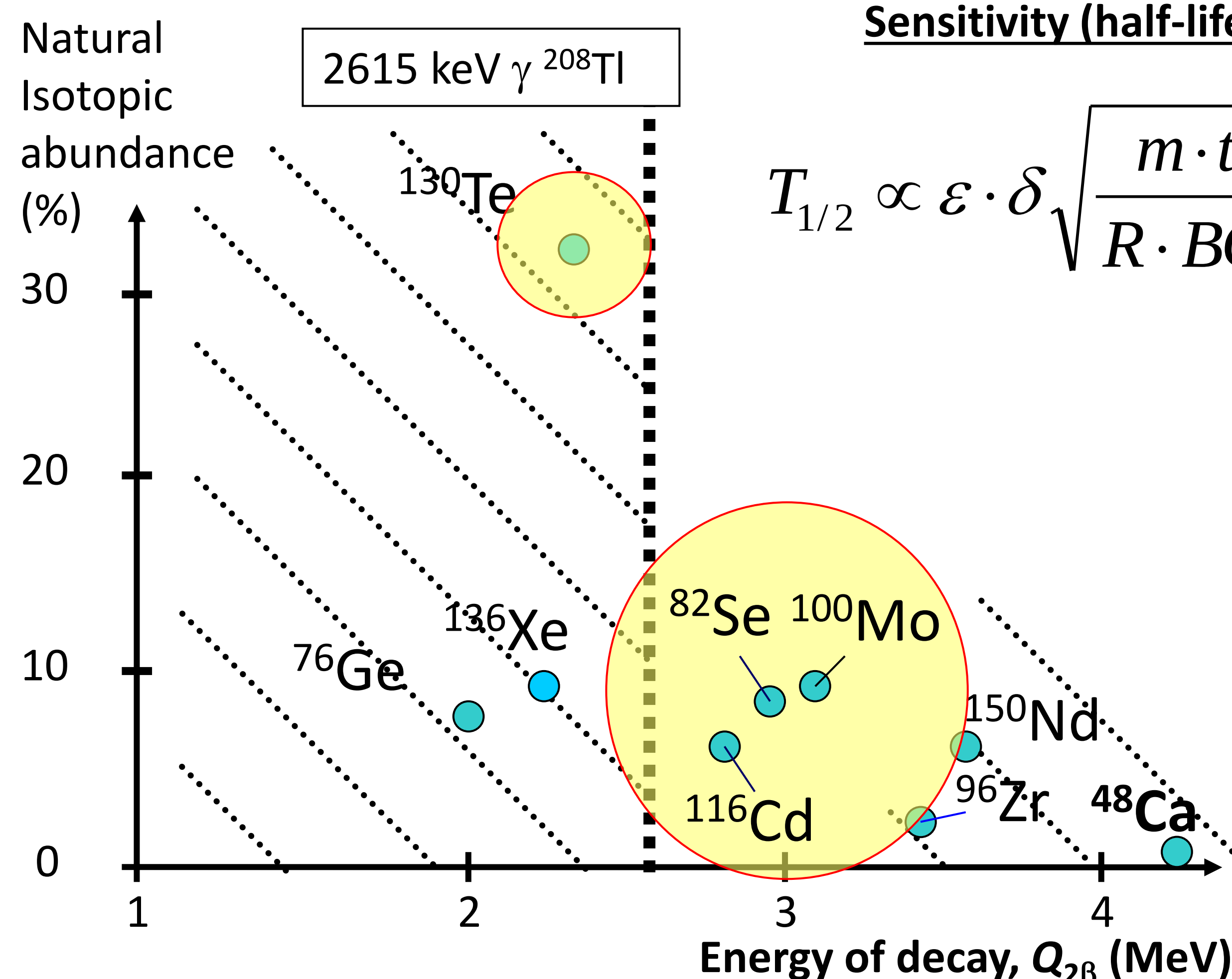
NME of the 0ν2β decay calculated in the framework of different approaches

- Investigations of several nuclei are requested:
  - observation of 0ν2β in several nuclei
  - the ambiguity of NME calculations
  - possible breakthroughs in detection technique
  - test the NME calculations by using the ratio of lifetimes

[1] J.D.Vergados, H.Ejiri, F.Šimkovic, Neutrinoless double beta decay and neutrino mass, IJMPE 25 (2016) 1630007

- Choice of ^{116}Cd

Choice of 2β nuclei



Sensitivity (half-life $T_{1/2}$) of 2β experiments:

$$T_{1/2} \propto \varepsilon \cdot \delta \sqrt{\frac{m \cdot t}{R \cdot BG}}$$

ε – detection efficiency
δ – concentration of 2β isotope
***m* – mass of detector**
***t* – time of measurements**
***R* – energy resolution**
***BG* – background**

- **Large $Q_{2\beta}$ > 2615 keV**

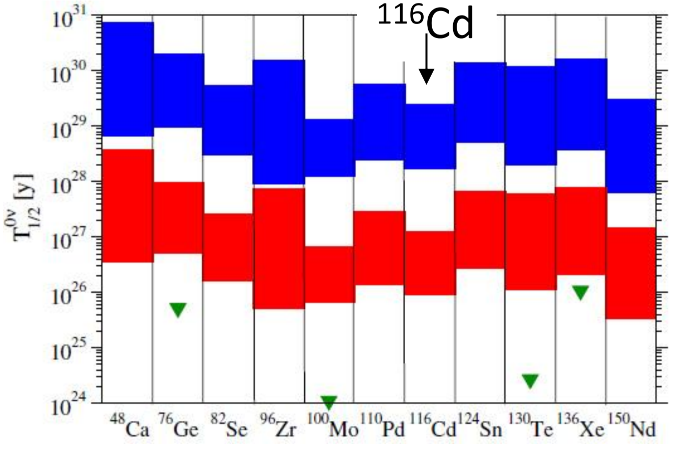
- **Enrichment ~ 10^2 - 10^3 kg**

- **High detection efficiency**
- **Low background**
- **High energy resolution**

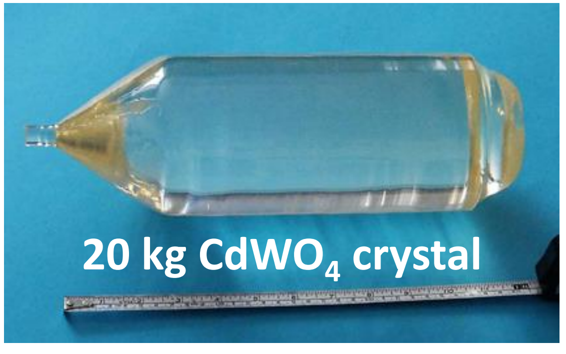
There are crystal scintillators with ^{82}Se, ^{100}Mo and ^{116}Cd, ^{130}Te is component of TeO_2

^{116}Cd is one of the "gold" 2β nuclei

- High energy of decay $Q_{2\beta}$=2813.49(13) keV, the $Q_{2\beta}$ is known with high accuracy
- Comparatively high isotopic abundance δ=7.5 2(54)%, possibility of gas centrifugation
- Promising theoretical estimations in the framework of different methods: IBM, QRPA-TBC, QRPA-Jy, NREDF, REDF [1]



- Existence of detector: $CdWO_4$ crystal scintillators

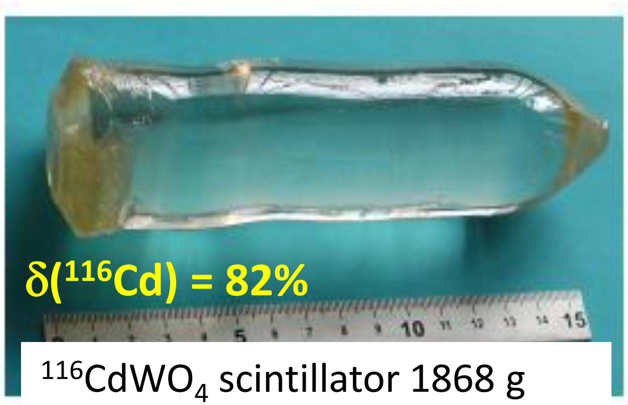


- Production of high quality $CdWO_4$ crystal scintillators is well established

[1] J.D.Vergados, H.Ejiri, F.Šimkovic, Neutrinoless double beta decay and neutrino mass, IJMPE 25 (2016) 1630007

• 2β of ^{116}Cd with conventional scintillation detectors

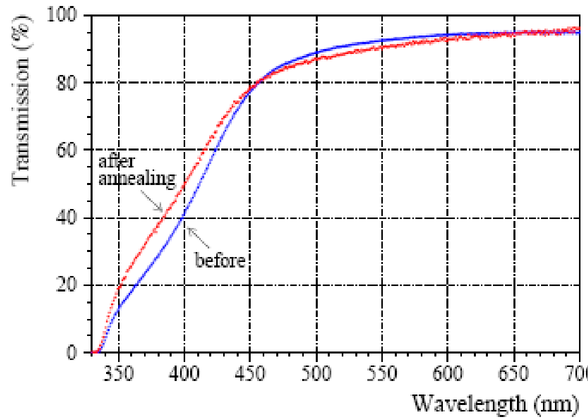
R&D of enriched $^{116}CdWO_4$ crystal scintillators



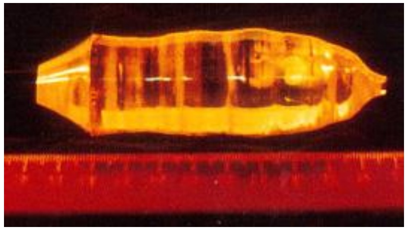
$^{116}CdWO_4$ scintillator 1868 g

Yield of crystal 87%

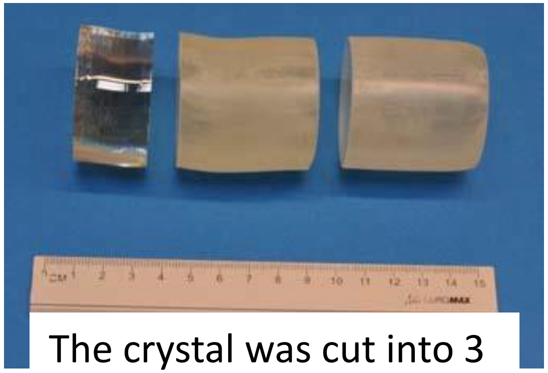
Losses of ^{116}Cd ≈ 2%



Optical transmission curve of $^{116}CdWO_4$ crystal before and after annealing

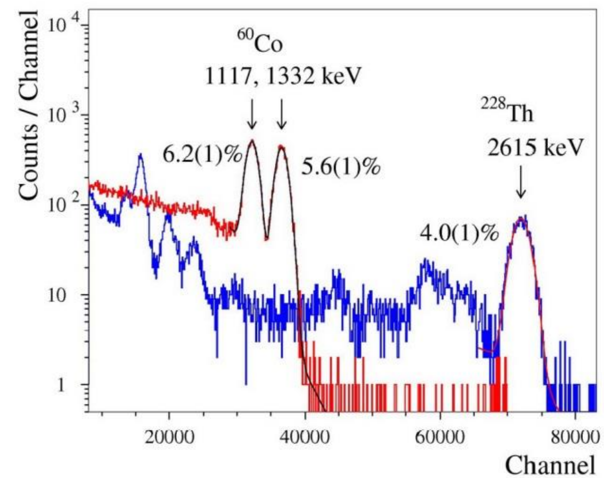


$^{116}CdWO_4$ crystal (510 g) grown in 1986 for the Solotvina experiment [2]



The crystal was cut into 3 scintillation elements

The excellent optical and scintillation properties were obtained thanks to the deep purification of ^{116}Cd and W, and advantages of the low-thermal-gradient Czochralski technique [1]

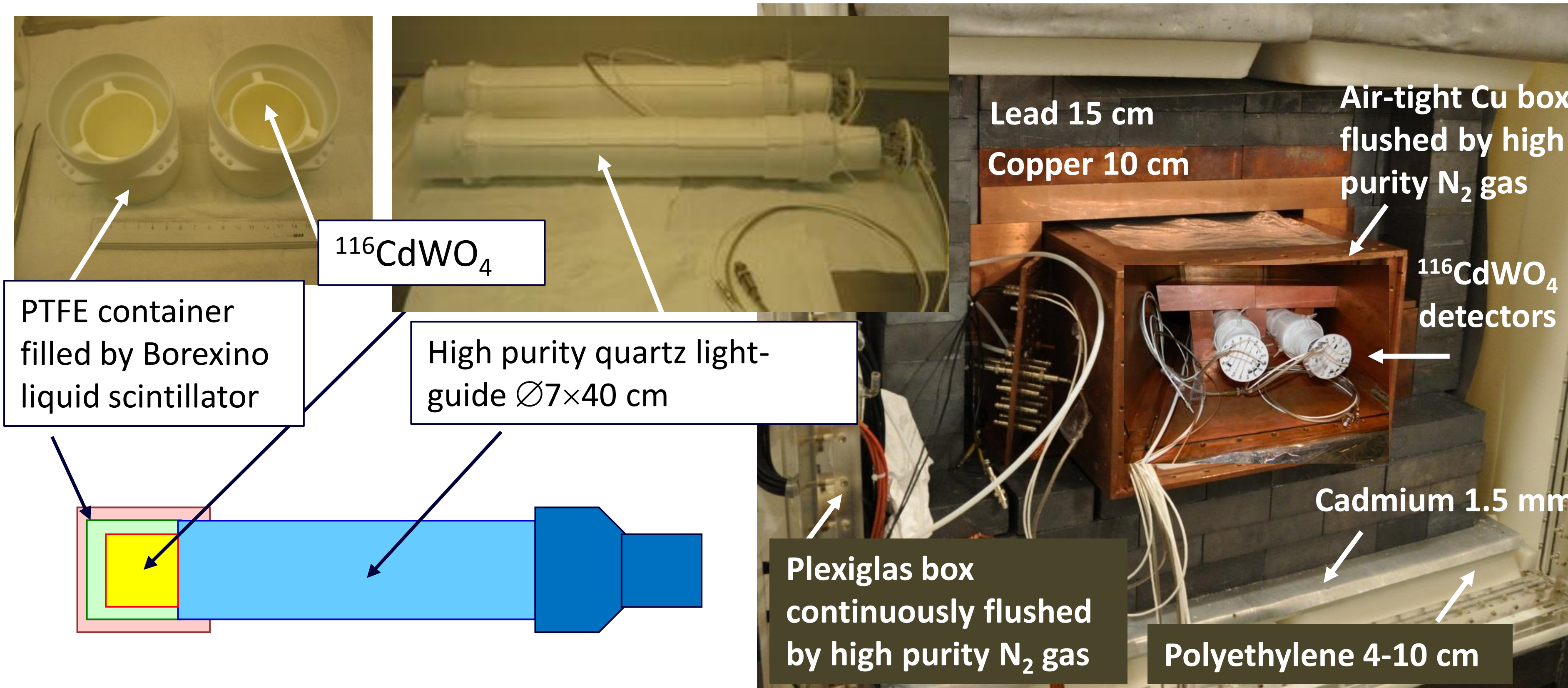


[1] A.S. Barabash et al., JINST 06(2011) p08011
[2] F.A.Danevich et al., JETP Lettt. 49 (1989) 476

- 2β of ^{116}Cd with conventional scintillation detectors

Low background $^{116}CdWO_4$ scintillation detector

Gran Sasso underground laboratory

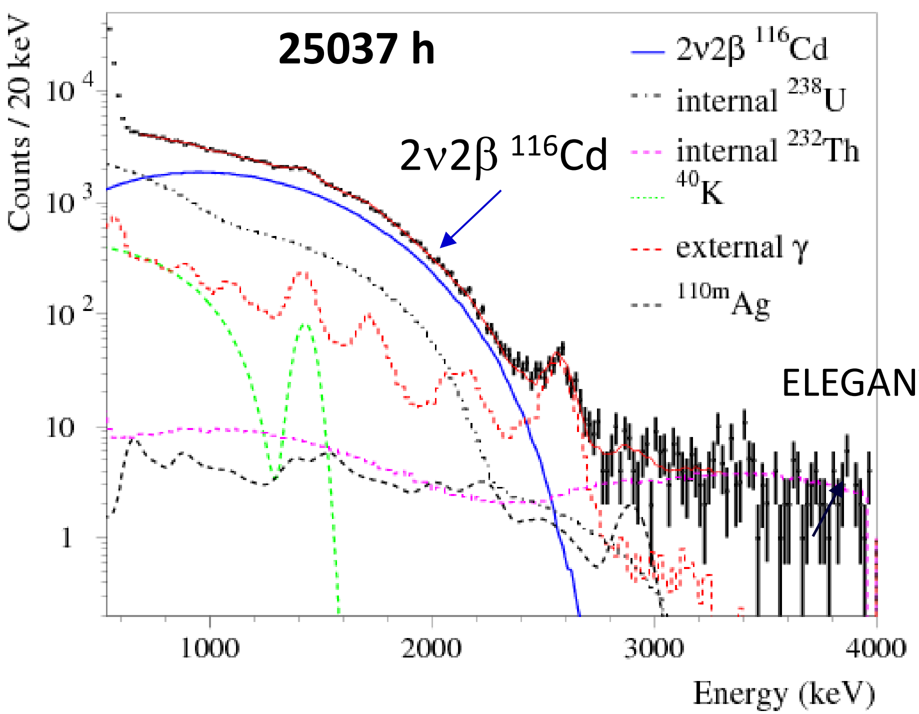


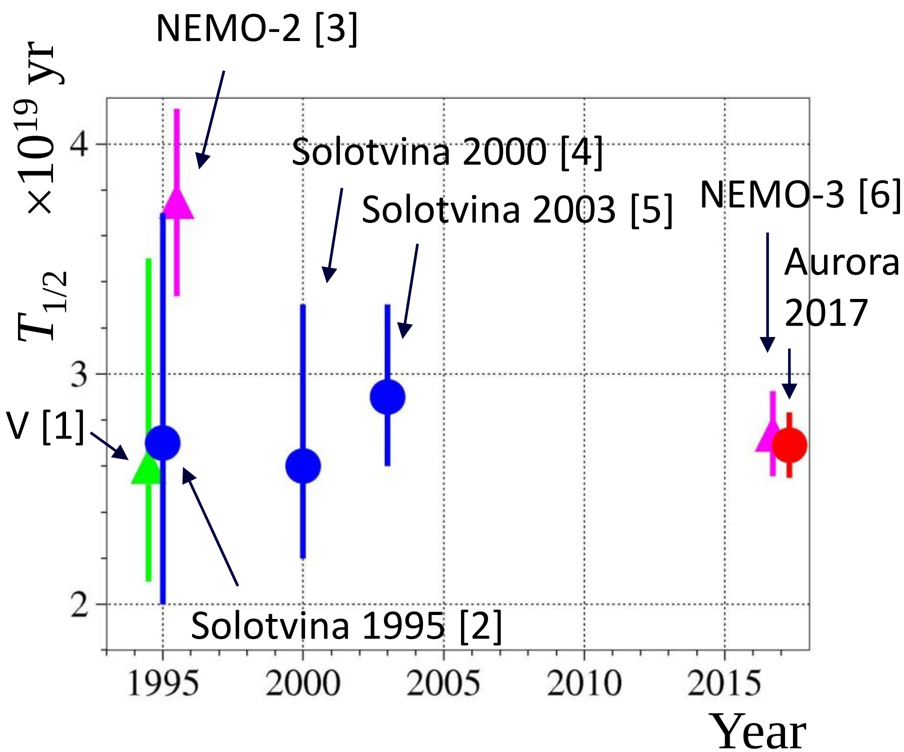
FWHM ≈ 5% at 2615 keV

DAMA R&D set-up

- 2β of ^{116}Cd with conventional scintillation detectors

Two neutrino 2β decay of ^{116}Cd





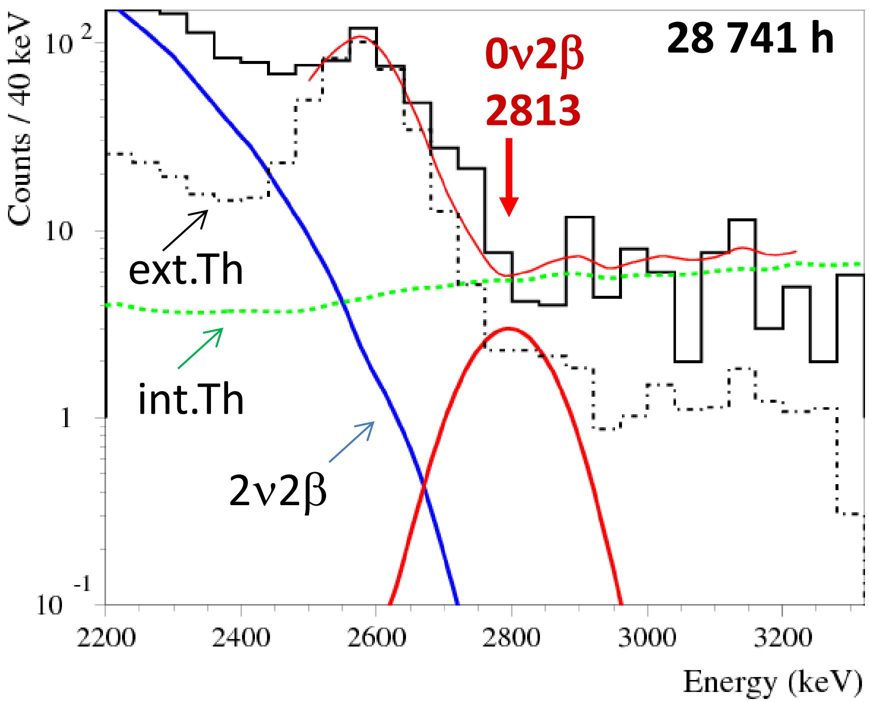
$$T_{1/2}^{2\nu 2\beta} = [2.69 \pm 0.02(\text{stat}) \pm 0.14(\text{syst})] \times 10^{19} \text{ yr}$$

The most accurate value of $T_{1/2}^{2\nu 2\beta}$ (error 5.3%)

[1] H. Ejiri et al., J. Phys. Soc. Japan 64 (1995) 339; [2] F.A. Danevich et al., Phys. Lett. B 344 (1995) 72; [3] R.Arnold et al., Z. Phys. C 72 (1996) 239; [4] F.A.Danevich et al., PRC 62 (2000) 045501; [5] F.A.Danevich et al., PRC 68 (2003) 035501; [7] R. Arnold et al., PRC 95 (2017) 012007;

- 2β of ^{116}Cd with conventional scintillation detectors

Limit on 0ν2β decay of ^{116}Cd



Background was reduced by selection of events:
^{212}Bi (α) → ^{208}Tl (Q_β = 5 MeV, $T_{1/2}$ = 3 min)
0.11 → 0.07 cnts/(keV yr kg) in the ROI 2.7-2.9 MeV

$$T_{1/2}^{0\nu} \geq 2.4 \times 10^{23} \text{ yr}$$

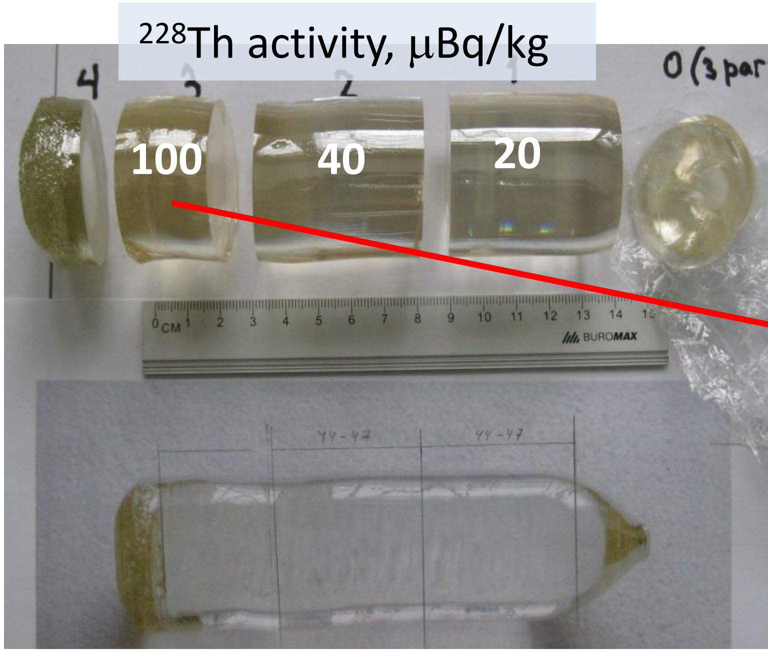
Effective Majorana neutrino mass:
$\langle m_\nu \rangle \leq (1.1 - 1.6)$ eV [1-4]

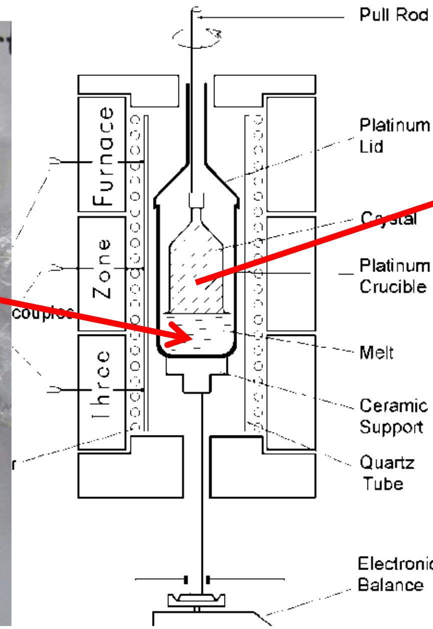
The best ^{116}Cd 2β experiment realized with a negligible budget

[1] T.R. Rodr´ıguez, G. Mart´ınez-Pinedo, Phys. Rev. Lett. 105, 252503 (2010).
[2] F. Šimkovic, V. Rodin, A. Faessler, P. Vogel, Phys. Rev. C 87, 045501 (2013).
[3] J. Hyvärinen, J. Suhonen, Phys. Rev. C 91, 024613 (2015).
[4] J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91, 034304 (2015).

- 2β of ^{116}Cd with conventional scintillation detectors

An important technical result: $^{116}CdWO_4$ crystals radiopurity was improved by recrystallization





2nd crystallization by the low-thermal-gradient Czochralski technique

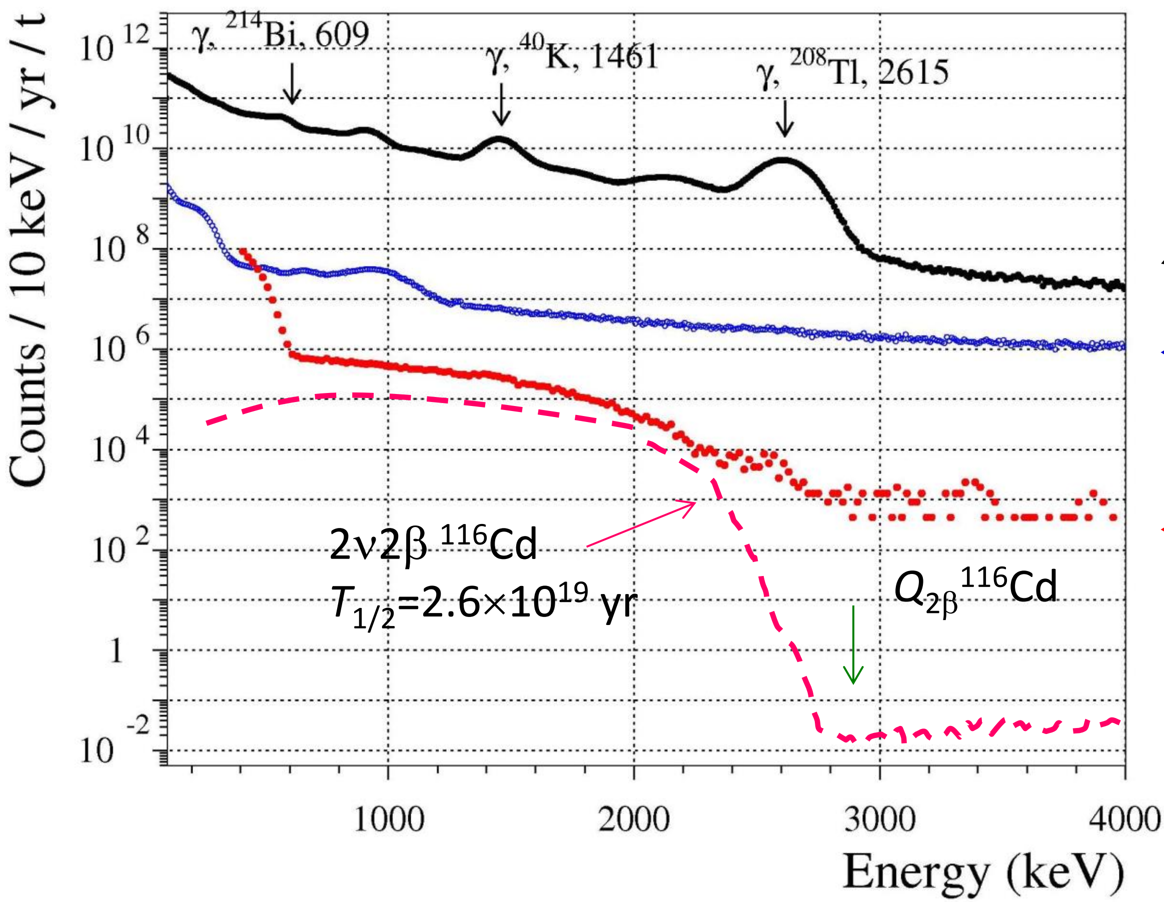
The Th contamination was reduced by a factor 10, down to the level 0.01 mBq/kg. The total α activity of U,Th was reduced by 3, down to 1.6 mBq/kg [1]

$^{116}CdWO_4$ crystals of ~μBq/kg purity can be obtained

[1] A.S.Barabash et al., NIMA 833 (2016) 77

- CYGNUS: low temperature breakthrough

A significant background reduction is requested for CUPID



$CdWO_4$ 2.2 kg no shield

$CdWO_4$ 2.2 kg
15 cm Pb, 11 cm Cu,
μ-veto (surface lab)

$^{116}CdWO_4$ 1.2 kg
DAMA R&D at LNGS

CUPID [1,2]

[1] G. Wang et al., CUPID: CUORE (Cryogenic Underground Observatory for Rare Events) Upgrade with Particle IDentification, arXiv:1504.03599

[2] G. Wang et al.,, R&D towards CUPID (CUORE Upgrade with Particle IDentification), arXiv:1504.03612

- CYGNUS: low temperature breakthrough

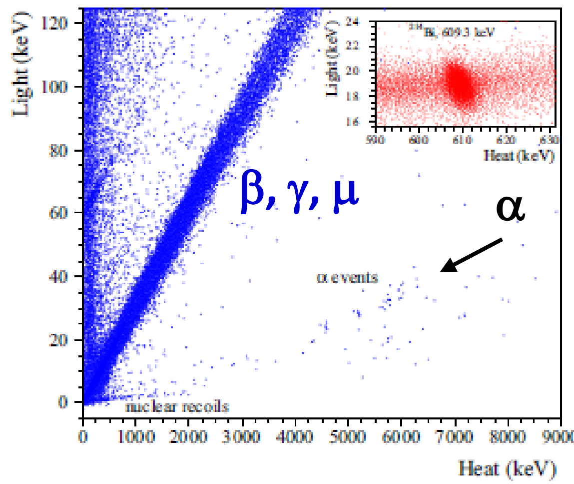
Cryogenic search for 0ν2β decay of ^{116}Cd

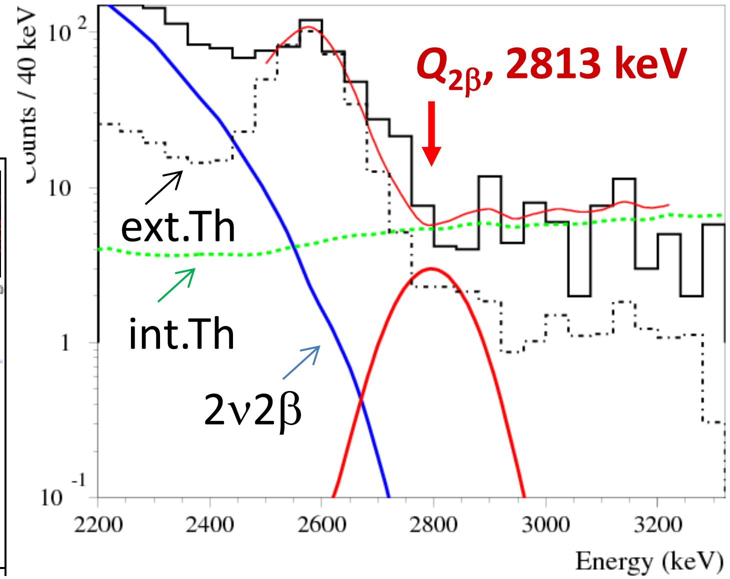
project **CYGNUS**: Cryogenic search for neutrinoless double beta decay of cadmium

- Energy resolution: 130 keV → 5-7 keV at $Q_{2\beta}$ [1,2]
- Background can be reduced: → 1.4 cnts in 10 keV ROI over 3 yr

The reduction of background (mainly ^{208}Tl) is expected due to particle discrimination and high energy resolution to αs

$$^{212}\text{Bi} \xrightarrow{\alpha} {}^{208}\text{Tl} \xrightarrow{\beta}$$





- **Search for 0ν2β decay of ^{116}Cd with advanced sensitivity:** $\lim T_{1/2}^{0\nu} \sim 8\times10^{23}$ yr (over 3 yr)
- **Demonstration of ^{116}Cd option capability for the large scale experiment (i.e., CUPID)**
- **Advantage of ^{116}Cd is lower BG due to random CC of 2ν2β decay** $(T_{1/2}^{2\nu} = 2.69\times10^{19}$ yr$)$

[1] A.S. Barabash et al., EPJC 76 (2016) 487
[2] C. Arnaboldi et al., Astropart. Phys. 34 (2010) 143.

In addition to $0\nu2\beta$ of ^{116}Cd one could investigate some other rare processes using $CdWO_4$:

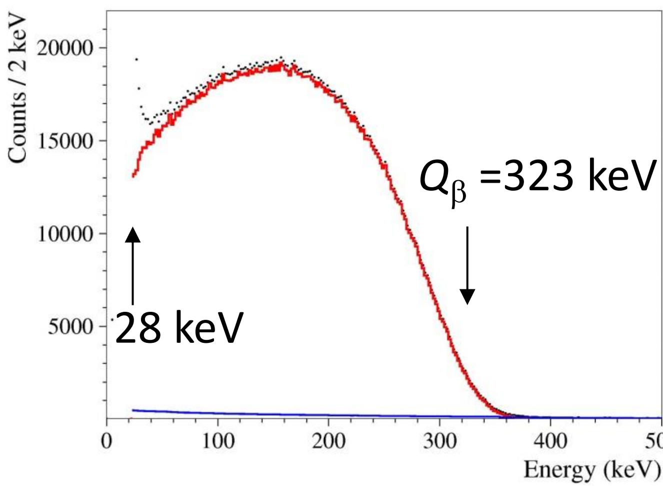
- Two neutrino 2β of ^{116}Cd can be studied with a very high accuracy (a good example is $2\nu2\beta$ of ^{100}Mo with $Li_2{}^{100}MoO_4$)
- 2β of ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{180}W (resonant $0\nu2\varepsilon$), ^{186}W
- β decay of ^{113}Cd to study the axial vector coupling constant g_A
- α decay of ^{180}W
- Search for eka-tungsten [1]

[1] P Belli et al., Search for long-lived superheavy eka-tungsten with radiopure ZnWO4 crystal scintillator, Phys. Scr. 90 (2015) 085301

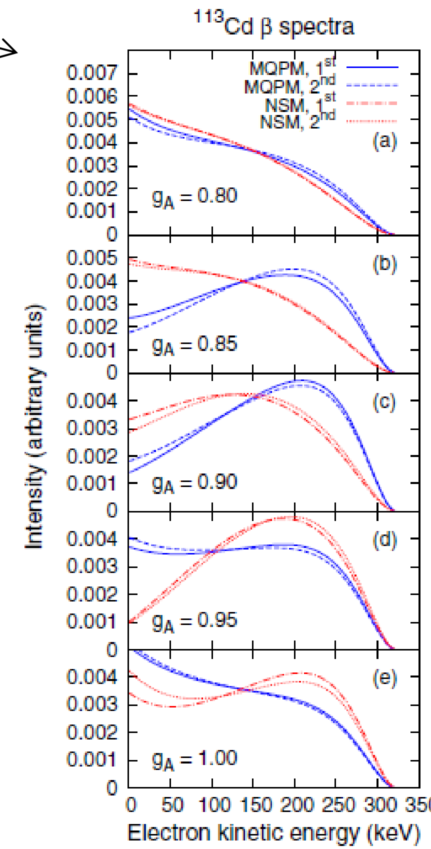
- CYGNUS: low temperature breakthrough

An example: β decay of ^{113}Cd

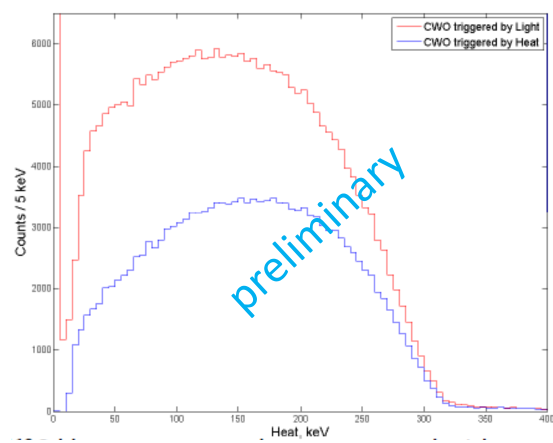
- the axial vector coupling constant g_A is a crucial parameter to calculate nuclear matrix elements for neutrinoless double beta decay
- the calculated shape of the ^{113}Cd β spectrum is quite sensitive to the values of g_V and g_A [1]



β spectrum of ^{113}Cd measured with $CdWO_4$ scintillator in the DAMA R&D set-up at the Gran Sasso Lab [2]



β spectrum of ^{113}Cd measured with $CdWO_4$ low temperature scintillator in the EDELWEISS set-up at the Modane Lab



Goal: energy threshold ~5 keV

[1] M. Haaranen, P. C. Srivastava, J. Suhonen, PRC 93 (2016) 034308

[2] P. Belli et al., PRC 76 (2007) 064603

Conclusions and Prospects

- ^{116}Cd is one of the most promising $0\nu2\beta$ candidates
- $CdWO_4$ scintillators: high energy resolution, radiopure, the production (including crystals from enriched cadmium) is well stablished
- CYGNUS low temperature $^{116}CdWO_4$ experiment will investigate the $0\nu2\beta$ decay of ^{116}Cd with a sensitivity $\lim T_{1/2}^{0\nu} \sim 8\times10^{23}$ yr (over 3 yr), and set a basis for ^{116}Cd in CUPID