Investigation of rare nuclear decays by using scintillation detectors

Fedor Danevich

Institute for Nuclear Research 03028 Kyiv, Ukraine
CSNSM, Univ. Paris-Sud, CNRS/IN2P3, Univ. Paris-Saclay, 91405 Orsay, France

Acknowledgment to the "Jean d'Alembert" grants program of the University of Paris-Saclay

université
PARIS-SACLAY

Content

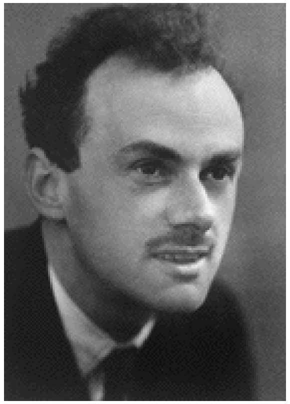
- Advantages of scintillators
- 2β with conventional scintillation detectors
- Prospects for 2β with low temperature scintillators
- β decay of ^{113}Cd and g_A
- Conclusions

Advantages of scintillators

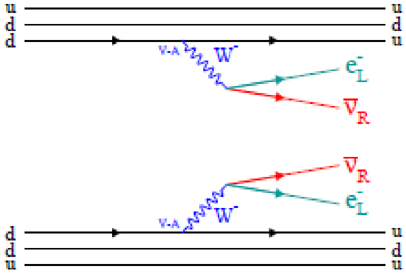
- **Presence of element of interest ⇒ high detection efficiency**
- Stable operation over years, Large volume, Low cost
- Low radioactive contamination (~ μBq/kg level of ^{228}Th and ^{226}Ra for the most radiopure materials)

Double beta (2β) decay

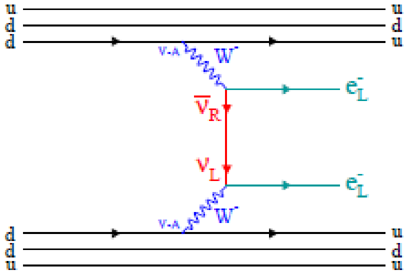
and neutrino physics



Paul Adrien Maurice Dirac



2ν2β decay



0ν2β decay

Ettore Majorana

The 2ν2β is detected in 11 nuclei ($T_{1/2} \sim 10^{18}$-10^{24} yr)

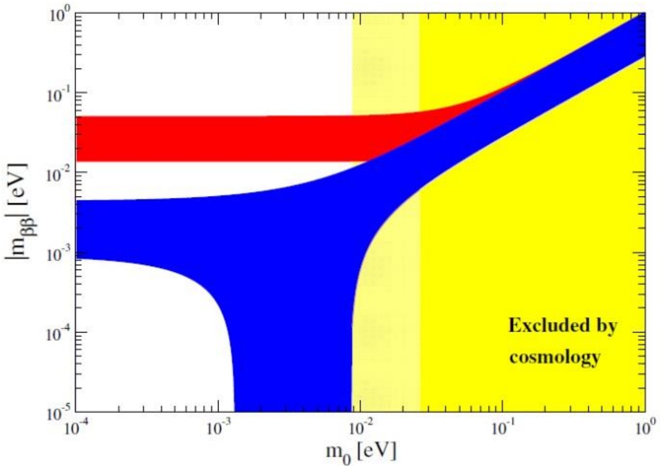
0ν2β decay breaks the Lepton number, and is possible if the neutrino is a Majorana particle [1]

- 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

[1] E. Majorana, Teoria simmetrica dell'elettrone e del positrone, Nuovo Cimento 14 (1937) 171

Status of 2β decay experiments

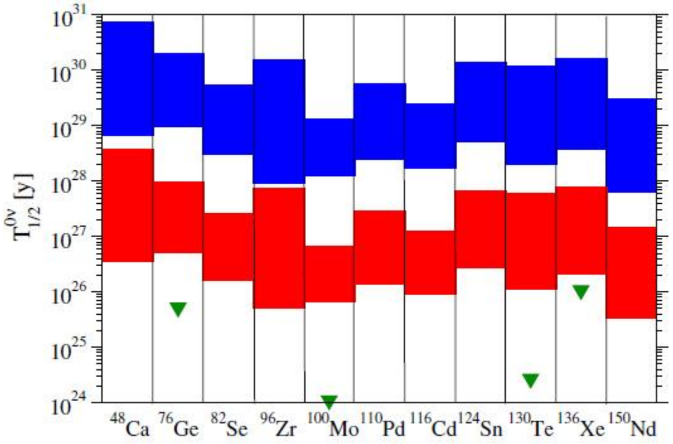
- The 0ν2β is not observed, the best limits: $\lim T_{1/2} \sim 10^{24}$-$10^{26}$ yr → $\langle m_\nu \rangle \sim 0.1$-1 eV
- The experimental sensitivity should be advanced to explore the inverted hierarchy of the neutrino mass $\langle m_\nu \rangle \sim 0.02$-0.05 eV, $T_{1/2} \sim 10^{26}$ - 10^{27}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



Normal Hierarchy

?

Inverted Hierarchy

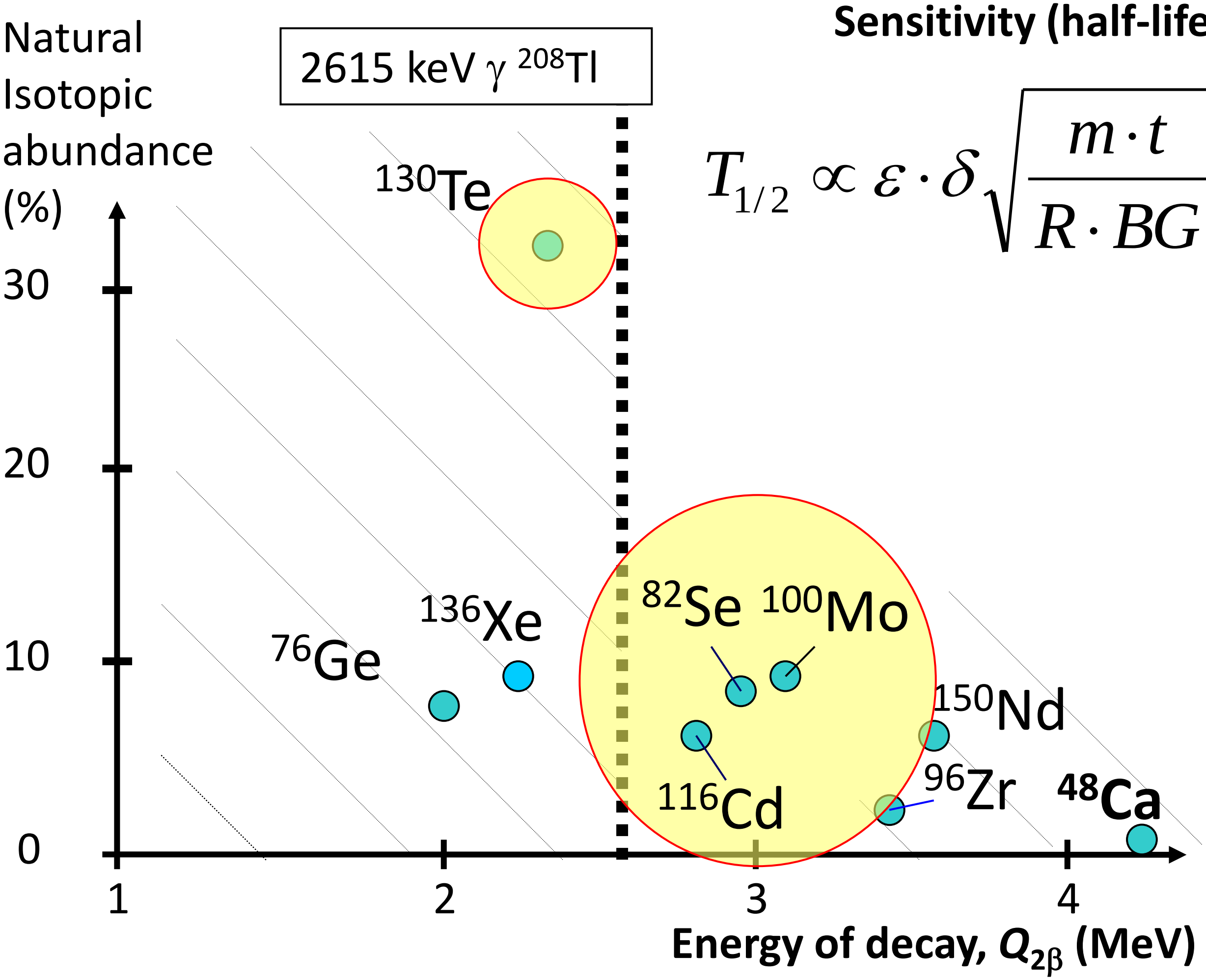


NME of the 0ν2β decay calculated in the framework of different approaches

- 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

Toward the inverted hierarchy: choice of 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**

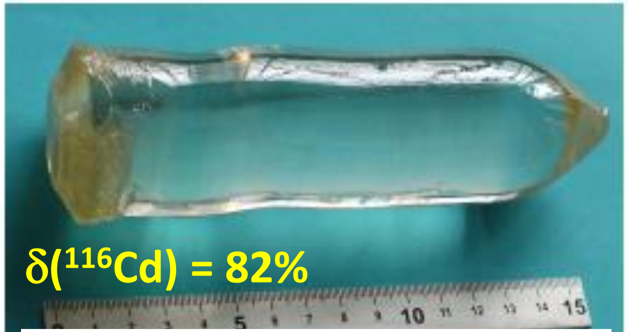
- **Enrichment ~ 10^2 - 10^3 kg**

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

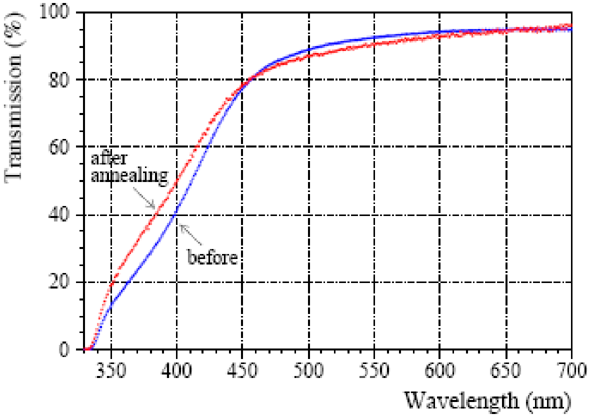
There are crystal scintillators with ^{82}Se, ^{100}Mo and ^{116}Cd, ^{130}Te is component of TeO_2 crystals

- 2β with conventional scintillation detectors

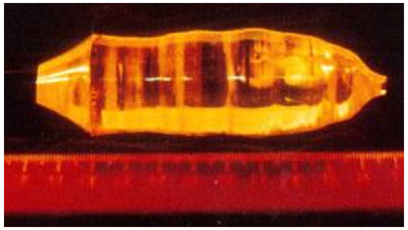
R&D of enriched $^{116}CdWO_4$ crystal scintillators



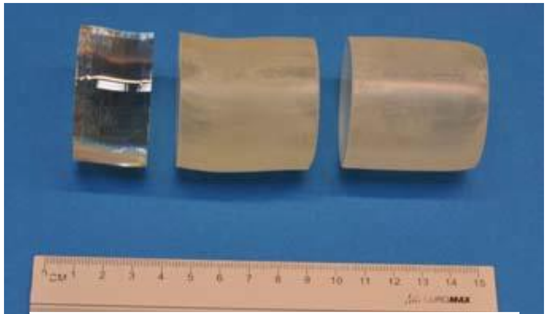
$^{116}CdWO_4$ scintillator 1868 g
Yield of crystal 87%
Losses of ^{116}Cd ≈ 2%



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

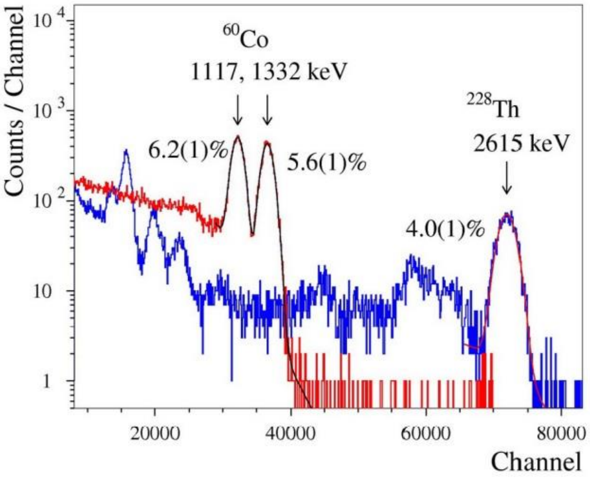


$^{116}CdWO_4$ crystal (510 g) grown in 1986 for the Solotvina experiment [2]



The crystal was cut into 3 scintillation elements

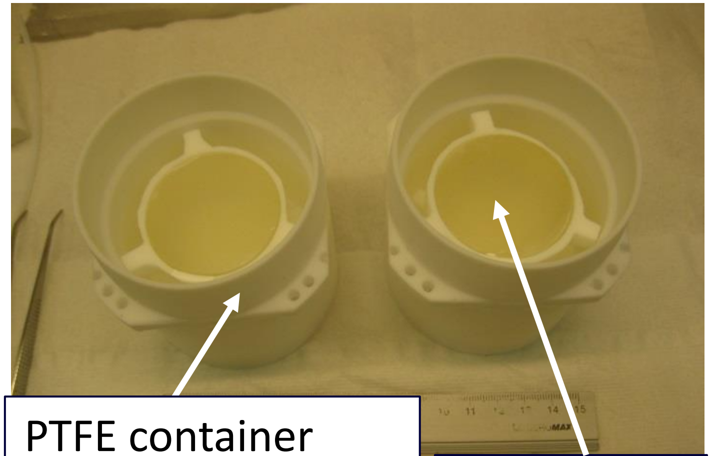
The excellent optical and scintillation properties of the crystal were obtained thanks to the deep purification of ^{116}Cd and W, and the advantage of the low-thermal-gradient Czochralski technique to grow the crystal [1]

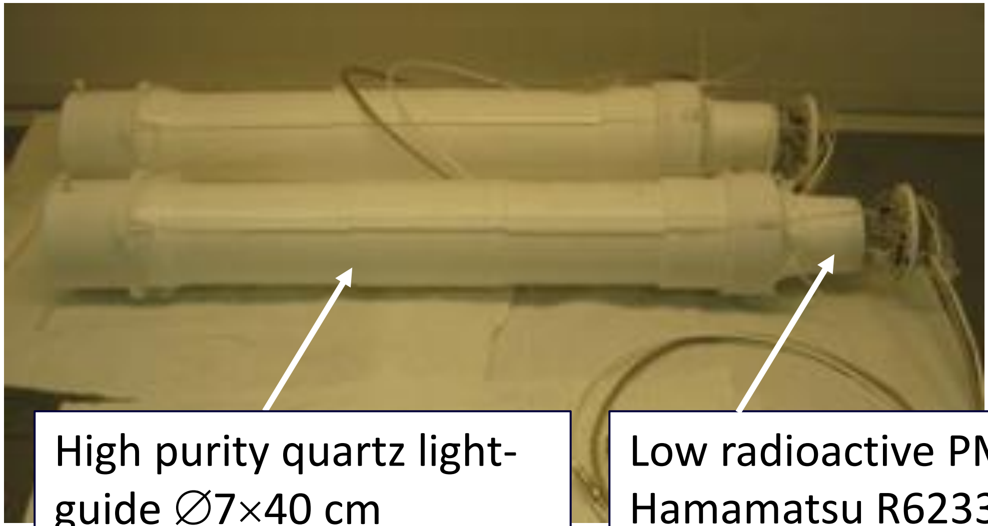


[1] A.S. Barabash et al., JINST 06(2011) p08011
[2] F.A.Danevich et al., JETP Lettt. 49 (1989) 476

- 2β with conventional scintillation detectors

$^{116}CdWO_4$ scintillation detector



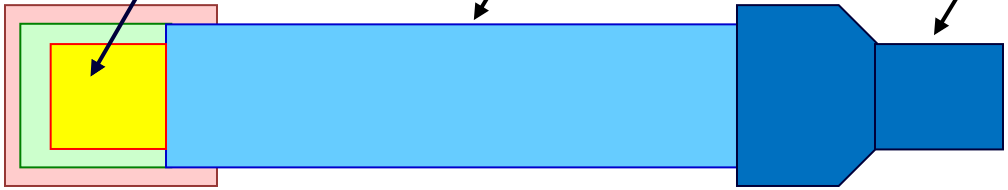


PTFE container filled by Borexino liquid scintillator

$^{116}CdWO_4$

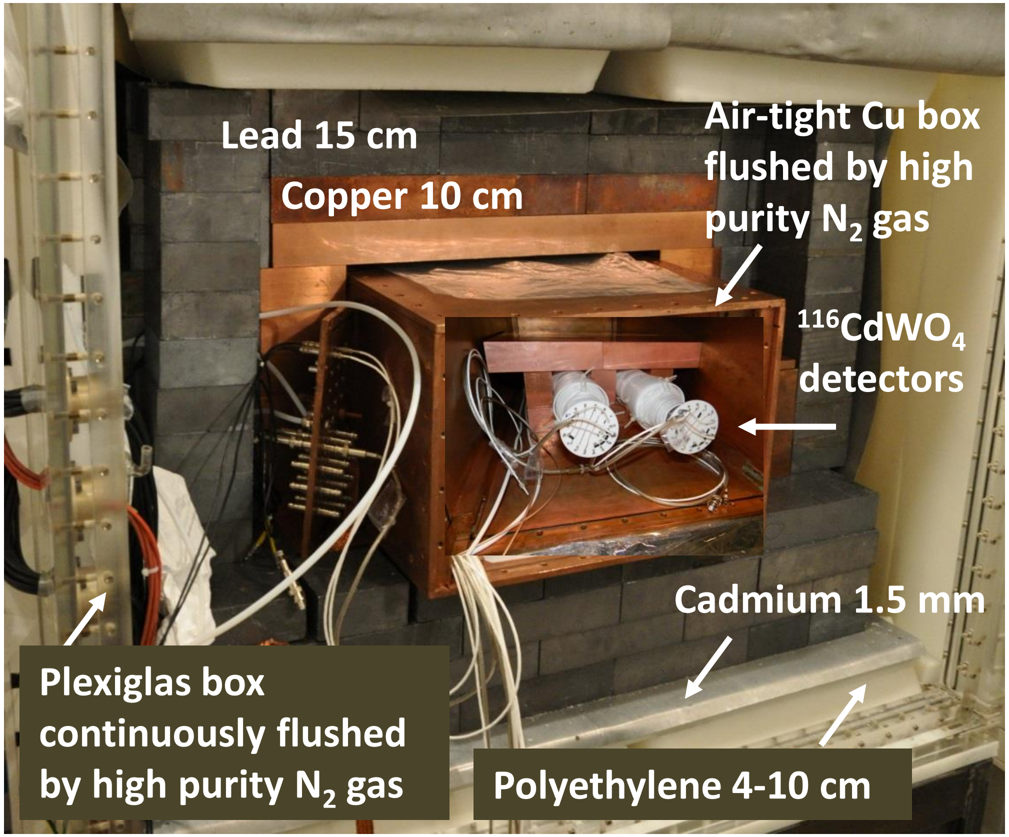
High purity quartz light-guide ∅7×40 cm

Low radioactive PMT Hamamatsu R6233



FWHM ≈ 5% at 2615 keV

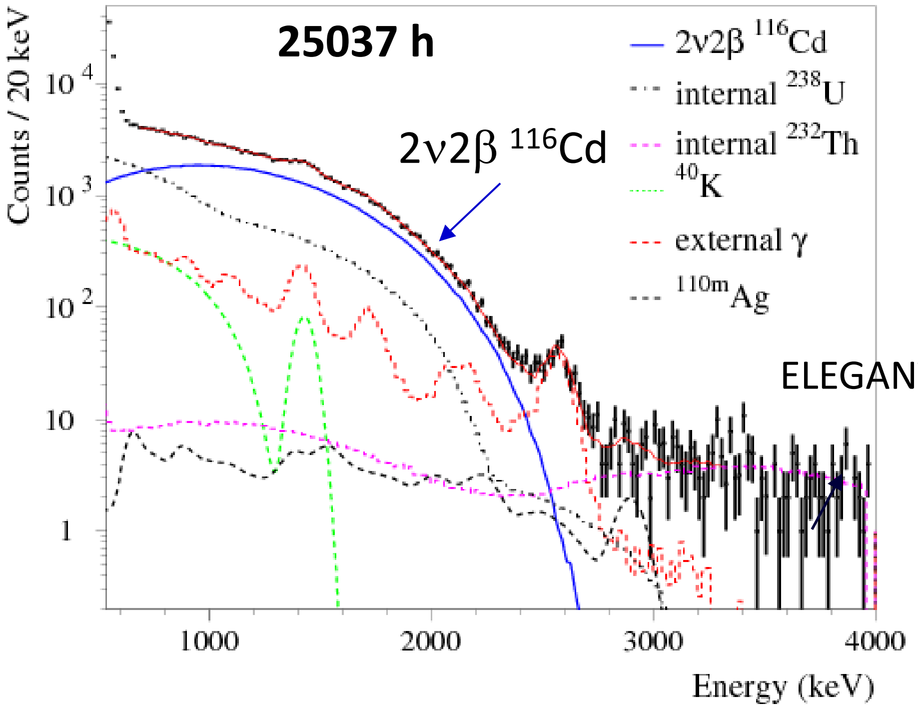
Low background DAMA R&D set-up at LNGS

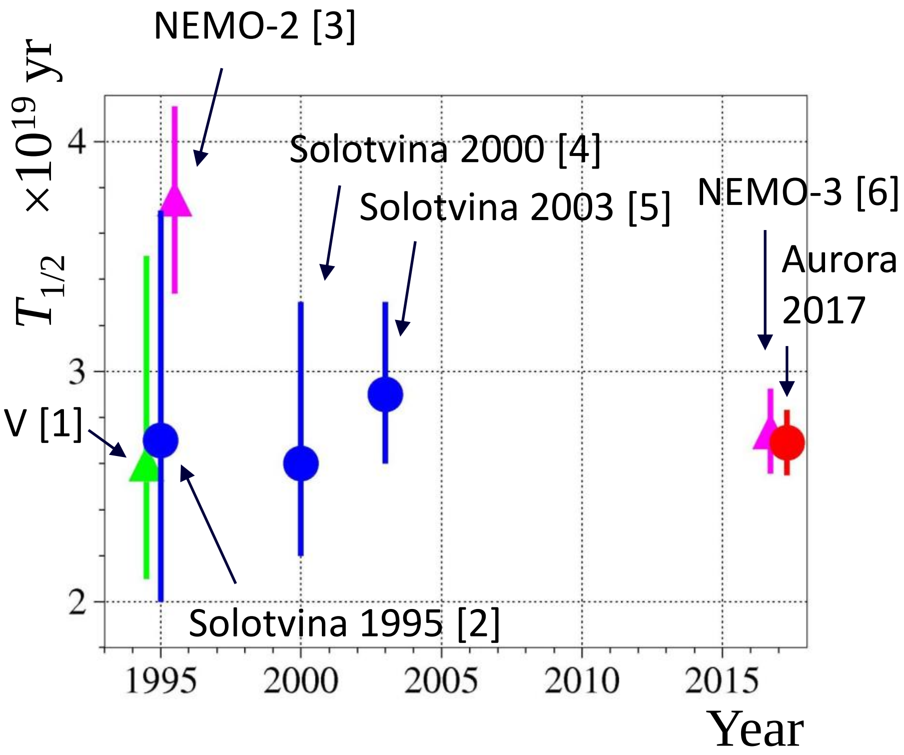


An event-by-event data acquisition system based on a 1 GS/s 8 bit transient digitizer (operated at 50 MS/s) records the time of each event and the pulse shape over a time window of ≈100 μs from the ^{116}CdWO$_4$ detectors

- 2β with conventional scintillation detectors

Two neutrino 2β decay of ^{116}Cd





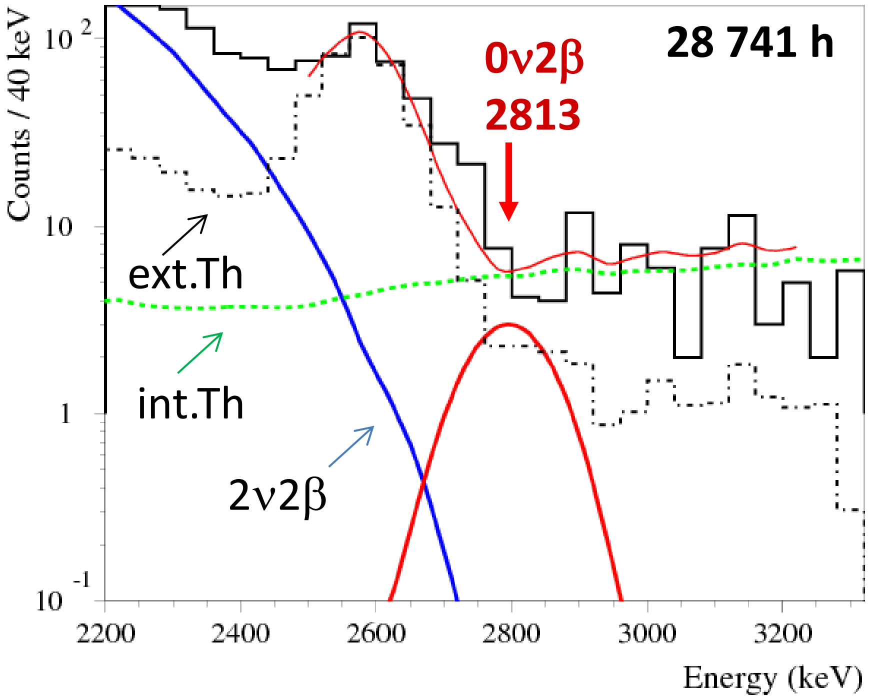
$$T_{1/2}^{2\nu 2\beta} = [2.69 \pm 0.02(\text{stat}) \pm 0.14(\text{syst})] \times 10^{19} \text{ yr}$$

the data analysis is in progress

[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 with conventional scintillation detectors

Limit on 0ν2β decay of ^{116}Cd



$$T_{1/2}^{0\nu} \geq 2.4\times10^{23}\ \text{yr}$$

Effective Majorana neutrino mass:

$\langle m_\nu \rangle \leq (1.1 - 1.6)$ eV [1-4]

Background in the ROI 2.7-2.9 MeV was reduced to the level of (0.11 → 0.07) cnts/(keV yr kg) by selection of the ^{212}Bi → ^{208}Tl events:
^{212}Bi (E_α = 6207 keV] → ^{208}Tl (Q_β = 4999 keV, $T_{1/2}$ = 3.053 min)

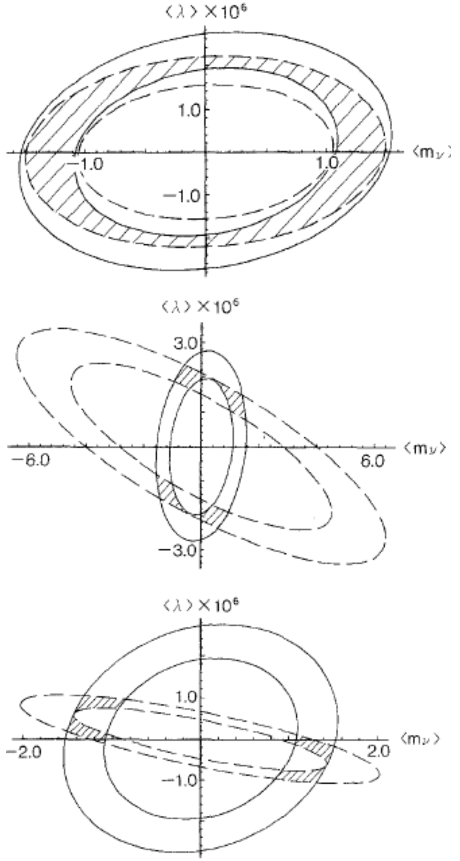
[1] T.R. Rodr´ıguez, G. Mart´ınez-Pinedo, Phys. Rev. Lett. 105, 252503 (2010).
[2] F. Šimkovic, V. Rodin, A. Faessler, P. Vogel, Phys. Rev. C 87, 045501 (2013).
[3] J. Hyvärinen, J. Suhonen, Phys. Rev. C 91, 024613 (2015).
[4] J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91, 034304 (2015).

Motivation to study 2ε, εβ$^+$, 2β$^+$

$$(T_{1/2}^{0\nu})^{-1} = C_{mn}^{0\nu}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2 + C_{m\lambda}^{0\nu}\langle\lambda\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right) + C_{m\eta}^{0\nu}\langle\eta\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right) + C_{\lambda\lambda}^{0\nu}\langle\lambda\rangle^2 + C_{\eta\eta}^{0\nu}\langle\eta\rangle^2 + C_{\lambda\eta}^{0\nu}\langle\lambda\rangle\langle\eta\rangle$$

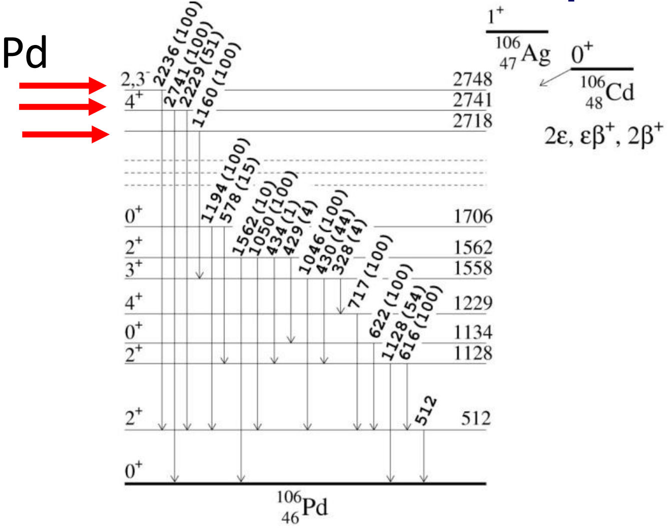
- **Right-handed weak current contribution**

Half-lives for 0νεβ$^+$ decay depend strongly on whether the decay is dominated by the mass mechanism or right-handed weak current [1]



- **Possibility of resonant 0ν double electron capture**

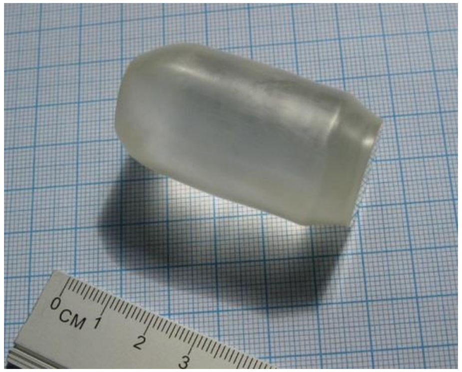
resonant levels of ^{106}Pd can be populated in 0ν2ε of ^{106}Cd



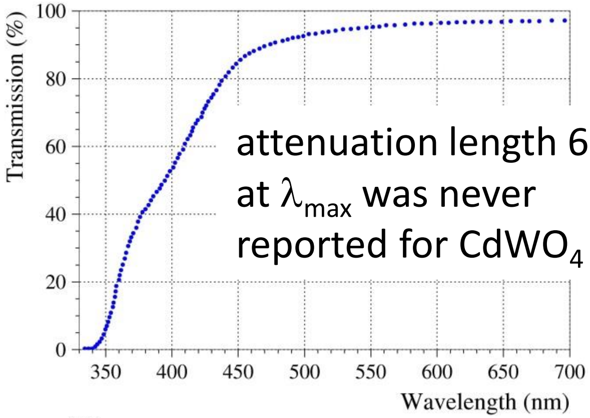
[1] M. Hirsch et al., Nuclear structure calculation of β+ β +, β +/EC and EC/EC decay matrix elements, Z. Phys. A 347 (1994) 151

R&D $^{106}CdWO_4$ crystal scintillator

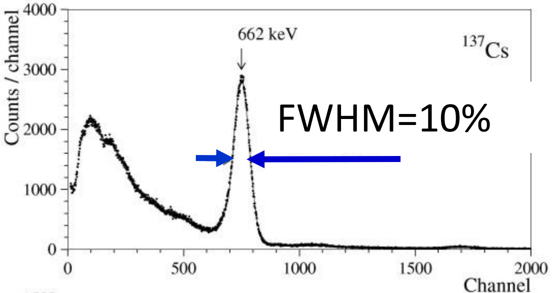
$^{106}CdWO_4$ crystal 231 g
$\delta(^{106}Cd) = 66\%$
yield of crystal = 87% of the initial powder



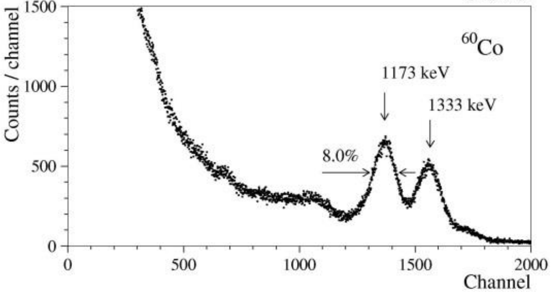
$^{106}CdWO_4$ scintillator 216 g
The total irrecoverable losses of ^{106}Cd = 2.3%



attenuation length 60 cm at λ_{max} 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

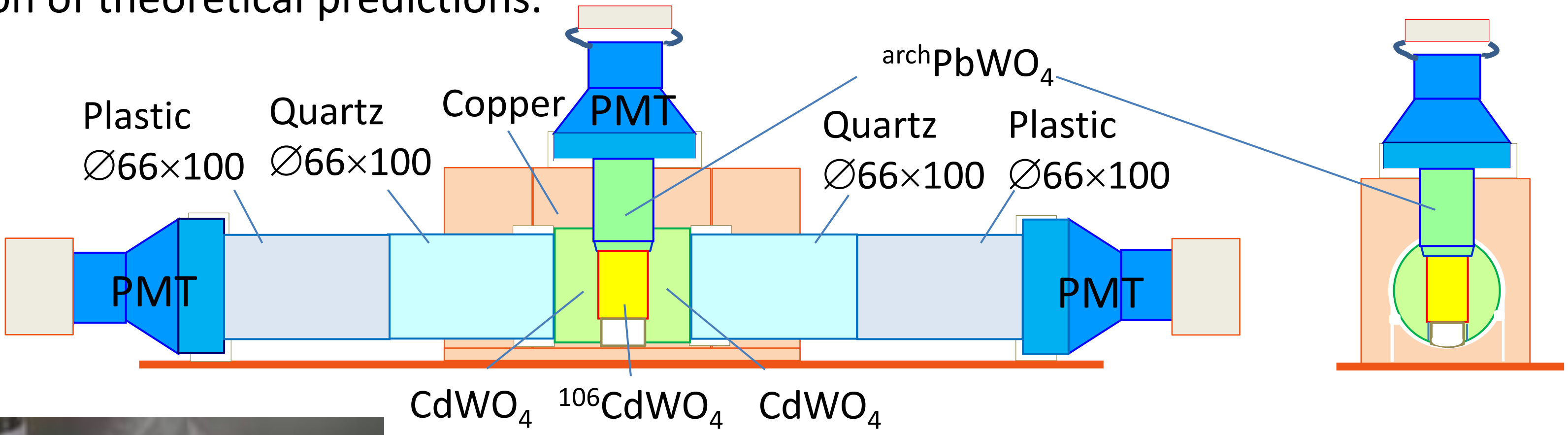
[1] P. Belli et al., Development of enriched $^{106}CdWO_4$ crystal scintillators to search for double β decay processes in ^{106}Cd, NIMA 615 (2010) 301

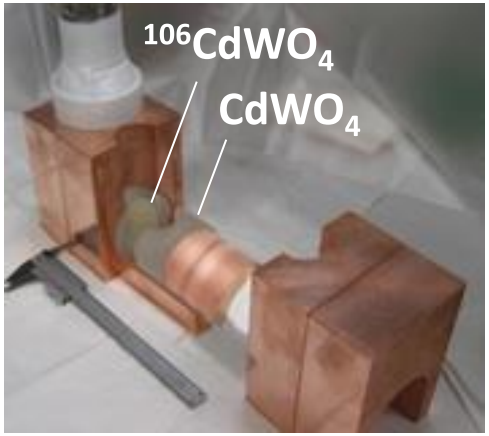
- 2β with conventional scintillation detectors

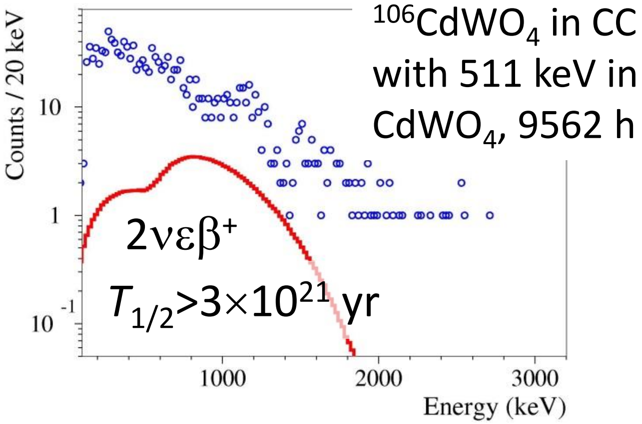
Double β decay of ^{106}Cd

The sensitivity $T_{1/2}$ ~10^{20}- 10^{21} yr was reached in the first stages of experiment [1,2].

In particular, the half-life limit on the 2νεβ$^+$ decay $T_{1/2}$ > 1.1 × 10^{21} yr, has reached the region of theoretical predictions.



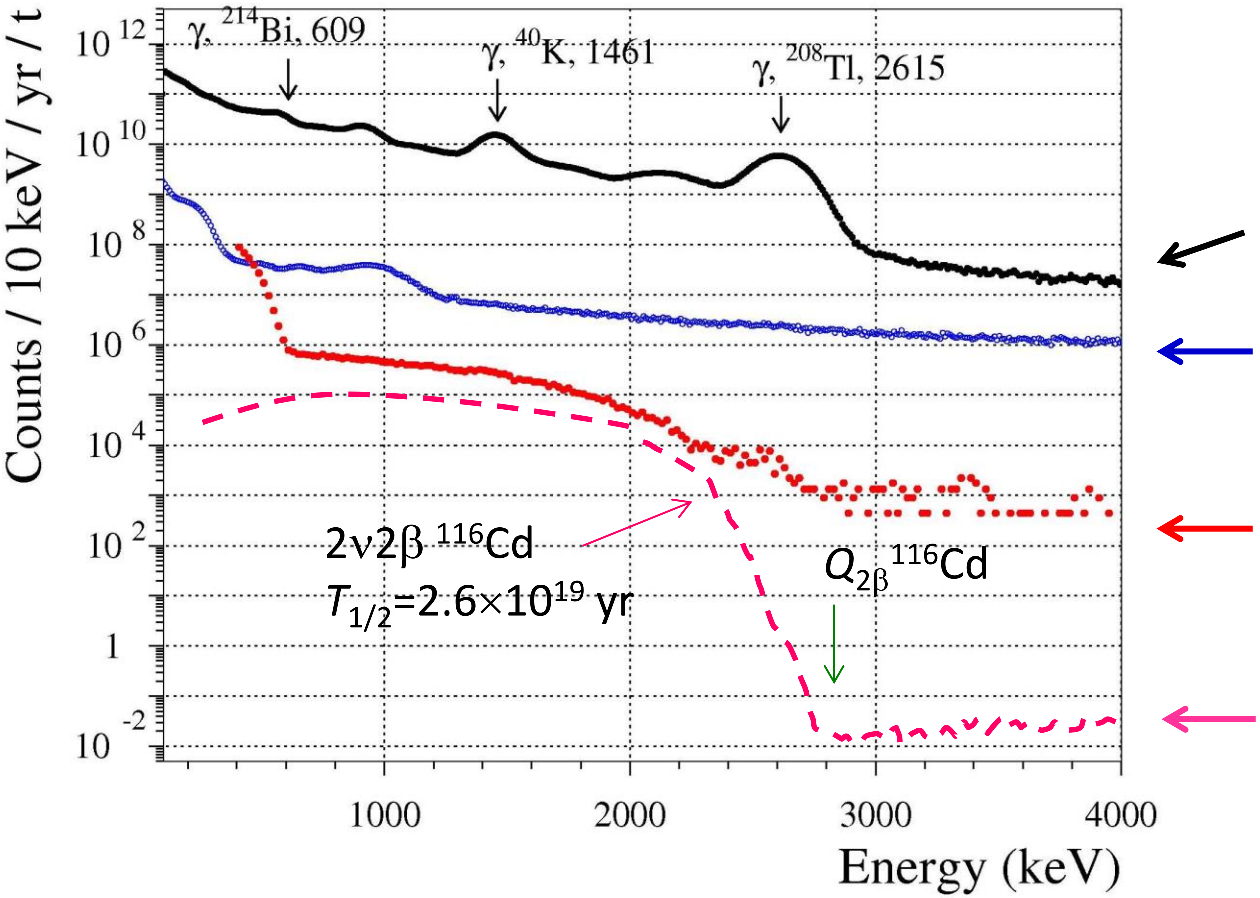




The measurements are in progress in the DAMA/CRYS set-up at LNGS

[1] P. Belli et al., PRC 85 (2012) 044610; [2] P. Belli et al., PRC 93 (2016) 045502

A significant background reduction is requested to investigate the inverted hierarchy



$CdWO_4$ 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

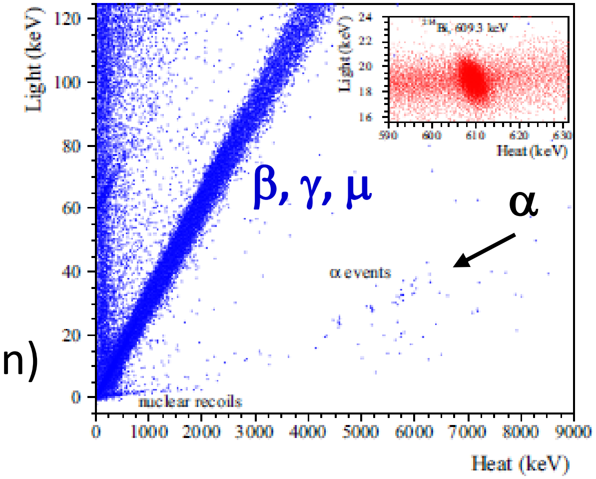
Cryogenic search for 0ν2β decay of ^{116}Cd

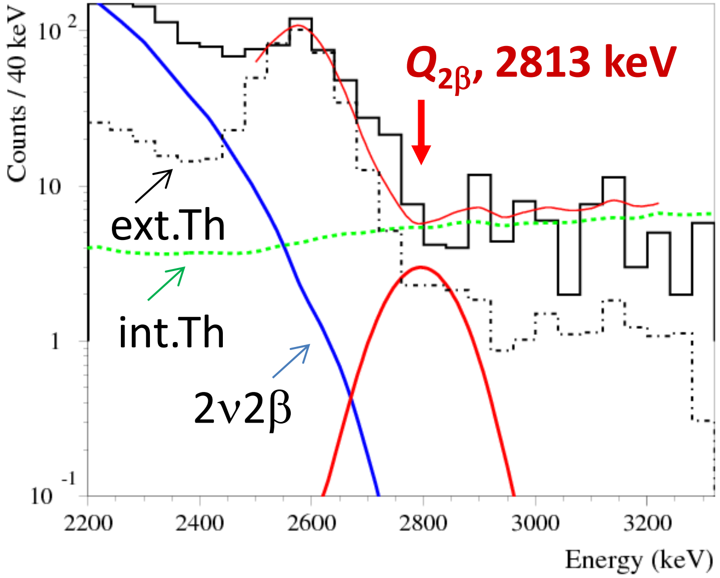
project **CYGNUS**: Cryogenic search for neutrinoless double beta decay of cadmium

- 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

$$^{212}\text{Bi} \xrightarrow{\alpha} {}^{208}\text{Tl} \xrightarrow{\beta\ (T_{1/2} \approx 3\text{ min})}$$





Search for 0ν2β decay of ^{116}Cd with advanced sensitivity: $\lim T_{1/2}^{0\nu} \sim 8\times10^{23}$ yr

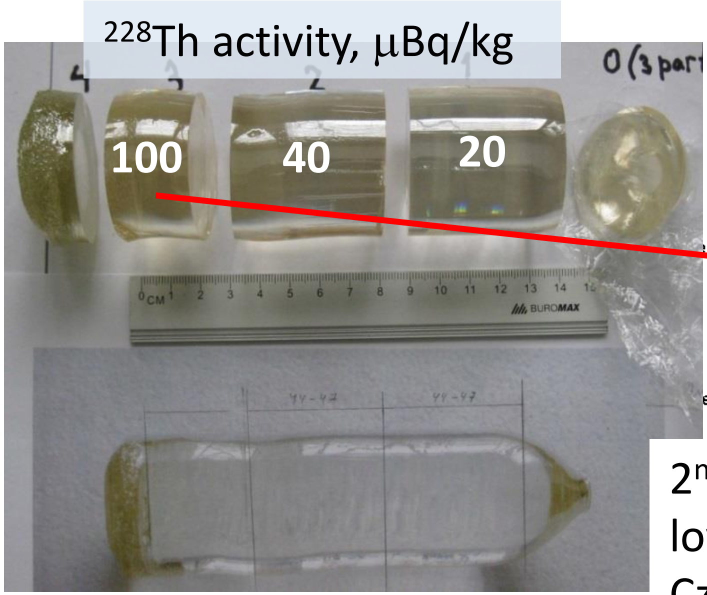
Demonstration of ^{116}Cd option capability for the large scale experiment (i.e., CUPID)

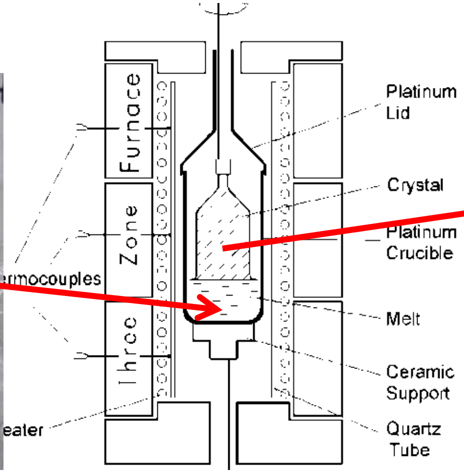
[1] A.S. Barabash et al., EPJC 76 (2016) 487
[2] C. Arnaboldi et al., Astropart. Phys. 34 (2010) 143.

- 2β decay: low temperature scintillators

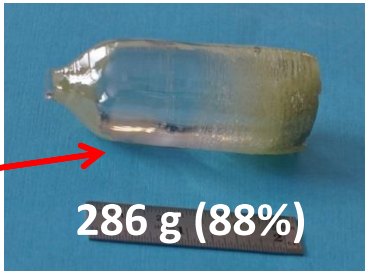
Prospects for $^{116}CdWO_4$ $0\nu2\beta$ experiment

- **Radiopurity level of $^{116}CdWO_4$ crystals can be further improved by recrystallization**



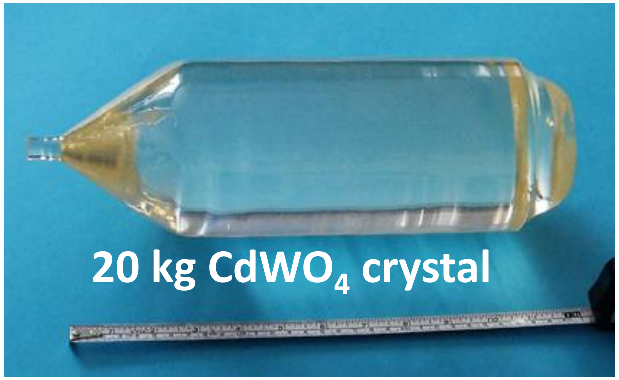


2nd crystallization by the low-thermal-gradient Czochralski method



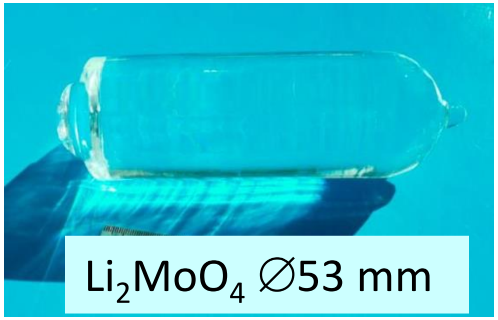
The thorium contamination of the $^{116}CdWO_4$ crystal was reduced by a factor 10, down to the level 10 μBq/kg [1]

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



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

R&D of cryogenic detectors to search for 0ν2β decay of ^{100}Mo

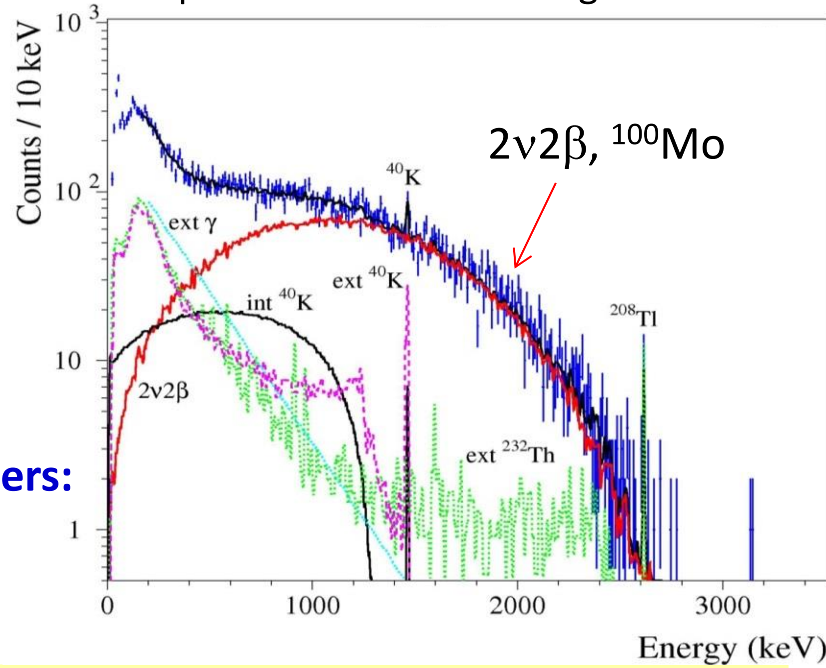

Li_2MoO_4 ∅53 mm

Production of high quality zinc ($ZnMoO_4$) and lithium molybdate (Li_2MoO_4) crystal scintillators (including scintillators from enriched ^{100}Mo) has been developed

High performance of $Li_2{}^{100}MoO_4$ scintillating bolometers:

- Energy resolution FWHM = 4-6 keV at 2615 keV
- Particle discrimination capability: $DP_{\alpha/\beta} = 9 - 18$
- Low radioactive contamination: < 10 μBq/kg of ^{226}Ra and ^{228}Th

186 g $Li_2{}^{100}MoO_4$, 1303 h in EDELWEISS set-up at the Modane underground Lab

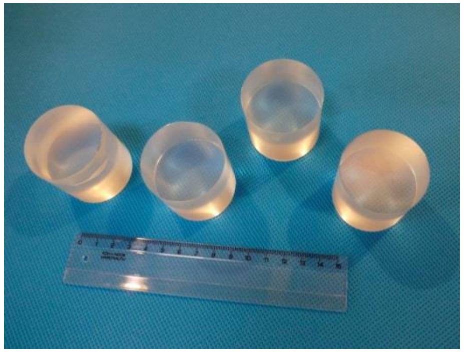


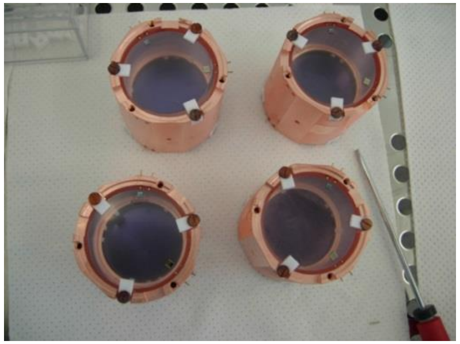
$$T_{1/2} = [6.90 \pm 0.15(\mathrm{stat}) \pm 0.37(\mathrm{syst})] \times 10^{18}\ \mathrm{yr}\ [1]$$

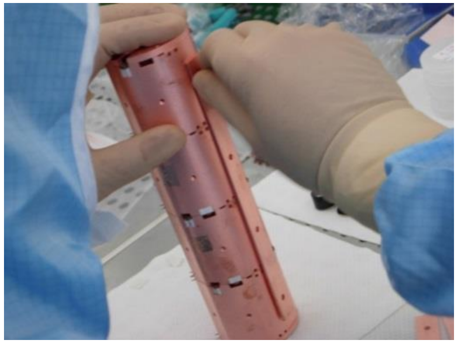
The most accurate $T_{1/2}$ of ^{100}Mo obtained with only 10 kg×d exposure

[1] E. Armengaud et al., Development of ^{100}Mo-containing scintillating bolometers for a high-sensitivity neutrinoless double-beta decay search submitted to EPJA ; arXiv:1704.01758v2 [physics.ins-det] 4 Oct 2017

The CUPID-Mo Demonstrator







- 20 enriched $Li_2{}^{100}MoO_4$ crystals are produced
- Assembling of the $Li_2{}^{100}MoO_4$ detectors is in progress aiming to start a pilot experiment beginning of 2018

Assumed background is 10^{-3} counts/yr/kg/keV in 10 keV window centered at $Q_{2\beta}$ of ^{100}Mo:

Sensitivity to $0\nu2\beta$ decay of ^{100}Mo over 6 month:

$$\lim T_{1/2}^{0\nu} \sim 1.3\times10^{24}\ \text{yr} \quad \Rightarrow \quad \langle m_\nu \rangle \approx 0.33\ \text{eV} - 0.56\ \text{eV}$$

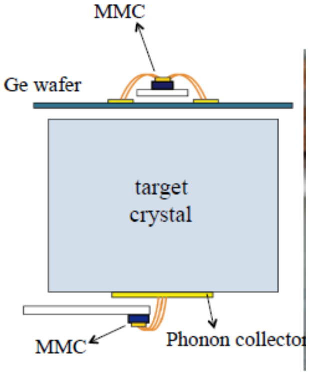
- Production of the next 20 $Li_2{}^{100}MoO_4$ detectors is foreseen in 2018

Sensitivity with 40 detectors over 3 yr:

$$\lim T_{1/2}^{0\nu} \sim 1.5\times10^{25}\ \text{yr} \quad \Rightarrow \quad \langle m_\nu \rangle \approx 0.1\ \text{eV} - 0.17\ \text{eV}$$

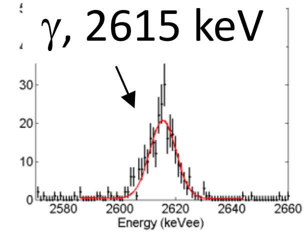
AMoRE: search for 0ν2β decay of ^{100}Mo

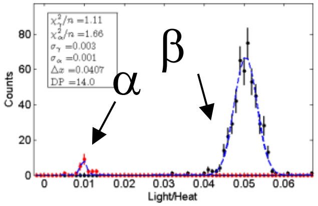
Search for 0ν2β of ^{100}Mo by using low temperature molybdate crystal scintillators and photodetectors equipped with Metallic Magnetic Calorimeter sensors

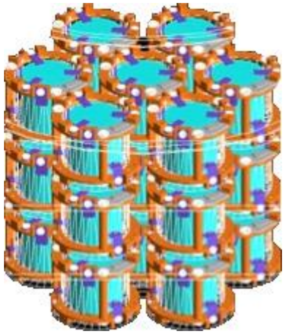


AMoRE Pilot, 2016-2017
1.8 kg of $^{depl}Ca^{100}MoO_4$

- FWHM≈16-25 keV
- $DP_{\beta\alpha}$ ≈ 7-14
- BG is reduced step by step, goal for Pilot: ~0.01 cnts/(keV kg yr)



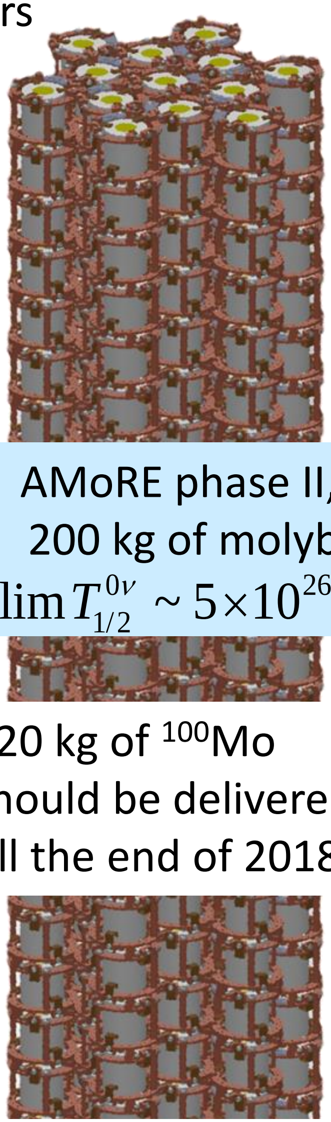




AMoRE phase I, 2018
~10 kg of $^{depl}Ca^{100}MoO_4$

$$\lim T_{1/2}^{0\nu} \sim 10^{25} \text{ yr}$$

- The crystals are produced
- Experiment should be done in the AMoRE Pilot cryostat



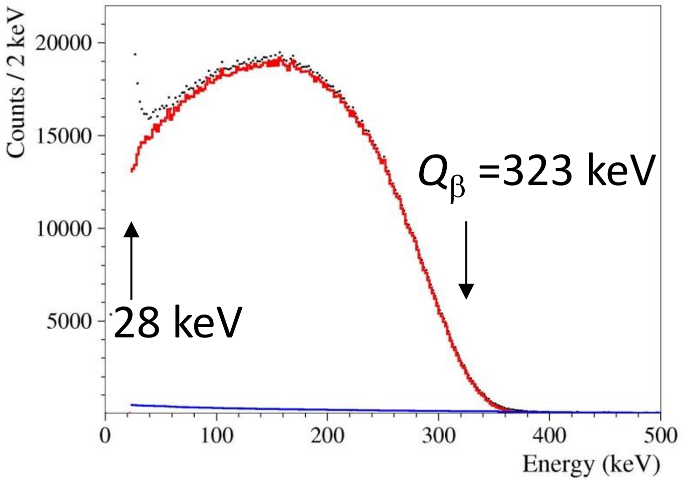
AMoRE phase II, 2021
200 kg of molybdates

$$\lim T_{1/2}^{0\nu} \sim 5\times 10^{26} \text{ yr}$$

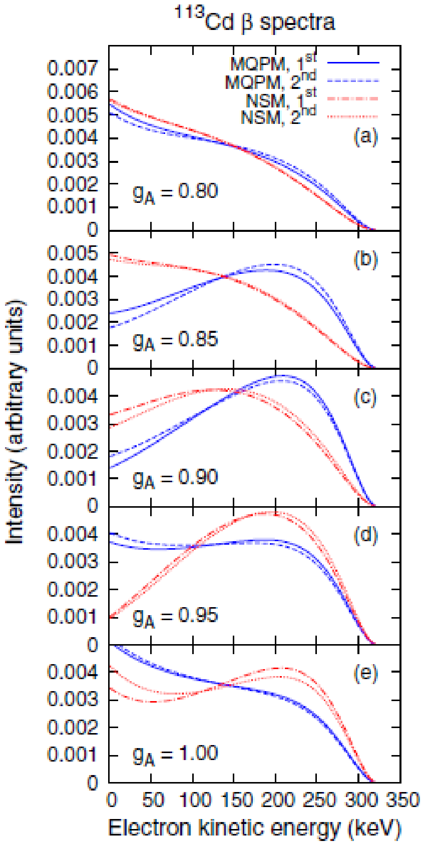
120 kg of ^{100}Mo should be delivered till the end of 2018

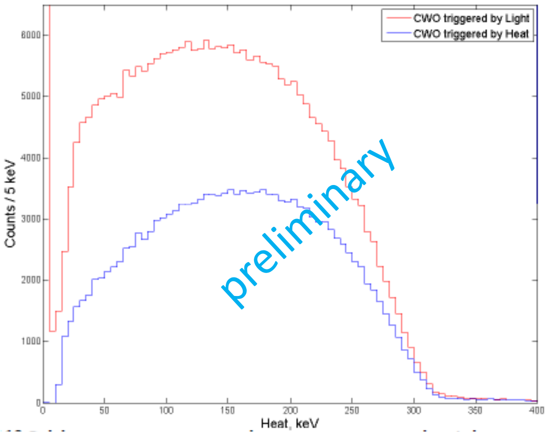
β decay of ^{113}Cd

- 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

- Crystal scintillators possess certain advantages in rare events experiments thanks to presence of the element of interest, that provides a high detection efficiency to the effect searched for
- High sensitivity 2β experiments were realized (in progress) with $CdWO_4$ crystals scintillators enriched in ^{106}Cd and ^{116}Cd
- An excellent energy resolution and efficient particle discrimination capability make the low temperature scintillating bolometers promising for 0ν2β experiments (AMoRE, CUPID) aiming at test the inverted neutrino mass scheme and even go toward the normal neutrino mass hierarchy