Search for 2β decay with scintillators

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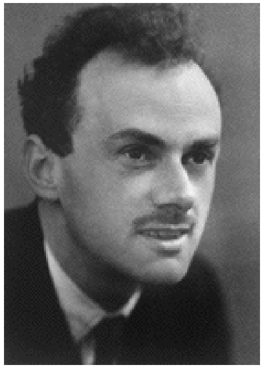
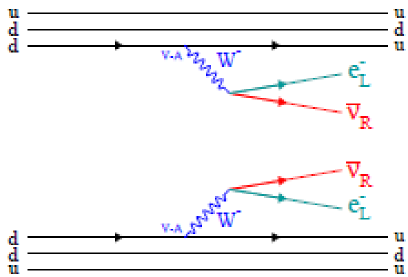
1. Introduction
2. 2β experiments with conventional scintillation detectors
3. Low temperature scintillators
4. Radio-purity of scintillators

2β decay and particle physics

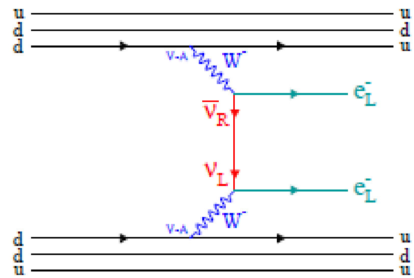


Paul Adrien Maurice Dirac

Neutrino considered by Ettore Majorana [1] is identical to its antiparticle: $\nu \equiv \overline{\nu}$, in contrast to the neutrinos proposed by Dirac



2ν2β decay



0ν2β decay

Ettore Majorana

- The neutrinoless (0ν) 2β decay is possible if neutrino is a Majorana particle
- Test of the Lepton number conservation
- Sensitive to the absolute value of the neutrino mass, the neutrino mass hierarchy, the Majorana CP phases
  - Majorana neutrino could explain the baryon asymmetry of the Universe
  - Neutrino is only known dark matter particle
- 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

The most sensitive 2β experiments with scintillators

2β transition	Scintillator	Main results ($T_{1/2}$, yr)	Refs.
$^{40}Ca \to {}^{40}Ar$	$CaWO_4$ (LT)	$\geq 9.9 \times 10^{21}$ yr (2ν2K)	[1]
$^{48}Ca \to {}^{48}Ti$	CaF_2(Eu)	$\geq 5.8 \times 10^{22}$ yr ($0\nu2\beta^-$)	[2]
$^{64}Zn \to {}^{64}Ni$	$ZnWO_4$	$\geq 9.4 \times 10^{20}$ yr ($2\nu\varepsilon\beta^+$)	[3]
$^{82}Se \to {}^{82}Kr$	$Zn^{82}Se$ (LT)	$\geq 2.4 \times 10^{24}$ yr ($0\nu2\beta^-$)	[4]
$^{106}Cd \to {}^{106}Pd$	$^{106}CdWO_4$	$\geq 1.1 \times 10^{21}$ yr ($2\nu\varepsilon\beta^+$) $\geq 2.2 \times 10^{21}$ yr ($0\nu\varepsilon\beta^+$)	[5] [6]
$^{116}Cd \to {}^{116}Sn$	$^{116}CdWO_4$	$= (2.63^{+0.11}_{-0.12}) \times 10^{19}$ yr ($2\nu2\beta^-$) $\geq 2.2 \times 10^{21}$ yr ($0\nu2\beta^-$)	[7]
$^{136}Xe \to {}^{136}Ba$	^{136}Xe loaded liquid scintillator	$= [2.21 \pm 0.02(st) \pm 0.07(sy)] \times 10^{21}$ yr ($2\nu2\beta^-$) $\geq 1.07 \times 10^{26}$ yr ($0\nu2\beta^-$)	[8]
$^{160}Gd \to {}^{160}Dy$	Gd_2SiO_5(Ce)	$\geq 1.3 \times 10^{21}$ yr ($0\nu2\beta^-$)	[9]

[1] G. Angloher et al., J.Phys.G 43 (2016) 095202
[2] S. Umehara et al., Phys. Rev. C 78 (2008) 058501
[3] P. Belli et al., J. Phys. G 38 (2011) 115107
[4] O. Azzolini et al., Phys. Rev. Lett. 120 (2018) 232502
[5] P. Belli et al., Phys. Rev. C 93 (2016) 045502
[6] P. Belli et al., Phys. Rev. C 85 (2012) 044610
[7] P. Belli et al., submitted to PRD
[8] A. Gando et al., Phys. Rev. Lett. 117 (2016) 082503
[9] F.A. Danevich et al., Nucl. Phys. A 694 (2001) 375

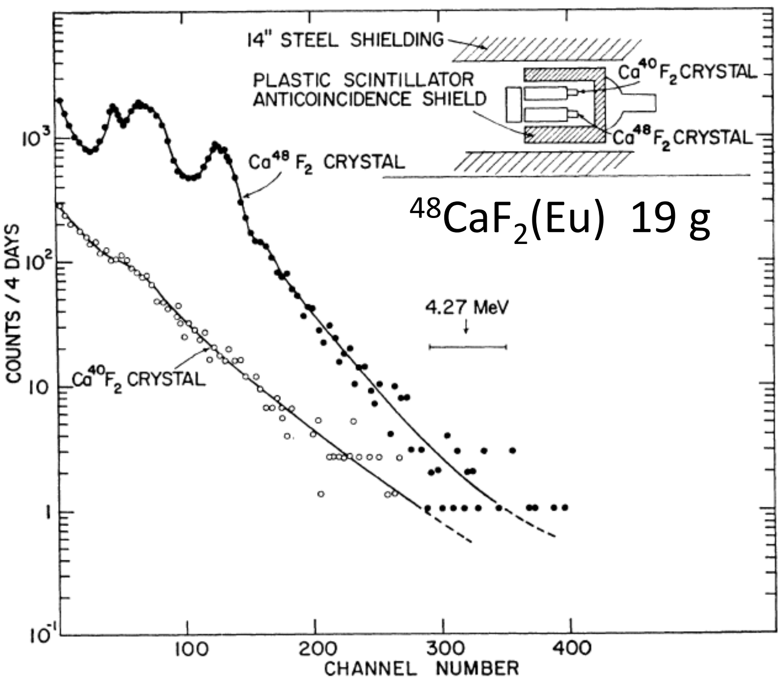
1st experiment with enriched scintillators

Limits for Lepton-Conserving and Lepton-Nonconserving Double Beta Decay in Ca48†

E. DER MATEOSIAN AND M. GOLDHABER
Brookhaven National Laboratory, Upton, New York

(Received 10 February 1966)

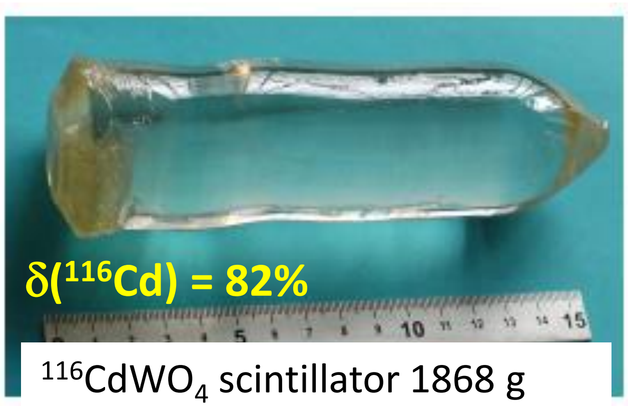
Phys. Rev. 146 (1966) 810



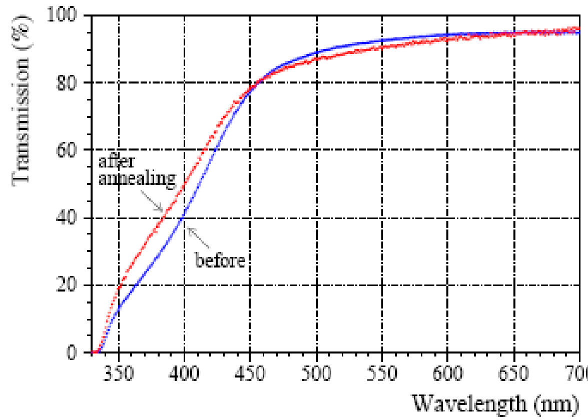
$T_{1/2}(0\nu2\beta) > 2\times10^{20}$ yr

A very different radioactive contamination of enriched and non-enriched scintillators

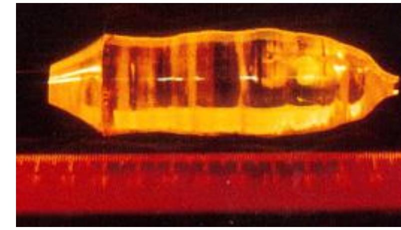
R&D of enriched $^{116}CdWO_4$ crystal scintillators



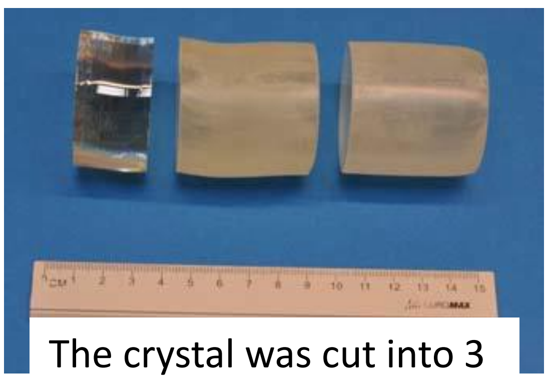
$^{116}CdWO_4$ scintillator 1868 g
Yield of crystal 87%
Losses of ^{116}Cd ≈ 2%



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

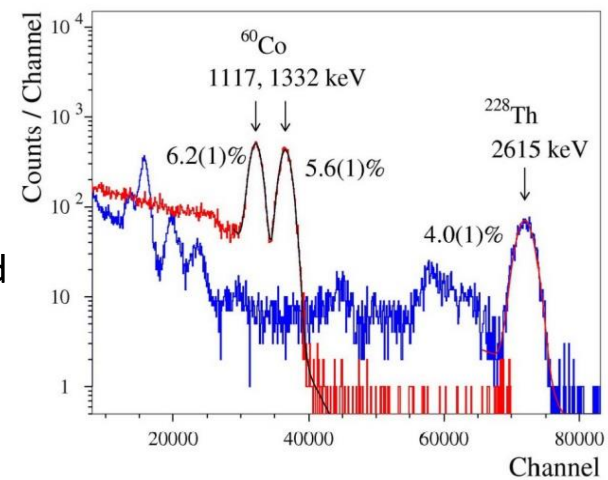


$^{116}CdWO_4$ crystal (510 g) grown in 1986 for the Solotvina experiment [2]



The crystal was cut into 3 scintillation elements

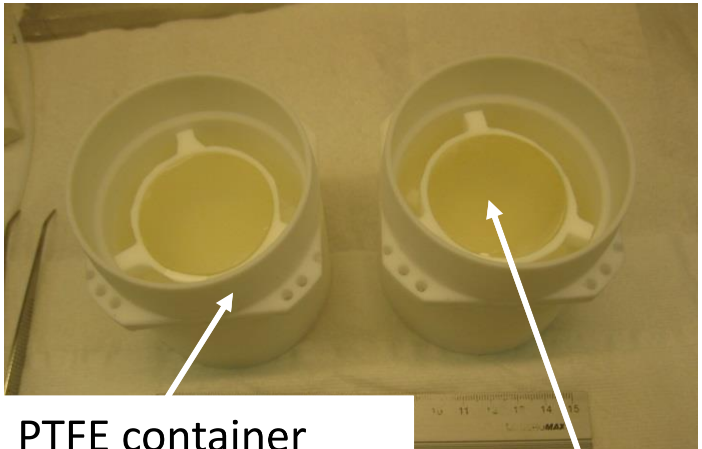
The excellent optical and scintillation properties of the crystal were obtained thanks to the **deep purification of ^{116}Cd** and W, and the advantage of the **low-thermal-gradient Czochralski** technique to grow the crystal [1]

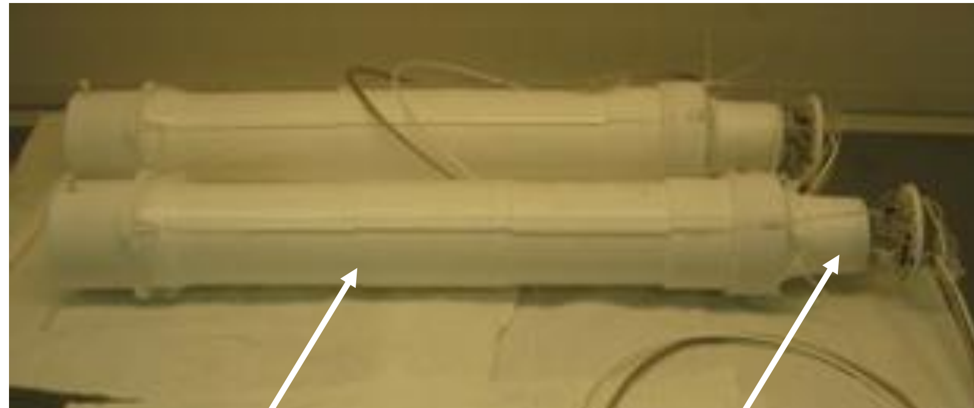


[1] A.S. Barabash et al., JINST 06 (2011) p08011
[2] F.A. Danevich et al., JETP Lettt. 49 (1989) 476

- 2β with conventional scintillation detectors

$^{116}CdWO_4$ scintillation detector



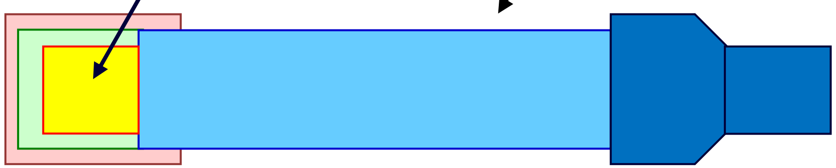


PTFE container filled by Borexino liquid scintillator

$^{116}CdWO_4$

High purity quartz light-guide ∅7×40 cm

Low radioactive PMT Hamamatsu R6233

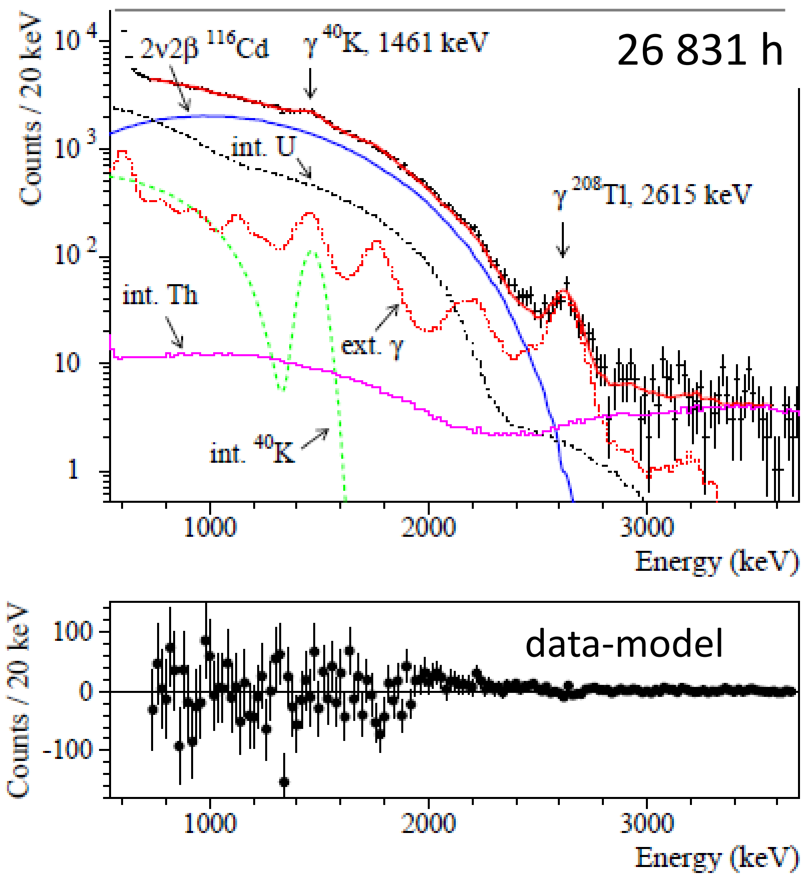


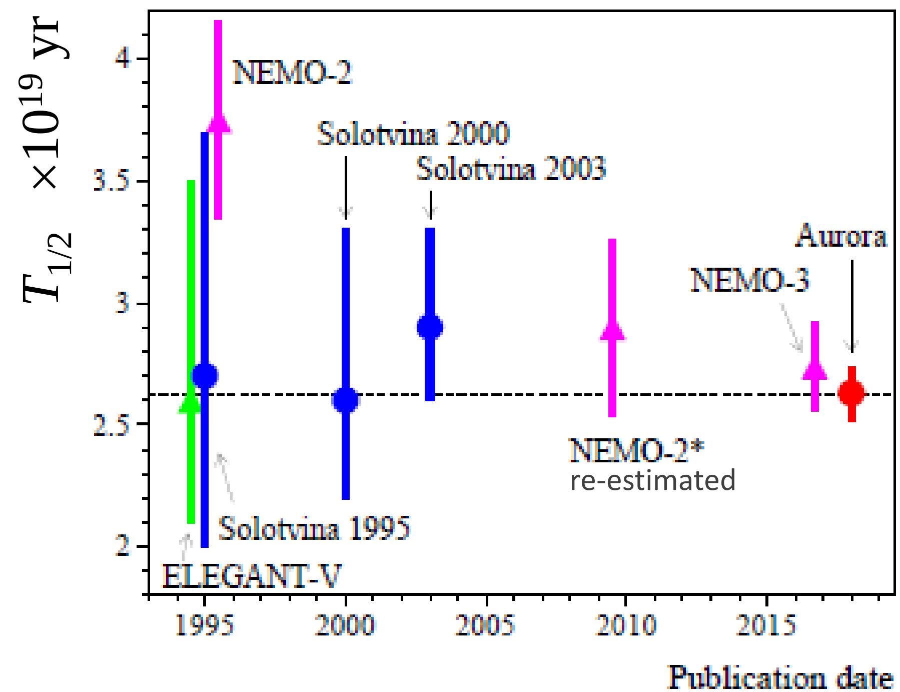
FWHM ≈ 5% at 2615 keV

The experiment was carried out in the DAMA R&D set-up at LNGS: 10 cm of Cu + 15 cm Pb + 1.5 mm of Cd + 4-10 cm of Polyethylene, the set-up volume was continuously flushed by high purity N_2 gas

• 2β with conventional scintillation detectors

2ν2β decay of ^{116}Cd





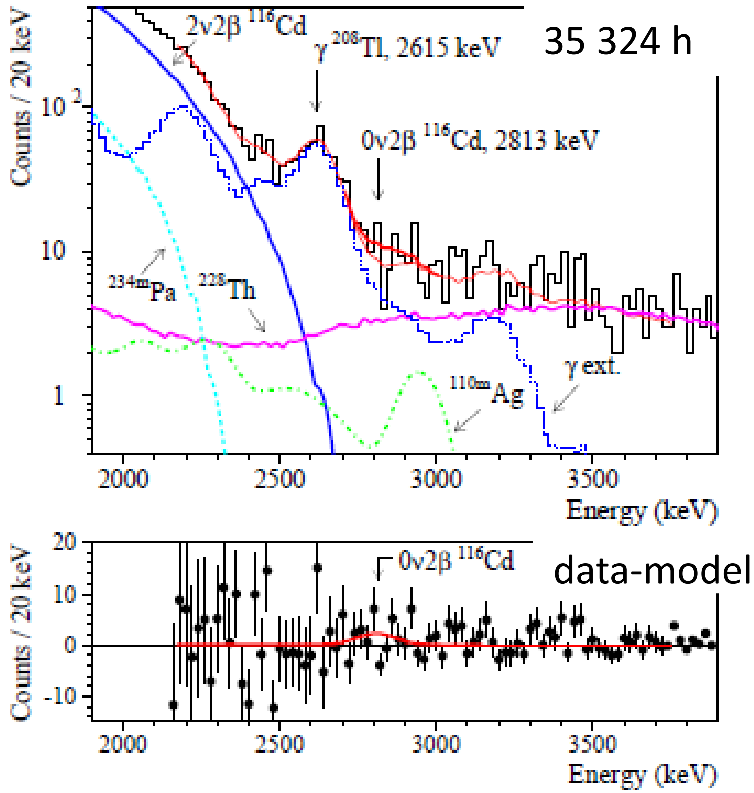
$$T_{1/2}^{2\nu2\beta} = [2.63 \pm 0.01(\text{stat})^{+0.11}_{-0.12}(\text{syst})] \times 10^{19} \text{ yr}$$

The most accurate $T_{1/2}$ for ^{116}Cd (≈ 4.4%)

[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 $0\nu 2\beta$ decay of ^{116}Cd



$$T_{1/2}^{0\nu} \geq 2.2\times10^{23}\ \text{yr}$$

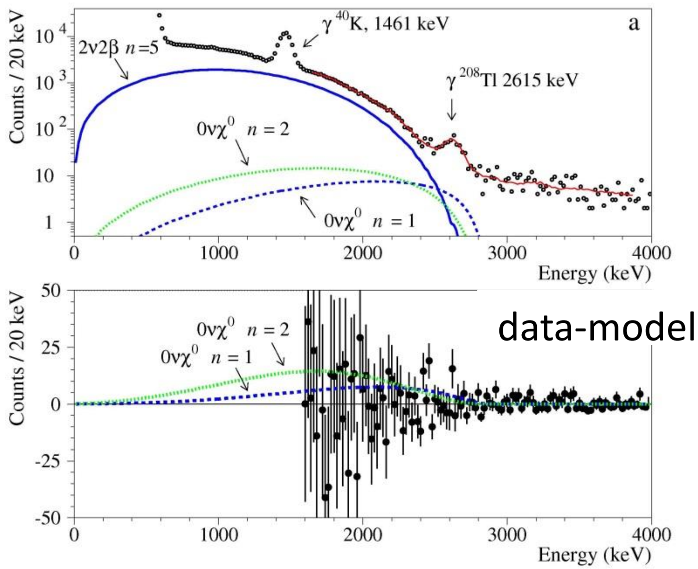
Effective Majorana neutrino mass:

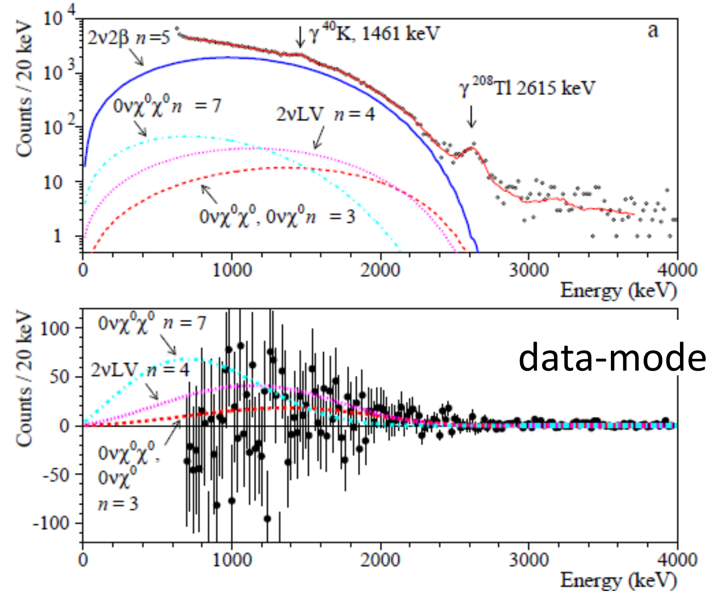
$\langle m_\nu \rangle \leq (1.0 - 1.7)$ eV

NMEs from [1-5], phase-space factors [6], $g_A = 1.27$

[1] N.L. Vaquero, T.R. Rodriguez, E.J. Luis, Phys. Rev. Lett. 111 (2013) 142501
[2] F. Šimkovic, V. Rodin, A. Faessler, P. Vogel, Phys. Rev. C 87 (2013) 045501
[3] J. Hyvärinen, J. Suhonen, Phys. Rev. C 91 (2015) 024613
[4] J. Barea, J. Kotila, F. Iachello, Phys. Rev. C 91 (2015) 034304
[5] L.S. Song, J.M. Yao, P. Ring, J. Meng, Phys. Rev. C 95 (2017) 024305
[6] J. Kotila, F. Iachello, Phys. Rev. C 85 (2012) , 034316

Limits on 0ν2β decay with majorons, and Lorentz-violating 2ν2β decay





$$T_{1/2}^{0\nu\chi^0\,(n=1)} \geq 8.2\times10^{21}\ \mathrm{yr}$$

$$T_{1/2}^{0\nu\chi^0\,(n=2)} \geq 4.1\times10^{21}\ \mathrm{yr}$$

$$T_{1/2}^{0\nu\chi^0\,(n=3)} \geq 2.6\times10^{21}\ \mathrm{yr}$$

$$T_{1/2}^{0\nu\chi^0\chi^0\,(n=3)} \geq 2.6\times10^{21}\ \mathrm{yr}$$

$$T_{1/2}^{0\nu\chi^0\chi^0\,(n=7)} \geq 8.9\times10^{20}\ \mathrm{yr}$$

$$T_{1/2}^{2\nu LV\,(n=4)} \geq 1.2\times10^{21}\ \mathrm{yr}$$

Lorentz-violating 2ν2β decay:

[1] J.S.Diaz, V.A.Kostelecky, R.Lehnert, PRD 88 (2013) 071902(R)
[2] J.S.Diaz, PRD 89 (2014) 036002

Limits on lepton-number violating parameters

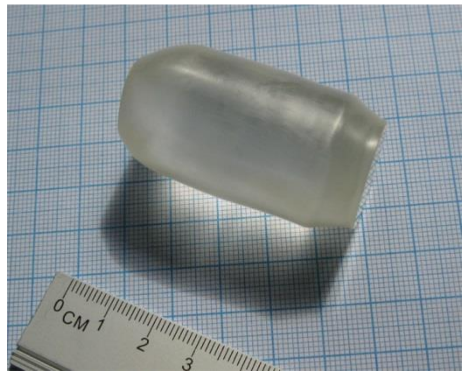
Parameter	Limit
Effective light Majorana neutrino mass $\langle m_\nu \rangle$	$\leq (1.0 - 1.7)$ eV
Effective heavy Majorana neutrino mass $\left|\left\langle m_{\nu_h}^{-1} \right\rangle\right|^{-1}$	$\geq (10 - 28) \times 10^6$ GeV
Right-handed current admixture $\langle \lambda \rangle$	$\leq (1.8 - 22) \times 10^{-6}$
Right-handed current admixture $\langle \eta \rangle$	$\leq (1.6 - 21) \times 10^{-8}$
Coupling constant of neutrino with majoron $\langle g_{ee} \rangle$	
χ^0, $n = 1$	$\leq (6.1 - 9.3) \times 10^{-5}$
χ^0, $n = 3$	$\leq 7.7 \times 10^{-2}$
$\chi^0\chi^0$, $n = 3$	$\leq (0.69 - 6.9)$
$\chi^0\chi^0$, $n = 7$	$\leq (0.57 - 5.7)$
R-parity violating parameter λ'_{111}	$\leq 2.5 \times 10^{-4} \times f$ *)
Lorentz-violating parameter $\mathring{a}^{(3)}_{\text{of}}$	$\leq 4 \times 10^{-6}$ GeV

*) $f = \left(m_{\tilde{q}} / 100 \text{ GeV}\right)^2 \times \left(m_{\tilde{g}} / 100 \text{ GeV}\right)^{1/2}$; $\tilde{q}$ and $\tilde{g}$ are the squark and gluino masses.

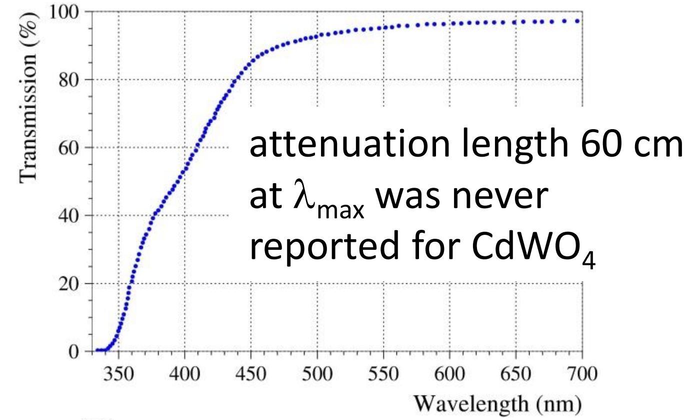
- 2β with conventional scintillation detectors

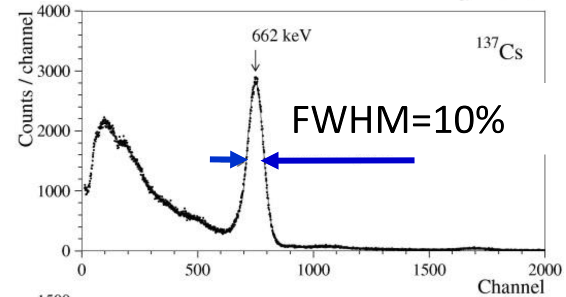
Search for 2β decay of ^{106}Cd with $^{106}CdWO_4$ crystal scintillator

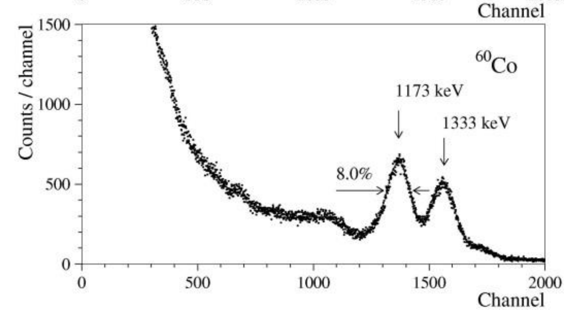
$^{106}CdWO_4$ crystal 231 g
$\delta(^{106}Cd)$ = 66%
yield of crystal = 87% of the initial powder



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





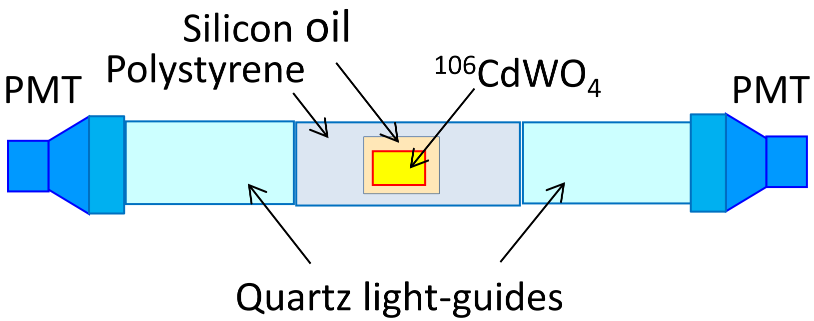


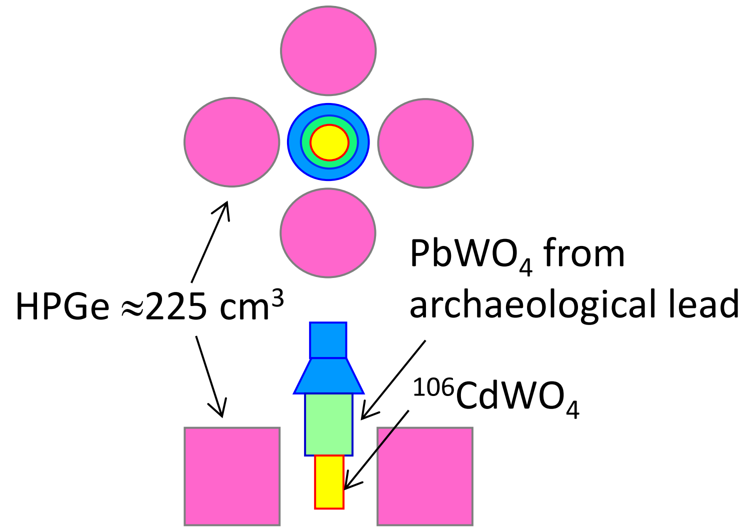
The excellent optical and scintillation properties of the crystal were obtained thanks to the **deep purification of ^{106}Cd and W**, and the advantage of the **low-thermal-gradient Czochralski technique** to grow the crystal

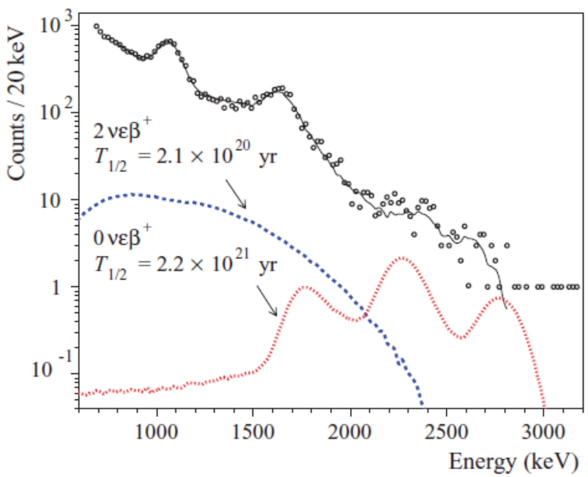
[1] P. Belli et al., Development of enriched $^{106}CdWO_4$ crystal scintillators to search for double β decay processes in ^{106}Cd, NIMA 615 (2010) 301

- 2β with conventional scintillation detectors

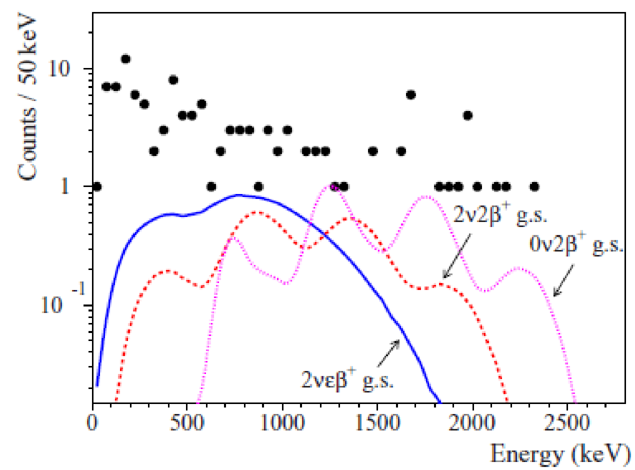
Previous phases of the experiment







$$T_{1/2}^{0\nu\varepsilon\beta^+} \geq 2.2\times10^{21} \text{ yr [1]}$$

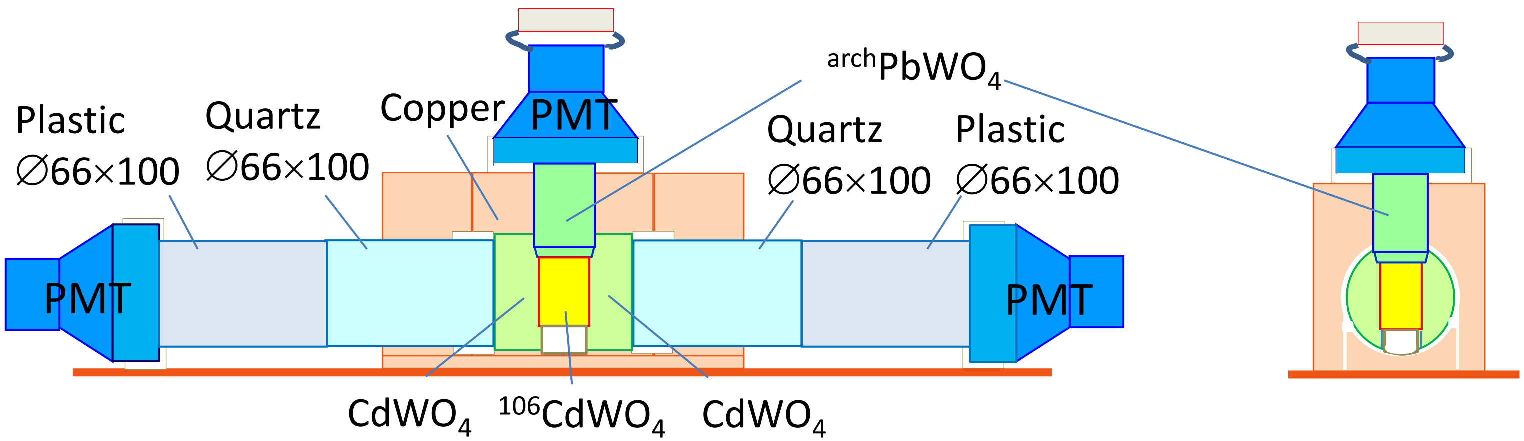


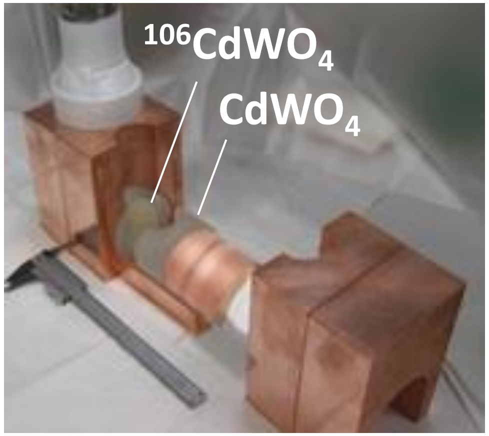
$$T_{1/2}^{2\nu\varepsilon\beta^+} \geq 1.1\times10^{21} \text{ yr [2]}$$

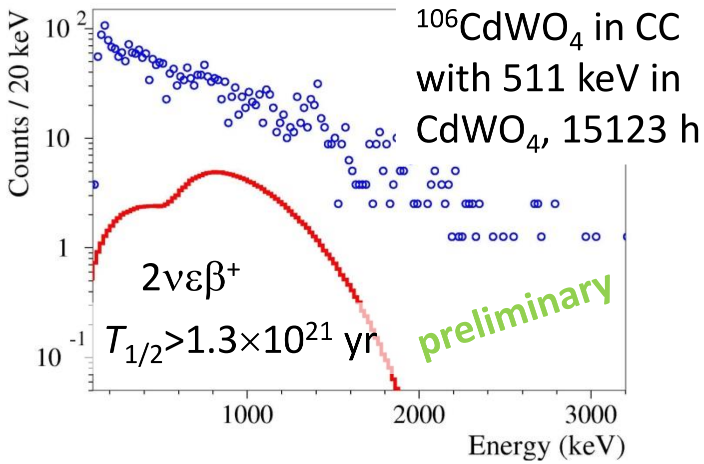
[1] P. Belli et al., PRC 85 (2012) 044610
[2] P. Belli et al., PRC 93 (2016) 045502

- 2β with conventional scintillation detectors

^{106}Cd experiment in the DAMA/Crys set-up



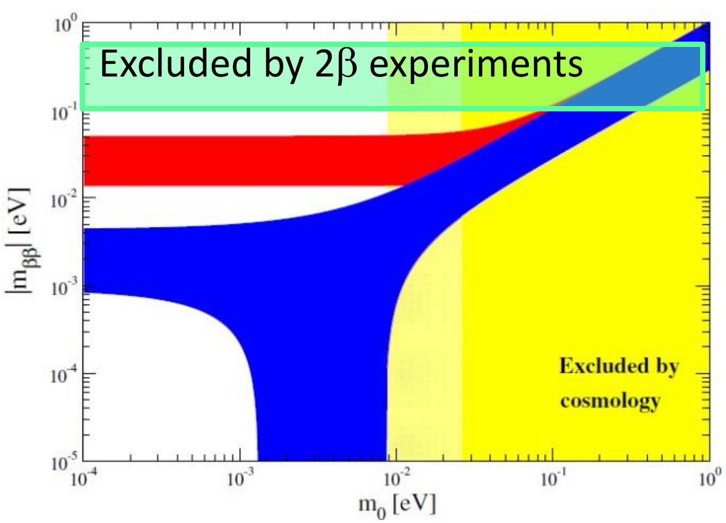




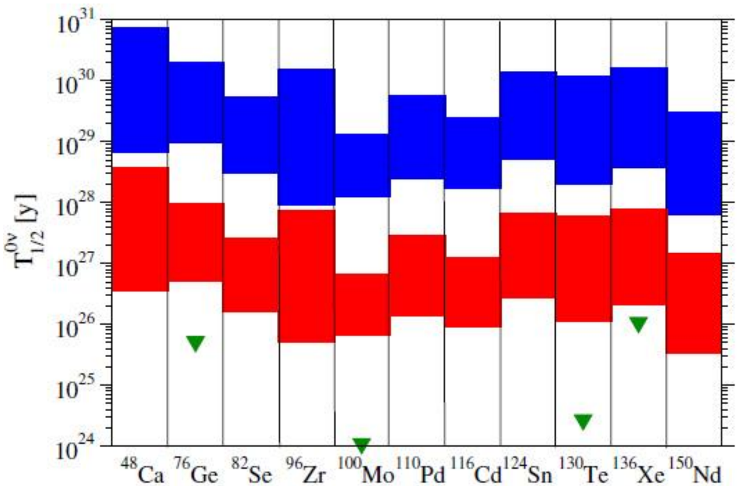
The sensitivity of the experiment is approaching the theoretical predictions for the $2\nu\varepsilon\beta^+$ decay of ^{106}Cd, that are within $T_{1/2}^{2\nu\varepsilon\beta^+} \sim (10^{20} - 10^{22})$ yr. The experiment is in progress.

Call for "Inverted hierarchy" $0\nu2\beta$ experiments

- The $0\nu2\beta$ is not observed, the best limits: $\lim T_{1/2}$~10^{24}-10^{26} yr $\rightarrow \langle m_\nu \rangle$~0.1-0.7 eV
- The experimental sensitivity should be advanced to explore the inverted hierarchy of the neutrino mass $\langle m_\nu \rangle$ **~ 0.02-0.05 eV,** $T_{1/2}$**~10^{26} – 10^{28} yr**



Normal Hierarchy
?
Inverted Hierarchy

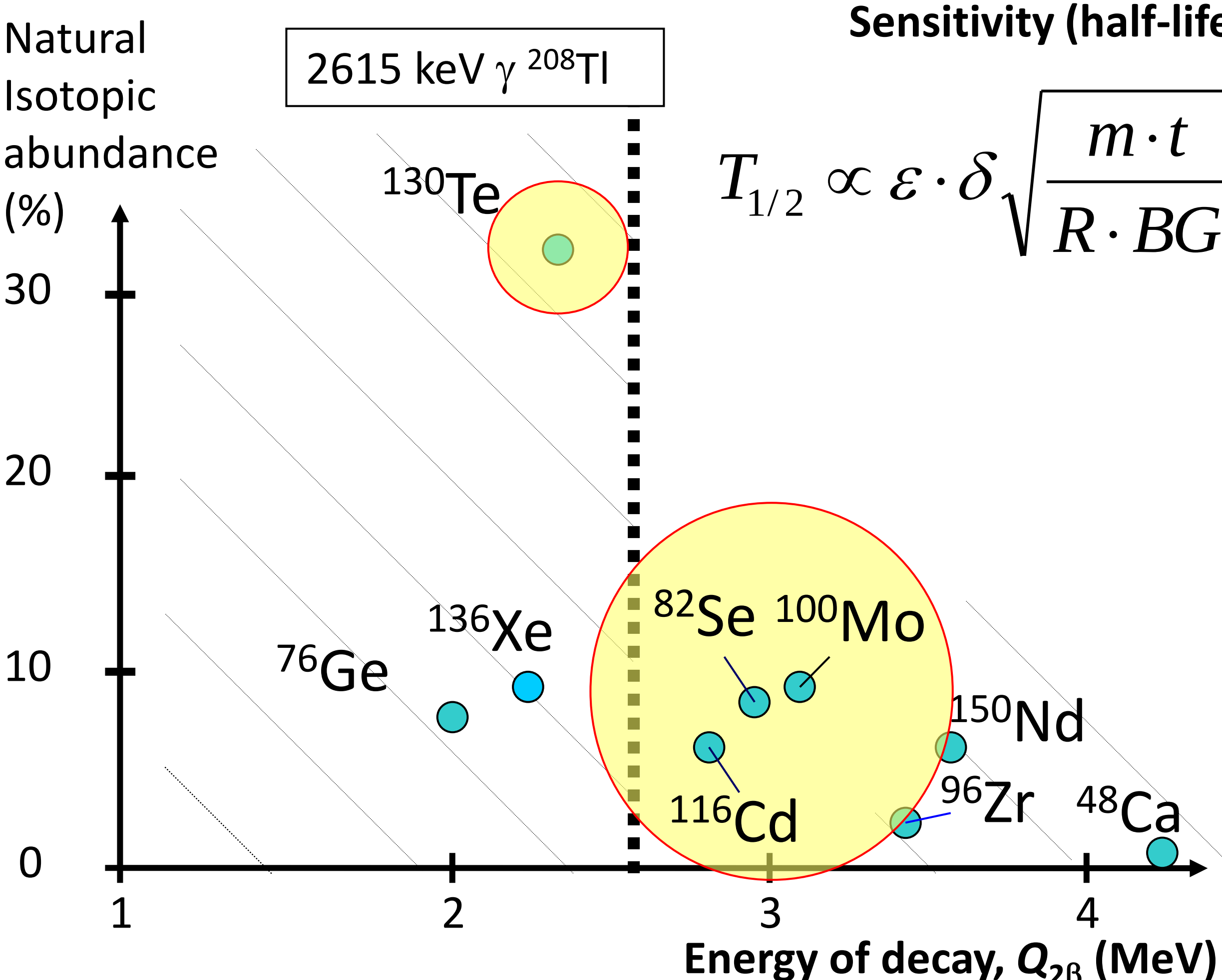


Nuclear matrix elements (NME) of the $0\nu2\beta$ decay calculated in the framework of different approaches [1]

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

- *Low temperature scintillators*

Toward the inverted hierarchy



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 Se, Mo and Cd, Te is component of TeO_2 crystals

CUPID

CUORE **U**pgrade with **P**article **ID**entification [1, 2]

CUPID is a proposed tonne-scale bolometric 0ν2β decay experiment to probe the Majorana nature of neutrinos and inverted hierarchy region of the neutrino mass. CUPID will be built on experience, expertise and lessons learned in CUORE, and will exploit the current CUORE infrastructure as much as possible. CUPID aims to increase the source mass and reduce the backgrounds in the region of interest

Léon Perrault (1832–1908)
Les flèches de Cupidon

Nuclei	Detector	$\langle m_\nu \rangle$ (meV)
^{130}Te	TeO_2	6-5
^{100}Mo	$ZnMoO_4$	7-17
^{82}Se	ZnSe	6-19
^{116}Cd	$CdWO_4$	8-15

CUORE

[1] G.Wang et al., CUPID: CUORE (Cryogenic Underground Observatory for Rare Events) Upgrade with Particle Identification, arXiv:1504.03599v1
[2] G.Wang et al., R&D towards CUPID (CUORE Upgrade with Particle IDentication), arXiv:1504.03612v1

Investigations of several nuclei are requested

There are theoretical, experimental and practical arguments to develop $0\nu2\beta$ decay experiments with several nuclei [1]:

<u>theoretical</u>

- Ambiguity of the nuclear matrix elements (NME) calculations
- Data on $0\nu2\beta$ decay rate in several nuclei can be useful to adjust NME calculations [2]

<u>experimental</u>

- In a case of positive evidence in one nucleus, an observation of the decay in other nuclei will be naturally requested
- Difficulties to predict possible breakthroughs in the detection techniques
- Prediction of background is rather complicate

<u>practical</u>

- Production of a large amount of a given isotope (at the ton scale) looks questionable

[1] A.Giuliani, F.A.Danevich, V.I.Tretyak, A multi-isotope $0\nu2\beta$ bolometric experiment, Eur. Phys. J. C 78 (2018) 272
[2] S.M.Bilenky, J.A.Grifols, The possible test of the calculations of nuclear matrix elements of the $(\beta\beta)0\nu$-decay, PLB 550(2002)154

Combined limit on $\langle m_\nu \rangle$

The Majorana neutrino mass can be derived from several experiments:

1) Sum of counts in the region of interest

$$\langle m_\nu \rangle = \frac{m_e}{\sqrt{\ln 2} \cdot g_A^2} \cdot \sqrt{\frac{\sum S_i}{\sum N_i \cdot \varepsilon_i \cdot t_i \cdot G_i^{0\nu} \left| M_i^{0\nu} \right|^2}}.$$

2) Weighted averages and errors of neutrino mass square

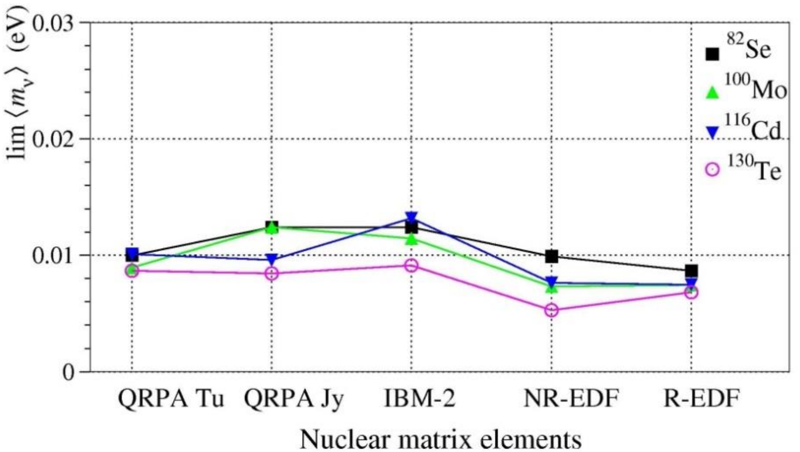
A value (limit) of neutrino mass can be derived from several experiments with different nuclei by using weighted averages and errors of square of the neutrino mass:

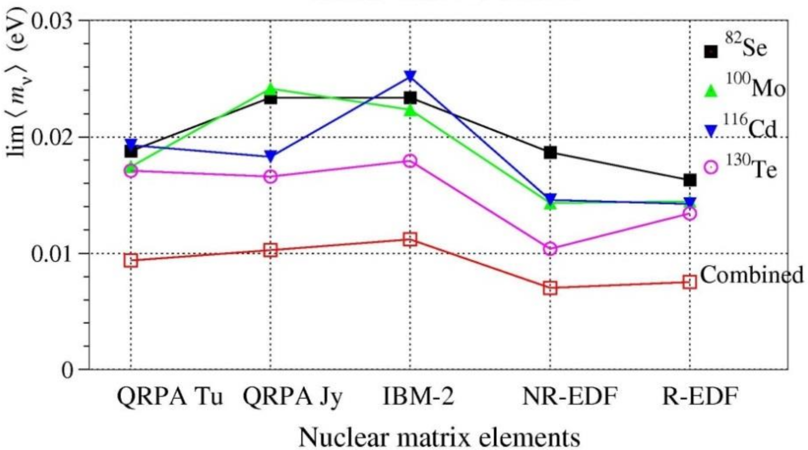
$$\langle m_\nu \rangle^2 \pm \sigma \langle m_\nu \rangle^2 = \frac{\sum w_i \langle m_\nu \rangle_i^2}{\sum w_i} \pm \left(\sum w_i \right)^{-1/2},$$

where $w_i = \dfrac{1}{\sigma \langle m_\nu \rangle_i^2}.$

A.Giuliani, F.A.Danevich, V.I.Tretyak, A multi-isotope $0\nu2\beta$ bolometric experiment, Eur. Phys. J. C 78 (2018) 272

Multi-isotope experiment is equivalent to an experiment with one nuclei *





The $\lim\langle m_\nu\rangle$ were estimated by using the NME calculated in the framework of different nuclear models: QRPA Tu [1]; QRPA Jy [2]; IBM-2 [3]; NR-EDF [4]; and R-EDF [53].

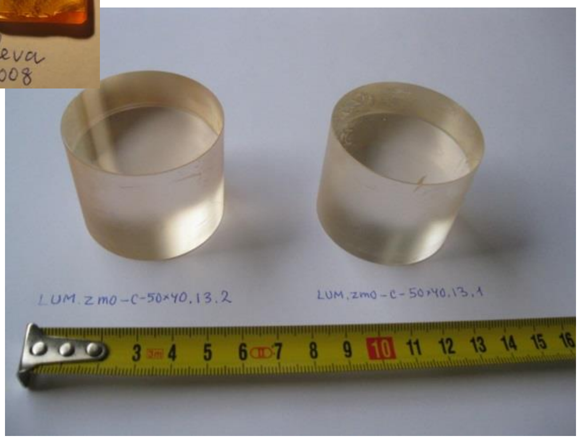
* Assume the same volume of the detectors in both cases

[1] F. Simkovic et al., PRC 87 (2013) 045501; [2] J. Hyvarinen, J. Suhonen, PRC 91 (2015) 024613; [3] J. Barea, J. Kotila, F. Iachello, PRC 91 (2015) 034304; [4] N.L. Vaquero, T.R. Rodriguez, E.J. Luis, PRL 111 (2013) 142501; [5] J.M. Yao et al., PRC 91 (2015) 024316

- *Low temperature scintillators*

LUMINEU: R&D of $ZnMoO_4$ cryogenic scintillating bolometers to search for $0\nu2\beta$ decay of ^{100}Mo

2008 (IGP, Moscow, Russia)



$ZnMoO_4$ crystals ∅5×4 cm (0.33 kg), 2013

First enriched $Zn^{100}MoO_4$ crystal (0.17 kg), 2014

1.4 kg enriched $Zn^{100}MoO_4$ crystal, 2015

- Radioactive contamination of $ZnMoO_4$ crystals is low: ^{226}Ra, ^{228}Th < 5 μBq/kg
- High energy resolution ~ 5-7 keV
- Powerful particle discrimination (~15σ)
- Yield of crystal boule: more than 80%, Irrecoverable losses: less than 4%

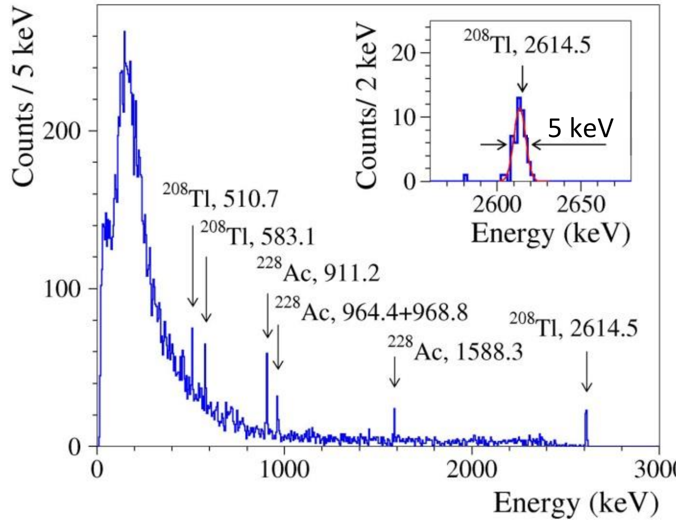
A very important result: purification methods for Mo and ^{100}Mo was developed [1]

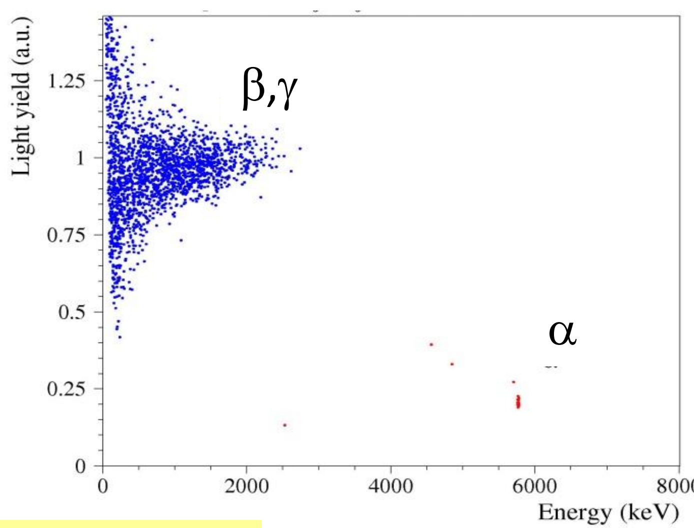
[1] L.Berge et al., Purification of molybdenum, growth and characterization of medium volume $ZnMoO_4$ crystals for the LUMINEU program, JINST 9 (2014) P06004

LUMINEU: Li_2MoO_4 is more promising detector

Production of high quality, radiopure $Li_2{}^{100}MoO_4$ is well established

- High yield of crystal boule: more than 80%
- Low enough irrecoverable losses (~2-3%)
- Recovery of Mo is easier



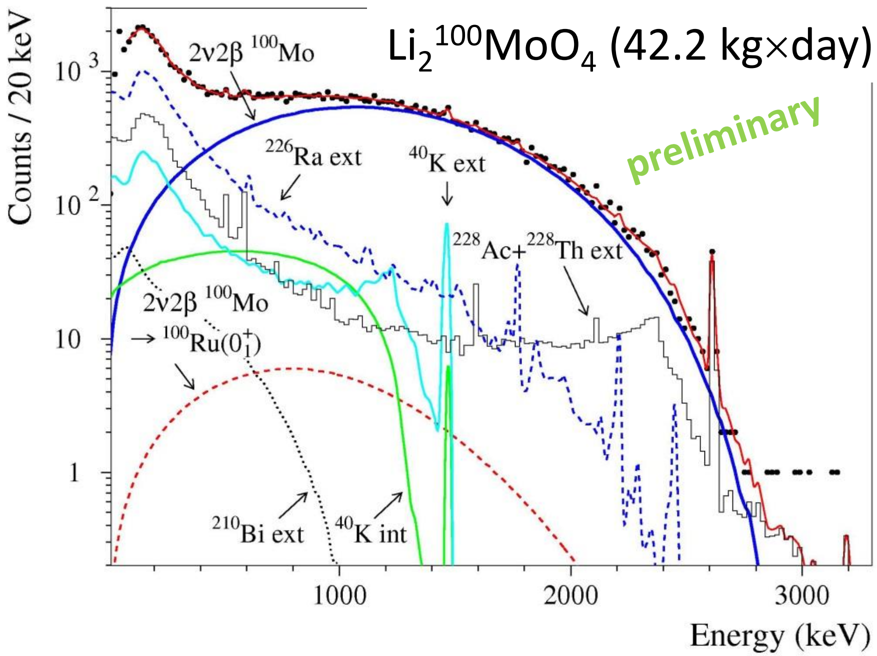


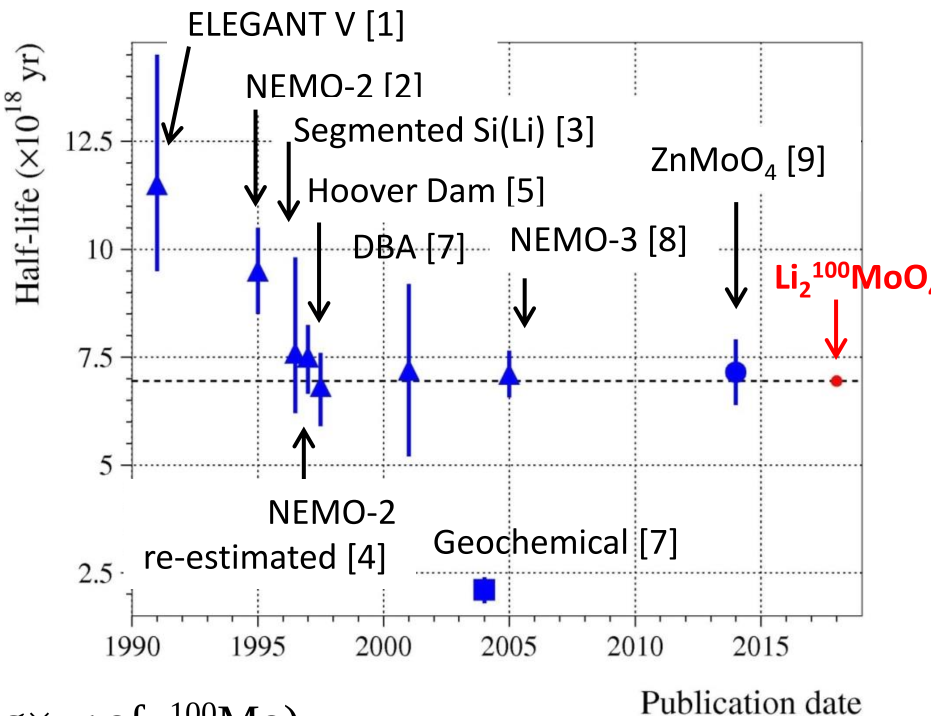
- High energy resolution: FWHM ≈ 4-6 keV at 2615 keV

- Excellent particle discrimination
- High radio-purity (< 6 μBq/kg of ^{228}Th)

E. Armengaud et al., Eur. Phys. J. C 77 (2017) 785

Precise measurement of the 2ν2β decay of ^{100}Mo





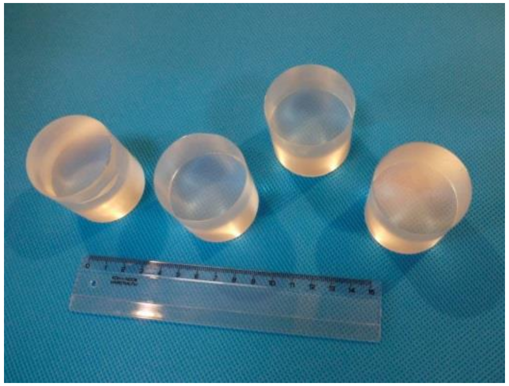
$T_{1/2}^{0\nu2\beta} > 7\times10^{22}$ yr (achieved with only 0.06 kg×yr of ^{100}Mo)

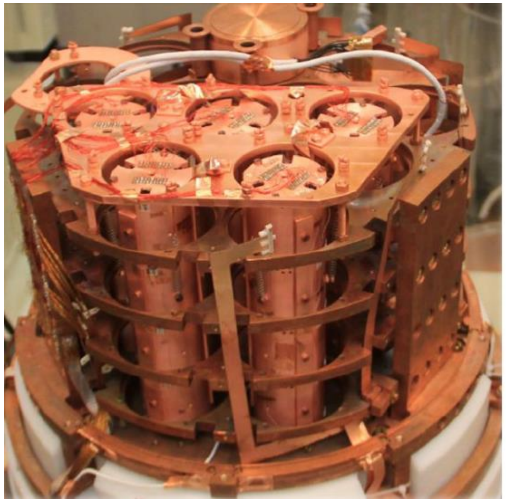
$T_{1/2}^{2\nu2\beta} = [6.903 \pm 0.055(\text{stat})^{+0.167}_{-0.137}(\text{syst})]\times10^{18}$ yr

is the most accurate $T_{1/2}$ for 2ν2β decay (≈2%)

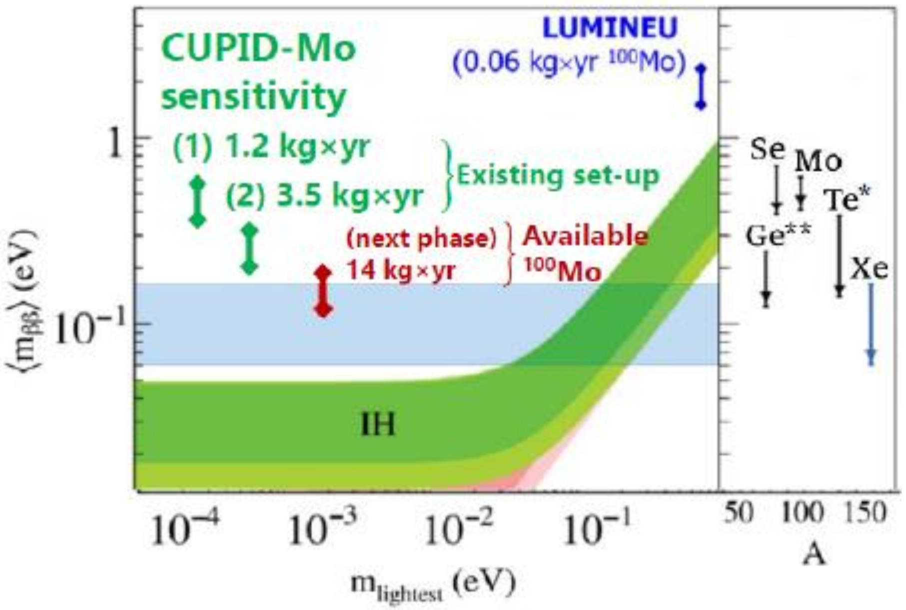
[1] H. Ejiri et al., Phys. Lett. B 258, 17 (1991)
[2] D. Dassié et al., Phys. Rev. D 51, 2090 (1995)
[3] M. Alston-Garnjost et al., Phys. Rev. C 55, 474 (1997)
[4] A. Vareille, PhD thesis, 1997
[5] A. De Silva et al., Phys. Rev. C 56, 2451 (1997)
[6] V.D. Ashitkov et al., JETP Lett. 74, 529 (2001)
[7] H. Hidaka et al., Phys. Rev. C 70, 025501 (2004)
[9] L. Cardani et al., J. Phys. G 41, 075204 (2014)

A current step: CUPID-Mo Demonstrator





- 35 enriched $Li_2{}^{100}MoO_4$ crystals are produced, production of about 15-18 crystals is in progress
- 20 $Li_2{}^{100}MoO_4$ detectors were installed in the EDELWEISS set-up at the Modane UL



Sensitivity with 40 detectors over 3 yr:

$$\lim T_{1/2}^{0\nu} \sim 1.5\times 10^{25}\ \text{yr} \quad \Rightarrow \quad \langle m_\nu \rangle \approx 0.1\ \text{eV} - 0.17\ \text{eV}$$

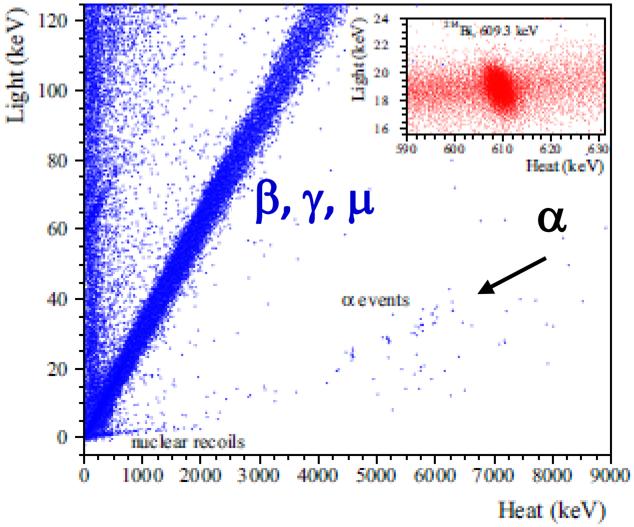
Cryogenic search for 0ν2β decay of ^{116}Cd

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

- Energy resolution: 5-7 keV at $Q_{2\beta}$ [1,2]
- Background: $\rightarrow$ 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 α

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



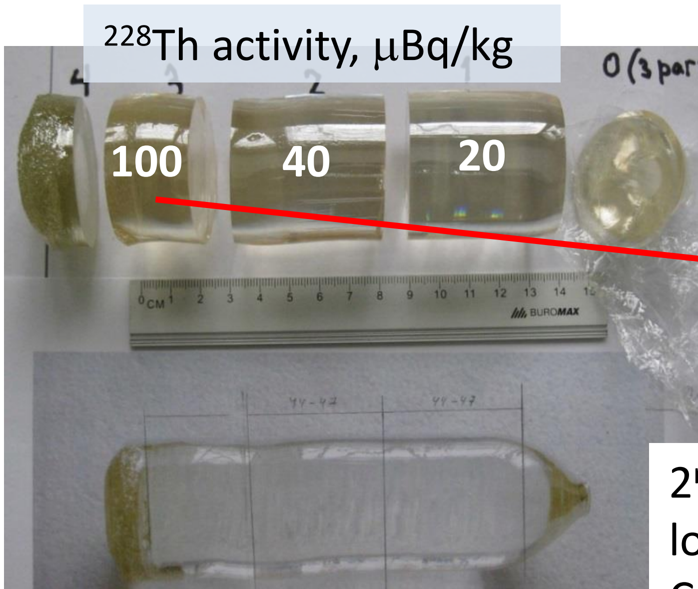
Search for 0ν2β decay of ^{116}Cd with a sensitivity: $\lim T_{1/2}^{0\nu} \sim 8\times10^{23}$ yr

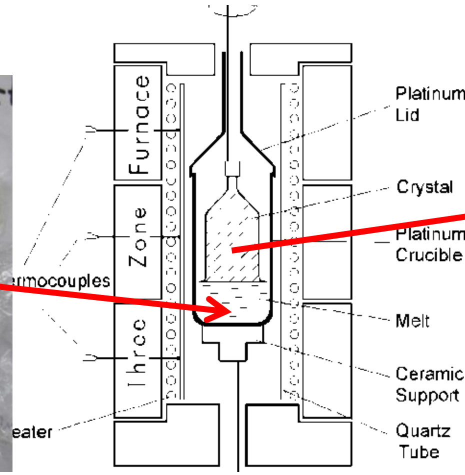
Demonstration of ^{116}Cd option capability for the large scale experiment (i.e., CUPID)

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

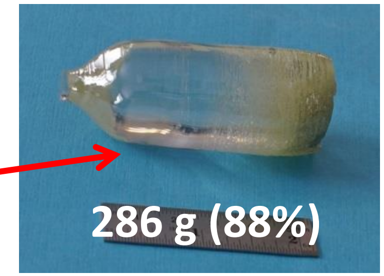
Prospects for ^{116}Cd 2β experiment

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



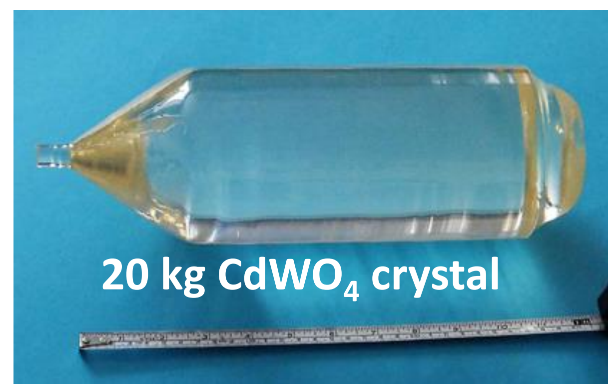


2nd crystallization by the low-thermal-gradient Czochralski method



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

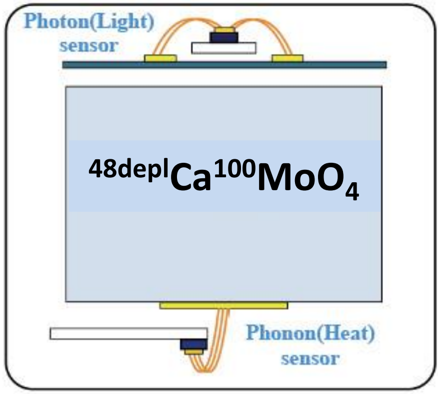
- **Production of large volume, high quality $CdWO_4$ crystal scintillators is well established [2]**



[1] A.S. Barabash et al., NIMA 833 (2016) 77
[2] V.N. Shlegel et al., JINST 12 (2017) C08011

AMoRE: Advanced Mo-based Rare process Experiment

Search for $0\nu2\beta$ of ^{100}Mo by using low temperature molybdate crystal scintillators and photodetectors equipped with MMC bolometers



MMC - Metallic Magnetic Calorimeter sensors

- Highest resolution
- Wide operating temperature
- Relatively fast signal (rejection of random coincidences)
- Adjustable parameters in design and operation stage

The experiment is scheduled to be realized in three phases:

1. **AMoRE pilot** is an R&D phase with a 1.9 kg array of six crystals enriched in ^{100}Mo and depleted in ^{48}Ca ($^{depl}Ca^{100}MoO_4$) (almost completed)
2. **The AMoRE I** phase will have 6 kg of $^{depl}Ca^{100}MoO_4$ and other ^{100}Mo-based detectors.
3. **AMoRE II** will utilize about 200 kg of molybdate crystal scintillators to explore the inverted neutrino mass hierarchy $T_{1/2} \sim 10^{27}$ yr, $\langle m_\nu \rangle \sim 0.015 - 0.04$ eV

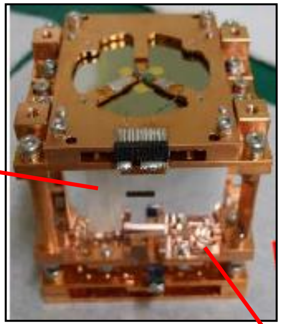
[1] V. Alenkov et al., Technical Design Report for the AMoRE 0 Decay Search Experiment, arXiv:1512.05957v1

- *Low temperature scintillators*

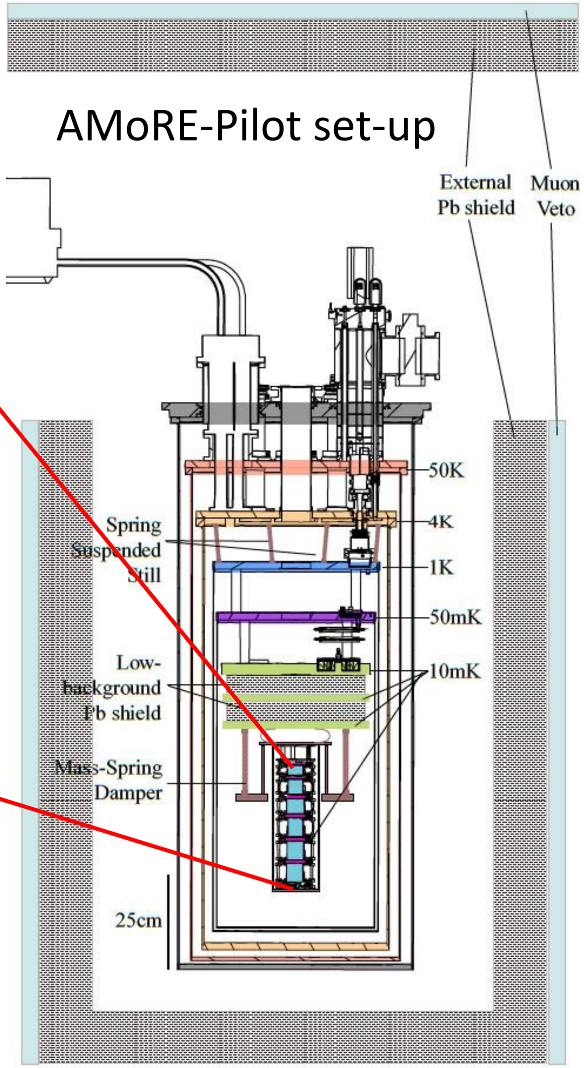
AMoRE-Pilot: 1.9 kg of $^{48depl}Ca^{100}MoO_4$

$^{depl}Ca^{100}MoO_4$

Detector module



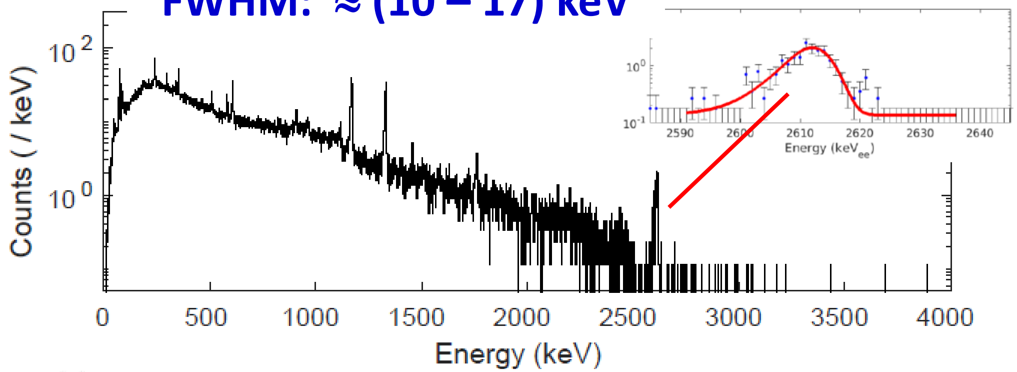
Detector tower

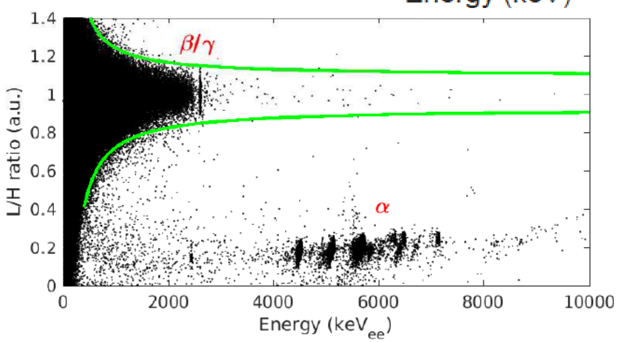


- *Low temperature scintillators*

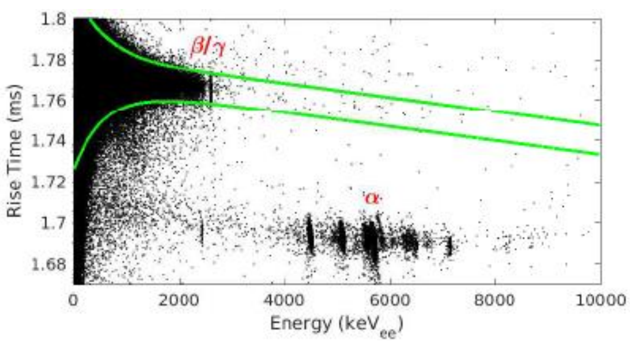
Energy resolution, particle discrimination, background

FWHM: ≈ (10 – 17) keV

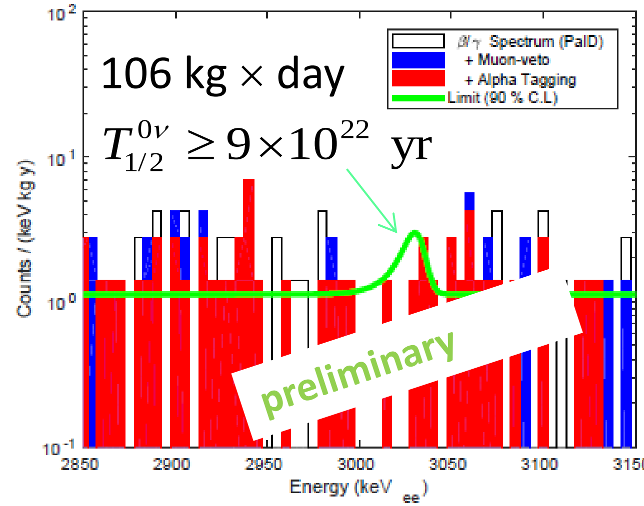




Event identification by light/heat ratio



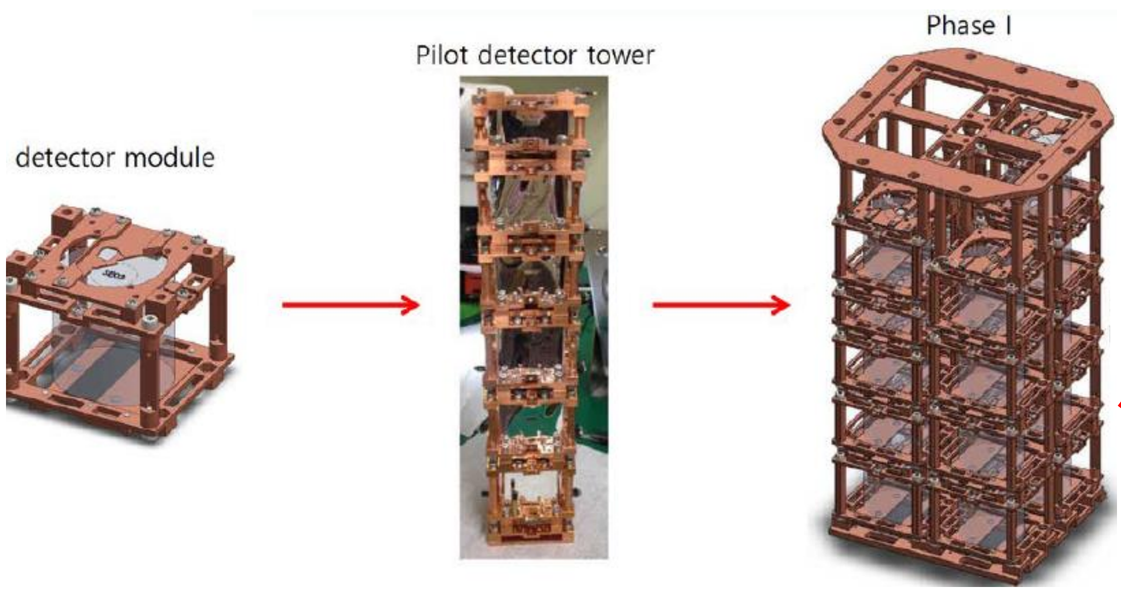
Event identification by pulse-shape discrimination

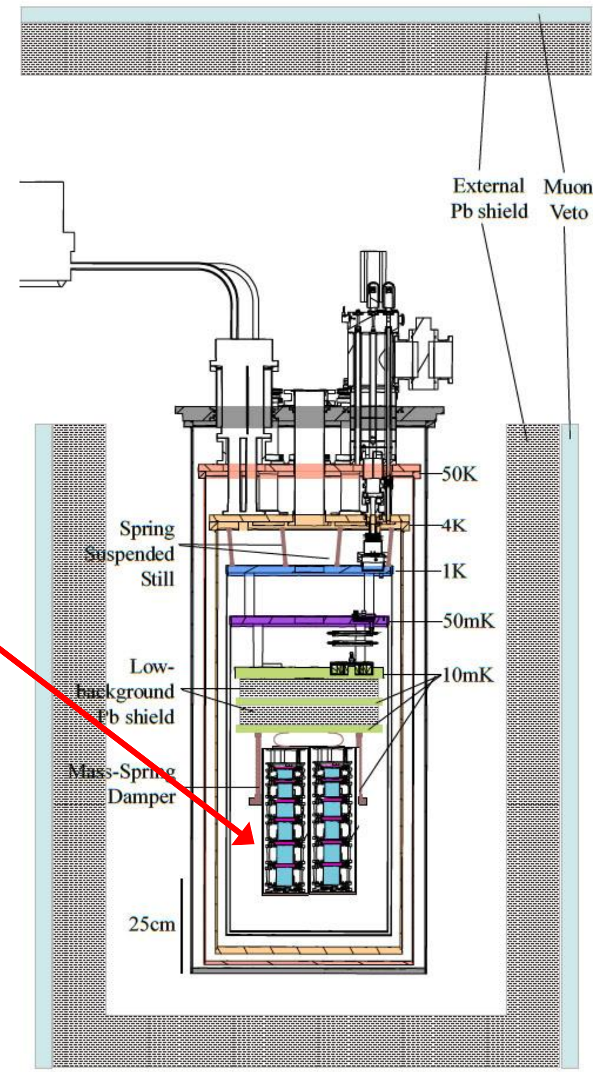


Background in ROI: ~ 0.3 counts/(yr keV kg)

Preliminary results, a paper is in preparation to EPJC

AMoRE I should start beginning of 2019

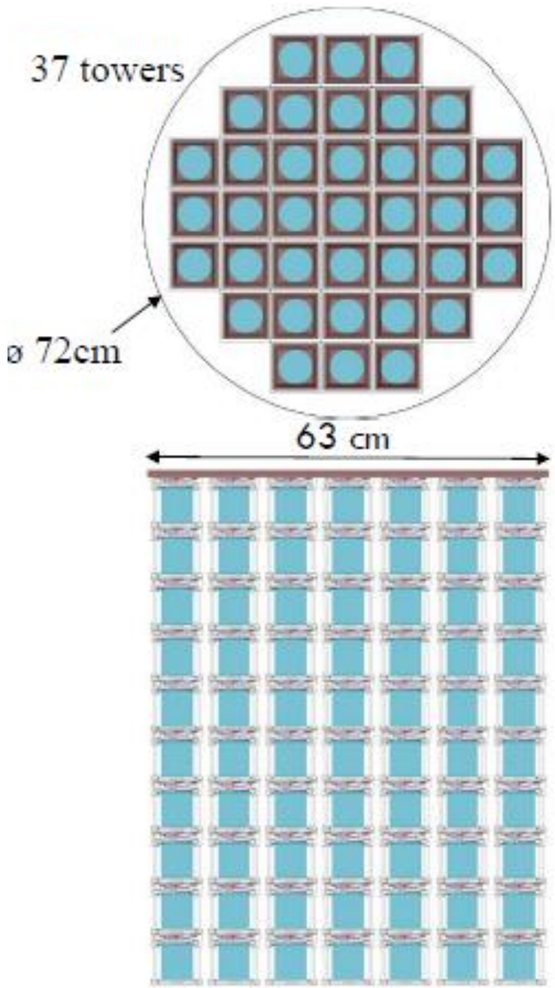


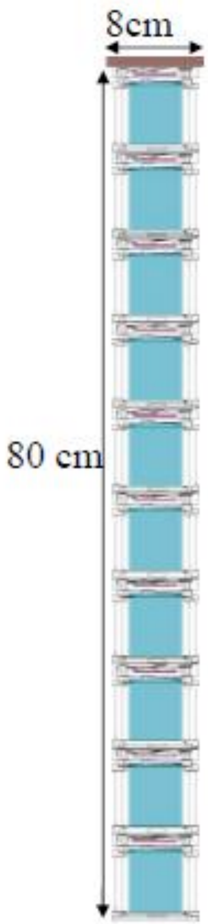


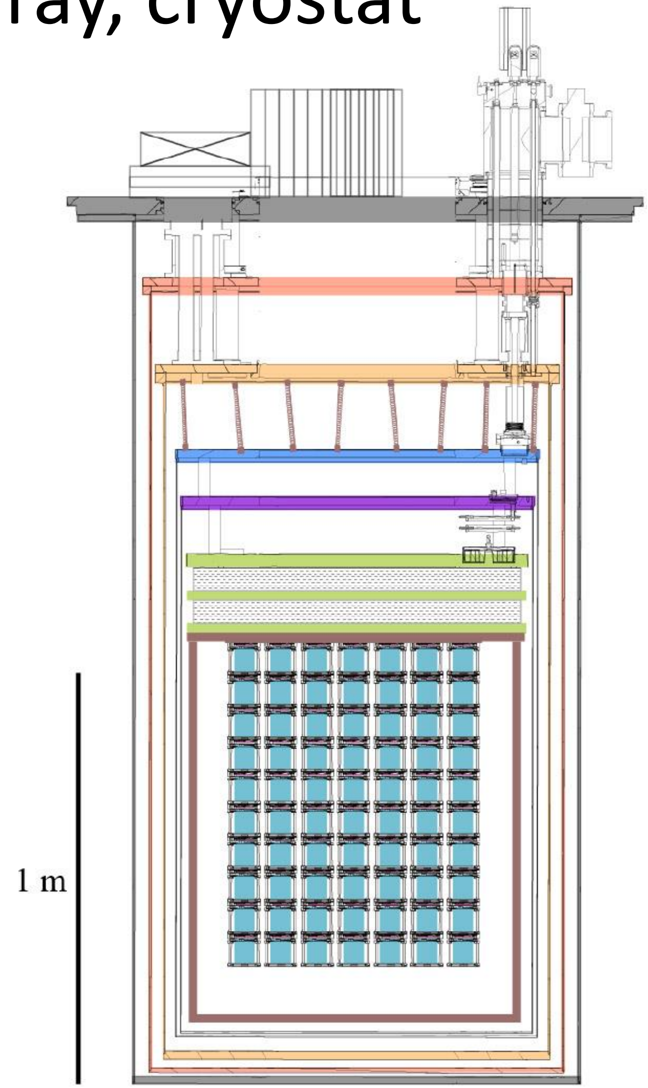
6 kg, 18 crystals with ≈ 3 kg of ^{100}Mo

13 $^{depl}Ca^{100}MoO_4$ crystals (4.6 kg) are ready, production of other molybdates ($Li_2{}^{100}MoO_4$, $Na_2{}^{100}Mo_2O_7$) is in progress

AMoRE II detector array, cryostat





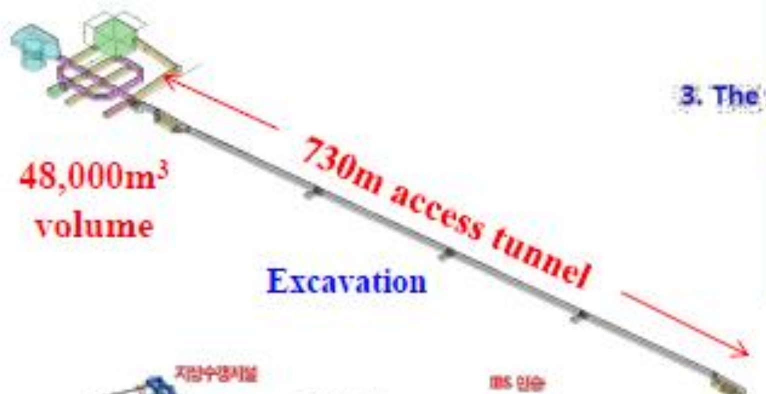


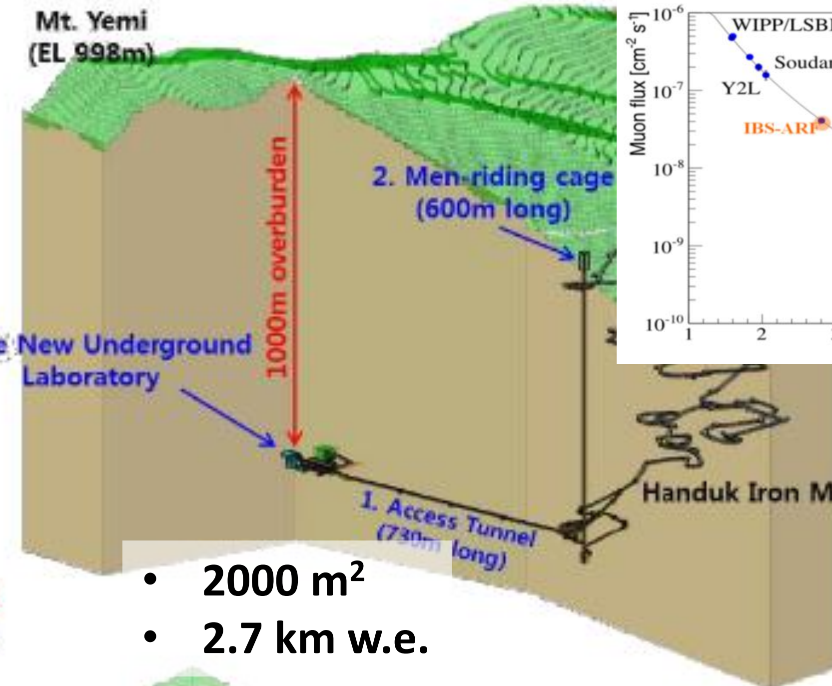
The AMoRE has already secured 60 kg of ^{100}Mo isotope out of 120 kg contracted

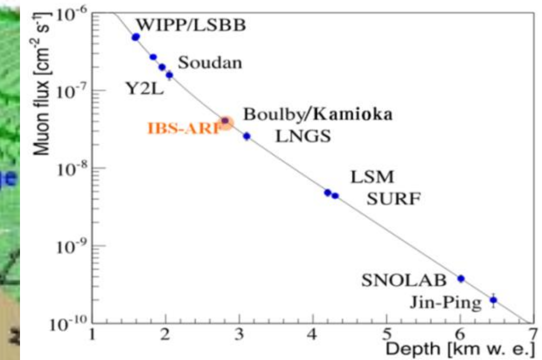
New underground lab at the Handuk (iron mine)

❑ **4 major constructions**

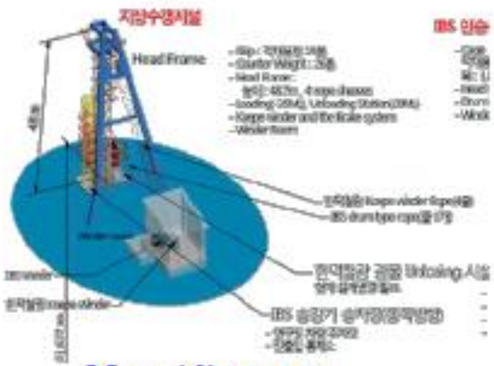
- Tunnel excavation
- Men-riding cage
- Underground lab
- Surface office/lab



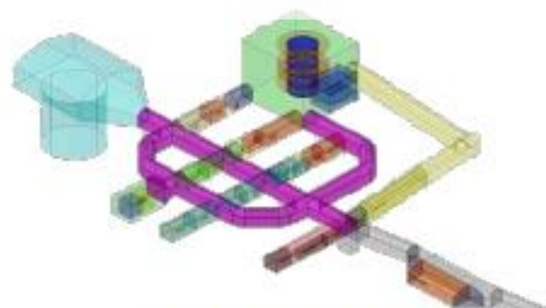




- **2000 m^2**
- **2.7 km w.e.**



Men-riding cage



Underground lab

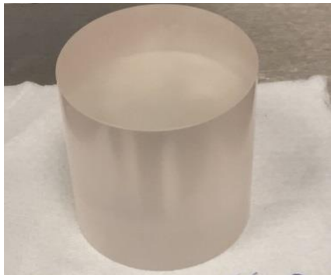
Surface office/lab

- Underground facility for crystal scintillators production is foreseen

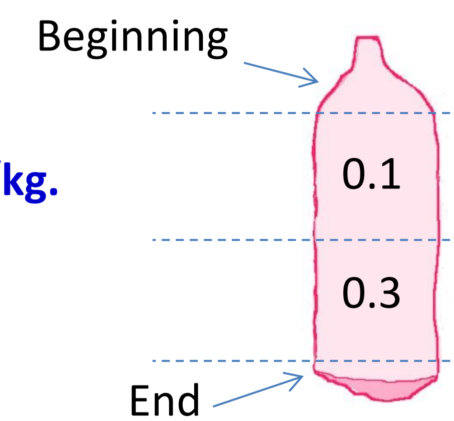
$ZnWO_4$ – an extremely radiopure crystal scintillator

$ZnWO_4$ crystal scintillator can be used:

- to search for 2β decay of Zn and W [1]
- to investigate directionality of dark matter particles [2]
- $ZnWO_4$ is one of the most radiopure inorganic scintillators [3]



$ZnWO_4$ ∅5×5 cm, 734 g



Four samples were measured in the DAMA R&D set-up.

Total α activity is (0.1-0.3) mBq/kg, activity of ^{228}Th < 170 nBq/kg.

A strong segregation of U and Th is observed

Measurements of $ZnWO_4$ crystal scintillator produced from additionally purified W is in progress. The next step will be re-crystallization of $ZnWO_4$ grown from the purified W

[1] P. Belli et al., J. Phys. G 38 (2011) 115107
[2] F. Cappella et al., Eur. Phys. J. C 73 (2013) 2276.
[3] F.A. Danevich, V.I. Tretyak, IJMPA 33 (2018) 1843007

Conclusions

1. 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

2. High sensitivity 2β experiments were realized (in progress) with $CdWO_4$ crystals scintillators enriched in ^{116}Cd and ^{106}Cd

3. An excellent energy resolution and efficient particle discrimination capability make the low temperature scintillating bolometers promising for $0\nu2\beta$ experiments (AMoRE, CUPID) aiming at test the inverted neutrino mass scheme and even go toward the normal neutrino mass hierarchy

4. Searches for $0\nu2\beta$ decay of several nuclei are highly required for theoretical, experimental and practical reasons. The sensitivity to the neutrino mass that can be achieved in an experiment with several nuclei is similar to the sensitivity of an experiment with only one nucleus

5. Radio-purity level of crystal scintillators ($ZnWO_4$) already approached nBq/kg level