Recent developments and results on ββ decays with crystal scintillators and HP-Ge spectrometry

"104° CONGRESSO NAZIONALE DELLA SOCIETÀ ITALIANA DI FISICA"
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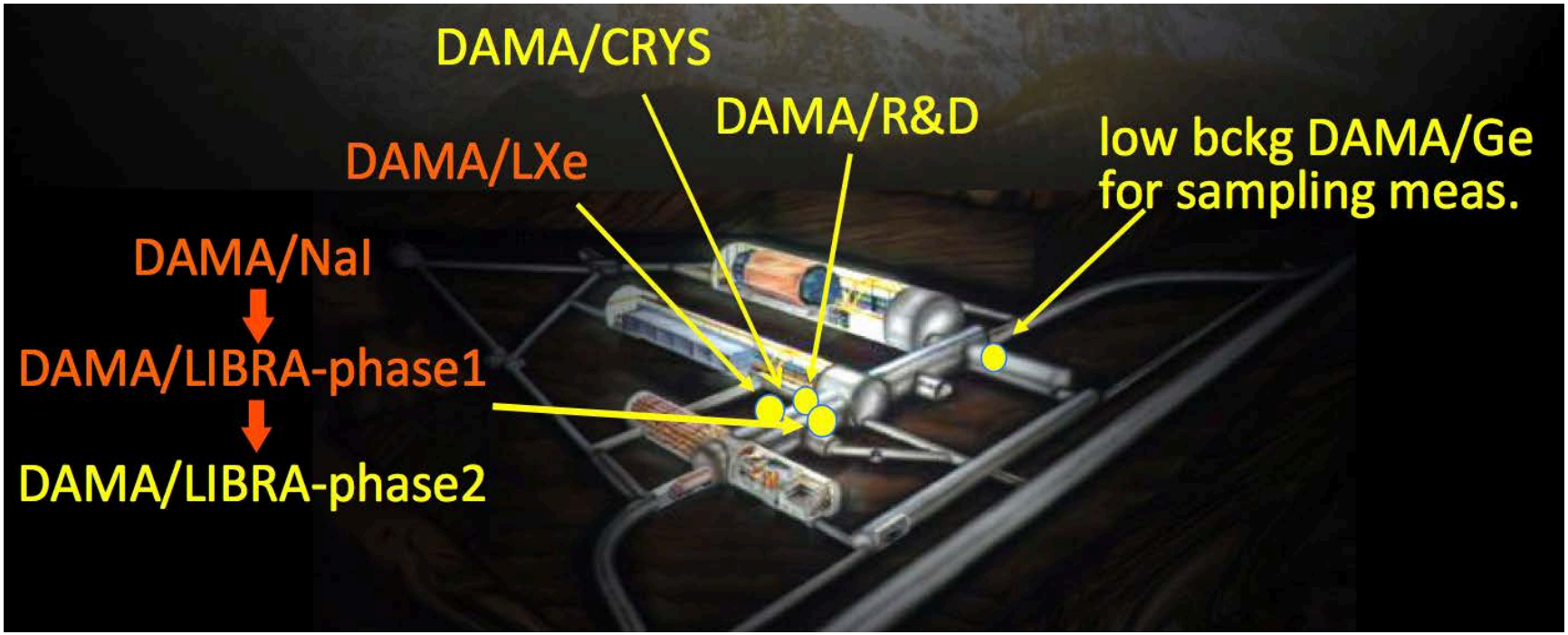
INFN-LNGS

Istituto Nazionale di Fisica Nucleare

DAMA set-ups

an observatory for rare processes @ LNGS



Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing

+ by-products and small scale expts.: INR-Kiev + other institutions

+ neutron meas.: ENEA-Frascati, ENEA-Casaccia

+ in some studies on $\beta\beta$ decays (DST-MAE & Inter-Univ. project): IIT Kharagpur and Ropar, India

web site: http://people.roma2.infn.it/dama

First or improved results for 2β decays of many isotopes

^{136}Ce $Q_{\beta\beta}$=2378.55 keV; 2ε, εβ$^+$, 2β$^+$; ^{138}Ce $Q_{\beta\beta}$=691 keV; 2ε

- CeO_2 sample (627 g) in GeCris detector (2299 h) ⇒ $T_{1/2}$ limits: 10^{17}-10^{19} yr [Eur. Phys. J. A 53 (2017) 172]
- CeO_2 sample (732 g) in GeCris detector (1900 h) ⇒ $T_{1/2}$ limits: 10^{17}-10^{18} yr [Nucl. Phys. A 930 (2014) 195]
- $CeCl_3$ crystal (6.9 g) in DAMA/Ge detec. (1280 h) ⇒ $T_{1/2}$ limits: (1÷6)10^{15} yr [Nucl. Phys. A 824 (2009) 101]

^{106}Cd $Q_{\beta\beta}$=2775.39 keV; 2ε (res 0ν), εβ$^+$, 2β$^+$ [Phys. Rev. C 93 (2016) 045502]

- $^{106}CdWO_4$ crystal scintillator (216 g) in GeMulti (13085 h) ⇒ $T_{1/2}$ limits: 10^{20}-10^{21} yr

^{96}Ru $Q_{\beta\beta}$=2714.51 keV; 2ε (res 0ν), εβ$^+$, 2β$^+$, ^{104}Ru $Q_{\beta\beta}$=1301.2 keV; 2β$^-$

- Purified Ru samples in GeMulti det. (0.56kg×yr) ⇒ $T_{1/2}$ limits: 10^{20}-10^{21} yr [Phys. Rev. C 87 (2013) 034607]
- Ru sample (473 g) in GeCrys detector (158 h) ⇒ $T_{1/2}$ limits: 10^{18}-10^{19} yr [Eur. Phys. J. A 42 (2009) 171]

^{184}Os $Q_{\beta\beta}$=1453.7 keV; 2ε (res 0ν), εβ$^+$; ^{192}Os $Q_{\beta\beta}$=412.4 keV; 2β$^-$ [Eur. Phys. J. A 49 (2013) 24]

- Os sample (173 g) in GeCris detector (2741 h) ⇒ $T_{1/2}$ limits: 10^{16}-10^{17} yr for ^{184}Os and 10^{19} yr for ^{192}Os

^{190}Pt $Q_{\beta\beta}$=1383 keV; 2ε (res 0ν), εβ$^+$; ^{198}Pt $Q_{\beta\beta}$=1049 keV; 2β$^-$ [Eur. Phys. J. A 47 (2011) 91]

- Pt sample (42.5 g) in GeCris detector (1815 h) ⇒ $T_{1/2}$ limits: 10^{14}-10^{16} yr for ^{190}Pt and 10^{18} yr for ^{198}Pt

^{156}Dy $Q_{\beta\beta}$=2005.95 keV; 2ε, εβ$^+$; ^{158}Dy $Q_{\beta\beta}$=282.7 keV; 2ε [Nucl. Phys. A 859 (2011) 126]

- Dy_2O_3 sample (322 g) in DAMA/Ge det. (2512 h) ⇒ $T_{1/2}$ limits: 10^{14}-10^{16} yr

^{100}Mo $Q_{\beta\beta}$=3035 keV; 2β$^-$ [Nucl. Phys. A 846 (2010) 143]

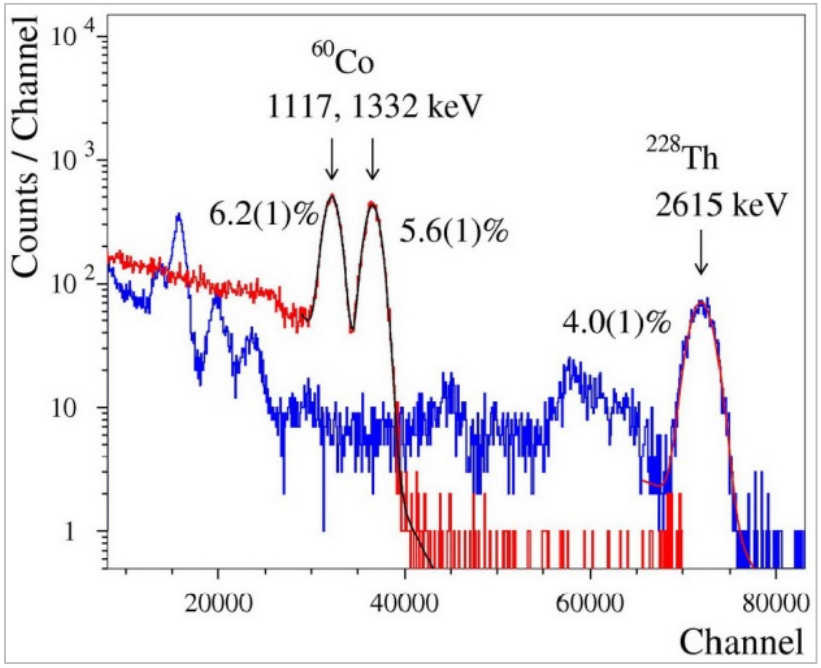
- $^{100}MoO_3$ sample (1199 g) enriched in ^{100}Mo at 99.5% in GeMulti detector
  ⇒ observation of ^{100}Mo→^{100}Ru(0_1^+) decay: $T_{1/2} = 6.9^{+1,0}_{-0,8}(stat) \pm 0.7(syst) \times 10^{20}$ yr

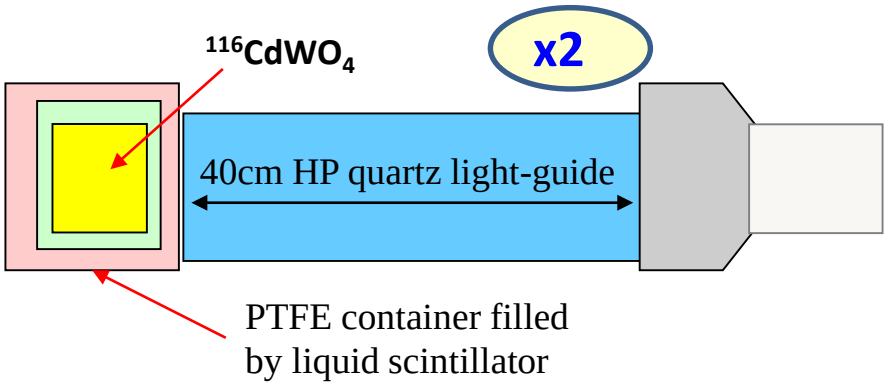
The best experimental sensitivities in the field for 2β decays with positron emission

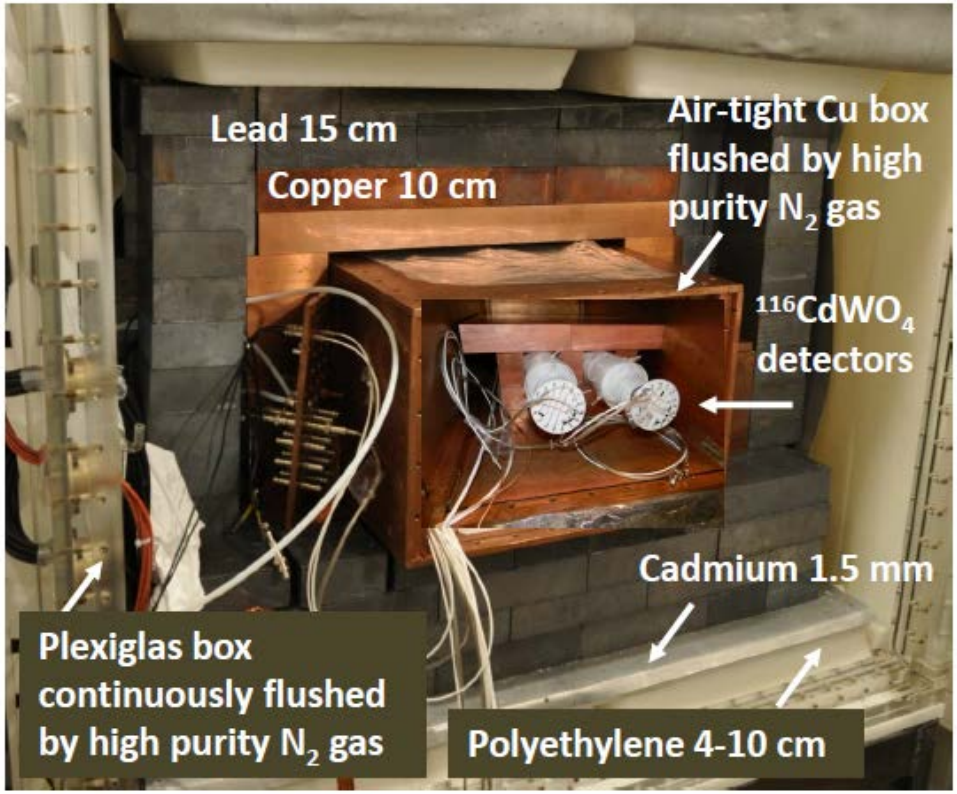
THE AURORA EXPERIMENT IN THE DAMA/R&D SET-UP

Two enriched **$^{116}CdWO_4$** crystal scintillators ($Q_{\beta\beta}$ = 2813.49(13) keV) (total mass: 1.162 kg, ^{116}Cd @ 82%)

- ✓ Started in 2011
- ✓ Upgrade - March 2014
- ✓ Total live time: 35324 h
- ✓ Background level at 2.7-2.9 MeV: **0.07 counts/keV/kg/yr**







Background identification: fit and results

Event-by-event DAQ based on a 1 GS/s 8 bit transient digitizer (operated at 50 MS/s) records the pulse shape over a time window of 100 μs from the $^{116}CdWO_4$ detectors

$SI = \Sigma f(t_k) \times P(t_k) / \Sigma f(t_k)$, $P(t) = [f_\alpha(t) - f_\gamma(t)]/[f_\alpha(t) + f_\gamma(t)]$

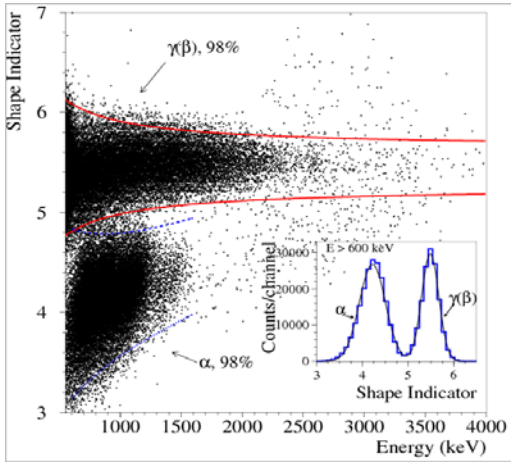
$f(t_k)$ → amplitude at t_k ; $P(t_k)$ → weight function;

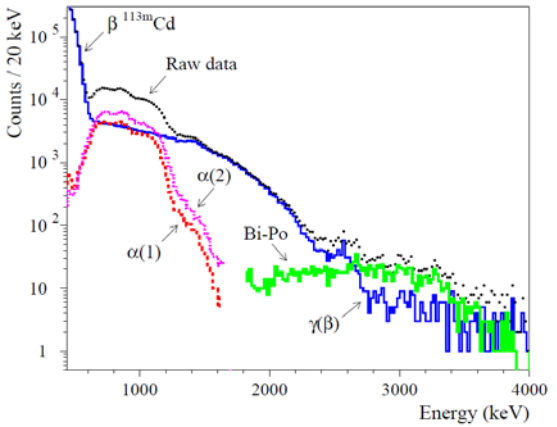
$f_{\alpha,\gamma}(t_k)$ → reference pulse

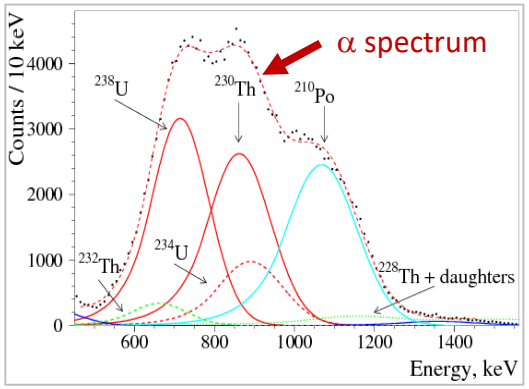
T=35324 h

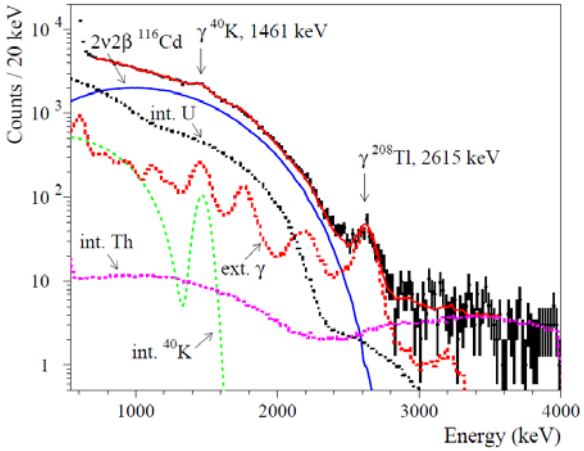
Radioactive contaminations of $^{116}CdWO_4$ crystal scintillators

Chain	Nuclide	Activity mBq/kg
^{232}Th	^{232}Th	0.61(2)
	^{228}Th	0.022(3)
^{238}U	^{238}U	0.59(7)
	^{234}Th	0.64(7)
	^{230}Th	0.11(2)
	^{226}Ra	≤ 0.01
	^{210}Pb	0.6(1)
	^{40}K	0.20(1)
	^{110m}Ag	<0.06









Total α activity = 2.27 mBq/kg

Result for two neutrino double beta decay of ^{116}Cd

Conditions of the Fit:

- Variation of bounds for radioactive contaminations
- Model of background
- Interval of fit
- Quenching for β (non prop. light response) [1,2]

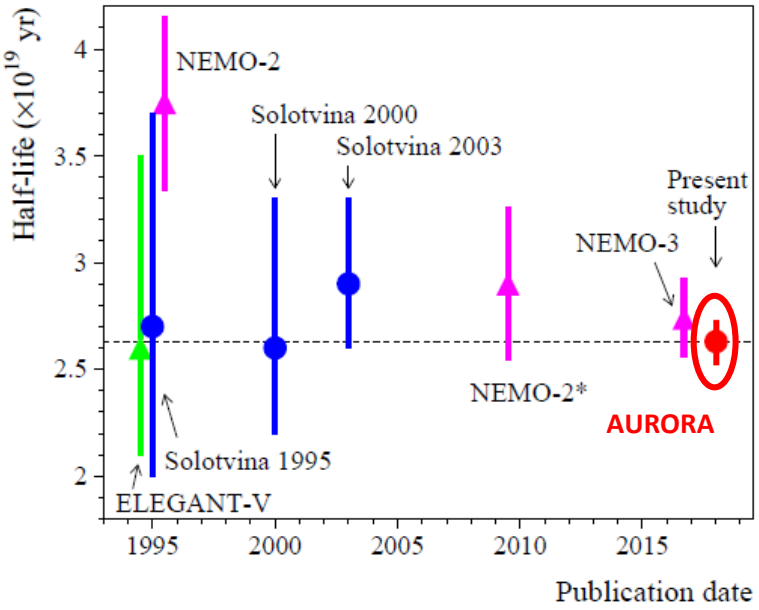
[1] PRC 76(2007)064603 [2] NIMA 696 (2012) 144

Signal to bkg ratio: 2.6 in [1.1–2.8] MeV

Systematic errors

Source	SE%
Rad. contamination of $^{116}CdWO_4$ crystals	65
BG models, MC, QF	15
PSD efficiency	10
Interval of the fit	7
Number of ^{116}Cd nuclei	3

$$T_{1/2} = [2.63^{+0,11}_{-0,12}(sys)] \times 10^{19}\ \text{yr}$$ (the most accurate value up to date)



ELEGANT: J. Phys. Soc. Japan 64(1995)339
Solotvina 1995: Phys. Lett. B 344(1995)72
NEMO-2: Z. Phys. C 72(1996)239
Solotvina (2000): PRC 62(2000)045501
Solotvina (2003): PRC 68(2003)035501
NEMO-2* (recalc.): PRC 81(2010)035501
NEMO-3: PRD 95(2017)012007

$T_{1/2}$ limit on 0ν2β decay of ^{116}Cd

Background reduction (**~1.5**) for 0ν2β decay by excluding events from:

^{212}Bi [Q_α=6207 keV, B.R. ~36%] → **^{212}Po [Q_β=8954 keV, $T_{1/2}$ = 299 ns] → ^{208}Pb**

⇒ **background rate in 2.7-2.9 MeV: 0.07 (counts/keV/kg/yr)**

Fit in 2.5–3.2 MeV: **-3.7 ± 10.6 counts**

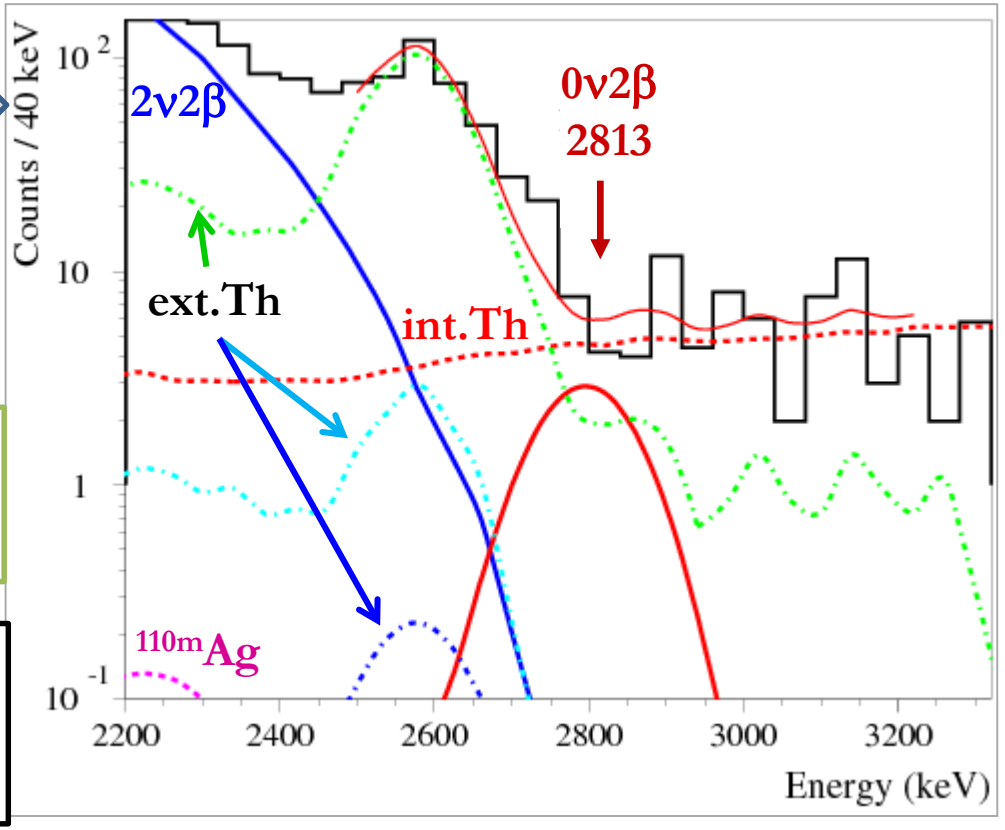
$T_{1/2} > 2.2 \times 10^{23}$ yr @ 90% C.L.

Effective Majorana neutrino mass:

$\langle m_\nu \rangle < 1.0 – 1.7$ eV [1-4]

\+ New improved limits on $T_{1/2}$ for 0ν2β decay to excited levels of ^{116}Sn in the range:

(3.6–6.3)×10^{22} yr

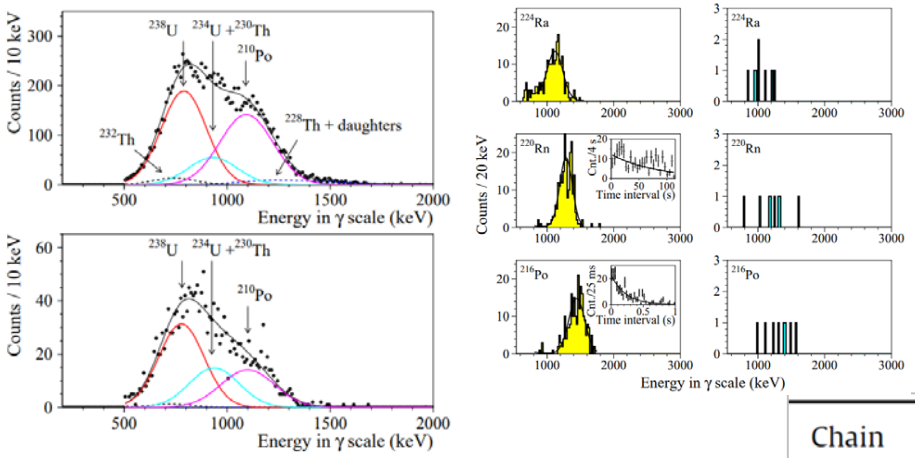


[1] T.R. Rodryguez et al., Phys.Rev.Lett. 105(2010)252503
[2] F. Simkovic et al., Phys.Rev.C 87 (2013)045501
[3] J. Hyvarinen et al., Phys.Rev.C 91 (2015)024613
[4] J. Barea et al., Phys.Rev.C 91(2015)034304

Improvement of radiopurity of $^{116}CdWO_4$ by recrystallization

A.S. Barabash et al., Nucl. Instr. Meth. A 833(2016)77

Re-crystallized by the low-thermal-gradient Czochralski technique in a platinum crucible



Crystal n.3 used (326 g mass)

60% of initial mass after re-crystallization

Side surface made opaque by grinding paper to improve light collection

Radioactive contamination of the samples (before an after recrystallization) measured in the DAMA/CRYS setup @ LNGS

Chain	Nuclide (sub-chain)	Activity (mBq/kg)	
		Before recrystallization	After recrystallization
^{232}Th	^{232}Th	0.13(7)	0.03(2)
	^{228}Th	0.10(1)	0.010(3)
^{238}U	^{238}U	1.8(2)	0.8(2)
	^{226}Ra	≤0.1	≤0.015
	^{234}U+^{230}Th	0.6(2)	0.4(1)
	^{210}Po	1.6(2)	0.4(1)
Total α		4.44(4)	1.62(4)

- ^{228}Th reduced by a factor ~10 ⇒ 0.01 mBq/kg
- α activity reduced by a factor ~3 ⇒ 1.6 mBq/kg

main background component for ^{116}Cd $0\nu2\beta$ decay

⇒ Strong segregation of the radioactive elements in the $CdWO_4$ crystals growing process

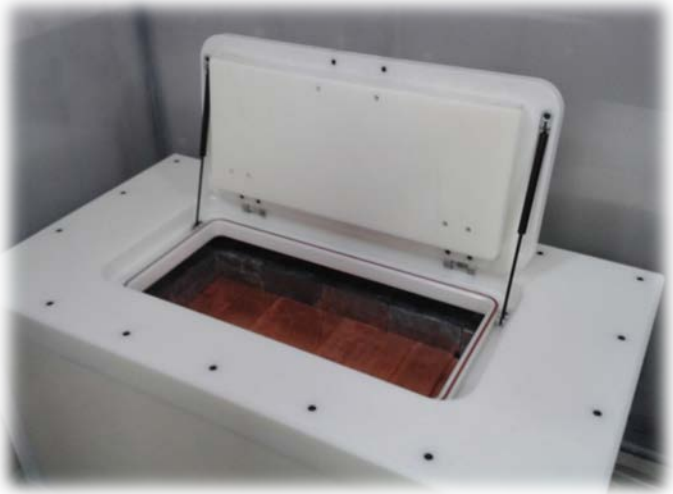
$^{106}CdWO_4$ experiment in DAMA/CRYS set-up: third phase

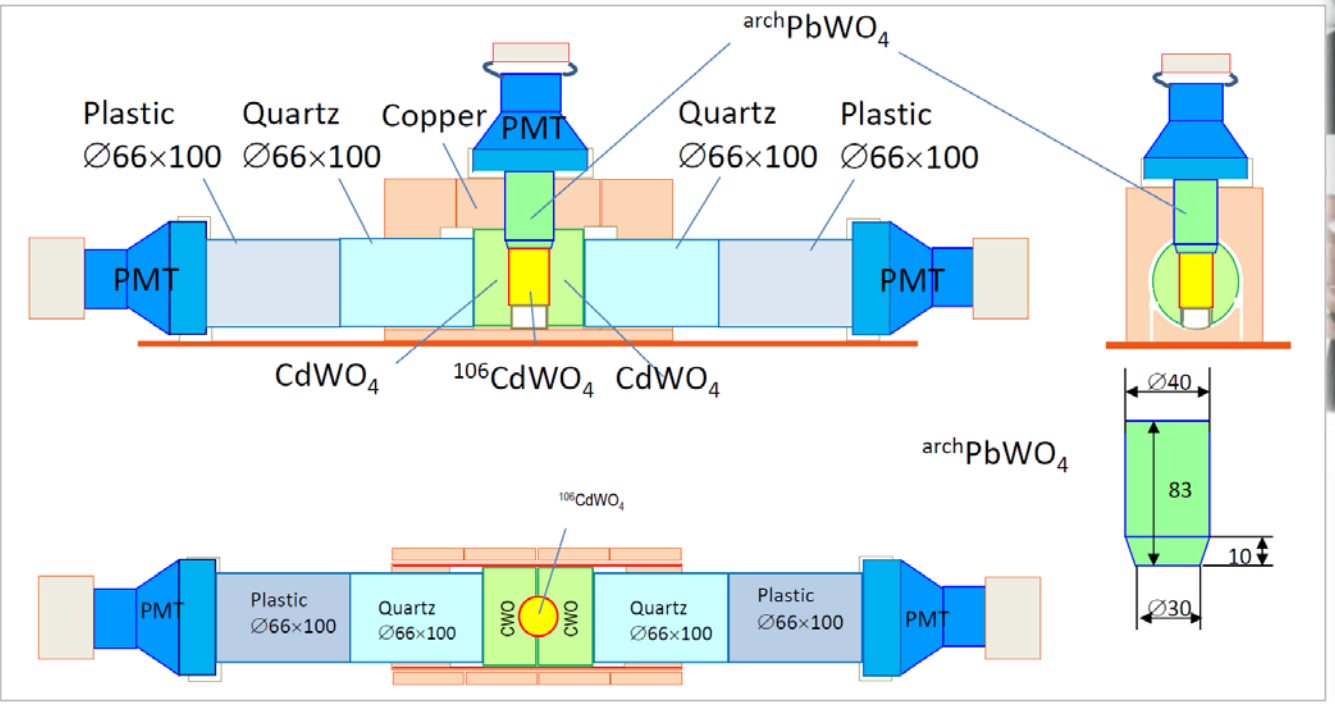
1) $^{106}CdWO_4$ in (anti)coincidence with two large $CdWO_4$ scintillators mounted in DAMA/CRYS set-up @ LNGS (Q=2775.39(10)keV, δ_{nat}=1.25(6)%, δ=66% enriched)
   Mass: 216 g, 66.4% enrichment in ^{106}Cd
2) High efficiency
3) Experiment in data taking since May 2016

1st exp: single crystal in DAMA/R&D: **PRC85(2012)044610**

2nd exp: coincidence with 4 HP-Ge: **PRC93(2016)045502**

DAMA/CRYS set-up

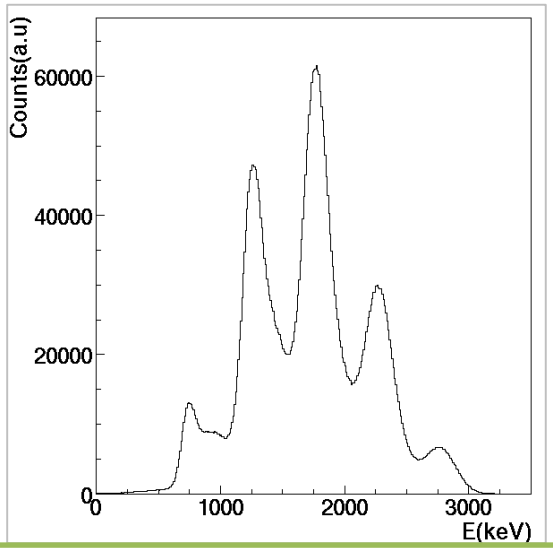




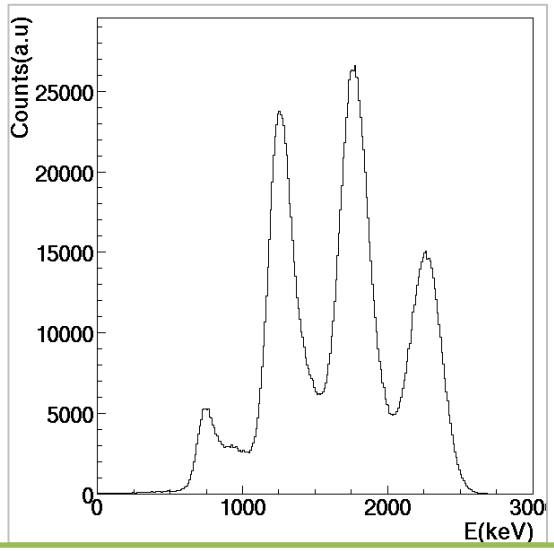
ESTIMATION OF SENSITIVITY

Expected signal for ^{106}Cd $0\nu2\beta(0^+ \rightarrow 0^+)$:

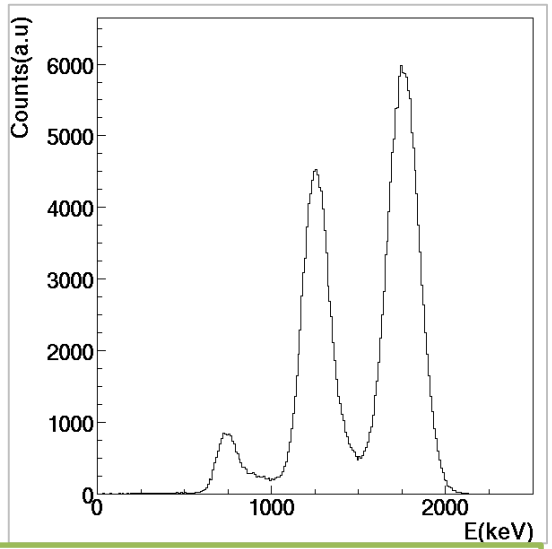
Spectrum of $^{106}CdWO_4$ detector



Spectrum of $^{106}CdWO_4$ detector when one of the two $CdWO_4$ detectors detects γ of 511 keV ($\pm2\sigma$)



Spectrum of $^{106}CdWO_4$ detector when both the $CdWO_4$ detectors detect γ of 511 keV ($\pm2\sigma$)



Sensitivity after 1yr in the hypothesis of about 30 background counts in [0.-3.] MeV:

$0\nu\varepsilon\beta^+$ (g.s.): $T_{1/2} \approx 5 \times 10^{21}$ yr

$2\nu\varepsilon\beta^+$ (g.s.): $T_{1/2} \approx 3 \times 10^{21}$ yr

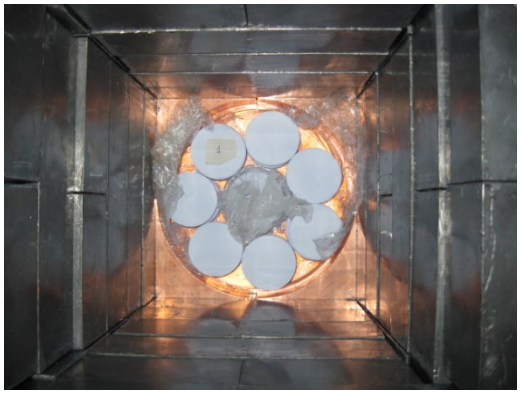
$2\nu2\beta^+$ (g.s.): $T_{1/2} \approx 2 \times 10^{21}$ yr

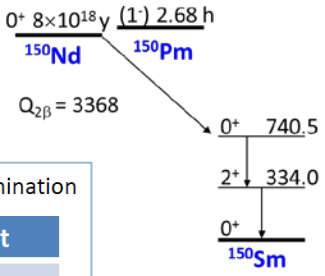
In the region of theoretical predictions: $T_{1/2} \sim 10^{20}$–10^{22} yr

Note that, up to now, 2ν mode of the $2\beta^+$ processes has not been detected unambiguously: there are only indications for ^{130}Ba and ^{78}Kr

Running and future experiments on HP-Ge

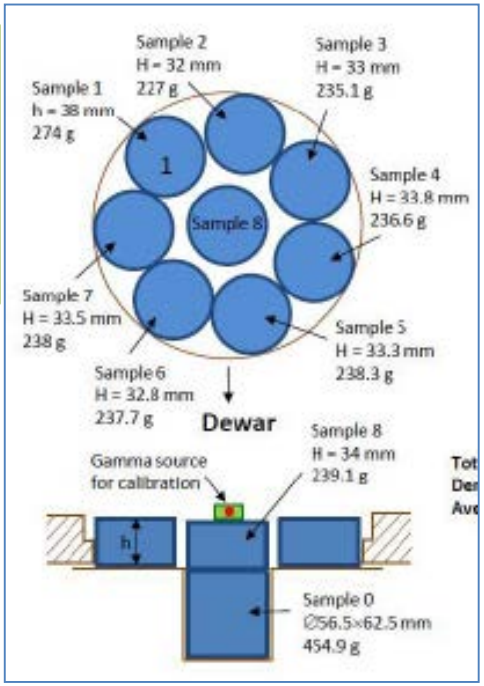
- Experiment running since February 2015 with deeply purified Nd_2O_3 sample (2381 g) in GeMulti detector to investigate 2β decay of ^{150}Nd to excited levels of ^{150}Sm:
  - ⇒ Background rate in the region of expected peaks (334.0 keV and 406.5 keV) ≈ 2 counts/keV/d
  - ⇒ Expected $T_{1/2}$ sensitivity after 500 days of measurements: 1.3×10^{20} yr (90%CL)



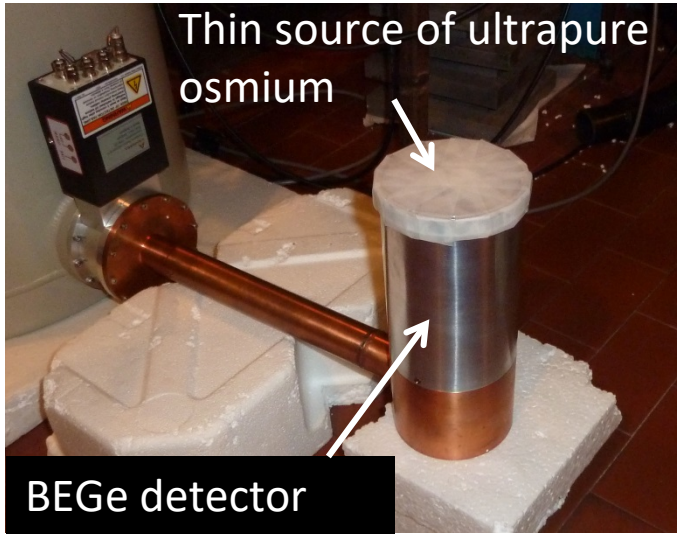


Improvement of Nd_2O_3 radioactive contamination

Contamination	Before [1]	Present
^{40}K	46	< 4
^{214}Bi (^{226}Ra)	1.1	<0.4
^{228}Ac (^{228}Ra)	0.9	<0.4



- New experiment to search for 2β of osmium (and α decay of osmium to excited level of daughter nuclei) in progress with BEGe detector:
  - ⇒ Detection efficiency significantly improved by cutting the osmium roads into thin (0.8-1 mm) plates and by using the BEGe detector



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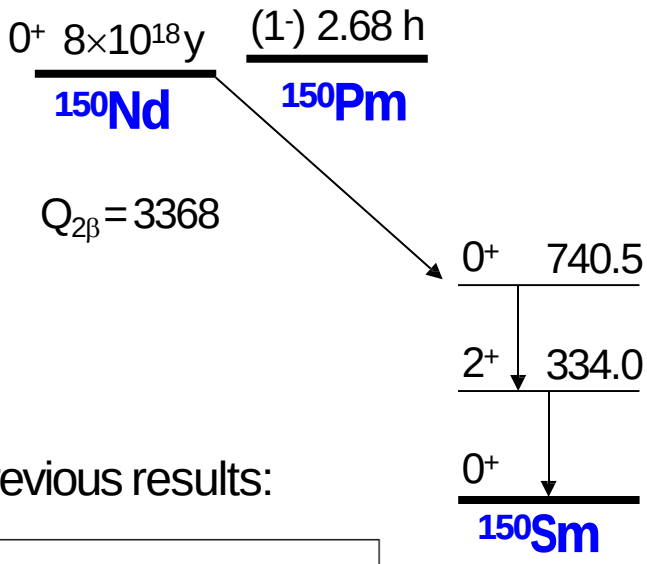
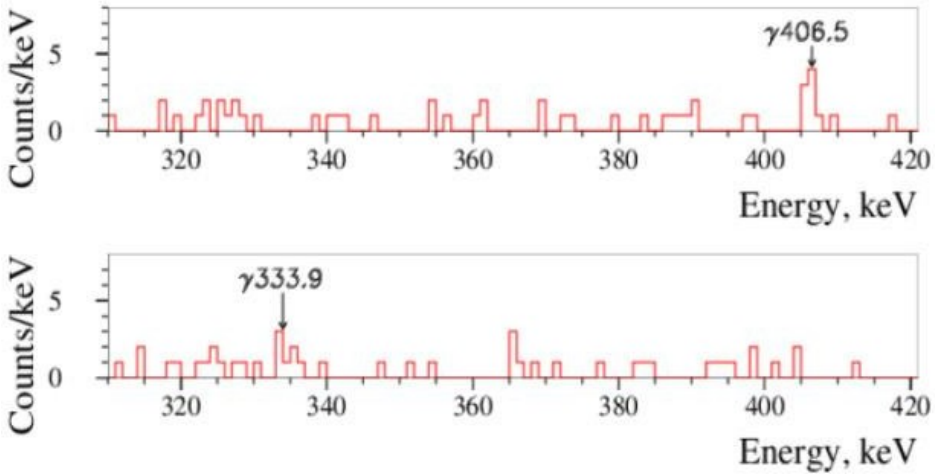
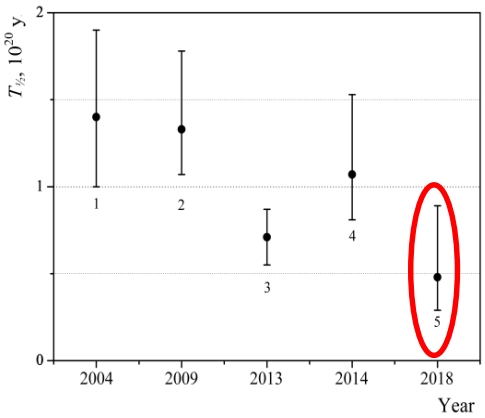
J. Phys. G: Nucl. Part. Phys. 45 (2018) 095101

An experiment with highly purified Nd_2O_3 source (2.381 kg) in the GeMulti (4 HPGe ~220 cm^3 each) detector of the STELLA facility





Previous results:



[1] JETP Lett. 79(2004)10
[2] PRC 79 (2009) 045501
[3] PhD thesis, NEMO-3 (2013).
[4] PRC 90 (2014) 055501
[5] Current work

re-estimation

8 events of the decay are observed over 16375 in coincidence with the HPGe. The half-life:

$$T_{1/2}^{2\nu2\beta} = (0.84^{+0.47}_{-0.22}) \times 10^{20} \text{ yr}$$

Preliminary

The experiment in progress aiming to improve the statistic accuracy to at least 3σ

First search for 2ε and εβ+ decay of ^{162}Er and search for 2β- decay of ^{170}Er to the excited levels of daughter nuclei has been realized with a highly purified erbium oxide samples are published (**J.P.G: Nucl. Part. Phys. 45 (2018) 095101**): **new limits at the level of 10^{15}-10^{18} yr for 2ε, εβ+, 2β- decays**.

Running and Some of the future Experiments/R&D

1. An experiment to search for 2β decay of ^{116}Cd to excited levels of ^{116}Sn is in preparation by using a recrystallized highly radiopure $^{116}CdWO_4$ crystal scintillator in coincidence with external gamma counters (HP Ge, CdWO4) is in preparation.

2. The experiment and data analysis to search for 2β processes in ^{106}Cd with enriched $^{106}CdWO_4$ crystal scintillator in CC with two large volume $CdWO_4$ in close geometry is in progress. An R&D of improved $PbWO_4$ light-guide from highly purified archaeological lead is in progress.

3. The experiment to search for 2β decay of ^{150}Nd to the excited level of is in progress, the data analysis and a paper preparation about preliminary result of the experiment is published.

4. The experiment to search for alpha decay of ^{184}Os and ^{186}Os to excited levels of daughter nuclei is in progress to improve the statistic.

5. First search for 2ε and εβ$^+$ decay of ^{144}Sm and ^{168}Yb and search for 2β$^-$ decay of ^{154}Sm and ^{176}Yb to the excited levels of daughter nuclei has been realized with a highly purified ytterbium and samarium oxide samples. Data analysis and paper are in preparation.

6. R&D of radiopure high quality $ZnWO_4$ also for dark matter directionality investigations: measurements of four samples (after one and two crystallizations) is going, the data analysis, R&D of radiopure WO_3 and 2nd crystallization are in progress.

7. Data analysis of an experiment aiming at accurate measurement of the ^{212}Po half-life with the help of thorium loaded liquid scintillator is in progress.

8. R&D of radiopure Gd_2SiO_5(Ce) crystal scintillators to search for 2β decay of ^{152}Gd and ^{160}Gd is in progress.

9. R&D of radiopure SrI_2(Eu) crystal scintillators to search for 2β decay of ^{84}Sr is in progress.

Thank you for the attention