RECENT DEVELOPMENTS AND RESULTS ON ββ DECAYS WITH CRYSTAL SCINTILLATORS AND HP-GE SPECTROMETRY

"7TH INTERNATIONAL CONFERENCE ON NEW FRONTIERS IN PHYSICS (ICNFP 2018) "

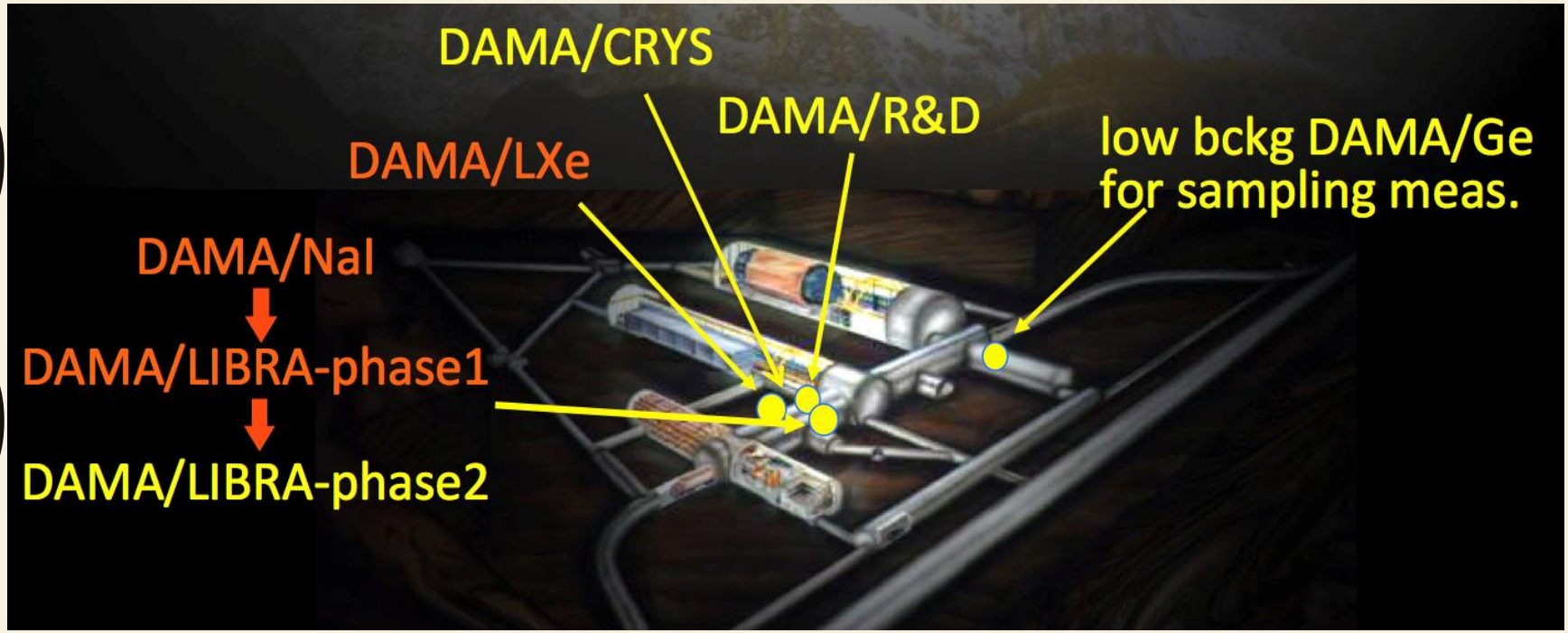
KOLYMBARI - CHANIA 3-12.07.2018

Dr. A. Di Marco
INFN Roma "Tor Vergata"

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

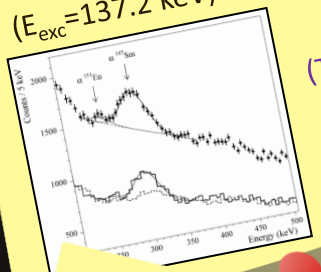
+ in some studies on ββ decays (DST-MAE & Inter-Univ. project): IIT Kharagpur and Ropar, India

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

MAIN RESULTS OBTAINED BY DAMA IN THE SEARCH FOR RARE PROCESSES

- First or improved results in the search for 2β decays of ~30 candidate isotopes: ^{40}Ca, ^{46}Ca, ^{48}Ca, ^{64}Zn, ^{70}Zn, ^{100}Mo, ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{108}Cd, ^{114}Cd, ^{116}Cd, ^{112}Sn, ^{124}Sn, ^{134}Xe, ^{136}Xe, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{142}Ce, ^{156}Dy, ^{158}Dy, ^{180}W, ^{186}W, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt (observed 2ν2β decay in ^{100}Mo, ^{116}Cd)
- The best experimental sensitivities in the field for 2β decays with positron emission (^{106}Cd)

First observation of α decays of ^{151}Eu with a CaF_2(Eu) scintillator and of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os ($T_{1/2}=5\times10^{18}$yr)



Observation of correlated e^+e^- pairs emission in α decay of ^{241}Am ($A_{e^+e^-}/A_\alpha \approx 5\times10^{-9}$)

Search for cluster decays of ^{127}I, ^{138}La and ^{139}La

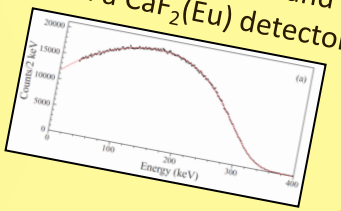
Search for PEP violating processes in Sodium and in Iodine

Search for N, NN, NNN decay into invisible channels in ^{129}Xe and ^{136}Xe

CNC processes, e.g. in ^{127}I, ^{136}Xe, ^{100}Mo and ^{139}La

Search for ^{7}Li solar axions using resonant absorption in LiF crystal

Investigations of rare β decays of ^{113}Cd ($T_{1/2}=8\times10^{15}$yr), ^{113m}Cd with $CdWO_4$ scintillator and ^{48}Ca with a CaF_2(Eu) detector



Search for spontaneous transition of ^{23}Na and ^{127}I nuclei to superdense state

Dark Matter investigation

… many others are in progress

Decay modes for Double Beta Decay (DBD)

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

$(A,Z) \rightarrow (A,Z-2) + 2e^+ + 2\nu_e$

$(A,Z) + e_a \rightarrow (A,Z-2) + e^+ + 2\nu_e$

$(A,Z) + 2e_a \rightarrow (A,Z-2) + 2\nu_e$

2ν Double Beta Decay (2νββ)
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ yr

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$

$(A,Z) \rightarrow (A,Z-2) + 2e^+$

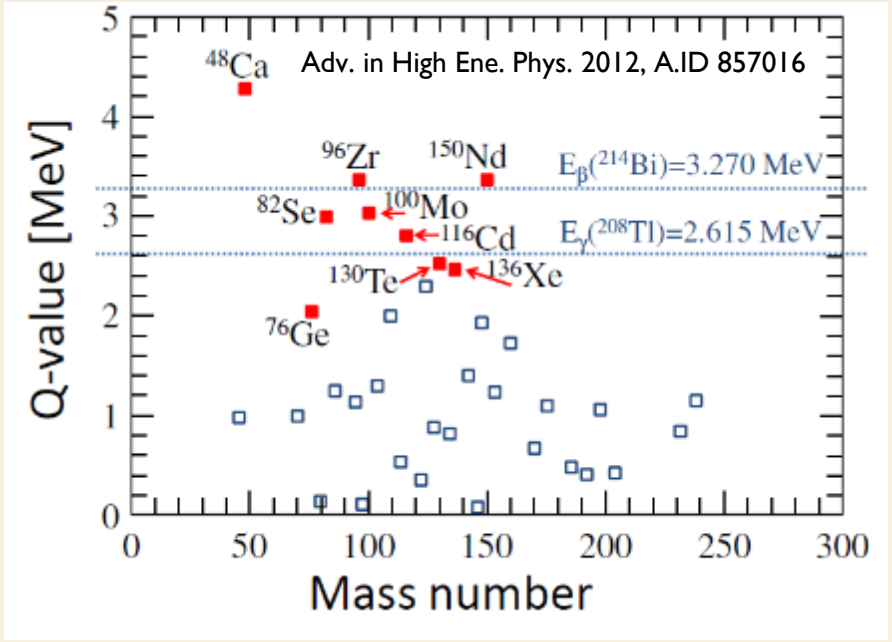
$(A,Z) + e_a \rightarrow (A,Z-2) + e^+$

$(A,Z) + 2e_a \rightarrow (A,Z-2) + \gamma$

neutrinoless Double Beta Decay (0νββ)
never observed except
Klapdor's meas. - $\tau \Rightarrow 10^{25}$ yr

③ 0νββ with Majoron
(light neutral boson)
never observed – $\tau > 10^{22}$ y

Processes ② and ③ would imply new physics beyond the Standard Model
violation of total lepton number conservation

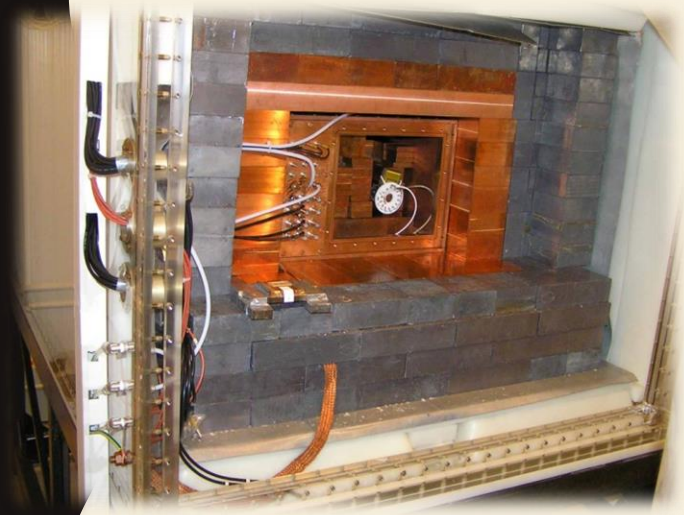


How many candidate nuclei?
Case of $2\beta^-$ processes →

SOME EXAMPLE OF ISOTOPES DECAYING ββ THAT COULD BE STUDIED BY CRYSTAL SCINTILLATORS WITH «SOURCE=DETECTOR» APPROACH

Isotops	Nat.Ab.(%)	Q(keV)	Decay Mode	Scintillator
^{64}Zn	8.63	1095.7	$\varepsilon\beta^+, 2\varepsilon$	$ZnWO_4$
^{70}Zn	0.62	998.5	$2\beta^-$	$ZnWO_4$
^{180}W	0.12	144	2ε	$ZnWO_4, CdWO_4, PbWO_4$
^{186}W	28.43	489.9	$2\beta^-$	$ZnWO_4, CdWO_4, PbWO_4$
^{106}Cd	1.25	2771	$2\beta^+, \varepsilon\beta^+, 2\varepsilon$	$^{106}CdWO_4$
^{108}Cd	0.89	269	2ε	$CdWO_4$
^{114}Cd	28.73	536.8	$2\beta^-$	$CdWO_4$
^{116}Cd	7.49	2805	$2\beta^-$	$^{116}CdWO_4$
^{40}Ca	96.941	193.78	2ε	$CaF_2, CaMoO_4$
^{46}Ca	0.004	990.4	$2\beta^-$	$CaF_2, CaMoO_4$
^{48}Ca	0.187	4272	$2\beta^-$	$CaF_2, CaMoO_4$
^{136}Ce	0.185	2419	$2\beta^+, \varepsilon\beta^+$	$CeCl_3, CeF_3, CeBr_3$
^{138}Ce	0.251	693	2ε	$CeCl_3, CeF_3, CeBr_3$
^{142}Ce	11.114	1416.9	$2\beta^-$	$CeCl_3, CeF_3, CeBr_3$
^{130}Ba	0.106	2611	$2\beta^+, \varepsilon\beta^+, 2\varepsilon$	$BaF_2, BaCl_2(Eu), BaI_2(Eu)$
^{92}Mo	14.84	1649	$\varepsilon\beta^+, 2\varepsilon$	$PbMoO_4, LiMoO_4, CaMoO_4$
^{100}Mo	9.63	3034	$2\beta^-$	$PbMoO_4, LiMoO_4, CaMoO_4$
^{84}Sr	0.56	1786.8	$\varepsilon\beta^+$	$SrCl_2, SrI_2(Eu)$

DAMA/R&D + DAMA/CRYS - SOME MAIN PREVIOUS RESULTS:



- scintillators developments: radio-purification enrichment, optical features, etc.
- exploiting the potentiality of the low background scintillation technique to investigate rare processes with high sensitivity
- realization of pilot experiments

Some example:

CaF_2(Eu), CeF_3, BaF_2, $CdWO_4$, $^{106}CdWO_4$, $^{116}CdWO_4$, $ZnWO_4$, $LaCl_3$(Ce), $LiEu(BO_3)_3$, LiF(W), $CeCl_3$, Li_2MoO_4, SrI_2(Eu), etc.

AP7(1997)73, N.Cim.A110(1997)189, NPB563(1999)97, AP10(1999)115, NPA705(2002)29, NIMA498(2003)352, NIMA525(2004)535, NIMA555(2005)270, UJP51(2006)1037, NPA789(2007)15, PRC76(2007)064603, PLB658(2008)193, EPJA36(2008)167, NPA824(2009)101, NPA826(2009)256, JPG:NPP38(2011)115107, JPG: NPP38(2011)015103, JINST6(2011)P08011, PRC85(2012)044610, EPJC73(2013)2276, EPJA50(2014)134, PS90(2015)085301

DAMA/GE AND LNGS STELLA FACILITY

Ge detectors used by DAMA in previous searches:

DAMA/Ge (GeBer)

- 244 cm^3 n-type HPGe detector
- Thin Carbon window: 0.76 mm thickness

GeCris

- 465 cm^3 p-type HPGe detector
- Thin Cu window: 1 mm thickness

GeMulti

- Four 225 cm^3 p-type HPGe detectors mounted in one cryostat with a well in the center
- Thin Al window: 1.3 mm thickness

GeBEGe

- Broad Energy Ge detector (especially designed for low energy γ spectrometry)
- Thin Cu window: 1.5 mm thickness

Typical shield from environmental radioactivity

- 5-10 cm of OFHC copper
- 5 cm of low activity lead (< 3 Bq/kg of ^{210}Pb)
- 15-25 cm of lead
- 10 cm of borated polyethylene (GeBer)
- Air-tight PMMA box flushed with HP nitrogen

DAMA results

- Search for $\beta\beta$ decays of many candidate isotopes (next slide)
- Search for ^7Li solar axions (NPA806(2008)388, PLB711(2012)41)
- First observation of α decay of ^{190}Pt to the first excited level of ^{186}Os (PRC83(2011)034603)
- Qualification of many materials: e.g. $CdWO_4$, $ZnWO_4$(NIMA626-7(2011)31, NIMA615(2010)301), $Li_6Eu(BO_3)_3$ (NIMA572(2007)734), Li_2MoO_4 (NIMA607(2009)573), SrI_2(Eu) (NIMA670(2012)10), ^{7}LiI(Eu) (NIMA704(2013)40)

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]

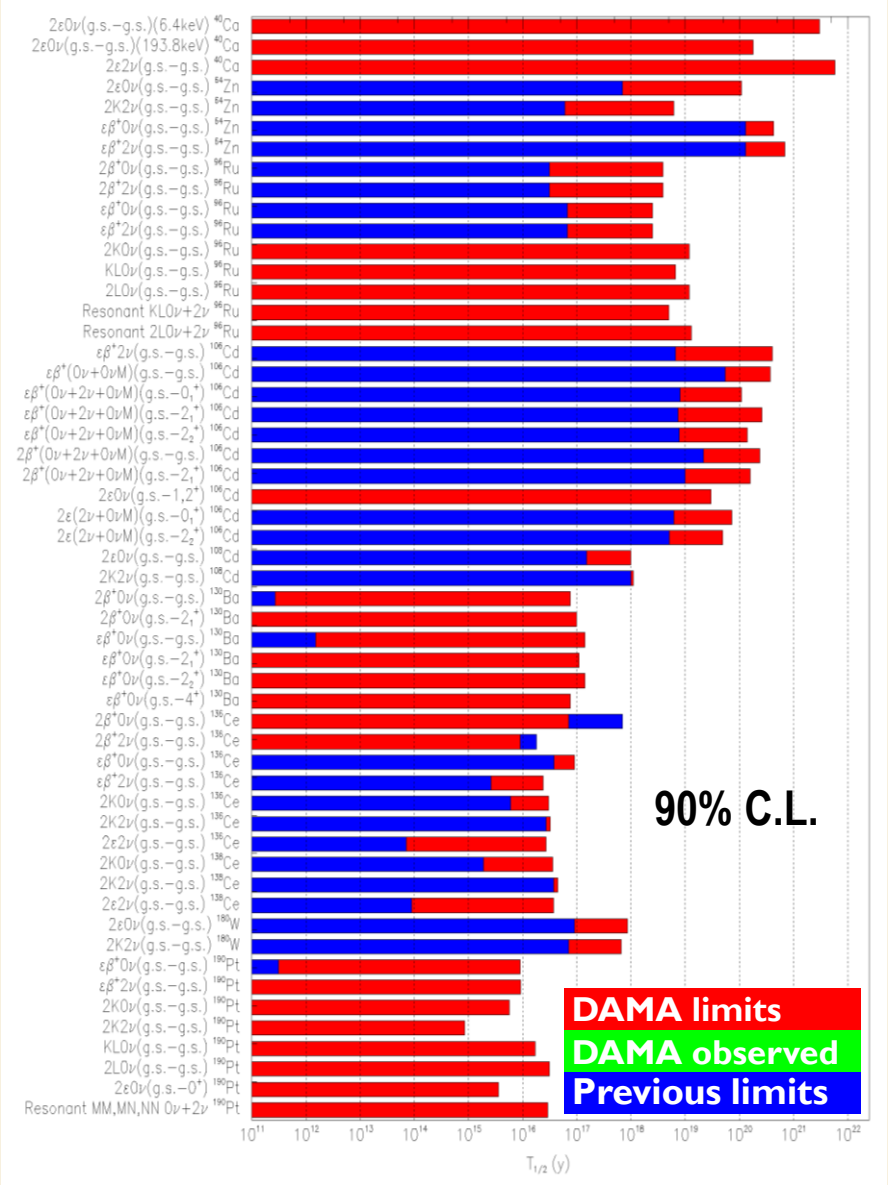
- Dy_2O_3 sample (322 g) in DAMA/Ge det. (2512 h) ⇒ $T_{1/2}$ limits: 10^{14}-10^{16} yr

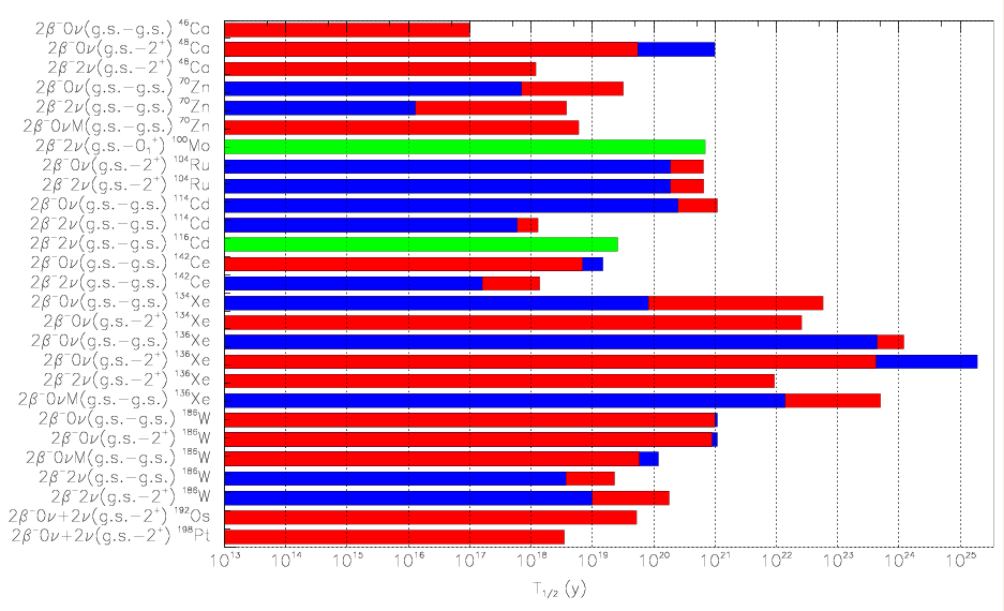
^{100}Mo $Q_{\beta\beta}$=3035 keV; 2β$^-$ [Nucl. Phys. A 846 (2010) 143]

- $^{100}MoO_3$ 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

Summary of searches for ββ decay modes in various isotopes (partial list)

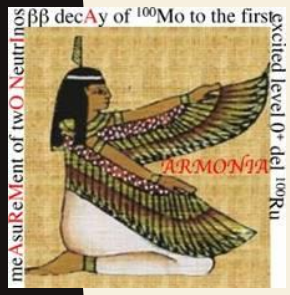




ARMONIA: New observation of $2\nu2\beta^-$ $^{100}Mo \rightarrow {}^{100}Ru$ ($g.s. \rightarrow 0_1^+$) decay NPA846 (2010)143

AURORA: New observation of $2\nu2\beta^-$ ^{116}Cd decay J.Phys.:Conf.Ser.718(2016)062009

- Many competitive limits obtained on lifetime of $2\beta^+$, $\varepsilon\beta^+$ and 2ε processes (^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, ^{184}Os, ^{156}Dy, ^{158}Dy, …).
- First searches for resonant $0\nu2\varepsilon$ decays in some isotopes



Armonia

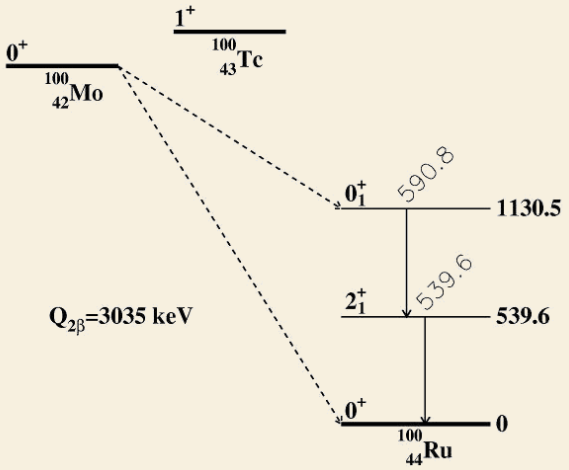
NPA846(2010)143

(meAsuReMent of twO-NeutrIno ββ decAy of ^{100}Mo to 0^+_1 level of ^{100}Ru)

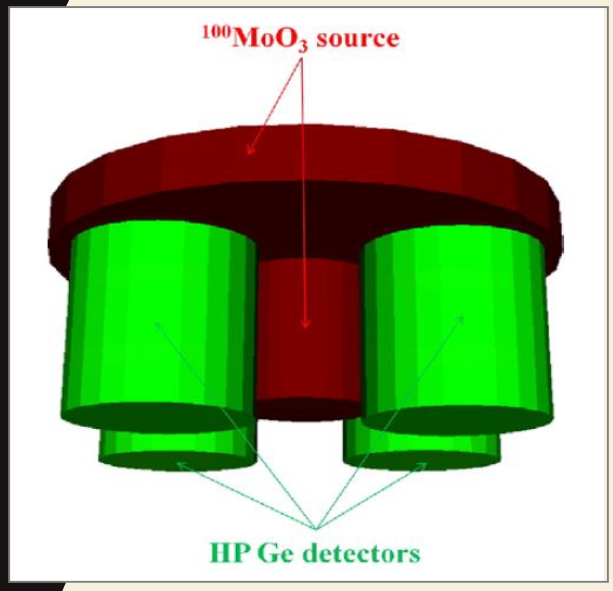
In addition to the transition to the g.s., the $2\beta 2\nu$ decay of ^{100}Mo was registered also for the transition to the first excited 0^+_1 level of ^{100}Ru

If 0^+_1 excited level of ^{100}Ru (E=1130 keV) populated

$\Rightarrow$ two γ quanta (591 keV + 540 keV) emitted in cascade



$^{100}MoO_3$ sample (mass =1199 g) enriched in ^{100}Mo at 99.5% installed in GeMulti setup



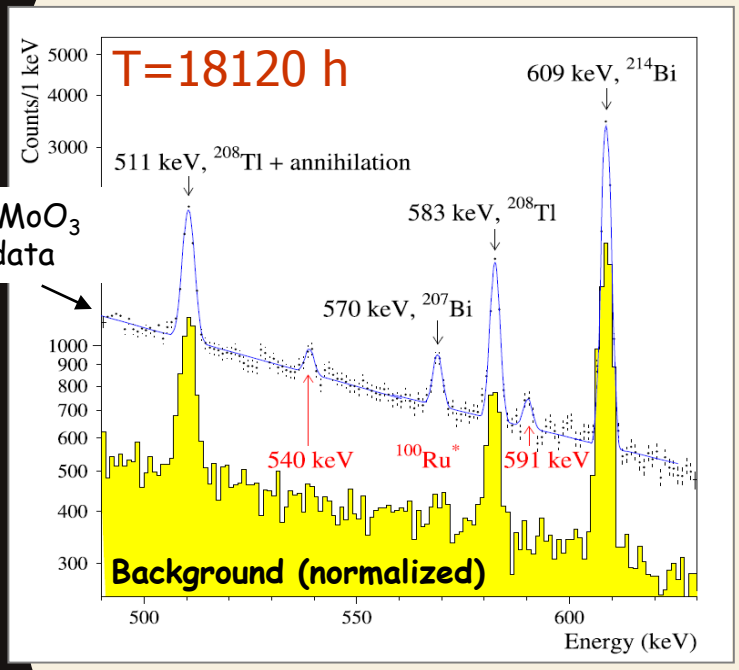
$T_{1/2}$ measured in several experiments:	$T_{1/2}$, 10^{20} yr	Year [Ref.]
Frejus UL (4800 m w.e.), HP Ge 100 cm^3, 994 g of ^{100}Mo (99.5%), 2298 h, only 1-d spectrum;	> 12	1992 [19]
Soudan mine (2090 m w.e.), HP Ge 114 cm^3, 956 g of ^{100}Mo (98.5%), 9970 h, 1-d spectrum;	$6.1^{+1.8}_{-1.1}$	1995 [11][a]
Modane UL (4800 m w.e.), 4 HP Ge detectors (100, 120, 380, 400 cm^3), 17 different ^{100}Mo samples (107–1005 g, 95.1–99.3%, 142–1599 h), sum of 1-d spectra;	$9.3^{+2.8}_{-1.7}$	1999 [14]
Modane UL (4800 m w.e.), NEMO-3 detector, 6914 g of ^{100}Mo foils in 12 sectors (95.1–98.9%), 8024 h, individual energies of γ and e^-, tracks for e^-;	$5.7^{+1.5}_{-1.2}$	2007 [15]
Ground level (10 m w.e.), 2 HP Ge detectors (300 cm^3) in coincidence, 1050 g of ^{100}Mo (98.4%), 21720 h, coincidence spectrum;	$5.5^{+1.2}_{-0.9}$	2009 [16][b]
Gran Sasso UL (3600 m w.e.), 4 HP Ge detectors (225 cm^3 each) in coincidence, 1199 g of $^{100}MoO_3$ (99.5%), 18120 h, coincidence and 1-d spectra.	$6.9^{+1.2}_{-1.1}$	This work

Aim of the experiment: remeasurement of the Mo sample used before in the Frejus exp. (not in agreement with other results)

Armonia Results

NPA846(2010)143

Sum spectrum of all 4 HPGe detectors



1-dimensional energy spectrum analysis

Both peaks at 540 keV and 591 keV expected for $2\beta2\nu$ decay $^{100}Mo \rightarrow {}^{100}Ru(0_1^+)$ are observed in the data collected with $^{100}MoO_3$

In the background spectrum they are absent

Fit of peak @ 539.5 keV: E=539.4±0.2 keV; S_{540} = 319±56 events

Fit of peak @ 590.8 keV: E= 590.9±0.2 keV; S_{591} = 278±53 events

$$T_{1/2} = 6.9^{+1.0}_{-0.8}(\text{stat.}) \pm 0.7(\text{syst.}) \times 10^{20}\ \text{yr.}$$

Most of systematic unc. due to calculation of the efficiencies

2-dim energy spectrum analysis

Double coincidences when fixing the energy of one of the Ge detectors

Eight events detected (red)

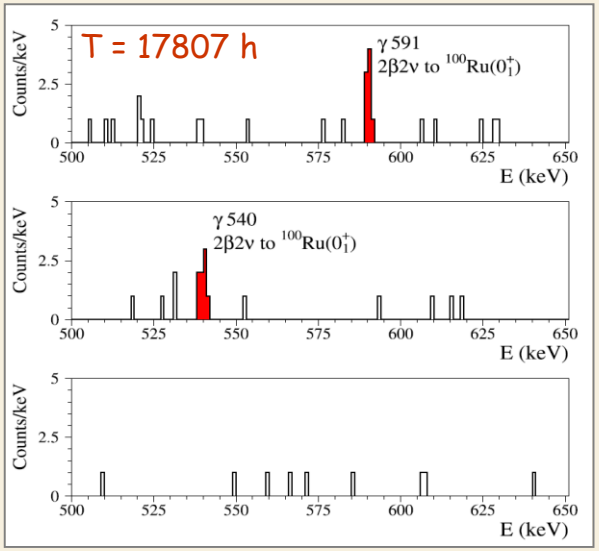
$$T_{1/2} = 6.8^{+3.7}_{-1.8}(\text{stat.}) \times 10^{20}\ \text{yr}$$

in agreement with the half life derived in 1-d analysis

EI = (540±2) keV

EI = (591±2) keV

EI = (545±2) keV (background)



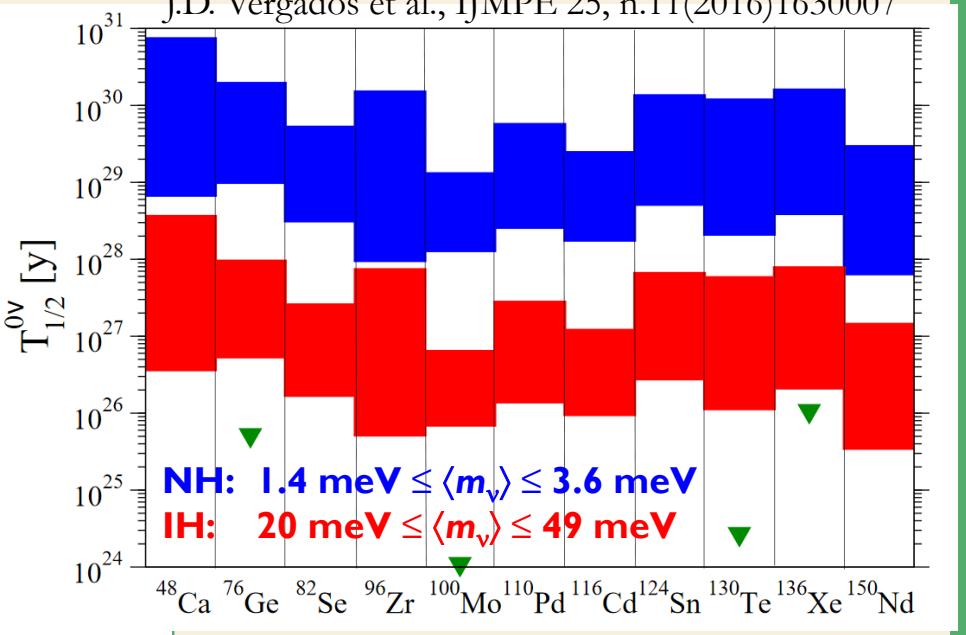
Investigation of 2β decay of ^{116}Cd with enriched $^{116}CdWO_4$ crystal scintillators

^{116}Cd

One of the best isotope for 0ν2β decay search:

- $Q_{\beta\beta}$ = 2813.44(13) keV
- δ = 7.49(18)%
- possible high isotopic enrichment
- promising theoretical calculation

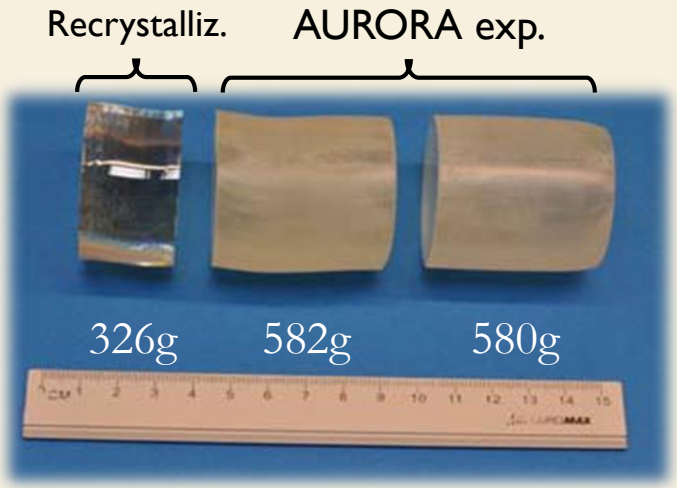
J.D. Vergados et al., IJMPE 25, n.11(2016)1630007



$^{116}CdWO_4$ crystal scintillators

Grown by the low-thermal-gradient Czochralski technique after deep purification of ^{116}Cd and W;
+ annealing to improve the optical transmission curve

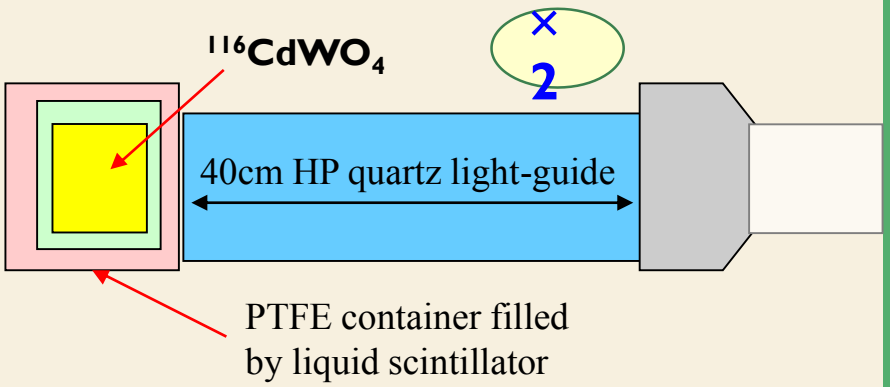
- ✓ Good optical and scintillation properties
- ✓ $^{116}CdWO_4$ crystals **enriched at 82%**
- ✓ Active source approach (high detection efficiency)
- ✓ Low levels of internal contamination in (U, Th, K)
- ✓ α/β discrimination capability

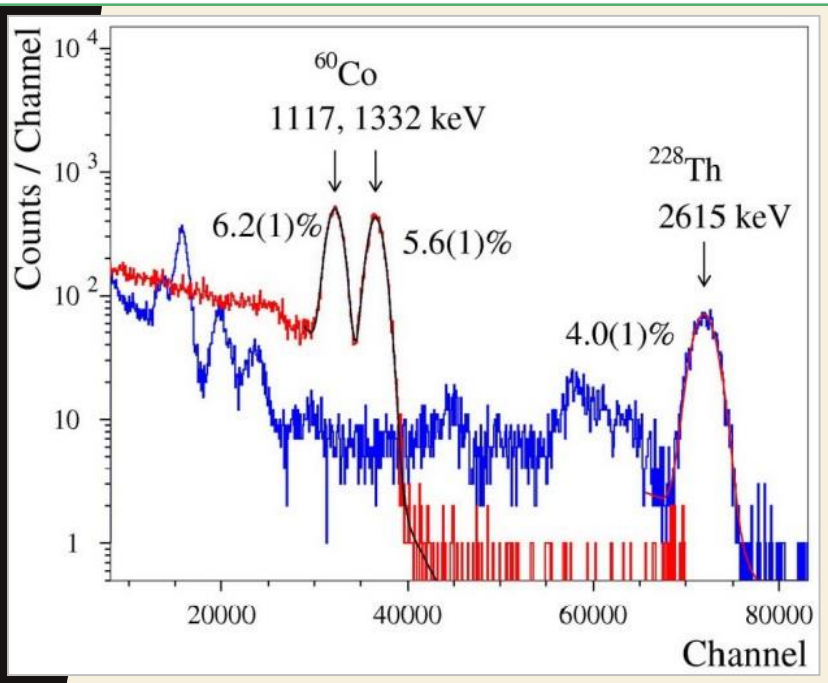


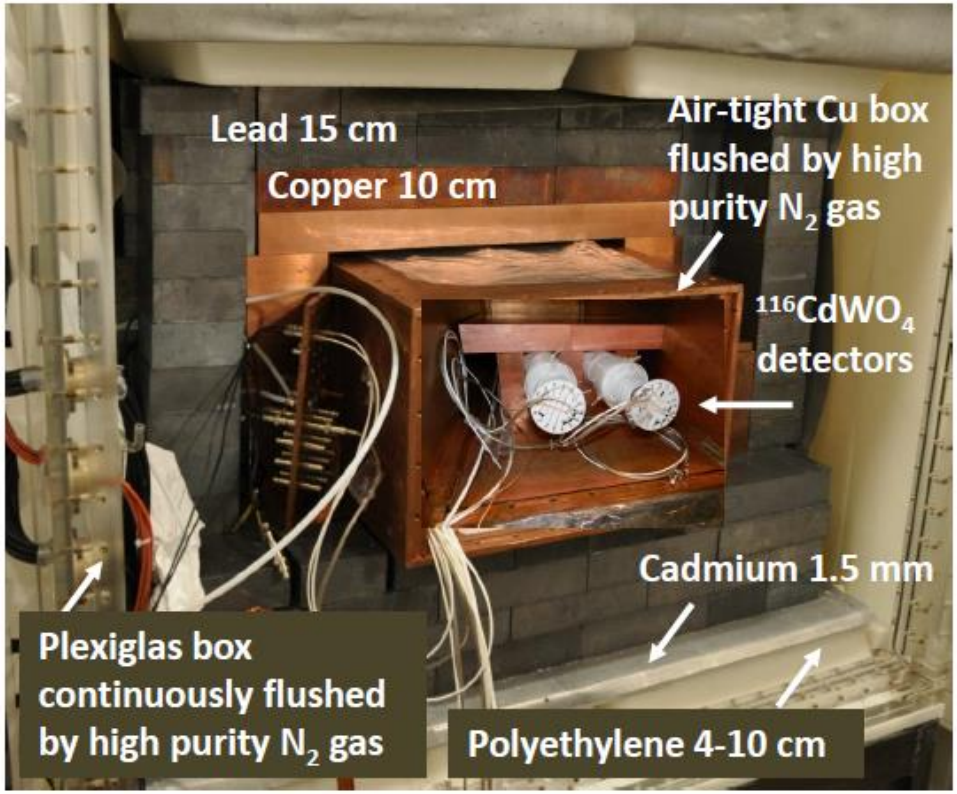
THE AURORA EXPERIMENT IN THE DAMA/R&D SET-UP

Two enriched $^{116}CdWO_4$ crystal scintillators
(total mass: 1.162 kg, ^{116}Cd @ 82%)

- ✓ Started in 2011
- ✓ Upgrade - March 2014
- ✓ Total live time since 2014: 25037 h
- ✓ Background level at 2.7-2.9 MeV: **0.1 counts/keV/kg/yr**

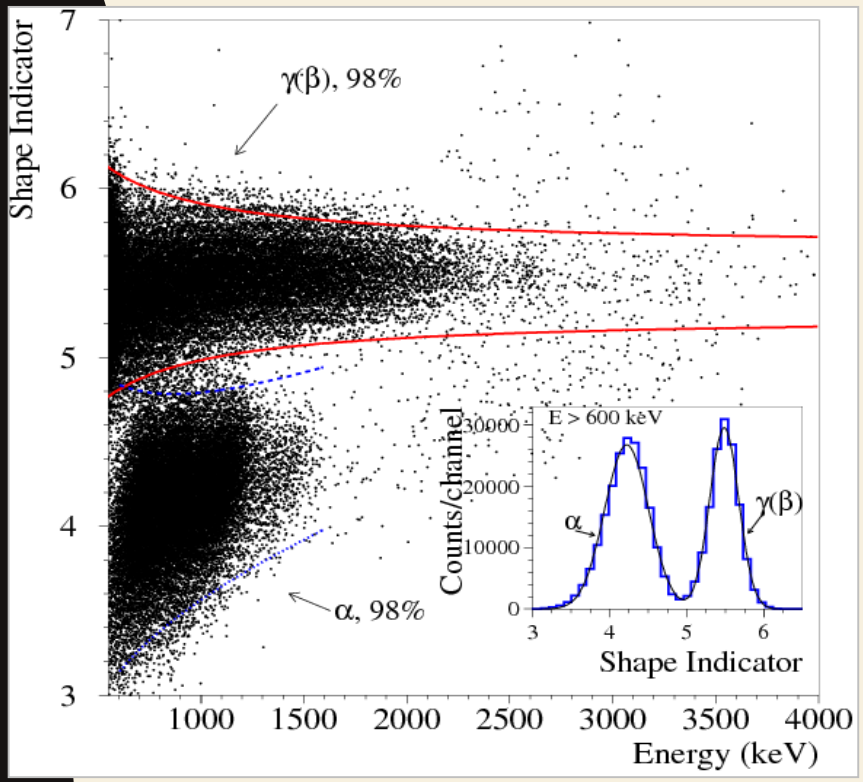






BACKGROUND IDENTIFICATION 1: PULSE SHAPE DISCRIMINATION

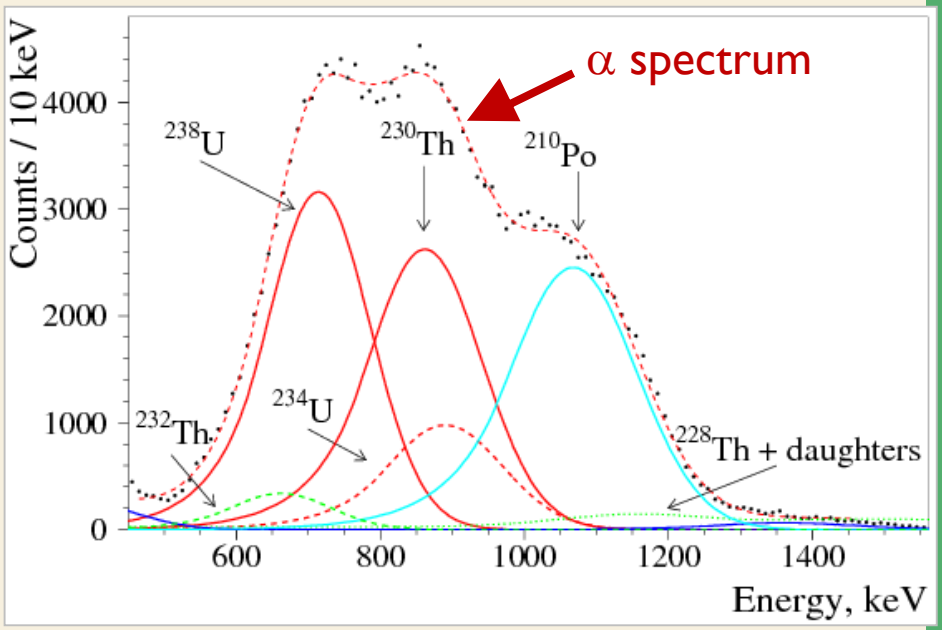
Event-by-event DAQ based on a 1 GS/s 8 bit transient digitizer (operated at 50 MS/s) records the pulse shape over a time window of 100 μs from the $^{116}CdWO_4$ detectors



$$SI = \Sigma f(t_k) \times P(t_k) / \Sigma f(t_k)$$

$$P(t) = [f_\alpha(t) - f_\gamma(t)]/[f_\alpha(t) + f_\gamma(t)]$$

$f(t_k)$ → amplitude at t_k
$P(t_k)$ → weight function
$f_{\alpha,\gamma}(t_k)$ → reference pulse



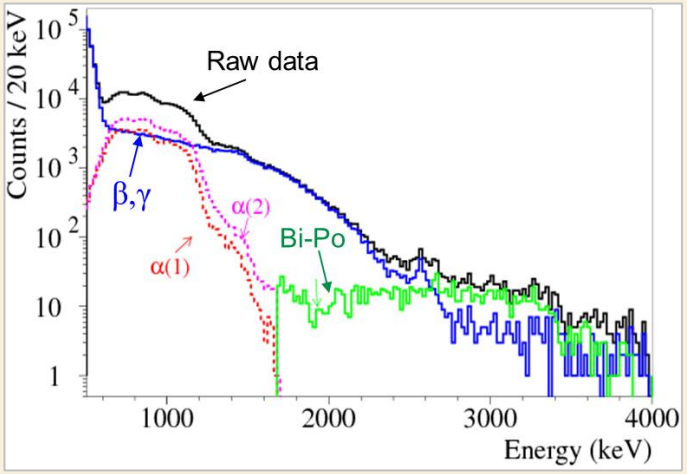
T=25037 h
M=1.162 kg

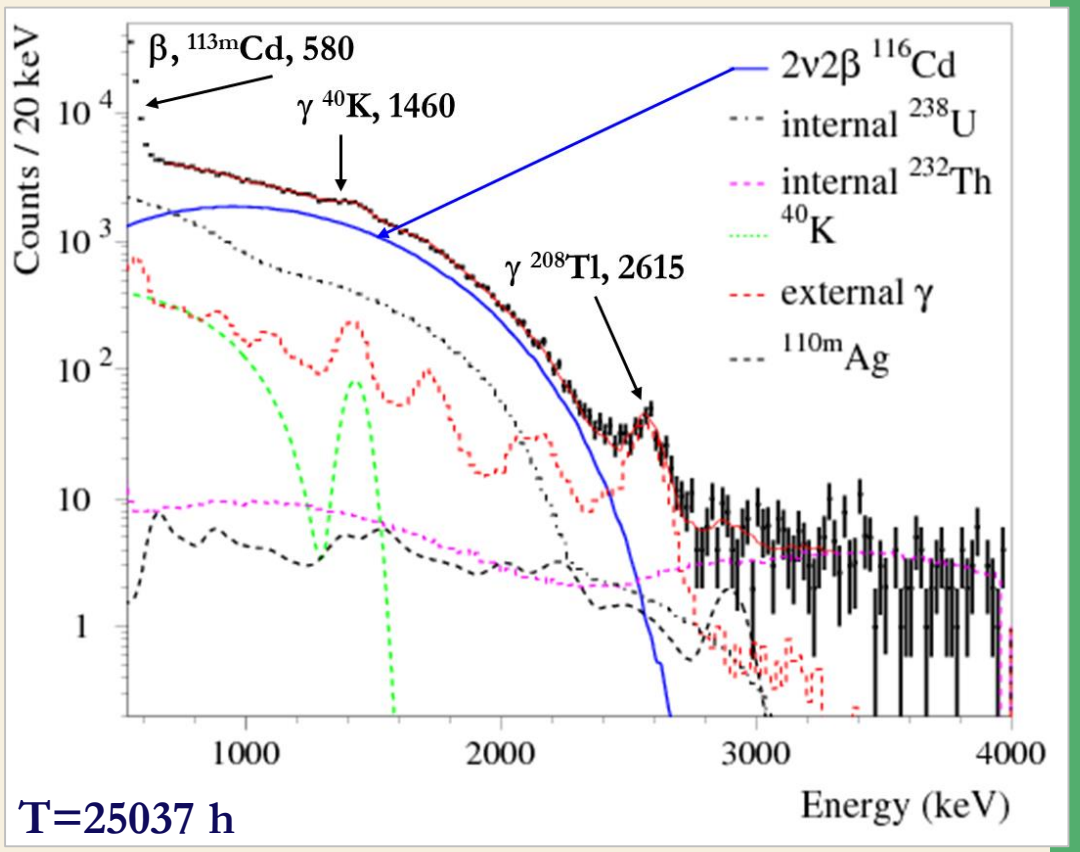
Background identification: fit and results

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	$\leq$ 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]

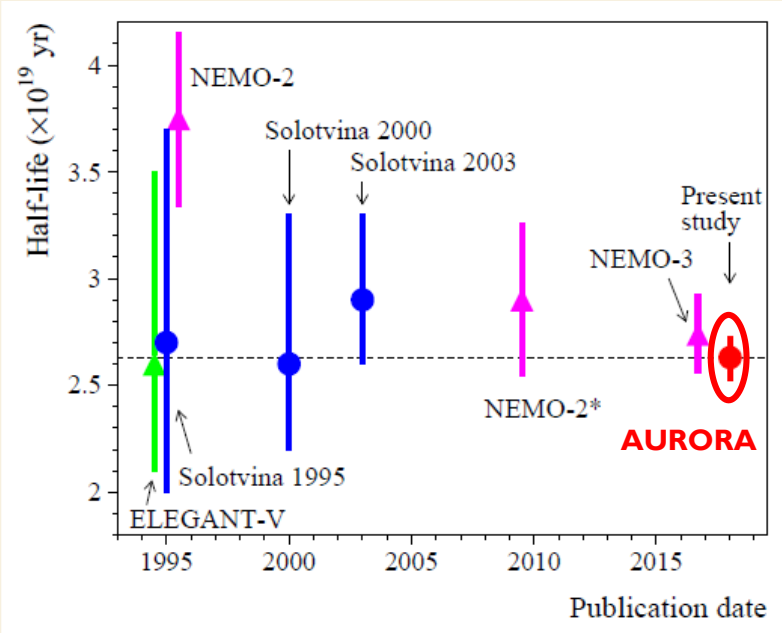
[1] PRC 76(2007)064603 [2] NIMA 696 (2012) 144

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

$$T_{1/2} = [2,63^{+0,11}_{-0,12}] \times 10^{19}\ \text{yr}$$ (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 $0\nu2\beta$ decay of ^{116}Cd

Further background reduction (**~35%**) for $0\nu2\beta$ decay by excluding events from:

^{212}Bi [Q_α=6207.26(3) keV, B.R. ~36%] → ^{208}Tl [Q_β=4998.9(18) keV, $T_{1/2}$ = 3.053(4) min

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

(live time reduction~15%)

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

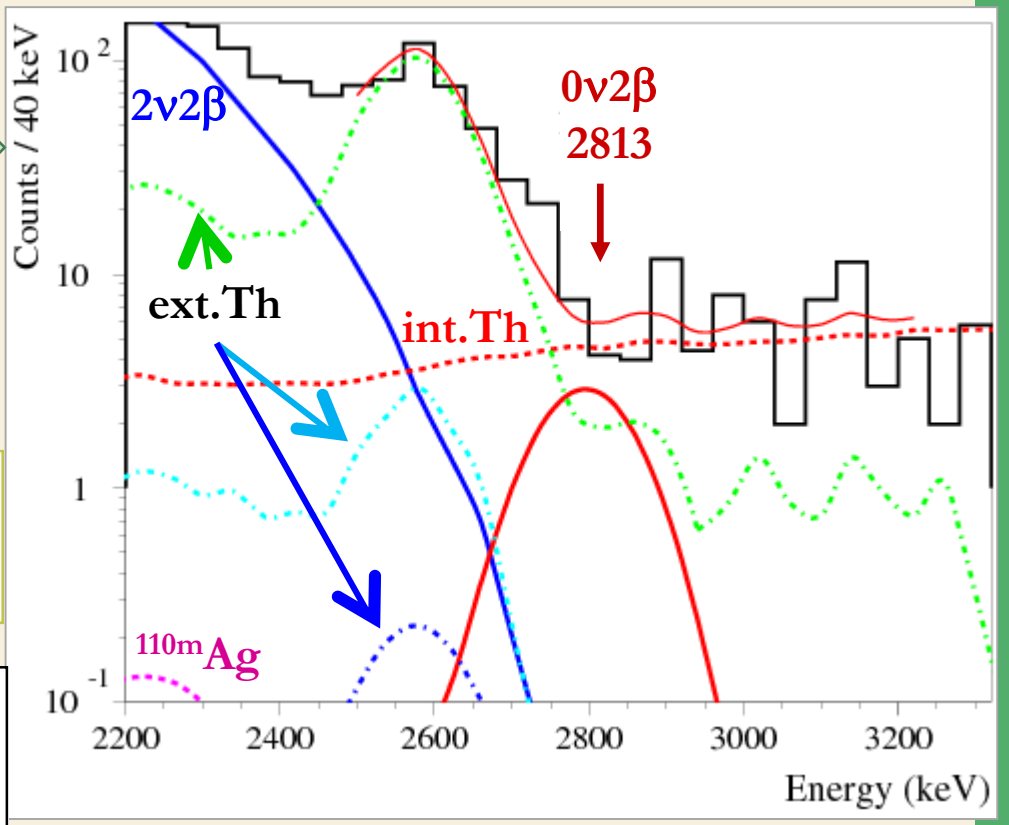
$T_{1/2} > 2.2 \times 10^{23}$ yr @ 90% C.L.

Effective Majorana neutrino mass:

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

\+ New improved limits on $T_{1/2}$ for $0\nu2\beta$ decay to excited levels of ^{116}Sn in the range:

(3.6–6.3)×10^{22} yr

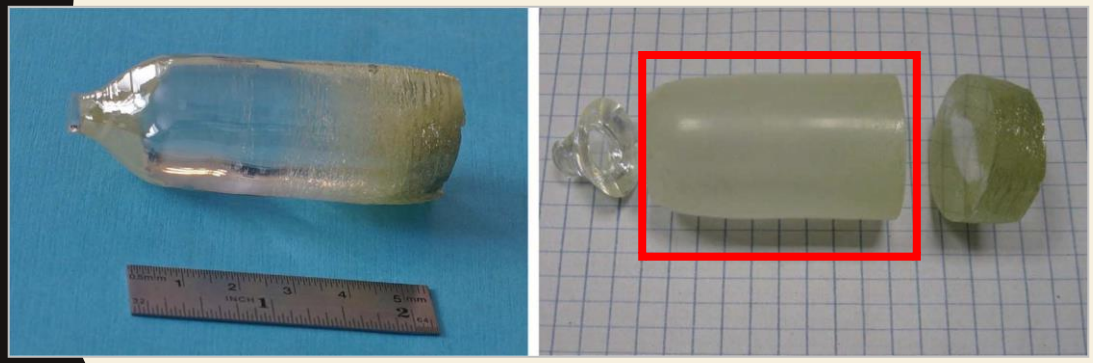


[1] T.R. Rodryguez et al., Phys.Rev.Lett. 105(2010)252503
[2] F. Simkovic et al., Phys.Rev.C 87 (2013)045501
[3] J. Hyvarinen et al., Phys.Rev.C 91 (2015)024613
[4] J. Barea et al., Phys.Rev.C 91(2015)034304

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

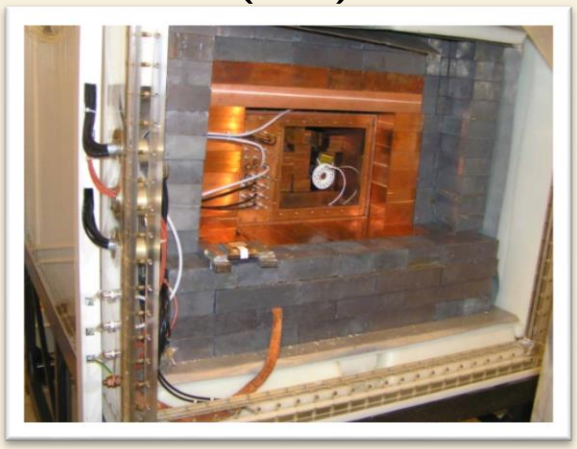
THE USED $^{106}CdWO_4$ CRYSTAL SCINTILLATOR

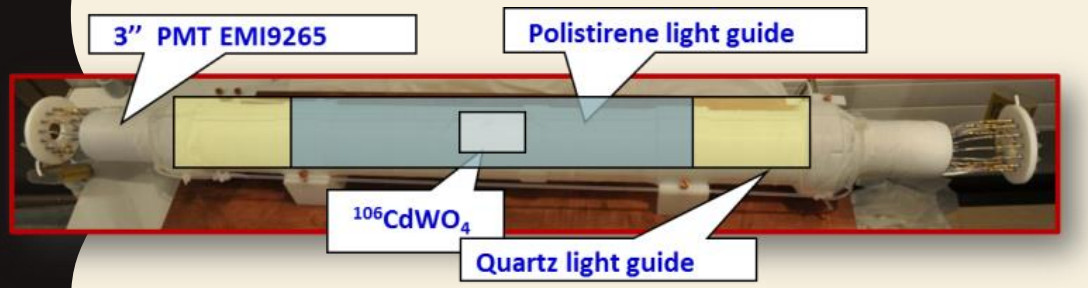
NIMA615(2010)301

- Samples of cadmium were purified by vacuum distillation (Institute of Physics and Technology, Kharkiv) and the Cadmium tungstate compounds were synthesized from solutions
- Crystal boule was grown by the low-thermal-gradient Czochralski technique (NIIC Novosibirsk) (initial powder 265 g)
- Crystal scintillator (**216 g** mass), **66.4%** enrichment in ^{106}Cd (**2.66×10^{23}** nuclei of ^{106}Cd) measured by thermal ionisation mass-spectrometry $\Rightarrow$ 2nd enriched $CdWO_4$ crystal ever produced

1st exp: single crystal in DAMA/R&D

PRC85(2012)044610

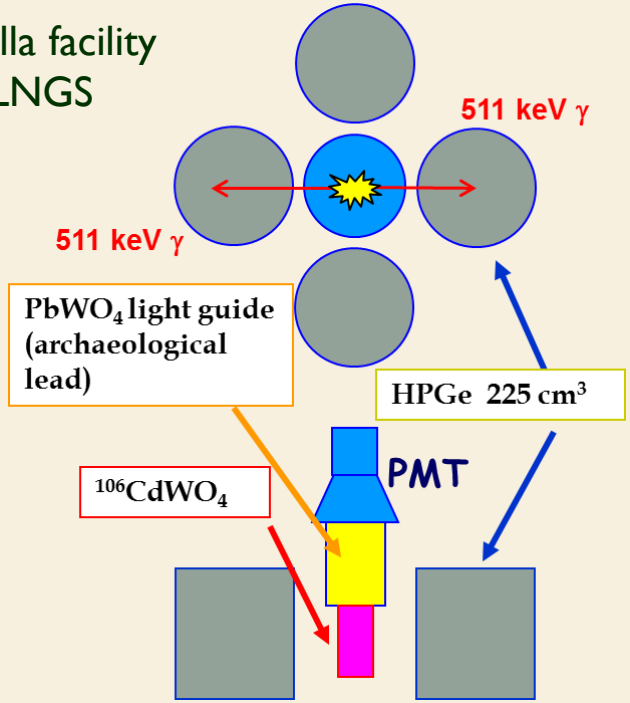




2nd exp: coincidence with 4 HP-Ge

PRC93(2016)045502

Stella facility @LNGS

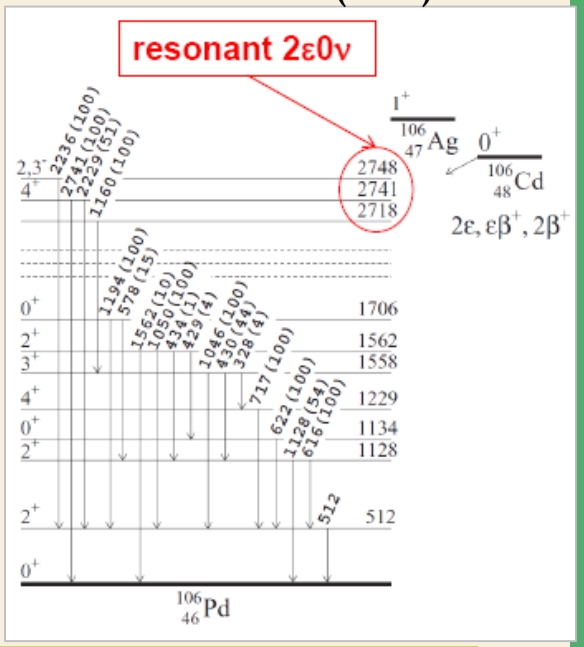


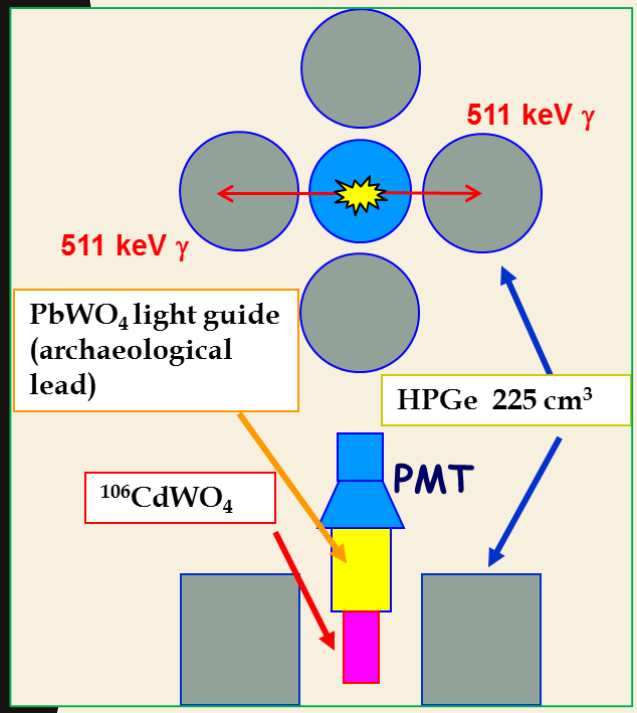
Search for ββ decay in ^{106}Cd with $^{106}CdWO_4$ scintillator in coincidence with 4 HPGe (GeMulti)

PRC93 (2016) 045502

^{106}Cd, a promising isotope:

- ✓ One of the six isotopes candidate for $2\beta^+$ decay
- ✓ δ=(1.25±0.06)% ⇒ possible enrichment up to 100%
- ✓ $Q_{2\beta}$= (2775.39±0.10) keV ⇒ $2\beta^+$, $\varepsilon\beta^+$, 2ε modes possible
- ✓ Possible resonant $2\varepsilon0\nu$ captures to excited level of ^{106}Pd
- ✓ Theoretical $T_{1/2}$ favorable for some 2ν modes (10^{20} – 10^{22} yr)





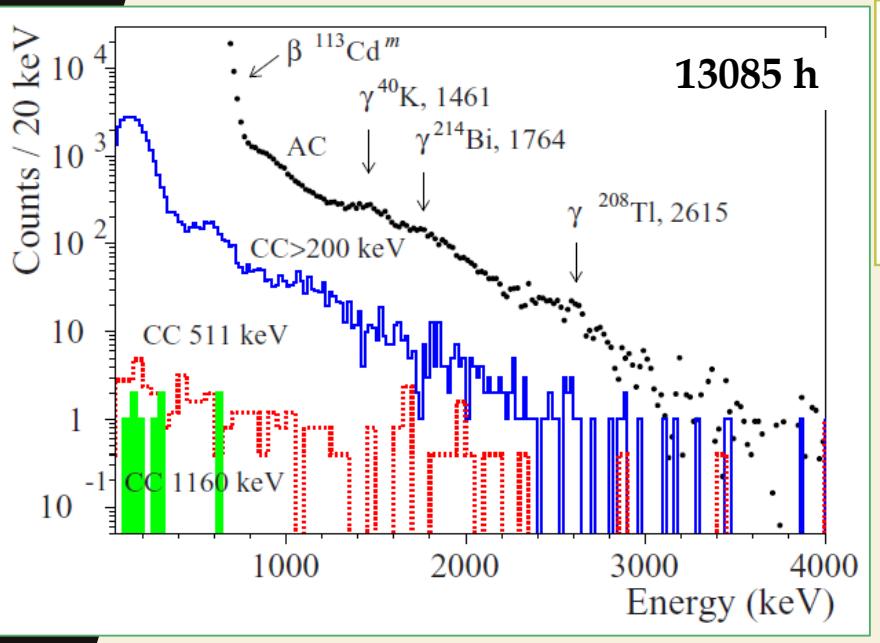
$^{106}CdWO_4$ crystal scintillator:

- ✓ Mass: 216 g, 66.4% enrichment in ^{106}Cd
- ✓ Good scintillation properties
- ✓ Active source approach (high detection efficiency)
- ✓ Low levels of internal contamination in (U, Th K)
- ✓ α/β discrimination capability

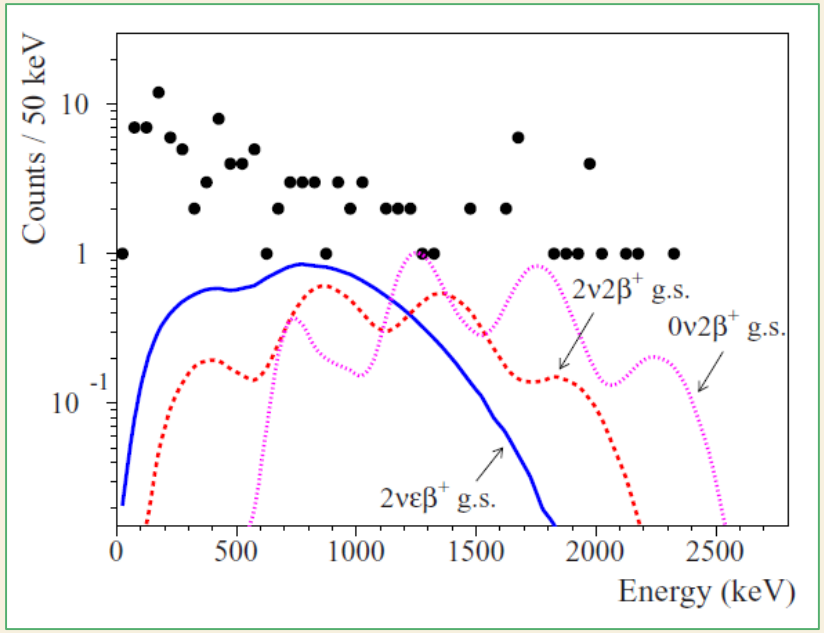
$PbWO_4$ light-guide (∅40 × 83 mm)

Reduce PMT background (archael. lead: A(^{210}Pb)<0.3 mBq/kg)

$^{106}CdWO_4$ crystal scintillator in GeMulti: Results



1. In anticoincidence with the HPGe detectors (**AC**)
2. In coincidence with E_{HPGe} > 200 keV (**CC >200**)
3. In coincidence with E_{HPGe} = 511 keV (**CC 511**)
4. In coincidence with E_{HPGe} = 1160 keV (**CC 1160**)



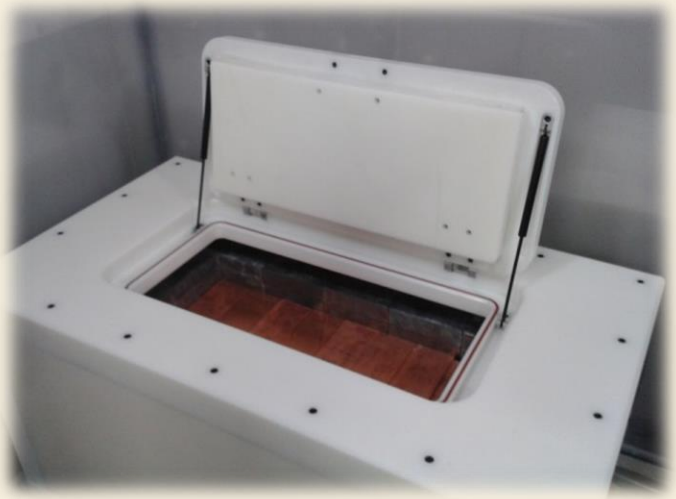
Energy spectrum of $^{106}CdWO_4$ detector in coincidence with 511 keV in HPGe (circles). Monte Carlo simulated distributions of 2β decay of ^{106}Cd excluded at 90% CL

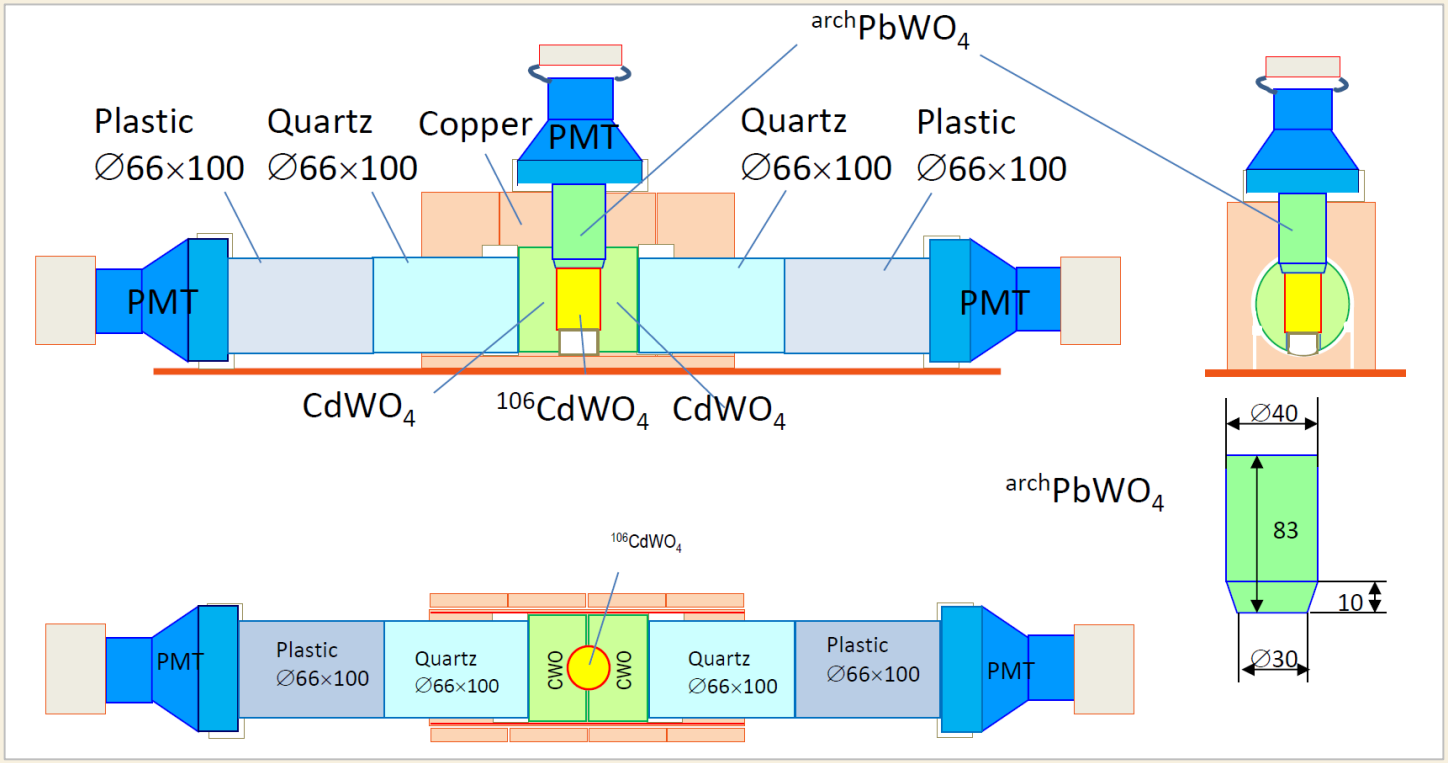
- **New limits on 2ε, εβ$^+$, 2β$^+$ processes on the level of $T_{1/2}$ > 10^{20} -10^{21} yr**
- **The half-life limit on the εβ$^+$2ν decay, $T_{1/2}$ > 1.1×10^{21} yr, reached the region of theoretical predictions**
- **For 2ε0ν resonant captures: $T_{1/2}$ > (8.5 × 10^{20} – 1.4 × 10^{21}) yr**

New $^{106}CdWO_4$ experiment in DAMA/CRYS set-up

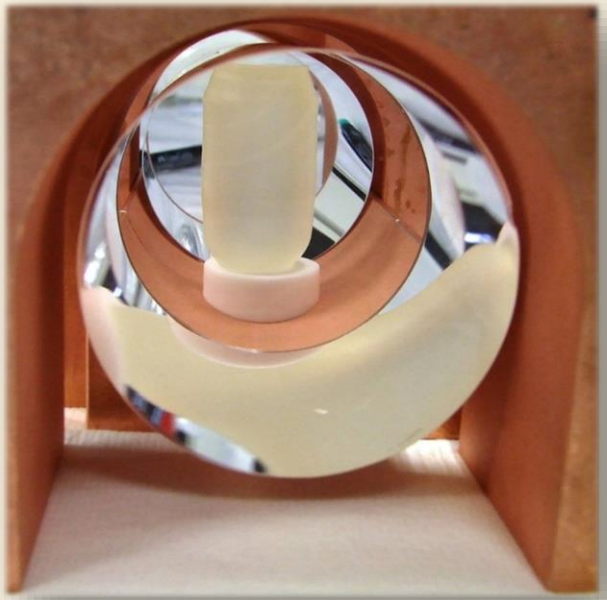
1) $^{106}CdWO_4$ in (anti)coincidence with two large $CdWO_4$ scintillators mounted in DAMA/CRYS set-up @ LNGS
2) High efficiency
3) Experiment in data taking since May 2016

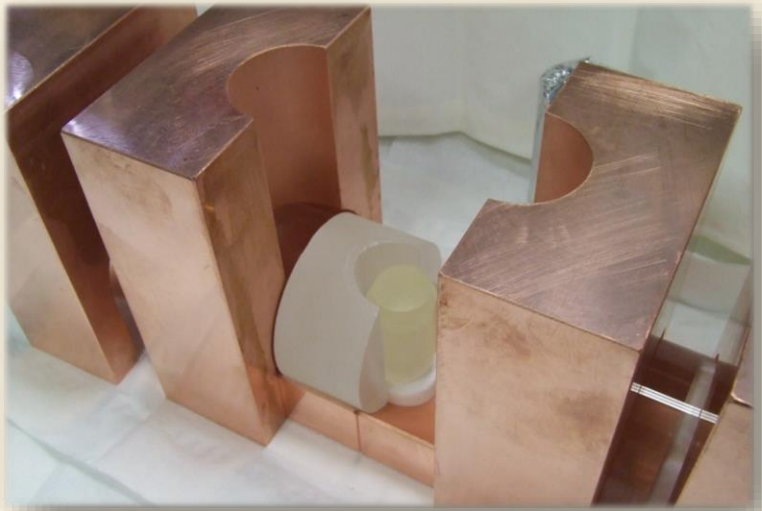
DAMA/CRYS set-up

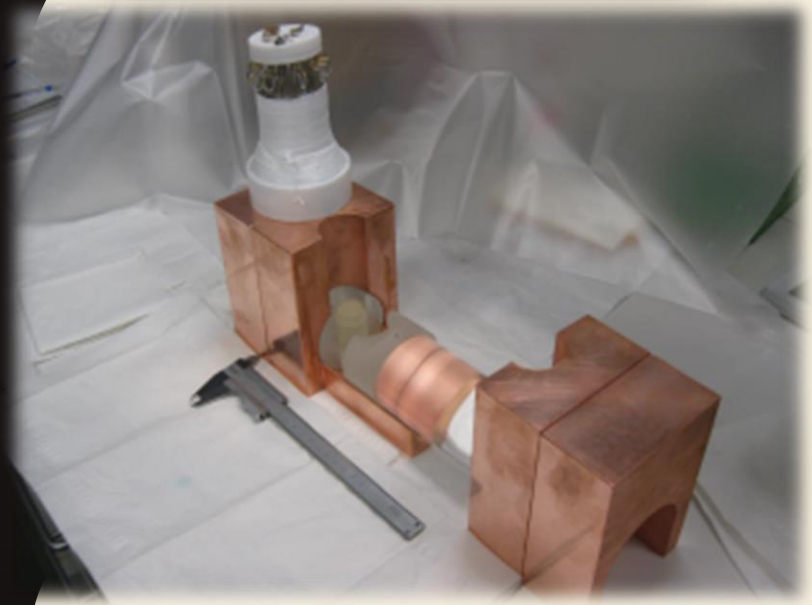




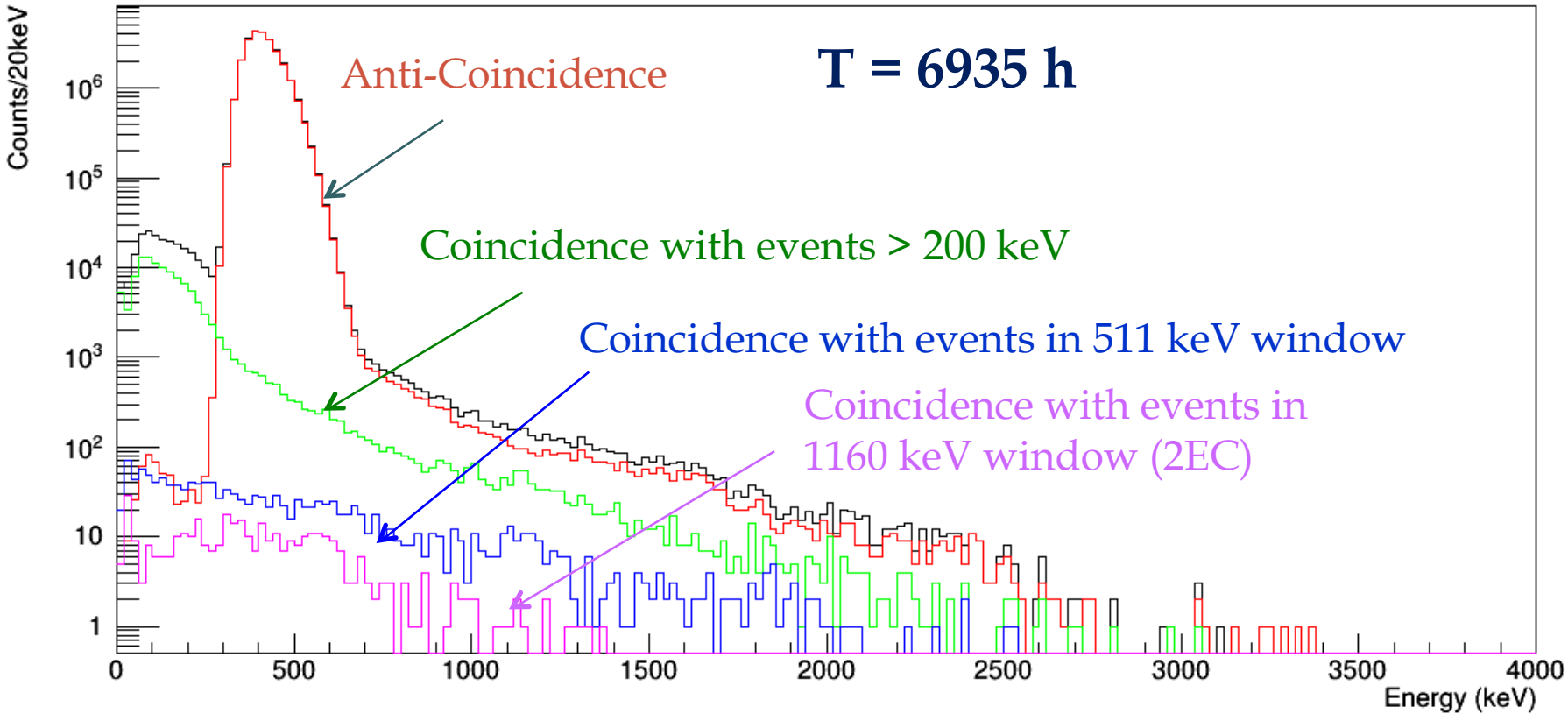
New $^{106}CdWO_4$ experiment in DAMA/CRYS set-up







ENERGY SPECTRA OF ^{106}Cd



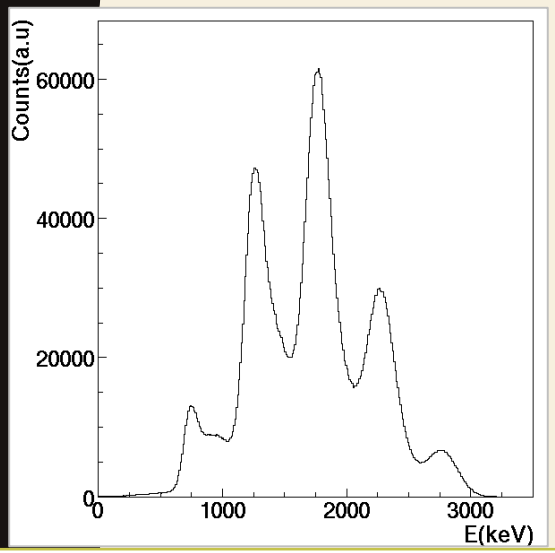
The energy spectra accumulated over **6935 h** by the $^{106}CdWO_4$ detector:

- in anticoincidence with the $^{nat}CdWO_4$ detectors
- in coincidence with event(s) in at least one of the $^{nat}CdWO_4$ detectors with energy:
  - E > 200 keV
  - E in energy window around 511 keV
  - E in energy window around 1160 keV

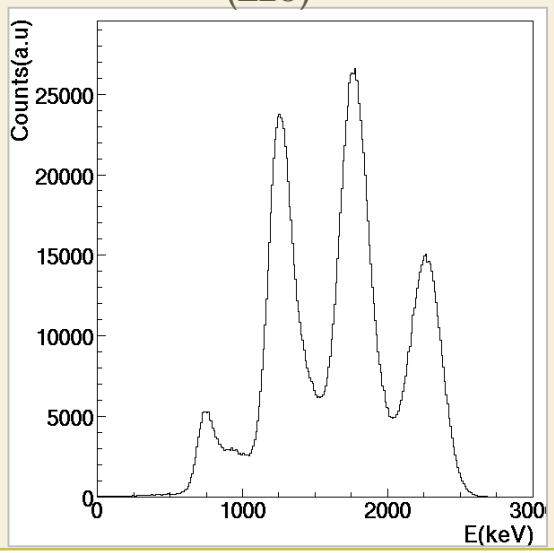
ESTIMATION OF SENSITIVITY

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

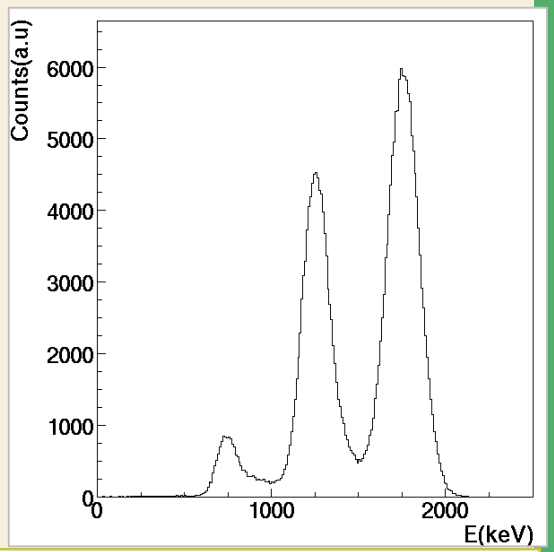
Spectrum of $^{106}CdWO_4$ detector



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

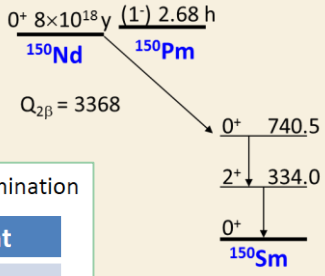
$2\nu2\beta^+$ (g.s.): $T_{1/2} \approx 2 \times 10^{21}$ yr

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

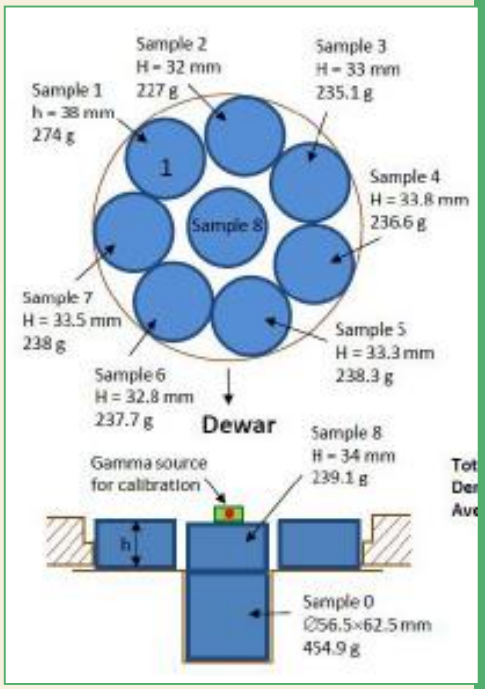
Running and future experiments on HPGE

- 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)

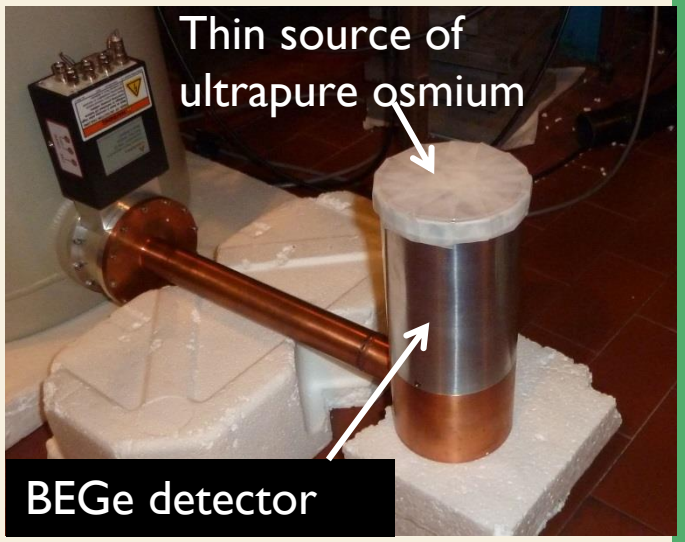


Improvement of Nd_2O_3 radioactive contamination

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



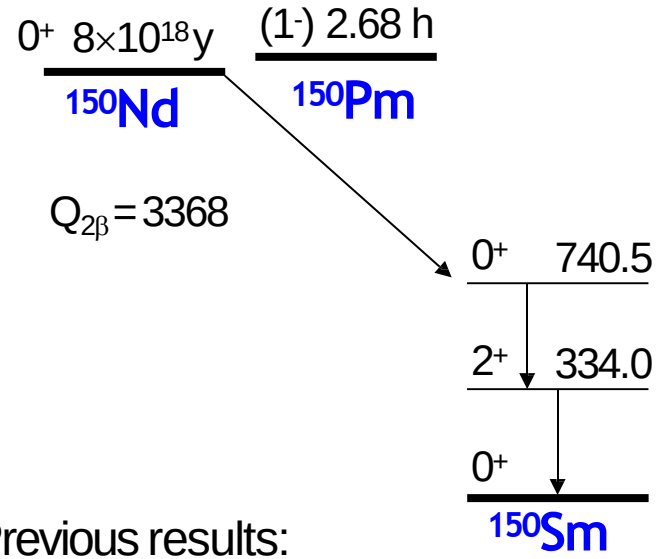
- New experiment to search for 2β of osmium (and α decay of osmium to excited level of daughter nuclei) in progress with BEGe detector:
  - ⇒ Detection efficiency significantly improved by cutting the osmium roads into thin (0.8-1 mm) plates and by using the BEGe detector

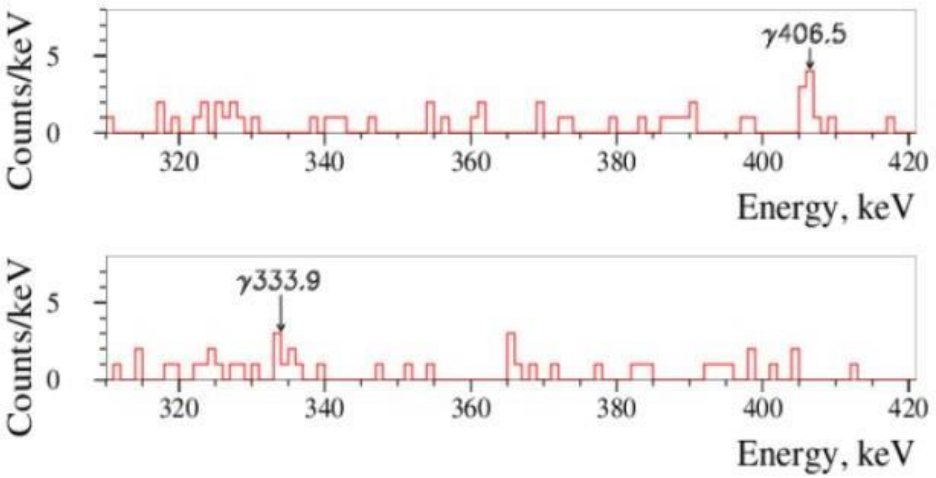


- Purification of Er, Yb, and Sm is in progress for experiments to search for resonant 2ε0ν processes in these nuclei

2β decay of ^{150}Nd to the excited states of ^{150}Sm

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:

$$T^{2\nu2\beta}_{1/2} = [1.33^{+0.36}_{-0.23}(\text{st})^{+0.27}_{-0.13}(\text{syst})]\times10^{20}\ \text{yr}\ [1]$$

$$T^{2\nu2\beta}_{1/2} = [1.07^{+0.45}_{-0.25}(\text{st}) \pm 0.07(\text{syst})]\times10^{20}\ \text{yr}\ [2]$$

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

$$T^{2\nu2\beta}_{1/2} = (0.84^{+0.47}_{-0.22})\times10^{20}\ \text{yr}$$

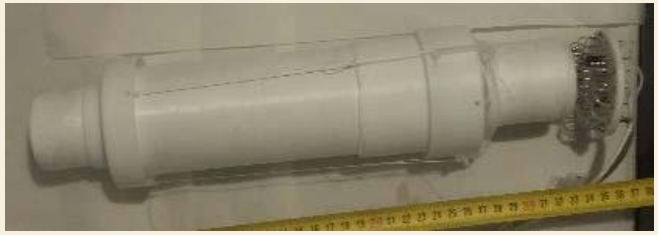
The experiment in progress aiming to improve the statistic accuracy to at least 3σ

[1] PRC 79 (2009) 045501
[2] PRC 90 (2014) 055501

Running and future experiments

$ZnWO_4$ running in DAMA/R&D

- New 4 crystal scintillators in the DAMA/R&D in data taking:
  - radioactive contamination and scintillation performances
  - study of double beta decay modes in Zn and W isotopes



Development of Detectors with Anisotropic Response for Dark Matter Search in Directionality Approach are in progress

$^{106}CdWO_4$ running in DAMA/CRYS

$^{106}CdWO_4$ in (anti)coincidence with two large $CdWO_4$ scintillators to study ββ decays of ^{106}Cd

Thanks for your attention