DAMA Collaboration
& INR-Kyiv
http://people.roma2.infn.it/dama

Results and perspectives in ββ decay experiments by the DAMA-Kyiv Collaboration with HPGe

103° Congresso SIF, September 2017

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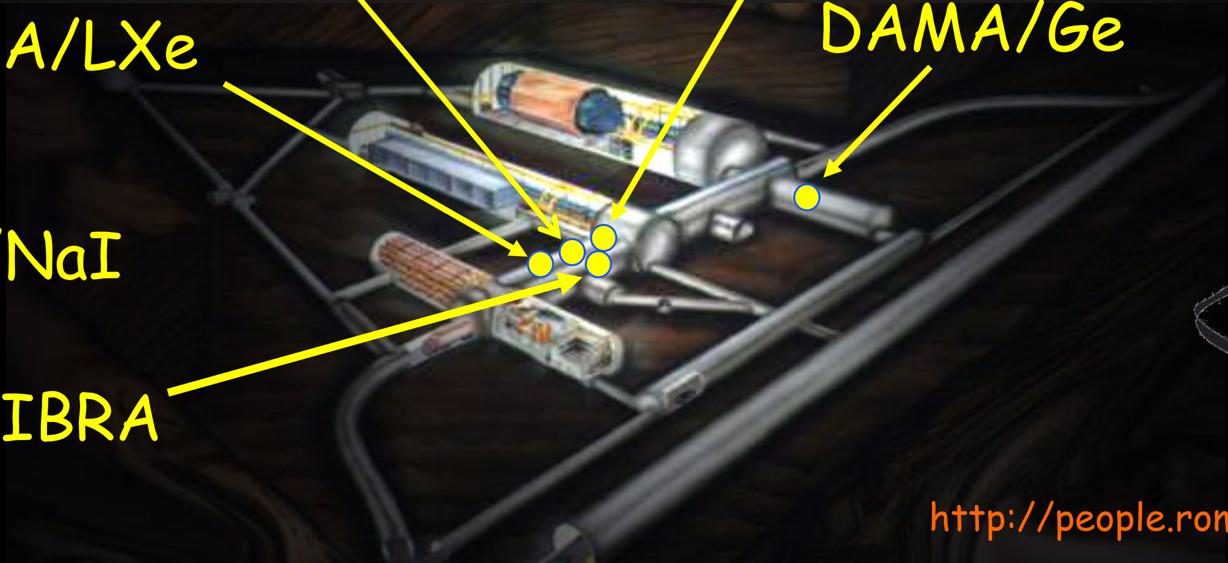
INFN-ROMA

DAMA: an observatory for rare processes @LNGS



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Collaboration

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

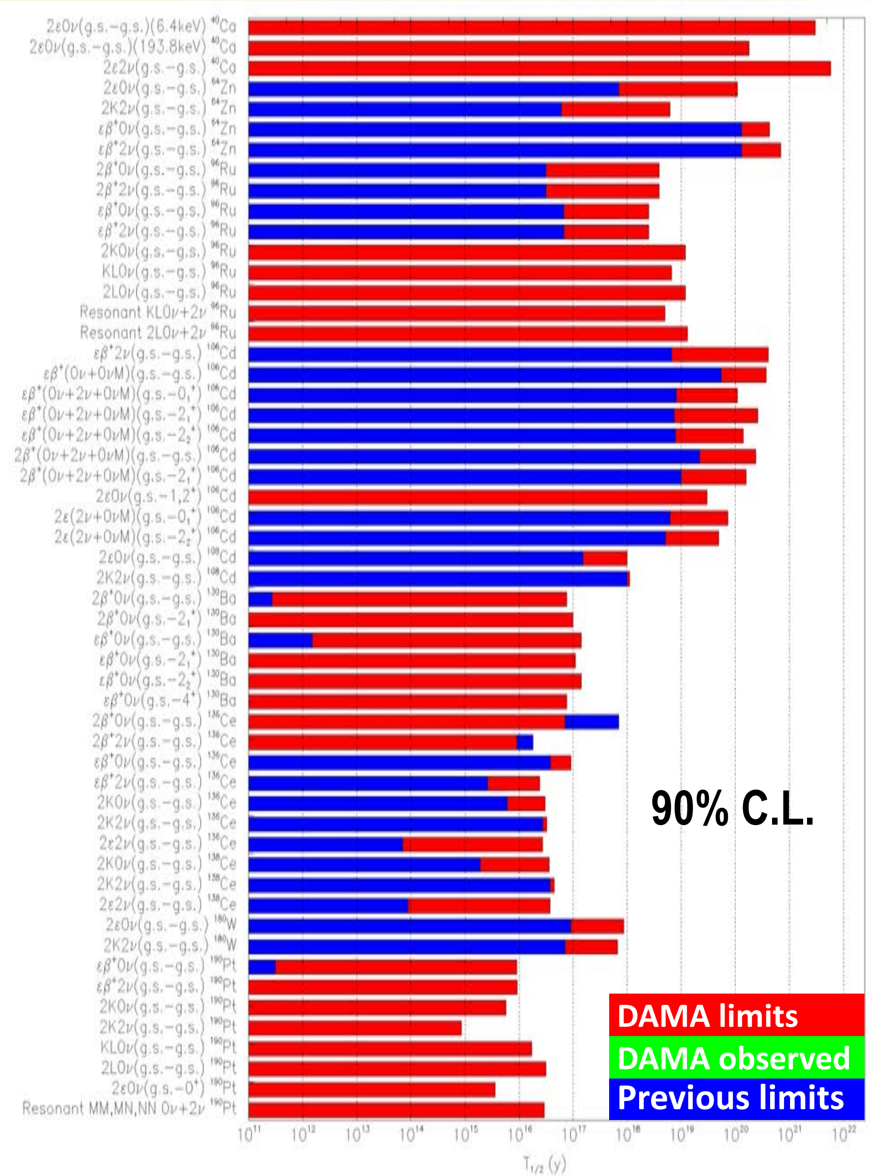
+ by-products and small scale experiments (MoU): INR-Kyiv

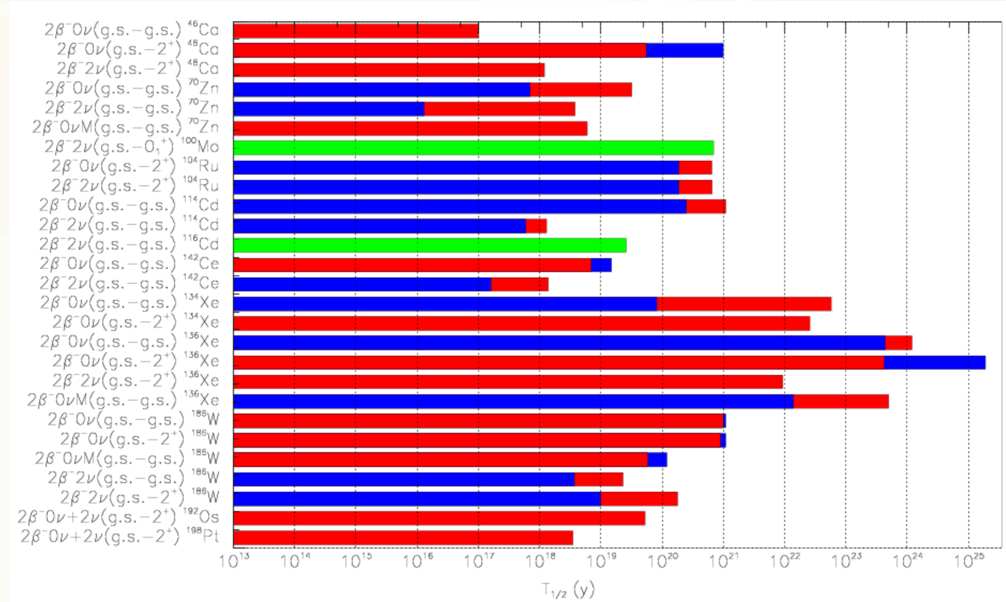
+ in some studies on ββ decays
(DST-MAE projects, inter-univ. Agreem.): IIT Ropar/Kharagpur, India

+ in some activites collaborators from

Ukraine	Kyiv National Taras Shevchenko University National Science Center Kharkiv Instit. of Physics and Technology; Institute for Scintillation Materials, Ukraine
Russia	Russian Chemistry-Technological University of D.I.Mendeleev Moscow Joint Institute for Nuclear Research, Dubna; Joint stock company NeoChem, Moscow Nikolaev Inst. of Inorganic Chemistry, Novosibirsk; Institute of Theoretical and Experimental Physics, Moscow
Australia	Department of Applied Physics, Curtin University, Perth
Finland	Dept. of Physics, University of Jyvaskyla, Jyvaskyla

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





ARMONIA: New observation of $2\nu2\beta^-$ ^{100}Mo⟶^{100}Ru ($g.s.\to 0_1^+$) 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 $2\varepsilon0\nu$ decays in some isotopes

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), ^7LiI(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

Armonia

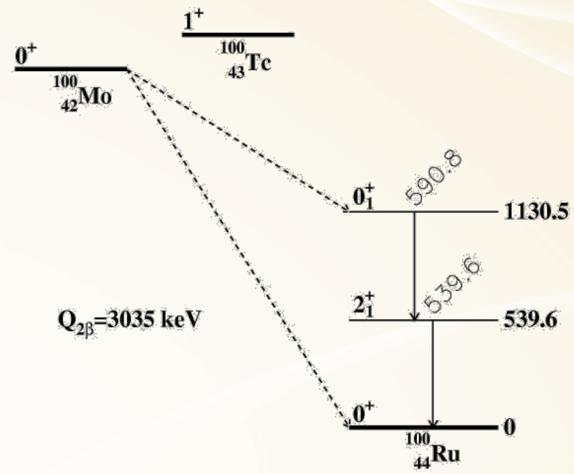
NPA846(2010)143

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

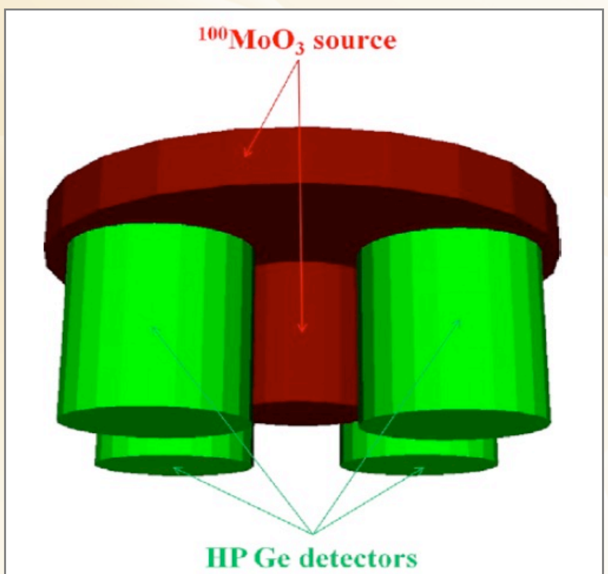
In addition to the transition to the g.s., the $2\beta2\nu$ decay of ^{100}Mo was registered also for the transition to the first excited 0^+_1 level of ^{100}Ru

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

⇒ 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

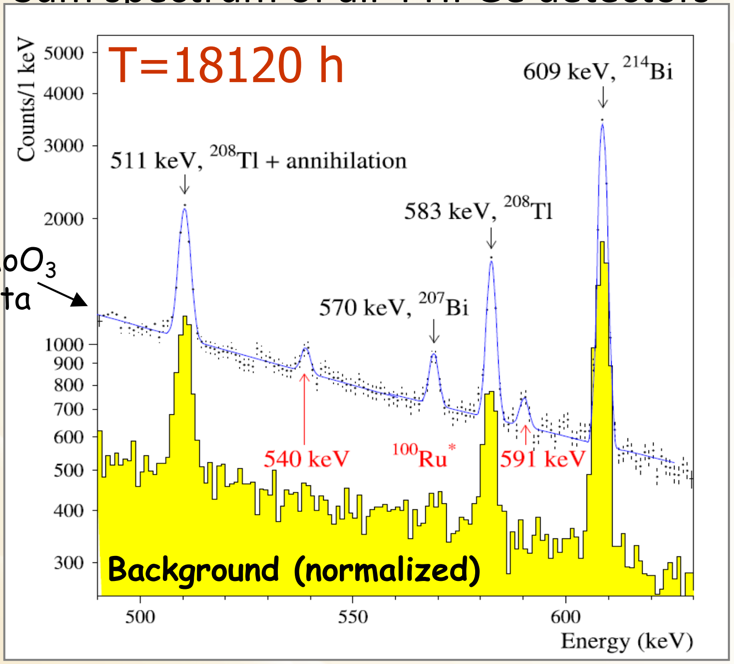
Aim of the experiment: remeasurement of the Mo sample used before in the Frejus exp. (not in agreement with other results)

Armonia Results

NPA846(2010)143

Sum spectrum of all 4 HPGe detectors

$^{100}MoO_3$ data



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)

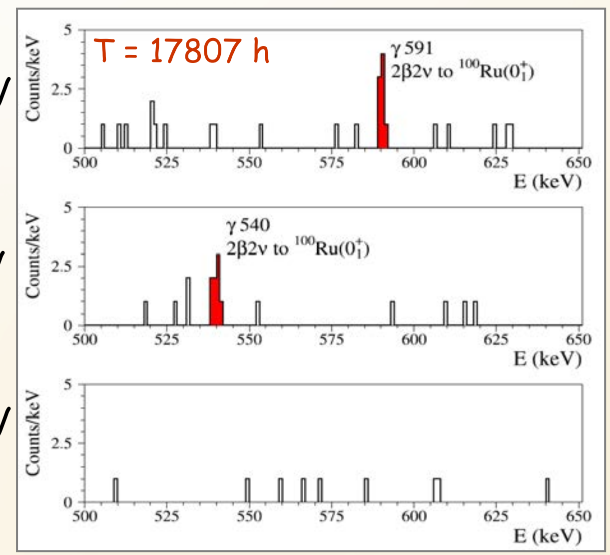
$$T_{1/2} = 6.8^{+3.7}_{-1.8}(\text{stat.}) \times 10^{20} \text{ yr}$$

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

E1 = (540±2) keV

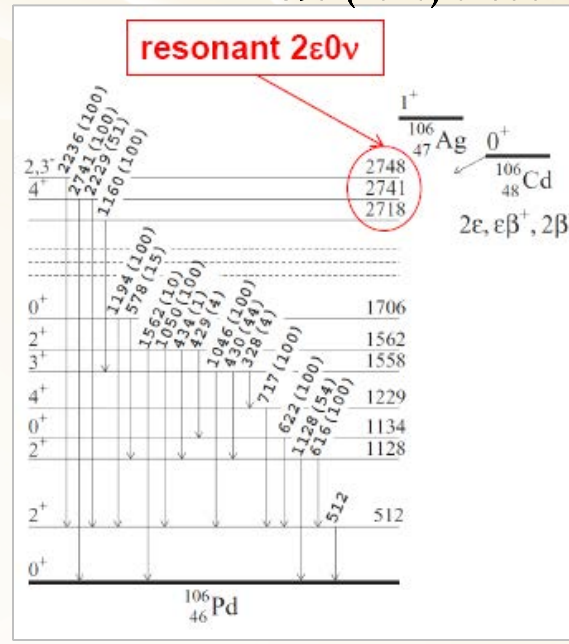
E1 = (591±2) keV

E1 = (545±2) keV (background)



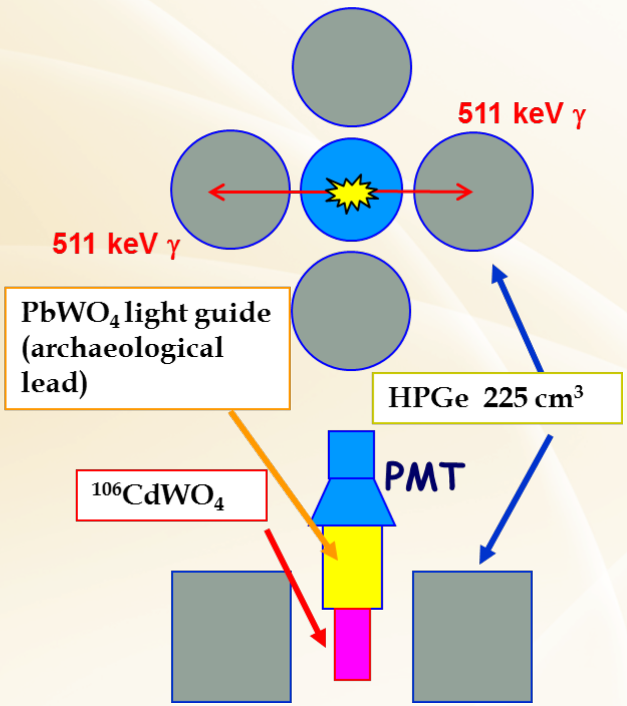
Search for ββ decay in ^{106}Cd with $^{106}CdWO_4$ scintillator in coincidence with 4 HPGe (GeMulti)

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)



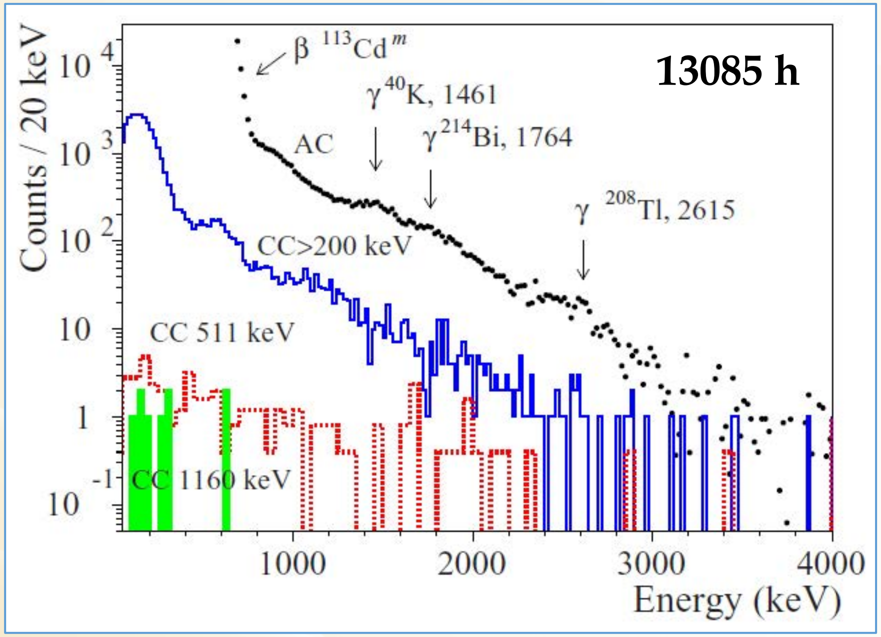
$^{106}CdWO_4$ crystal scintillator:

- ✓ 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

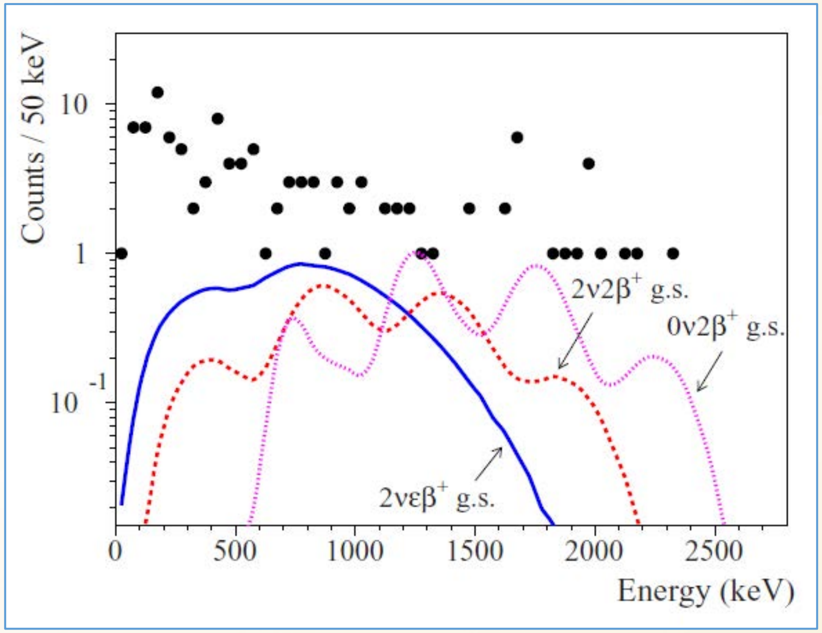
$PbWO_4$ light-guide (∅40 × 83 mm)

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**)



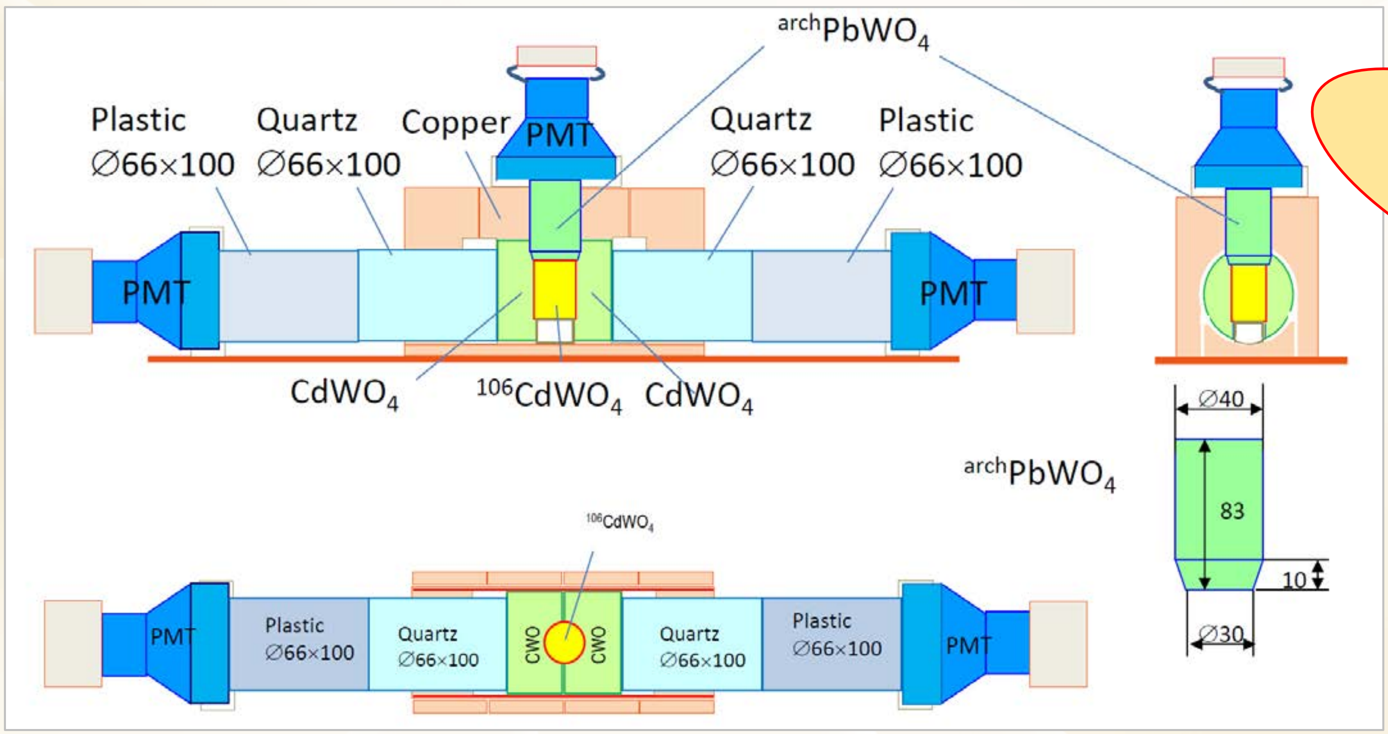
Energy spectrum of $^{106}CdWO_4$ detector in coincidence with 511 keV in HPGe (circles). Monte Carlo simulated distributions of 2β decay of ^{106}Cd excluded at 90% CL

- **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) New experiment with $^{106}CdWO_4$ 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



See the talk of V. Caracciolo

New limits on $2\beta^+$ decay of ^{136}Ce and ^{138}Ce with deeply purified cerium sample

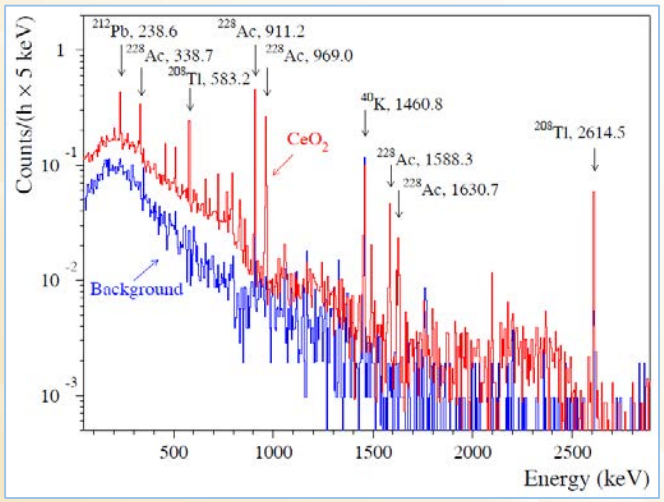
Eur. Phys. J. A 53 (2017) 172

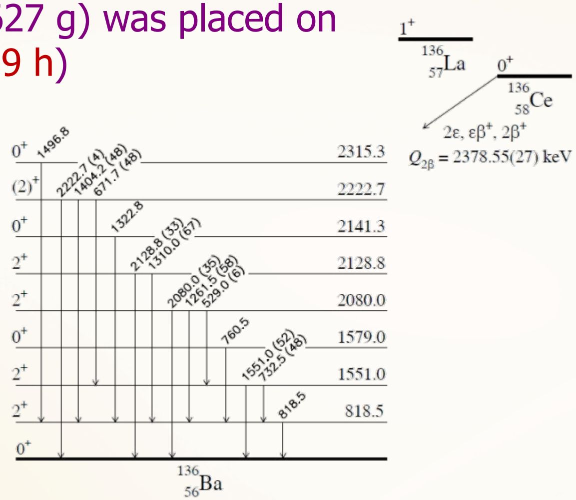
Ce purification performed by the liquid-liquid extraction method

- ⇒ thorium concentration reduced by a factor ≈ 60
- ⇒ improved 2β sensitivity ≈ one order of magnitude

The sample of deeply purified CeO_2 (627 g) was placed on the endcap of GeCris detector (T=2299 h)

Chain	Nuclide	Activity (mBq kg^{-1}) before purification [31]	after 1st purification [31]	after 2nd purification
	^{40}K	77(28)	≤ 9	≤ 4
	^{137}Cs	≤ 3	≤ 2	0.4 ± 0.2
	^{138}La	–	≤ 0.7	≤ 0.6
	^{139}Ce	–	6 ± 1	1.4 ± 0.3
	^{152}Eu	–	≤ 0.5	≤ 0.2
	^{154}Eu	–	≤ 0.9	≤ 0.08
	^{176}Lu	–	≤ 0.5	0.4 ± 0.1
^{232}Th	^{228}Ra	850 ± 50	53 ± 3	30.4 ± 0.7
	^{228}Th	620 ± 30	573 ± 17	9.8 ± 0.5
^{235}U	^{235}U	38 ± 10	≤ 1.8	≤ 0.4
	^{231}Pa	–	≤ 24	≤ 0.4
	^{227}Ac	–	≤ 3	≤ 1.4
^{238}U	^{238}U	≤ 870	≤ 40	≤ 12
	^{226}Ra	11 ± 3	≤ 1.5	≤ 0.3

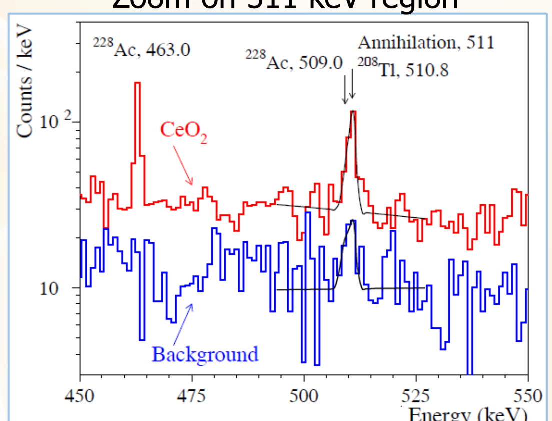




No peculiarities in CeO_2 spectrum can be ascribed to 2β decay of ^{136}Ce or ^{138}Ce

⇒ New improved half-life limits: $T_{1/2} > 10^{17}$–10^{19} yr

Zoom on 511 keV region

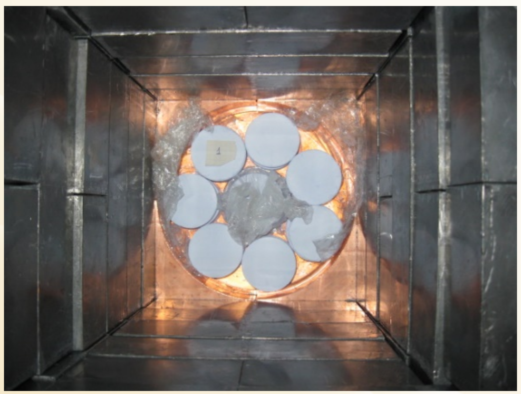


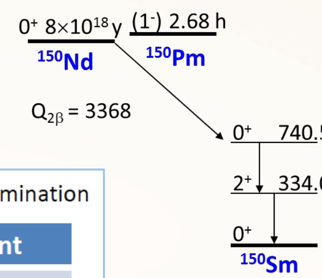
NB:
Cerium purification is also motivated in the light of radiopure crystal scintillators development; In fact, Ce is used

- ✓ to develop Ce-containing crystal scintillators (e.g., CeF_3, $CeCl_3$)
- ✓ as a dopant in inorganic scintillators as Gd_2SiO_5(Ce), $YAlO_3$(Ce), $LaBr_3$(Ce)

Running and future experiments

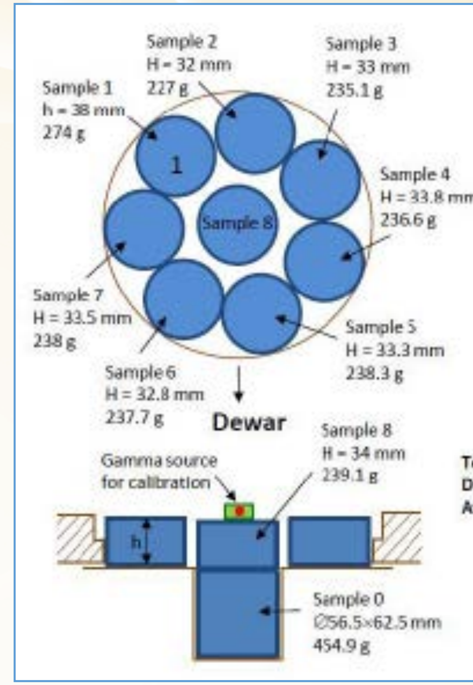
- Experiment running since February 2015 with deeply purified Nd_2O_3 sample (2381 g) in GeMulti detector to investigate 2β decay of ^{150}Nd to excited levels of ^{150}Sm:
  - ⇒ Background rate in the region of expected peaks (334.0 keV and 406.5 keV) ≈ 2 counts/keV/d
  - ⇒ Expected $T_{1/2}$ sensitivity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



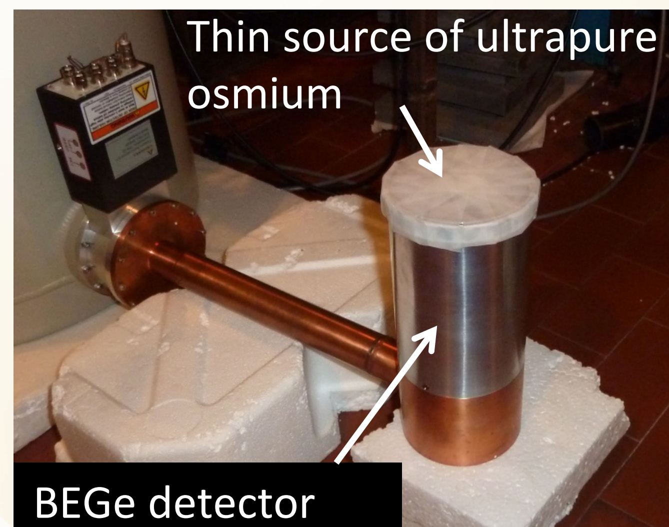


Improvement of Nd_2O_3 radioactive contamination

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

Conclusions

Many and competitive results have been obtained by the DAMA-Kyiv collab. in the search for ββ decays with HPGe detectors @ the STELLA facility of LNGS:

- ✓ First or improved limits on the half-lives of double beta decays of ^{96}Ru, ^{104}Ru, ^{106}Cd, ^{112}Sn, ^{124}Sn, ^{136}Ce, ^{138}Ce, ^{156}Dy, ^{158}Dy, ^{184}Os, ^{192}Os, ^{190}Pt and ^{198}Pt
- ✓ The best experimental sensitivities in the field for 2β decays with positron emission (useful to distinguish the mechanism of neutrinoless 2β decay)
- ✓ Possible resonant 2ε0ν processes investigated in several candidate isotopes
- ✓ New observation of the 2β2ν decay of ^{100}Mo to the first excited 0^+_1 level of ^{100}Ru with the coincidence technique in the ARMONIA experiment
- ✓ New and competitive limits on 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes of ^{106}Cd with a $^{106}CdWO_4$ detector in coincidence with 4 HPGe detetors ($T_{1/2} > 10^{20}$-10^{21} yr, reached the region of theoretical predictions for the $\varepsilon\beta^+2\nu$ decay)