Rare processes investigations with DAMA set-ups at LNGS

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DAMA: an observatory for rare processes @LNGS

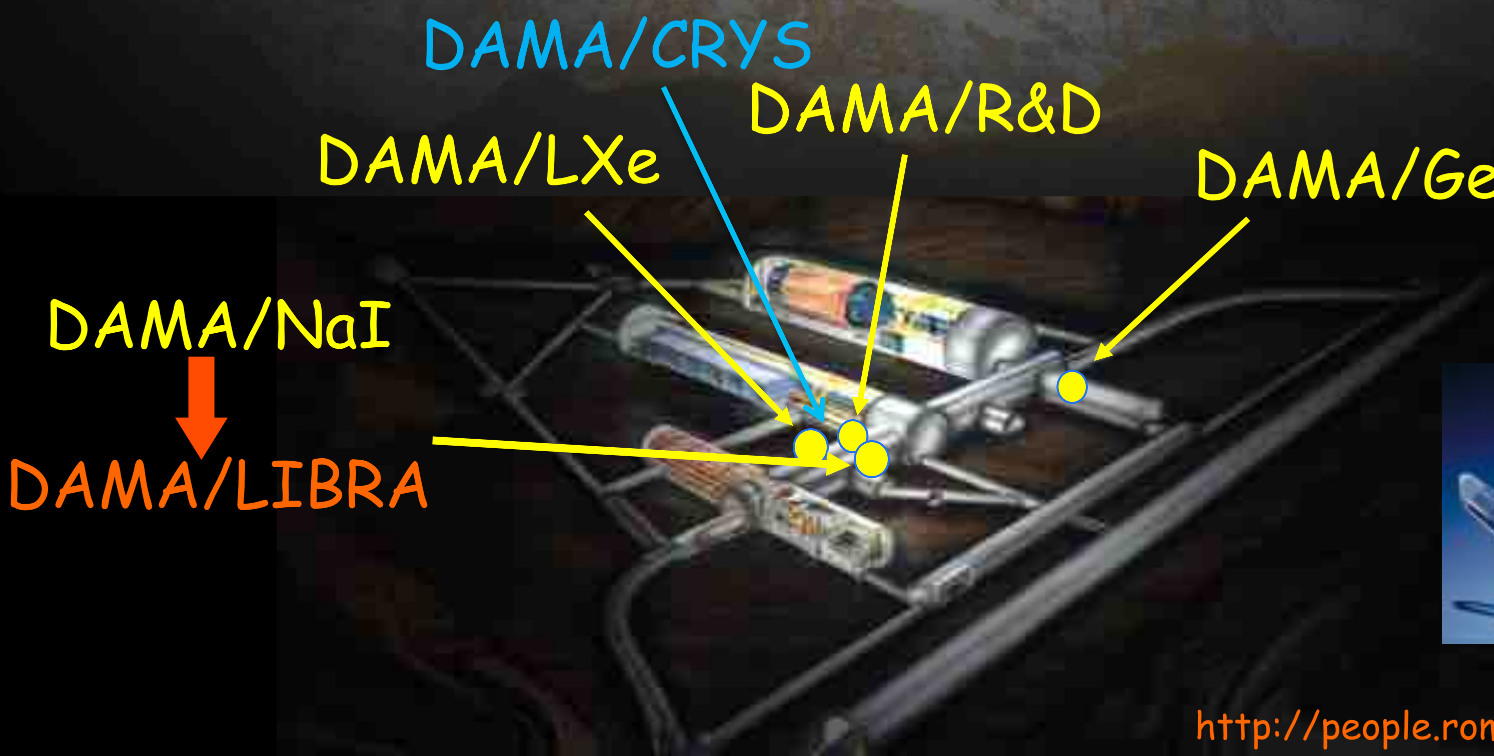
Collaboration:

Roma Tor Vergata, Roma La Sapienza, LNGS, IHEP/Beijing
(+ Jinggangshan Univ)

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

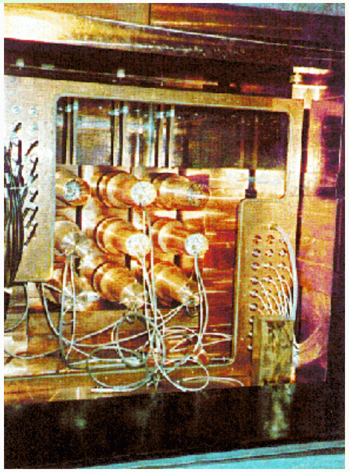
+ neutron meas.: ENEA-Frascati

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



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

Several results on rare processes with low background scintillators



DAMA/NaI

- Possible Pauli exclusion principle violation (PLB408(1997)439)
- CNC processes (PRC60(1999)065501)
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) (PLB460(1999)235)
- Search for solar axions (PLB515(2001)6)
- Exotic Matter search (EPJDIRECT C14(2002)1)
- Search for superdense nuclear matter (EPJA23(2005)7)
- Search for heavy clusters decays (EPJA24(2005)51)

DM and $\beta\beta$ not considered here

DAMA/LIBRA

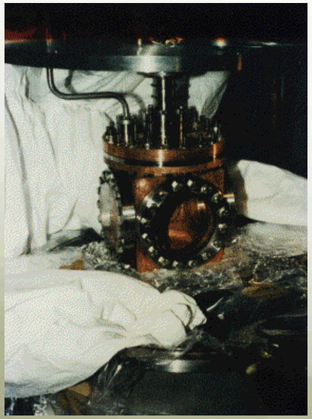
- PEP violation in Na, I: EPJC62(2009)327
- CNC in I: EPJC72(2012)1920
- IPP: EPJA49 (2013) 64

DAMA/R&D

- α decay in ^{142}Ce, in ^{nat}Eu (NPA789(2007)15)
- β decay in ^{48}Ca (NPA705(2002)29)
- β decay in ^{113}Cd (PRC76(2007)064603)
- Cluster decay in $LaCl_3$(Ce) (NIMA555(2005)270)
- CNC decay $^{139}La \rightarrow {}^{139}Ce$ (UJP51(2006)1037)
- β decay in ^{222}Rn (EPJA50(2014)134)
- Long-lived superheavy eka-tungsten (PhysScr90(2015)085301)

DAMA/Ge & LNGS Ge facility

- Search for ^{7}Li 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)

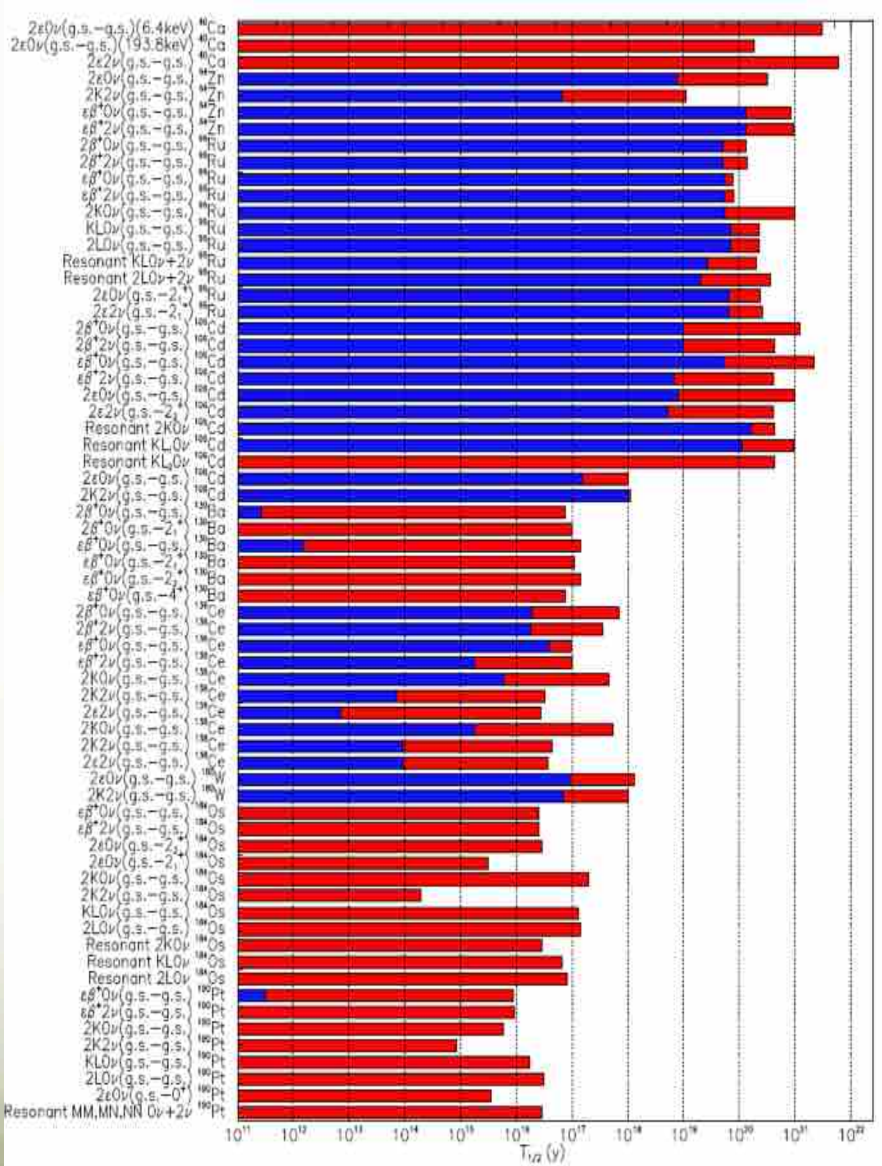


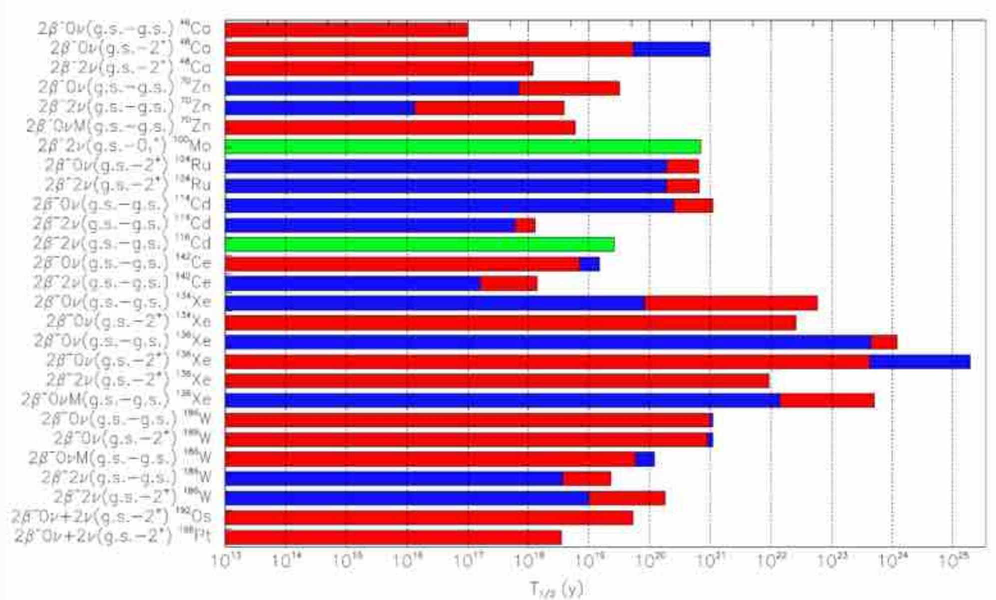
DAMA/LXe

- CNC processes: e^- decay into invisible channels (AP5(1996)217);
- $e^- \rightarrow \nu_e \gamma$ (PRD61(2000)117301);
- nuclear level excitations (PLB465(1999)315);
- $^{136}Xe \rightarrow {}^{136}Cs$ (Beyond the Desert (2003) 365)
- N, NN, NNN decay (PLB493(2000)12, EPJA27 s01 (2006)35)

- ^{106}Cd, ^{116}Cd in progress (PRC85(2012)044610, JINST6(2011)P08011)
- ADAMO project: Study of the DM directionality approach with $ZnWO_4$ anisotropic detectors (EPJC73(2013)2276)
- Qualification and meas. 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)
- Many other meas. planned
- All the set-ups are continuously running

Summary of searches for ββ decay modes (partial list)





$T_{1/2}$ experimental limits by DAMA (in red) and previous ones (in blue). All the limits are at 90% C.L. except for 0ν2β⁺ in ^{136}Ce and 2β⁻0ν in ^{142}Ce at 68% C.L.. In green observed!

ARMONIA: New observation (green) of 2ν2β⁻ ^{100}Mo→^{100}Ru (g.s.→0_1^+) decay
NPA846 (2010)143

AURORA: New observation of 2ν2β⁻ ^{116}Cd decay
NPAE2012

- **Many competitive limits obtained on lifetime of 2β⁺, εβ⁺ and 2ε processes (^{40}Ca, ^{64}Zn, ^{96}Ru, ^{106}Cd, ^{108}Cd, ^{130}Ba, ^{136}Ce, ^{138}Ce, ^{180}W, ^{190}Pt, …).**
- **The limits on 2β⁻ modes in ^{136}Xe are the presently best ones for this isotope**
- **First searches for resonant ββ decays in some isotopes**

Many publications on detectors developments and results
Many future measurements in preparation

- Rare processes in DAMA/LIBRA
- Rare nuclear processes
- Double beta decays
- Others

- Rare processes in DAMA/LIBRA
- Rare nuclear processes
- Double beta decays
- Others

The DAMA/LIBRA set-up ~250 kg NaI(Tl) (Large sodium Iodide Bulk for RAre processes)

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)

Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g

- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648. Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239
- Results on rare processes: PEPv: EPJC62(2009)327; CNC: EPJC72(2012)1920; IPP in ^{241}Am: EPJA49(2013)64

Internal Pair Production – IPP

R. Bernabei et al., EPJA 49 (2013) 64

Eur. Phys. J. A (2013) **49**: 64
DOI 10.1140/epja/i2013-13064-1

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

New search for correlated e^+e^- pairs in the α decay of ^{241}Am

R. Bernabei[1,2,a], P. Belli[1,2], F. Cappella[3,4], V. Caracciolo[5], S. Castellano[5], R. Cerulli[5], C.J. Dai[6], A. d'Angelo[3,4], A. Di Marco[1,2], H.L. He[6], A. Incicchitti[3,4], M. Laubenstein[5], X.H. Ma[6], F. Montecchia[1,7], X.D. Sheng[6], V.I. Tretyak[8], R.G. Wang[6], and Z.P. Ye[6,9]

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Internal Pair Production – IPP

R. Bernabei et al., EPJA 49 (2013) 64

β decay - internal bremsstrahlung (IB) and internal pair production (IPP) are known effects

α decay - IB is known; what about IPP?

In fact, it was observed previously in 3 experiments (1973, 1986, 1990):

Source	Experiment				Theory		
	λ ($\times 10^{-9}$)	Detectors	Year	Ref.	λ ($\times 10^{-9}$)	Year	Ref.
^{210}Po	5.3 ± 1.7	NaI(Tl)+Ge(Li)	1986	[10]	4.4	1978	[6]
^{239}Pu	7 ± 9	NaI(Tl)+Ge(Li)	1986	[10]	2.2	1978	[6]
^{241}Am	3.1 ± 0.6	NaI(Tl)+Ge(Li)	1973	[2]	1.2	1973	[2]
	2.15 ± 0.25	NaI(Tl)+Ge(Li)	1986	[10]	2.3	1978	[6]
	$1.8 \pm 0.7^{(a)}$	Plastics+Ge	1990	[16]			
	4.70 ± 0.63	NaI(Tl) pairs	2013	This work			

$$\lambda = \frac{A_{e^+e^-}}{A_\alpha}$$

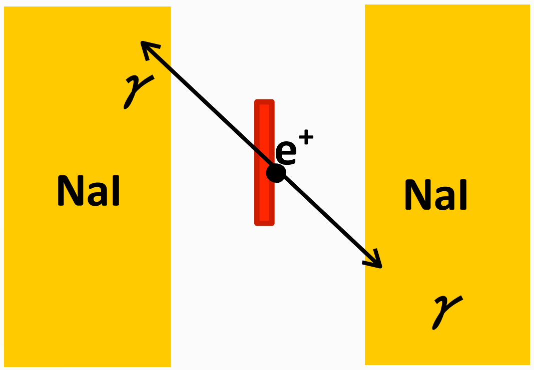
[2] A. Ljubicic, B.A. Logan, Phys. Rev. C 7 (1973) 1541
[6] K. Pisk et al., Phys. Rev. C 17 (1978) 739
[10] J. Stanicek et al., Nucl. Instrum. Meth. B 17 (1986) 462
[16] T. Asanuma et al., Phys. Lett. B 237 (1990) 588

The theory, which describes the effect as creation of bremsstrahlung γ with E_γ > 1.022 MeV during α acceleration, gives the right order of magnitude of λ.

Study of IPP in DAMA/LIBRA-phase2

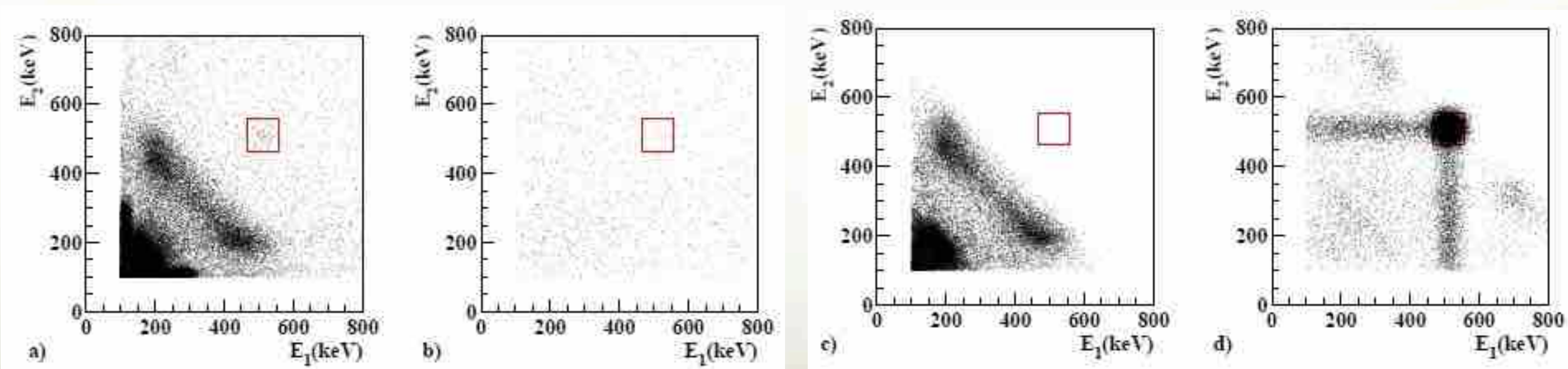
R. Bernabei et al., EPJA 49 (2013) 64

In the α decay of ^{241}Am sources



Searched signal:

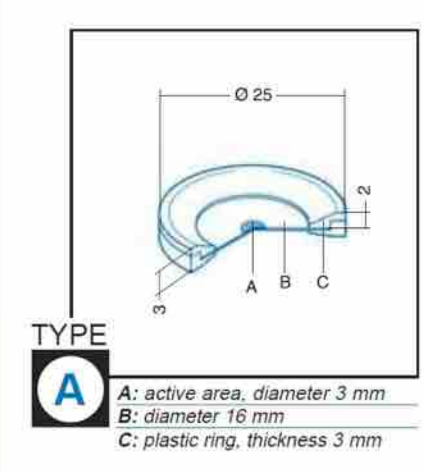
2 γ of 511 keV due to the annihilation of e^+, in the two detectors with the source in between

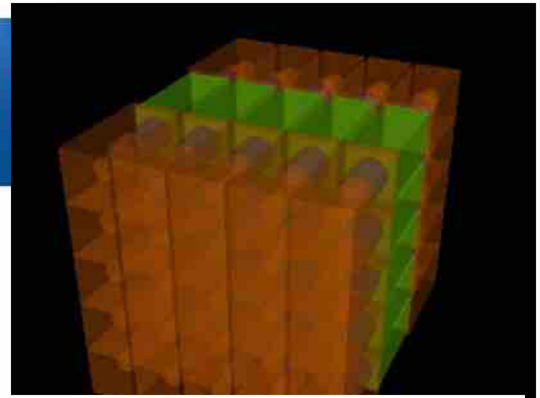


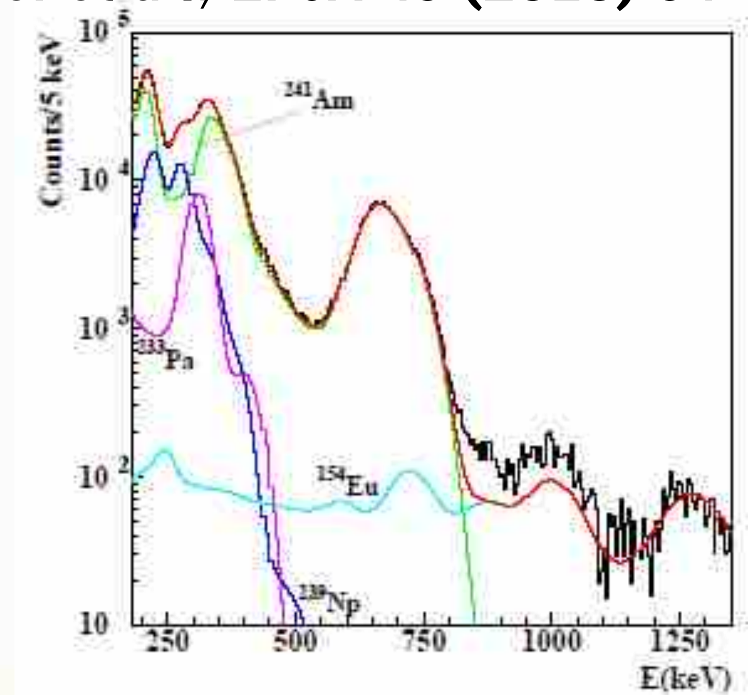
Experimental spectrum with ^{241}Am source	Experimental spectrum without sources	Simulated spectrum with 241Am (MC)	Simulated e^+ annihilation (MC)

Study of IPP in DAMA/LIBRA-phase2

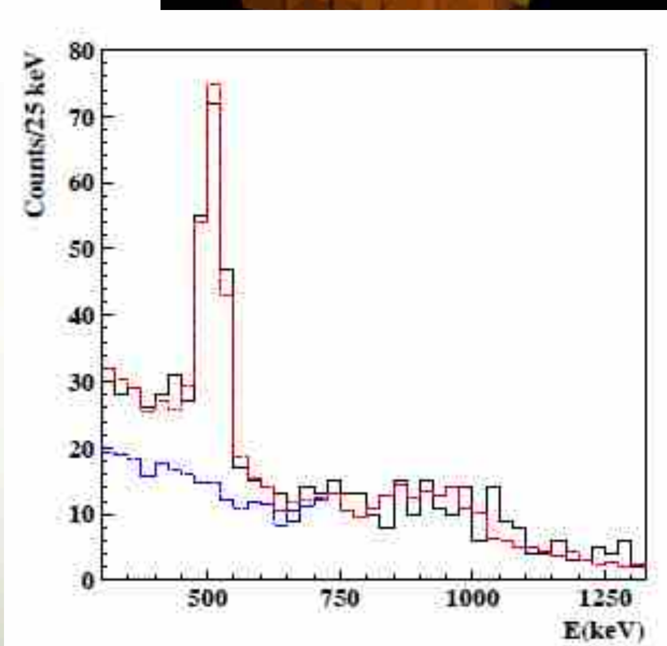
R. Bernabei et al., EPJA 49 (2013) 64







Spectrum of one NaI(Tl) when energy of second is 465-557 keV



S=220±30 counts
$\lambda=(4.70\pm0.63)\times10^{-9}$

Analysis of data: presence of

- **(12.6 ± 0.6) mBq of ^{154}Eu**
- **(908 ± 5) mBq of ^{239}Np (daughter of ^{243}Am)**
- **(208 ± 3) mBq of ^{233}Pa (daughter of ^{241}Am)**

A small excess at ≈900 keV which may be ascribed to a trace contaminant (≈3.4×10^{-2} ppt) of ^{234m}Pa in the ^{238}U chain

Experimental tests for PEP violation

- Since 1948 many experimental tests of CNC processes have been performed
- The first test was the search for possible PEP-forbidden (PEPf) electronic states
- The best sensitivities obtained for 4 classes of experiments for PEPf states are:

Experiment	Result	Ref.
searches for PEPf electronic states in atoms	$[^{12}C']/[^{12}C] < 2.5\cdot10^{-12}$ $[Be']/[Be] < 9\cdot10^{-12}$	A.S. Barabash et al., JETPL 68 (1998) 112 D. Javorsek II et al., PRL 85 (2000) 2701
searches for PEPf nuclear states	$[^{5}He']/[^{4}He] < 2\cdot10^{-15}$	E. Nolte et al., J. Phys. G 17 (1991) S355
searches for PEPf electronic transitions	$\delta^2 < 4.7\cdot10^{-29}$ $\delta^2 < 1.1\cdot10^{-46}$ $\delta^2 < 1.3\cdot10^{-47}$	C. Curceanu et al., JP:Con.Se. 306(2011)012036 H. Ejiri et al., NPB(Proc.Sup.) 28A (1992) 219 R. Bernabei et al., EPJC 62 (2009) 327
searches for PEPf nuclear transitions	$\delta^2 < 3\text{-}4\cdot10^{-55}$ $\delta^2 < 4.1\cdot10^{-60}$	R. Bernabei et al., EPJC 62 (2009) 327 G. Bellini et al., PRC 81 (2010) 034317

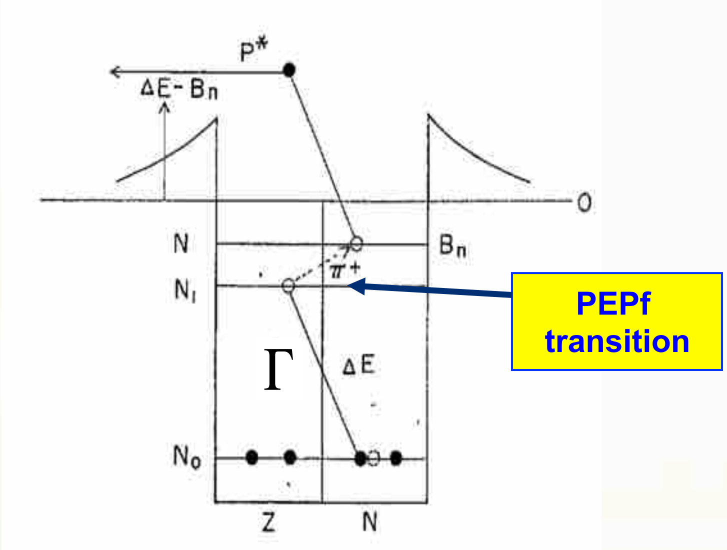
It is worth noting that in 1980 Amado & Primakoff [PRC 22(1908)1338] criticized the possibility of testing the Pauli principle by looking for PEP-forbidden transitions. However their arguments can be evaded either as demonstrated in PRL 68(1992)1826 or PRD39(1989)2032 (for example extra dimensions could lead to apparent PEP violations)

Thus experimental tests of PEPf transitions can also investigate the deep structure of matter and/or of space-time

PEP forbidden transitions (1/2)

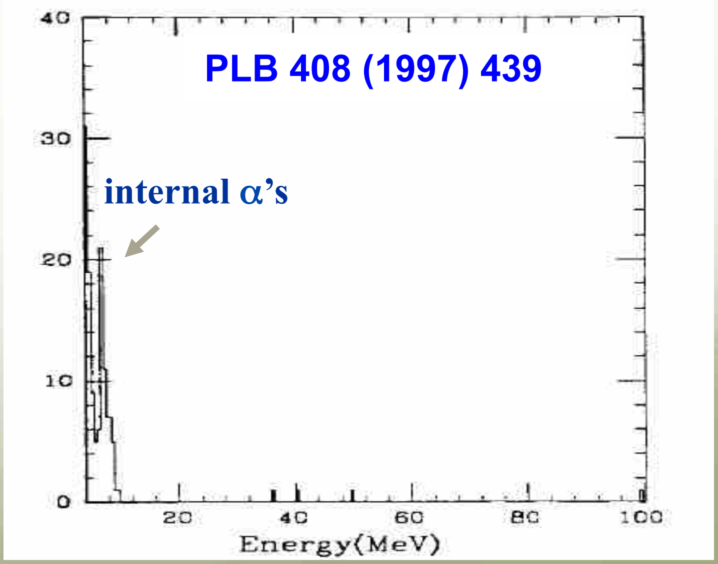
Underground experimental site and highly radiopure set-up allow to reduce background due to PEP-allowed transitions induced by cosmic rays and due to environmental radioactivity

1) Search for non-paulian nuclear processes



Example of a process PEP violating: deexcitation of a nucleon from the shell N_i to the N_0 lower (full) shell

The energy is converted to another nucleon at shell N through strong interaction, resulting to excitation to the unbound region (analogy: Augér emission)



This process was studied in 1997 with DAMA/NaI set-up obtaining a sensitivity of

$$\tau > 0.7 \times 10^{25} \text{ y for } {}^{23}\text{Na (68\% C.L.)}$$

$$\tau > 0.9 \times 10^{25} \text{ y for } {}^{127}\text{I (68\% C.L.)}$$

PEP-violating nuclear processes (1/2)

R. Bernabei et al., EPJC 62 (2009) 327

Eur. Phys. J. C (2009) 62: 327–332
DOI 10.1140/epjc/s10052-009-1068-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

New search for processes violating the Pauli exclusion principle in sodium and in iodine

R. Bernabei[1,2,a], P. Belli[2], F. Cappella[3,4], R. Cerulli[5], C.J. Dai[6], A. d'Angelo[3,4], H.L. He[6], A. Incicchitti[4], H.H. Kuang[6], X.H. Ma[6], F. Montecchia[1,2], F. Nozzoli[1,2], D. Prosperi[3,4], X.D. Sheng[6], Z.P. Ye[6,7]

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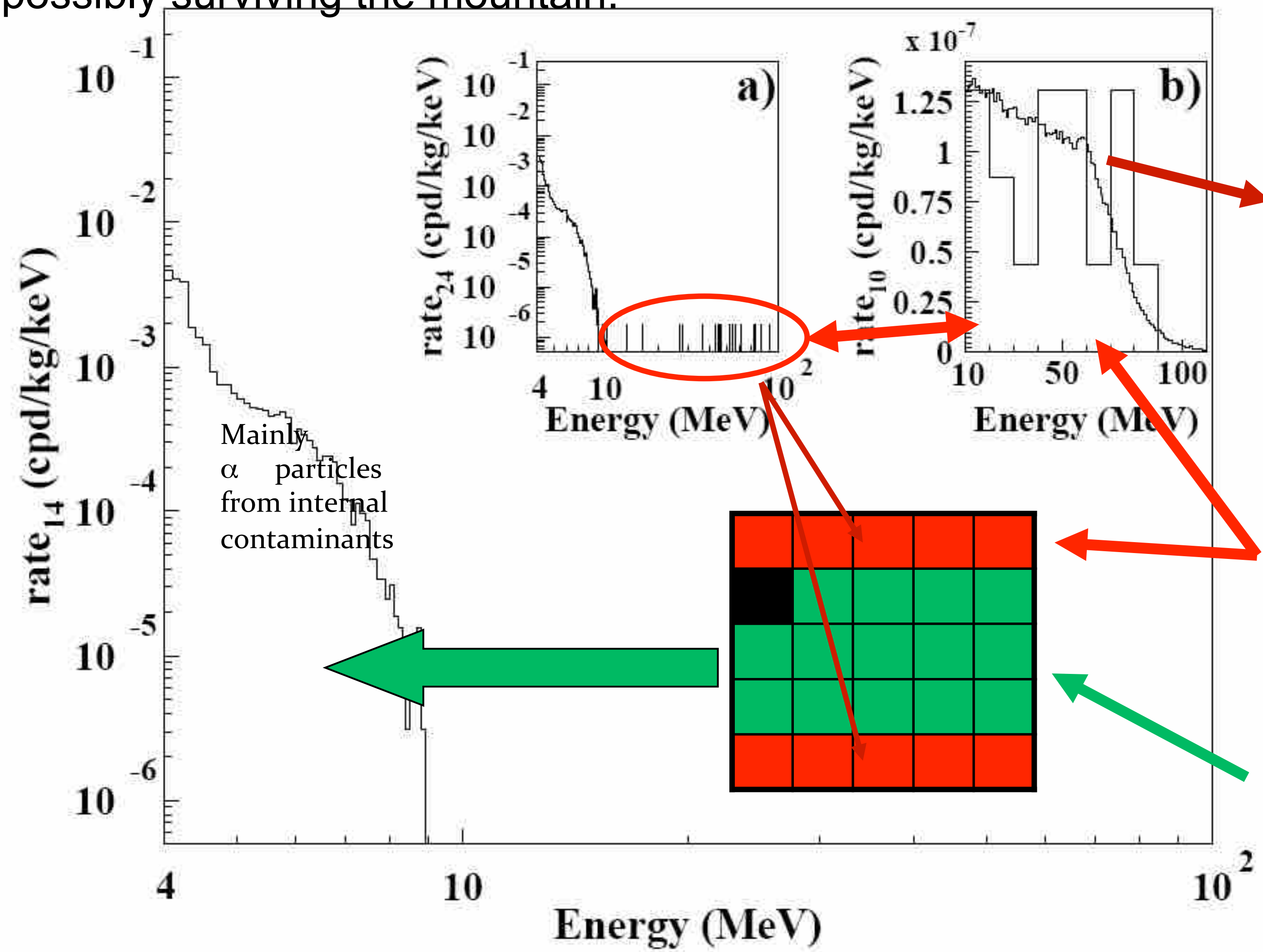
PEP-violating nuclear processes (1/2)

R. Bernabei et al., EPJC 62 (2009) 327

570h running time, optimized for very high energy

Above 10 MeV background due to very high energy muons possibly surviving the mountain.



For PEP violating nuclear processes: events where just one detector fires

Continous line: bkg muon events evaluated by MC not present in the inner core (veto)

For E > 10 MeV:

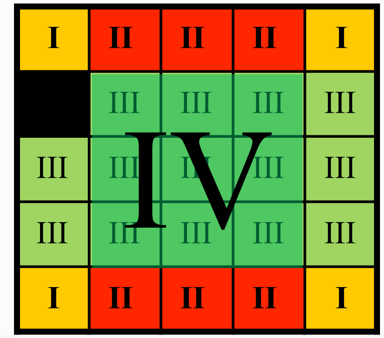
17 events in the upper/lower plane of detector (10 cryst.)

0 events in the central planes of detector (14 cryst.)

PEP-violating nuclear processes (2/2)

R. Bernabei et al., EPJC 62 (2009) 327

Group (J) of considered detectors	Corresponding exposure ($N_J t$) (nuclei × s)	Expected background events (b_J)	Measured events (n_J)	Upper Limit on λ (90% C.L.) (s^{-1})
Just the 4 detectors at corners (I)	3.2×10^{32}	12.1	11	1.99×10^{-32}
Just the remaining 6 detectors in the upper and lower rows (II)	4.8×10^{32}	8.7	6	9.33×10^{-33}
Just the 14 central detectors (III)	1.1×10^{33}	2.2	0	2.06×10^{-33}
Just the 9 core detectors (IV)	7.2×10^{32}	0.057	0	3.19×10^{-33}
Combined analysis (I+II+III):				1.63×10^{-33}



Case	$^A X$	$\tilde{\Gamma}$ (MeV)	δ^2 Upper Limit (90% C.L.)
a)	^{23}Na ^{127}I	1.65 4.64	1.7×10^{-55}
b)	^{23}Na ^{127}I	4.59 11.1	6.8×10^{-56}

$$\Gamma = \Gamma(^{23}Na) + \Gamma(^{127}I) = \hbar\lambda \leq 1.1 \times 10^{-54} MeV$$

a) Fermi momentum distribution with k_F = 255 Mev/c

b) ^{56}Fe momentum distribution accounting for correlation effects

Lower limit on the mean life for non-paulian proton emission in frame b) (90% C.L.):

$\tau > 2 \times 10^{25}$ y for ^{23}Na

$\tau > 2.5 \times 10^{25}$ y for ^{127}I

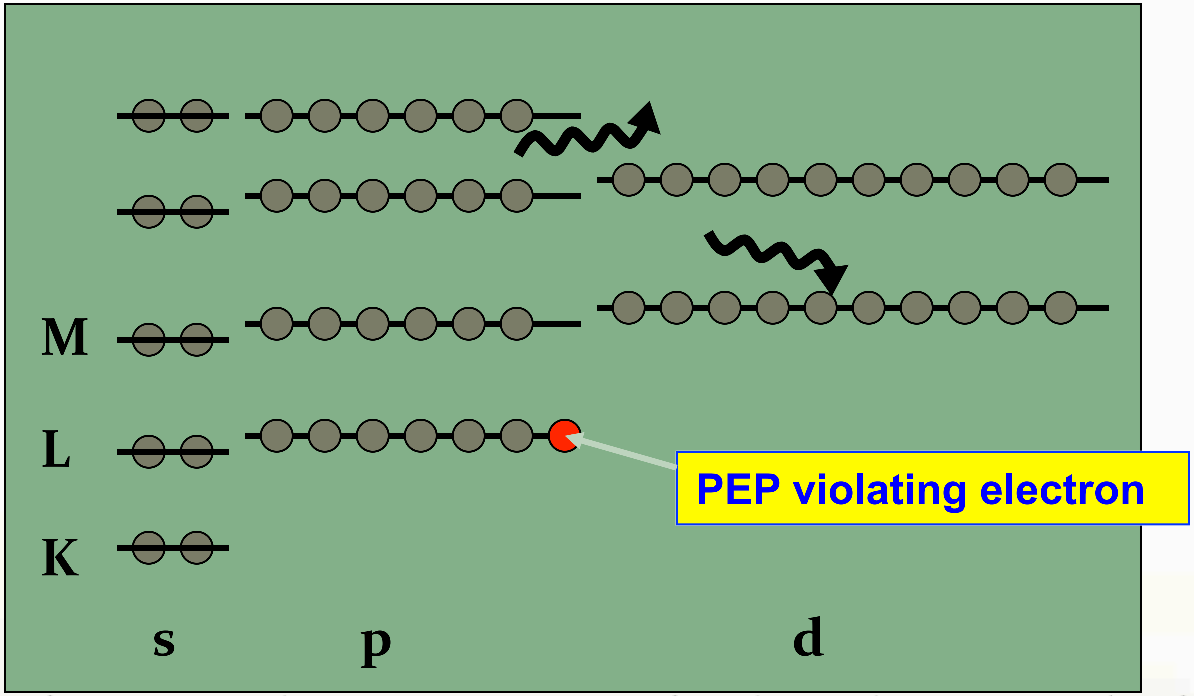
cautious approach:

$$\delta^2 \lesssim 3 - 4 \times 10^{-55}$$

PEP forbidden transitions (2/2)

2) Search for non-paulian electronic transitions to L-shell

Electronic configuration schema of I anion (54 electrons) in Na^+I^- crystal



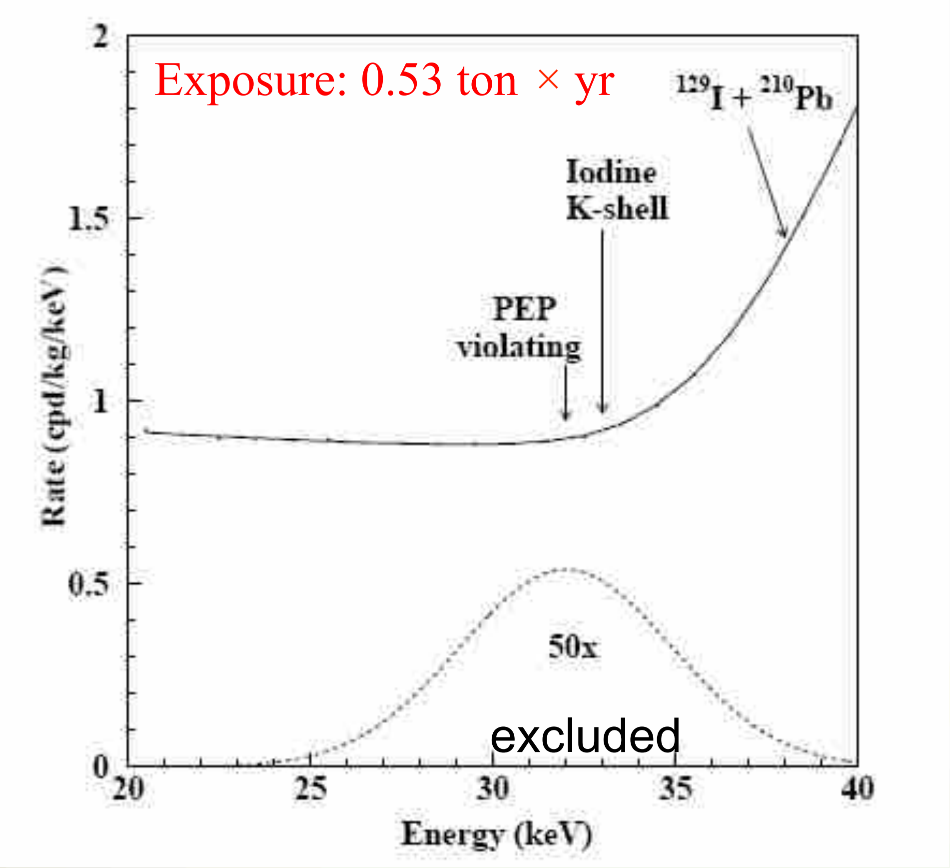
example of a PEP violating transition of Iodine electron to the full L-shell followed by the atomic shells rearrangement

The total released energy (X-ray + Augér electrons) is approximately equal to L-shell ionization potential (≈ 5 keV)

In 1999 DAMA searched for this process in DAMA/NAI obtaining the sensitivity:

$\tau > 4.2\times10^{24}$ yr (68% C.L.) [P. Belli et al., PLB 460 (1999) 236]

PEP-violating electron processes



R. Bernabei et al., EPJC 62 (2009) 327

$\tau_{PV} > 4.7 \times 10^{30}$ s (90% C.L.)

$$\tau^0 = \delta_e^2 \tau_{PV}$$

considering normal electromagnetic dipole transition to Iodine K-shell:

$\tau^0 \approx 6 \times 10^{-17}$ s

$\delta_e^2 < 1.28 \times 10^{-47}$ (90% C.L.).

one order of magnitude more stringent than the previous one (ELEGANTS V)

This limit can also be related to a possible finite size of the electron in composite models of quarks and leptons providing superficial violation of the PEP

[PRL 68(1992)1826]

$$\delta_e^2 = \left[\frac{4}{3}\left(\frac{3}{7}\right)^5\left(\frac{Zr_0}{a_0}\right)^3\right]^2$$

The obtained upper limit on the electron size is: $r_0 < 5.7\times10^{-18}$ cm (energy scale E > 3.5 TeV)

Charge Non-Conserving (CNC) processes

- ✓ Electric Charge Conservation (CC) is a fundamental law in QED
- ✓ This law is correlated with gauge invariance and photon mass (Weinberg theorem)
- ✓ The possibility that CC may be broken in future unified theories and the relative implications have been discussed in last years since the first experimental test in 1959
- ✓ At present no self-consistent theories have been developed, but in some modern theories (for example extra-dimensions) these processes can be possible
- ✓ In 1978 Zeldovich, Voloshin and Okun considered problems due to a phenomenological description of CNC processes; they demonstrated that CNC can not be due to a spontaneous breaking if photon mass is zero

CNC processes are possible if photon mass is not zero

Searches for invisible decays are also related with extra-dimensions:

- Probably, our world is a brane inside higher-dimensional space
- Particles can escape from the brane to extra dimensions

"The presence and properties of the extra dimensions will be investigated by looking for any loss of energy from our 3-brane into the bulk" [N.Arkani-Hamed et al., PLB 429(1998)263]

Thus we could expect disappearance of *e, p, n…*

$\tau\,(p \rightarrow nothing) = 9.2\times10^{34}$ y; [S.L.Dubovsky, JHEP 01(2002)012]

$\tau\,(e \rightarrow nothing) = 9.0\times10^{25}$ yr

Experimental tests for CNC processes

- ✓ Since 1959 many experimental tests fot CNC processes have been done
- ✓ The first test was the search for electron decay, but other possible processes have been considered
- ✓ The best sensitivities obtained for some CNC precesses are:

$$b.r.(\mu^- \rightarrow invisible) < 5.3 \cdot 10^{-3}$$
$$b.r.(\tau^- \rightarrow invisible) < 1.6 \cdot 10^{-3}$$

[S.N.Gninenko, arXiv:0707.3492]

Process	τ (yr)	Ref.
CNC-β decay (^{71}Ga)	$>1.4 \cdot 10^{27}$	M. Torres et al. MPLA 19 (2004) 639
$p \rightarrow anything$	$>4 \cdot 10^{23}$	V.I. Tretyak & Yu.G. Zdesenko PLB 505 (2001) 59
$p \rightarrow invisibile$	$>2.1 \cdot 10^{29}$	S. N. Ahmed et al. PRL 92 (2004) 102004
$n \rightarrow invisibile$	$>5.8 \cdot 10^{29}$	T. Araki et al. PRL 96 (2006) 101802
$pp \rightarrow invisibile$	$>5.0 \cdot 10^{25}$	H.O. Back et al. Phys. Lett. B 563 (2003) 23
$nn \rightarrow invisibile$	$>1.4 \cdot 10^{30}$	T. Araki et al. PRL 96 (2006) 101802
$nnp \rightarrow invisibile$	$>1.4 \cdot 10^{22}$	R.Bernabei et al., EPJA 27,s01(2006)35
$npp \rightarrow invisibile$	$>2.7 \cdot 10^{22}$	R.Bernabei et al., EPJA 27,s01(2006)35
$ppp \rightarrow invisibile$	$>3.6 \cdot 10^{22}$	R.Bernabei et al., EPJA 27,s01(2006)35
$e^- \rightarrow invisible$	$>2.4 \cdot 10^{24}$	P.Belli et al. PLB 460(1999)236
$e^- \rightarrow \nu_e \gamma$	$>4.6 \cdot 10^{26}$	H. O. Back et al. PLB 525(2002)29
CNC-Elect. Capt. (^{129}Xe)	$>3.7 \cdot 10^{24}$	P.Belli et al. PLB 465(1999)315

Electron stability and CNC:

- $e^- \rightarrow \nu_e \gamma$
- $e^- \rightarrow \nu_e \nu \bar{\nu}$
- $e^- \rightarrow$ nothing

} electron disappearance

- $e^- + (A,Z) \rightarrow \nu_e + (A,Z)^*$ [CNC electron capture]
- $(A,Z) \rightarrow \nu_e + (A,Z+1)^* + \bar{\nu}_e$ [CNC β-decay]

CNC EC in NaI detectors

$e^- + (A,Z) \rightarrow \nu_e + (A,Z)^*$ *This process is more probable by K-shell electrons!*

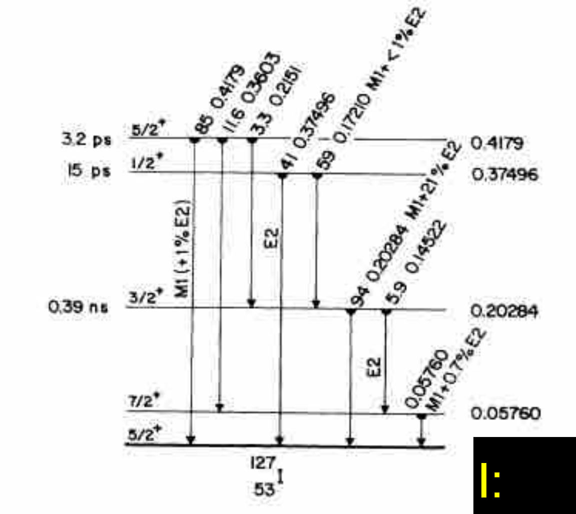
In NaI(Tl) detectors the possible excited states that can be produced by this process are:

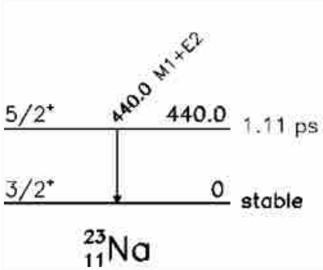
^{127}I four possible excited states: 57.6 keV, 202.8 keV, 375 keV and 418 keV

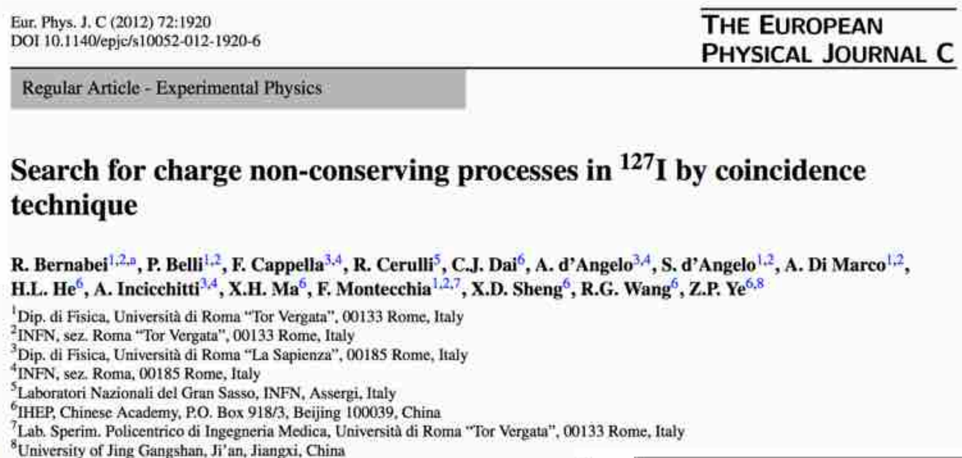
^{23}Na one excited state at 440 keV

We search for γ emitted in de-excitation processes

R. Bernabei et al., EPJC 72 (2012) 1920







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Regular Article - Experimental Physics

Search for charge non-conserving processes in ^{127}I by coincidence technique

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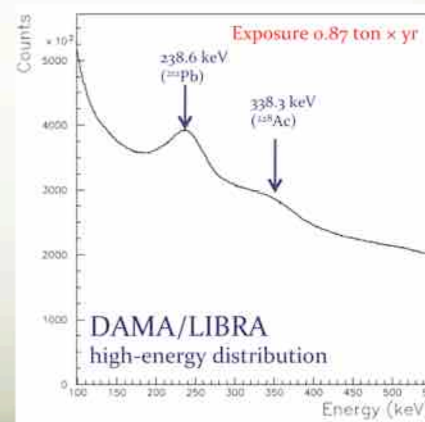
I: E_K = 33.3 keV

Na: E_K = 1.1 keV

Under the energy threshold



We choose to study the production of ^{127}I in the excited level 418 keV

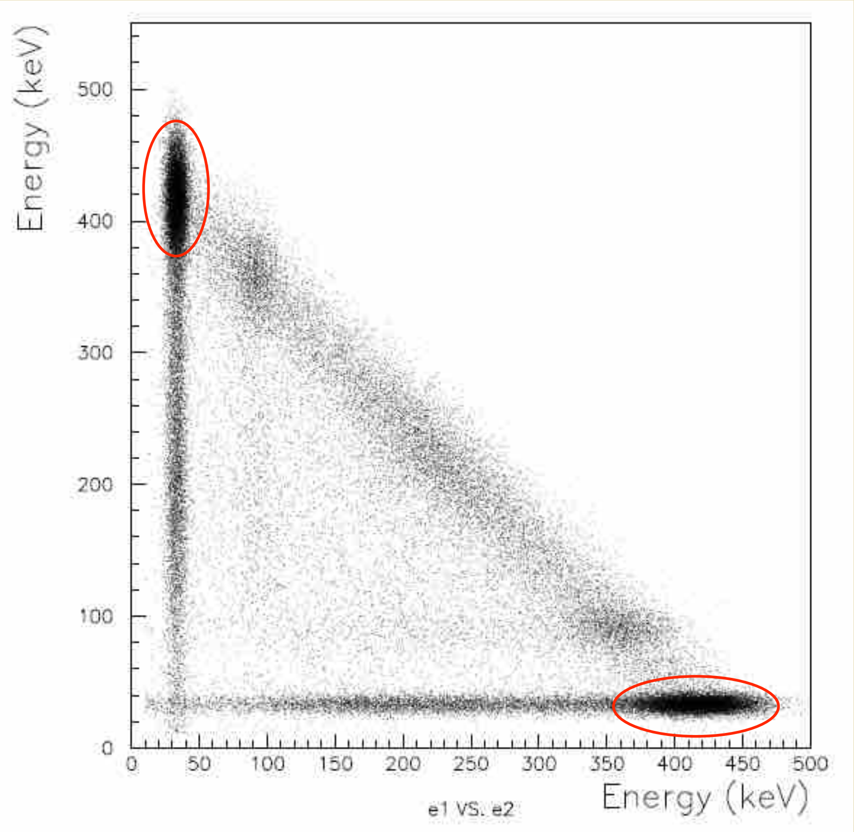
To improve our sensitivity and reduce the background we search for events in coincidence

Each CNC electron capture in Iodine produces X-rays/Augér electrons at 33.3 keV and γ emission due to de-excitation processes of ^{127}I (for example for the 418 keV level γ energies 418 keV, 203 keV and 360 keV)

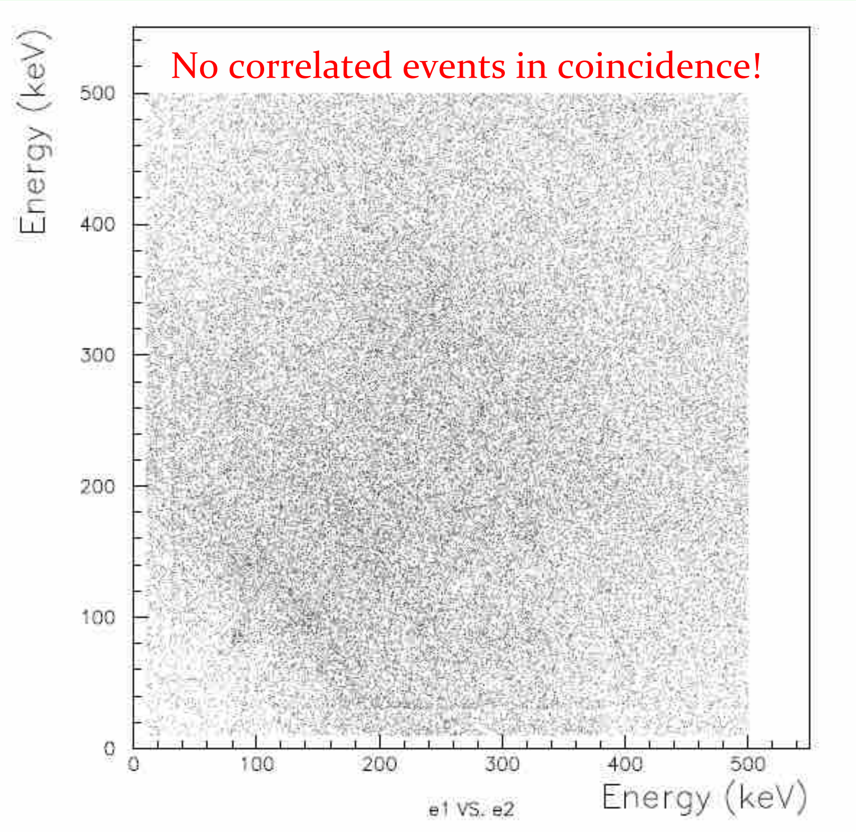
CNC Electron capture

Comparison of experimental data distribution with Montecarlo expectation

R. Bernabei et al., EPJC 72 (2012) 1920



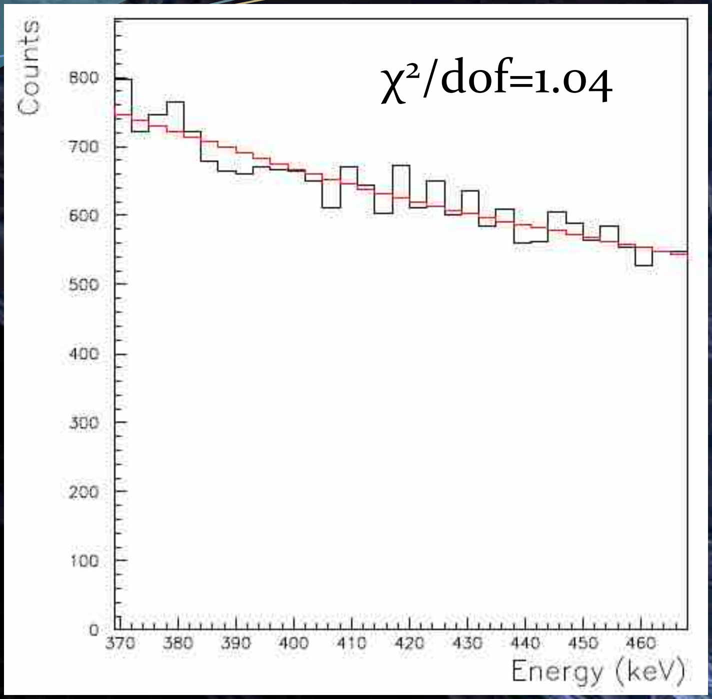
Montecarlo expectation



Experimental data

The experimental data with multiplicity 2 don't show the expected structures for events in coincidence: **No evidence for any signal!**

CNC Electron capture



Data selection with multiplicity 2 and the first event in the energy window 24.7-41.9 keV reduces the background of a factor larger than 10^3

Fittting data with a sum of an exponential function for the continous background and the expected peak we obtain: S = - (260 ± 296) events

Using Feldman and Cousins procedure:
S < 264 events (90% C.L.), corresponding to:

$\tau > 1.2 \times 10^{24}$ yr (90% C.L.)

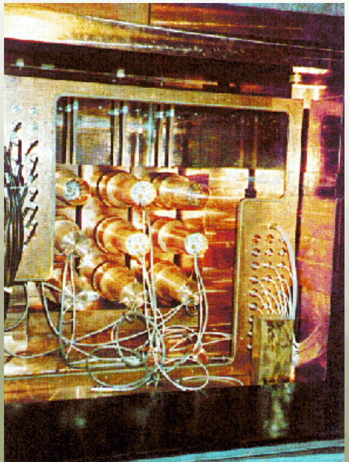
The obtained limit is the best one available for this process in NaI(Tl)

Best limits previously obtained for this process by:
- DAMA/NaI for the production of excited levels of ^{127}I: $\tau > 2.4 \cdot 10^{23}$ yr [P.Belli et al., PRC 60(1999)065501]
- DAMA/LXe for the production of excited levels of ^{129}Xe: $\tau > 3.7 \cdot 10^{24}$ yr [P.Belli et al., PLB 465(1999)315]

$$\varepsilon_W^2 = \frac{0.298}{\tau_{CNC}} < 2.5 \times 10^{-25}$$

$$\varepsilon_\gamma^2 = \frac{5.89 \times 10^{-15}}{\tau_{CNC}} < 4.95 \times 10^{-39}$$

[Nuclear Data Sheet 112(2011)1647; T. Kibèdi et al., NIMA 589(2008)202]



DAMA/LXe: results on CNC processes

- Electron decay into invisible channels [Astrop.P.5(1996)217]
- Nuclear level excitation of ^{129}Xe during CNC processes [PLB465(1999)315]
- N, NN decay into invisible channels in ^{129}Xe [PLB493(2000)12]
- Electron decay: $e^- \rightarrow \nu_e \gamma$ [PRD61(2000)117301]
- CNC decay $^{136}Xe \rightarrow {}^{136}Cs$ [Beyond the Desert(2003)365]
- N, NN, NNN decay into invisible channels in ^{136}Xe [EPJA27 s01 (2006) 35]

DAMA/R&D set-up: results on CNC processes

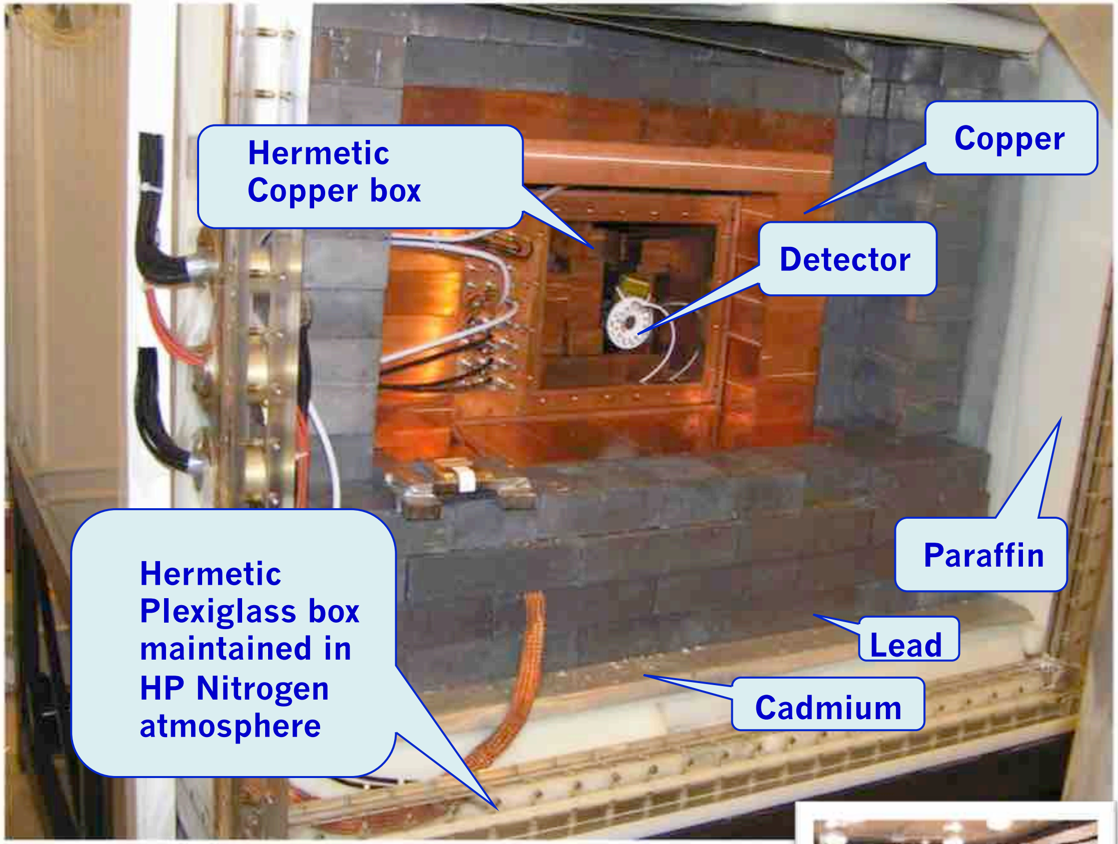
- CNC decay $^{139}La \rightarrow {}^{139}Ce$ [UJP51(2006)1037]

DAMA/NaI: results on CNC processes and PEPv

- Possible Pauli exclusion principle violation [PLB408(1997)439]
- CNC processes [PRC60(1999)065501]
- Electron stability and non-paulian transitions in Iodine atoms (by L-shell) [PLB460(1999)235]

DAMA/Ge and STELLA

DAMA/R&D



Materiale	^{238}U (ppb)	^{232}Th (ppb)	^{nat}K (ppm)
Cu	< 0.5	< 1	< 0.6
Pb boliden	< 8	< 0.03	< 0.06
Pb boliden2	< 3.6	< 0.027	< 0.06
Polish Pb	< 7.4	< 0.042	< 0.03
Polietilene	< 0.3	< 0.7	< 2
Plexiglass	< 0.64	< 27.2	< 3.3

DAMA activity in the DAMA/R&D and in the LNGS Ge facility

- Systematical studies and development of various crystal scintillators for low background physics:
  - scintillator development: radio-purification, enrichment, optical features, etc.
  - exploiting the potentiality of the low background scintillation technique
  - studying various experimental approaches to perform measurements on rare processes with high sensitivity
  - realization of pilot experiments

  $CaF_2(Eu)$, CeF_3, BaF_2, $CdWO_4$, $^{106}CdWO_4$, $^{116}CdWO_4$, $ZnWO_4$, $LaCl_3(Ce)$, $LiEu(BO_3)_3$, LiF(W), $^{7}LiI(Eu)$, $CeCl_3$, Li_2MoO_4, $SrI_2(Eu)$, BaF_2, etc.

- Samples and powders measurements in HPGe also to investigate several rare processes

  Platinum, Osmium, Dysprosium, Molybdenum, Ruthenium, Lithium, Cerium, etc.

- Rare processes in DAMA/LIBRA
- Rare nuclear processes
- Double beta decays
- Others

Recent studies on rare nuclear decays

- **Recent searches and discoveries of rare α decays (^{151}Eu, ^{180}W, ^{178m2}Hf*, ^{190}Pt*, ^{204,206,207,208}Pb, ^{209}Bi, ^{209}Bi*)**
- **Investigations of rare β decays (^{48}Ca, ^{50}V, ^{96}Zr, ^{113}Cd, ^{115}In*, ^{123}Te, ^{180m}Ta, ^{222}Rn)**
- **Observation of emission of e^+e^- pairs in α decay of ^{241}Am**

Many of them have been done by DAMA

Classification of radioactive decays:

Old known α, β, γ decays

α: (A,Z) → (A-4,Z-2), starting from ^{106}Te to superheavy; $T_{1/2}$ from 10^{-8} s (^{217}Ac) to 10^{19} y (^{209}Bi)
β: (A,Z) → (A,Z±1), from ^{3}H; from 10^{-2} s (^{11}Li) to 10^{16} y (^{113}Cd)
γ: (A,Z)* → (A,Z), from 10^{-12} s to 10^5 y (^{186m}Re)

Cluster decays: emission of nuclides heavier than α particle, from ^{14}C to ^{34}Si (~40 mothers from ^{221}Fr to ^{242}Cm, residue close to double magic ^{208}Pb – “lead radioactivity”), 10^3 - 10^{20} y; predicted in 1980 (or earlier?), observed in 1984

2β decays: allowed in SM $2\beta2\nu$ in several nuclei, as e.g. ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, 10^{18} - 10^{24} y; forbidden in SM $2\beta0\nu$ $T_{1/2}>10^{25}$ y

Spontaneous fission: heavy nuclei from ^{232}Th; $T_{1/2}$ from 10^{-3} s (^{264}Hs) to 10^{19} y (^{235}U)

p, 2p, 3p, 2n, …: in short living isotopes (~40 mothers); from ps to s

First observation of α decay of ^{190}Pt to the first excited level of ^{186}Os

P. Belli et al., PRC83 (2011)034603

Pt isotopes potentially unstable to α decay

Parent isotope	δ (%) [11]	Q_α (keV) [16]	N_i/1 g
^{190}Pt	0.014(1)	3251(6)	4.32×10^{17}
^{192}Pt	0.782(7)	2418.6(2.2)	2.41×10^{19}
^{194}Pt	32.767(99)	1518.3(1.6)	1.01×10^{21}
^{195}Pt	33.832(10)	1172.0(1.6)	1.04×10^{21}
^{196}Pt	25.242(41)	808.1(2.6)	7.79×10^{20}
^{198}Pt	7.163(55)	100(4)	2.21×10^{20}

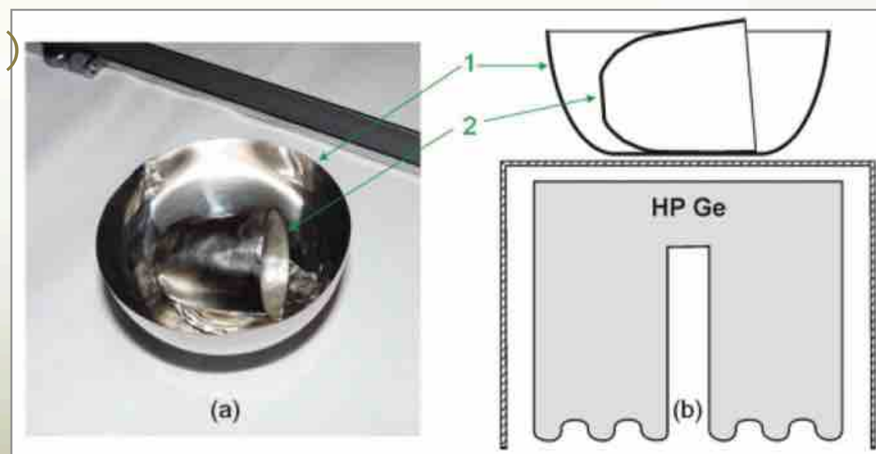
- α decay ^{190}Pt → of ^{186}Os (g.s.) previously observed:
  $T_{1/2} = (6.5 \pm 0.3) \times 10^{11}$ yr

- Our work: α decay to 1st excited level ^{186}Os ($J^p = 2^+$)
  E_{exc} = 137.2 keV ⇒ Q_α = 3114(6) keV
  (Theor. half-life ~10^{13}–10^{14} yr)

The experimental set-up

Pt crucibles (42.53 g) measured in **HPGe (GeCris)** (468 cm^3, FWHM=2.0 keV@1332 keV)

- T (sample) = 1815.4 h
- T(bckg) = 1045.6 h
- detector shielded by layers of low-radioactive copper (~10 cm) and lead (~ 20 cm)
- Setup continuously flushed by high-purity boil-off nitrogen



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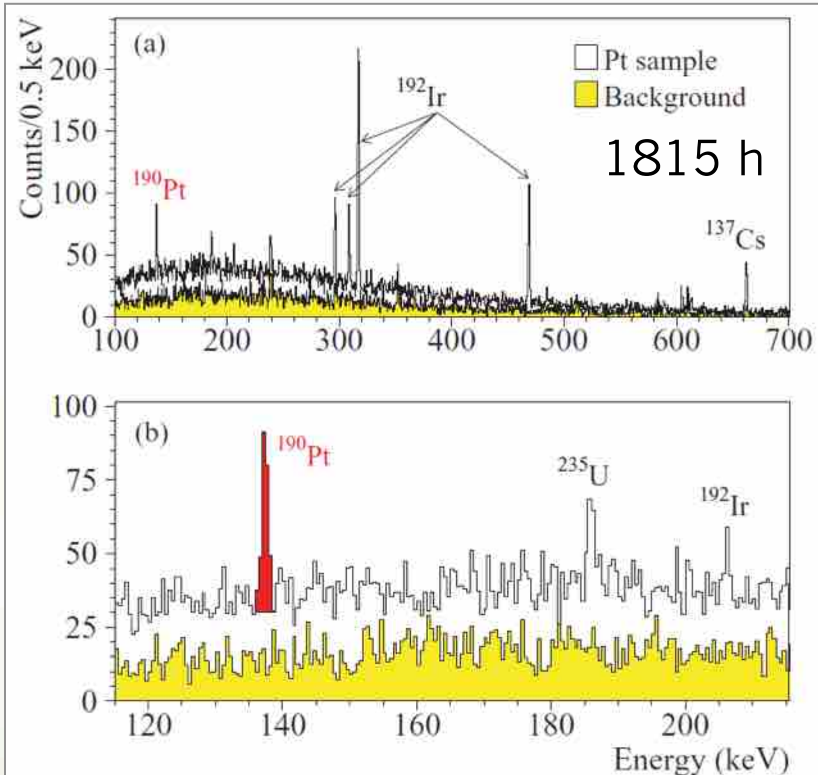


- No significant contamination by "usual" radioactive contaminants: U/Th series, ^{40}K, ^{60}Co
- ^{192}Ir present: 49 ±3 mBq/kg (cosmogenic activation of Pt by cosmic rays at the Earth's surface)

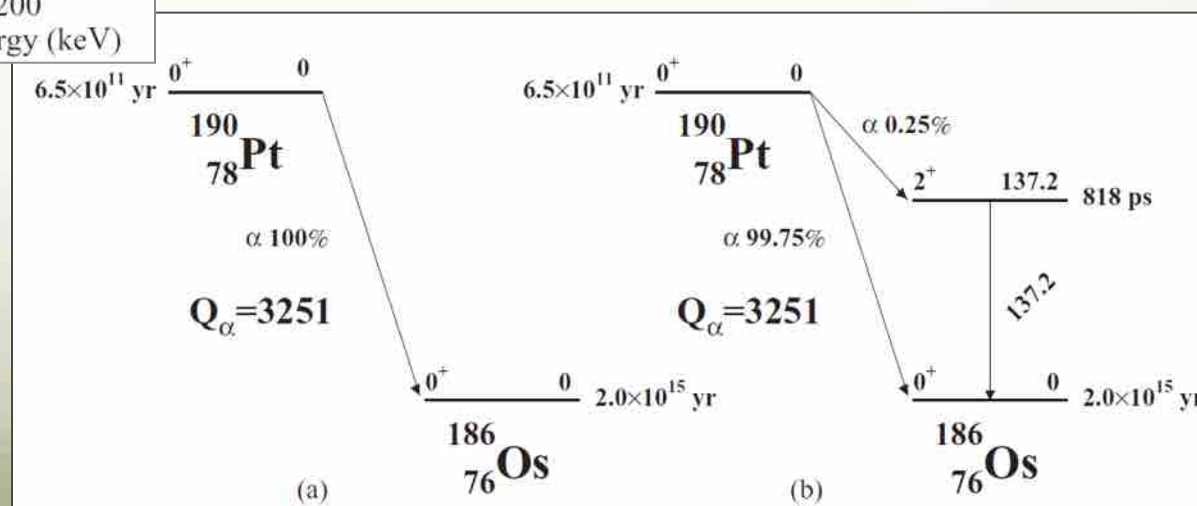
Peak at (137.1 ± 0.1) keV absent in the background spectrum

The presence of an excess around 137 keV is credited at about **8σ**

Other processes mimicking the decay excluded

$$T_{1/2} = 2.6^{+0.4}_{-0.3}(\text{stat.}) \pm 0.6(\text{syst.}) \times 10^{14}\ \text{yr}$$

$T_{1/2}$ in relevant agreement with theoretical calculations based on the liquid drop model and the description of the α decay as a very asymmetric fission process

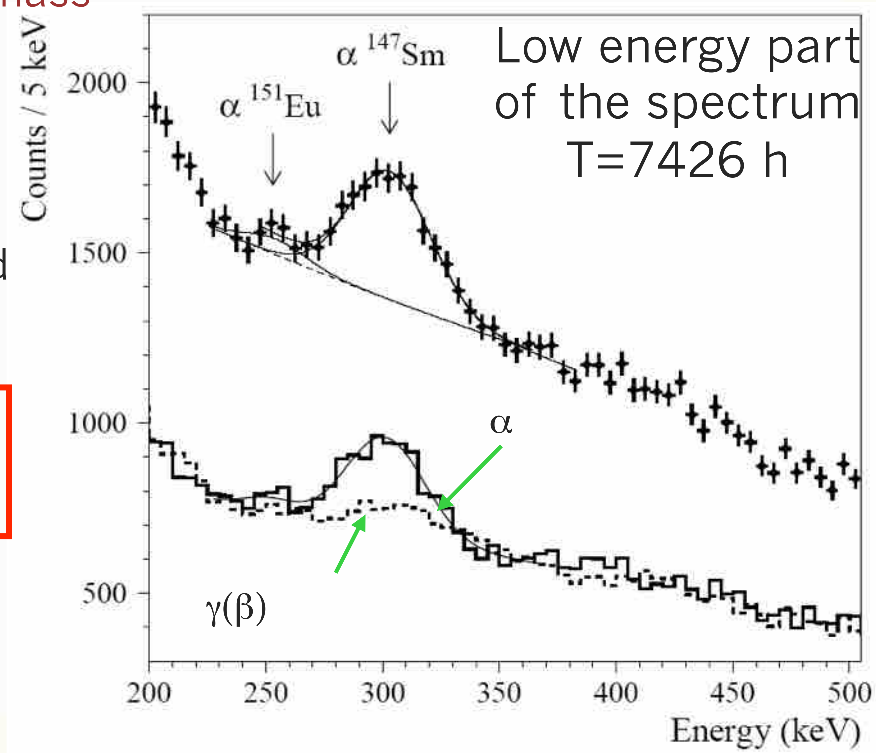


First observation of the α decay of ^{151}Eu in ^{147}Pm

P. Belli et al., NPA 789 (2007) 15

- Low background **CaF_2(Eu) scintillator**, **370 g** mass
- Eu concentration measured by ICP-MS
- 10 cm pure quartz light guide (TETRASIL-B)
- Low background PMT

Peculiarity on the left of the ^{147}Sm peak can be attributed to the **α decay of ^{151}Eu** (expected peak at 1.912 MeV⇒**245±36 keV**)



^{151}Eu α decay: $$T_{1/2} = 5^{+11}_{-3} \times 10^{18}\ \text{yr}$$

... or in a cautious approach:

$$T_{1/2} \geq 1.7 \times 10^{18}\ \text{yr (68\% C.L.)}$$

$T_{1/2}$ is in agreement with theoretical values based on liquid drop model and α as asymmetric fission process

No evidence α decay of ^{151}Eu to the first excited level of ^{147}Pm

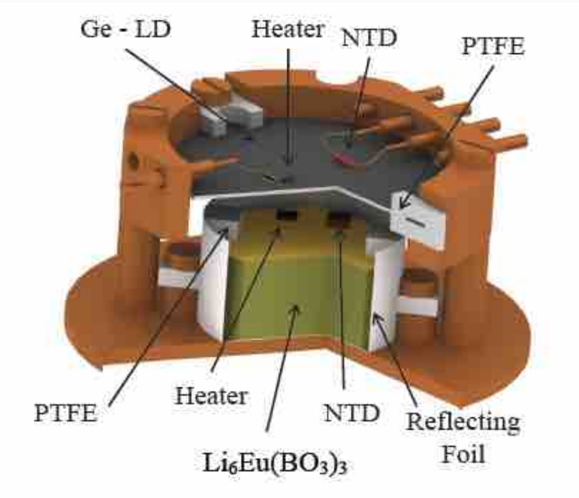
$T_{1/2}$(g.s. – 5/2$^+$) > 6 x 10^{17} yr (68% C.L.)

Presence of Promethium in the Earth crust:
Taking into account the abundance of Europium in the crust (2×10^{-4}%) (equilibrium mass of natural Pm in Earth crust 560 g)

⇒ additional 12^{+17}_{-8} g natural Pm born by ^{151}Eu

Confirmation: N. Casali et al., J. Phys. G 41(2014)075101

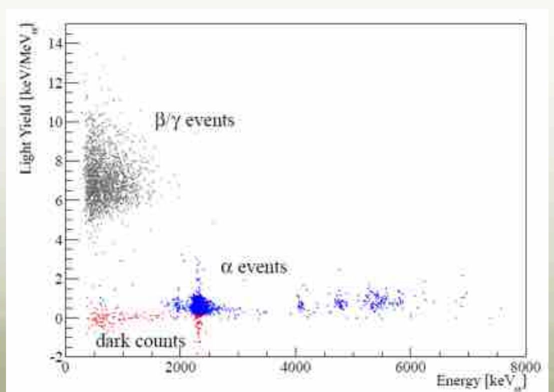
LUCIFER, $Li_6Eu(BO_3)_3$ scintillating bolometer 6.15 g, FWHM = 65 keV, 462 h of measurements, low background set-up at LNGS (3600 m w.e. underground)

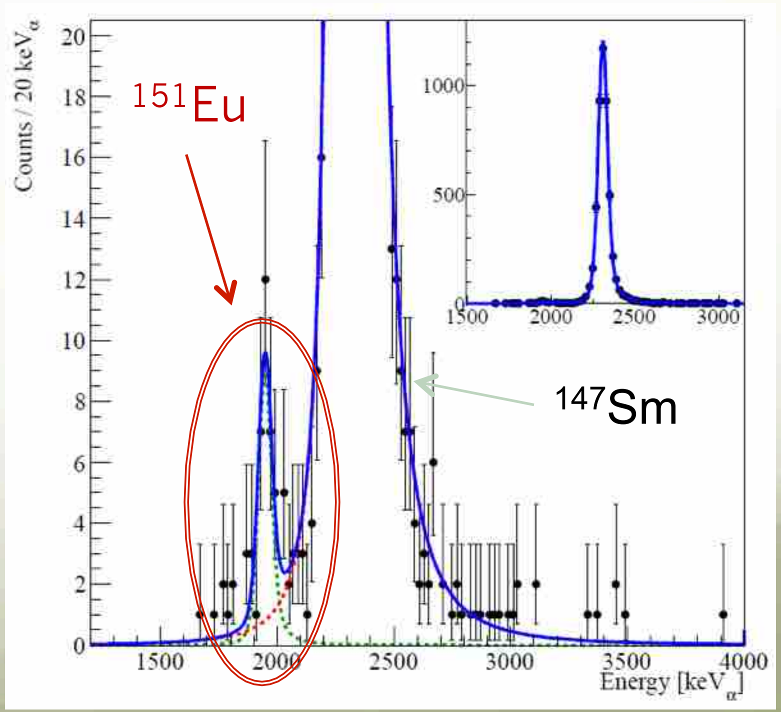


L. Pattavina, talk at RPScint'2013 workshop, Kyiv, 17-20.09.2013

S = 38±8, $T_{1/2}$ = (4.6±1.2)×10^{18} y
Measured Q_α = 1948.9±8.6 keV

Excellent discrimination of β/γ events from α events





- Rare β decay of ^{113}Cd

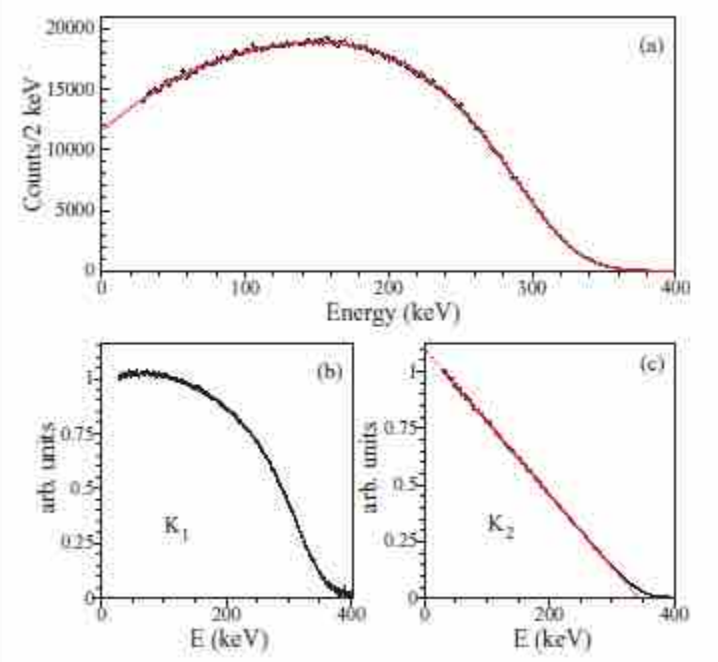
P. Belli et al., PRC 76 (2007) 064603

$CdWO_4$ scintillator 434 g in DAMA/R&D, 2758 h

δ=12.22%; $1/2^+ \rightarrow 9/2^+$; $\Delta J^{\Delta\pi} = 4^+$ classified as 4 FNU

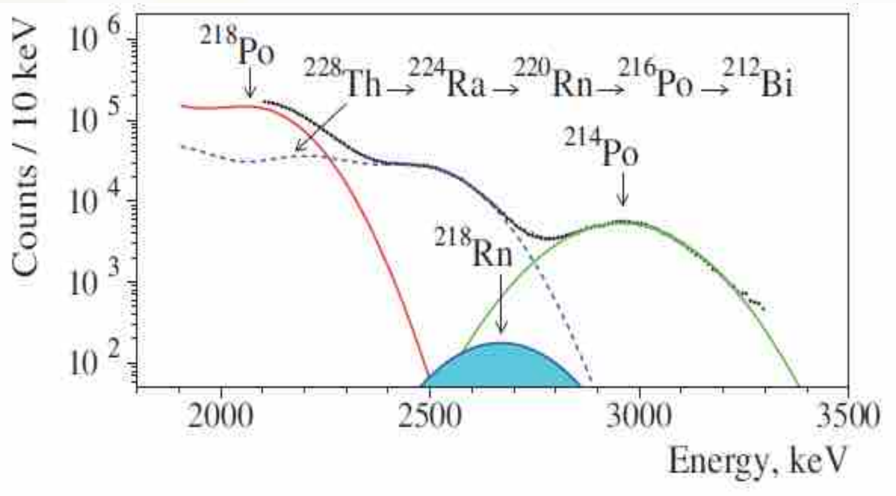
Big statistics, purity of crystal lead to determination of $T_{1/2}$ with small uncertainty:

$$T_{1/2}=(8.04\pm0.05)\times10^{15}\ y$$



- β decay of ^{222}Rn

P. Belli et al., EPJ A 50(2014)134



- **BaF_2 scintillator, 1.714 kg in DAMA/R&D, 101 h.**
- **High contamination by ^{226}Ra – 7.8 Bq/kg (high experimental rate 75 cps).**

In all nuclear tables, ^{222}Rn (in chain of ^{238}U) is 100% α decaying. However, β decay of ^{222}Rn is also energetically allowed with Q=24±21 keV.

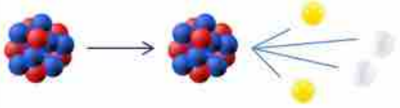
$$T^{\beta}_{1/2}(^{222}\mathrm{Rn}) > 8.0\,\mathrm{y} \quad \text{at} \quad 90\%\ \mathrm{C.L.}$$

- Rare processes in DAMA/LIBRA
- Rare nuclear processes
- Double beta decays
- Others

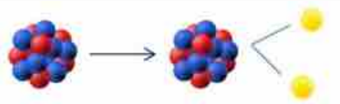
Double beta decay: (A,Z) → (A,Z±2)

Allowed in SM:

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ – two-neutrino $2\beta^-$ decay



Forbidden in SM, $\Delta L=2$:



$(A,Z) \rightarrow (A,Z+2) + 2e^-$ – neutrinoless $2\beta^-$ decay

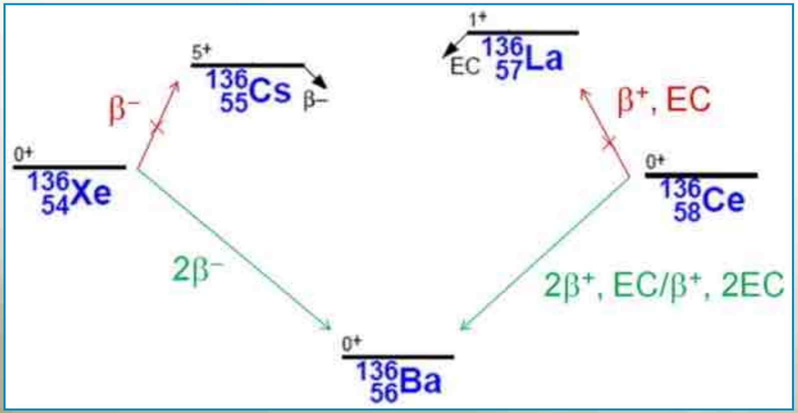
$(A,Z) \rightarrow (A,Z+2) + 2e^- + M$ – $2\beta^-0\nu$ decay with Majoron emission

$2\beta^+/\ \varepsilon\beta^+/2\varepsilon$ processes, decays to excited states, different Majorons …

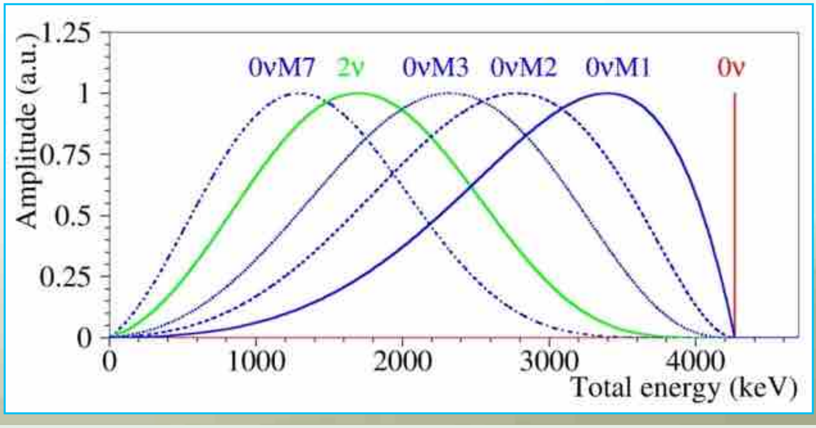
$2\beta0\nu$ requires: $\nu_e = -\nu_e$ **(Majorana particle)**

$m(\nu_e) \neq 0$ **(or right-handed admixtures, …)**

Many extensions of the SM predict $m(\nu_e) \neq 0$ and, as a result, $2\beta0\nu$ pro-cesses. Experimental observation of this exotic phenomenon would be an unambiguous signal of new physics which lies beyond the SM.



β^-, β^+ energetically forbidden $2\beta^-$, $2\beta^+$ allowed



e_1+e_2 energy spectra in different 2β modes

Status of experimental investigations of 2β decay

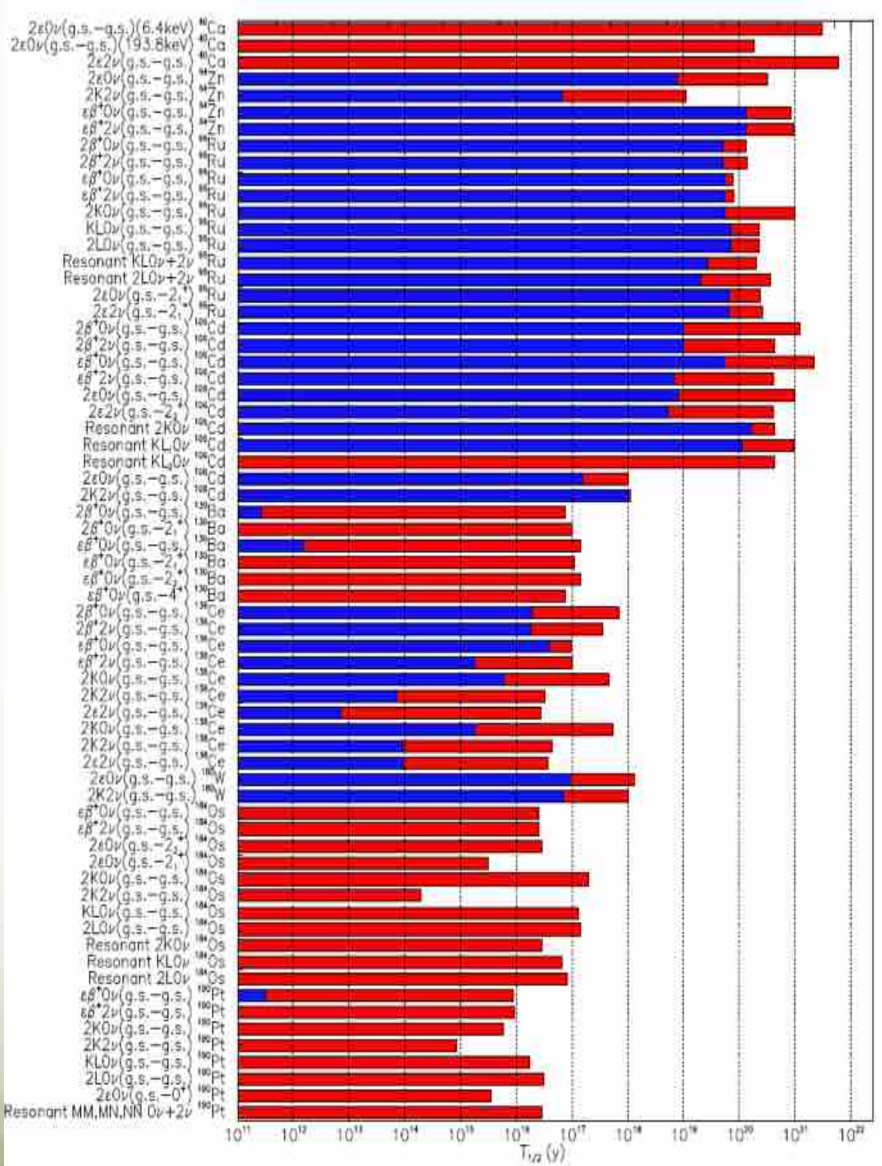
$2\beta^-$	$2\beta^+/\varepsilon\beta^+/2\varepsilon$
35 candidates	34 candidates
Nat. abundances δ ~ (5-10-100)%	Typical δ < 1% with few exclusions
$Q_{2\beta}$ up to 4.3 MeV	$Q_{2\beta}$ > 2 MeV only for 6 nuclides
$2\beta2\nu$ is registered for several nuclei as ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U with $T_{1/2} = 10^{18} – 10^{24}$ yr	$2\varepsilon2\nu$ - ^{130}Ba ? ($T_{1/2} \sim 10^{21}$ yr) - ^{78}Kr ? ($T_{1/2} \sim 10^{22}$ yr)
Sensitivity to $2\beta0\nu$ up to 10^{25} yr	Sensitivity to 0ν up to 10^{21} yr

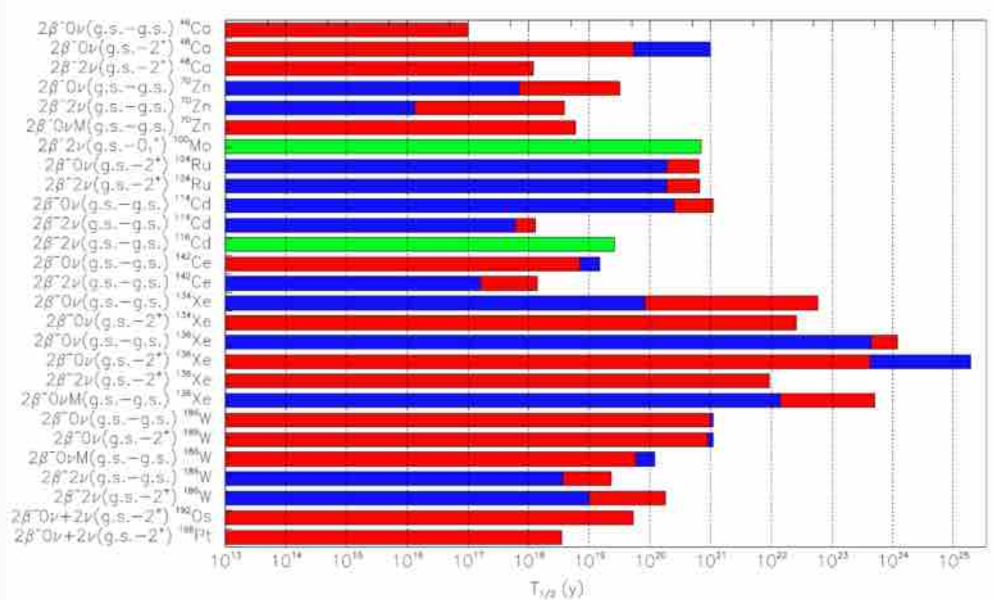
One positive claim on observation of $2\beta^-0\nu$ in ^{76}Ge by part of HM ($T_{1/2} = 2.2\times10^{25}$ yr), on the edge of current sensitivity of GERDA (2.1×10^{25} yr)

$2\beta^+/\varepsilon\beta^+/2\varepsilon$ studies are less popular but nevertheless:

- Information from $2\beta^+/\varepsilon\beta^+/2\varepsilon$ is supplementary to $2\beta^-$
- Possibility to refine mechanism of $0\nu2\beta^-$ decay (neutrino mass or right handed currents contribution). Enhancement of $0\nu\varepsilon\beta^+$ mode is expected for the right handed current mechanism of decay (M. Hirsch et al., ZPA 347 (1994) 151)
- Resonant $0\nu2\varepsilon$ transitions

Summary of searches for ββ decay modes (partial list)





$T_{1/2}$ experimental limits by DAMA (in red) and previous ones (in blue). All the limits are at 90% C.L. except for $0\nu2\beta^+$ in ^{136}Ce and $2\beta^-0\nu$ in ^{142}Ce at 68% C.L.. In green observed!

ARMONIA: New observation (green) 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
NPAE2012

- **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, …).**
- **The limits on $2\beta^-$ modes in ^{136}Xe are the presently best ones for this isotope**
- **First searches for resonant ββ decays in some isotopes**

Many publications on detectors developments and results
Many future measurements in preparation

Armonia

P. Belli et al., NPA846(2010)143

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

- Allowed 2β2ν decay to the g.s. of ^{100}Ru observed in several direct experiments, $T_{1/2}$ ~ **(3.3–11.5) × 10^{18} yr** (from NEMO-3 (7 kg of ^{100}Mo),

$$T_{1/2}(2\nu;\ g.s. - g.s.) = (7.1 \pm 0.5) \times 10^{18}\ yr$$

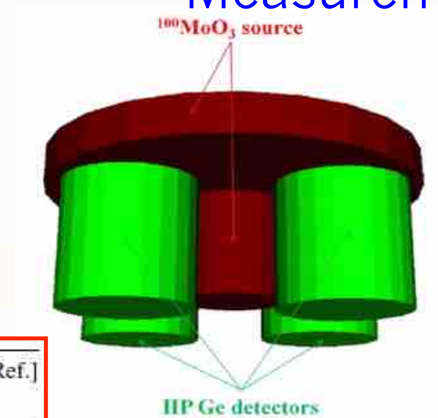
- 2β2ν decay of ^{100}Mo to the first excited **0^+_1 level of ^{100}Ru** registered in contradiction with an early measurement
- 1 kg of the Molybdenum used to set the limit was re-measured

Strategy

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

⇒ **two γ quanta** (591 keV + 540 keV) **emitted in cascade** in deexcitation

Measurement:



- Molybdenum sample (mass ≈ **1 kg** enriched in **^{100}Mo at 99.5%**) installed in **4 low-background HPGe** detectors (~225 cm^3 each one)
- Set-up enclosed in a lead and copper passive shielding and with a nitrogen ventilation system in order to avoid radon
- 2 Stage: 1) first meas.; 2) sample **purification performed and new meas. (14 times lower ^{40}K)**

$T_{1/2}$ measured in several experiments:	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

Armonia

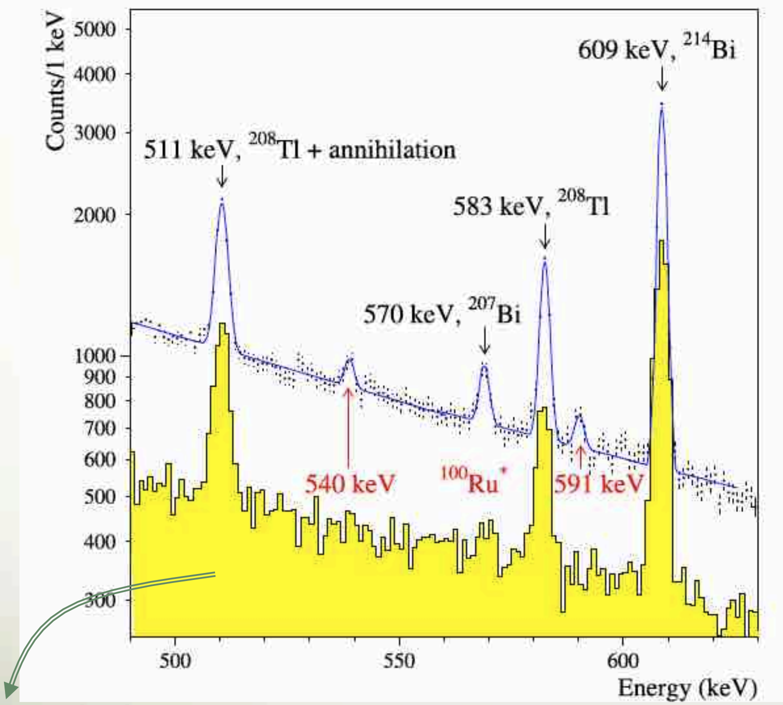
P. Belli et al., NPA846(2010)143

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

Molybdenum sample (mass ≈ **1 kg** enriched in **^{100}Mo at 99.5%**) installed in **4 low-background HPGe** detectors (~225 cm³ each one), T=18120 h

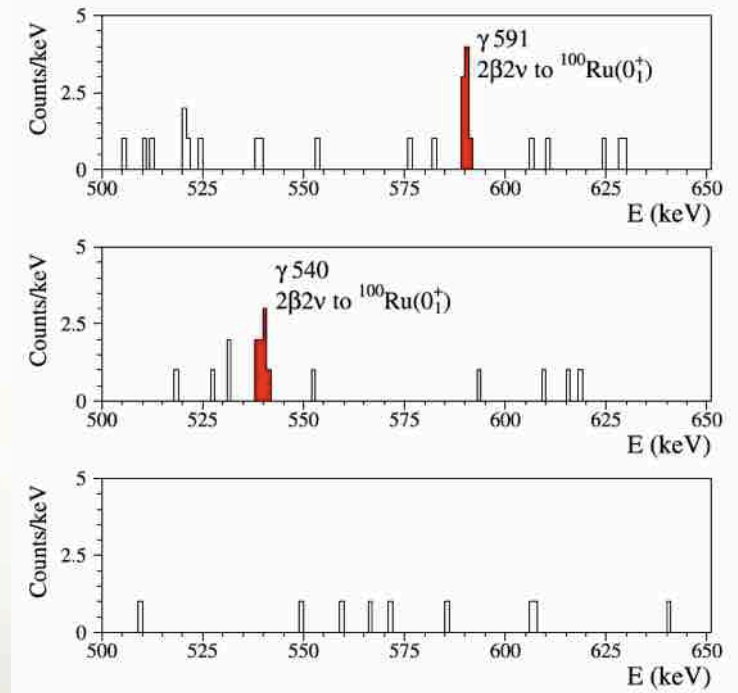
After sample purification

1-dim spectrum



normalized background

8 coincidence events in the coincidence spectrum between any two HP Ge



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

The observed ^{100}Mo →^{100}Ru* 2β2ν decay is in agreement with previous results, while the old limit $T_{1/2}$ >1.2 x 10^{21} yr is not confirmed

Search for double beta processes in ^{106}Cd with enriched $^{106}CdWO_4$ crystal scintillator in coincidence with four crystals HPGe detector

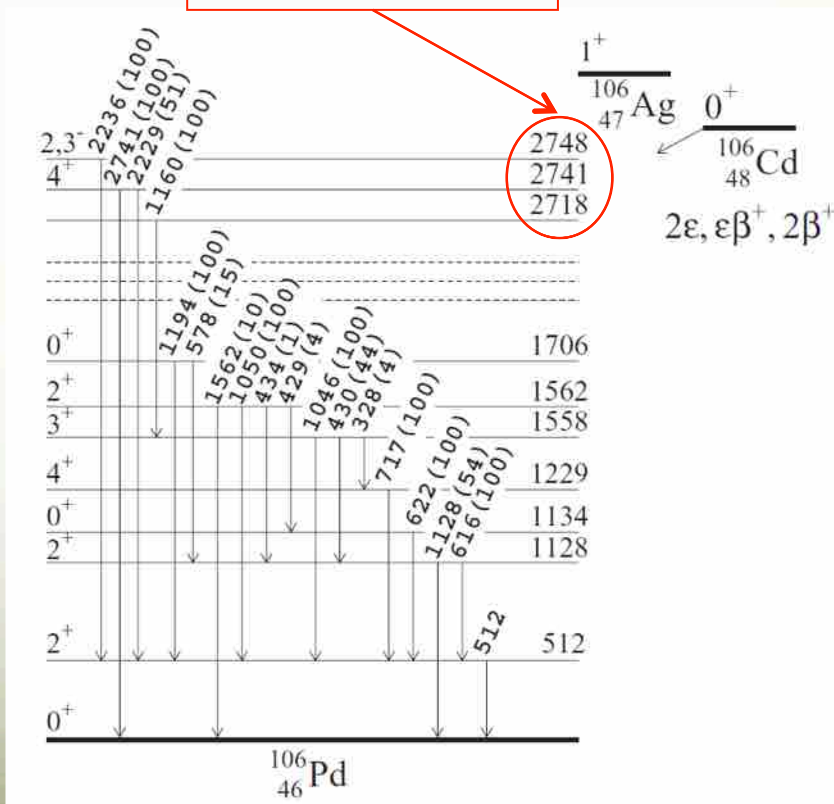
^{106}Cd is attractive because of:

(1) $Q_{2\beta}$ = 2775.39±0.10 keV – one of only six $2\beta^+$ nuclides
(2) Quite high natural abundance δ = 1.25%
(3) Possibility of resonant $2\varepsilon 0\nu$ captures to excited levels of daughter ^{106}Pd (2718 keV – $2K0\nu$, 2741 keV – $KL_1 0\nu$, 2748 keV – $KL_3 0\nu$)
(4) Theoretical $T_{1/2}$ are quite optimistic for some modes (g.s.→g.s.):

$2\varepsilon 2\nu$ · $(2.0\text{-}2.6)\times 10^{20}$ yr [1],
· 4.8×10^{21} yr [2],
$\varepsilon\beta^+ 2\nu$ · $(1.4\text{-}1.6)\times 10^{21}$ yr [1],
· 2.9×10^{22} yr [2]

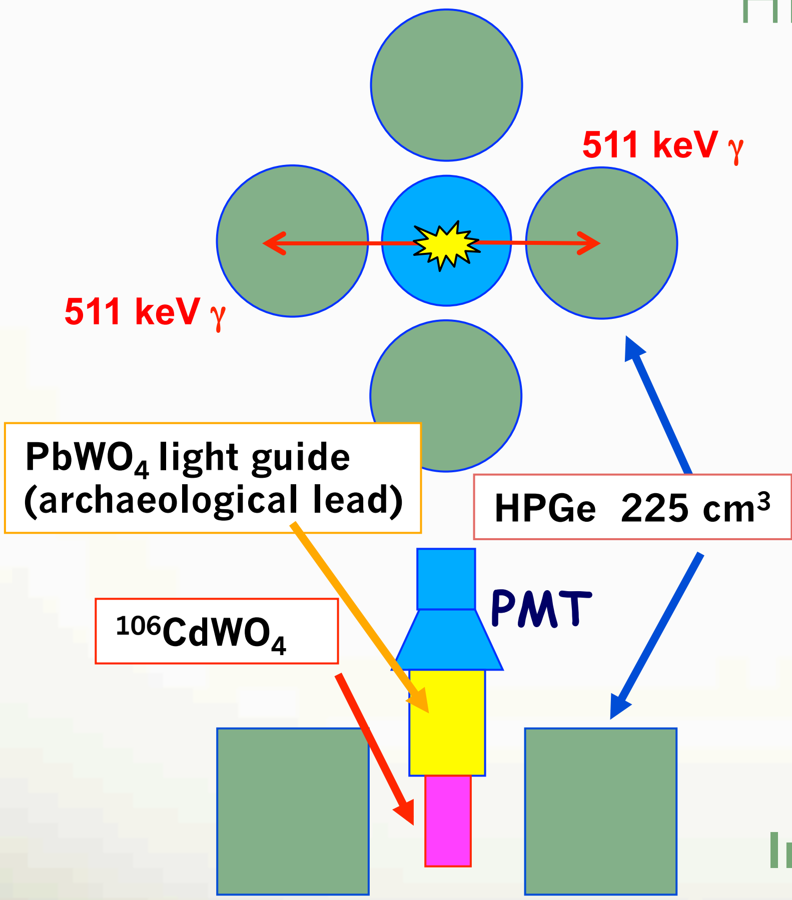
[1] S. Stoica et al., EPJA 17 (2003) 529
[2] J. Suhonen, PRC 86 (2012) 024301

resonant $2\varepsilon 0\nu$



Decay scheme of ^{106}Cd

Search for double beta processes in ^{106}Cd with enriched $^{106}CdWO_4$ crystal scintillator in coincidence with four crystals HPGe detector



- $^{106}CdWO_4$ in coincidence / anticoincidence with 4-crystals HPGe detector (GeMulti)
- Detection efficiency ~ (5–7)%
- External shield: radiopure Cu + Pb, sealed in PMMA air-tight box flushed by nitrogen
- Expected background ~ a few counts/yr

Sensitivity to 2ν εβ⁺ and 2β⁺ in ^{106}Cd:

$T_{1/2}$ ~ 10^{20} - 10^{21} yr

Theory: 2ν2K: 10^{20} - 5×10^{21} yr,

2νεβ⁺: 8×10^{20} - 4×10^{22} yr

In data taking since December 2012 up to 2015

Further step: production of $^{106}CdWO_4$ from the ^{106}Cd depleted in ^{113}Cd to remove ^{113m}Cd

Future and general perspectives:

increase mass, running time, enrichment, ... reasonable goal

$^{106}CdWO_4$ crystals

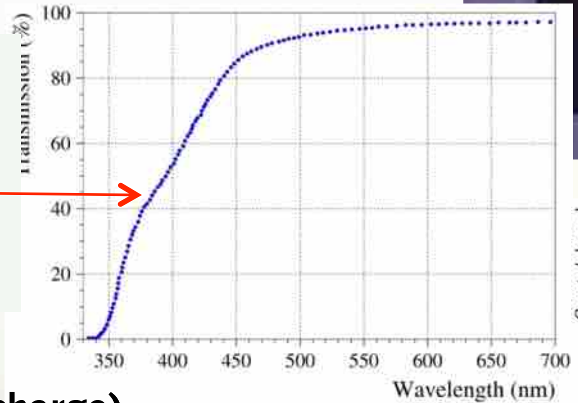
R&D for $^{106}CdWO_4$ Purification of ^{nat}Cd & ^{106}Cd by vacuum distillation (~ 0.1 ppm; Kharkiv Phys. Techn. Institute, Kharkiv, Ukraine); Synthesis of $CdWO_4$ & $^{106}CdWO_4$ powders; Growth of $^{nat}CdWO_4$ of improved quality (Czochralski method). [R. Bernabei et al., Metallofiz. Nov. Tekhn. 30 (2008) 477]

Growth of $^{106}CdWO_4$ crystals by Low-Thermal-Gradient Czochralski technique (Nikolaev Institute of Inorg. Chem., Novosibirsk, Russia): output ~90%, loss of powder <0.3%, better quality and radiopurity [P. Belli et al., NIMA 615 (2010) 301]

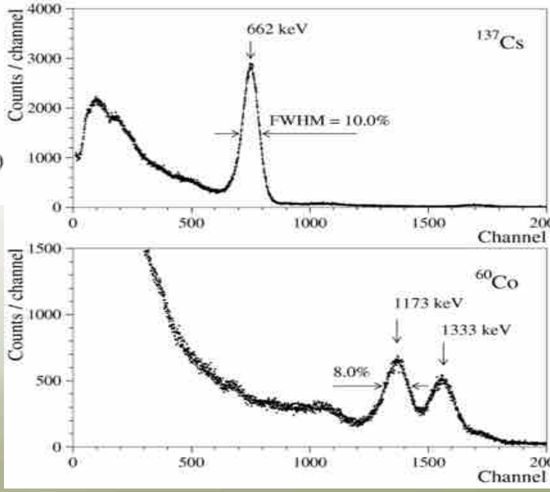
Example of $CdWO_4$ grown by the LTG Cz technique (20 kg) [V.V. Atuchin et al., J. Solid State Chem., in press]

$^{106}CdWO_4$ crystal scintillators (^{106}Cd enrichment – 66%)

Attenuation length 60 cm (the best reported for $CdWO_4$)



$^{106}CdWO_4$ boule 231 g (87.2% of initial charge)
Total irrecoverable losses of ^{106}Cd = 2.3%

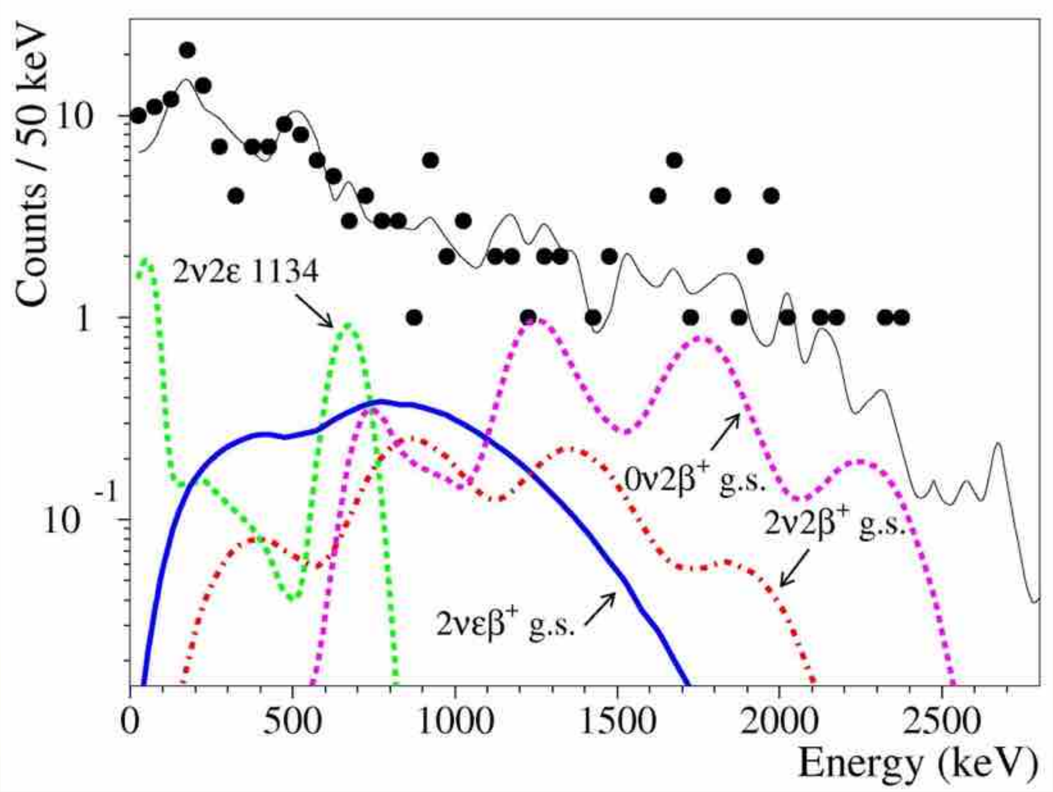


FWHM=10% at 662 keV

Excellent optical and scintillation properties thanks to special R&D to purify raw materials and Low-Thermal-Gradient Czochralski technique to grow the crystal [P. Belli et al., NIMA 615 (2010) 301]

$^{106}CdWO_4$ in coincidence with 511 keV in HPGe

F.A. Danevich , talk at MEDEX'15



Energy spectrum of the $^{106}CdWO_4$ detector accumulated over 13085 h in coincidence with 511 keV annihilation γ quanta at least in one of the HPGe detectors (circles).
The Monte Carlo simulated distributions for different modes of 2ν and 0ν 2ε, εβ$^+$ 2β$^+$ decays are shown.

Limits (preliminary) on 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes in ^{106}Cd

F.A. Danevich , talk at MEDEX'15

Decay, level of ^{106}Pd (keV)	$T_{1/2}$ (yr) at 90% C.L.	
	Present work	Previous limit
$2\nu2\varepsilon$, 0_1^+ 1134	$\geq 9.0\times10^{20}$ (AC)	$\geq 1.7\times10^{20}$ [1]
$0\nu2\varepsilon$, g.s.	$\geq 2.7\times10^{20}$ (AC)	$\geq 1.0\times10^{21}$ [1]
$2\nu\varepsilon\beta^+$, g.s.	$\geq 1.9\times10^{21}$ (CC 511)	$\geq 4.1\times10^{20}$ [2]
$2\nu\varepsilon\beta^+$, 0_1^+ 1134	$\geq 1.4\times10^{21}$ (CC 511)	$\geq 3.7\times10^{20}$ [1]
$0\nu\varepsilon\beta^+$, g.s.	$\geq 1.6\times10^{21}$ (CC >50)	$\geq 2.2\times10^{21}$ [1]
$2\nu2\beta^+$, g.s.	$\geq 5.5\times10^{21}$ (CC 511)	$\geq 4.3\times10^{20}$ [1]
$0\nu2\beta^+$, g.s.	$\geq 2.2\times10^{21}$ (CC 511)	$\geq 1.2\times10^{21}$ [1]
$0\nu2K$, 2718	$\geq 8.3\times10^{20}$ (CC 511)	$\geq 4.3\times10^{20}$ [1]
$0\nu KL_1$, 4^+ 2741	$\geq 5.0\times10^{20}$ (HPGe)	$\geq 9.5\times10^{20}$ [1]
$0\nu KL_3$, $2,3^-$ 2748	$\geq 8.7\times10^{20}$ (HPGe)	$\geq 4.3\times10^{20}$ [1]

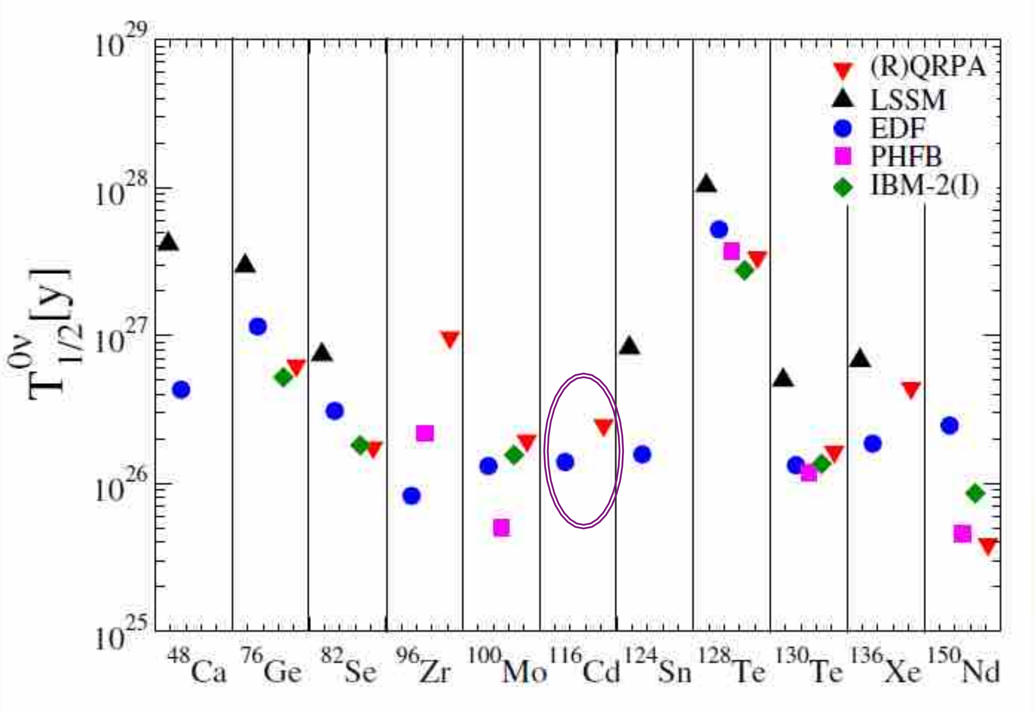
[1] P. Belli et al., PRC 85 (2012) 044610
[2] P. Belli et al., APP 10 (1999) 115

Also limits for 2β processes to other excited levels of ^{106}Pd (512, 1128, 1134, 1562, 1706, 2001, 2278 keV) were set on the level of $T_{1/2}\sim10^{19}$-10^{21} yr

2β physics with enriched $^{116}CdWO_4$ crystal scintillators

^{116}Cd – one of the best candidates to search for $2\beta0\nu$ decay:

- $Q_{2\beta}$ = 2813.5(13) keV
- δ = 7.5%
- promising theoretical calculation
- isotopic enrichment in large amount by cheap centrifugation method



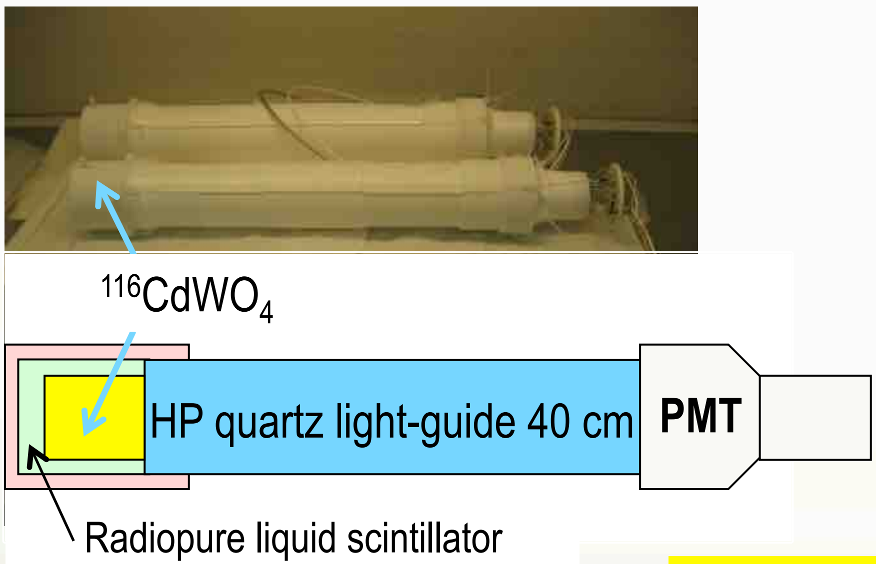
J.D. Vergados, H. Ejiri, F. Simkovic, RPP 75 (2012) 106301 – m_ν = 50 meV

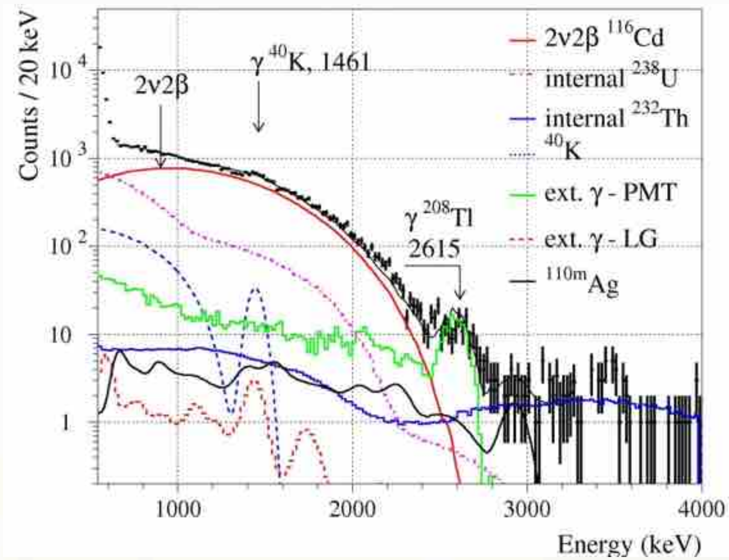
The most sensitive $2\beta0\nu$ experiments (90% C.L.):

- Solotvina, F.A. Danevich et al., PRC 68 (2003) 035501 – $T_{1/2} > 1.7e23$ yr
- NEMO-3, R.B. Pahlka et al., Phys. Proc. 37 (2012) 1241 – $T_{1/2} > 1.3e23$ yr

AURORA: Investigation of double β decay of ^{116}Cd

Experiment is running with two radiopure high quality $^{116}CdWO_4$ (1.176 kg) enriched in ^{116}Cd to 82%. After a few improvement of the set-up the FWHM (at $Q_{2\beta}$ of ^{116}Cd) = 5.2%, background in the ROI ≈ 0.1 cnt/(keV yr kg) (we have 17656 h of data with the background level).





Energy spectrum accumulated over 8397 h after the last upgrade of the detector. The two neutrino decay of ^{116}Cd with the half-life ≈2.6×10^{19} y dominates in the background

Our goals are to measure the $T_{1/2}^{2\nu 2\beta}$ with high (10-20%) accuracy and set new limits on different channels. Modes with majorons, transitions to the excited levels will be improved too. The experiment is in progress.

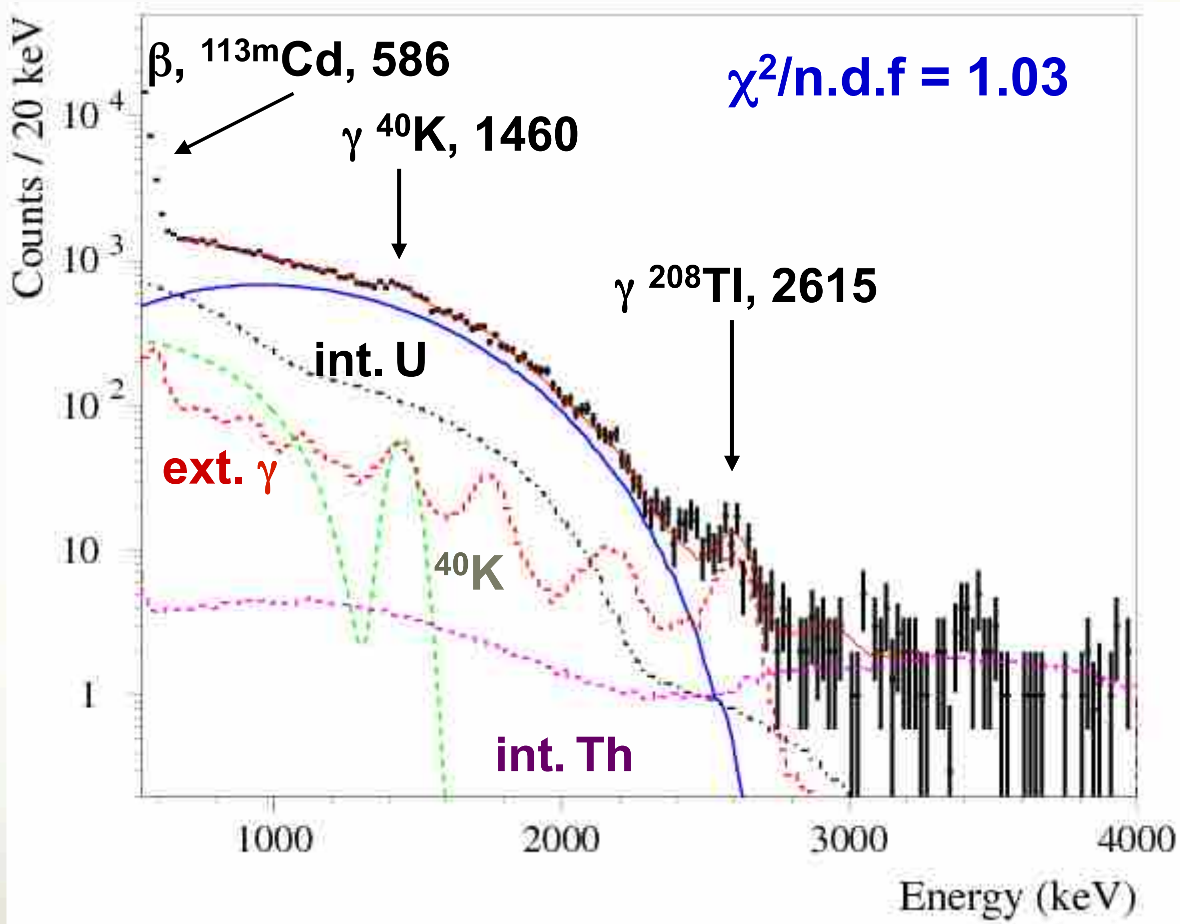
Preliminary results on EPJ Web of Conf 65 (2014) 01005

Two neutrino double beta decay of ^{116}Cd

O.G. Polischuk, talk at MEDEX'15

Simulations (EGS4 + DECAY0 generator):

$^{116}CdWO_4$ contaminations
PMT
Cu shield
...

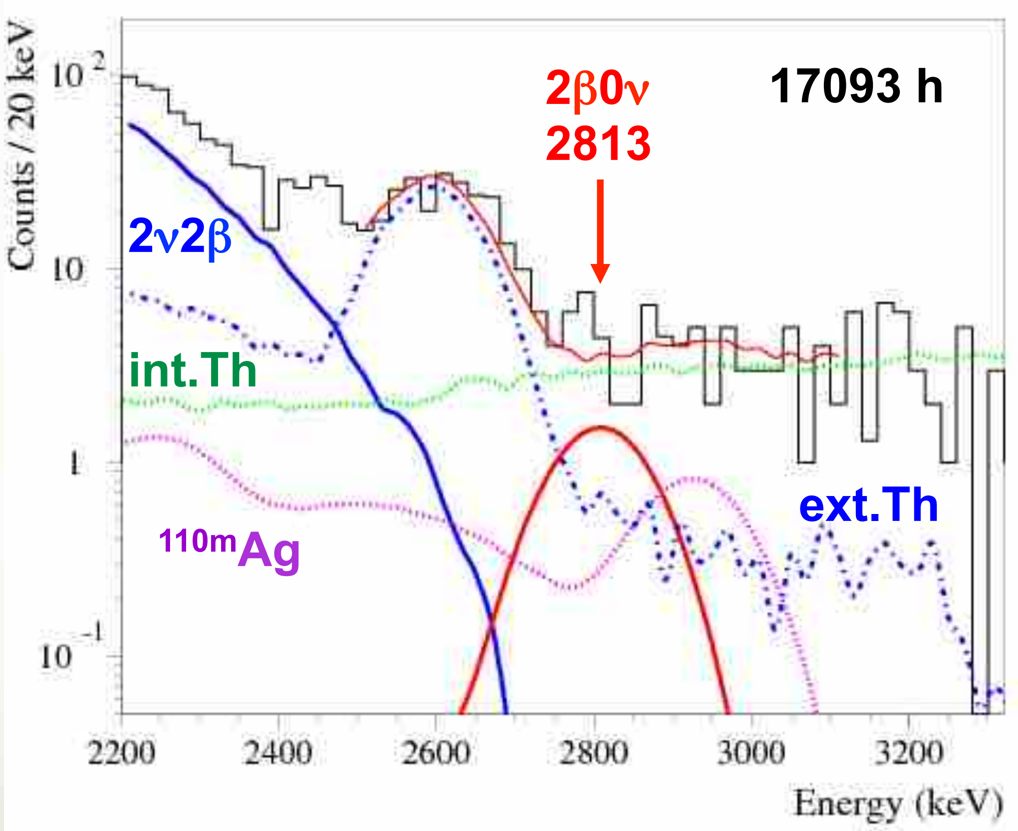


$T_{1/2}$ = [2.51 ± 0.02(stat.) ± 0.14(syst.)] × 10^{19} yr

S/B ratio = 2.6 in 1.1–2.8 MeV interval

Limit on $2\beta0\nu$ decay of ^{116}Cd to g.s. of ^{116}Sn

V. Tretyak at NDM 2015



Fit in 2.5–3.1 MeV χ^2/n.d.f.=1.13
S = 2.1 ± 6.8 counts
lim S = 13.3 counts 90% C.L. FC
$T_{1/2} > 1.6\times10^{23}$ yr

(Simple square root estimation: $T_{1/2} \geq 1.5 \times 10^{23}$ yr 90% C.L.)

On the level of Solotvina ($T_{1/2} > 1.7\times10^{23}$ yr) and NEMO-3 ($T_{1/2} > 1.6\times10^{23}$ yr) results

Effective Majorana neutrino mass:
$\langle m_\nu \rangle \sim 1.7$ eV J. Barea et al., PRL 109 (2012) 042501
$\langle m_\nu \rangle \sim 1.4 – 1.8$ eV J.D. Vergados et al., RPP 75 (2012) 106301

Results for ^{116}Cd 2β decay (preliminary, data taking is in progress)

V. Tretyak at NDM 2015

Decay mode	Transition	$T_{1/2}$, yr [present results]	$T_{1/2}$, yr [1]
0ν	g.s.- g.s.	$\geq 1.6\times10^{23}$	$\geq 1.7\times10^{23}$
0ν	g.s.- 2^+ (1294 keV)	$\geq 5.8\times10^{22}$	$\geq 2.9\times10^{22}$
0ν	g.s.- 0^+ (1757 keV)	$\geq 7.8\times10^{22}$	$\geq 1.4\times10^{22}$
0ν	g.s.- 0^+ (2027 keV)	$\geq 4.5\times10^{22}$	$\geq 0.6\times10^{22}$
0ν	g.s.- 2^+ (2112 keV)	$\geq 2.9\times10^{22}$	
0ν	g.s.- 2^+ (2225 keV)	$\geq 4.0\times10^{22}$	
0νM1	g.s.- g.s.	$\geq 0.2\times10^{22}$	$\geq 0.8\times10^{22}$
0νM2	g.s.- g.s.	$\geq 0.9\times10^{21}$	$\geq 0.8\times10^{21}$
0νbM	g.s.- g.s.	$\geq 0.8\times10^{21}$	$\geq 1.7\times10^{21}$
2ν	g.s.- g.s.	$[2.51\pm0.14(syst.)\pm0.02(stat.)]\times10^{19}$	$2.9^{+0.4}_{-0.3}\times10^{19}$
2ν	g.s.- 2^+ (1294 keV)	$\geq 0.5\times10^{21}$	$\geq 2.3\times10^{21}$ [2]
2ν	g.s.- 0^+ (1757 keV)	$\geq 1.1\times10^{21}$	$\geq 2.0\times10^{21}$ [2]
2ν	g.s.- 0^+ (2027 keV)	$\geq 0.9\times10^{21}$	$\geq 2.0\times10^{21}$ [2]
2ν	g.s.- 2^+ (2112 keV)	$\geq 1.7\times10^{21}$	
2ν	g.s.- 2^+ (2225 keV)	$\geq 1.6\times10^{21}$	

[1] F.A. Danevich et al., PRC 68 (2003) 035501 [2] A. Piepke et al., NPA 577 (1994) 493

Possibility to improve the radiopurity of $^{116}CdWO_4$ by re-crystallization

V. Tretyak at NDM 2015

Beginning of the crystal

Activity of ^{228}Th

10(2)

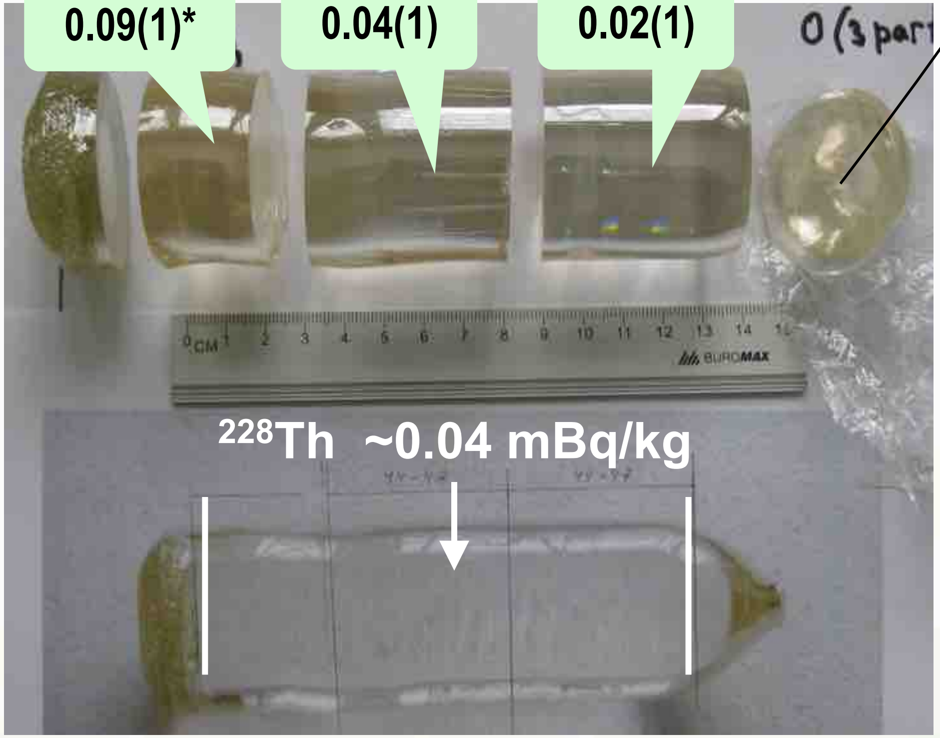
0.09(1)*

0.04(1)

0.02(1)

rest of the melt after the crystal growth

Nuclide	Crystal	Rest of melt
^{40}K	<1	27(11)
^{226}Ra	<0.005	64(4)
^{228}Th	0.02 - 0.09	10(2)



^{228}Th in the initial $^{116}CdWO_4$ powder ~1.4 mBq/kg

Thorium expected to be reduced by a factor ~35 → 1 μBq/kg

We expect to reduce K, Th, U and Ra contamination by recrystallization

⇒ reduction of the background by a factor 4

⇒ advancing the 2β0ν sensitivity to ~ 5×10^{23} yr

Other double beta decay searches

- Search for 2β decays of ^{96}Ru and ^{104}Ru by ultra-low background HP Ge γ spectrometry **EPJA42(2009)171 PRC87(2013) 034607**
- Investigation of rare nuclear decays with BaF_2 crystal scintillator contaminated by radium **EPJ A 50 (2014) 134**

  Analysis of Bi-Po events (half-life of ^{212}Po; search for 2β decay of ^{212}Pb); search for β and 2β decay of ^{222}Rn; search for 2β decay of ^{226}Ra

- Search for 2β decay of ^{136}Ce and ^{138}Ce **NPA930(2014)195**

  Deeply purified CeO_2 sample (732 g) in HPGe (STELLA facility), T=1900 h
- A new kind of scintillator detector: SrI_2(Eu) crystal scintillator. R&D in progress **NIMA670(2012) 10**
- Purification of Ce, Nd and Gd for low bckg experiments

  Liquid-liquid extraction technique to purify CeO_3, Nd_2O_3 and Gd_2O_3 from U/Th
- Study of 2β decay of ^{150}Nd to the excited states of ^{150}Sm

  A deeply purified Nd_2O_3 source (2.381 kg) was installed in GeMulti (4 HPGe ~220 cm^3 each) on 10 Feb 2015. **The experiment is in progress**

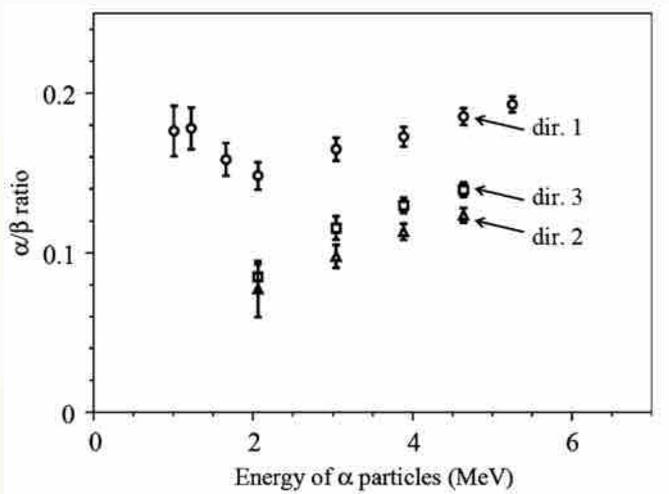
- First search for rare decays of Osmium by low background HPGe detector **EPJ A 49(2013)24**
- $ZnWO_4$ crystal scintillators (low bckg and large volume): double beta decay modes in Zn and W isotopes **PLB658(2008)193, NPA826(2009)256, NIMA626-627(2011)31, JPG: NPP 38(2011)115107**
- Search for long-lived superheavy eka-tungsten with radiopure $ZnWO_4$ crystal scintillator **Phys. Sc. 90 (2015) 085301**

The ADAMO project: Study of the directionality approach for DM with $ZnWO_4$ anisotropic detectors

EPJ C73 (2013) 2276

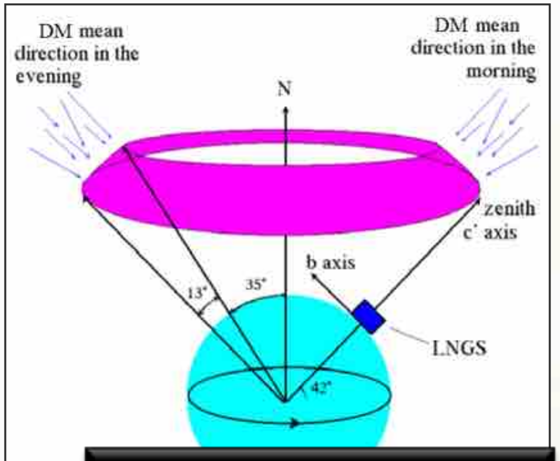
- Only for candidates inducing just recoils
- Identification of the Dark Matter particles by exploiting the non-isotropic recoil distribution correlated to the Earth velocity

The ADAMO project: Study of the directionality approach with $ZnWO_4$ anisotropic detectors



Nuclear recoils are expected to be strongly correlated with the DM impinging direction

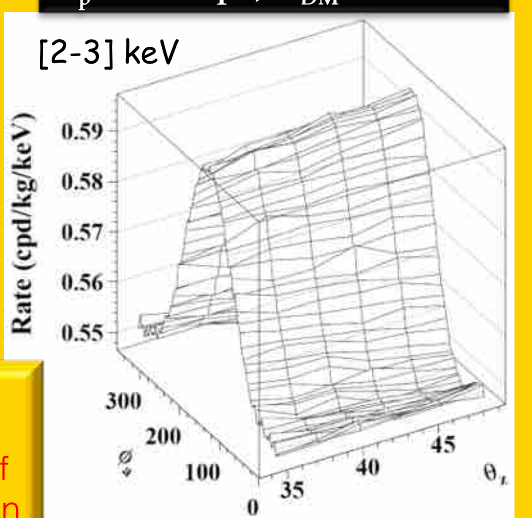
This effect can be pointed out through the study of the variation in the response of anisotropic scintillation detectors during sidereal day



The light output and the pulse shape of $ZnWO_4$ detectors depend on the direction of the impinging particles with respect to the crystal axes

Both these anisotropic features can provide two independent ways to exploit the directionality approach

$\sigma_p = 5\times10^{-5}$ pb, m_{DM}= 50 GeV



Example (for a given model framework) of the expected counting rate as a function of the detector velocity direction

These and others competitive characteristics of $ZnWO_4$ detectors could permit to reach sensitivity comparable with that of the DAMA/LIBRA positive result

Conclusions

- Continue efforts to develop new/improved crystal scintillators for low background physics
- Potentiality of the low background scintillation technique for the search of rare processes proved
- Many rare processes investigated with high sensitivity in DAMA/R&D and STELLA as e.g.:
  - ✓ Sensitivity for $2\beta^+$ decay at level of 10^{21} yr
  - ✓ First observation of rare α decay of ^{190}Pt, ^{151}Eu
  - ✓ Improvement foreseen
- Experiments on 2β decay of ^{106}Cd and ^{116}Cd running/under-improvement
- Other new measurements in preparation and/or foreseen (Gd, Nd, Ru, SrI, etc.)
- Other rare processes investigated also by DAMA/LIBRA and future long dedicated measurements for special topics foreseen
- DAMA/LXe running and the activity of DAMA/CRYS in progress
- Other rare processes studies in DAMA and not discussed here:
  - Cluster decays of ^{23}Na, ^{127}I and La isotopes;
  - Spontaneous transition of nuclei to a superdense state
  - N, NN, NNN decays
  - CNC electron decay in $\nu_e\gamma$
  - Solar axions
  - ...