Searches for neutrinoless resonant 2ε captures at LNGS

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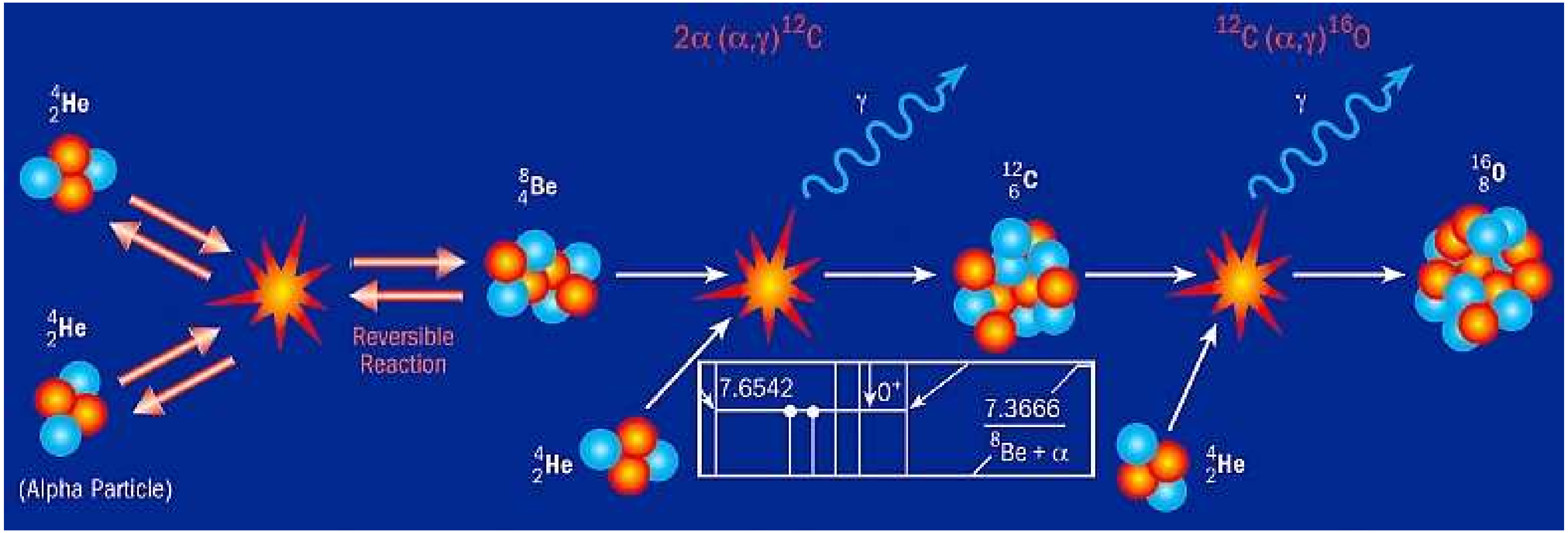
There are no stable nuclei with A=5 (and 8). Triple-α reaction plays a critical role for nucleosynthesis of heavier elements:

$\alpha + \alpha \rightarrow {}^{8}Be\ (10^{-16}\ s)$ ${}^{8}Be + \alpha \rightarrow {}^{12}C$ …

However, cross-section of ${}^{8}Be + \alpha$ reaction is not big enough to explain abundances quantitatively. In 1953, F. Hoyle supposed [1] that ${}^{12}C$ should have excited level at 7.68 MeV, and this results in resonant enhancement of the cross-section by orders of magnitude. It was searched for and observed by experimentalists at 7.68+-0.03 MeV [2].



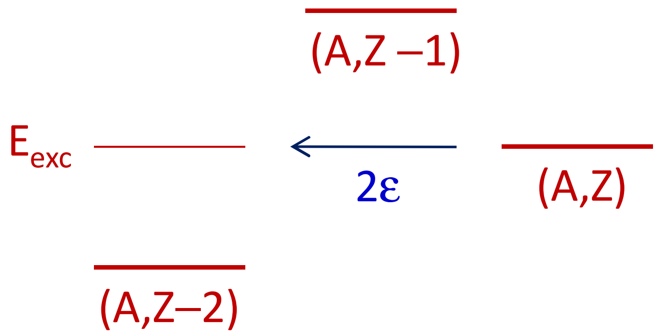
http://www.scidacreview.org/1002/html/adlb.html

It seems, all of us exist because of resonant enhancement of this nuclear reaction.

1. F. Hoyle, Astrophys. J. Suppl. 1 (1954) 121.
2. D.N.F. Dunbar et al., Phys. Rev. 92 (1953) 649.

Resonant enhancement is expected also for $2\varepsilon0\nu$ capture in case of mass degeneracy of the initial and final (excited) nuclei:

$Q_{2\beta} - E_{b1} - E_{b2} = E_{exc}$ $(Q_{2\beta} = \Delta M_a)$



Theory (main papers):

M.B. Voloshin, G.V. Mitsel'makher, R.A. Eramzhyan, JETP Lett. 35 (1982) 656
J. Bernabéu, A. De Rujula, C. Jarlskog, Nucl. Phys. B 223 (1983) 15
Z. Sujkowski, S. Wycech, Phys. Rev. C 70 (2004) 052501
M.I. Krivoruchenko et al., Nucl. Phys. A 859 (2011) 140
J. Suhonen, PLB 701 (2011) 490

In case of almost exact degeneracy, $2\varepsilon0\nu$ capture could be competitive to $2\beta^{-}0\nu$ decay in sensitivity to m_{ν}

Below, summary of our searches for resonant $2\varepsilon0\nu$ captures of different nuclides (mainly during the last 2 years) will be given.

^{106}Cd – P. Belli et al., Astropart. Phys. 10 (1999) 115

Cd 154 g (enriched in ^{106}Cd to 68%; $^{nat}\delta$=1.25%) + 2 NaI(Tl) 10×10×10 cm in coincidence, 4321 h

^{106}Cd: $Q_{2\beta}$=2771±8 keV, $2\varepsilon+\varepsilon\beta^{+}+2\beta^{+}$ r-$2\varepsilon0\nu$ is possible (also, 1 of 6 $2\beta^{+}$ decayers)

$E_b(K)$=24.4, $E_b(L_1)$=3.6
$Q(KL_1)$=2743±8 → E_{exc}=2741 – $1^{+},2^{+}$: $T_{1/2} > 3.0\times10^{19}$

(I use here old values of $Q_{2\beta}$ and J^{π})

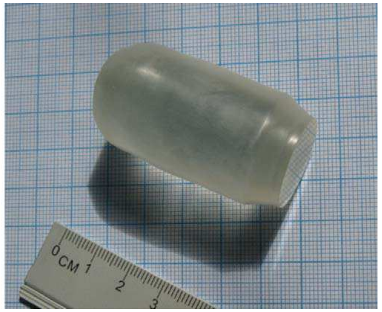
To my knowledge, it was the first experimental limit for r-$2\varepsilon0\nu$ process

Limits for other possible 2β processes in ^{106}Cd: $T_{1/2} > 4.9\times10^{19}$–$4.1\times10^{20}$ yr
(1–2 orders of magnitude higher than those known before).

and decay channels. We note, in particular, that in the case of neutrinoless EC/EC mode (K- and L-electrons capture) the energy release $Q = (2743 \pm 8)$ keV is practically equal – within the errors – to the energy of ^{106}Pd excited level $1,2^{+}$ (2741.0 keV) [14]. If this level and the ground state of ^{106}Cd would be degenerated, some resonant effects could enhance the probability of this transition.

^{106}Cd – P. Belli et al., submitted

$^{106}CdWO_4$ scintillating crystal was developed, 216 g, 66.4% enrichment in ^{106}Cd, FWHM=10.0% at 662 keV [P. Belli et al., Nucl. Instrum. Meth. A 615 (2010) 301]



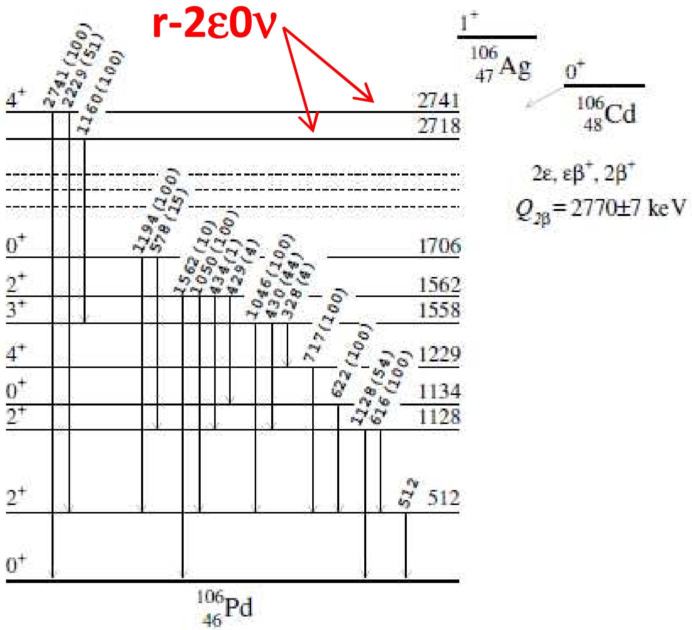
6590 h data taking

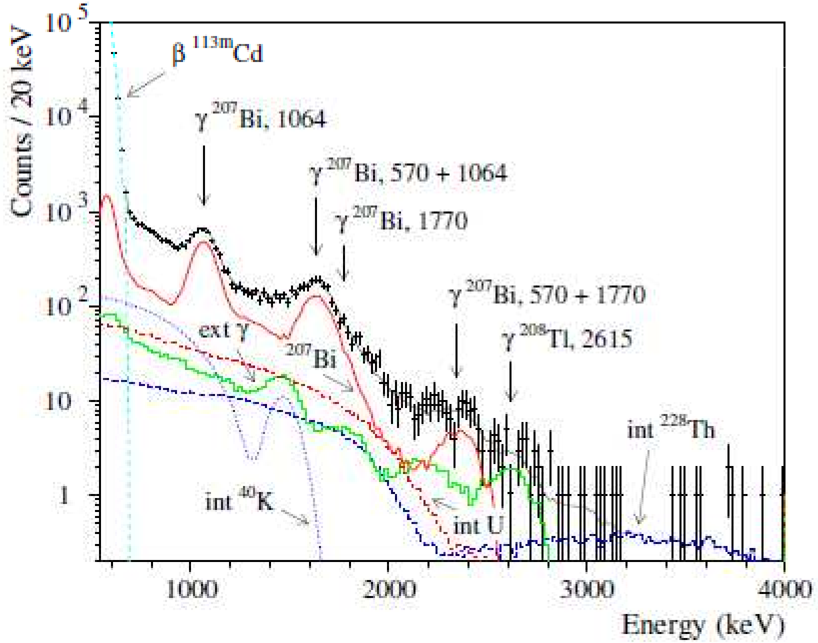
See more details in talk of F.A. Danevich today

$Q_{2\beta}=2770\pm7$, $E_b(K)=24.4$, $E_b(L_1)=3.6$

$Q(KL_1)=2742\pm7 \rightarrow E_{exc}=2741 – 4^+$: $T_{1/2} > 9.6\times10^{20}$

$Q(2K)=2721\pm7 \rightarrow E_{exc}=2718 – ?^?$: $T_{1/2} > 3.8\times10^{20}$





Limits for other possible 2β processes in ^{106}Cd: $T_{1/2}$ > ~10^{20}–10^{21} yr (mostly best today).

Pollution by ^{113m}Cd (116 Bq/kg) and some pollution by ^{207}Bi (probably surface).

New measurements of $Q_{2\beta}$ for ^{106}Cd: 2775.39±0.10 keV [M. Goncharov et al., PRC 84 (2011) 028501] instead of old 2770±7 keV [G. Audi et al., 2003]

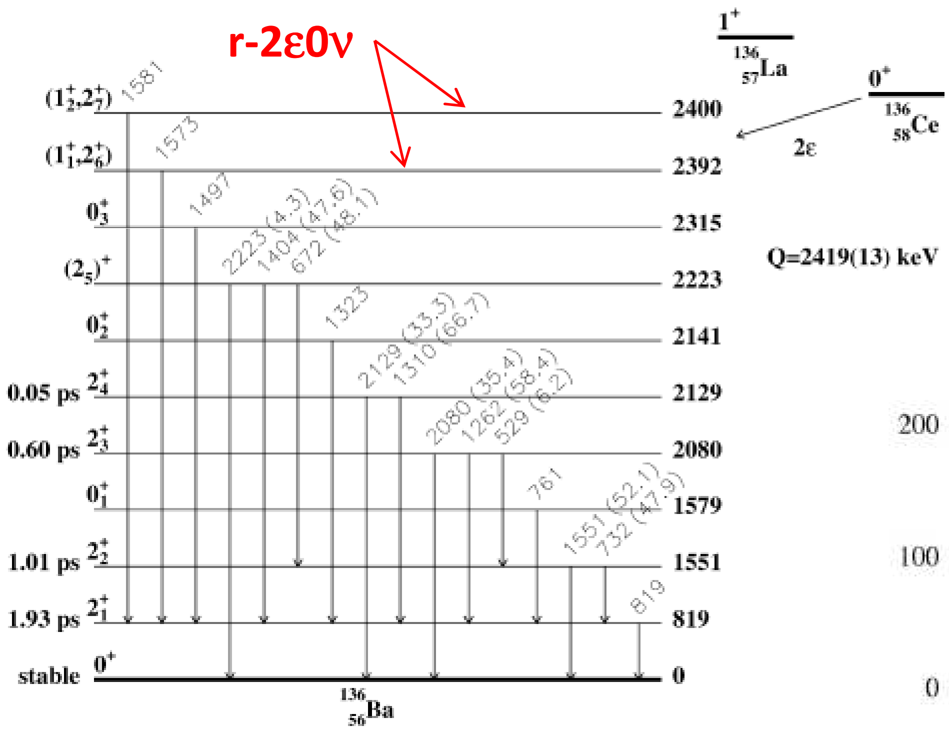
If so, r-2ε0ν to 2741 and 2718 keV levels are excluded, but still possibilities of r-2ε0ν for some other levels:
$Q(KL_3)$=2747.9±0.1 → E_{exc}=2748.2±0.4 – $2,3^-$ (J. Suhonen)
or for capture of external electrons → 2775.9±0.8 – (4^+) (but suppressed)

New stage of the experiment: combination of $^{106}CdWO_4$ + HP Ge 4×225 cm^3 – see details in talk of F.A. Danevich.

^{136}Ce – P. Belli et al., Nucl. Phys. A 824 (2009) 101

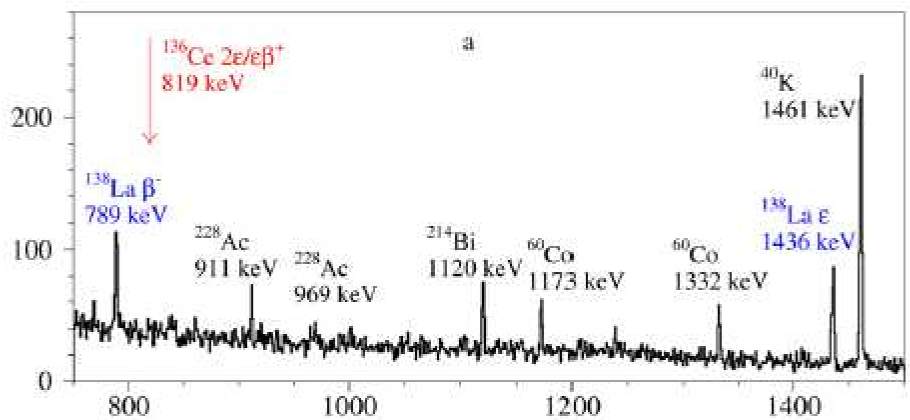
$CeCl_3$ crystal 6.9 g, HP Ge 244 cm^3, 1280 h

^{136}Ce: δ=0.185%, $Q_{2\beta}$=2419±13 keV, $2\varepsilon+\varepsilon\beta^++2\beta^+$ r-2ε0ν is possible (also, 1 of 6 $2\beta^+$ decayers)
^{138}Ce: δ=0.251%, $Q_{2\beta}$=693±10 keV, 2ε
^{142}Ce: δ=11.114%, $Q_{2\beta}$=1416.7±2.1 keV, $2\beta^-$



$E_b(L_1)$=6.0, $Q(2L_1)$=2407±13

E_{exc}=2392 – (1$^+$,2$^+$): $T_{1/2}$ > 2.4×10^{15}
E_{exc}=2400 – (1$^+$,2$^+$): $T_{1/2}$ > 4.1×10^{15}

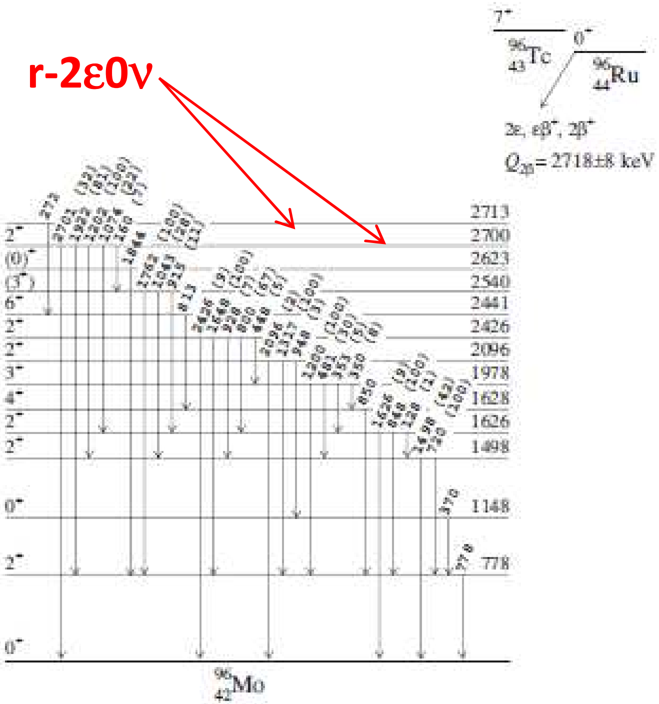


Limits for other possible 2β processes in ^{136}Ce and ^{138}Ce: $T_{1/2}$ > (1–6)×10^{15} yr.
The crystal is polluted by ^{138}La (0.68 Bq/kg) but not polluted by ^{40}K, ^{60}Co, ^{137}Cs, ^{232}Th.
However, new value $Q_{2\beta}$=2378.53±0.27 keV [V.S. Kolhinen et al., PLB 697 (2011) 116].

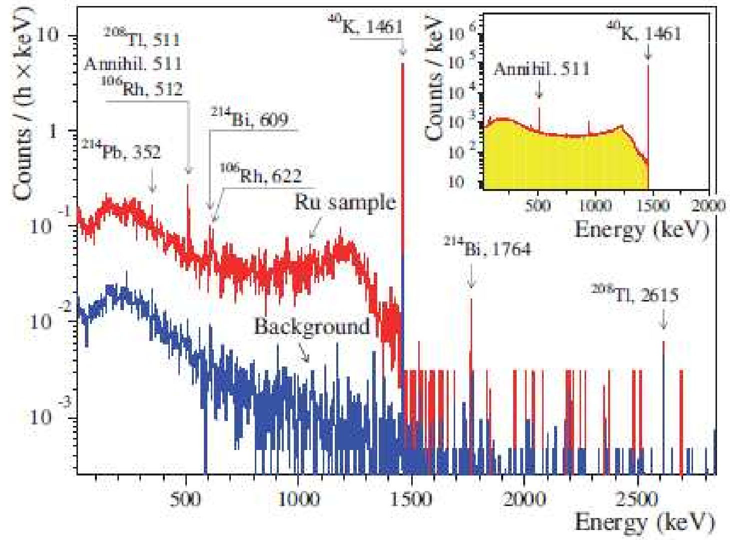
^{96}Ru – P. Belli et al., Eur. Phys. J. A 42 (2009) 171 and P. Belli et al., Proc. NPAE-Kyiv2010, Kyiv, 2011, p. 437

Ru 473 g, 99.99% purity grade, HP Ge 468 cm^3, (158 + 828) h + 4 HP Ge 225 cm^3, 1176 h

^{96}Ru: δ=5.54%, $Q_{2\beta}$=2718±8 keV, $2\varepsilon+\varepsilon\beta^++2\beta^+$ r-2ε0ν is possible (also, 1 of 6 $2\beta^+$ decayers)
^{104}Ru: δ=18.62%, $Q_{2\beta}$=1301±4 keV, $2\beta^-$



$E_b(K)$=20.0, $E_b(L_1)$=2.9
$Q(KL_1)$=2695±8 → E_{exc}=2700 – 2⁺: $T_{1/2}$ > 2.2×10^{19}
$Q(2L_1)$=2712±8 → E_{exc}=2713 – ?$^?$: $T_{1/2}$ > 5.1×10^{19}



Limits for other possible 2β processes in ^{96}Ru and ^{104}Ru: $T_{1/2}$ > 2.5×10^{18}–3.5×10^{19} yr (2–3 orders of magnitude higher than those known from E.B. Norman, PRC 31 (1985) 1937).
Pollution by ^{40}K at 3.4 Bq/kg.

New measurements of $Q_{2\beta}$ for ^{96}Ru: 2714.51$\pm$0.13 keV [S. Eliseev et al., PRC 83 (2011) 038501] instead of old 2718$\pm$8 keV [G. Audi et al., 2003]

If so, still some hope for r-2ε0ν to level of 2713 keV in case of capture of external electrons (which decreases probability of the process)

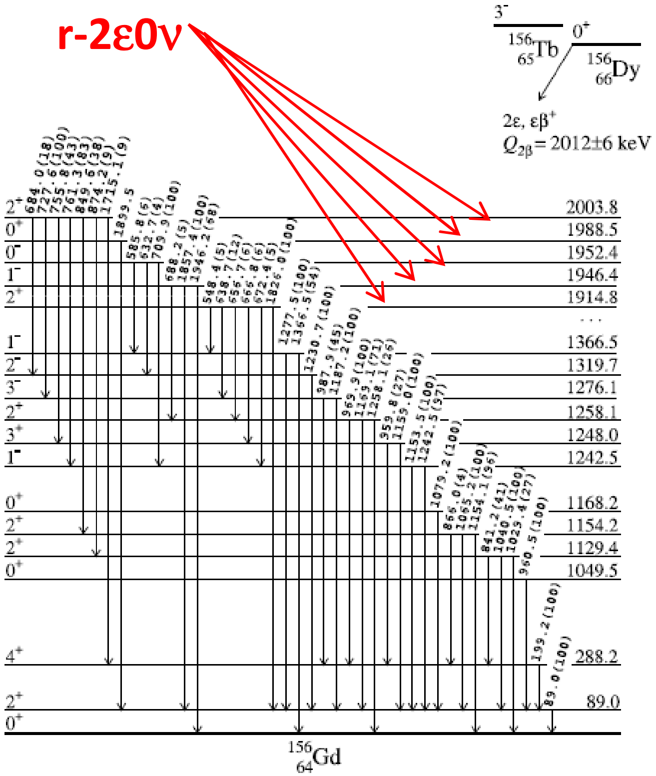
Sample of Ru near 1 kg is purified (KIPT, ^{40}K activity lower ~9 times), and new measurements are planned

^{156}Dy, ^{158}Dy – P. Belli et al., Nucl. Phys. A 859 (2011) 126

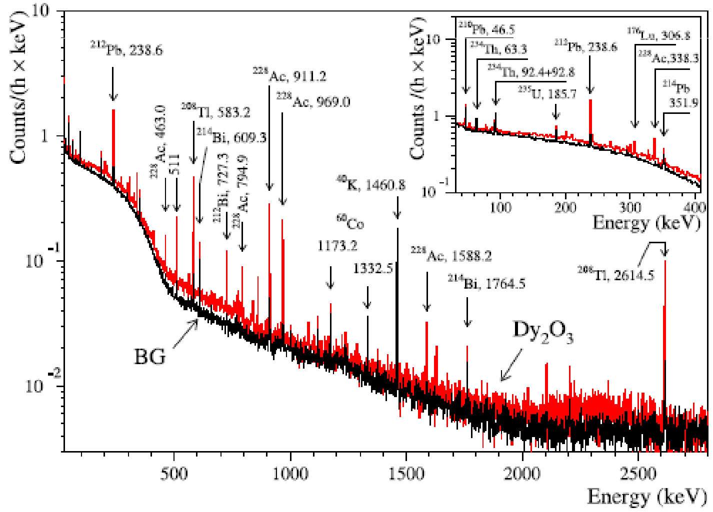
Dy_2O_3 322 g, 99.98% purity grade, HP Ge 244 cm^3, 2512 h

^{156}Dy: δ=0.056%, $Q_{2\beta}$=2012±6 keV, $2\varepsilon+\varepsilon\beta^+$ — r-2ε0ν is possible
^{158}Dy: δ=0.095%, $Q_{2\beta}$=284.6±2.5 keV, 2ε — r-2ε0ν is possible

First search for 2β in Dy



$E_b(K)$=50.2, $E_b(L_1)$=8.4
Few levels could be populated in r-2ε0ν, f.e.:
Q(2K)=1912±6 → E_{exc}=1915 – 2^+: $T_{1/2}$ > 1.1×10^{16}
Q(KL_1)=1954±6 → E_{exc}=1952 – 0^-: $T_{1/2}$ > 2.6×10^{16}



Limits for other possible 2β processes in ^{156}Dy and ^{158}Dy: $T_{1/2}$ > 1.8×10^{14}–7.1×10^{16} yr.
Slight pollution by U/Th and ^{176}Lu (9 mBq/kg).
By product: limits for α decays of $^{156,158,160,161,162}Dy$ to $^{152,154,156,157,158}Gd^*$: $T_{1/2}$ > 10^{16}–10^{17} yr.
New $Q_{2\beta}$ for ^{156}Dy: 2005.95±0.10 keV [S. Eliseev et al., PRC 84 (2011) 012501].

^{190}Pt – P. Belli et al., Eur. Phys. J. A 47 (2011) 91

Pt 42.5 g, HP Ge 468 cm^3, 1815 h

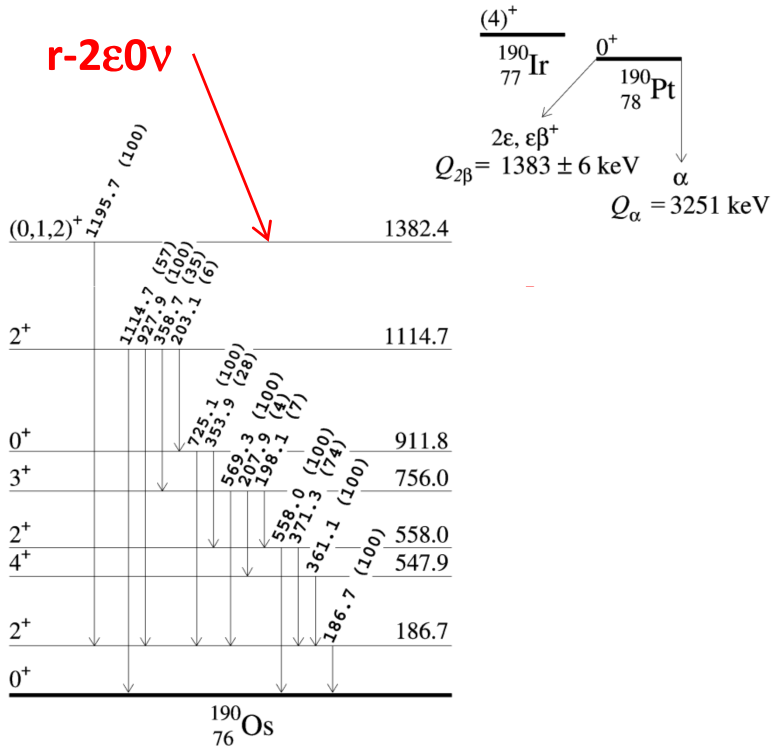
^{190}Pt: δ=0.014%, $Q_{2\beta}$=1383±6 keV, 2ε+$\varepsilon\beta^+$ **r-$2\varepsilon0\nu$ is possible**

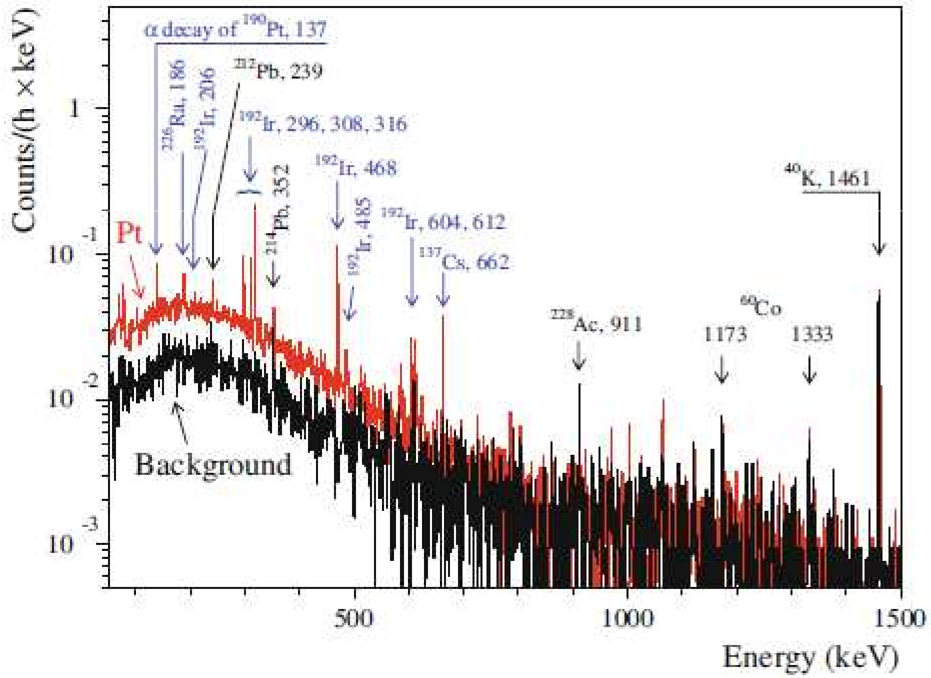
^{198}Pt: δ=7.163%, $Q_{2\beta}$=1047±3 keV, $2\beta^-$

$E_b(M_{1-5})$=3.0–2.0, $E_b(N_{1-7})$=0.65–0.05

E_{exc}=1382 – (0,1,2)$^+$: $T_{1/2}$ > 2.9×10^{16}

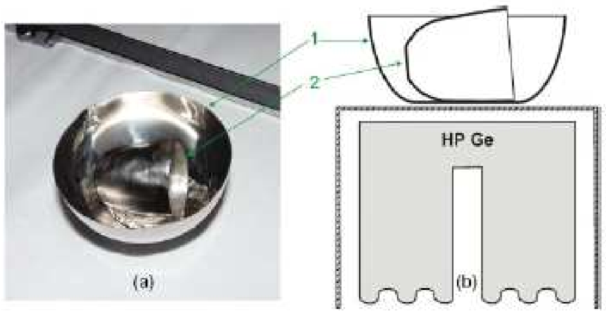
r-$2\varepsilon0\nu$

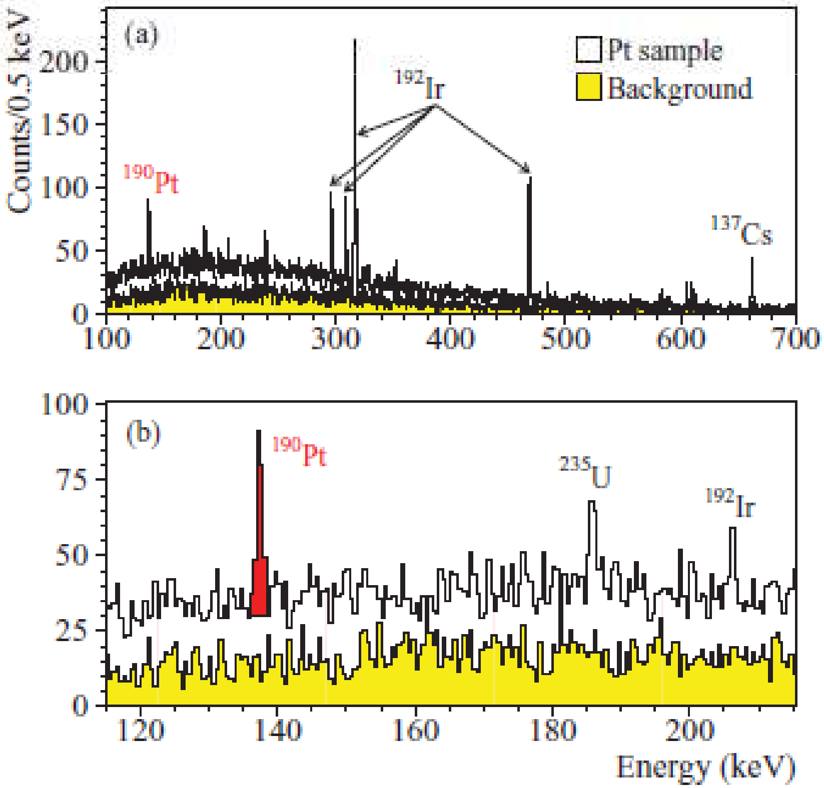




Limits for other possible 2β transitions in ^{190}Pt: $T_{1/2}$ > 8.4×10^{14} – 3.1×10^{16} yr, ^{198}Pt: $T_{1/2}$ > 3.5×10^{18} yr (earlier limits are absent or very poor, ~10^{11} yr from old photoemulsion exp.). The Pt is polluted by ^{192m}Ir (40 mBq/kg) and ^{137}Cs (7 mBq/kg), but not polluted by ^{40}K, ^{60}Co, U/Th (important for growth of crystals in Pt crucibles).

Interesting by-product of the Pt measurements:
First observation of α decay of ^{190}Pt to the first excited level (E_{exc}=137.2 keV) of ^{186}Os
– P. Belli et al., Phys. Rev. C 83 (2011) 034603

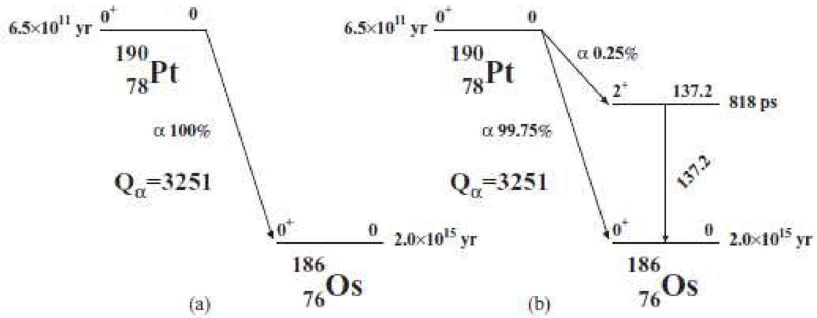




^{190}Pt $\rightarrow$ ^{186}Os* (E_{exc}=137.2 keV):
S = 132$\pm$17 counts
$T_{1/2}$ = $2.6^{+0.4}_{-0.3}$(stat.)$\pm$0.6(syst.)$\times 10^{14}$ yr

Alternative mimicking processes were not found.
Reasonable agreement with theoretical expectations: (3.2–7.0)$\times 10^{13}$ yr.

Old and new schemes of ^{190}Pt α decay:

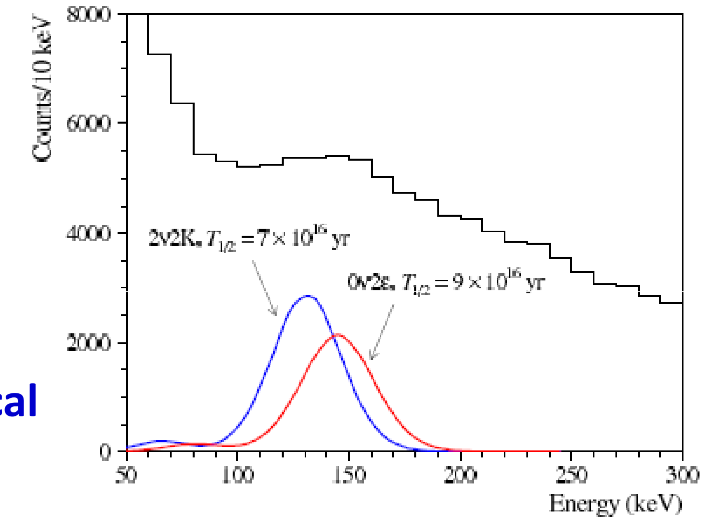


^{180}W – P. Belli et al., submitted

$ZnWO_4$ crystal scintillators , up to 699 g, near 19,000 h

^{180}W: δ=0.12%, $Q_{2\beta}$=144±4 keV, 2ε **r-2ε0ν is possible to g.s.**
E_b(K)=65.4, Q(2K)=13±4 → g.s. – 0^+: **$T_{1/2} > 1.3\times10^{18}$**

Transition	Energy release ($Q_{\beta\beta}$), keV [25]	Isotopic abundance (%) [26]	Decay channels	Number of mother nuclei in 100 g of $ZnWO_4$ crystal
^{64}Zn → ^{64}Ni	1095.7(0.7)	49.17(75)	2ε, εβ^+	9.45×10^{22}
^{70}Zn → ^{70}Ge	998.5(2.2)	0.61(10)	2β^-	1.17×10^{21}
^{180}W → ^{180}Hf	144(4)	0.12(1)	2ε	2.31×10^{20}
^{186}W → ^{186}Os	489.9(1.4)	28.43(19)	2β^-	5.47×10^{22}



$ZnWO_4$ is excellent crystal scintillator with good optical properties and low radioactive contamination.

See also:
P. Belli et al., PLB 658 (2008) 193; NPA 825 (2009) 256; NIMA 626 (2011) 31

Limits for possible 2β transitions in ^{64}Zn, ^{70}Zn, ^{180}W, ^{186}W : $T_{1/2} > 1.0\times10^{18} – 1.0\times10^{21}$ yr
(better than previous the ones up to 2 orders of magnitude).
Rare α decay of ^{180}W was once more observed ($T_{1/2}$ = 1.3±0.5×10^{18} yr).

^{184}Os – under measurements now

Os 172.5 g, purity grade >99.999% (purified in Kharkiv Institute of Physics and Technology; probably the most pure Os in the world), HP Ge 468 cm^3

^{184}Os: δ=0.02%, $Q_{2\beta}$=1451.2$\pm$1.0 keV, 2ε+$\varepsilon\beta^+$
^{192}Os: δ=40.78%, $Q_{2\beta}$=412.4$\pm$2.9 keV, 2β^-

Very poor to-date $T_{1/2}$ limits (10^{10}–10^{13} yr, extracted from old experiment with photoemulsions [J.H. Fremlin et al., Proc. Phys. Soc. A 65 (1952) 911])

Practically no excess in comparison with background; some presence of cosmogenic ^{185}Os ($T_{1/2}$=93.6 d) and ^{184}Re ($T_{1/2}$=38.0 d).

E_b(K)=69.5, $E_b(L_1)$=12.1

Q(2K)=1312.2$\pm$1.0 $\rightarrow$ E_{exc}=1322.2 – $(0)^+$
Q(KL_1)=1369.6$\pm$1.0 $\rightarrow$ E_{exc}=1360.4 – (4^+)
Q($2L_1$)=1427.0$\pm$1.0 $\rightarrow$ E_{exc}=1425.0 – $(3)^+$ & E_{exc}=1431.0 – 2^+

$Q_{2\beta}$(^{192}Os) = 413.5$\pm$3.0 [G. Audi et al., 1995]; 412.4$\pm$2.9 [2003]; 408.2$\pm$3.3 [2011]
$Q_{2\beta}$(^{102}Pd) = 1173.0$\pm$2.4 [G. Audi et al., 2003] but 1203.27$\pm$0.36 [M. Goncharov et al., PRC 84 (2011) 028501]
^{106}Pd level 2741 keV – J^π=$(1,2^+)$ [Tol, 1998] but 4^+ [NNDC, 6.09.2011]

Summary of results on resonant $2\varepsilon 0\nu$ captures

Transition	Level (keV) – J^{π}	$T_{1/2}$ (yr), 90% C.L.		Reference
$^{96}Ru \rightarrow ^{96}Mo$	2700 – 2^+	$> 2.2\times10^{19}$	HP Ge	EPJA 42 (2009) 171
	2713	$> 5.1\times10^{19}$		further measurements
$^{106}Cd \rightarrow ^{106}Pd$	2718	$> 3.8\times10^{20}$	NaI(Tl)	APP 10 (1999) 115
	2741 – 4^+	$> 9.6\times10^{20}$	$^{106}CdWO_4$	submitted
$^{136}Ce \rightarrow ^{136}Ba$	2392 – $(1^+,2^+)$	$> 2.4\times10^{15}$	HP Ge	NPA 824 (2009) 101
	2400 – $(1^+,2^+)$	$> 4.1\times10^{15}$		
$^{156}Dy \rightarrow ^{156}Gd$	1915 – 2^+	$> 1.1\times10^{16}$	HP Ge	NPA 859 (2011) 126
	1946 – 1^-	$> 9.6\times10^{15}$		
	1952 – 0^-	$> 2.6\times10^{16}$		
	1988 – 0^+	$> 1.9\times10^{16}$		
	2004 – 2^+	$> 3.0\times10^{14}$		
$^{158}Dy \rightarrow ^{158}Gd$	261 – 4^+	$> 3.2\times10^{16}$	HP Ge	NPA 859 (2011) 126
$^{180}W \rightarrow ^{180}Hf$	0 – 0^+	$> 1.3\times10^{18}$	$ZnWO_4$	submitted
$^{184}Os \rightarrow ^{184}W$			HP Ge	under measurements
$^{190}Pt \rightarrow ^{190}Os$	1382 – $(0,1,2)^+$	$> 2.9\times10^{16}$	HP Ge	EPJA 47 (2011) 91

Conclusions

1. **Resonant $2\varepsilon0\nu$ captures were in ^{96}Ru, ^{106}Cd, ^{136}Ce, ^{156,158}Dy, ^{180}W, ^{190}Pt were searched for with HP Ge spectrometry and with scintillating crystals $ZnWO_4$ and $^{106}CdWO_4$. Limits: $T_{1/2} > 3.0\times10^{14} - 9.6\times10^{20}$ yr**

2. **The obtained $T_{1/2}$ limits are mostly the best today, sometimes better than previous ones by few orders of magnitude, sometimes obtained at the first time. But they still are orders of magnitude worse than those predicted by theory. Excellent candidate for r-$2\varepsilon0\nu$ still not found**

3. **In searches for resonant $2\varepsilon0\nu$ captures, exact knowledge of $Q_{2\beta}$ values and J^{π} properties of excited levels is needed. There was progress recently for many 2β nuclei (^{74}Se, ^{96}Ru, ^{102}Pd, ^{106}Cd, ^{112}Sn, ^{120}Te, ^{128}Te, ^{130}Te, ^{136}Xe, ^{136}Ce, ^{144}Sm, ^{150}Nd and others) but we still need more exact information for other nuclei**

4. **Interesting by-products sometimes happen (like first observation of α decay $^{190}\text{Pt} \rightarrow {}^{186}\text{Os}^{*}$, $T_{1/2} = 2.6\times10^{14}$ yr)**