Searches for neutrinoless resonant $2\epsilon$ captures at LNGS
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There are no stable nuclei with A=5 (and 8). Triple-$\alpha$ reaction plays a critical role for nucleosynthesis of heavier elements:

$$\alpha + \alpha \rightarrow ^8\text{Be} \ (10^{-16} \text{ s}) \hspace{1cm} ^8\text{Be} + \alpha \rightarrow ^{12}\text{C} \hspace{1cm} \ldots$$

However, cross-section of $^8\text{Be} + \alpha$ reaction is not big enough to explain abundances quantitatively. In 1953, F. Hoyle supposed [1] that $^{12}\text{C}$ 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].

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

Resonant enhancement is expected also for $2\varepsilon 0\nu$ capture in case of mass degeneracy of the initial and final (excited) nuclei:

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

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

Below, summary of our searches for resonant $2\varepsilon 0\nu$ captures of different nuclides (mainly during the last 2 years) will be given.

Cd 154 g (enriched in 106Cd to 68%; natδ=1.25%) + 2 NaI(Tl) 10×10×10 cm in coincidence, 4321 h

106Cd: Q_{2β}=2771±8 keV, 2ε+εβ+2β⁺  r-2ε0ν is possible  (also, 1 of 6 2β⁺ decayers)

E_b(K)=24.4, E_b(L₁)=3.6  
Q(KL₁)=2743±8 → E_{exc}=2741 – 1⁺,2⁺: T_{1/2} > 3.0×10^{19}  (I use here old values of Q_{2β}

To my knowledge, it was the first experimental limit for r-2ε0ν process

Limits for other possible 2β processes in 106Cd: T_{1/2} > 4.9×10^{19} – 4.1×10^{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 106Pd excited level \( 1.2^+ \) (2741.0 keV) [14]. If this level and the ground state of 106Cd would be degenerated, some resonant effects could enhance the probability of this transition.
$^{106}\text{Cd} - \text{P. Belli et al., submitted}$

$^{106}\text{CdWO}_4$ scintillating crystal was developed, 216 g, 66.4\% enrichment in $^{106}\text{Cd}$, 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

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

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

$Q(2K)=2721\pm7 \rightarrow E_{\text{exc}}=2718 - 7^?: T_{1/2} > 3.8\times10^{20}$

Limits for other possible $2\beta$ processes in $^{106}\text{Cd}$: $T_{1/2} > \sim10^{20} - 10^{21}$ yr (mostly best today).

Pollution by $^{113m}\text{Cd}$ (116 Bq/kg) and some pollution by $^{207}\text{Bi}$ (probably surface).
New measurements of $Q_{2\beta}$ for $^{106}$Cd: $2775.39 \pm 0.10$ keV [M. Goncharov et al., PRC 84 (2011) 028501] instead of old $2770 \pm 7$ keV [G. Audi et al., 2003]

If so, r-$2\varepsilon 0\nu$ to 2741 and 2718 keV levels are excluded, but still possibilities of r-$2\varepsilon 0\nu$ for some other levels:

$Q(KL_3)=2747.9 \pm 0.1 \rightarrow E_{\text{exc}}=2748.2 \pm 0.4 - 2,3^- \quad \text{(J. Suhonen)}$

or for capture of external electrons $\rightarrow 2775.9 \pm 0.8 -(4^+)$ (but suppressed)

New stage of the experiment: combination of $^{106}$CdWO$_4$ + HP Ge 4$\times$225 cm$^3$ – see details in talk of F.A. Danevich.
CeCl₃ crystal 6.9 g, HP Ge 244 cm³, 1280 h

\[ ^{136}\text{Ce}: \delta=0.185\%, \quad Q_{2\beta}=2419\pm13 \text{ keV}, \quad 2\epsilon+\epsilon\beta^++2\beta^+ \text{ r-2}\epsilon0\nu \text{ is possible (also, 1 of 6 2}\beta^+ \text{ decayers)} \]

\[ ^{138}\text{Ce}: \delta=0.251\%, \quad Q_{2\beta}=693\pm10 \text{ keV}, \quad 2\epsilon \]

\[ ^{142}\text{Ce}: \delta=11.114\%, \quad Q_{2\beta}=1416.7\pm2.1 \text{ keV}, \quad 2\beta^- \]

\[ E_b(L_1)=6.0, \quad Q(2L_1)=2407\pm13 \]

\[ E_{\text{exc}}=2392-(1^+,2^+): T_{1/2} > 2.4\times10^{15} \]

\[ E_{\text{exc}}=2400-(1^+,2^+): T_{1/2} > 4.1\times10^{15} \]

Limits for other possible 2β processes in \(^{136}\text{Ce}\) and \(^{138}\text{Ce}\): \(T_{1/2} > (1-6)\times10^{15}\) yr.

The crystal is polluted by \(^{138}\text{La}\) (0.68 Bq/kg) but not polluted by \(^{40}\text{K}, ^{60}\text{Co}, ^{137}\text{Cs}, ^{232}\text{Th}\).

However, new value \(Q_{2\beta}=2378.53\pm0.27 \text{ keV}\) [V.S. Kolhinen et al., PLB 697 (2011) 116].

Ru 473 g, 99.99% purity grade, HP Ge 468 cm³, (158 + 828) h + 4 HP Ge 225 cm³, 1176 h

96Ru: δ=5.54%, Q_{2β}=2718±8 keV, 2ε+εβ+2β⁺ r-2ε0ν is possible (also, 1 of 6 2β⁺ decayers)

104Ru: δ=18.62%, Q_{2β}=1301±4 keV, 2β⁻

E_b(K)=20.0, E_b(L₁)=2.9
Q(KL₁)=2695±8 → E_{exc}=2700 – 2⁺: T₁/₂ > 2.2×10¹⁹
Q(2L₁)=2712±8 → E_{exc}=2713 – ??: T₁/₂ > 5.1×10¹⁹

Limits for other possible 2β processes in 96Ru and 104Ru: T₁/₂ > 2.5×10¹⁸–3.5×10¹⁹ yr (2–3 orders of magnitude higher than those known from E.B. Norman, PRC 31 (1985) 1937).

Pollution by 40K at 3.4 Bq/kg.
New measurements of $Q_{2\beta}$ for $^{96}$Ru: $2714.51\pm0.13$ keV [S. Eliseev et al., PRC 83 (2011) 038501] instead of old $2718\pm8$ keV [G. Audi et al., 2003]

If so, still some hope for $r$-$2\varepsilon 0\nu$ 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
Dy$_2$O$_3$ 322 g, 99.98% purity grade, HP Ge 244 cm$^3$, 2512 h

$^{156}$Dy: $\delta=0.056\%$, $Q_{2\beta}=2012\pm6$ keV, $2\varepsilon+\varepsilon\beta^+$

$^{158}$Dy: $\delta=0.095\%$, $Q_{2\beta}=284.6\pm2.5$ keV, $2\varepsilon$

- $r$-$2\varepsilon0\nu$ is possible
- First search for $2\beta$ in Dy

$E_b(K)=50.2$, $E_b(L_{1})=8.4$

Few levels could be populated in $r$-$2\varepsilon0\nu$, f.e.:

- $Q(2K)=1912\pm6 \rightarrow E_{\text{exc}}=1915-2^+: T_{1/2} > 1.1\times10^{16}$
- $Q(KL_{1})=1954\pm6 \rightarrow E_{\text{exc}}=1952-0^-: T_{1/2} > 2.6\times10^{16}$

Limits for other possible $2\beta$ processes in $^{156}$Dy and $^{158}$Dy: $T_{1/2} > 1.8\times10^{14} - 7.1\times10^{16}$ yr.

Slight pollution by U/Th and $^{176}$Lu (9 mBq/kg).

**By product:** limits for $\alpha$ 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: $2005.95\pm0.10$ keV [S. Eliseev et al., PRC 84 (2011) 012501].
Pt 42.5 g, HP Ge 468 cm$^3$, 1815 h

$^{190}$Pt: $\delta=0.014\%$, $Q_{2\beta}=1383\pm6$ keV, $2\epsilon+\epsilon\beta^+$

$^{198}$Pt: $\delta=7.163\%$, $Q_{2\beta}=1047\pm3$ keV, $2\beta^-$

$r-2\epsilon0\nu$ is possible

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

$E_{\text{exc}}=1382-(0,1,2)^+: T_{1/2} > 2.9\times10^{16}$

Limits for other possible $2\beta$ transitions in $^{190}$Pt: $T_{1/2} > 8.4\times10^{14} - 3.1\times10^{16}$ yr, $^{198}$Pt: $T_{1/2} > 3.5\times10^{18}$ yr (earlier limits are absent or very poor, $\sim10^{11}$ 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 $\alpha$ decay of $^{190}\text{Pt}$ to the first excited level ($E_{\text{exc}}=137.2$ keV) of $^{186}\text{Os}$


$^{190}\text{Pt} \rightarrow ^{186}\text{Os}^*$ ($E_{\text{exc}}=137.2$ keV):
$S = 132\pm17$ counts
$T_{1/2} = 2.6^{+0.4}_{-0.3}\text{(stat.)}\pm0.6\text{(syst.)} \times 10^{14}$ 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 $^{190}\text{Pt} \alpha$ decay:
ZnWO₄ crystal scintillators, up to 699 g, near 19,000 h

\(^{180}\)W: \(\delta=0.12\%\), \(Q_{2\beta}=144\pm4\text{ keV}\), \(2\epsilon\) \(\rightarrow\) \(2\epsilon\) \(0\nu\) is possible to g.s.
\(E_b(K)=65.4\), \(Q(2K)=13\pm4\) → g.s. \(-0^+\): \(T_{1/2} > 1.3 \times 10^{18}\)

ZnWO₄ is excellent crystal scintillator with good optical properties and low radioactive contamination.

See also:
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Limits for possible \(2\beta\) transitions in \(^{64}\)Zn, \(^{70}\)Zn, \(^{180}\)W, \(^{186}\)W: \(T_{1/2} > 1.0 \times 10^{18} - 1.0 \times 10^{21}\) yr
(better than previous the ones up to 2 orders of magnitude).
Rare \(\alpha\) decay of \(^{180}\)W was once more observed \((T_{1/2} = 1.3\pm0.5 \times 10^{18}\) yr).
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 cm³

184Os: δ=0.02%, Q2β=1451.2±1.0 keV, 2ε+εβ⁺
192Os: δ=40.78%, Q2β=412.4±2.9 keV, 2β⁻

Very poor to-date T1/2 limits (10¹⁰–10¹³ 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 185Os (T1/2=93.6 d) and 184Re (T1/2=38.0 d).

E_b(K)=69.5, E_b(L₁)=12.1
Q(2K)=1312.2±1.0 → E_exc=1322.2 – (0)⁺
Q(KL₁)=1369.6±1.0 → E_exc=1360.4 – (4⁺)
Q(2L₁)=1427.0±1.0 → E_exc=1425.0 – (3)⁺ & E_exc=1431.0 – 2⁺

Q2β(192Os) = 413.5±3.0 [G. Audi et al., 1995]; 412.4±2.9 [2003]; 408.2±3.3 [2011]
Q2β(102Pd) = 1173.0±2.4 [G. Audi et al., 2003] but 1203.27±0.36 [M. Goncharov et al., PRC 84 (2011) 028501]
106Pd level 2741 keV – Jπ=(1,2⁺) [Tol, 1998] but 4⁺ [NNDC, 6.09.2011]
### Summary of results on resonant $2\epsilon 0\nu$ captures

<table>
<thead>
<tr>
<th>Transition</th>
<th>Level (keV) $- J^\pi$</th>
<th>$T_{1/2}$ (yr), 90% C.L.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{96}\text{Ru} \rightarrow ^{96}\text{Mo}$</td>
<td>$2700 - 2^+$ $\quad$ $2713$</td>
<td>$&gt; 2.2 \times 10^{19}$ $\quad$ $&gt; 5.1 \times 10^{19}$</td>
<td>HP Ge $\quad$ EPJA 42 (2009) 171 $\quad$ further measurements</td>
</tr>
<tr>
<td>$^{106}\text{Cd} \rightarrow ^{106}\text{Pd}$</td>
<td>$2718$ $\quad$ $2741 - 4^+$</td>
<td>$&gt; 3.8 \times 10^{20}$ $\quad$ $&gt; 9.6 \times 10^{20}$</td>
<td>NaI(Tl) $\quad$ $^{106}\text{CdWO}_4$ $\quad$ APP 10 (1999) 115 $\quad$ submitted</td>
</tr>
<tr>
<td>$^{136}\text{Ce} \rightarrow ^{136}\text{Ba}$</td>
<td>$2392 -(1^+,2^+)$ $\quad$ $2400 -(1^+,2^+)$</td>
<td>$&gt; 2.4 \times 10^{15}$ $\quad$ $&gt; 4.1 \times 10^{15}$</td>
<td>HP Ge $\quad$ NPA 824 (2009) 101</td>
</tr>
<tr>
<td>$^{156}\text{Dy} \rightarrow ^{156}\text{Gd}$</td>
<td>$1915 - 2^+$ $\quad$ $1946 - 1^-$ $\quad$ $1952 - 0^-$ $\quad$ $1988 - 0^+$ $\quad$ $2004 - 2^+$</td>
<td>$&gt; 1.1 \times 10^{16}$ $\quad$ $&gt; 9.6 \times 10^{15}$ $\quad$ $&gt; 2.6 \times 10^{16}$ $\quad$ $&gt; 1.9 \times 10^{16}$ $\quad$ $&gt; 3.0 \times 10^{14}$</td>
<td>HP Ge $\quad$ NPA 859 (2011) 126</td>
</tr>
<tr>
<td>$^{158}\text{Dy} \rightarrow ^{158}\text{Gd}$</td>
<td>$261 - 4^+$</td>
<td>$&gt; 3.2 \times 10^{16}$</td>
<td>HP Ge $\quad$ NPA 859 (2011) 126</td>
</tr>
<tr>
<td>$^{180}\text{W} \rightarrow ^{180}\text{Hf}$</td>
<td>$0 - 0^+$</td>
<td>$&gt; 1.3 \times 10^{18}$</td>
<td>ZnWO$_4$ $\quad$ submitted</td>
</tr>
<tr>
<td>$^{184}\text{Os} \rightarrow ^{184}\text{W}$</td>
<td></td>
<td></td>
<td>HP Ge $\quad$ under measurements</td>
</tr>
<tr>
<td>$^{190}\text{Pt} \rightarrow ^{190}\text{Os}$</td>
<td>$1382 -(0,1,2)^+$</td>
<td>$&gt; 2.9 \times 10^{16}$</td>
<td>HP Ge $\quad$ EPJA 47 (2011) 91</td>
</tr>
</tbody>
</table>
Conclusions

1. Resonant $2\epsilon0\nu$ captures were in $^{96}\text{Ru}$, $^{106}\text{Cd}$, $^{136}\text{Ce}$, $^{156,158}\text{Dy}$, $^{180}\text{W}$, $^{190}\text{Pt}$ were searched for with HP Ge spectrometry and with scintillating crystals ZnWO$_4$ and $^{106}\text{CdWO}_4$. Limits: $T_{1/2} > 3.0 \times 10^{14} - 9.6 \times 10^{20}$ 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 $r$-$2\epsilon0\nu$ still not found

3. In searches for resonant $2\epsilon0\nu$ captures, exact knowledge of $Q_{2\beta}$ values and $J^\pi$ properties of excited levels is needed. There was progress recently for many $2\beta$ nuclei ($^{74}\text{Se}$, $^{96}\text{Ru}$, $^{102}\text{Pd}$, $^{106}\text{Cd}$, $^{112}\text{Sn}$, $^{120}\text{Te}$, $^{128}\text{Te}$, $^{130}\text{Te}$, $^{136}\text{Xe}$, $^{136}\text{Ce}$, $^{144}\text{Sm}$, $^{150}\text{Nd}$ and others) but we still need more exact information for other nuclei

4. Interesting by-products sometimes happen (like first observation of $\alpha$ decay $^{190}\text{Pt} \rightarrow ^{186}\text{Os}^*$, $T_{1/2} = 2.6 \times 10^{14}$ yr)