DOUBLE BETA DECAY TO THE EXCITED STATES: REVIEW

A.S. BARABASH

ITEP, MOSCOW

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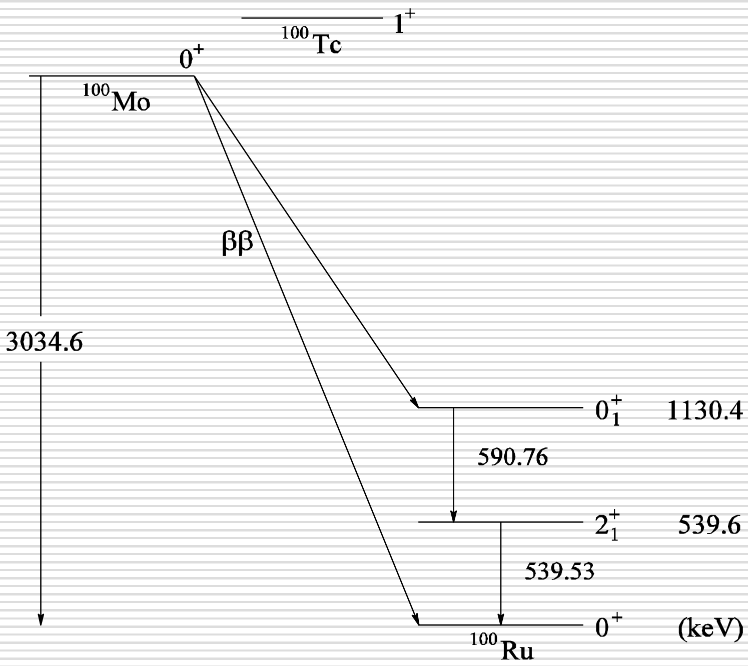
OUTLINE

- Introduction
- **$2\beta^-(2\nu)$** -decay to the excited ststates
- **$2\beta^-(0\nu)$** –decay to the excite states
- **ECEC** to the excited states
- Conclusion

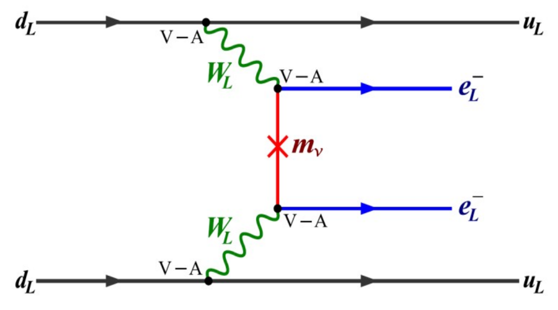
1. Introduction



^{100}Mo ⇒ ^{100}Ru + 2e-

^{100}Mo ⇒ ^{100}Ru + 2e- + χ0 (+χ0)

^{100}Mo ⇒ ^{100}Ru + 2e- + 2ν



There are 35 candidates for 2β-decay

W ~ Q^5 (0ν); W ~ Q^7 (0νχ^0)
W ~ Q^{11} (2ν)

1.1. Historical introduction

E. Fiorini (**1977, NEUTRINO'77**) – first time limit on **0^+-2^+** decay in Ge-76 was obtained (as by-product for 0^+-0^+ transition)*):

$T_{1/2}$ (0ν)> $3 \cdot 10^{21}$ y (68% C.L.)

*) Of course, from geochemical experiments one can extract limits too.

1982 – first special experimental work to investigate 2β-decay to the excited states has been done:
E. Bellotti et al., Lett. Nuov. Cim. 33 (1982) 273.

(^{58}Ni, ^{76}Ge, ^{92}Mo, ^{100}Mo, ^{148}Nd, ^{150}Nd;

Transitions to 2^+_1, 0^+_1, 2^+_2, … excited states)

Limits on the level **(1.2-3.2)·10^{21} y** for ^{76}Ge and **~ 10^{18}-10^{19} y** for other nuclei have been obtained.

1983-1988

- Many new results for **^{76}Ge (0^+-2^+).** And even “evidence” of the decay on 2.5σ level ($T_{1/2} \approx 10^{22}$ y) has been obtained.
- 3 experiments were done by **E. Norman** (^{50}Cr, ^{58}Ni, ^{64}Zn, ^{92}Mo, ^{94}Zr, ^{96}Zr, ^{96}Ru, ^{106}Cd, ^{116}Cd, ^{124}Sn; natural samples).

Limits on the level **~ 10^{17}-10^{19}** y have been obtained.

1989-1990

- It was demonstrated that **2β(2ν;0+-0^+_1)-decay** can be detected in **^{100}Mo**, **^{96}Zr** and **^{150}Nd** by existing low-background HPGe detectors and new experiments were proposed **(A.S.B. preprint ITEP, 188-89, 1989; JETP Lett. 51 (1990) 207).**
- ITEP-USC-PNL-UM experiment with **1 kg of ^{100}Mo** was started on 30 May 1990 (in Soudan mine).

Measurement was stopped in September’91

- First “positive” result was reported at a few International Conferences (Moriond’91, TAUP’91, WEIN’92,...)
- Final result was published in 1995

[PL B 345 (1995) 408]:

$$T_{1/2} = 6.1^{+1.8}_{-1.1} \cdot 10^{20}\ y$$

1999 – 2-nd positive result for ^{100}Mo (ITEP-BORDEAUX);

2001 – 3-d positive result for ^{100}Mo (**ITEP-TUNL)**;

2004 – 1-st positive result for ^{150}**Nd** **(ITEP-BORDEAUX)**;

2007 – 4-th positive result for ^{100}**Mo** (**NEMO-3**);

2010 - 5-th positive result for ^{100}**Mo** (**ARMONIA**)

2014 – 6-th positive result for ^{100}**Mo** (**NEMO-3 - OBELIX**);

2014 - 2-nd positive result for ^{150}**Nd** **(TUNL).**

2015-2016

EXO-200, KamLAND-Zen, GERDA-II:

Sensitivuity to excited states for ^{136}Xe and ^{76}Ge is ~ 10^{24}–10^{25} yr !!!

1.2. Present motivation

- **2ν**-decay:
  - nuclear spectroscopy;
  -NME problem;
  - g_A problem;
  - Checking of some “creasy” ideas (“bosonic” neutrino, ...)
- **0ν**-decay:
  - very nice signature (**2β-**);
  - distinguishing between the various **0νββ** mechanisms;
  - possible high sensitivity (**ECEC**; resonance conditions).

II. $2\beta^-(2\nu)$-decay to the excited states

Table 1. **2ν** transition to **2^+_1** excited state.

Nucleus	$E_{2\beta}$, keV	$T_{1/2}$, y Experiment	Theory, 2007 [1]	Theory, 2015 [2]
^{48}Ca	3279.4	$>1.8\cdot10^{20}$	$1.7\cdot10^{24}$	-
^{150}Nd	3037.4	$>2.2\cdot10^{20}$	-	$7.2\cdot10^{24}$ [3]
^{96}Zr	2577.6	$>7.9\cdot10^{19}$	$2.3\cdot10^{25}$	**$(1.1\text{-}1.4)\cdot10^{21}$ [4]**
^{100}Mo	2494.9	$>2.5\cdot10^{21}$	$1.2\cdot10^{25}$	**$2\cdot10^{22}$ - 10^{23}**

Table 1. (Continue)

^{82}Se	2221.4	$>1\cdot10^{22}$	$1.7\cdot10^{27}$	$(1.0\text{-}2.4)\cdot10^{24}$ [4]
^{130}Te	1991.7	$>2.8\cdot10^{21}$	$6.9\cdot10^{26}$	$(4.2\text{-}9.1)\cdot10^{23}$
^{136}Xe	1639.3	**$>4.6\cdot10^{23}$**	$3.9\cdot10^{26}$	$1.6\cdot10^{25}\text{-}\ 4.8\cdot10^{26}$
^{116}Cd	1519.9	$>2.3\cdot10^{21}$	$3.4\cdot10^{26}$	$(2.5\text{-}5.2)\cdot10^{24}$
^{76}Ge	1480	**$>1.6\cdot10^{23}$**	$5.8\cdot10^{28}$	$(2.4\text{-}4.3)\cdot10^{26}$ [4]
^{124}Sn	1689.9	$>9.1\cdot10^{20}$	-	$(5.3\text{-}6.4)\cdot10^{24}$

Table 2. 2ν-decay to 0^+_1 excited state

Nucleus	$E_{2\beta}$, keV	$T_{1/2}$, y Experiment	Theory [2]	Theory [5-7] (PSF prediction)
^{150}Nd	2630.9	$=1.2^{+0.3}_{-0.2}\cdot 10^{20}$	-	
^{96}Zr	2207.7	$>3.1\cdot 10^{20}$	$(2.4\text{-}2.7)\cdot 10^{21}$	$(2.7\text{-}3.8)\cdot 10^{21}$ ($\sim 10^{21}$)
^{100}Mo	1903.7	$=6.7^{+0.5}_{-0.4}\cdot 10^{20}$	$8.1\cdot 10^{21}$ - $4.1\cdot 10^{22}$	$2.1\cdot 10^{21}$ $1.6\cdot 10^{21}$ [8]
^{82}Se	1510.3	$>3.4\cdot 10^{22}$	-	$(1.5\text{-}3.3)\cdot 10^{21}$ ($\sim 4\cdot 10^{22}$)
^{48}Ca	1265.7	$>1.5\cdot 10^{20}$	-	-

Table 2. (Continue)

^{124}Sn	1131	$>1.1\cdot10^{21}$	-	-
^{116}Cd	1056.6	**$>2.0\cdot10^{21}$**	$(1.6\text{-}3.3)\cdot10^{24}$	$1.1\cdot10^{21}$ — $1.1\cdot10^{22}$ **($\sim 10^{23}$)**
^{76}Ge	916.7	**$>3.7\cdot10^{23}$**	-	$4.5\cdot10^{21}$ — $3.1\cdot10^{23}$ **($\sim 10^{24}$)**
^{136}Xe	878.8	**$>8.3\cdot10^{23}$**	$(1.3\text{-}8.9)\cdot10^{23}$	$2.5\cdot10^{21}$ — $6.3\cdot10^{21}$ **($\sim 10^{25}$)**
^{130}Te	734	**$>1.3\cdot10^{23}$**	$7.2\cdot10^{23}$ - $1.6\cdot10^{24}$	- **($\sim 2\cdot10^{25}$)**

References

[1] A.A. Raduta and C.M. Raduta, Phys. Lett. B 647 (2007) 265.

[2] P. Pirinen and J. Suhonen, Phys. Rev. C 91 (2015) 054309.

[3] J.G. Hirsch et al., Nucl. Phys. A 589 (1995) 445.

[4] J. Schwieger et al., Phys. Rev. C 57 (1998) 1738.

[5] M. Aunola and J. Suhonen, Nucl. Phys. A 602 (1996) 133.

[6] J. Toivanen and J. Suhonen, Phys. Rev. C 55 (1997) 2314.

[7] S. Stoica and I. Mihut, Nucl. Phys. A 602 (1996) 197.

[8] J.G. Hirsch et al., Phys. Rev. C 51 (1995) 2252.

Table 3. Present "positive" results on $2\beta(2\nu)$ decay of ^{100}Mo to the first 0^+ excited state of ^{100}Ru

$T_{1/2}$, y; x10^{20}	N	S/B	Year, method
$6.1^{+1.8}_{-1.1}$	133	~ 1/7	1995, HPGe [9]
$9.3^{+2.8}_{-1.7} \pm 1.4$	153	~ 1/4	1999, HPGe (many samples) [10]
$6.0^{+1.9}_{-1.1} \pm 0.6$	19.5	8	2001, 2xHPGe (coincidence) [11,12]
$5.7^{+1.3}_{-0.9} \pm 0.8$	37.5	3	2007, NEMO-3, ($2e+2\gamma$) [13]
$5.5^{+1.2}_{-0.8} \pm 0.3$	35.5	8	2009, 2xHPGe (coincidence) [14]
$6.9^{+1.0}_{-0.8} \pm 0.7$	597	~ 1/10	2010, HPGe [15]
$7.5 \pm 0.6 \pm 0.6$	239	2	HPGe, 2014 [16]

Average value: $6.7^{+0.5}_{-0.4} \cdot 10^{20}$ y

References

[9] A.S. Barabash et al., Phys. Lett. B 345 (1995) 408.

[10] A. S. Barabash et al., Phys. At. Nucl. 62 (1999) 2039.

[11] L. De Braeckeleer et al., Phys. Rev. Lett. 86 (2001) 3510.

[12] M.J. Hornish et al., Phys. Rev. C 74 (2006) 044314.

[13] R. Arnold et al., Nucl. Phys. A 781 (2007) 209.

[14] M.F. Kidd, et al., Nucl. Phys. A 821 (2009) 251.

[15] P. Belli, et al., Nucl. Phys. A 846 (2010) 143.

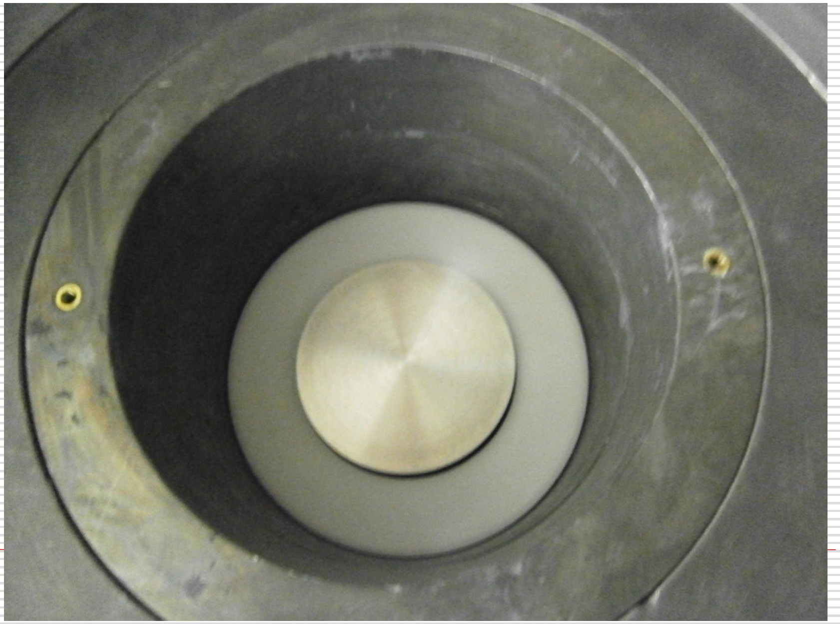
[16] R. Arnold, et al., Nucl. Phys. A 925 (2014) 25.

Double beta decay of ^{100}Mo to the excited states [NPA 925 (2014) 25]

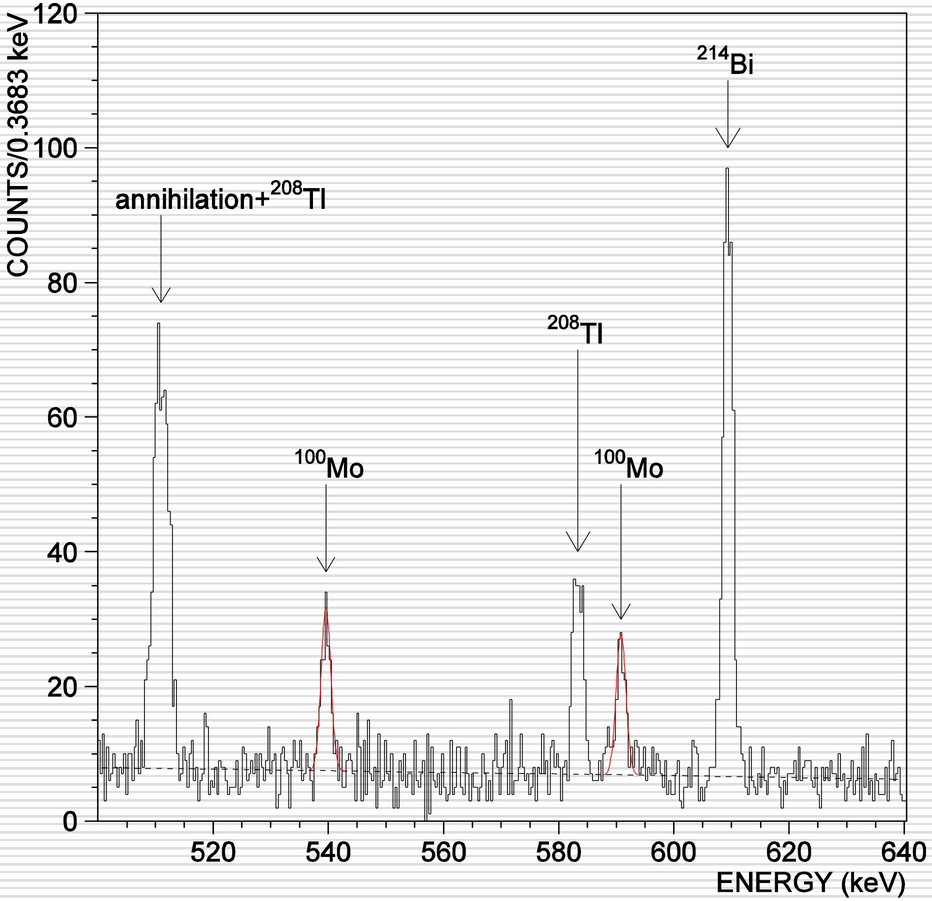
^{100}Mo source (metallic foils):

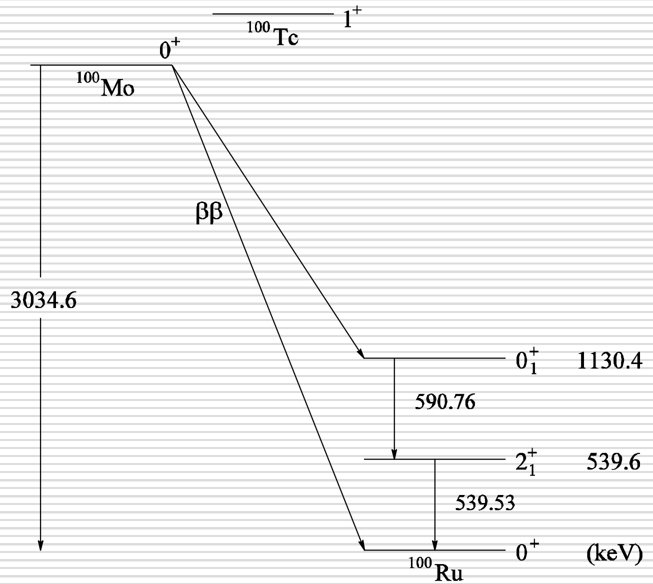
Location: LMS (Frejus, France; 4800 m w.e.)

- ^{100}**Mo** foil was packed into bobbin, specially made for the 600 cm^3 detector **(OBELIX)**
- Mass of foils is **2588 g**
- Mass of Mo is **2583 g** (99.8%)
- Average enrichment is **97.5%**
- Mass of ^{100}**Mo** is **2518 g (1.52·10^{25} nuclei)**
- Measurement time is **2288 h**



Double beta decay of ^{100}Mo to the excited states [NPA 925 (2014) 25]





$E_{\gamma 1}$ = 539.5 keV

$E_{\gamma 2}$ = 590.8 keV

$T_{1/2}(2\nu)$ = [7.5 ± 0.6(stat) ± 0.6 (syst)]· 10^{20} yr

^{150}Nd. Transition to the 0^+ excited state

I. $T_{1/2} = [1.33^{+0.36}_{-0.23}(stat)\ ^{+0.27}_{-0.13}(syst)]\cdot 10^{20}$ yr

(JETP. Lett. 79 (2004) 10; PRC 79 (2009) 045501)

II. $T_{1/2} = [1.07^{+0.45}_{-0.25}(stat) \pm 0.07(syst)]\cdot 10^{20}$ yr

(PRC 90 (2014) 055501)

Average value: $1.2^{+0.3}_{-0.2}\cdot 10^{20}$ yr

Comparison of NME for transition to the 0^+ ground and 0^+_1 excited states (for ^{100}Mo and ^{150}Nd)

- **Conclusion is**

$$NME(g.s.) \approx NME(0^+_1)$$

- **But, in fact, it looks like:**

$$NME(g.s.) \approx (1.2) \times NME(0^+_1)$$

Is this important!?

III. 2β(0ν)-decay to excited states

Very nice signature:

2e- and **two (one)** gamma with fixed energy

⇓

Possibility to have **“zero”** background

⇓

Possibility to have high sensitivity

(if registration efficiency and energy resolution are high enough)

3.1. 2β(0ν)-decay to 2^+_1 excited state

Many years people thought that this decay is sensitive only to right-handed currents.

T. Tomoda demonstrated that this is not through:

"…relative sensitivity of **0^+-2^+** decays to the neutrino mass and the right-handed currents are comparable to those of **0^+-0^+** decays."

[T. Tomoda, Phys. Lett. B 474 (2000) 245]

The decay is suppressed in ~ 3-5 order of magnitude in comparison to transition to **$0^+_{g.s.}$**

Table 4. Best present limits on 2β(0ν)-decay to 2^+_1 excited state

Nucleus	$E_{2\beta}$, keV	$T_{1/2}$, y (90%CL)
^{76}Ge	1480	$> 8.2 \cdot 10^{23}$ (G-M)
^{100}Mo	2494.5	$> 1.6 \cdot 10^{23}$ (NEMO-3)
^{130}Te	1992.7	$> 1.4 \cdot 10^{23}$ (MiBeta)
^{116}Cd	1411.5	$> 2.9 \cdot 10^{22}$ (Solotvino)
^{136}Xe	1649.4	**$> 2.6 \cdot 10^{25}$** (KamLAND)
^{82}Se	2218.5	$> 1.0 \cdot 10^{22}$ (LUCIFER)

Table 5. Best present limits on 2β(0ν)-decay to the 0^+_1 excited state

Nucleus	$E_{2\beta}$, keV	$T_{1/2}$, y (90%CL)	Theory [1] ($<m_\nu> = 1$ eV)	Theory [2] ($<m_\nu> = 1$ eV)
^{150}Nd	2627.1	$>1.0 \cdot 10^{20}$	$1.8 \cdot 10^{25}$	-
^{96}Zr	2202.5	$>3.1 \cdot 10^{20}$	$8.8 \cdot 10^{27}$	$(0.9-1.7) \cdot 10^{24}$
^{100}Mo	1903.7	**$>8.9 \cdot 10^{22}$**	$2.8 \cdot 10^{25}$	$(6.4-1.2) \cdot 10^{25}$
^{82}Se	1507.5	$>3.4 \cdot 10^{22}$	$1.2 \cdot 10^{26}$	$(3.8-7.6) \cdot 10^{25}$
^{48}Ca	1274.8	$>1.5 \cdot 10^{20}$	$2.3 \cdot 10^{25}$	$7.4 \cdot 10^{25}$ [3]

Table 5 (Continue)

^{116}Cd	1056.6	> $6.3 \cdot 10^{22}$	$(2.5\text{-}2.7) \cdot 10^{26}$	$(5.5\text{-}12) \cdot 10^{25}$
^{76}Ge	916.7	> $6.2 \cdot 10^{21}$	$1.4 \cdot 10^{26}$	$(4.2\text{-}8.3) \cdot 10^{25}$ $2.3 \cdot 10^{26}$ [3]
^{136}Xe	878.8	**> $2.4 \cdot 10^{25}$** **(<m> < 0.36-0.84 eV)**	$(5.8\text{-}6.4) \cdot 10^{25}$	$(3.7\text{-}7.5) \cdot 10^{24}$ $5 \cdot 10^{26}$ [3]
^{130}Te	734	> $9.4 \cdot 10^{23}$	$(3.7\text{-}4.4) \cdot 10^{25}$	$(0.5\text{-}1.1) \cdot 10^{25}$ $6.1 \cdot 10^{27}$ [3]

[1] J. Kotila et al., PRC 85 (2012) 034316.
[2] J. Hyvarinen, J. Suhonen, PRC 93 (2016) 064306.
[3] J. Menendez et al., NPA 818 (2009) 139.

2β(0ν)-decay to 0^+_1 excited state

- Future possibilities:

  - **LEGEND** with ^{76}**Ge** → **~ 10^{27} y**;
  - **KamLAND-Zen (1 t) with** ^{136}**Xe** → **~ $5 \cdot 10^{26}$ y**;
  - **CUORE, SNO+** with ^{130}**Te** → **~ 10^{26} y**;
  - **SuperNEMO** with ^{82}**Se** (or ^{150}**Nd**)

    → **~ 10^{24}–10^{25} y**;

IV. ECEC to the excited states

- **1994 (A.S.B. JETP Lett. 59 (1994) 677).**

  Main assumption: **NME(2ν; $0^+_{g.s.}$) ≈ NME(2ν; 0^+_1):**

  then $T_{1/2}(0^+_1)$ **~ 10^{21}-10^{22} y** for ^{96}Ru, ^{106}Cd, ^{124}Xe, ^{136}Ce;

  ~ 10^{23} y for ^{78}Kr and ^{130}Ba

Very nice signature: in addition to **two X-rays** we have here **two gamma** with strictly fixed energy (E ~ 300-1300 keV)

⇓

New experiments were proposed

Table 6. Best present limits on ECEC(2ν) to the 0^+_1 excited state

Nucleus, isotopical abundance	**Q_{ECEC}, keV**	**$T_{1/2}$, y (90%CL)**	**Prediction**
^{130}Ba; 0.11%	829.8	$>1.5\cdot10^{21}$ *)	$\sim 10^{23}$
^{106}Cd; 1.25%	1641.4	$>1\cdot10^{21}$	$\sim 10^{22}$-10^{23}
^{78}Kr; 0.35%	1349.3	$>5.4\cdot10^{21}$	$\sim 10^{23}$-10^{24}
^{136}Ce; 0.185%	799.5	$>1.6\cdot10^{18}$	$\sim 10^{23}$
^{96}Ru; 5.54%	1566.4	$>2.5\cdot10^{20}$	$\sim 10^{23}$-10^{24}
^{112}Sn; 0.97%	695.4	$>1.6\cdot10^{21}$	$\sim 10^{23}$-10^{24}

IV.2. ECEC(0ν); resonance conditions

Transition to the ground state. For the best candidates ($\langle m_\nu \rangle = 1$ **eV**):

$\beta^+\beta^+$ (0ν) ~ 10^{28}-10^{30} y

β^+EC(0ν) ~ 10^{26}-10^{27} y

ECEC(0ν) ~ 10^{28}-10^{31} y

(One can compare these values with **~ 10^{24}-10^{25} y for 2β^--decay**)

ECEC(0ν) to the ground state

- $2e_b + (A,Z) \rightarrow (A,Z\text{-}2) + 2X + \gamma_{brem}$

  $+ 2\gamma$

  $+ e^+e^-$

  $+ e^-_{int}$

$E_{\gamma,..} = \mathbf{\Delta M} - \varepsilon_{e1} - \varepsilon_{e2}$

Suppression factor is ~ 10^4 (in comparison with $EC\beta^+(0\nu)$) – M. Doi and T. Kotani, Prog. Theor. Phys. 89 (1993)139.

Resonance conditions

- In **1955** (**R.Winter, Phys. Rev. 100 (1955) 142**) it was mentioned that if there is excited level with “right” energy then decay rate can be very high.

  (Q’-E has to be close to zero. Q’-energy of decay, E-energy of excited state)
- In **1982** the same idea for transition to ground and excited states was discussed (**M. Voloshin, G. Mizelmacher, R. Eramzhan, JETP Lett. 35 (1982)).**
- In **1983** (**J. Bernabeu, A. De Rujula, C. Jarlskog, Nucl. Phys. B 223 (1983) 15**) this idea was discussed for **^{112}Sn** (transition to 0^+ excited state). It was shown that enhancement factor can be on the level **~ 10^6!**
- **In 2004 the same conclusion was done by Z. Sujkowski and S. Wycech (Phys. Rev. C 70 (2004) 052501).**

Main candidates:

^{74}Se, ^{78}Kr, ^{96}Ru, ^{102}Pd, ^{106}Cd, ^{112}Sn, ^{124}Xe, ^{130}Ba, ^{144}Sm, ^{136}Ce, ^{152}Gd, ^{156}Dy, ^{162}Er, ^{164}Er, ^{168}Yb, ^{180}W, ^{184}Os, ^{190}Pt

Resonance conditions have not been confirmed (practically for all of them). Mainly because of **$\Delta Q > 1$ keV.** And, in some cases, because of **«not good» quantum numbers (spin and parity)** of the states.

Best experimental sensitivity ~ 10^{21} yr (^{112}Sn, ^{106}Cd)
(but ~ 10^{16}-10^{19} yr in most cases)

^{156}Dy — ^{156}Gd transitions

E*, keV	I^{π}	e- orbitals	ΔQ, keV	EF
1946.375	1^-	KL_1	0.75(10)	$4.1 \cdot 10^6$
1952.385	0^-	KM_1	1.37(10)	$1.7 \cdot 10^6$
1988.5(2)	**0^+**	**L_1L_1**	**0.54(24)**	**$2.5 \cdot 10^6$**
2003.749	2^+	M_1N_1	0.04(24)	$7.7 \cdot 10^8$

$T_{1/2} \approx 10^{28}$-10^{30} yr (for transition to 1988.5 keV)

(S. Eliseev et al., PRC 84 (2011) 012501;
J. Kotila et al., PRC 89 (2014) 064319)

Isot. abundance 0.06%

Problems

- There is no “good” candidate up to now
- Concentration of isotope-candidates is low **(~ 0.1-1%)**. Exception is **^{96}Ru – 5.5%.**
- There is no «reliable» information about high energy excited states (information from 50-th and 60-th years of last century). **So, «good candidate» can be found in the future!**

CONCLUSION

- 2β(2ν)-decay to 0^+ excited states was detected for ^{100}Mo and ^{150}Nd in many independent experiments.

  Next good candidates are ^{96}Zr and ^{82}Se.
- There are good prospects to search for 2β(2ν) and 2β(0ν)-decay to 0^+ excited states in future large-scale experiments.
- ECEC(0ν) is a “new-old” possibility to search for neutrino mass (in case of resonance conditions). But still there is no «good» candidate here.

J. Bernabeu, A. De Rujula, C. Jarlskog, Nucl. Phys. B 223 (1983) 15

$^{112}Sn \rightarrow {}^{112}Cd\ [0^{+}(1871)]$

$\Delta M = 1919.5 \pm 4.8$ keV

$\Delta Q(KK;0^{+}) = \Delta M - E^{*}(0^{+}) - 2E_K =$

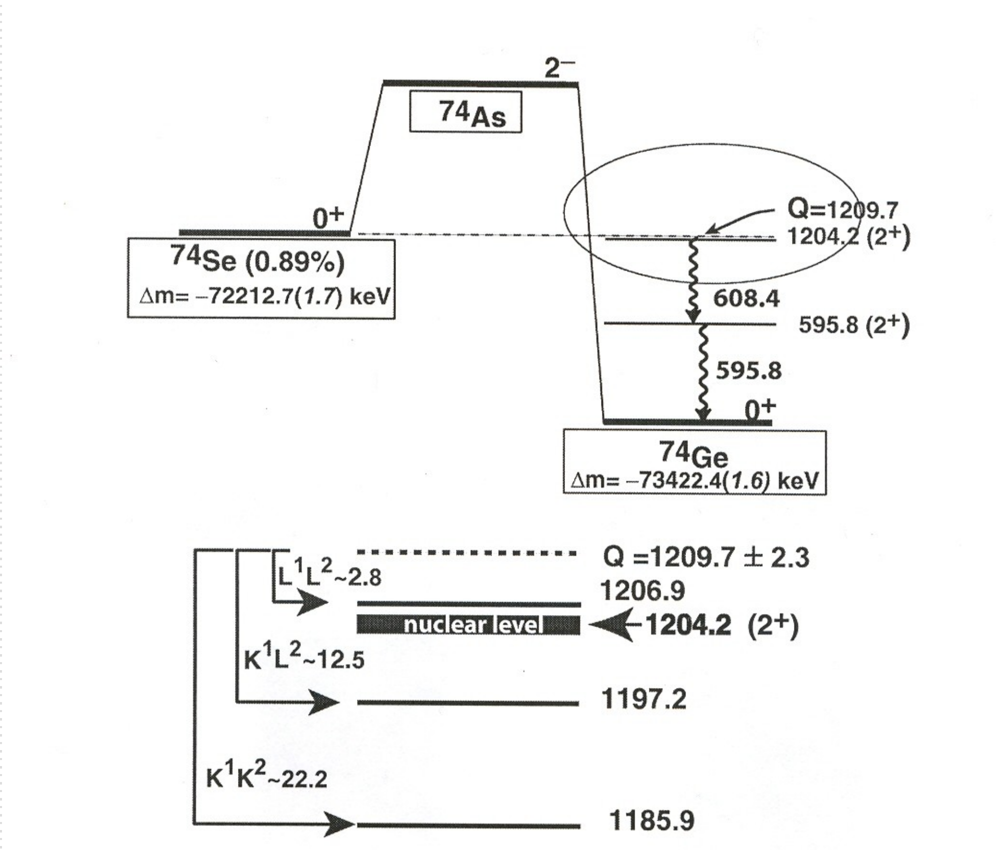
$= (-4.9 \pm 4.8)$ keV

$T_{1/2} \approx 3 \cdot 10^{24}$ y (for $m_\nu = 1$ eV)

(if $\Delta Q \sim 10$ eV)

Present velue: $\Delta Q = -\,4.72 \pm 0.23$ keV

Decay-scheme of ^{74}Se



Here Q = ΔM = 1209.7

$Q' = \Delta M - 2E_b$

$\Delta Q'(E^*) = Q' - 1204.2 =$

$= 2.1 \pm 0.1$ keV

g.s.-g.s. transitions

^{152}Gd (0.2%), ^{164}Er (1.56%), ^{180}W(0.13%)

(There are only X-rays in this case)

^{152}Gd: $\Delta Q = 0.91(18)$ keV $\Rightarrow$
$T_{1/2} \approx 10^{26}$ y ($<m_\nu> = 1$ eV)

(Penning-trap mass spectrometry)