

Weak Nuclear Decays – the Playground of Nuclear, Particle and Atomic Physics

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- Intro: $\beta^- \beta^-$ Decays
- Positron-emitting/EC Decays

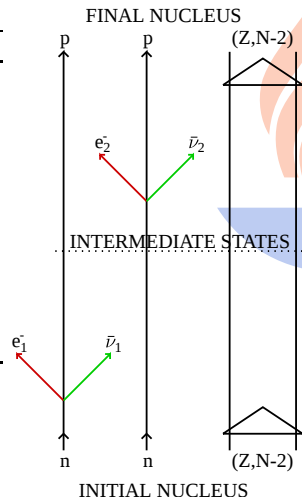
INTRO: Double β^- Decays

$\beta^- \beta^-$ Decays

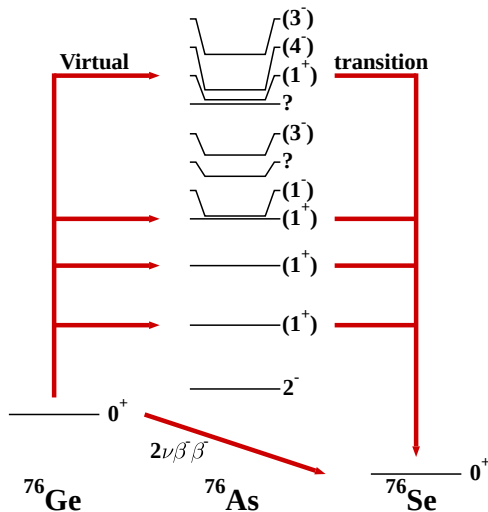
MODE 1: Two-Neutrino Double Beta Decay

Nucleus	half-life (years)	experiments
^{48}Ca	$4.2 \cdot 10^{19}$	laboratory
^{76}Ge	$1.42 \cdot 10^{21}$	laboratory
^{82}Se	$9 \cdot 10^{19}$	laboratory, geochemical
^{96}Zr	$2.1 \cdot 10^{19}$	laboratory, geochemical
^{100}Mo	$8.0 \cdot 10^{18}$	laboratory
^{116}Cd	$3.3 \cdot 10^{19}$	laboratory
^{128}Te	$2.5 \cdot 10^{24}$	geochemical
^{130}Te	$9 \cdot 10^{20}$	geochemical
^{150}Nd	$7.0 \cdot 10^{18}$	laboratory
^{238}U	$2.0 \cdot 10^{21}$	radio-chemical

10^{20} years =
 $10000000000 \times$ age of the UNIVERSE



Two-Neutrino Double Beta Decay of ^{76}Ge

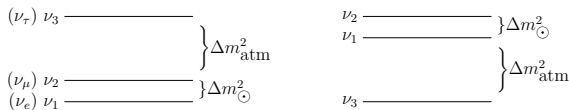


The decay goes through 1^+ virtual states

MODE 2: Neutrinoless Double Beta Decay

$0\nu\beta\beta$ Decay is Able to:

- Reveal if the neutrino is a **Majorana particle**
- Probe the neutrino **effective mass**
 $\langle m_\nu \rangle = \sum_{j=\text{light}} \lambda_j^{\text{CP}} |U_{ej}|^2 m_j$
- Probe the **degenerate** or **inverted** mass hierarchies (next-generation experiments!)
- Probe possibly the **CP phases** (nuclear matrix elements are critical!)



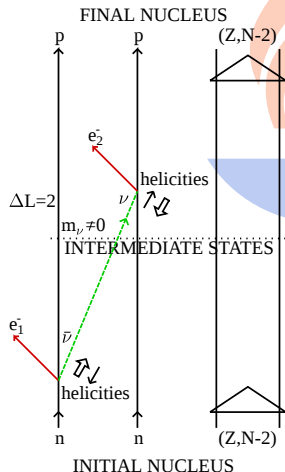
$$\Delta m_{\odot}^2 = 7.67^{+0.16}_{-0.19} \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{atm}}^2 = 2.39^{+0.11}_{-0.08} \times 10^{-3} \text{ eV}^2$$

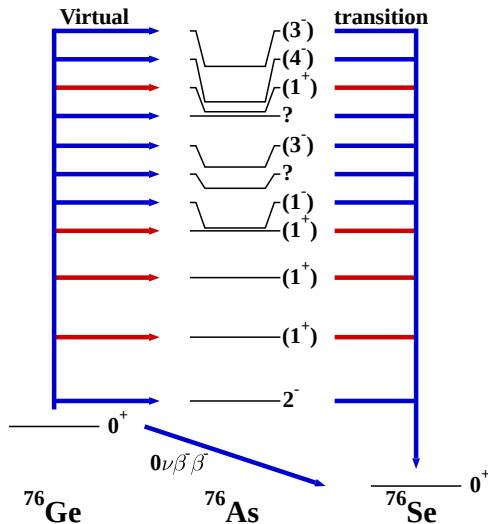
[Global 3ν oscillation analysis (2008)]

MASS MODE:

$$T_{1/2} \propto \langle m_\nu \rangle^2$$



Neutrinoless Double Beta Decay of ^{76}Ge



The decay goes through all J^π virtual states

Rates of Neutrinoless Double Beta Decays

Decay rates:

$$\frac{\ln 2}{T_{1/2}^{\alpha}(0^+)} = g_{0\nu}^{\alpha}(0^+) [\mathcal{M}^{(0\nu)'}]^2 \langle m_{\nu} \rangle^2, \quad \alpha = \beta^- \beta^-, \beta^+ \beta^+, \beta^+ \text{EC},$$

$g_{0\nu}^{\alpha}(0^+)$ is the phase-space factor

Effective neutrino mass:

$$\langle m_{\nu} \rangle = \sum_{j=\text{light}} \lambda_j^{\text{CP}} |U_{ej}|^2 m_j$$

Standard NME:

$$\mathcal{M}^{(0\nu)'} = \left(\frac{g_A}{1.25} \right)^2 \left[M_{\text{GT}}^{(0\nu)} - \left(\frac{g_V}{g_A} \right)^2 M_{\text{F}}^{(0\nu)} + M_{\text{T}}^{(0\nu)} \right]$$

$g_A = 1.25$ = the bare-nucleon value of the axial-vector coupling constant

Comparison of the Yale and Jyväskylä NMEs

The IBM-2 results are taken from: F. Iachello, J. Barea and J. Kotila, AIP Conf. Proc. 1417 (2011) 62-68 (**MEDEX'11 Workshop**) ; Results are obtained with **Jastrow** s.r.c.

Transition	0_{gs}^+		0_1^+	
	IBM-2	QRPA	IBM-2	QRPA
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	2.00	1.09 – 1.89 [1]	5.90	-
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	5.46	2.28 – 4.17 [2]	2.48	2.47 – 5.38 [3]
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	4.41	2.11 – 3.51 [2]	1.25	0.83 – 1.85 [3]
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	2.53	2.00 – 2.07 [4]	0.04	1.96 (0.18) [5]
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	3.73	2.26 – 2.74 [4]	0.42	0.31 [6]
$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$	3.62	3.63 – 4.51 [7]	1.60	0.96 – 1.73 [7]
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	2.78	2.36 – 3.98 [4]	1.05	0.25 [5]
$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$	3.53	2.58 – 4.18 [7]	2.72	3.96 – 5.88 [7]
$^{128}\text{Te} \rightarrow ^{128}\text{Xe}$	4.52	2.74 – 4.15 [2]	3.24	-
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	4.06	2.60 – 3.78 [2]	3.09	3.88 – 6.61 [8]
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	3.35	1.83 – 2.53 [2]	1.84	2.75 – 6.08 [3]

[1] J. Suhonen, JPGA 19 (1993) 139 ; [2] J. Suhonen and O. Civitarese, NPA 847 (2010) 207 ; [3] J. Suhonen, NPA 853 (2011) 36 ; [4] J. Suhonen and M. Kortelainen, IJMP E 17 (2008) 1 ; [5] J. Suhonen, PRC 62 (2000) 042501 ; [6] J. Suhonen, NPA 700 (2002) 649 ; [7] J. Suhonen, NPA 864 (2011) 63 ; [8] J. Suhonen, unpublished

Comparison of the Darmstadt-Madrid and Jyväskylä NMEs

The energy-density functional (Gogny D1S) results are taken from: T.R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503 ; Results are obtained with UCOM s.r.c. for $g_A = 1.25$

Transition	EDF	QRPA
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	2.37	-
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	4.60	4.11 – 5.52 [1,2]
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	4.22	3.72 – 4.57 [1,2]
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	5.65	3.12 [1]
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	5.08	3.93 [1]
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	4.72	3.94 [1]
$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$	4.81	3.30 – 5.51 [3]
$^{128}\text{Te} \rightarrow ^{128}\text{Xe}$	4.11	4.79 – 5.62 [1,2]
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	5.13	4.22 – 5.12 [1,2]
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	4.20	2.80 – 3.35 [1,2]

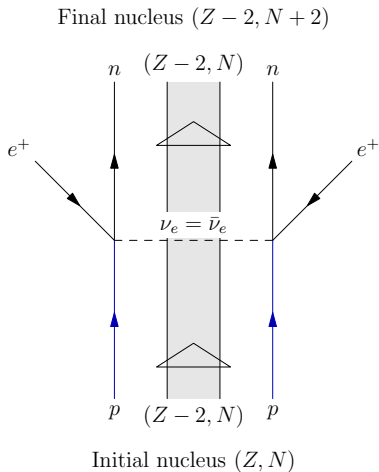
[1] J. Suhonen and M. Kortelainen, IJMP E 17 (2008) 1 ; [2] J. Suhonen and O. Civitarese, NPA 847 (2010) 207 ; [3] J. Suhonen, NPA 864 (2011) 63

PART II. Double Positron/EC Decays

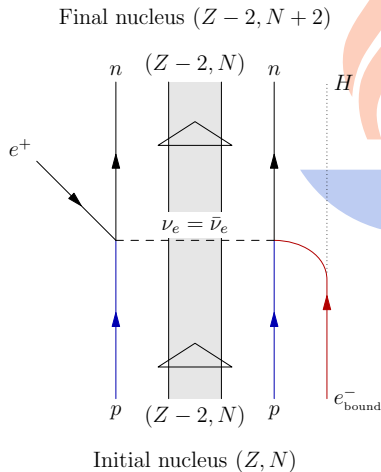
$\beta^+ \beta^+, \beta^+ \text{EC}$ and ECEC Decays

$2\nu/0\nu$ Double Positron/EC Decays

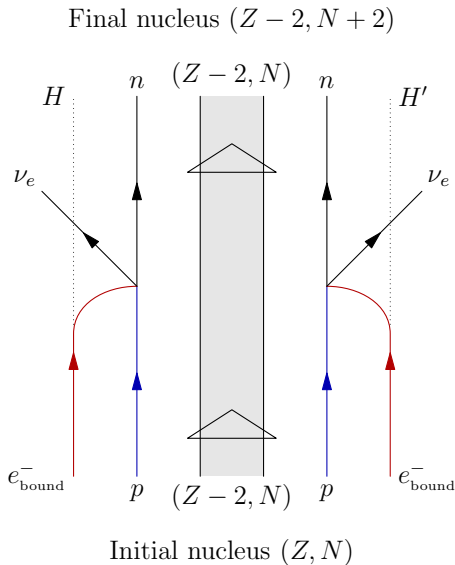
$0\nu\beta^+\beta^+$ Decay



$0\nu\beta^+\text{EC}$ Decay



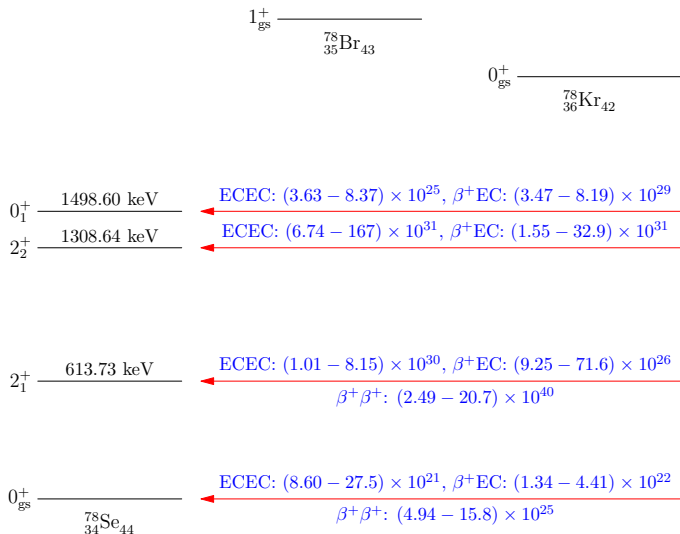
Two-Neutrino Double Electron Capture



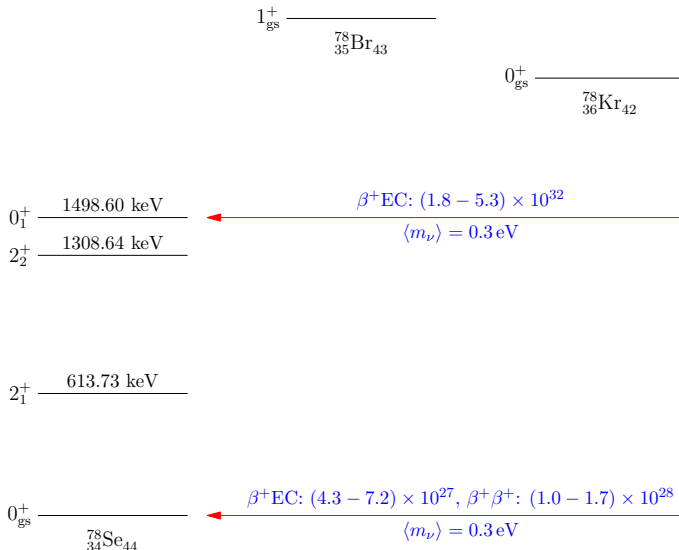
Example: Double Positron/EC Decays

Decays of ^{78}Kr

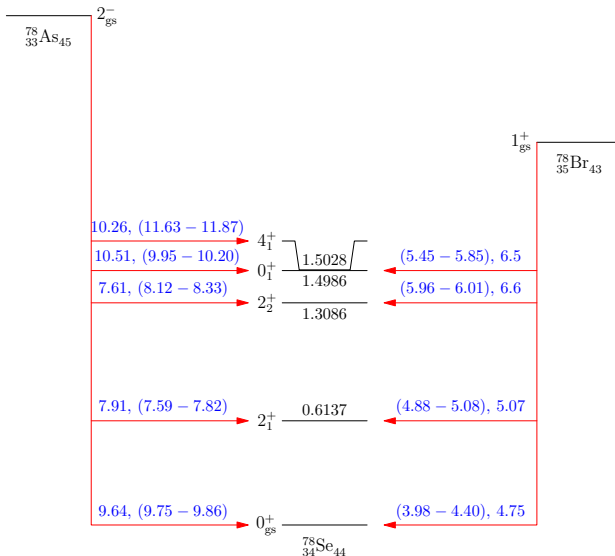
Various $2\nu 2\beta$ Decay Modes of ^{78}Kr



Various $0\nu2\beta$ Decay Modes of ^{78}Kr

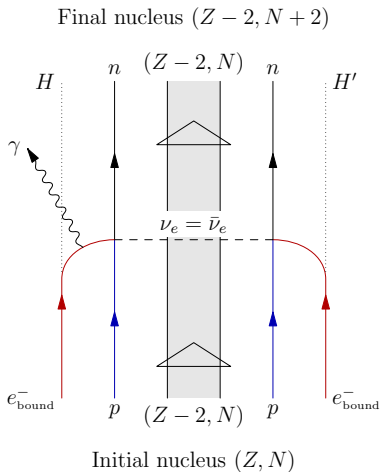


Check: Beta-Decay Transitions Feeding ^{78}Se

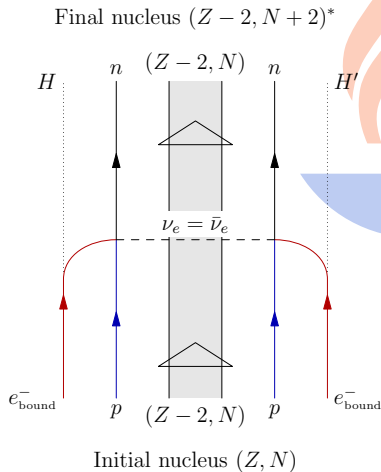


Neutrinoless Double Electron Capture

Radiative $0\nu\text{ECEC}$



Resonant $0\nu\text{ECEC}$



Rate of Resonant 0ν ECEC Decay

$$\frac{\ln 2}{T_{1/2}} = g^{\text{ECEC}} [M^{\text{ECEC}}]^2 \frac{\langle m_\nu \rangle^2 \Gamma}{(Q - E)^2 + \Gamma^2/4}, \quad Q - E = \text{degeneracy parameter}$$

- phase-space factor

$$g^{\text{ECEC}}(0^+) = \left(\frac{G_F \cos \theta_C}{\sqrt{2}} \right)^4 \frac{g_A^4}{4\pi^2} m_e^6 \mathcal{N}_{0,-1}^2,$$

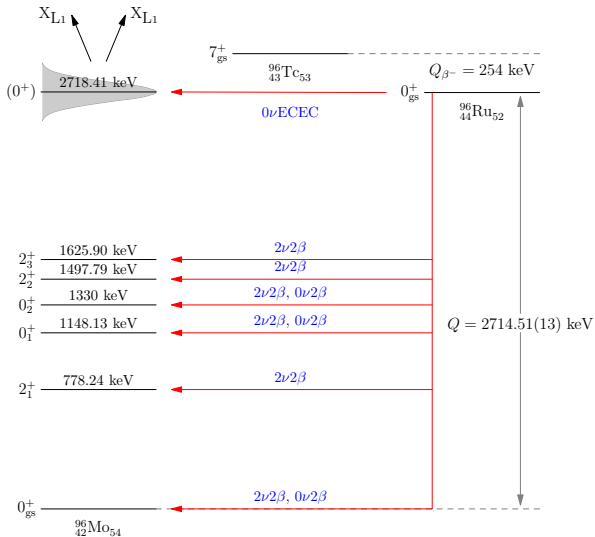
where $\mathcal{N}_{0,-1}$ is the normalization of the relativistic K-shell($1s_{1/2}$) Dirac wave function for a uniformly charged spherical nucleus

- $Q = M(Z, A) - M(Z - 2, A)$ = difference between the initial and final atomic masses
- $E = E^* + E_H + E_{H'} + E_{HH'}$ = nuclear excitation energy + electron binding
- $\Gamma = \Gamma^* + \Gamma_H + \Gamma_{H'}$ = nuclear and atomic radiative widths
- NUCLEAR MATRIX ELEMENT: $M^{\text{ECEC}} = \frac{1}{R_A} M^{(0\nu)'}$, $R_A = 1.2A^{1/3}$ fm

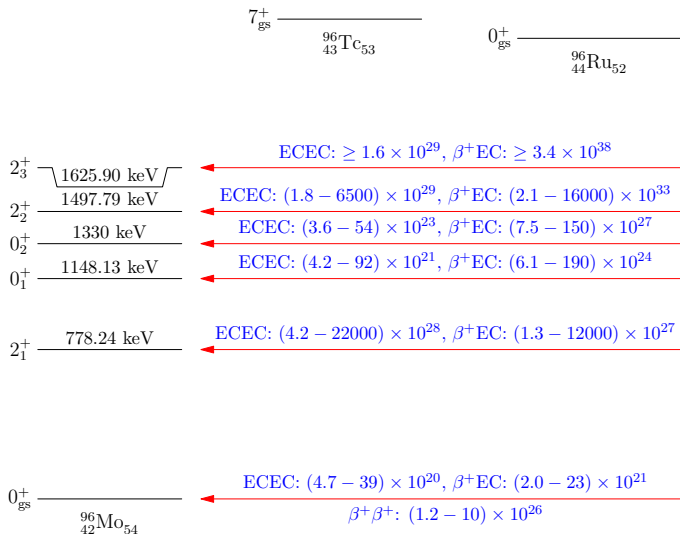
Enhancement factors of 10^6 possible (J. Bernabeu, A. De Rujula, and C. Jarlskog, Nucl. Phys. B 223 (1983) 15 ; Z. Sujkowski and S. Wycech, Phys. Rev. C 70 (2004) 052501(R))

Decays of ^{96}Ru

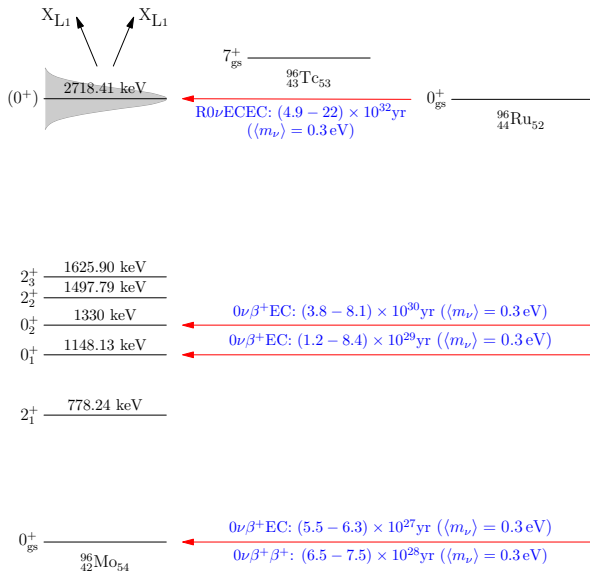
Various Decay Modes of ^{96}Ru



Various $2\nu 2\beta$ Decay Modes of ^{96}Ru



Various $0\nu 2\beta$ Decay Modes of ^{96}Ru



Concise List of Other Cases

Transition	J_f^π	$Q - E$ [keV]	At. orb.	Ref.
$^{74}\text{Se} \rightarrow ^{74}\text{Ge}$	2^+	2.23	L_2L_3	[1]
$^{96}\text{Ru} \rightarrow ^{96}\text{Mo}$	2^+	8.92(13)	L_1L_3	[2]
	$0^+?$	-3.90(13)	L_1L_1	Q from [2]
$^{102}\text{Pd} \rightarrow ^{102}\text{Ru}$	2^+	75.26(36)	KL_3	[3]
$^{106}\text{Cd} \rightarrow ^{106}\text{Pd}$	$0^+?$	8.39	KK	[4], Q from [3]
	$(2, 3)^-?$	-0.33(41)	KL_3	[3]
$^{112}\text{Sn} \rightarrow ^{112}\text{Cd}$	0^+	-4.5	KK	[5]
$^{136}\text{Ce} \rightarrow ^{136}\text{Ba}$	0^+	-11.67	KK	[6]
$^{144}\text{Sm} \rightarrow ^{144}\text{Nd}$	2^+	171.89(87)	KL_3	[3]
$^{152}\text{Gd} \rightarrow ^{152}\text{Sm}$	0_{gs}^+	0.91(18)	KL_1	[7]
$^{156}\text{Dy} \rightarrow ^{156}\text{Gd}$	1^-	0.75(10)	KL_1	[8]
	0^+	0.54(24)	L_1L_1	[8]
	2^+	0.04(10)	M_1N_3	[8]
$^{162}\text{Er} \rightarrow ^{162}\text{Dy}$	2^+	2.69(30) keV	KL_3	[2]
$^{168}\text{Yb} \rightarrow ^{168}\text{Er}$	(2^-)	1.52(25) keV	M_1M_3	[2]

[1] V. Kolhinen *et al.*, PLB 684 (2010) 17 (JYFLTRAP, JYFL); [2] S. Eliseev *et al.*, PRC 83 (2011) 038501 (SHIPTRAP, GSI); [3] M. Goncharov *et al.*, PRC 84 (2011) 028501 (SHIPTRAP, GSI); [4] J. Suhonen, PLB 701 (2011) 490; [5] S. Rahaman *et al.*, PRL 103 (2009) 042501 (JYFLTRAP, JYFL); [6] V. Kolhinen *et al.*, PLB 697 (2011) 116 (JYFLTRAP, JYFL); [7] S. Eliseev *et al.*, PRL 106 (2011) 052504 (SHIPTRAP, GSI); [8] S. Eliseev *et al.*, PRC 84 (2011) 012501(R) (SHIPTRAP, GSI)

Conclusions and Outlook

Conclusions:

- The field of double β^- decays has livened up since many new groups have entered the field (IBM-2, energy-density functionals, ...)
- The positron emitting/electron-capture modes are less studied (smaller Q values, less observational potential)
- Most $R0\nu\text{ECEC}$ decays are **NOT OBSERVABLE** due to badly fulfilled resonance condition and/or tiny NME.
Possible exceptions are: Decay of ^{106}Cd to $(2, 3)^-$ in ^{106}Pd (**NMEs are unknown**); decay of ^{152}Gd to the ground state of ^{152}Sm ; Decays of ^{156}Dy to 1^- , 0^+ and 2^+ states in ^{156}Gd (**NMEs are unknown**)

Outlook (and recommendations):

- Reliable calculation of the **NMEs** of the above-mentioned decay modes, in particular for the $R0\nu\text{ECEC}$, should be pursued.