Exotic Weak Decays of Atomic Nuclei

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

Neutrino Properties and $\beta\beta$ Decays

Neutrino Properties from Experiments

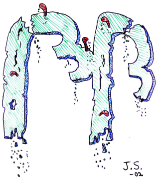
Neutrino Properties from Oscillation Experiments:

From solar, atmospheric, accelerator and reactor-neutrino data (SuperKamiokande, SNO, KamLAND, etc.):

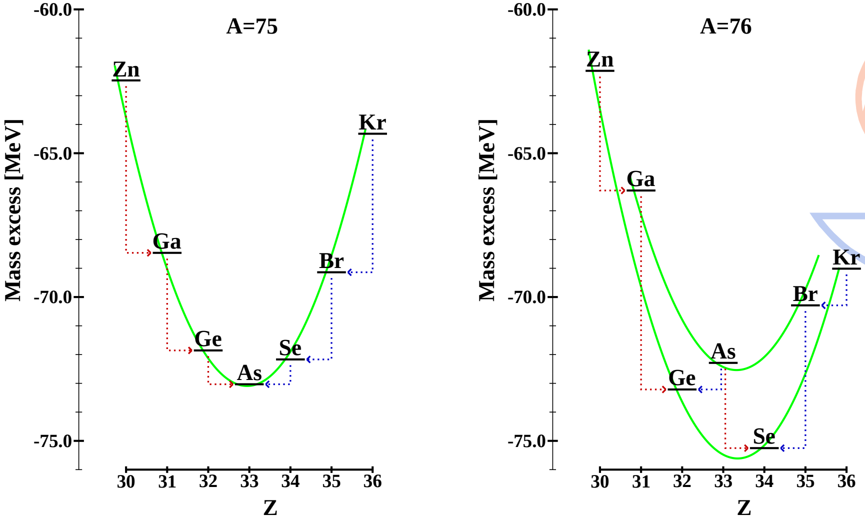
- Squared mass differences Δm^2 of neutrinos
- Matrix elements of the neutrino mixing matrix $\Leftrightarrow$ flavor eigenstates in terms of mass eigenstates: $\nu_e \rightarrow \nu_i \rightarrow \nu_\mu \rightarrow \nu_j \rightarrow \nu_e \rightarrow \nu_k \rightarrow \nu_\mu \cdots$

Complementary Experiments:

- Tritium beta decay (absolute neutrino mass), KATRIN
- **Double beta decay** (nature, absolute mass and hierarchy of neutrinos)



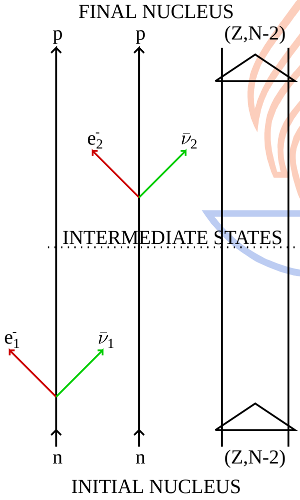
Double Beta Decay (Isobars $A = 76$)



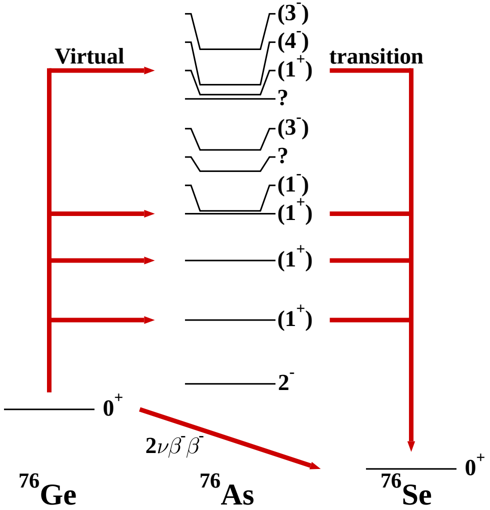
MODE 1: Two-Neutrino Double Beta Decay

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 × age of the UNIVERSE



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

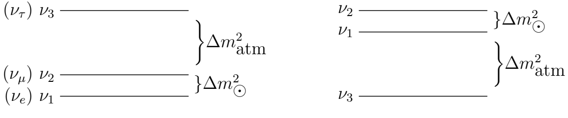


The decay goes through 1^+ virtual states

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
  $\langle m_\nu \rangle = \sum_{j=\mathrm{light}} \lambda_j^{\mathrm{CP}} |U_{ej}|^2 m_j$
- Probe the degenerate or inverted mass hierarchies (next-generation experiments!)
- Probe possibly the CP phases (nuclear matrix elements are critical!)



Normal hierarchy

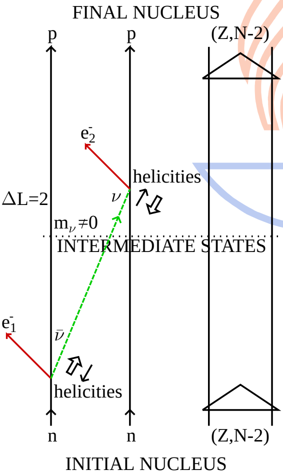
Inverted hierarchy

$$\Delta m^2_\odot = 7.67^{+0.16}_{-0.19} \times 10^{-5}\,\mathrm{eV}^2$$
$$\Delta m^2_{\mathrm{atm}} = 2.39^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

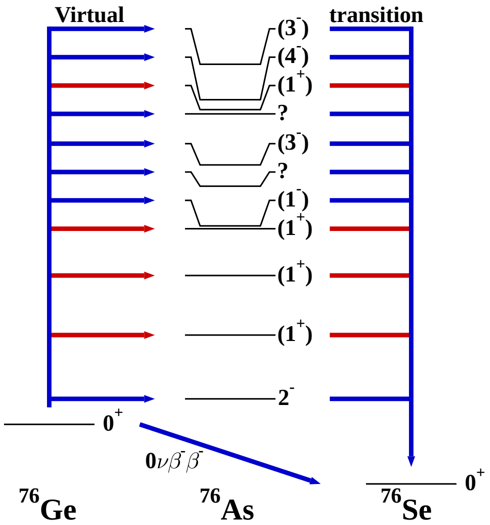
[Global 3ν oscillation analysis (2008)]

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:

$$\frac{\ln 2}{T^{\alpha}_{1/2}(0^+)} = g^{\alpha}_{0\nu}(0^+)[M^{(0\nu)\prime}]^2 \langle m_\nu \rangle^2 \,, \quad \alpha = \beta^-\beta^-,\, \beta^+\beta^+,\, \beta^+\mathrm{EC}\,,$$

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

Effective neutrino mass:

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

Standard NME:

$$M^{(0\nu)\prime} = \left(\frac{g_{\mathrm{A}}}{1.25}\right)^2 \left[M^{(0\nu)}_{\mathrm{GT}} - \left(\frac{g_{\mathrm{V}}}{g_{\mathrm{A}}}\right)^2 M^{(0\nu)}_{\mathrm{F}} + M^{(0\nu)}_{\mathrm{T}} \right]$$

$g_{\mathrm{A}} = 1.25 =$ the bare-nucleon value of the axial-vector coupling constant

$\beta^-\beta^-$ Decays

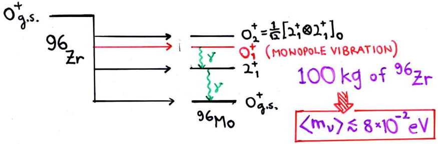
Comparison of the Yale and Jyväskylä NMEs

The IBM-2 results are taken from: F. Iachello, J. Barea and J. Kotila, AIP Conf. Proc. 1417 (2011) 62-68 (MEDEX'11 Workshop)

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

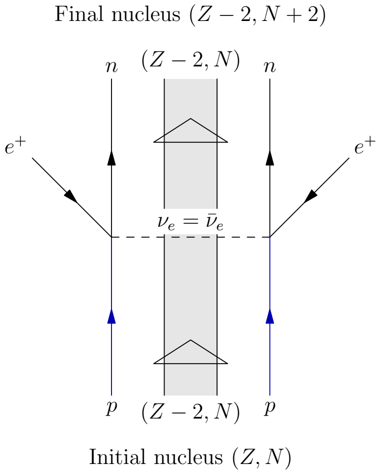
The ZORRO Experiment



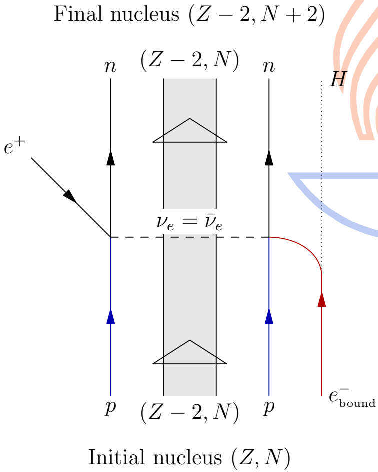
$\beta^+\beta^+$, β^+EC and ECEC Decays

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

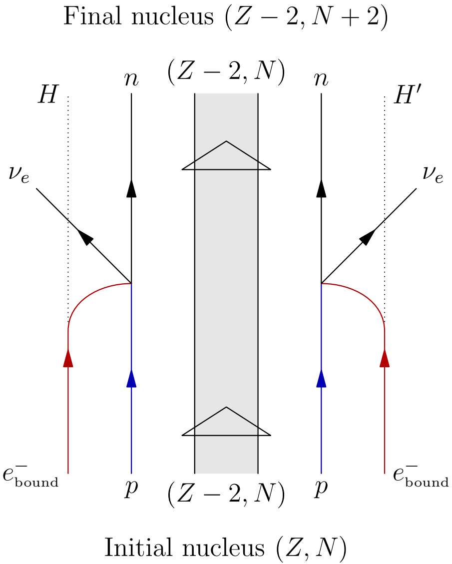
$0\nu\beta^+\beta^+$ Decay



$0\nu\beta^+$EC Decay

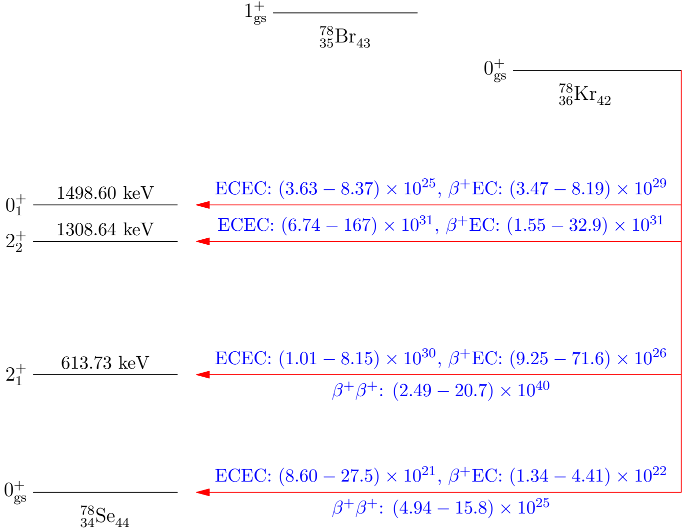


Two-Neutrino Double Electron Capture

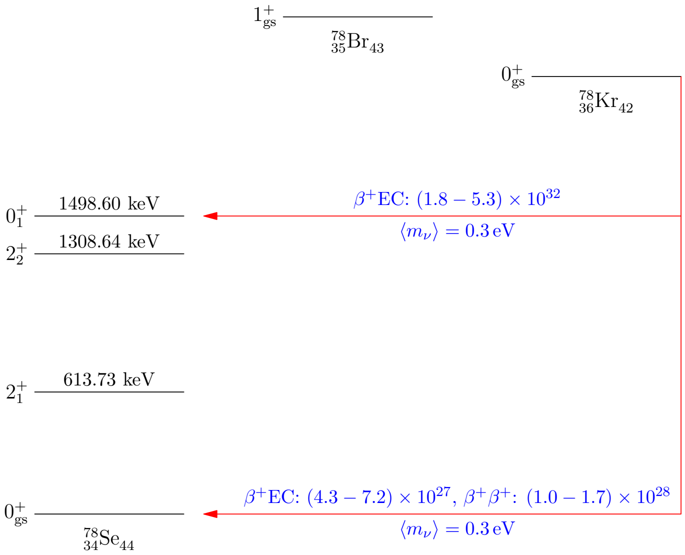


Decays of ^{78}Kr

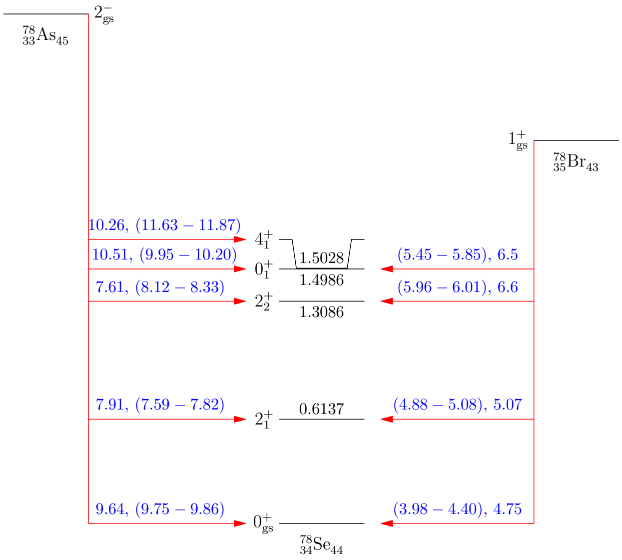
Various $2\nu2\beta$ Decay Modes of ^{78}Kr



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

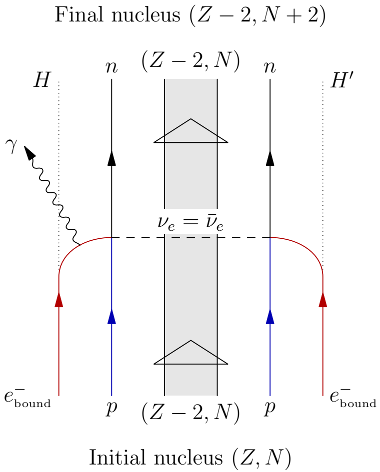


Check: Beta-Decay Transitions Feeding ^{78}Se

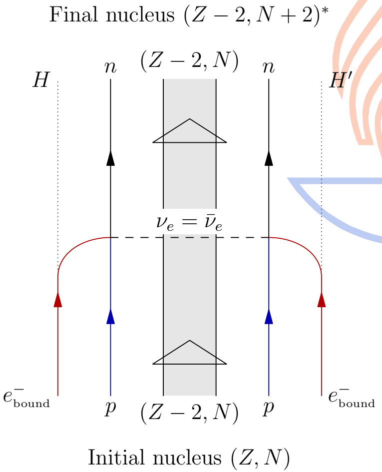


Neutrinoless Double Electron Capture

Radiative 0νECEC



Resonant 0νECEC



Rate of Resonant 0νECEC Decay

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

- phase-space factor

$$g^{\rm ECEC}(0^+) = \left(\frac{G_{\rm F}\cos\theta_{\rm C}}{\sqrt{2}}\right)^4 \frac{g_{\rm A}^4}{4\pi^2} m_{\rm e}^6 \mathcal{N}_{0,-1}^2\,,$$

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

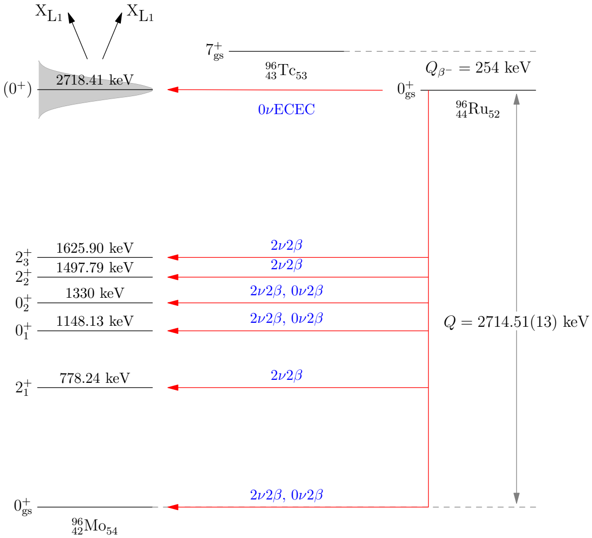
- $Q = M(Z,A) - M(Z-2,A) =$ difference between the initial and final atomic masses
- $E = E^* + E_H + E_{H'} + E_{HH'} =$ nuclear excitation energy + electron binding
- $\Gamma = \Gamma^* + \Gamma_H + \Gamma_{H'} =$ nuclear and atomic radiative widths
- NUCLEAR MATRIX ELEMENT: $M^{\rm ECEC} = \frac{1}{R_A}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

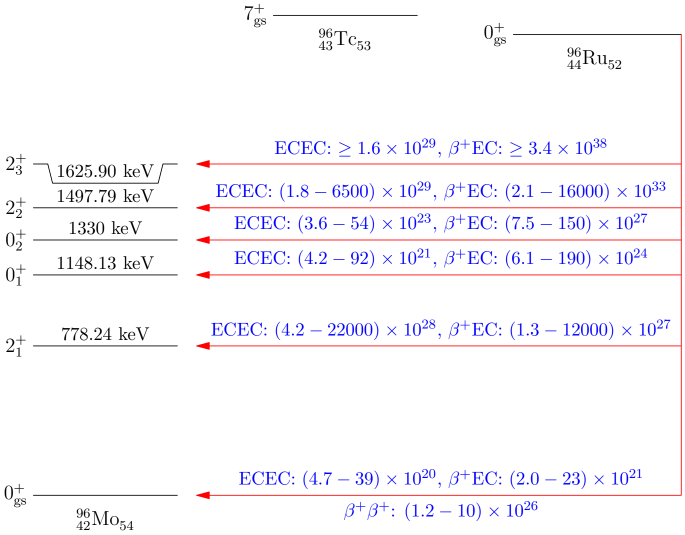
Example

Decays of ^{96}Ru

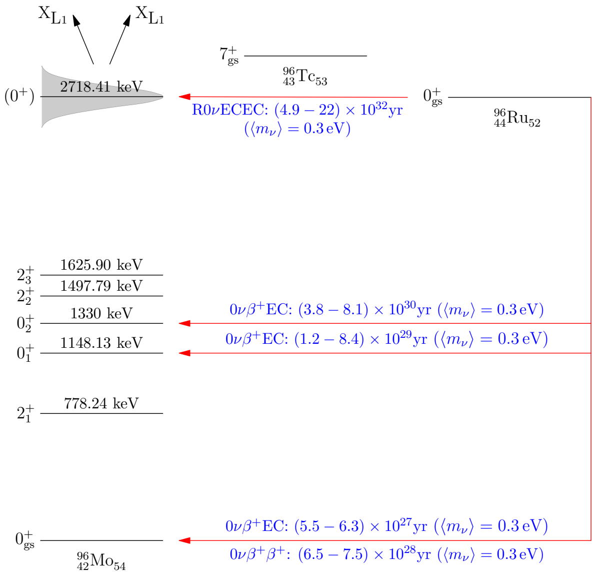
Various Decay Modes of ^{96}Ru



Various $2\nu2\beta$ Decay Modes of ^{96}Ru



Various $0\nu2\beta$ Decay Modes of ^{96}Ru



Concise List of Other Cases

Transition	J_f^π	$Q-E$ [keV]	At. orb.	Ref.
$^{74}Se \rightarrow {}^{74}Ge$	2^+	2.23	L_2L_3	[1]
$^{96}Ru \rightarrow {}^{96}Mo$	2^+	8.92(13)	L_1L_3	[2]
	$0^+?$	−3.90(13)	L_1L_1	Q from [2]
$^{102}Pd \rightarrow {}^{102}Ru$	2^+	75.26(36)	KL_3	[3]
$^{106}Cd \rightarrow {}^{106}Pd$	$0^+?$	8.39	KK	[4], Q from [3]
	$(2,3)^-?$	−0.33(41)	KL_3	[3]
$^{112}Sn \rightarrow {}^{112}Cd$	0^+	−4.5	KK	[5]
$^{136}Ce \rightarrow {}^{136}Ba$	0^+	−11.67	KK	[6]
$^{144}Sm \rightarrow {}^{144}Nd$	2^+	171.89(87)	KL_3	[3]
$^{152}Gd \rightarrow {}^{152}Sm$	0^+_{gs}	0.91(18)	KL_1	[7]
$^{156}Dy \rightarrow {}^{156}Gd$	1^-	0.75(10)	KL_1	[8]
	0^+	0.54(24)	L_1L_1	[8]
	2^+	0.04(10)	M_1N_3	[8]
$^{162}Er \rightarrow {}^{162}Dy$	2^+	2.69(30) keV	KL_3	[2]
$^{168}Yb \rightarrow {}^{168}Er$	(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 R0νECEC 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 R0νECEC, should be pursued.

The U(5) Limit of Franco, Artist's View