DOUBLE BETA DECAY AND NEUTRINO MASSES

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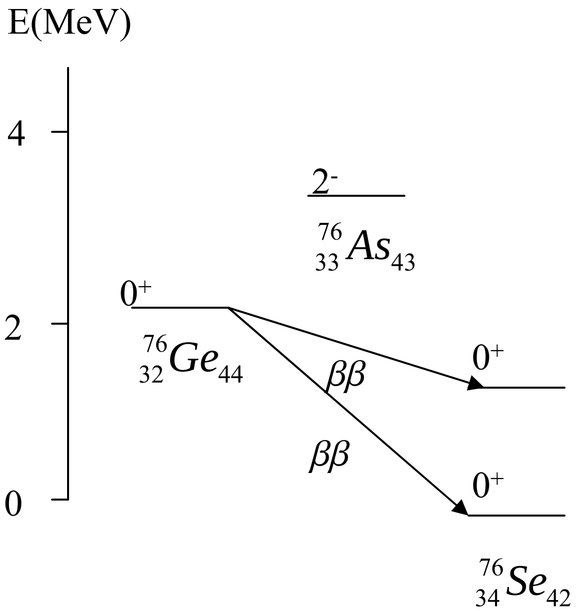
Lecture 3

BRIEF THEORY OF 0νββ

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z\pm 2}Y_{N\mp 2} + 2e^{\mp} $$



Half-life for the process:

$$ \left[T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+) \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^2 \left| f(m_i, U_{ei}) \right|^2 $$

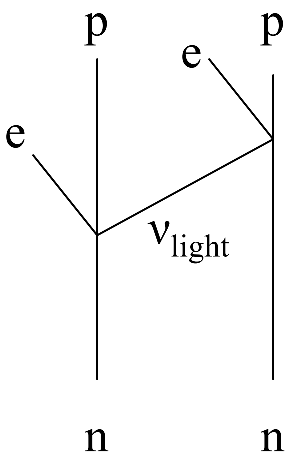
Beyond the standard model
(Particle physics)

Matrix elements
(Nuclear physics)

Phase-space factor
(Atomic physics)

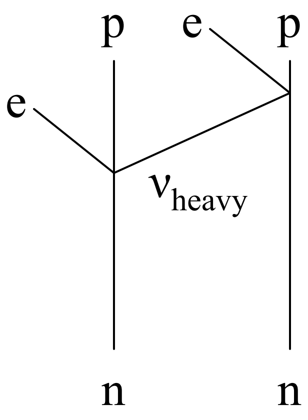
Three scenarios have been considered [¶,§].

1



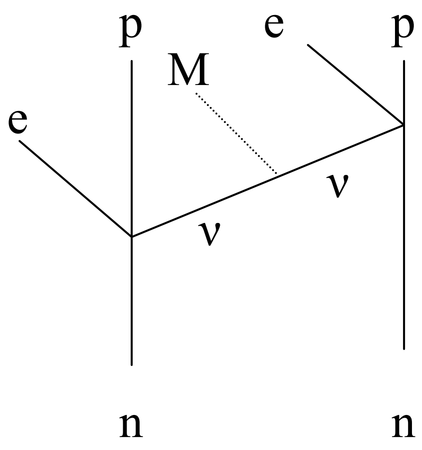
$m_{\nu light} \ll 1\text{MeV}$

2



$m_{\nu heavy} \gg 1\text{GeV}$

3



[¶] T.Tomoda, Rep. Prog. Phys. 54, 53 (1991).

[§] F.Šimkovic *et al.*, Phys. Rev. C60, 055502 (1999).

In this lecture, only scenarios 1 and 2 will be considered.

PHASE SPACE FACTORS (PSF)

PSF were calculated in the 1980's by Doi *et al.* [*]. Also, a calculation of phase-space factors is reported in the book of Boehm and Vogel [§]. These calculations use an approximate expression for the electron wave functions at the nucleus.

PSF have been recently recalculated [**] with exact Dirac electron wave functions and including screening by the electron cloud.

These new PSF are available from jenni.kotila@yale.edu
and are on the webpage www.nucleartheory.yale.edu

[*] M. Doi, T. Kotani, N. Nishiura, K. Okuda and E. Takasugi, Prog. Theor. Phys. 66 (1981) 1739.

[§] F. Bohm and P. Vogel, *Physics of massive neutrinos*, Cambridge University Press, 1987.

[**] J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).

The wave functions are obtained by solving numerically[¶] the Dirac equation with potential

$$V(r) = \begin{bmatrix} -\dfrac{Z_d}{r} \\ -Z_d\left(\dfrac{3-(r/R)^2}{2R}\right) \end{bmatrix} \varphi(r) \qquad \begin{matrix} r>R \\ r<R \end{matrix}$$

The function φ(r) is obtained numerically[§] by solving the Thomas-Fermi equation

$$\frac{d^2\varphi}{dx^2} = \frac{\varphi^{3/2}}{\sqrt{x}}$$

$$x = r/b$$

$$b \simeq 0.885 a_0 Z_d^{-1/3}$$

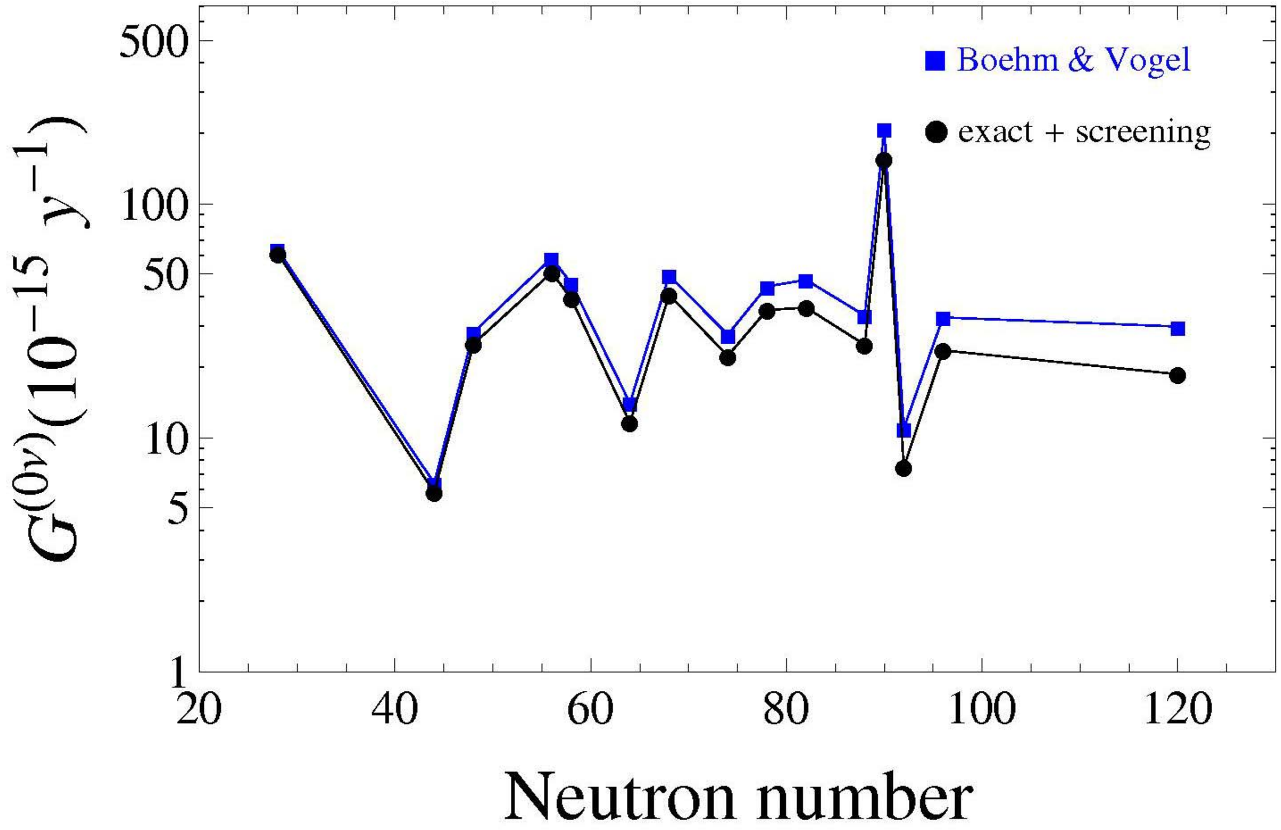
with boundary conditions (final nucleus positive ion with charge +2)

$$\varphi(0) = 1 \qquad \varphi(\infty) = \frac{2}{Z_d}$$

[¶] F. Salvat, J.M. Fernadez-Varea, and W. Williamson Jr., Comp. Phys. Comm. 90 (1995) 151.

[§] S. Esposito, Am. J. Phys. 70 (2002) 852. Method of solution suggested by Ettore Majorana.

Comparison between approximate § and exact + screening ¶ phase space factors



§ F. Böhm and P. Vogel, *loc. cit.*

¶ J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).

2νββ $\quad 0^+_1 \rightarrow 0^+_1$

Calculated quantities: $\boxed{G^{(0)}_{2\nu}}$ $\quad$ $\boxed{G^{(1)}_{2\nu}}$ $\quad$ [units yr^{-1}]

NME

From these, one has, with $N_{2\nu} = g_A^4 \left| m_e c^2 M^{2\nu} \right|^2 = \left| M_{2\nu} \right|^2 \longleftarrow$

Half-life $\quad \left[\tau^{2\nu}_{1/2}\right]^{-1} = N_{2\nu} G^{(0)}_{2\nu}$

Differential decay rate $\quad \dfrac{dW_{2\nu}}{d\varepsilon_1} = N_{2\nu} \dfrac{dG^{(0)}_{2\nu}}{d\varepsilon_1}$

Summed energy spectrum of the two electrons

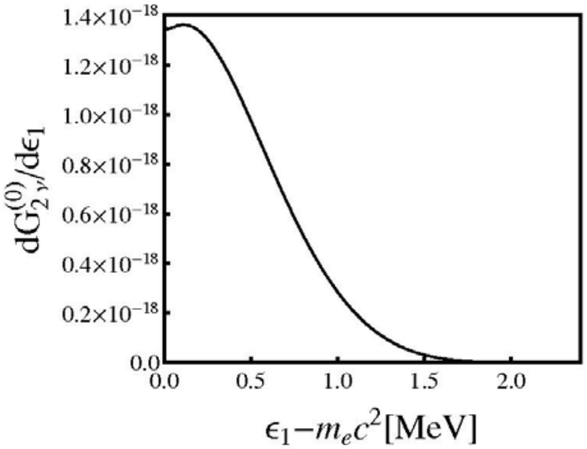
$$\frac{dW_{2\nu}}{d\left(\varepsilon_1 + \varepsilon_2 - 2m_e c^2\right)} = N_{2\nu} \frac{dG^{(0)}_{2\nu}}{d\left(\varepsilon_1 + \varepsilon_2 - 2m_e c^2\right)}$$

Angular correlation between the two electrons $\quad \alpha(\varepsilon_1) = \dfrac{dG^{(1)}_{2\nu} / d\varepsilon_1}{dG^{(0)}_{2\nu} / d\varepsilon_1}$

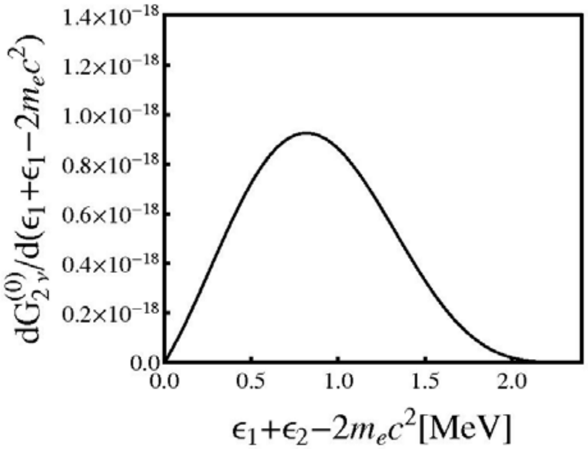
Double differential rate $\quad \dfrac{dW_{2\nu}}{d\varepsilon_1 d\left(\cos\theta_{12}\right)} = N_{2\nu} \dfrac{dG^{(0)}_{2\nu}}{d\varepsilon_1}\left[1 + \alpha(\varepsilon_1)\cos\theta_{12}\right]$

Example ^{136}Xe⟶^{136}Ba (EXO)

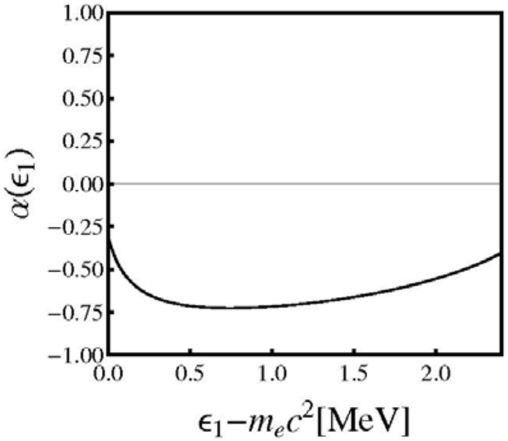
Differential rate



Summed electron spectrum

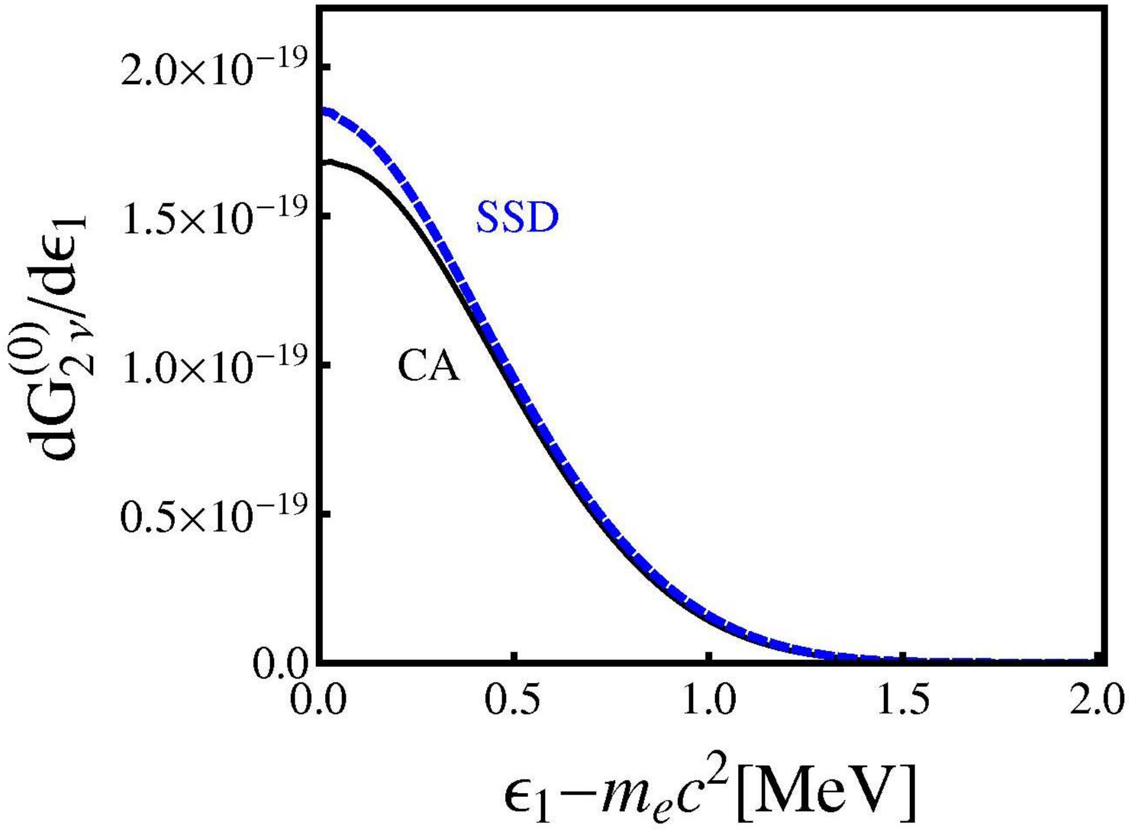


Angular correlation



If accurately measured one can distinguish between single state dominance (SSD) and closure approximation (CA).

Example: $^{110}\text{Pd} \longrightarrow {}^{110}\text{Cd}$ (COBRA)



0νββ $0_1^+ \to 0_1^+$

Calculated quantities $\boxed{G_{0\nu}^{(0)}}$ $\boxed{G_{0\nu}^{(1)}}$ [Units yr^{-1}]

$$f = \frac{\langle m_\nu \rangle}{m_e}$$

From these one has, with $$N_{0\nu} = g_A^4 \left| M^{0\nu} \right|^2 \left| f \right|^2$$

$$f_h = \frac{m_p}{\langle m_{\nu_h} \rangle}$$

Half-life $$\left[\tau_{1/2}^{0\nu} \right]^{-1} = N_{0\nu} G_{0\nu}^{(0)}$$

$$g_A^4 \left| M^{0\nu} \right|^2 = \left| M_{0\nu} \right|^2$$

$\nwarrow$

NME

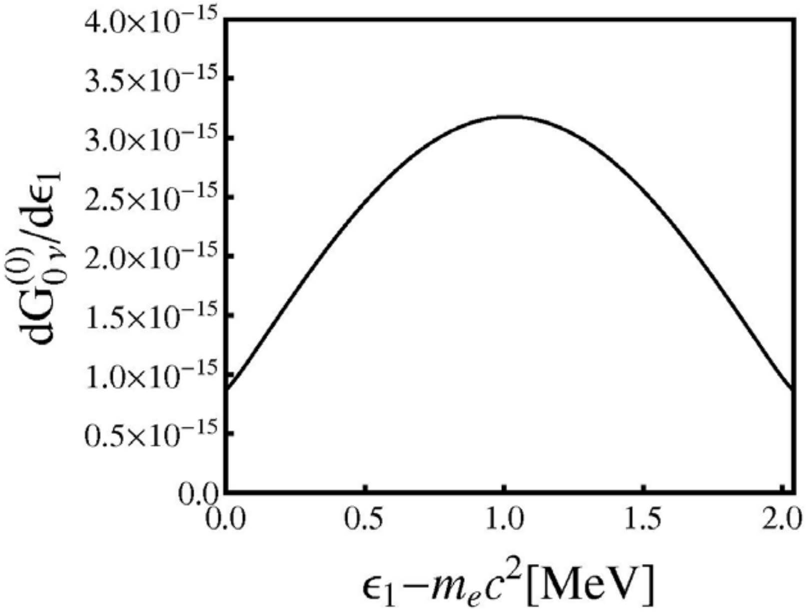
Single electron spectrum $$\frac{dW_{0\nu}}{d\varepsilon_1} = N_{0\nu} \frac{dG_{0\nu}^{(0)}}{d\varepsilon_1}$$

Angular correlation between the two electrons $$\alpha(\varepsilon_1) = \frac{dG_{0\nu}^{(1)} / d\varepsilon_1}{dG_{0\nu}^{(0)} / d\varepsilon_1}$$

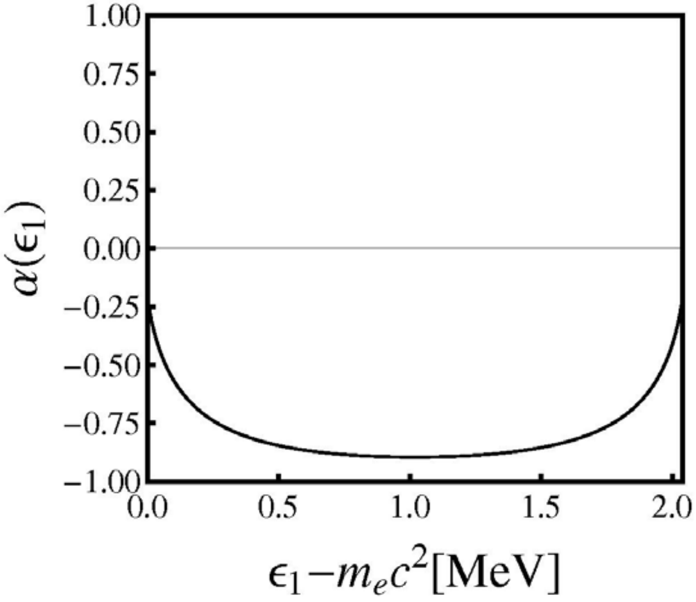
Double differential rate $$\frac{dW_{0\nu}}{d\varepsilon_1 d(\cos\theta_{12})} = N_{0\nu} \frac{dG_{0\nu}^{(0)}}{d\varepsilon_1} [1 + \alpha(\varepsilon_1) \cos\theta_{12}]$$

Example $^{76}\text{Ge} \longrightarrow {}^{76}\text{Se}$ (GERDA)

Single electron spectrum



Angular correlation

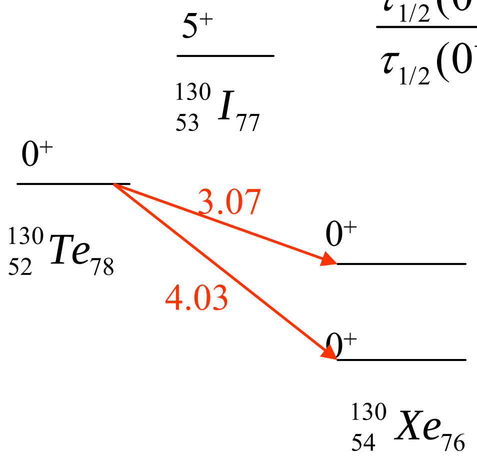


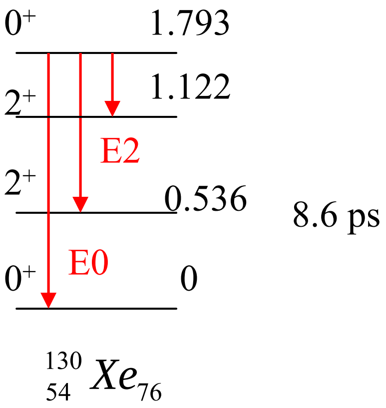
EXCITED STATES
Calculations of PSF for 0^+_2 states have been completed

In some cases, the matrix elements to the first excited 0^+ state are large. Although the kinematical factor hinders the decay to the excited state, large matrix elements offer the possibility of a direct detection, by looking at the γ-ray de-exciting the 0^+ level.

[On the contrary, matrix elements 0ν to the excited 2^+ state are zero in lowest order since with two leptons in the final state we cannot form angular momentum 2.]

$$\frac{\tau_{1/2}(0^+ \rightarrow 0^+_2)}{\tau_{1/2}(0^+ \rightarrow 0^+_1)} = 79.4$$





USE OF PSF

Simulations of expected spectra and fit to observed spectra

EXO

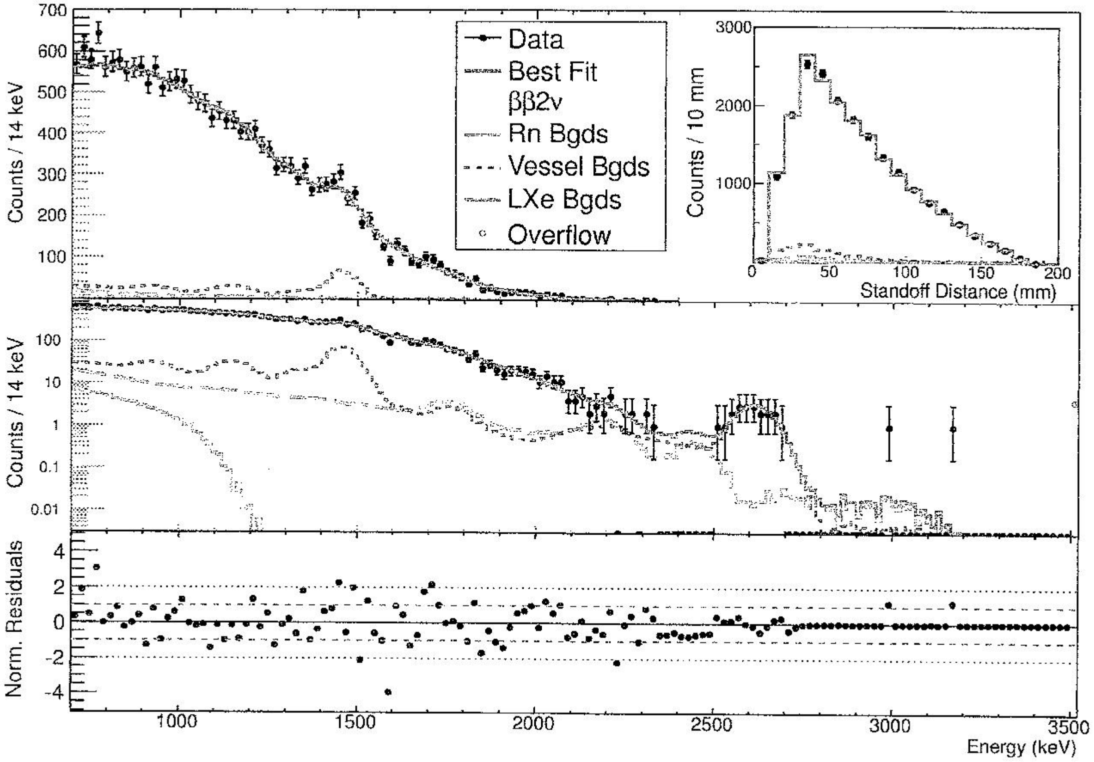
GERDA

SUPERNEMO

CUORE

J.B. Albert *et al*.

(EXO-200)



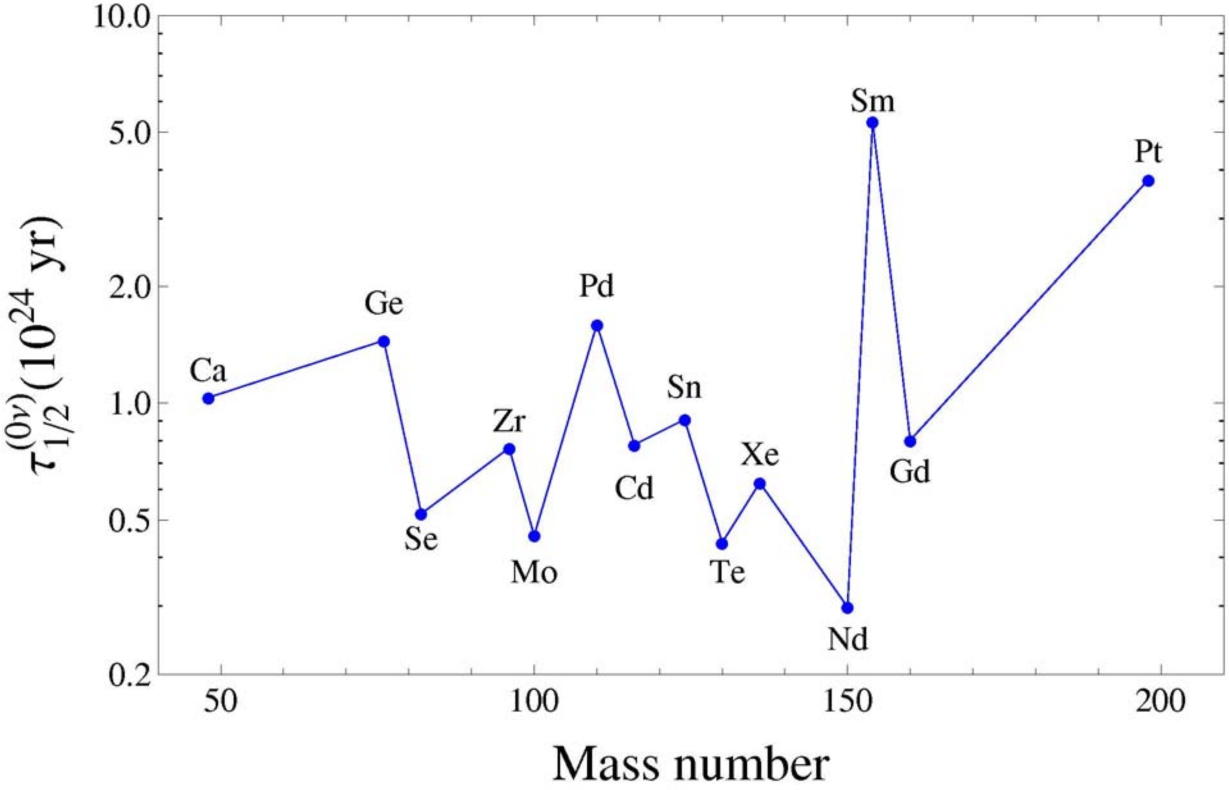
[For simulations, one may also need the
Triple differential rate

$$\frac{d^3 W_{2\nu}}{d\varepsilon_1 d\varepsilon_2 d(\cos\theta_{12})} = N_{2\nu}\left[\frac{d^2 G_{2\nu}^{(0)}}{d\varepsilon_1 d\varepsilon_2} + \frac{d^2 G_{2\nu}^{(1)}}{d\varepsilon_1 d\varepsilon_2}\cos\theta_{12}\right] \equiv T\left(\varepsilon_1, \varepsilon_2, \theta_{12}\right)$$

This was not reported in KI but can be extracted easily from the program and is now (2015) available.]

From the calculated NME (lecture 2) and PSF (lecture 3), and using the formulas of lecture 1, one can calculate the expected half-lives for neutrinoless double beta decay, double positron decay and double resonant electron capture

FINAL RESULTS FOR HALF-LIVES (LIGHT NEUTRINOS) (2013)



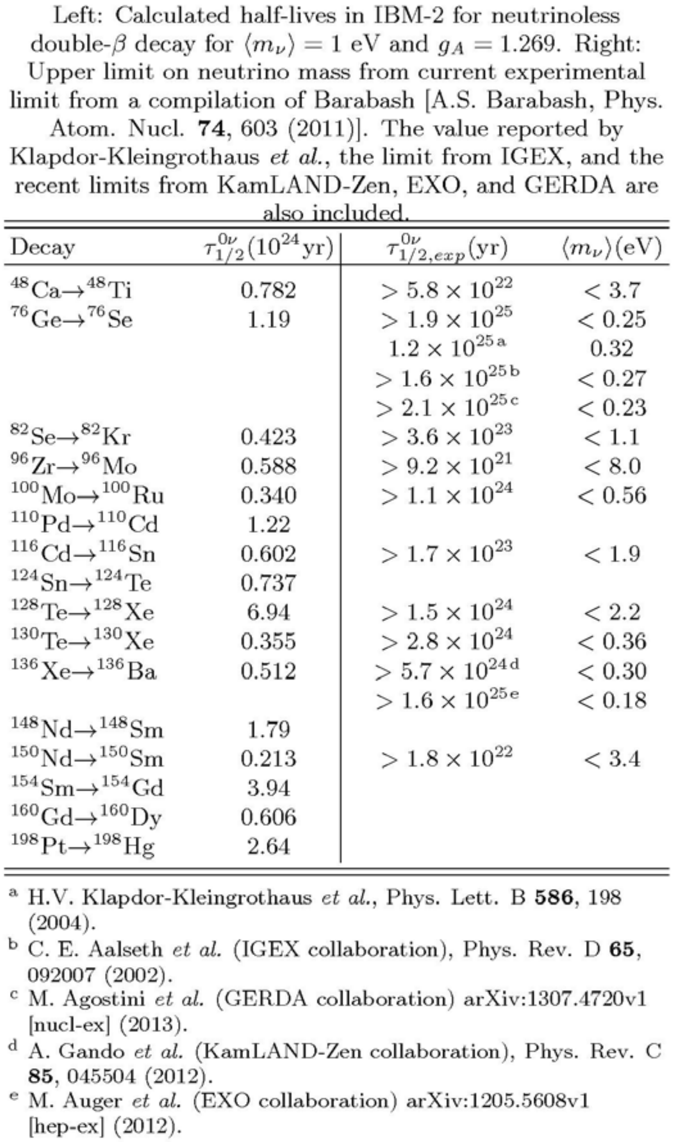
m_ν= 1 eV
g_A=1.269

Nuclear matrix elements from J. Barea and F. Iachello, Phys. Rev. C79, 044301 (2009) and J. Barea, J. Kotila and F. Iachello, Phys. Rev. C87, 014315 (2013). Phase space factors from J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012).

From experimental limits on half lives one can extract limits on neutrino masses. The best limit is from EXO (2012) in ^{136}Xe

$$\tau^{0\nu}_{1/2,\exp}(^{136}Xe) > 1.6 \times 10^{25}\, yr$$

IBM-2 HALF-LIVES AND MASS LIMITS: LIGHT NEUTRINO (2013)



Left: Calculated half-lives in IBM-2 for neutrinoless double-β decay for $\langle m_\nu \rangle = 1$ eV and $g_A = 1.269$. Right: Upper limit on neutrino mass from current experimental limit from a compilation of Barabash [A.S. Barabash, Phys. Atom. Nucl. **74**, 603 (2011)]. The value reported by Klapdor-Kleingrothaus *et al.*, the limit from IGEX, and the recent limits from KamLAND-Zen, EXO, and GERDA are also included.

Decay	$\tau^{0\nu}_{1/2}(10^{24}\text{yr})$	$\tau^{0\nu}_{1/2,exp}(\text{yr})$	$\langle m_\nu \rangle(\text{eV})$
^{48}Ca$\to^{48}$Ti	0.782	$> 5.8 \times 10^{22}$	< 3.7
^{76}Ge$\to^{76}$Se	1.19	$> 1.9 \times 10^{25}$	< 0.25
		1.2×10^{25} [a]	0.32
		$> 1.6 \times 10^{25}$ [b]	< 0.27
		$> 2.1 \times 10^{25}$ [c]	< 0.23
^{82}Se$\to^{82}$Kr	0.423	$> 3.6 \times 10^{23}$	< 1.1
^{96}Zr$\to^{96}$Mo	0.588	$> 9.2 \times 10^{21}$	< 8.0
^{100}Mo$\to^{100}$Ru	0.340	$> 1.1 \times 10^{24}$	< 0.56
^{110}Pd$\to^{110}$Cd	1.22		
^{116}Cd$\to^{116}$Sn	0.602	$> 1.7 \times 10^{23}$	< 1.9
^{124}Sn$\to^{124}$Te	0.737		
^{128}Te$\to^{128}$Xe	6.94	$> 1.5 \times 10^{24}$	< 2.2
^{130}Te$\to^{130}$Xe	0.355	$> 2.8 \times 10^{24}$	< 0.36
^{136}Xe$\to^{136}$Ba	0.512	$> 5.7 \times 10^{24}$ [d]	< 0.30
		$> 1.6 \times 10^{25}$ [e]	< 0.18
^{148}Nd$\to^{148}$Sm	1.79		
^{150}Nd$\to^{150}$Sm	0.213	$> 1.8 \times 10^{22}$	< 3.4
^{154}Sm$\to^{154}$Gd	3.94		
^{160}Gd$\to^{160}$Dy	0.606		
^{198}Pt$\to^{198}$Hg	2.64		

[a] H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).

[b] C. E. Aalseth *et al.* (IGEX collaboration), Phys. Rev. D **65**, 092007 (2002).

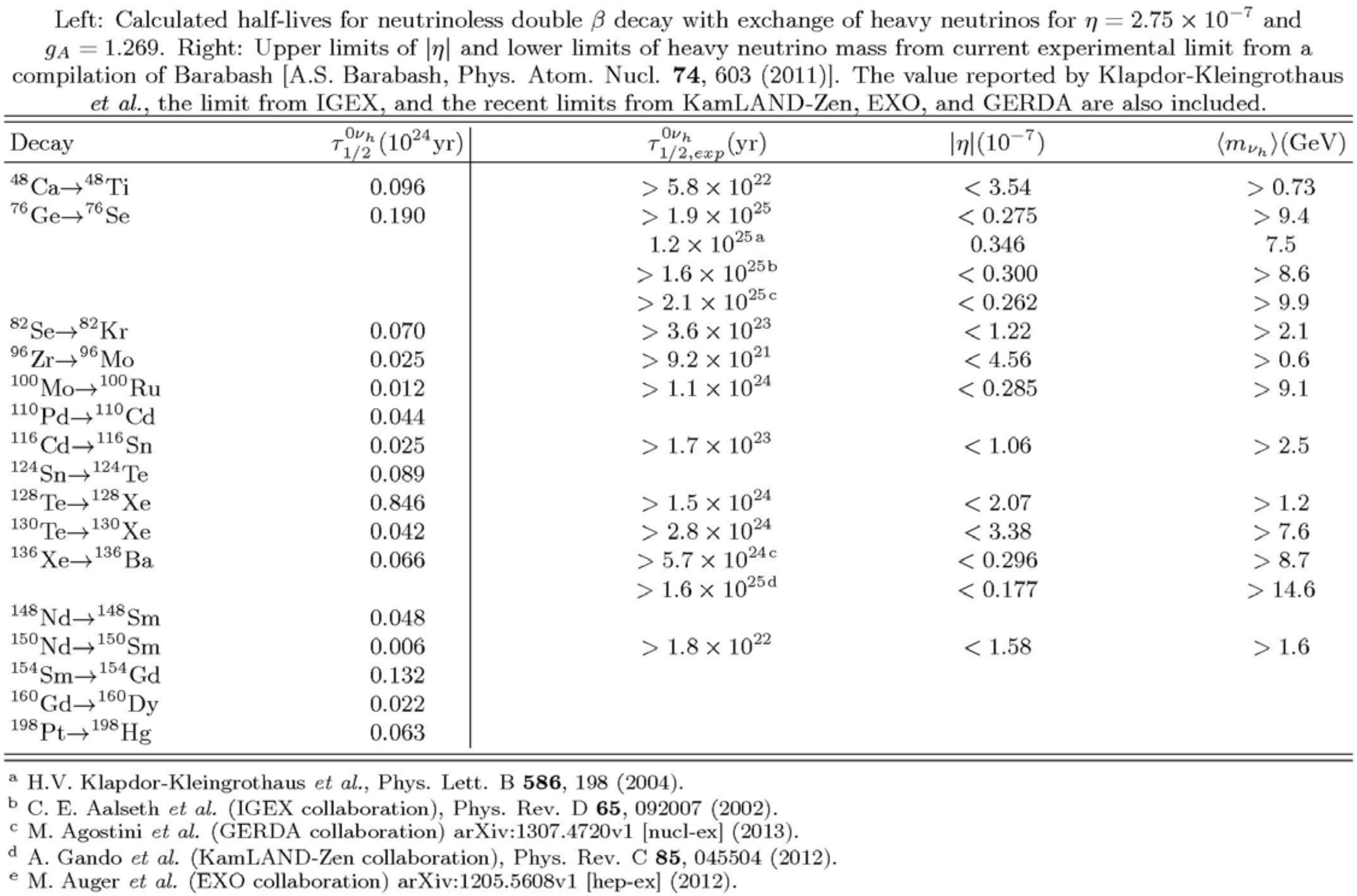
[c] M. Agostini *et al.* (GERDA collaboration) arXiv:1307.4720v1 [nucl-ex] (2013).

[d] A. Gando *et al.* (KamLAND-Zen collaboration), Phys. Rev. C **85**, 045504 (2012).

[e] M. Auger *et al.* (EXO collaboration) arXiv:1205.5608v1 [hep-ex] (2012).

← Best limit

IBM-2 HALF-LIVES AND MASS LIMITS: HEAVY NEUTRINO (2013)



Left: Calculated half-lives for neutrinoless double β decay with exchange of heavy neutrinos for $\eta = 2.75 \times 10^{-7}$ and $g_A = 1.269$. Right: Upper limits of $|\eta|$ and lower limits of heavy neutrino mass from current experimental limit from a compilation of Barabash [A.S. Barabash, Phys. Atom. Nucl. **74**, 603 (2011)]. The value reported by Klapdor-Kleingrothaus *et al.*, the limit from IGEX, and the recent limits from KamLAND-Zen, EXO, and GERDA are also included.

Decay	$\tau^{0\nu_h}_{1/2}(10^{24}\mathrm{yr})$	$\tau^{0\nu_h}_{1/2,exp}(\mathrm{yr})$	$\lvert\eta\rvert(10^{-7})$	$\langle m_{\nu_h}\rangle(\mathrm{GeV})$
^{48}Ca→^{48}Ti	0.096	$> 5.8 \times 10^{22}$	< 3.54	> 0.73
^{76}Ge→^{76}Se	0.190	$> 1.9 \times 10^{25}$	< 0.275	> 9.4
		1.2×10^{25} [a]	0.346	7.5
		$> 1.6 \times 10^{25}$ [b]	< 0.300	> 8.6
		$> 2.1 \times 10^{25}$ [c]	< 0.262	> 9.9
^{82}Se→^{82}Kr	0.070	$> 3.6 \times 10^{23}$	< 1.22	> 2.1
^{96}Zr→^{96}Mo	0.025	$> 9.2 \times 10^{21}$	< 4.56	> 0.6
^{100}Mo→^{100}Ru	0.012	$> 1.1 \times 10^{24}$	< 0.285	> 9.1
^{110}Pd→^{110}Cd	0.044			
^{116}Cd→^{116}Sn	0.025	$> 1.7 \times 10^{23}$	< 1.06	> 2.5
^{124}Sn→^{124}Te	0.089			
^{128}Te→^{128}Xe	0.846	$> 1.5 \times 10^{24}$	< 2.07	> 1.2
^{130}Te→^{130}Xe	0.042	$> 2.8 \times 10^{24}$	< 3.38	> 7.6
^{136}Xe→^{136}Ba	0.066	$> 5.7 \times 10^{24}$ [c]	< 0.296	> 8.7
		$> 1.6 \times 10^{25}$ [d]	< 0.177	> 14.6
^{148}Nd→^{148}Sm	0.048			
^{150}Nd→^{150}Sm	0.006	$> 1.8 \times 10^{22}$	< 1.58	> 1.6
^{154}Sm→^{154}Gd	0.132			
^{160}Gd→^{160}Dy	0.022			
^{198}Pt→^{198}Hg	0.063			

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[a] H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).

[b] C. E. Aalseth *et al.* (IGEX collaboration), Phys. Rev. D **65**, 092007 (2002).

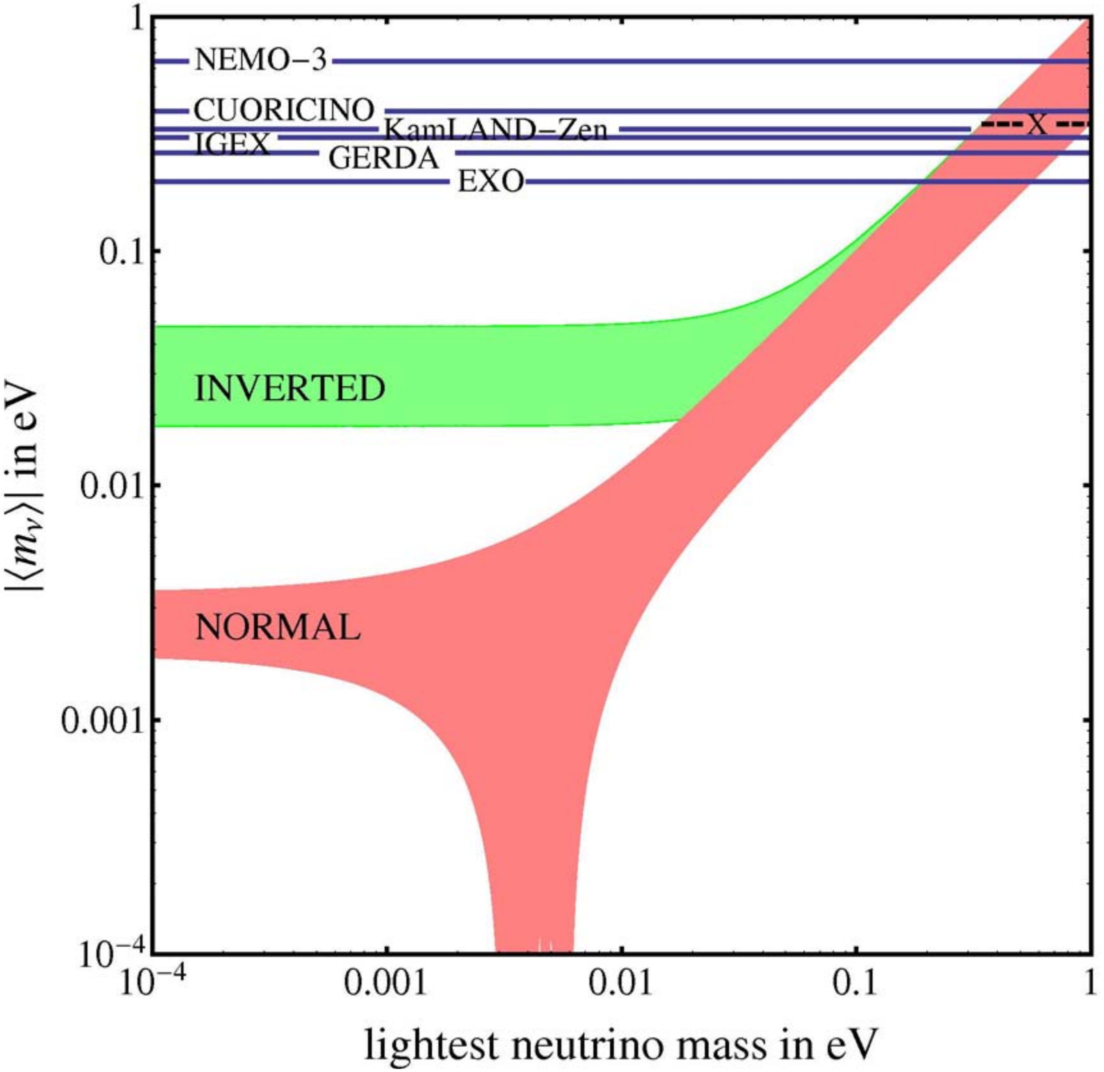
[c] M. Agostini *et al.* (GERDA collaboration) arXiv:1307.4720v1 [nucl-ex] (2013).

[d] A. Gando *et al.* (KamLAND-Zen collaboration), Phys. Rev. C **85**, 045504 (2012).

[e] M. Auger *et al.* (EXO collaboration) arXiv:1205.5608v1 [hep-ex] (2012).

Best limit
MS-SRC
and
$M_{WR} = 3.5 TeV$

SUMMARY OF RESULTS ¶
LIGHT NEUTRINO (2013)



$g_A=1.269$

x H. V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B586, 198 (2004).

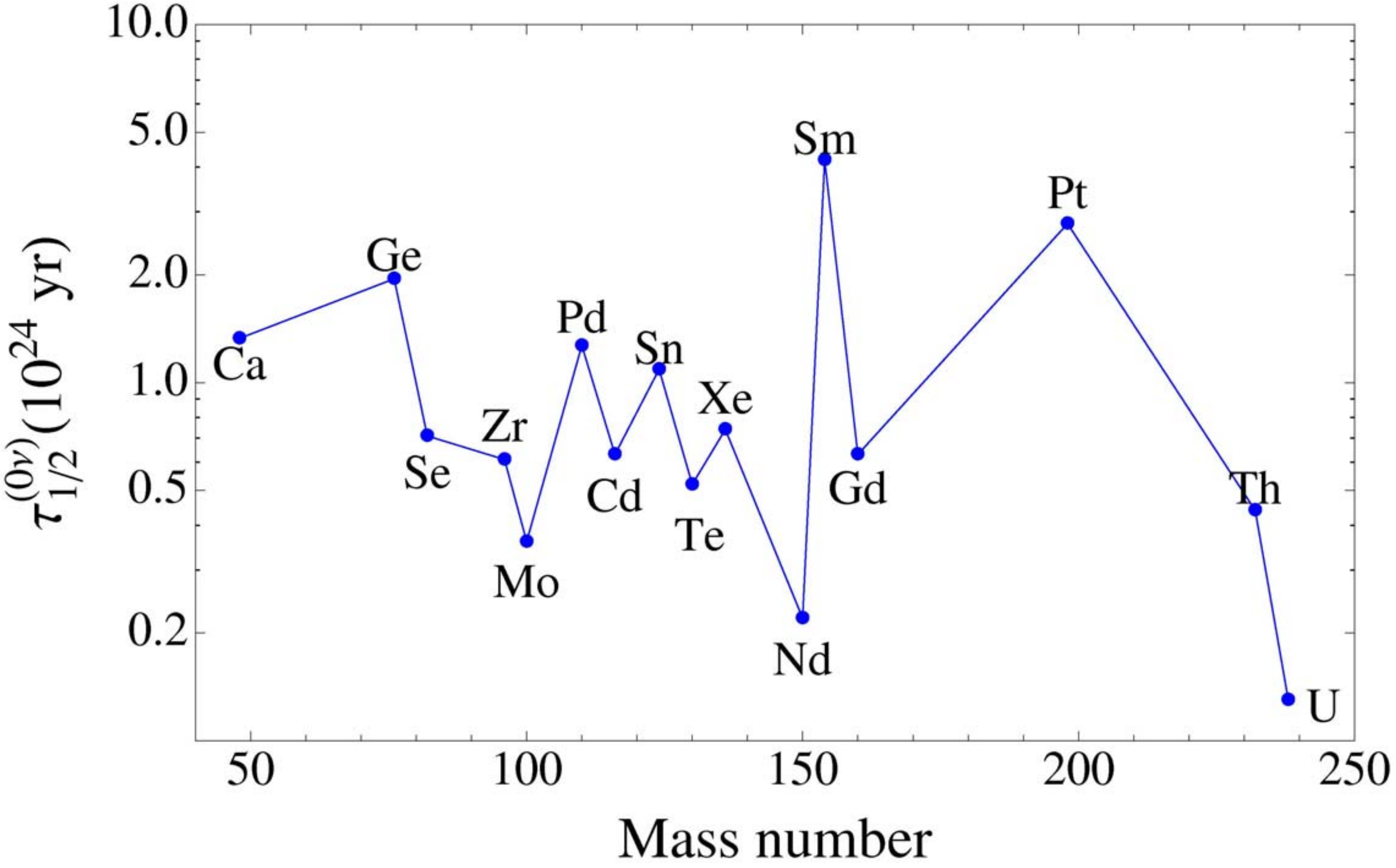
NOTE ADDED (2015)

As mentioned in lecture 2, a better choice of SRC is Argonne hard SRC and isospin projection should be included. These corrections affect only mildly light neutrino exchange but greatly heavy neutrino exchange

The best limit on half-lives is now from KamLAND-Zen (2013)

$$\tau^{0\nu}_{1/2,\exp}(^{136}Xe) > 1.9 \times 10^{25}\, yr$$

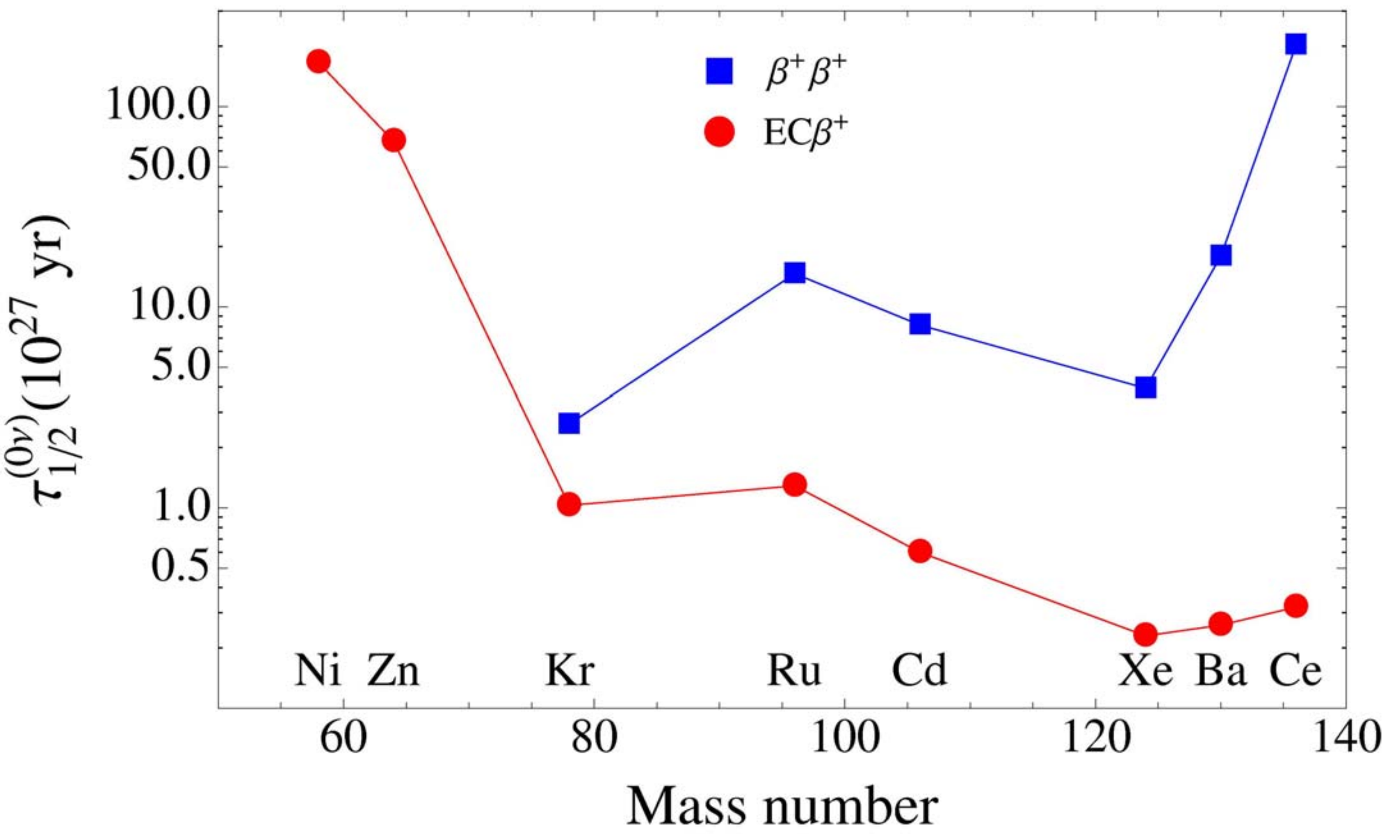
EXPECTED HALF-LIVES (2015) $0\nu\beta^-\beta^-$



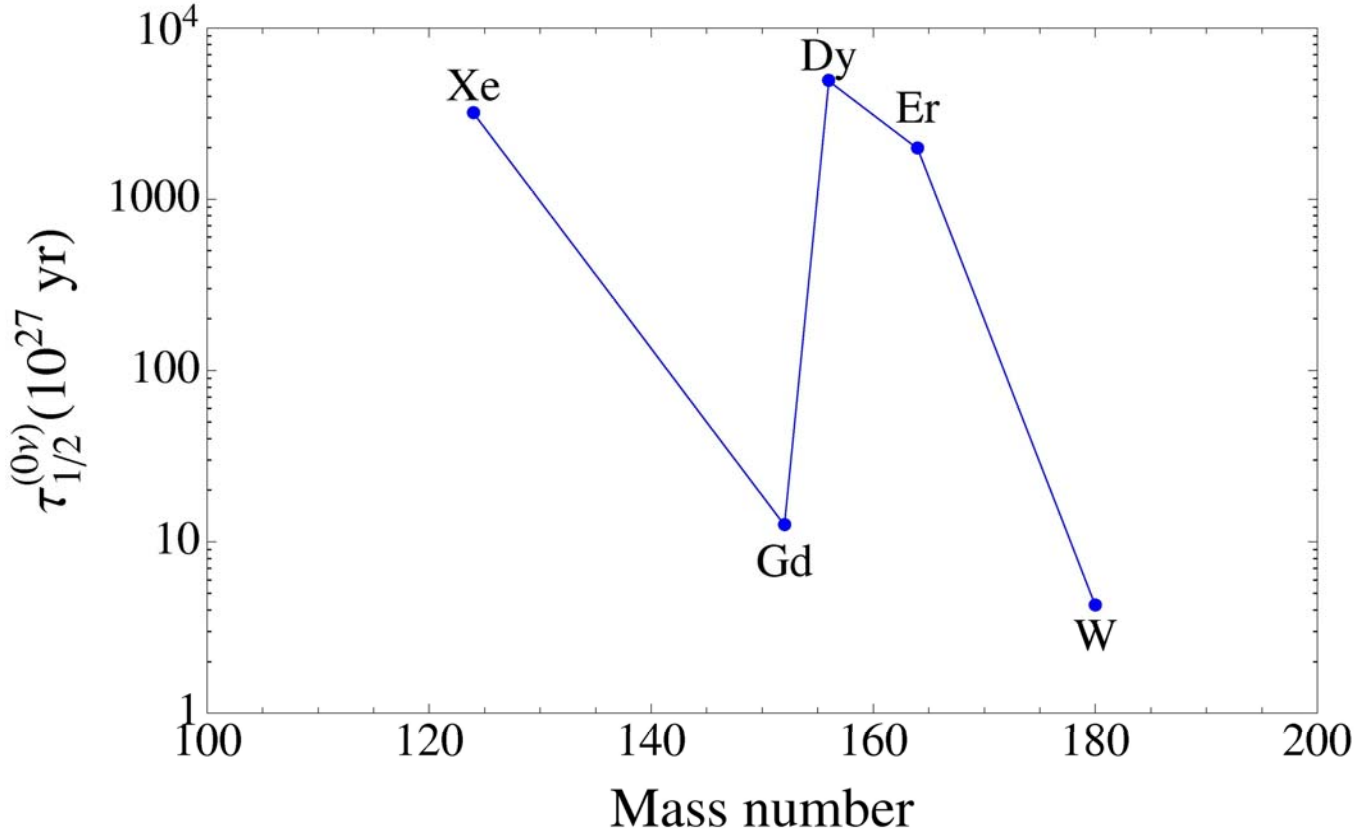
$$\langle m_\nu \rangle = 1.0eV$$

$$g_A = 1.269$$

EXPECTED HALF-LIVES (2015) $0\nu\beta^+\beta^+/0\nu\beta^+EC$



EXPECTED HALF-LIVES (2015) R0νECEC

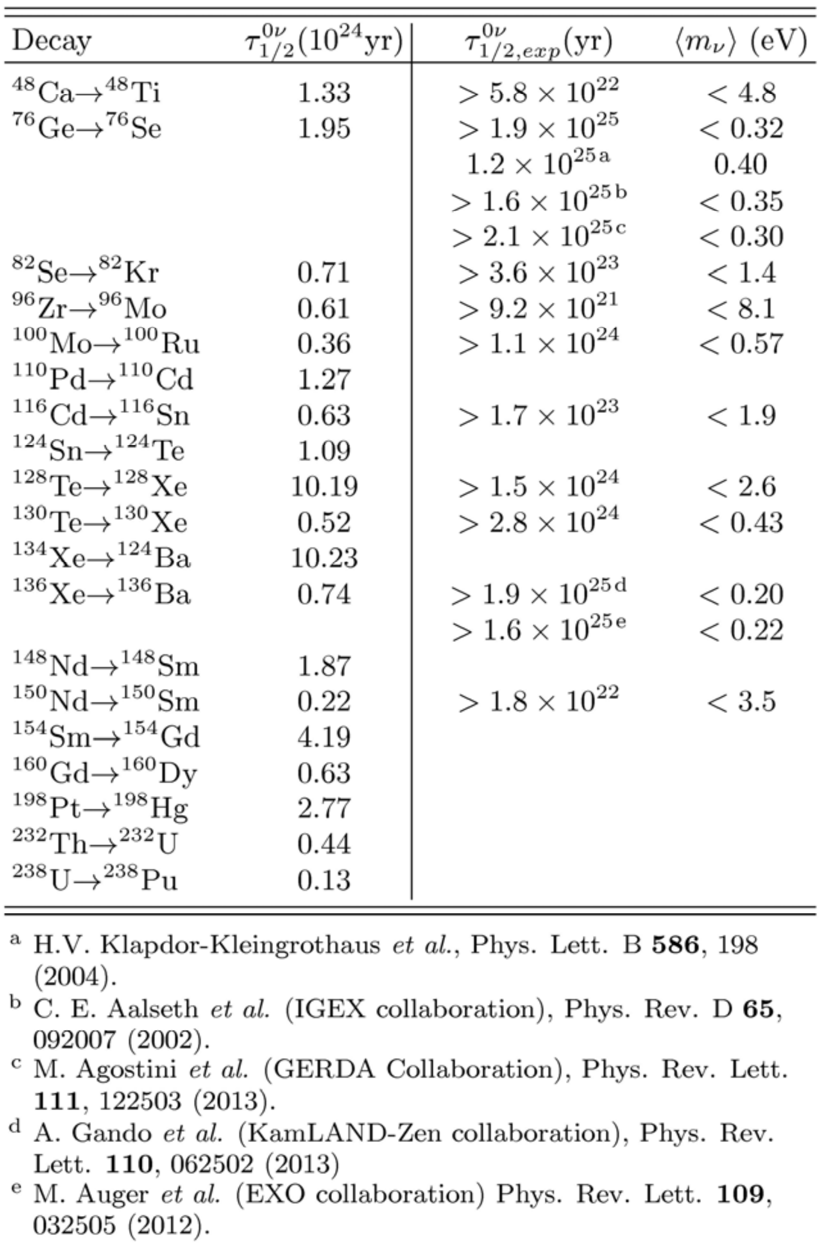


g_A=1.269

$$\langle m_\nu \rangle = 1eV$$

LIMITS ON NEUTRINO MASSES (2015)

g_A=1.269



Decay	$\tau^{0\nu}_{1/2}(10^{24}\mathrm{yr})$	$\tau^{0\nu}_{1/2,exp}(\mathrm{yr})$	$\langle m_\nu \rangle$ (eV)
$^{48}\mathrm{Ca}\to{}^{48}\mathrm{Ti}$	1.33	$> 5.8 \times 10^{22}$	< 4.8
$^{76}\mathrm{Ge}\to{}^{76}\mathrm{Se}$	1.95	$> 1.9 \times 10^{25}$	< 0.32
		$1.2 \times 10^{25\,\mathrm{a}}$	0.40
		$> 1.6 \times 10^{25\,\mathrm{b}}$	< 0.35
		$> 2.1 \times 10^{25\,\mathrm{c}}$	< 0.30
$^{82}\mathrm{Se}\to{}^{82}\mathrm{Kr}$	0.71	$> 3.6 \times 10^{23}$	< 1.4
$^{96}\mathrm{Zr}\to{}^{96}\mathrm{Mo}$	0.61	$> 9.2 \times 10^{21}$	< 8.1
$^{100}\mathrm{Mo}\to{}^{100}\mathrm{Ru}$	0.36	$> 1.1 \times 10^{24}$	< 0.57
$^{110}\mathrm{Pd}\to{}^{110}\mathrm{Cd}$	1.27		
$^{116}\mathrm{Cd}\to{}^{116}\mathrm{Sn}$	0.63	$> 1.7 \times 10^{23}$	< 1.9
$^{124}\mathrm{Sn}\to{}^{124}\mathrm{Te}$	1.09		
$^{128}\mathrm{Te}\to{}^{128}\mathrm{Xe}$	10.19	$> 1.5 \times 10^{24}$	< 2.6
$^{130}\mathrm{Te}\to{}^{130}\mathrm{Xe}$	0.52	$> 2.8 \times 10^{24}$	< 0.43
$^{134}\mathrm{Xe}\to{}^{124}\mathrm{Ba}$	10.23		
$^{136}\mathrm{Xe}\to{}^{136}\mathrm{Ba}$	0.74	$> 1.9 \times 10^{25\,\mathrm{d}}$	< 0.20
		$> 1.6 \times 10^{25\,\mathrm{e}}$	< 0.22
$^{148}\mathrm{Nd}\to{}^{148}\mathrm{Sm}$	1.87		
$^{150}\mathrm{Nd}\to{}^{150}\mathrm{Sm}$	0.22	$> 1.8 \times 10^{22}$	< 3.5
$^{154}\mathrm{Sm}\to{}^{154}\mathrm{Gd}$	4.19		
$^{160}\mathrm{Gd}\to{}^{160}\mathrm{Dy}$	0.63		
$^{198}\mathrm{Pt}\to{}^{198}\mathrm{Hg}$	2.77		
$^{232}\mathrm{Th}\to{}^{232}\mathrm{U}$	0.44		
$^{238}\mathrm{U}\to{}^{238}\mathrm{Pu}$	0.13		

[a] H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).

[b] C. E. Aalseth *et al.* (IGEX collaboration), Phys. Rev. D **65**, 092007 (2002).

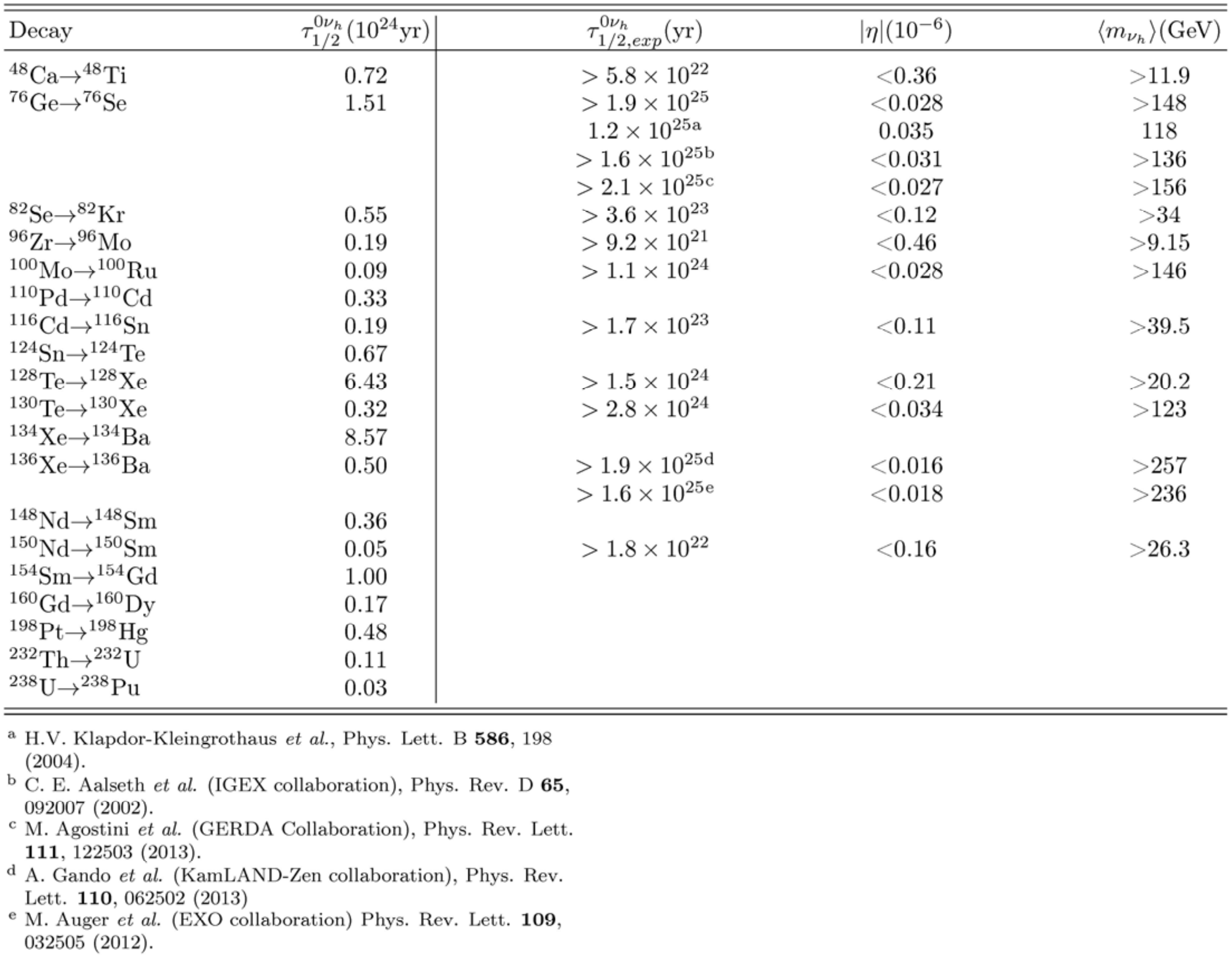
[c] M. Agostini *et al.* (GERDA Collaboration), Phys. Rev. Lett. **111**, 122503 (2013).

[d] A. Gando *et al.* (KamLAND-Zen collaboration), Phys. Rev. Lett. **110**, 062502 (2013)

[e] M. Auger *et al.* (EXO collaboration) Phys. Rev. Lett. **109**, 032505 (2012).

LIMITS ON MEUTRINO MASSES (HEAVY EXCHANGE) 2015

g_A=1.269



Decay	$\tau_{1/2}^{0\nu_h}(10^{24}\mathrm{yr})$	$\tau_{1/2,exp}^{0\nu_h}(\mathrm{yr})$	$\|\eta\|(10^{-6})$	$\langle m_{\nu_h}\rangle(\mathrm{GeV})$
$^{48}\mathrm{Ca}\rightarrow^{48}\mathrm{Ti}$	0.72	$> 5.8 \times 10^{22}$	<0.36	>11.9
$^{76}\mathrm{Ge}\rightarrow^{76}\mathrm{Se}$	1.51	$> 1.9 \times 10^{25}$	<0.028	>148
		$1.2 \times 10^{25\mathrm{a}}$	0.035	118
		$> 1.6 \times 10^{25\mathrm{b}}$	<0.031	>136
		$> 2.1 \times 10^{25\mathrm{c}}$	<0.027	>156
$^{82}\mathrm{Se}\rightarrow^{82}\mathrm{Kr}$	0.55	$> 3.6 \times 10^{23}$	<0.12	>34
$^{96}\mathrm{Zr}\rightarrow^{96}\mathrm{Mo}$	0.19	$> 9.2 \times 10^{21}$	<0.46	>9.15
$^{100}\mathrm{Mo}\rightarrow^{100}\mathrm{Ru}$	0.09	$> 1.1 \times 10^{24}$	<0.028	>146
$^{110}\mathrm{Pd}\rightarrow^{110}\mathrm{Cd}$	0.33			
$^{116}\mathrm{Cd}\rightarrow^{116}\mathrm{Sn}$	0.19	$> 1.7 \times 10^{23}$	<0.11	>39.5
$^{124}\mathrm{Sn}\rightarrow^{124}\mathrm{Te}$	0.67			
$^{128}\mathrm{Te}\rightarrow^{128}\mathrm{Xe}$	6.43	$> 1.5 \times 10^{24}$	<0.21	>20.2
$^{130}\mathrm{Te}\rightarrow^{130}\mathrm{Xe}$	0.32	$> 2.8 \times 10^{24}$	<0.034	>123
$^{134}\mathrm{Xe}\rightarrow^{134}\mathrm{Ba}$	8.57			
$^{136}\mathrm{Xe}\rightarrow^{136}\mathrm{Ba}$	0.50	$> 1.9 \times 10^{25\mathrm{d}}$	<0.016	>257
		$> 1.6 \times 10^{25\mathrm{e}}$	<0.018	>236
$^{148}\mathrm{Nd}\rightarrow^{148}\mathrm{Sm}$	0.36			
$^{150}\mathrm{Nd}\rightarrow^{150}\mathrm{Sm}$	0.05	$> 1.8 \times 10^{22}$	<0.16	>26.3
$^{154}\mathrm{Sm}\rightarrow^{154}\mathrm{Gd}$	1.00			
$^{160}\mathrm{Gd}\rightarrow^{160}\mathrm{Dy}$	0.17			
$^{198}\mathrm{Pt}\rightarrow^{198}\mathrm{Hg}$	0.48			
$^{232}\mathrm{Th}\rightarrow^{232}\mathrm{U}$	0.11			
$^{238}\mathrm{U}\rightarrow^{238}\mathrm{Pu}$	0.03			

[a] H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).

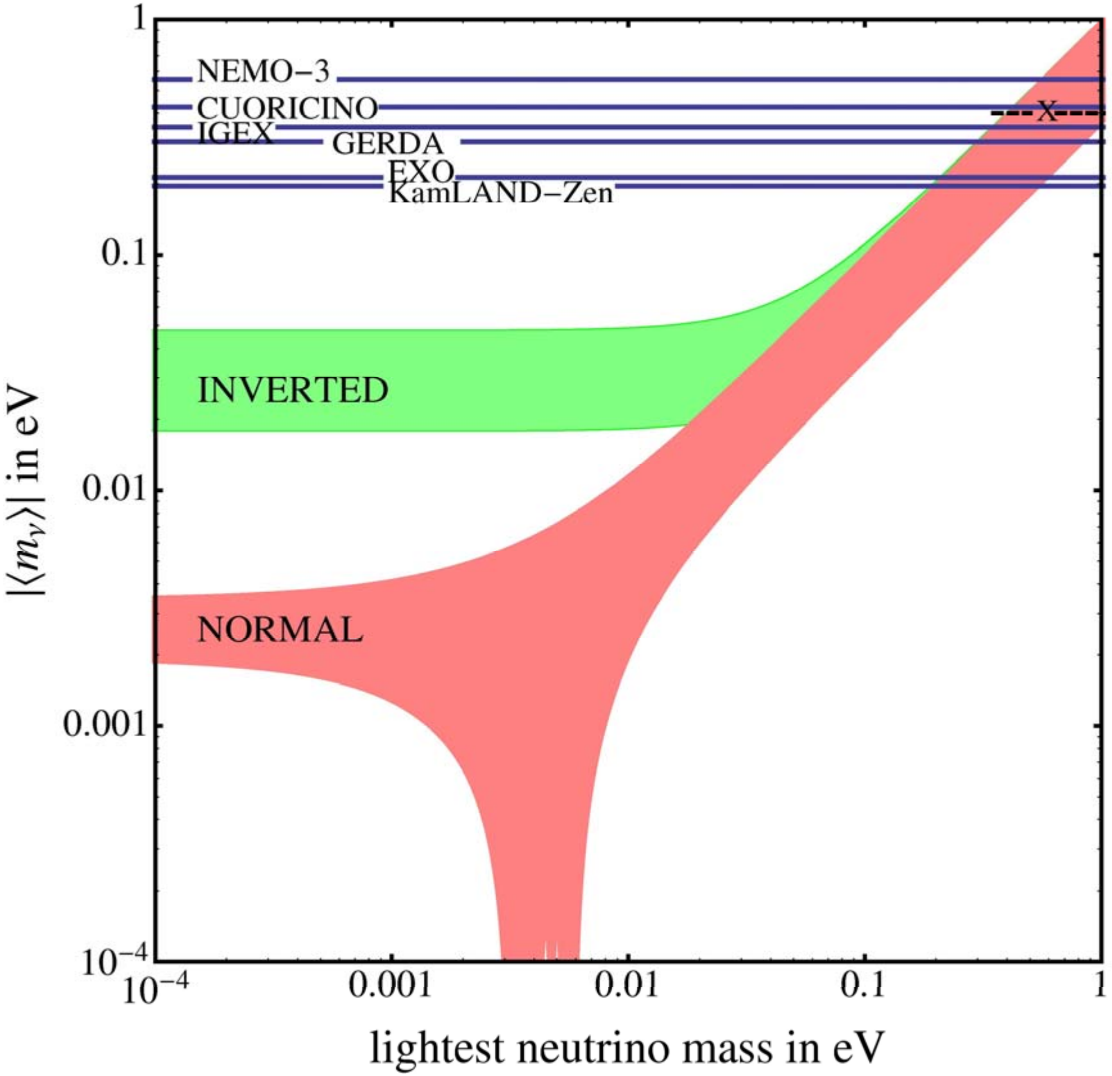
[b] C. E. Aalseth *et al.* (IGEX collaboration), Phys. Rev. D **65**, 092007 (2002).

[c] M. Agostini *et al.* (GERDA Collaboration), Phys. Rev. Lett. **111**, 122503 (2013).

[d] A. Gando *et al.* (KamLAND-Zen collaboration), Phys. Rev. Lett. **110**, 062502 (2013)

[e] M. Auger *et al.* (EXO collaboration) Phys. Rev. Lett. **109**, 032505 (2012).

SUMMARY OF RESULTS (LIGHT NEUTRINOS) 2015



$g_A = 1.269$

CONCLUSIONS

Major progress has been made in the last two years to narrow down predictions for NME in all nuclei of interest.

Calculations are available for NME and PSF for all processes, 0νββ, 0νβEC, 0νECEC; 2νββ, 2νβEC, 2νECEC.

With current estimates and g_A=1.269:

For light neutrino exchange, only the degenerate region can be tested in the immediate future. The current best limit (with g_A=1.269) is from KamLAND-Zen, $m_\nu<0.20$ eV.
Exploration of the inverted region >1 ton
Exploration of the normal region >>1 ton

For heavy neutrino exchange, the limit is model dependent. In the model of Tello *et al.* ¶, the current best limit from KamLAND-Zen is $m_{\nu h}>257$ GeV$(3.5/M_{WR})^4$.

¶ V. Tello, M. Nemevšek, F. Nesti, O. Senjanovic, and F. Vissani, Phys. Rev. Lett. 106, 151801 (2011).

The major remaining question is the value of g_A.

Three scenarios are[¶,§] :

$g_A = 1.269$ ← Free value

$g_A = 1$ ← Quark value

$g_A = 1.269A^{-0.18}$ ← Maximal quenching

[¶] J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C 87, 014315 (2013).

[§] S. Dell'Oro, S. Marcocci, and F. Vissani, Phys. Rev. D90, 033005 (2014)

If g_A is renormalized to 0.8-0.6, as in single β/EC, and 2νββ (discussed in lecture 2), maximal quenching, all estimates should be increased by a factor of 4-16 making it impossible to reach, in the foreseeable future, even the inverted region.

Possibilities to escape this negative conclusion are:
(1) The neutrino masses are degenerate and large.

This possibility will be in tension with the cosmological bound on the sum of the neutrino masses (lecture 1)

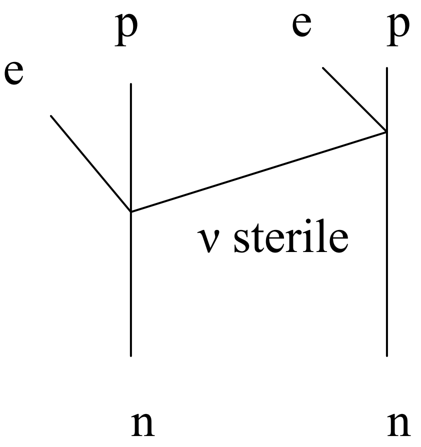
(2) Both mechanisms, light and heavy contribute simultaneously, are of the same order of magnitude, and interfere constructively.

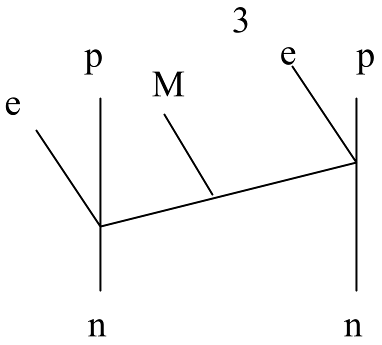
$$[\tau_{1/2}^{0\nu\beta\beta}(0^+ \to 0^+)] = G_{0\nu}\left| M_{0\nu,light}\frac{\langle m_\nu \rangle}{m_e} + M_{0\nu,heavy}\frac{m_p}{\langle m_{\nu_h} \rangle}\right|^2$$

This possibility requires a fine tuning which is quite unlikely.

(3) Other scenarios (Majoron emission, …) and/or new mechanisms (sterile neutrinos, …) must be considered.

These possibilities are currently being investigated (see lecture 1).





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