RECENT RESULTS IN THE THEORY OF DOUBLE β-DECAY

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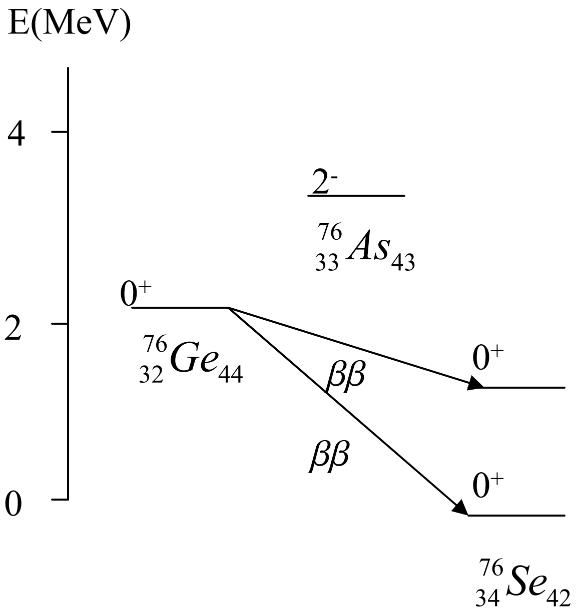
Neutrinoless double beta decay is of fundamental importance for determining the Majorana[§] *, or Dirac, nature of the neutrino and for confirming a non-zero value of its mass as established by neutrino oscillation experiments.*

[§] E. Majorana, Nuovo Cimento 14, 171 (1937).
G. Racah, Nuovo Cimento 14, 322 (1937).

INTRODUCTION

Fundamental Process $0\nu\beta\beta$:

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



Half-life for the process:

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

Beyond the standard model
(Particle physics)

Matrix elements
(Nuclear physics)

Phase-space factor
(Atomic physics)

BRIEF REVIEW OF THEORY OF NEUTRINOLESS DBD

Weak Lagrangean L → Transition operator T

p=momentum transferred to the leptons

$$\boxed{T(p)=H(p)f(m_i,U_{ei})}$$

$$\boxed{H(p)=\sum_{n,n'}\tau_n^{\dagger}\tau_{n'}^{\dagger}\left[-h^{F}(p)+h^{GT}(p)\vec{\sigma}_n\cdot\vec{\sigma}_{n'}+h^{T}(p)S^{p}_{nn'}\right]}$$

$$\boxed{h^{F,GT,T}(p)=v(p)\tilde{h}^{F,GT,T}(p)}$$

Neutrino “potential”

Form factors listed in F. Šimkovic *et al.*, Phys. Rev. C60, 055502 (1999)

This form assumes the closure approximation (good for 0νββ).

Finite nucleon size (FNS) is taken into account by taking the coupling constants, g_V and g_A, momentum dependent

$$g_V(p^2) = g_V \frac{1}{\left(1+\frac{p^2}{M_V^2}\right)^2} \qquad g_V = 1; M_V^2 = 0.71\left(GeV/c^2\right)^2$$

$$g_A(p^2) = g_A \frac{1}{\left(1+\frac{p^2}{M_A^2}\right)^2} \qquad g_A = 1.269; M_A^2 = 1.09\left(GeV/c^2\right)^2$$

Short range correlations (SRC) are taken into account by convoluting the “potential” v(p) with the correlation function J(p) taken as a Jastrow function. J(p) is the Fourier transform of

$$J(r) = 1 - ce^{-ar^2}\left(1 - br^2\right)$$

with Miller-Spencer (MS), Argonne (AR) or Bonn (BO) parametrizations. [Also, other methods, UCOM, have been used.]

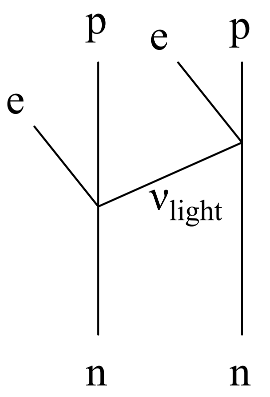
The functions $f(m_i,U_{ei})$ and $H(p)$ depend on the model of $0\nu\beta\beta$decay.

We have explicitly considered two scenarios:

(i) Emission and re-absorption of a light ($m_{light} \ll 1keV$) neutrino.

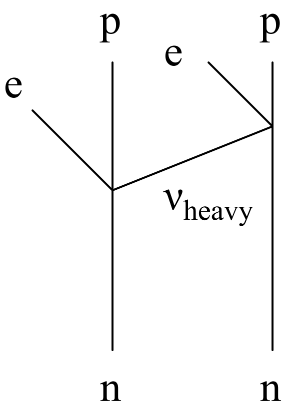
(ii) Emission and re-absorption of a heavy ($m_{heavy} \gg 1GeV$) neutrino.

1



$m_{\nu ligth} \ll 1keV$

2



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

For scenario (i)

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

$$\boxed{\langle m_\nu \rangle = \sum_{k=light} (U_{ek})^2 m_k}$$

$$\boxed{v(p) = \frac{2}{\pi} \frac{1}{p(p+\tilde{A})}}$$

Closure energy

The average light neutrino mass is well constrained by atmospheric, solar, reactor and accelerator neutrino oscillation experiments §

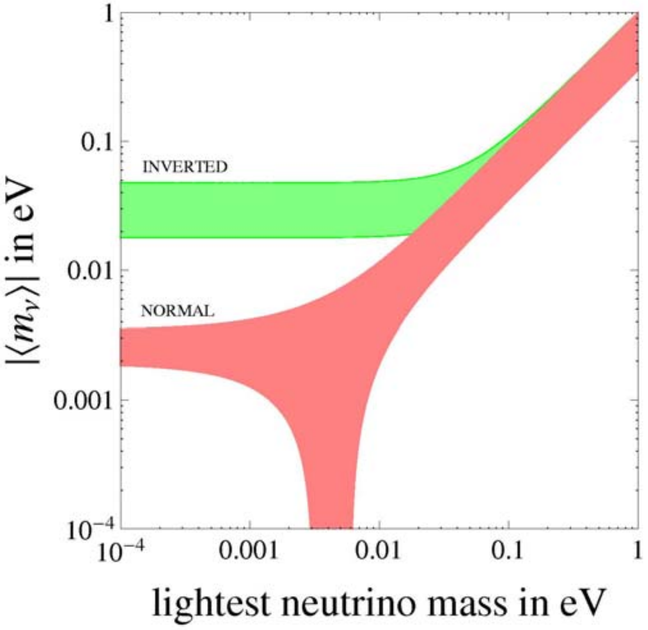
$$\langle m_\nu \rangle = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\varphi_2} + s_{13}^2 m_3 e^{i\varphi_3} \right|$$

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}, \varphi_{2,3} = [0, 2\pi]$$

$$\left(m_1^2, m_2^2, m_3^2\right) = \frac{m_1^2 + m_2^2}{2} + \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm\Delta m^2\right)$$

$$\sin^2\theta_{12} = 0.312, \sin^2\theta_{13} = 0.016, \sin^2\theta_{23} = 0.466$$

$$\delta m^2 = 7.67 \times 10^{-5} eV^2, \Delta m^2 = 2.39 \times 10^{-3} eV^2$$



§ G.L. Fogli *et al.*, Phys. Rev. D75, 053001(2007); D78, 033010 (2008).

Recent result from Daya Bay, Phys. Rev. Lett. 108, 171803 (2012): $\sin^2\theta_{13} = 0.024 \pm 0.005$.

For scenario (ii) $T_h(p) = H_h(p) f_h(m_i, U_{ei})$

heavy

$$\boxed{f_h = m_p \left\langle \frac{1}{m_h} \right\rangle} \qquad \boxed{\left\langle \frac{1}{m_h} \right\rangle = \sum_{k=heavy} \left(U_{ek_h}\right)^2 \frac{1}{m_{k_h}}}$$

$$\boxed{v_h(p) = \frac{2}{\pi} \frac{1}{m_e m_p}}$$

f_h is often written as η (flavor violating parameter)

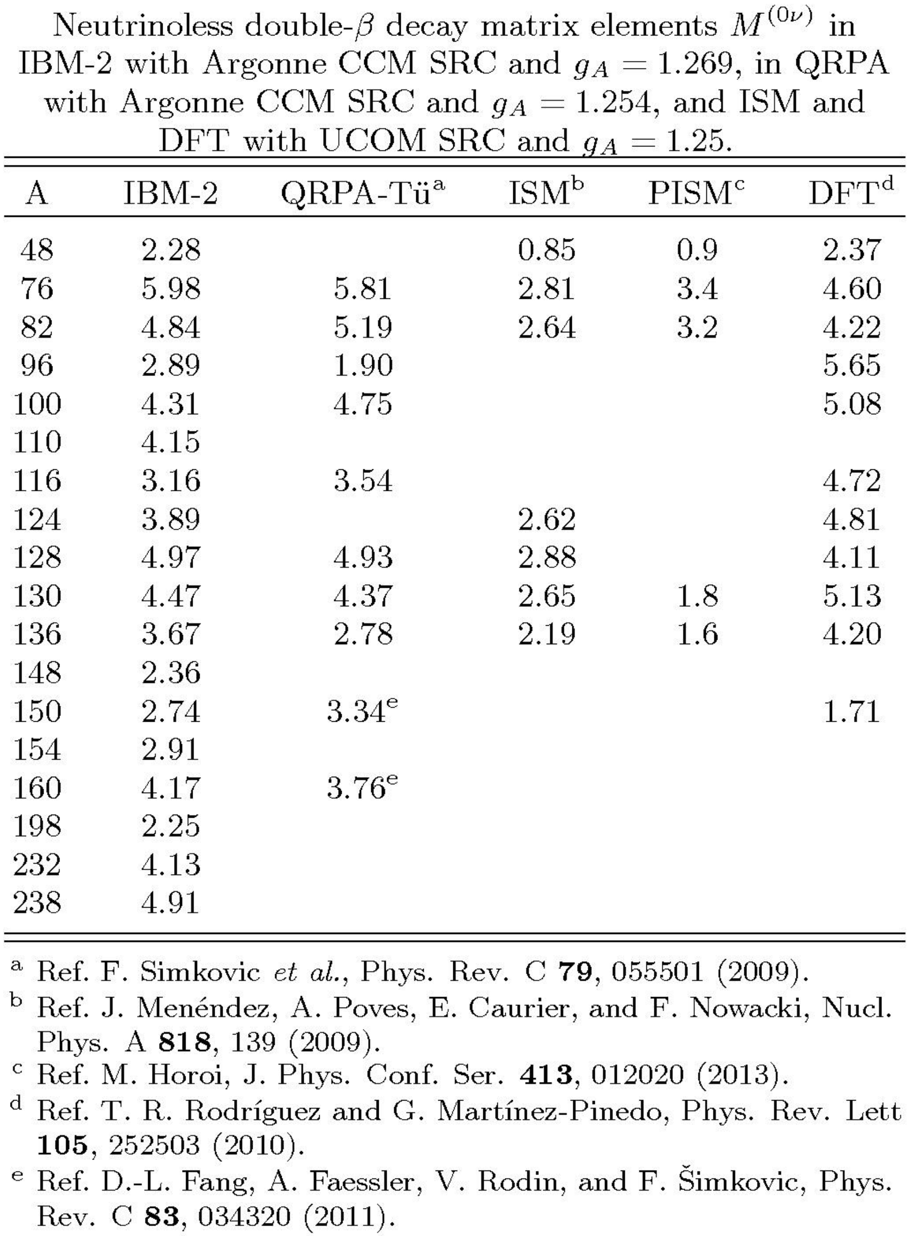
The inverse heavy neutrino mass has been considered in the past as an unconstrained parameter. Recently, it has been suggested ¶ that constraints can be put from LHC physics and lepton flavor violating processes. To obtain the heavy neutrino mass from η we use the parametrization

$$\frac{\langle m_{\nu_h} \rangle}{m_p} = \left(\frac{M_W^4}{M_{WR}^4} \right) \frac{1}{\eta} \qquad \begin{aligned} M_W &= (80.41 \pm 0.10) GeV \\ M_{WR} &= 3.5 TeV \end{aligned}$$

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

IBM-2 RESULTS ¶

LIGHT NEUTRINO



Neutrinoless double-β decay matrix elements $M^{(0\nu)}$ in IBM-2 with Argonne CCM SRC and $g_A = 1.269$, in QRPA with Argonne CCM SRC and $g_A = 1.254$, and ISM and DFT with UCOM SRC and $g_A = 1.25$.

A	IBM-2	QRPA-Tü[a]	ISM[b]	PISM[c]	DFT[d]
48	2.28		0.85	0.9	2.37
76	5.98	5.81	2.81	3.4	4.60
82	4.84	5.19	2.64	3.2	4.22
96	2.89	1.90			5.65
100	4.31	4.75			5.08
110	4.15				
116	3.16	3.54			4.72
124	3.89		2.62		4.81
128	4.97	4.93	2.88		4.11
130	4.47	4.37	2.65	1.8	5.13
136	3.67	2.78	2.19	1.6	4.20
148	2.36				
150	2.74	3.34[e]			1.71
154	2.91				
160	4.17	3.76[e]			
198	2.25				
232	4.13				
238	4.91				

[a] Ref. F. Simkovic *et al.*, Phys. Rev. C **79**, 055501 (2009).

[b] Ref. J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (2009).

[c] Ref. M. Horoi, J. Phys. Conf. Ser. **413**, 012020 (2013).

[d] Ref. T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett **105**, 252503 (2010).

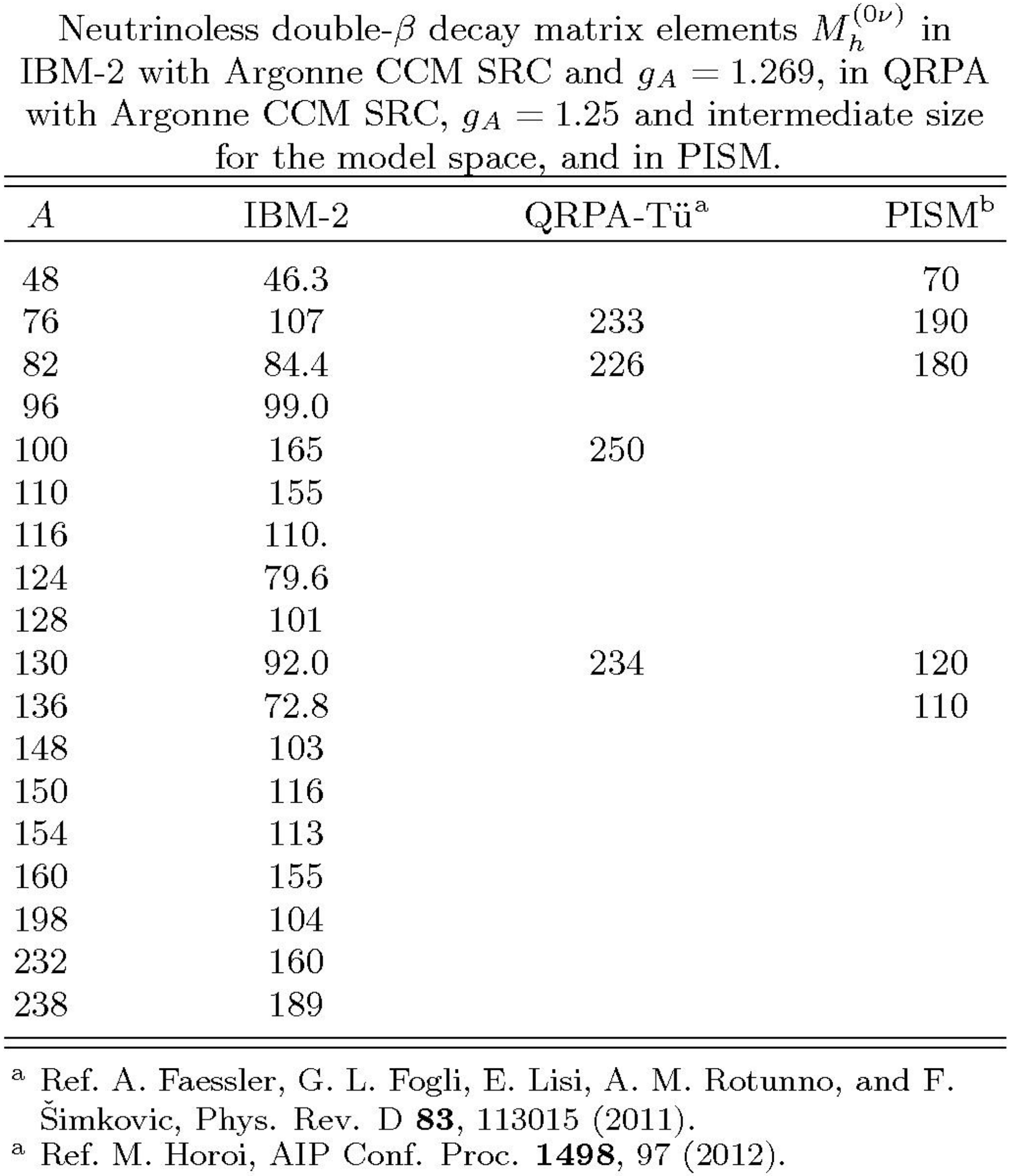
[e] Ref. D.-L. Fang, A. Faessler, V. Rodin, and F. Šimkovic, Phys. Rev. C **83**, 034320 (2011).

¶ J. Barea, J. Kotila and F. Iachello, Phys. Rev. Lett. 109, 042501 (2012).

IBM-2 RESULTS ¶

HEAVY NEUTRINO

¶ J. Barea, J. Kotila and F. Iachello, Phys. Rev. Lett. 109, 042501 (2012).



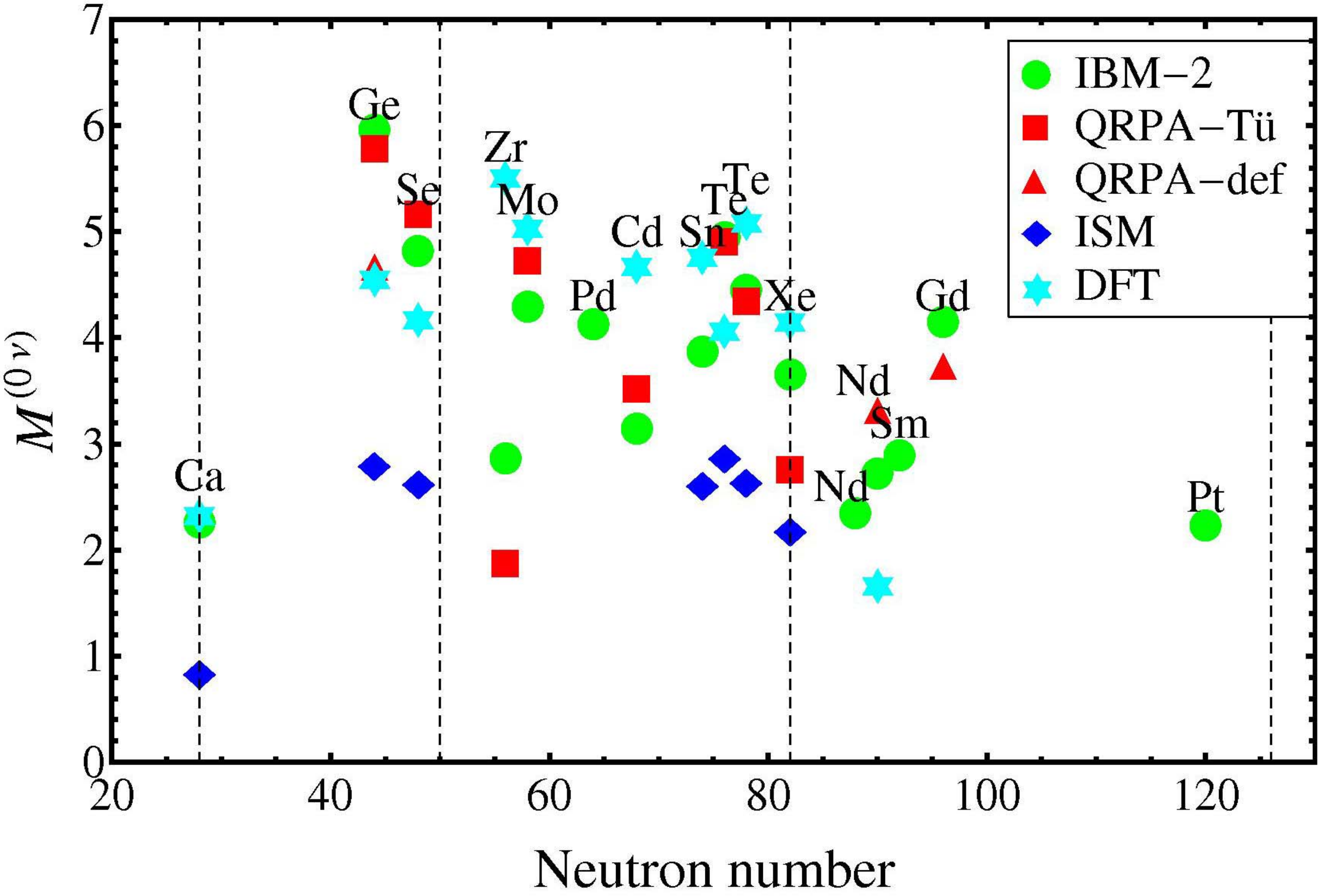
Neutrinoless double-β decay matrix elements $M_h^{(0\nu)}$ in IBM-2 with Argonne CCM SRC and $g_A = 1.269$, in QRPA with Argonne CCM SRC, $g_A = 1.25$ and intermediate size for the model space, and in PISM.

A	IBM-2	QRPA-Tü[a]	PISM[b]
48	46.3		70
76	107	233	190
82	84.4	226	180
96	99.0		
100	165	250	
110	155		
116	110.		
124	79.6		
128	101		
130	92.0	234	120
136	72.8		110
148	103		
150	116		
154	113		
160	155		
198	104		
232	160		
238	189		

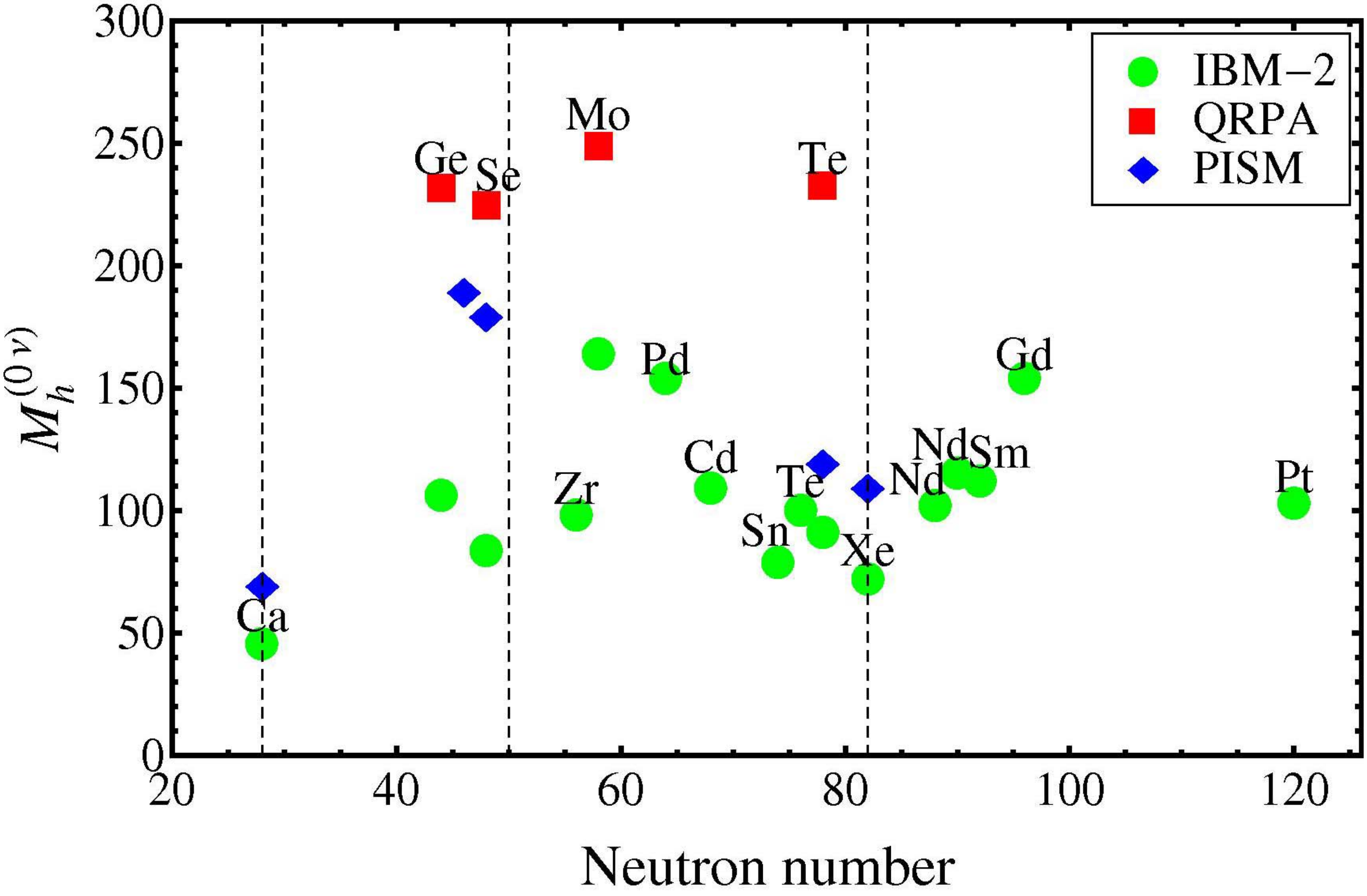
[a] Ref. A. Faessler, G. L. Fogli, E. Lisi, A. M. Rotunno, and F. Šimkovic, Phys. Rev. D **83**, 113015 (2011).

[a] Ref. M. Horoi, AIP Conf. Proc. **1498**, 97 (2012).

IBM-2 RESULTS
LIGHT NEUTRINO EXCHANGE



IBM-2 RESULTS
HEAVY NEUTRINO EXCHANGE



IBM-2 NME RESULTS WITH ERROR ESTIMATES

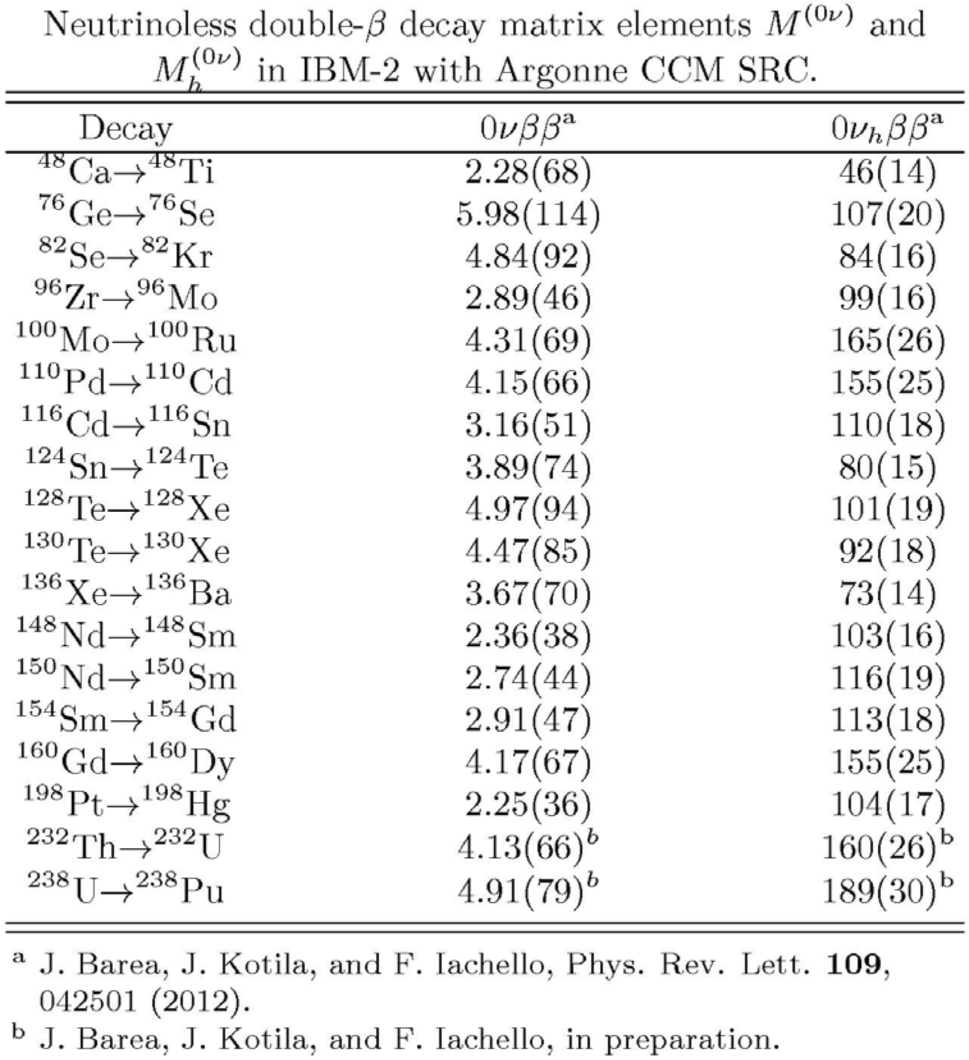
LIGHT NEUTRINO	^{76}Ge	5.98(113)	GERDA
	^{130}Te	4.47(85)	CUORE
	^{136}Xe	3.67(70)	EXO

The largest contribution to the error comes from spurious isospin violating contributions. This problem has now been solved (October 2013) bringing the error down from 19% to 5% (to be published).

HEAVY NEUTRINO	^{76}Ge	107(57)	GERDA
	^{130}Te	92(49)	CUORE
	^{136}Xe	73(39)	EXO

The largest contributions to the error come from SRC and from treatment of tensor components. This problem is in the course of solution (November 2013). The aim is to bring down the error estimate of 53%.

COMPLETE LIST OF IBM-2 NME WITH ERROR



Neutrinoless double-β decay matrix elements $M^{(0\nu)}$ and $M_h^{(0\nu)}$ in IBM-2 with Argonne CCM SRC.

Decay	$0\nu\beta\beta^{a}$	$0\nu_h\beta\beta^{a}$
^{48}Ca→^{48}Ti	2.28(68)	46(14)
^{76}Ge→^{76}Se	5.98(114)	107(20)
^{82}Se→^{82}Kr	4.84(92)	84(16)
^{96}Zr→^{96}Mo	2.89(46)	99(16)
^{100}Mo→^{100}Ru	4.31(69)	165(26)
^{110}Pd→^{110}Cd	4.15(66)	155(25)
^{116}Cd→^{116}Sn	3.16(51)	110(18)
^{124}Sn→^{124}Te	3.89(74)	80(15)
^{128}Te→^{128}Xe	4.97(94)	101(19)
^{130}Te→^{130}Xe	4.47(85)	92(18)
^{136}Xe→^{136}Ba	3.67(70)	73(14)
^{148}Nd→^{148}Sm	2.36(38)	103(16)
^{150}Nd→^{150}Sm	2.74(44)	116(19)
^{154}Sm→^{154}Gd	2.91(47)	113(18)
^{160}Gd→^{160}Dy	4.17(67)	155(25)
^{198}Pt→^{198}Hg	2.25(36)	104(17)
^{232}Th→^{232}U	4.13(66)[b]	160(26)[b]
^{238}U→^{238}Pu	4.91(79)[b]	189(30)[b]

[a] J. Barea, J. Kotila, and F. Iachello, Phys. Rev. Lett. **109**, 042501 (2012).

[b] J. Barea, J. Kotila, and F. Iachello, in preparation.

NOVEL CALCULATION OF PHASE SPACE FACTORS (PSF)

For an extraction of the neutrino mass and for estimates of the half-life one also needs the phase-space factor $G_{0\nu}$. A general formulation was given by Doi *et al.* [*] and by Tomoda [¶], who tabulated results for selected cases. Also, a calculation of phase-space factors is reported in the book of Boehm and Vogel [§] where a complete tabulation is given. These calculations use an approximate expression for the electron wave functions at the nucleus.

We have done a novel calculation [**] of both $G_{0\nu}$ and $G_{2\nu}$ with exact Dirac electron wave functions and including screening by the electron cloud.

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

[¶] T. Tomoda, *loc.cit.*

[§] 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

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

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

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

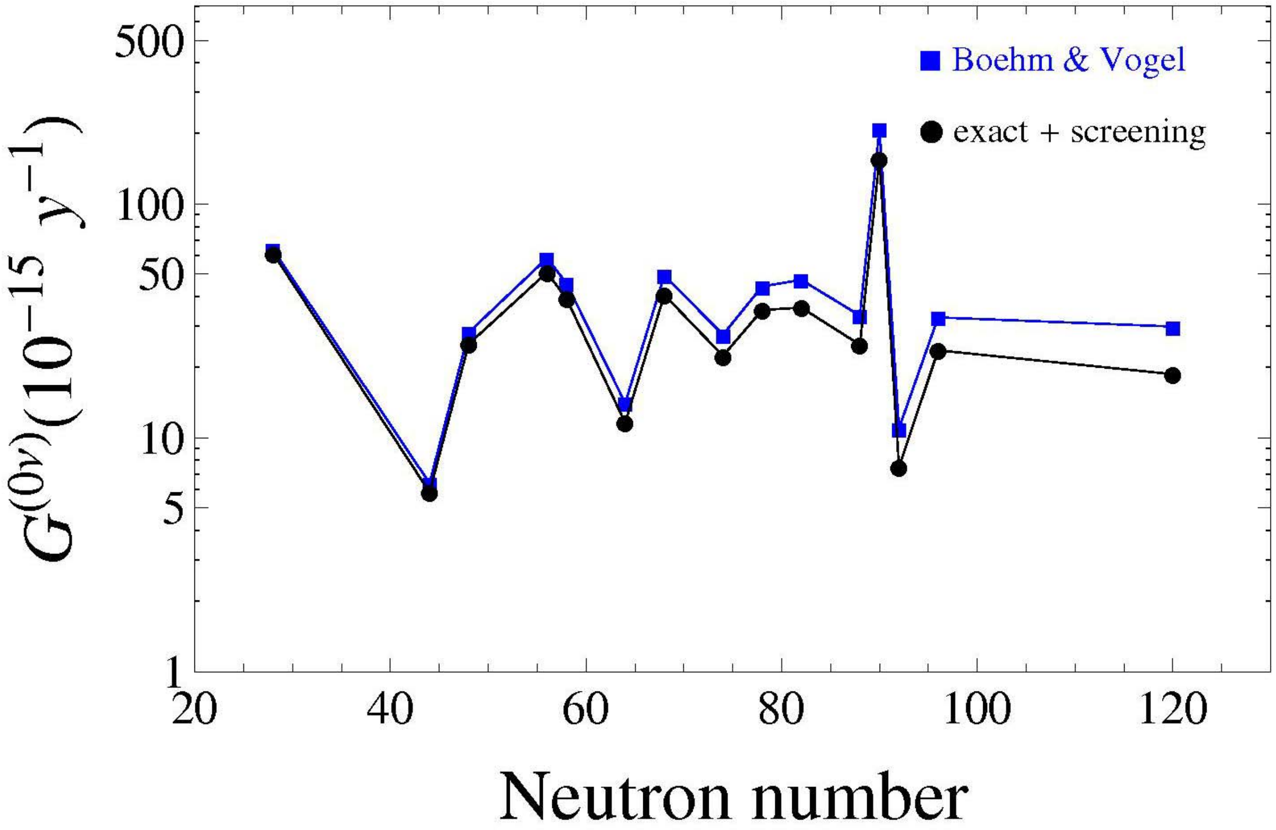
$$\varphi(0) = 1 \qquad \varphi(\infty) = \frac{2}{Z_d}$$

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

[§] S. Esposito, Am. J. Phys. 70 (2002) 852.

[This method of solution was invented by Ettore Majorana].

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

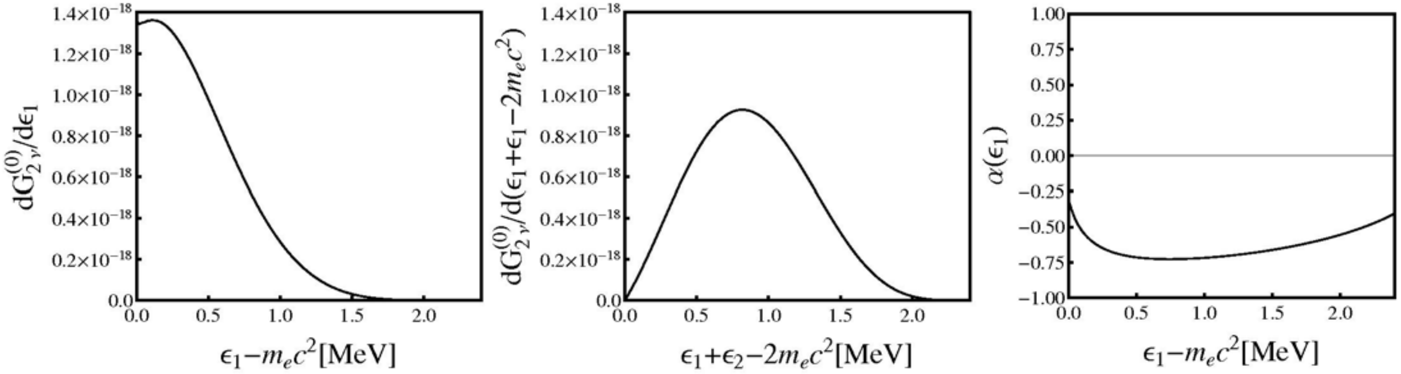


[§] F. Böhm and P. Vogel, *loc. cit.*

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

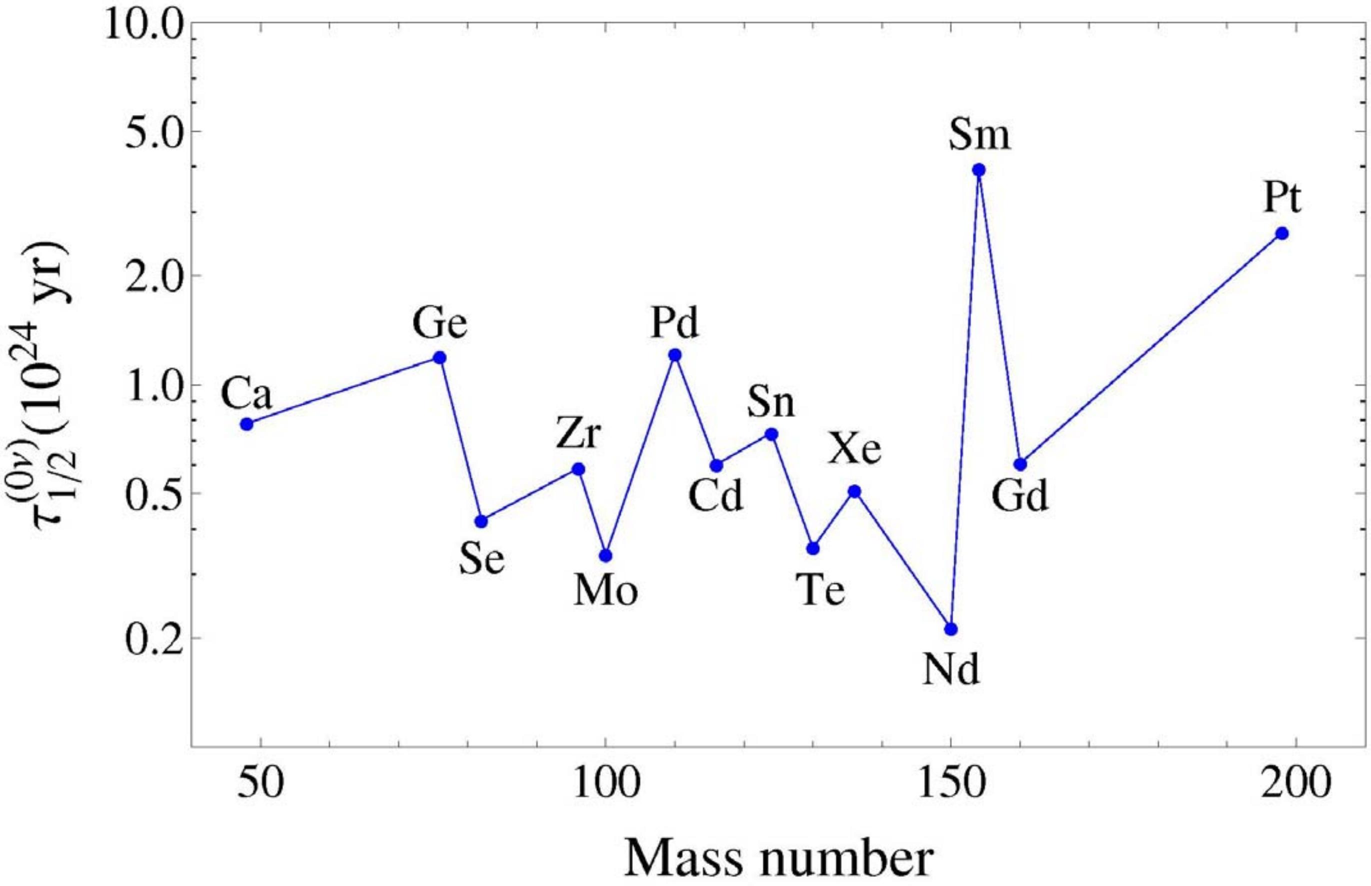
The calculations of PSF include single and summed electron spectra, and angular electron correlations. They are available upon request.

Example: $^{136}Xe \rightarrow ^{136}Ba$ 2νββ decay



(a) Single electron spectrum; (b) summed spectra; (c) angular correlation

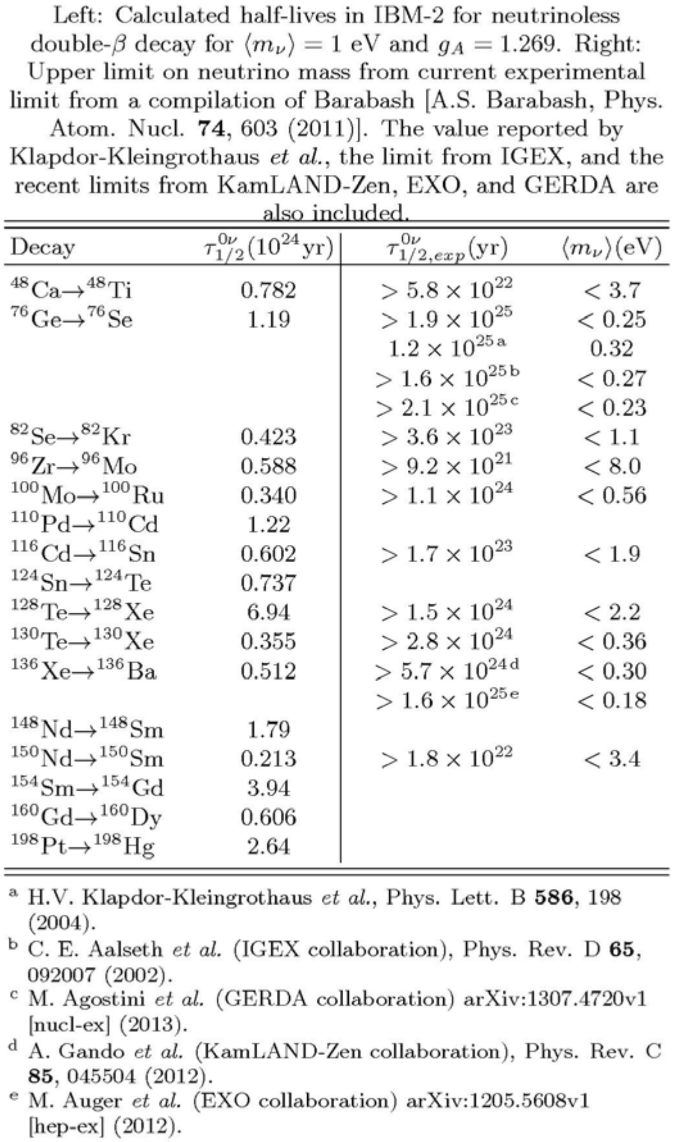
Combining NME with PSF we obtain the expected half-lives



Expected half-lives for light neutrino exchange with $<m_\nu>=1$eV, $g_A=1.269$.
^{128}Te and ^{148}Nd not included in this figure. For other values, scale with $<m_\nu>^2$ and $g_A{}^4$.

By comparing the calculated half-lives with experimental limits we obtain the corresponding limits for masses.

IBM-2 HALF-LIVES AND MASS LIMITS: LIGHT NEUTRINO



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→^{48}Ti	0.782	$> 5.8 \times 10^{22}$	< 3.7
^{76}Ge→^{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→^{82}Kr	0.423	$> 3.6 \times 10^{23}$	< 1.1
^{96}Zr→^{96}Mo	0.588	$> 9.2 \times 10^{21}$	< 8.0
^{100}Mo→^{100}Ru	0.340	$> 1.1 \times 10^{24}$	< 0.56
^{110}Pd→^{110}Cd	1.22		
^{116}Cd→^{116}Sn	0.602	$> 1.7 \times 10^{23}$	< 1.9
^{124}Sn→^{124}Te	0.737		
^{128}Te→^{128}Xe	6.94	$> 1.5 \times 10^{24}$	< 2.2
^{130}Te→^{130}Xe	0.355	$> 2.8 \times 10^{24}$	< 0.36
^{136}Xe→^{136}Ba	0.512	$> 5.7 \times 10^{24}$ [d]	< 0.30
		$> 1.6 \times 10^{25}$ [e]	< 0.18
^{148}Nd→^{148}Sm	1.79		
^{150}Nd→^{150}Sm	0.213	$> 1.8 \times 10^{22}$	< 3.4
^{154}Sm→^{154}Gd	3.94		
^{160}Gd→^{160}Dy	0.606		
^{198}Pt→^{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).

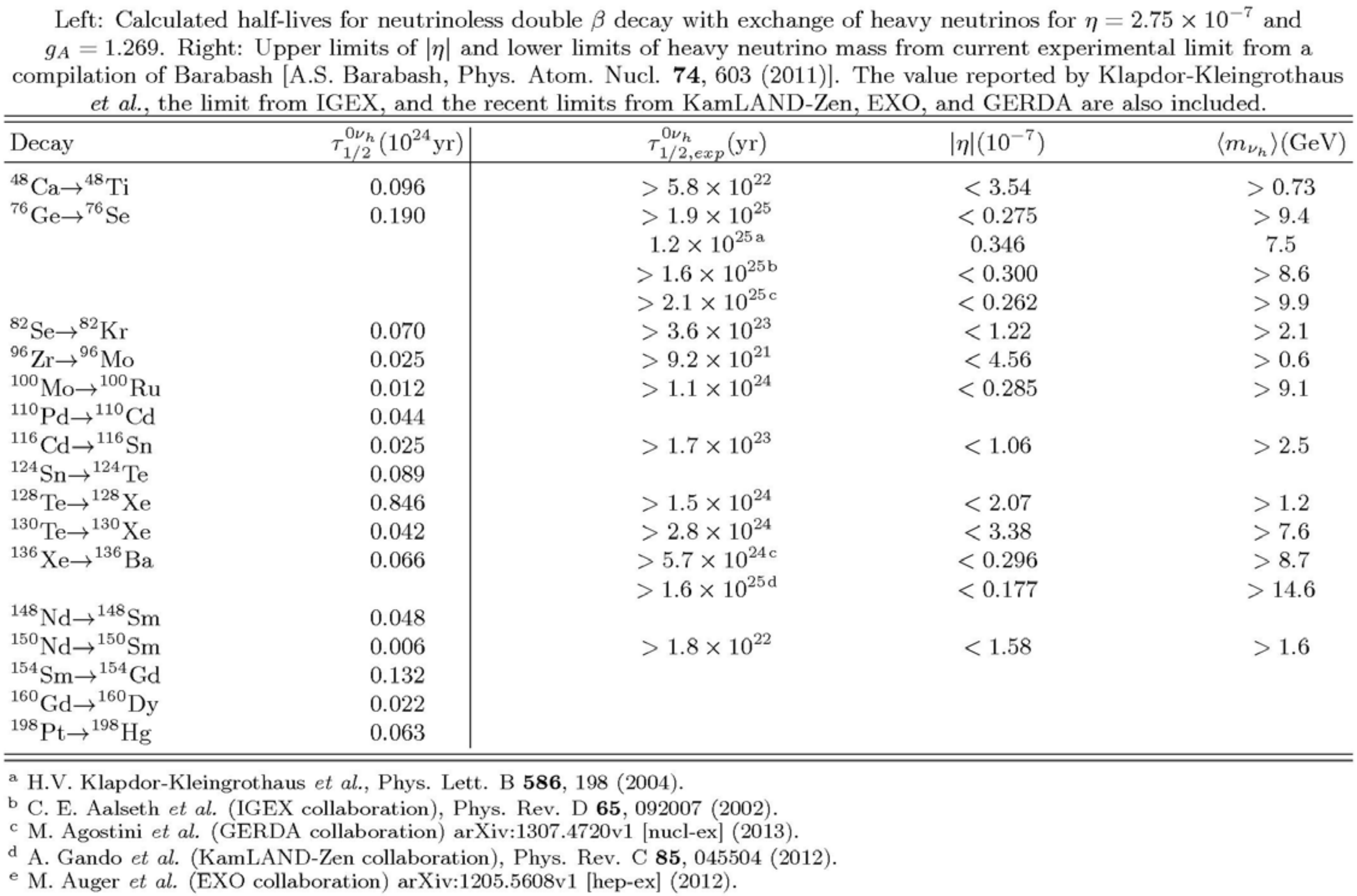
[c] M. Agostini *et al.* (GERDA collaboration) arXiv:1307.4720v1 [nucl-ex] (2013).

[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



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

← Best limit

[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).

SUMMARY OF LIMITS FROM RECENT EXPERIMENTS

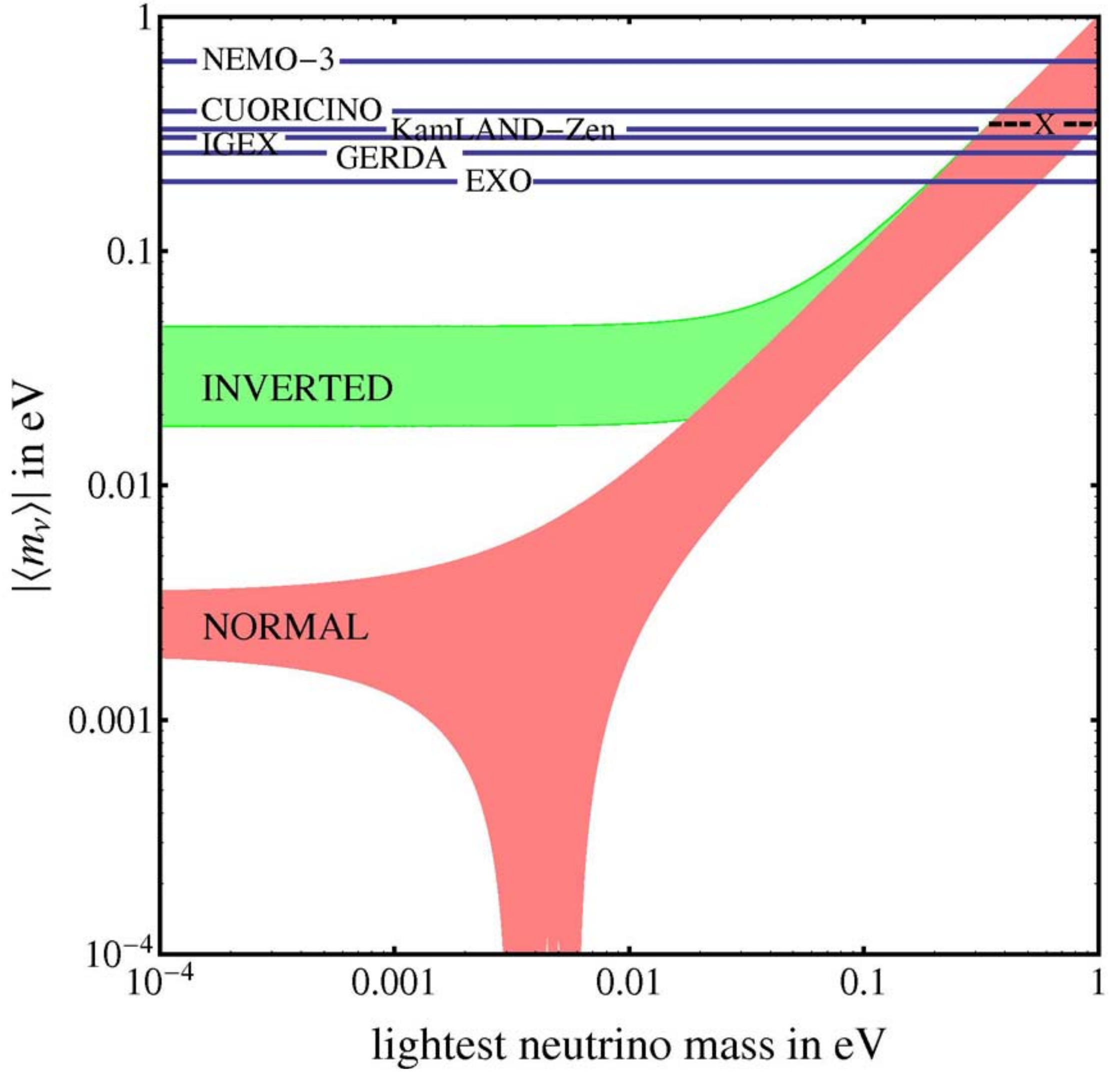
		LIGHT NEUTRINO(eV)	HEAVY NEUTRINO(GeV)	
^{76}Ge	$>2.1\times10^{25}$	<0.23	>9.9	GERDA[¶]
^{136}Xe	$>5.7\times10^{24}$	<0.30	>8.7	KAMLAND[*]
^{136}Xe	$>1.6\times10^{25}$	<0.18	>14.6	EXO[§]

[¶] M. Agostini *et al.* (GERDA Collaboration) arXiv:1307.4720v1 [nucl-ex] (2013).
[*] A. Gando *et al.* (KamLAND-Zen Collaboration) Phys. Rev. C 85, 045504 (2012).
[§] M. Auger *et al.* (EXO Collaboration) arXiv:1205.5608v1 [hep-ex] (2012).

^{76}Ge	1.2×10^{25}	0.32	7.5	KLAPDOR[×]

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

SUMMARY OF RESULTS ¶
LIGHT NEUTRINO



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

¶ J. Barea, J. Kotila, and F. Iachello, Phys. Rev. Lett. 109, 042501 (2012).

RENORMALIZATION OF g_A

Results in the previous slides are obtained with g_A=1.269.

It is well-known from single β-decay/EC and from 2νββ that g_A is renormalized in models of nuclei. Two reasons:

(i) Limited model space

(ii) Omission of non-nucleonic degrees of freedom (Δ, N*,…)

For each model (ISM/QRPA/IBM-2) one can define an effective $g_{A,eff}$ by writing

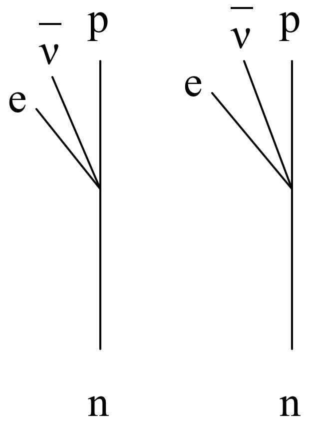
$$M_{2\nu}^{eff} = \left(\frac{g_{A,eff}}{g_A}\right)^2 M_{2\nu}$$

$$M_{\beta/EC}^{eff} = \left(\frac{g_{A,eff}}{g_A}\right) M_{\beta/EC}$$

The value of $g_{A,eff}$ in each nucleus can then be obtained by comparing the calculated and measured half-lives for β/EC and for 2νββ.

APPROXIMATE ESTIMATE FROM 2νββ IN THE CLOSURE APPROXIMATION

An *approximate* estimate of the renormalization effect can be done from a study of 2νββ in the *closure* approximation. To this end, a simultaneous calculation of NME in 2νββ decay in the closure approximation has been completed, as well as a novel calculation of 2νββ phase space factors.



The calculation of 2νββ in the closure approximation is similar to that of 0νββ except that the neutrino “potential” is different

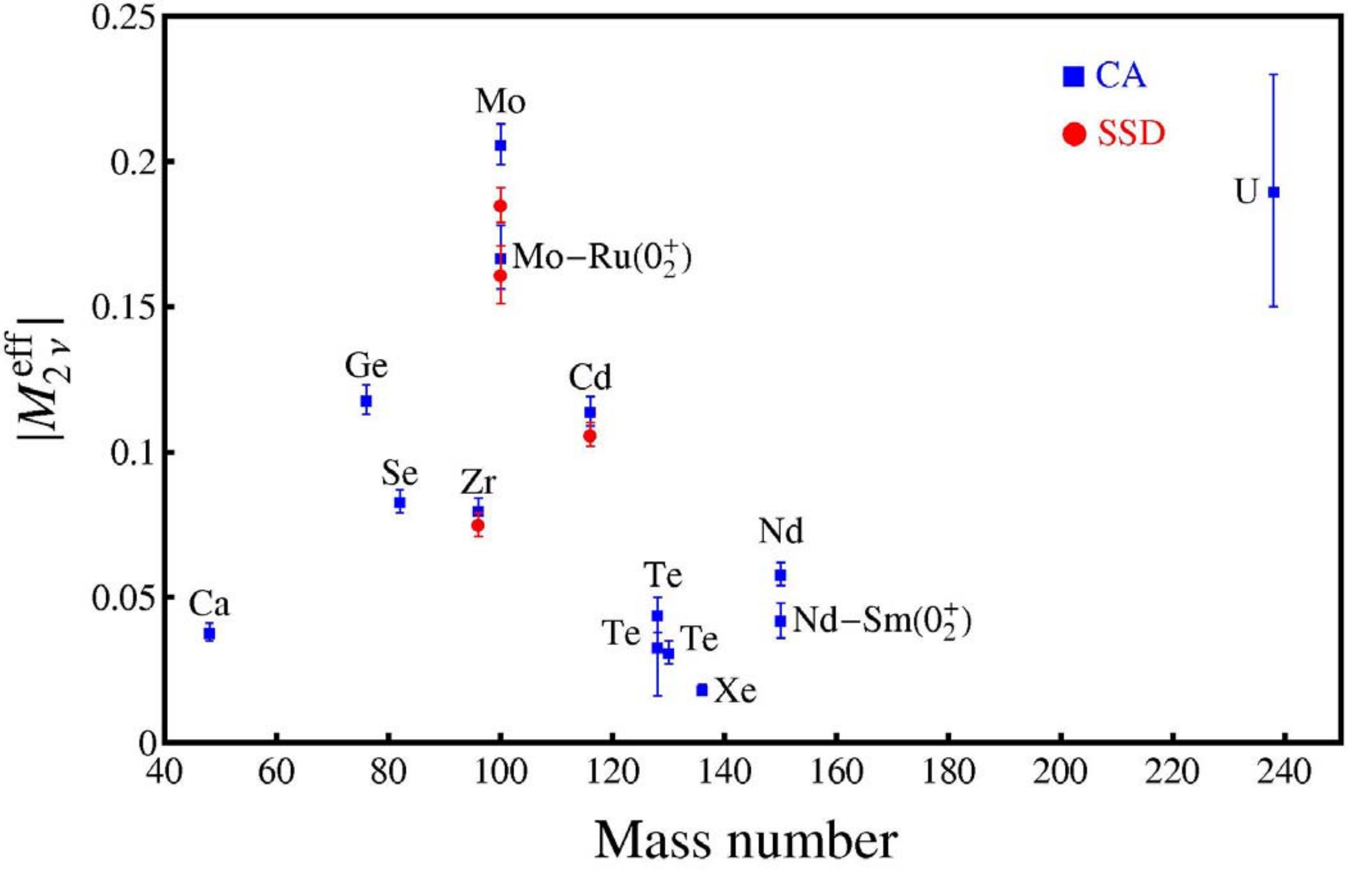
$$\boxed{v^{(2\nu)}(p) = \frac{\delta(p)}{p^2}}$$

In the IBM-2 approach in momentum space all calculations, 0ν-light-neutrino, heavy-neutrino, (Majoron, sterile neutrinos, …) and 2ν can be done at the same time, by changing the neutrino “potential”, and thus eliminating possible sources of systematic and accidental error.

The half-lives for 2νββ are calculated using

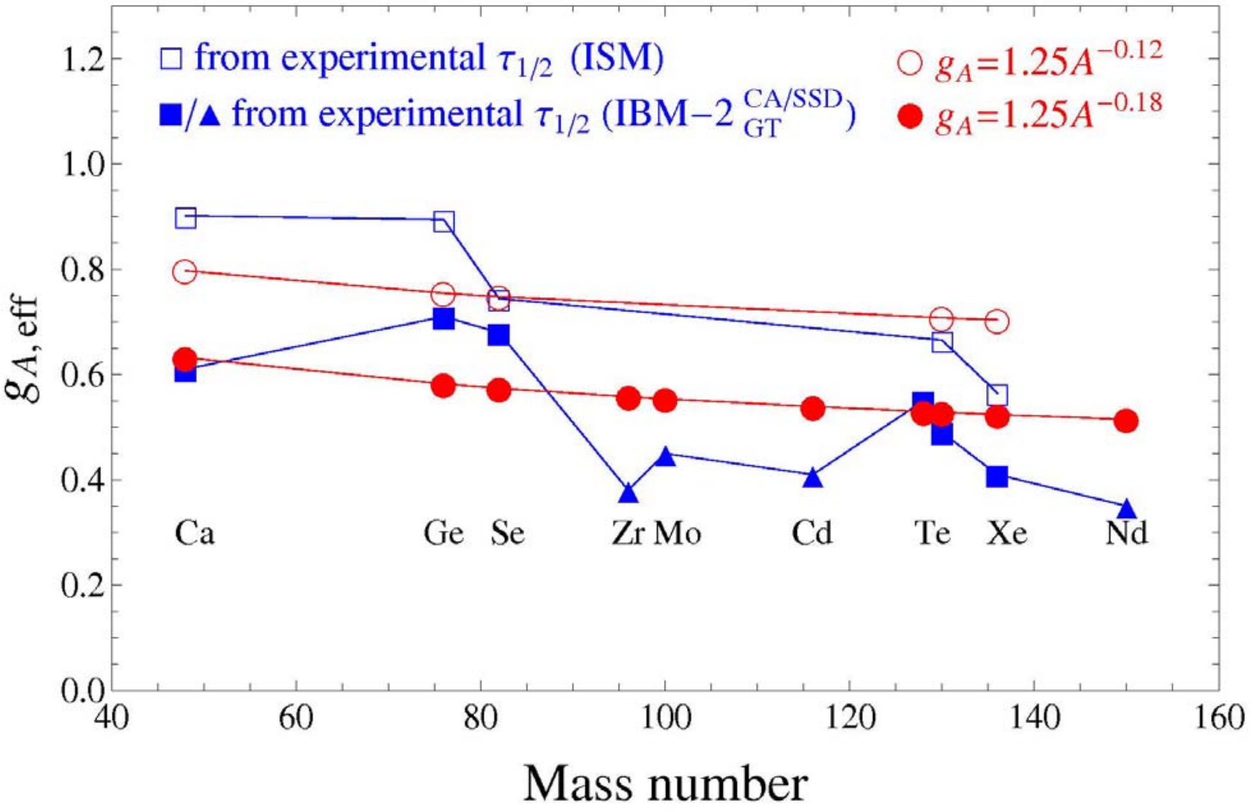
$$\left[\tau_{1/2}^{2\nu}\right]^{-1} = G_{2\nu}\left|m_e c^2 M_{2\nu}\right|^2$$

By comparing the values of $|M_{2\nu}^{\mathrm{eff}}|$ obtained from experimental half-lives



with those calculated in IBM-2 (or other models), one can obtain the values of $g_{A,\mathrm{eff}}$.

Effective axial vector coupling constant in nuclei from 2νββ



One obtains $g_{A,\mathrm{eff}}^{\mathrm{IBM\text{-}2}}$~0.6-0.5.

The extracted values can be parametrized as

$$g_{A,eff}^{IBM2} = 1.269\,A^{-0.18}$$

A similar analysis can be done for the ISM for which $g_{A,\mathrm{eff}}^{\mathrm{ISM}}$~0.8-0.7.

$$g_{A,eff}^{ISM} = 1.269\,A^{-0.12}$$

g_A appears to the fourth power in the half-life

$g_{A,eff}$, as extracted from β/EC and 2νββ decay ~0.8-0.5

Therefore, the results of the previous tables should be multiplied by 4-8 to have realistic estimates of expected half-lives.

The question of whether or not g_A in 0νββ is renormalized as much as in 2νββ is of much debate. In 2νββ only the 1^+ (GT) multipole contributes. In 0νββ all multipoles 1^+, 0^+, 2^-, 1^- … contribute. Some of these could be unquenched. However, even in 0νββ, 1^+ intermediate states dominate. Hence, our current understanding is that g_A is renormalized in 0νββ as much as in 2νββ.

This problem is currently being addressed from various sides. Experimentally by measuring the matrix elements to and from the intermediate odd-odd nucleus in $2\nu\beta\beta$ decay [§]. Theoretically, by using effective field theory (EFT) to estimate the effect of non-nucleonic degrees of freedom (two-body currents) [¶].

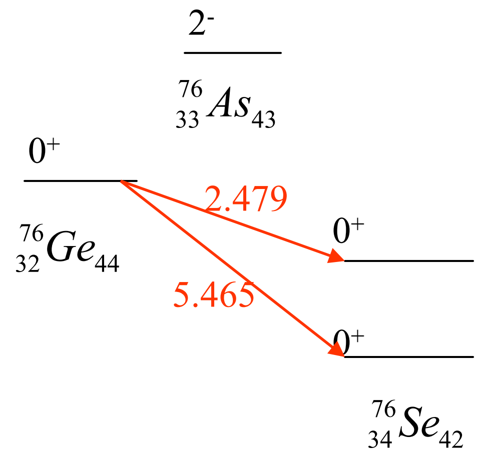
[§] P. Puppe *et al.*, Phys. Rev. C 86, 044603 (2012).

[¶] J. Menendez, D. Gazit, and A. Schwenk, Phys. Rev. Lett. 107, 062501 (2011).

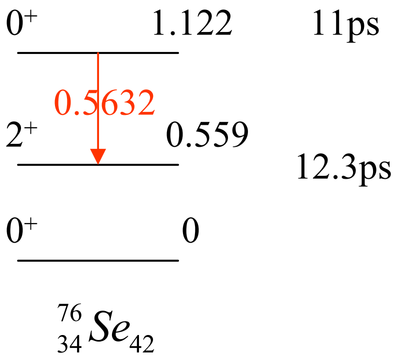
OTHER WORK COMPLETED

(1) NME AND PSF TO EXCITED STATES

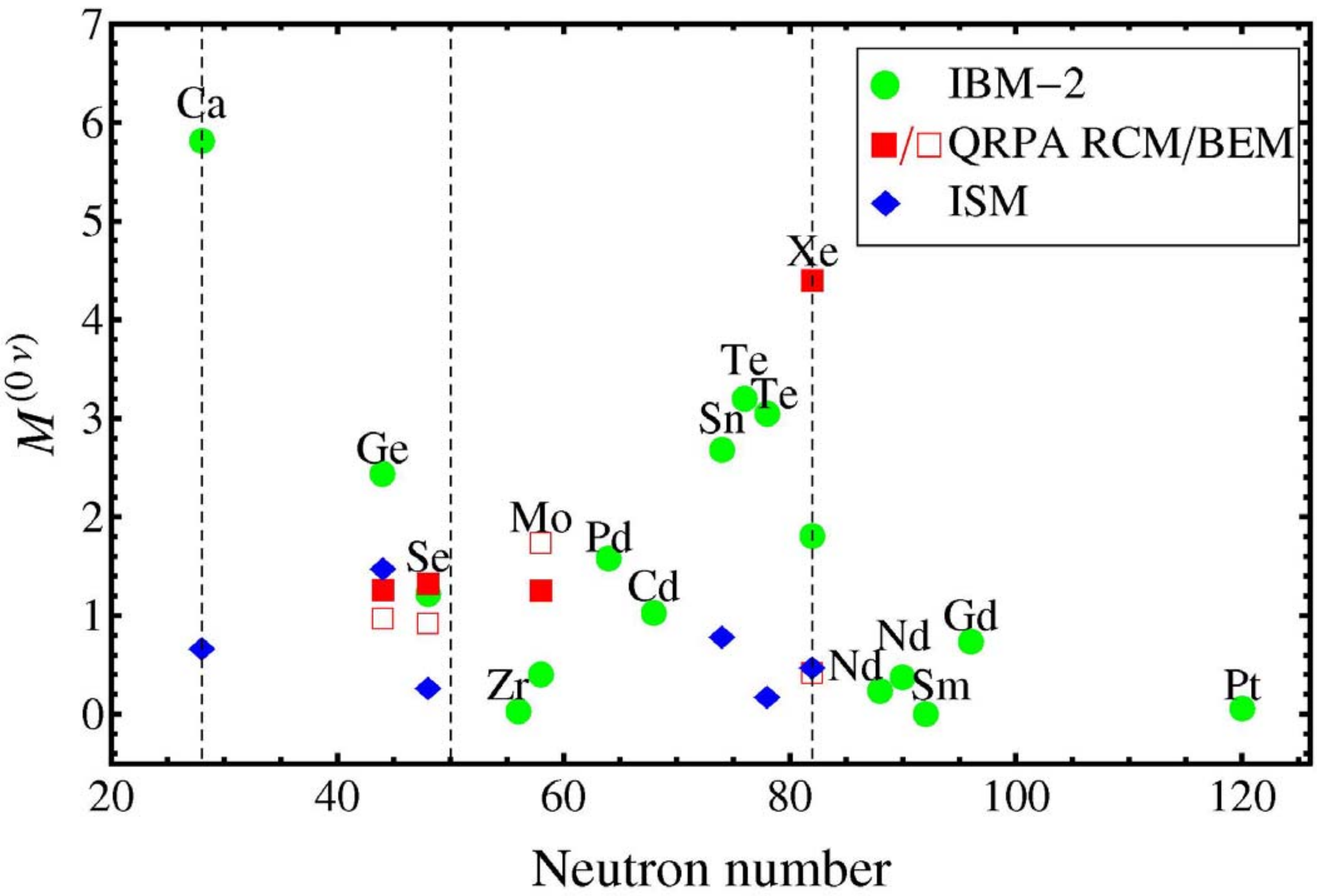
In some cases, the matrix elements to the first excited 0^+ state are large. Although the kinematical factor hinders the decay to the excited state, large matrix elements offer the possibility of a direct detection, by looking at the γ-ray de-exciting the 0^+ level.



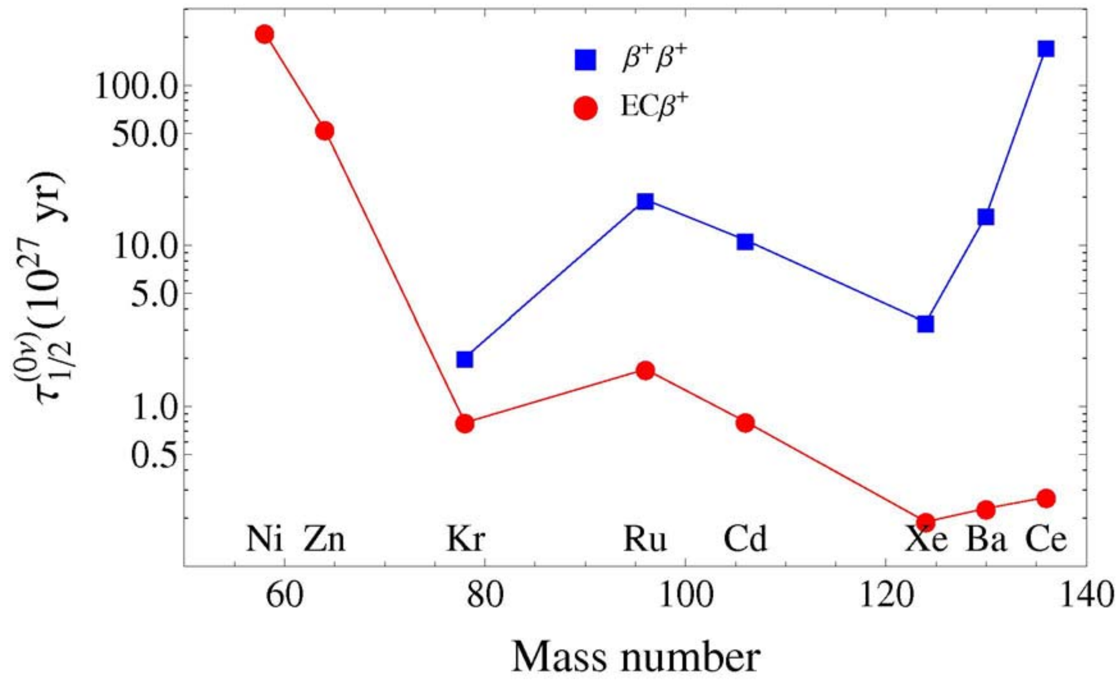
[On the contrary, matrix elements to the excited 2^+ state are zero in lowest order since with two leptons in the final state we cannot form angular momentum 2.]



IBM-2 RESULTS
LIGHT NEUTRINO EXCHANGE
TO FIRST EXCITED 0^+ STATE



(2) CALCULATION OF NME AND PSF FOR $0\nu\beta^+\beta^+$, $0\nu\beta^+EC$, $2\nu\beta^+\beta^+$, $2\nu\beta^+EC$, $2\nu ECEC$



m_ν=1eV
g_A=1.269

Half-lives are three orders of magnitude longer than in $0\nu\beta^-\beta^-$.

PSF: J. Kotila and F. Iachello, Phys. Rev. C 87, 024313 (2013).
NME: J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 87, 057301 (2013).

(3) RESONANTLY ENHANCED 0νECEC DECAY¶

The half-life for this process is given by

$$\left[\tau_{1/2}^{ECEC}(0^+)\right]^{-1} = g_A^4 G_{0\nu}^{ECEC} \left|M_{0\nu}^{ECEC}\right|^2 \frac{\left|\langle m_\nu \rangle\right|^2 \Gamma/(m_e c^2)}{\left(Q - E_{e_1+e_2} - E\right)^2 + \Gamma^2/4}$$

$$\Delta = \left|Q - E_{e_1+e_2} - E\right| \qquad \Gamma = \Gamma_{e_1} + \Gamma_{e_2} \qquad F = \frac{\Gamma}{\left(\Delta^2 + \Gamma^2/4\right)}$$

(a) Degeneracy parameter; (b) two-hole width; (c) enhancement factor

Best candidates: ^{152}Gd→^{152}Sm(g.s.); ^{156}Dy→^{156}Gd(1.9885)

Half-lives are five orders of magnitude larger than 0ν$\beta^-\beta^-$ §

¶ J. Bernabeu *et al.*, Nucl. Phys. B223, 15 (1983).

§ J. Barea, J. Kotila and F. Iachello, in preparation (2013).

CONCLUSIONS

Major progress has been made in the last two years to narrow down predictions of 0νββ decay to realistic values in *all* nuclei of interest.

With current estimates:
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 EXO, m_ν<0.18 eV.
Exploration of the inverted region >1 ton
Exploration of the normal region >>1 ton
For heavy neutrino exchange, we expect $m_{\nu h}$> 1 TeV. The current best limit from EXO is $m_{\nu h}$>14.6 GeV. We need again >>1 ton to test models of heavy neutrino exchange.

If g_A is renormalized to ~0.8-0.5, all estimates should be increased by factors of 4-8, making it impossible to reach in the foreseeable future even the inverted region.

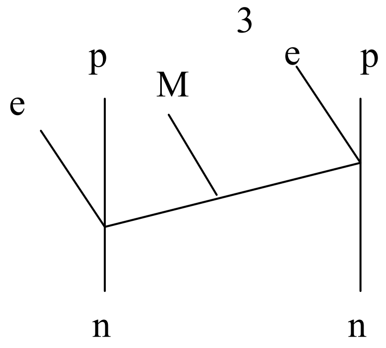
Possibilities to escape this negative conclusion are:

(1)The neutrino masses are degenerate and large. (Cosmology?)

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

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

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



…

Despite these drawbacks, the search for neutrinoless double beta decay remains one of the most fundamental endeavors in physics today as, if observed, it will provide a window into physics beyond the standard model.