LIMITS ON NEUTRINO MASSES FROM NEUTRINOLESS DOUBLE β-DECAY

Francesco Iachello

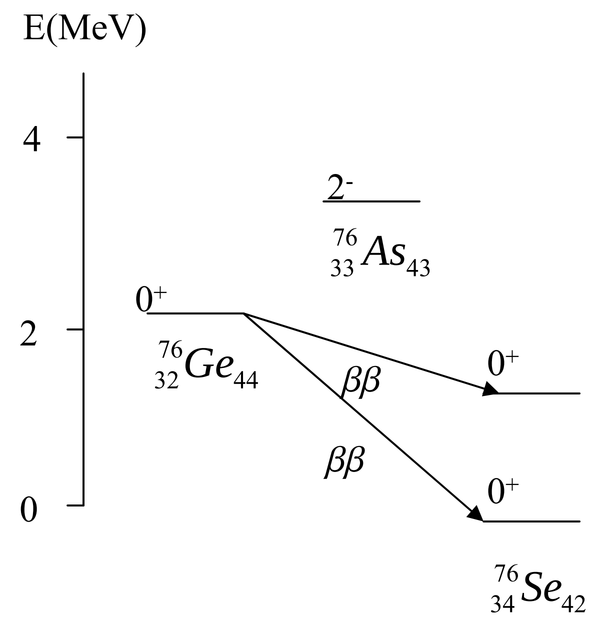
Yale University

Neutrino Oscillations Workshop
Otranto, September 10, 2012

INTRODUCTION

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

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



Half-life for the process:

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

Phase-space factor (Atomic physics)

Matrix elements (Nuclear physics)

Beyond the standard model (Particle physics)

We have recently (i) introduced a new method (IBM-2) [§] to calculate NME in a consistent way in *all* nuclei of interest; (ii) improved the calculation of PSF by solving the Dirac equation in the presence of a charge distribution and including electron screening [¶]. In this talk, results of the calculation combining NME and PSF to half-lives will be presented.

Weak Lagrangean $L \rightarrow$ Transition operator T

p=momentum transferred to the leptons

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

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

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

Neutrino "potential" ($v(p)$)

Form factors ($\tilde{h}^{F,GT,T}$) listed in F. Šimkovic *et al.*, Phys. Rev. C60, 055502 (1999)

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

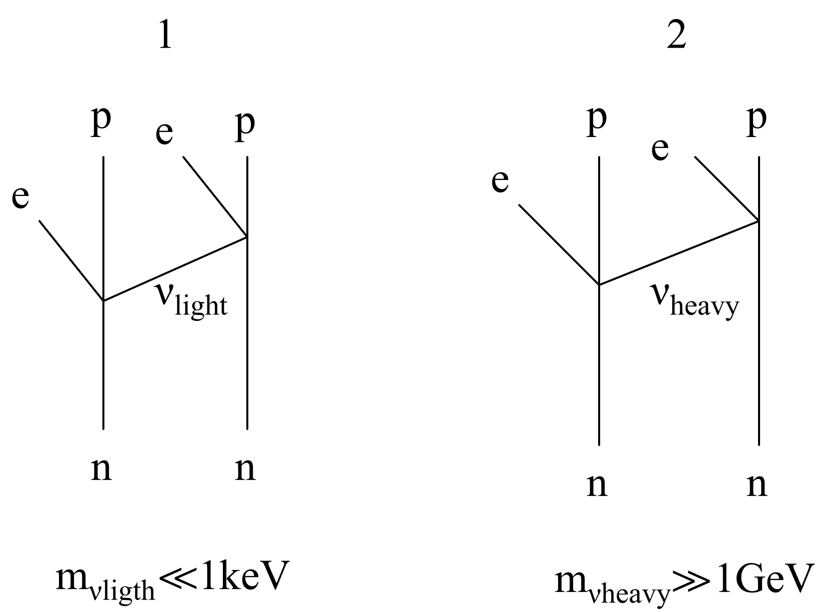
§ J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009).

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

Finite nucleon size (FNS) → Coupling constants g_A, g_F p-dependent.
Short range correlations (SRC) → Convoluting v(p) with the correlation function J(p) taken as a Jastrow function.

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

(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.



For scenario (i)

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

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

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

← Closure energy

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

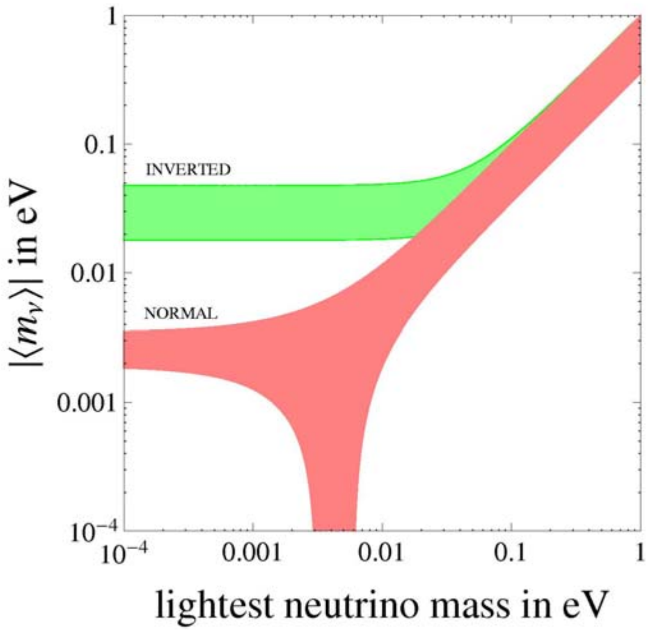
$$\langle m_\nu \rangle = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\varphi_2} + s_{13}^2 m_3 e^{i\varphi_3} \right|$$

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

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

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

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



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

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

$$f_h = m_p \left\langle \frac{1}{m_h} \right\rangle$$

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

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

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 some constraints can be put from LHC physics and lepton flavor violating processes. To obtain the heavy neutrino mass from η we use the parametrization

$$\frac{\langle m_{\nu_h} \rangle}{m_p} = \left(\frac{M_W^4}{M_{WR}^4} \right) \frac{1}{\eta}$$

$$M_W = (80.41 \pm 0.10) GeV$$
$$M_{WR} = 3.5 TeV$$

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

IBM-2 RESULTS (MAY 2012) ¶

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 with UCOM SRC and $g_A = 1.25$.

A	IBM-2	QRPA[a]	ISM[b]
48	2.28		0.85
76	5.98	5.81	2.81
82	4.84	5.19	2.64
96	2.89	1.90	
100	4.31	4.75	
110	4.15		
116	3.16	3.54	
124	3.89		2.62
128	4.97	4.93	2.88
130	4.47	4.37	2.65
136	3.67	2.78	2.19
148	2.36		
150	2.74		
154	2.91		
160	4.17		
198	2.25		

[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).

HEAVY NEUTRINO

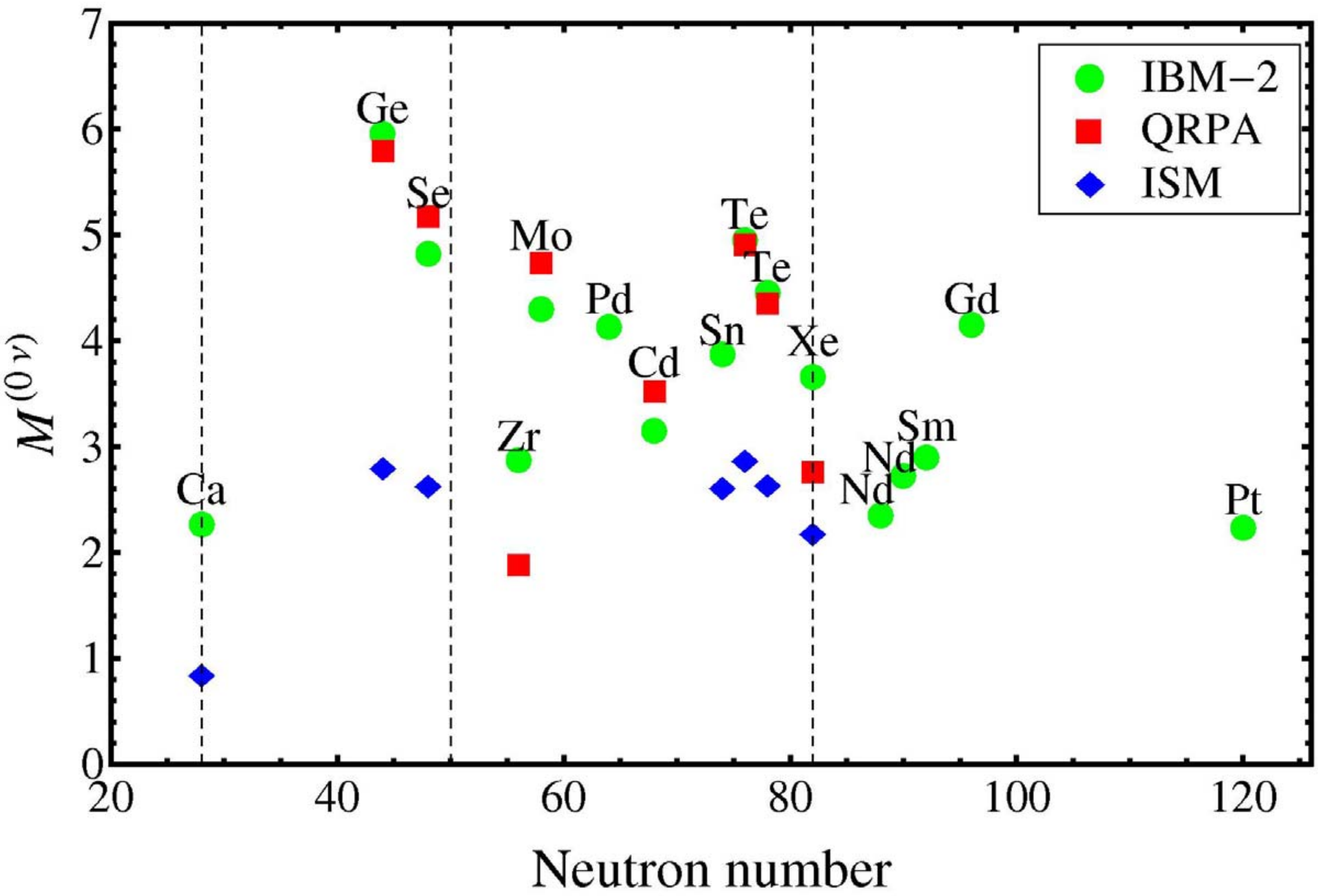
Neutrinoless double-β decay matrix elements $M_h^{(0\nu)}$ in IBM-2 with Argonne CCM SRC and $g_A = 1.269$, and in QRPA with Argonne CCM SRC, $g_A = 1.25$ and intermediate size for the model space.

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

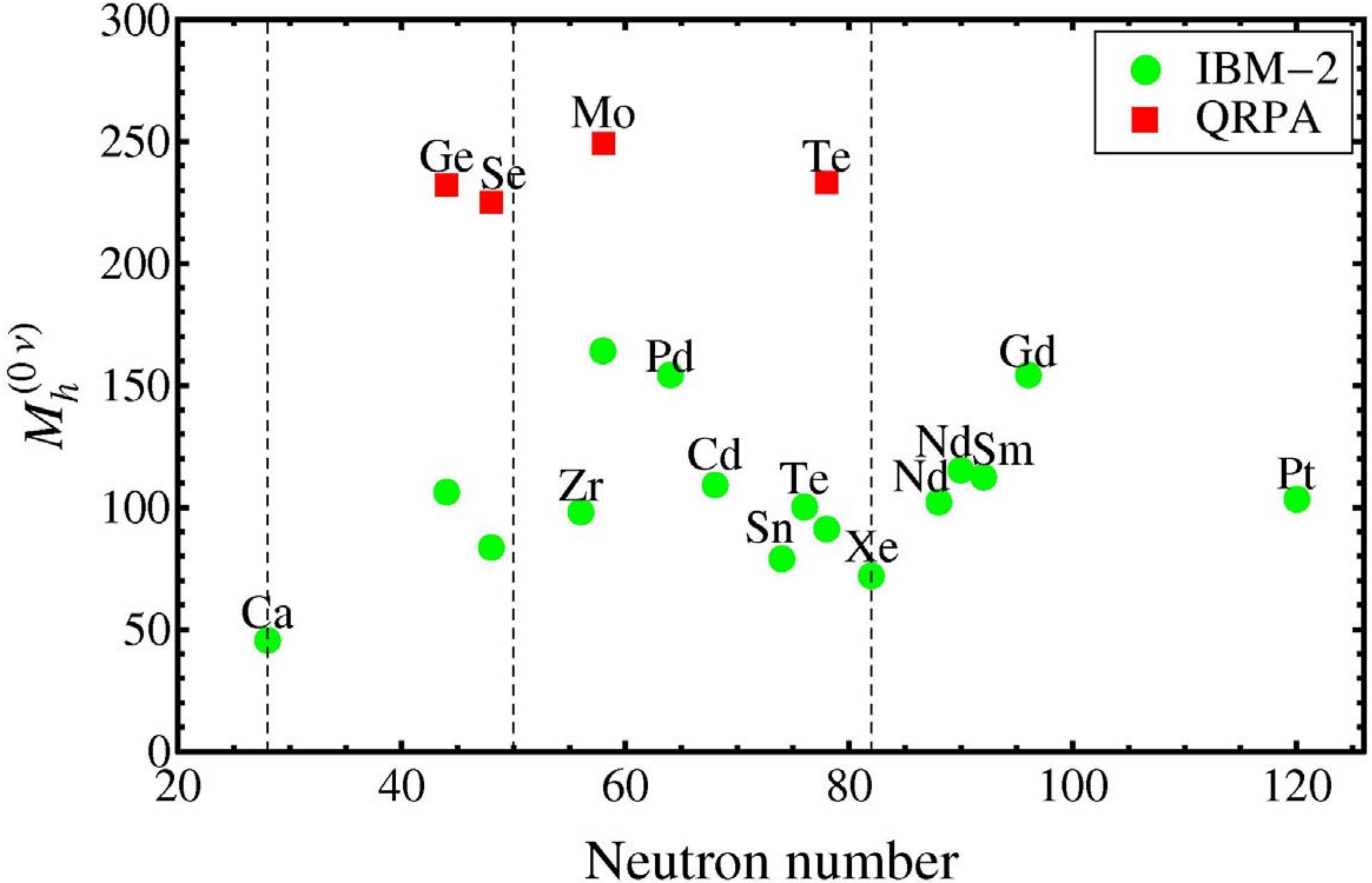
[a] Ref. A. Faessler, G. L. Fogli, E. Lisi, A. M. Rotunno, and F. Šimkovic, Phys. Rev. D **83**, 113015 (2011).

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

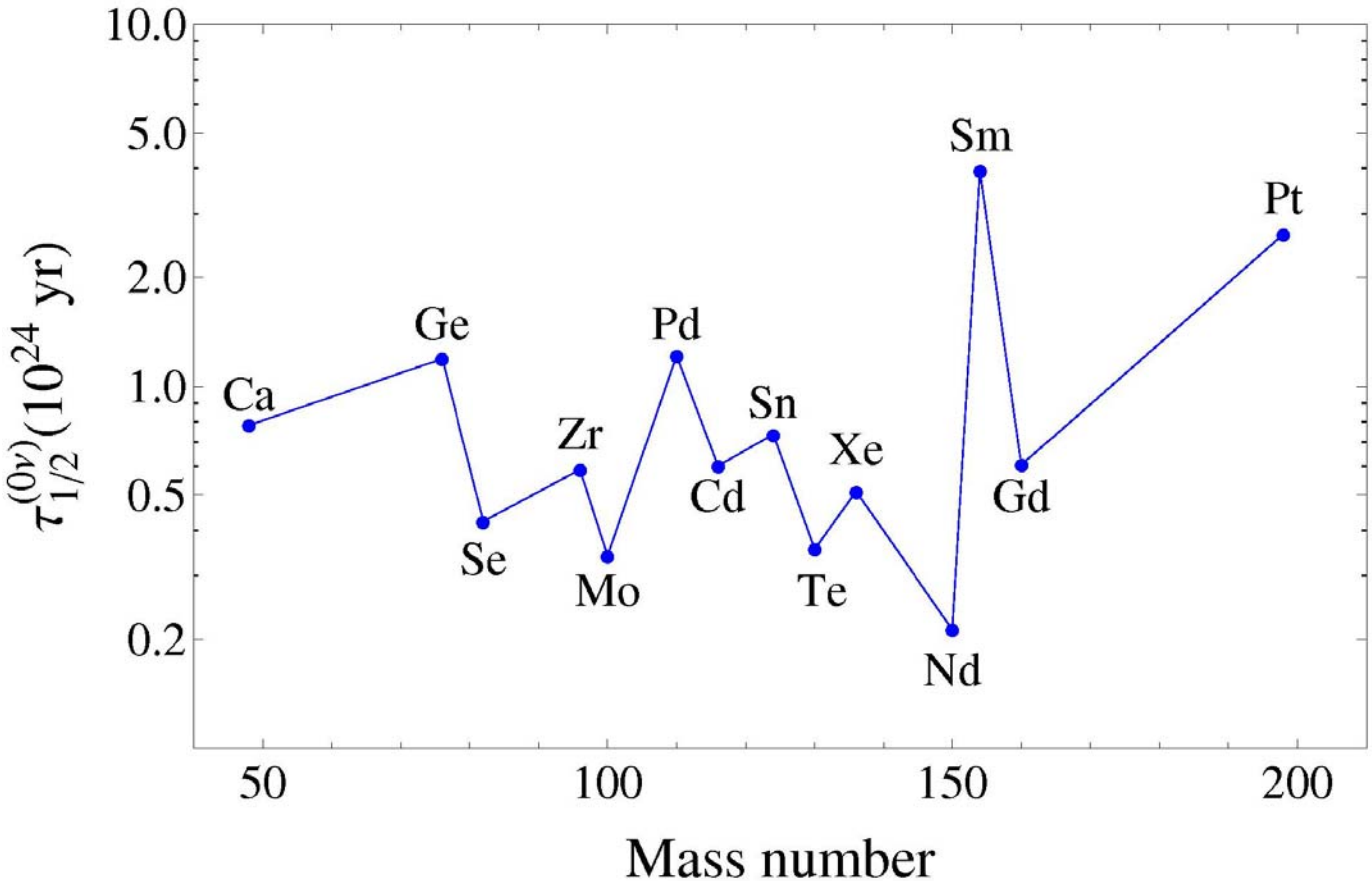
IBM-2 RESULTS (MAY 2012)
LIGHT NEUTRINO EXCHANGE



IBM-2 RESULTS (MAY 2012)
HEAVY NEUTRINO EXCHANGE



Combining NME with PSF we obtain the expected half-lives



Expected half-lives for light neutrino exchange with $\langle m_\nu \rangle$=1eV, g_A=1.269.
^{128}Te and ^{148}Nd not included in this figure. For other values, scale with $\langle m_\nu \rangle^2$ 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 (MAY 2012): LIGHT NEUTRINO

TABLE I. 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 and EXO are also included.

Decay	$\tau^{0\nu}_{1/2}(10^{24}\text{yr})$	$\tau^{0\nu}_{1/2,exp}(\text{yr})$	$\langle m_\nu \rangle(\text{eV})$
$^{48}Ca\rightarrow^{48}Ti$	0.782	$> 5.8 \times 10^{22}$	< 3.7
$^{76}Ge\rightarrow^{76}Se$	1.19	$> 1.9 \times 10^{25}$	< 0.25
		1.2×10^{25} [a]	0.32
		$> 1.6 \times 10^{25}$ [b]	< 0.27
$^{82}Se\rightarrow^{82}Kr$	0.423	$> 3.6 \times 10^{23}$	< 1.1
$^{96}Zr\rightarrow^{96}Mo$	0.588	$> 9.2 \times 10^{21}$	< 8.0
$^{100}Mo\rightarrow^{100}Ru$	0.340	$> 1.1 \times 10^{24}$	< 0.56
$^{110}Pd\rightarrow^{110}Cd$	1.22		
$^{116}Cd\rightarrow^{116}Sn$	0.602	$> 1.7 \times 10^{23}$	< 1.9
$^{124}Sn\rightarrow^{124}Te$	0.737		
$^{128}Te\rightarrow^{128}Xe$	6.94	$> 1.5 \times 10^{24}$	< 2.2
$^{130}Te\rightarrow^{130}Xe$	0.355	$> 2.8 \times 10^{24}$	< 0.36
$^{136}Xe\rightarrow^{136}Ba$	0.512	$> 5.7 \times 10^{24}$ [c]	< 0.30
		$> 1.6 \times 10^{25}$ [d]	< 0.18 ← Best limit
$^{148}Nd\rightarrow^{148}Sm$	1.79		
$^{150}Nd\rightarrow^{150}Sm$	0.213	$> 1.8 \times 10^{22}$	< 3.4
$^{154}Sm\rightarrow^{154}Gd$	3.94		
$^{160}Gd\rightarrow^{160}Dy$	0.606		
$^{198}Pt\rightarrow^{198}Hg$	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] A. Gando *et al.* (KamLAND-Zen collaboration), Phys. Rev. C **85**, 045504 (2012).
[d] M. Auger *et al.* (EXO collaboration) arXiv:1205.5608v1 [hep-ex] (2012).

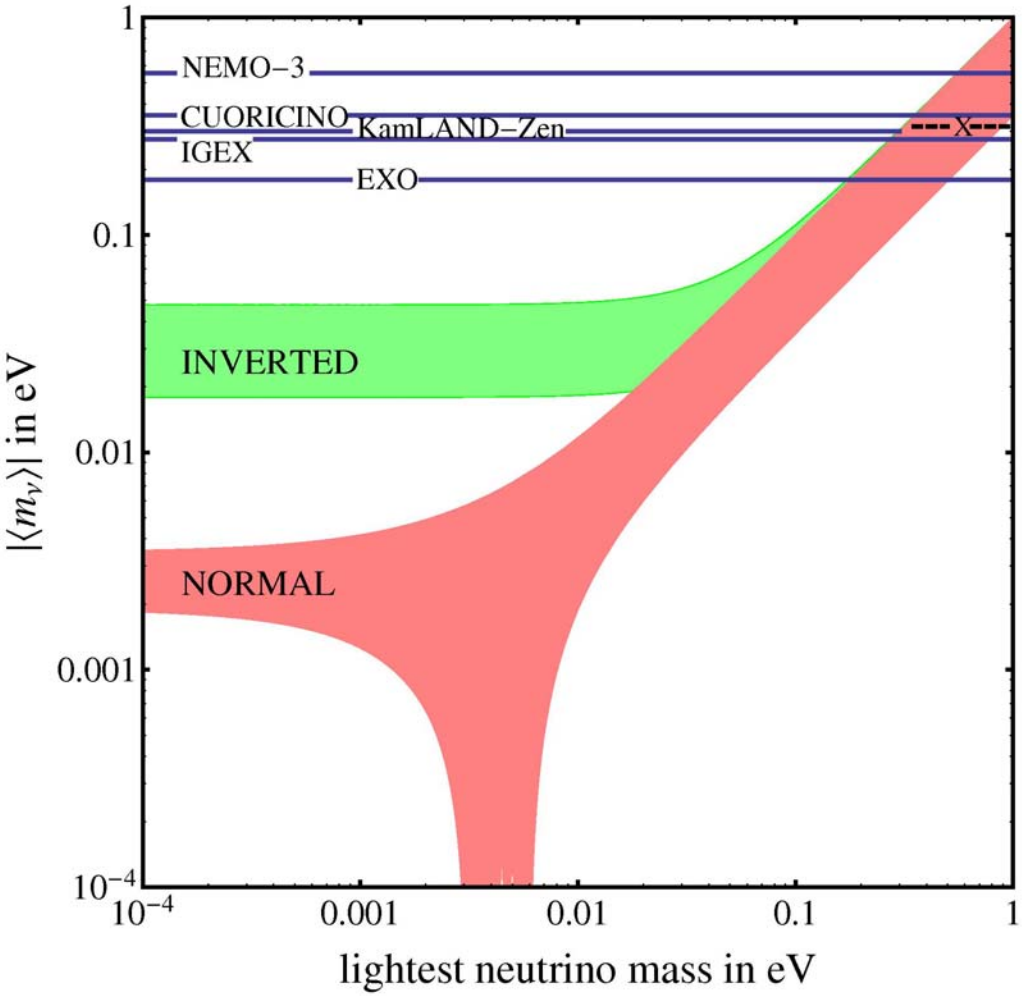
IBM-2 HALF-LIVES AND MASS LIMITS (MAY 2012): HEAVY NEUTRINO

TABLE I. 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 and EXO are also included.

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

[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] A. Gando *et al.* (KamLAND-Zen collaboration), Phys. Rev. C **85**, 045504 (2012).
[d] M. Auger *et al.* (EXO collaboration) arXiv:1205.5608v1 [hep-ex] (2012).

SUMMARY OF RESULTS (MAY 2012) ¶
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 nuclei. Two reasons:

(i) Limited model space

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

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) and 0^+ (F) multipoles contribute. In 0νββ all multipoles 1^+,0^+, 2^-, … 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.

CONCLUSIONS

Major progress has been made in the last two years to narrow down predictions of $0\nu\beta\beta$ 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.

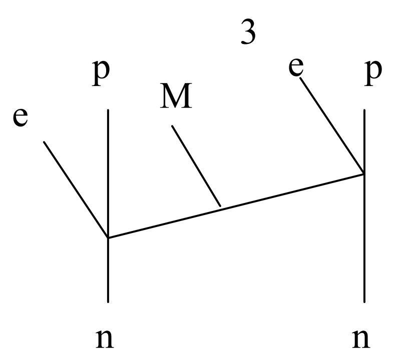
Possibilities to escape this negative conclusion are:

(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.

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

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



…

OTHER WORK COMPLETED

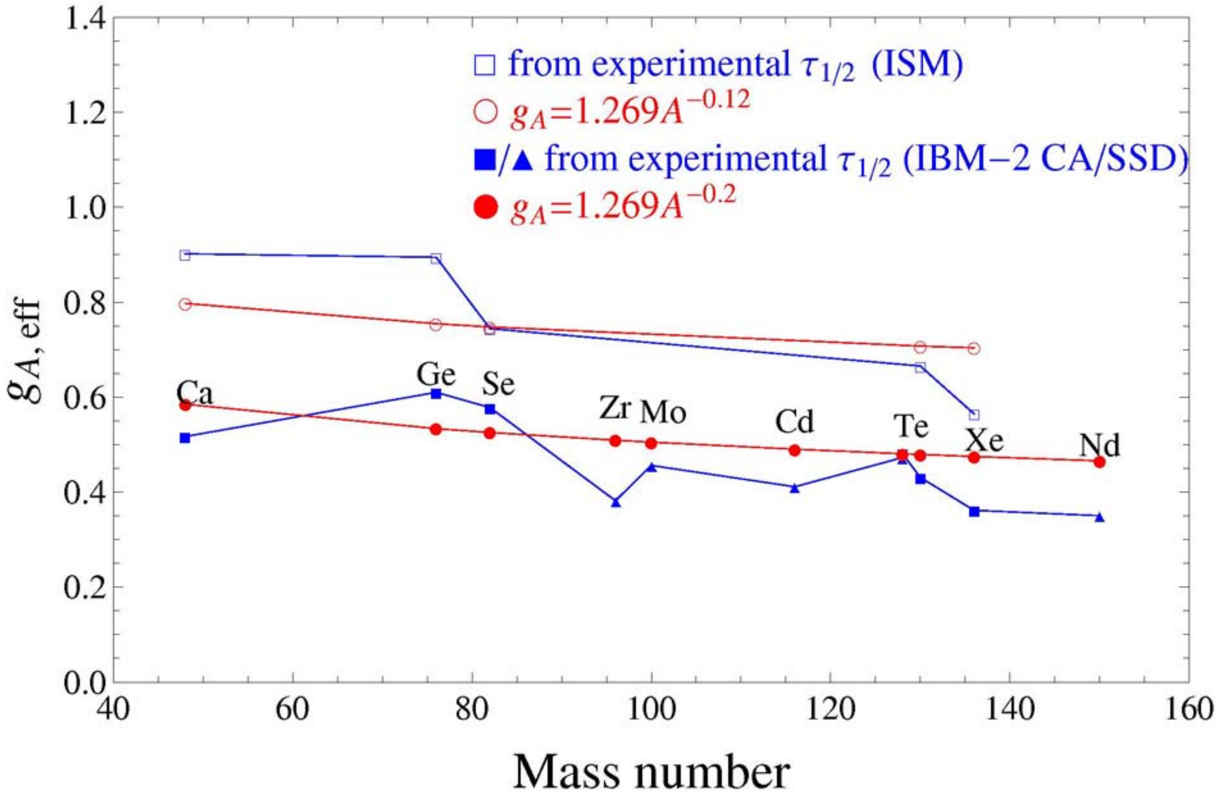
Calculation of NME and PSF to excited states in the final nucleus. (Completed May 2012).

WORK IN PROGRESS

Calculation of NME and PSF for β+β+, β+EC, ECEC processes in all nuclei of interest. (Expected to be completed in September 2012. Preliminary results available).

Study of the effect of sterile neutrinos on DBD. Of utmost importance in view of the comments in the previous slide.

APPENDIX A
Effective axial vector coupling constant in nuclei from 2νββ



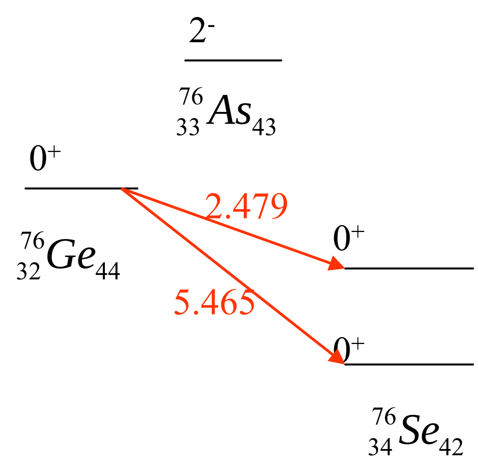
One obtains $g_{A,eff}^{IBM\text{-}2}$~0.6-0.5.

The extracted values can be parametrized as $$g_{A,eff}^{IBM2} = 1.269 A^{-0.2}$$

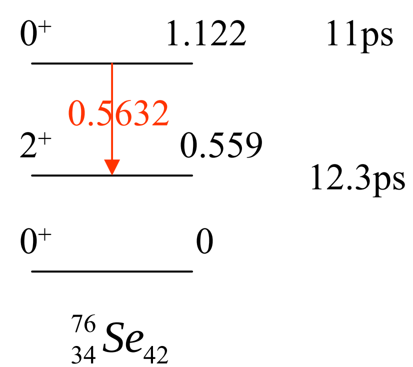
A similar analysis can be done for the ISM for which $g_{A,eff}^{ISM}$~0.8-0.7. $$g_{A,eff}^{ISM} = 1.269 A^{-0.12}$$

APPENDIX B
MATRIX ELEMENTS 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 (MAY 2012)
LIGHT NEUTRINO EXCHANGE
TO FIRST EXCITED 0^+ STATE