QUENCHING OF g_A AND ITS IMPACT IN DOUBLE BETA DECAY

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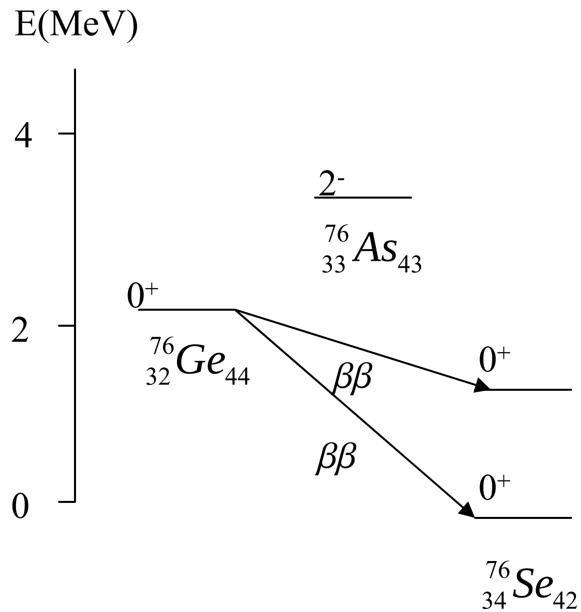
DOUBLE BETA DECAY

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



Half-life for processes not allowed by the standard model:

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

Beyond the standard model
(Particle physics)

Matrix elements
(Nuclear physics)
NME

Phase-space factor
(Atomic physics)
PSF

For processes allowed by the standard model, the half-life can be, to a good approximation, factorized in the form

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

Phase-space factor
(Atomic Physics) PSF

Matrix elements
(Nuclear Physics) NME

A special case is 0νECEC, which is forbidden by energy and momentum conservation, but can occur under resonance conditions. In this case the inverse half-life is given by

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|f(m_i, U_{ei})\right|^2 \frac{(m_e c^2)\Gamma}{\Delta^2 + (\Gamma^2/4)}$$

← Resonance factor

Prefactor (Atomic Physics) PF

Matrix elements (Nuclear Physics) NME

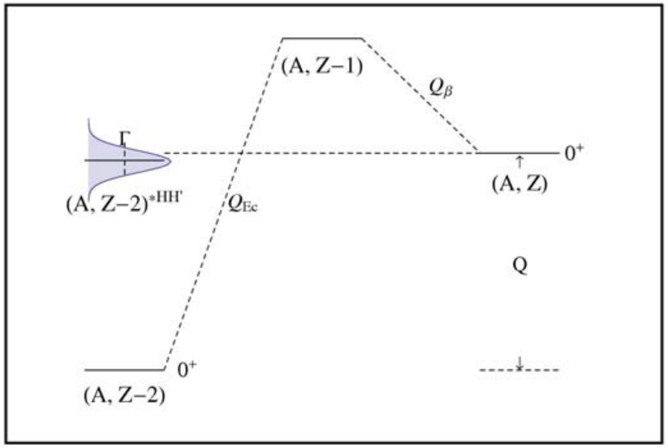
Beyond the SM (Particle Physics)

$$\Delta = \left|Q - B_{2h} - E\right|$$

← Degeneracy parameter (Atomic and Nuclear Physics)

$$\Gamma = \Gamma_{e_1} + \Gamma_{e_2}$$

↑ Two-hole width (Atomic Physics)



NUCLEAR MATRIX ELEMENTS (NME)

NME can be written as:

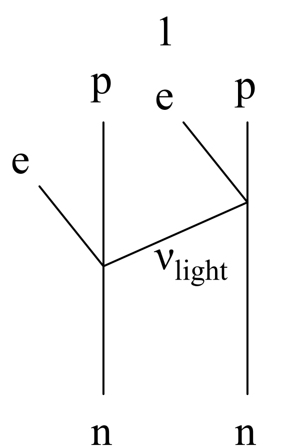
$$M_{0\nu} = g_A^2 M^{(0\nu)}$$

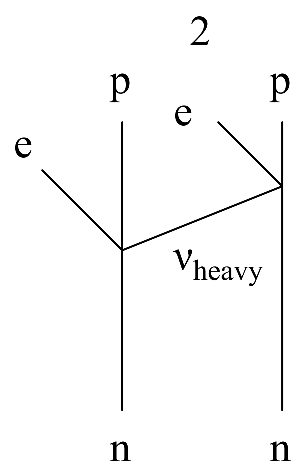
$$M^{(0\nu)} \equiv M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$

Several methods have been used to evaluate $M_{0\nu}$:
QRPA (Quasiparticle Random Phase Approximation)
ISM (Shell Model)
IBM-2 (Interacting Boson Model)
DFT (Density Functional Theory)

Calculations of NME in IBM-2 for all processes have been completed (2015) and are available upon request.
A list of references is given in Appendix A.

For 0ν processes two scenarios have been considered:
(i) Emission and re-absorption of a light ($m_{light} \ll 1$MeV) neutrino.
(ii) Emission and re-absorption of a heavy ($m_{heavy} \gg 1$GeV) neutrino.





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

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

Long range

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

Short range

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

Scenario 1: LIGHT NEUTRINO EXCHANGE

Dependence on the average neutrino mass

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

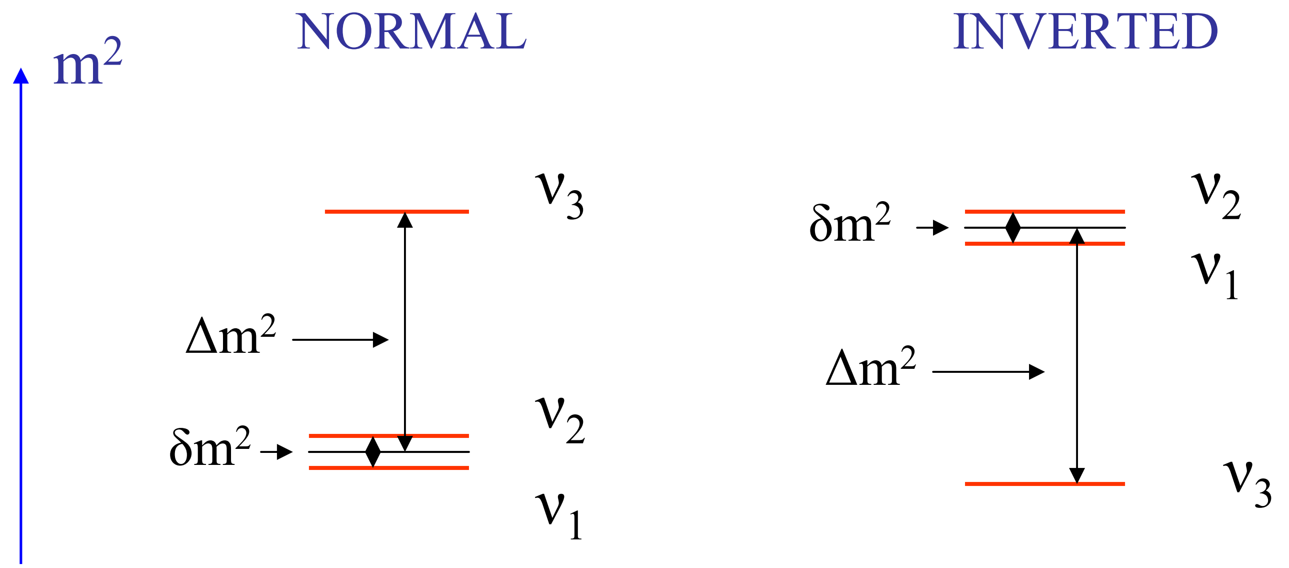
$$\langle m_\nu \rangle = \sum_{k=ligth} (U_{ek})^2 m_k$$

Fourier transform of the neutrino "potential"

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

$\tilde{A}$=closure energy=1.12$A^{1/2}$(MeV)

In the last few years atmospheric, solar, reactor and accelerator neutrino oscillation experiments have provided information on light neutrino mass differences and their mixings. Two possibilities, normal and inverted hierarchy, are consistent with experiment.



The average light neutrino mass can be written as

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

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

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

A fit to oscillation experiments gives §

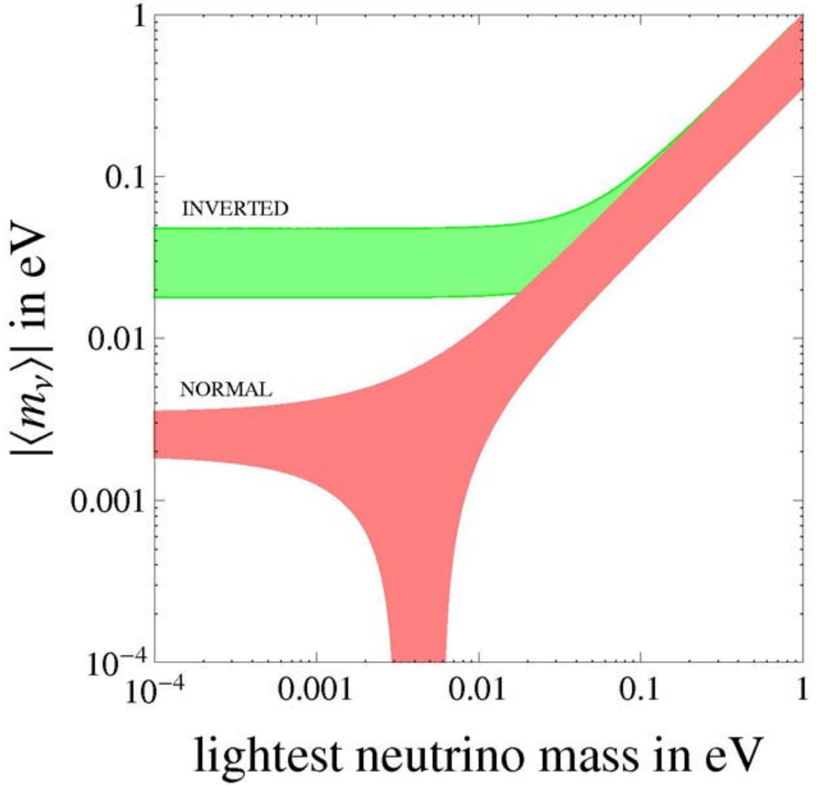
$$\sin^2\theta_{12} = 0.312, \sin^2\theta_{13} = 0.016, \sin^2\theta_{23} = 0.466$$

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

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

[A recent result from Daya Bay, Phys. Rev. Lett. 108, 171803 (2012) gives $\sin^2\theta_{13}$=0.024±0.005, which slightly modifies the fit.]

Variation of the phases φ_2 and φ_3 from 0 to 2π gives the values of $<m_\nu>$ consistent with oscillation experiments (constraints on the neutrino masses)



Vissani-Strumia plot ¶

¶ F. Vissani, J. High Energy Phys. 06, 022 (1999)

Scenario 2: HEAVY NEUTRINO EXCHANGE

Dependence on the average neutrino mass

$$f = m_p \left\langle \frac{1}{m_{\nu_h}} \right\rangle$$

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

Fourier transform of the neutrino "potential"

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

Constraints on the average inverse heavy neutrino mass are model dependent. V. Tello *et* al. ¶ have recently (2011) worked out constraints from lepton flavor violating processes and (potentially LHC experiments). In this model

$$f \equiv \eta = \frac{M_W^4}{M_{WR}^4} \sum_{k=heavy} \left(V_{ek_h}\right)^2 \frac{m_p}{m_{k_h}} \equiv \frac{M_W^4}{M_{WR}^4} \frac{m_p}{\left\langle m_{\nu_h} \right\rangle}$$

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

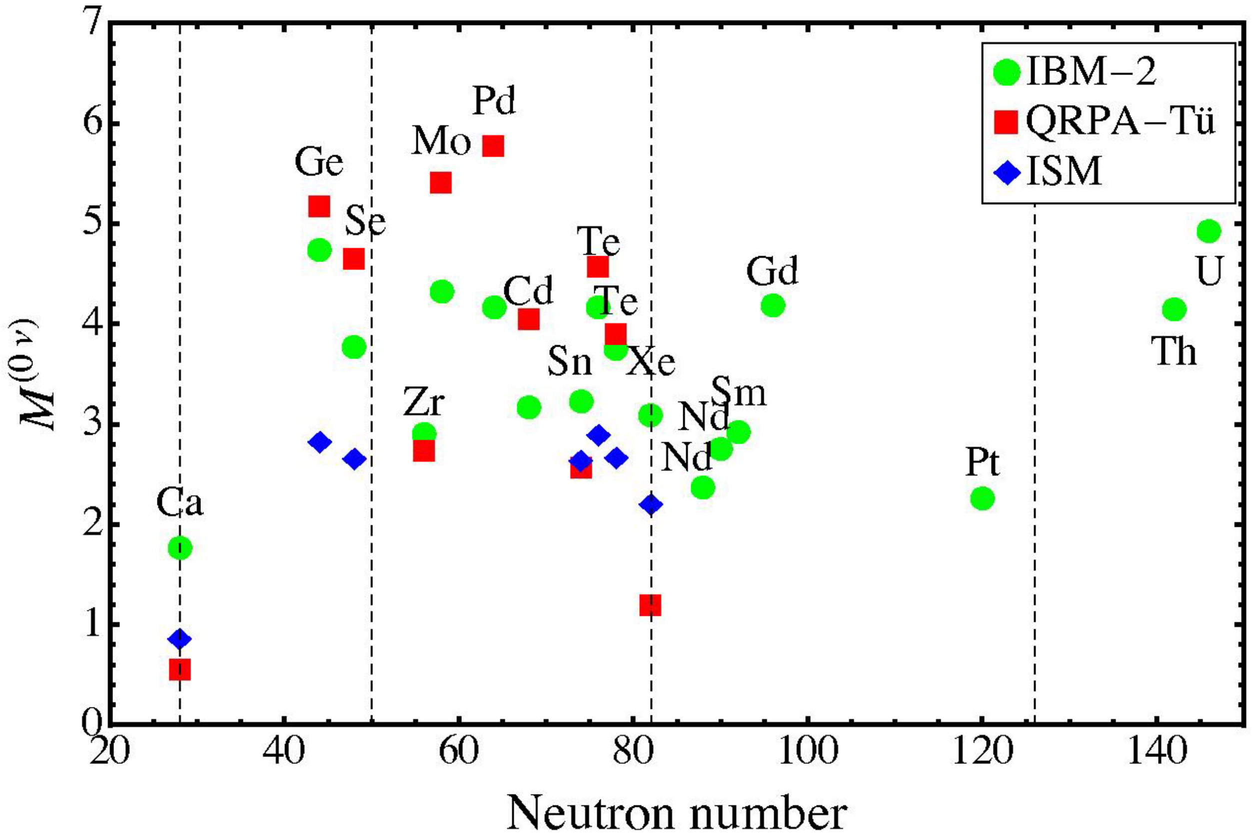
η=lepton violating parameter.

Constraints on η can then be converted into constraints on the average heavy neutrino mass as

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

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

Most recent (2015) results for $0\nu\beta^-\beta^-$ (light neutrino exchange)

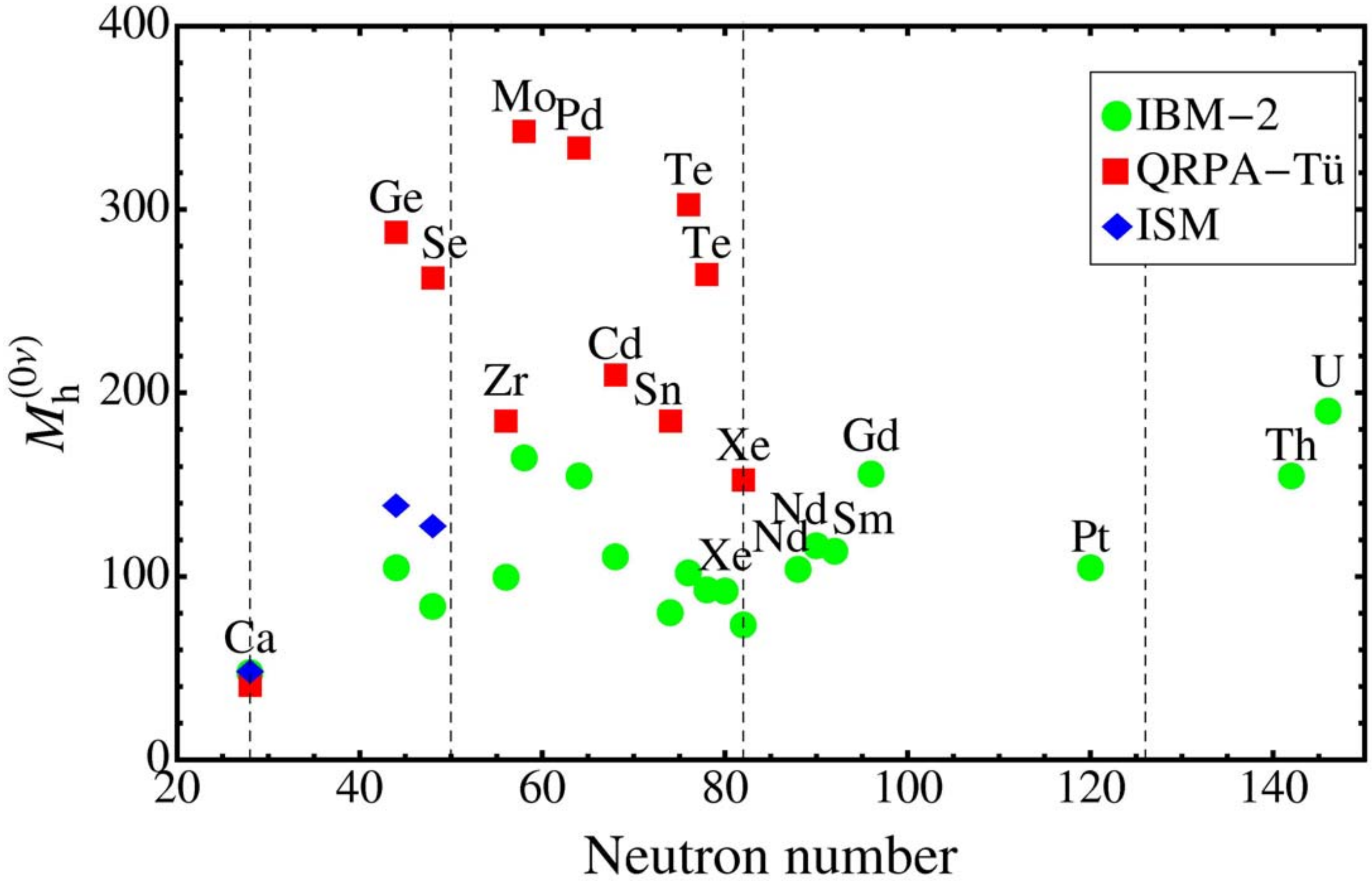


g_A=1.269

IBM-2 *: J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C, in press (2015).
QRPA-Tu *: F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C 87, 045501 (2013).
ISM: J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A 818, 139 (2009).

* With isospin restoration and Argonne SRC

Most recent (2015) results for $0\nu\beta^-\beta^-$ (heavy neutrino exchange)



g_A=1.269

* With isospin restoration and Argonne SRC

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 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).

QUENCHING 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

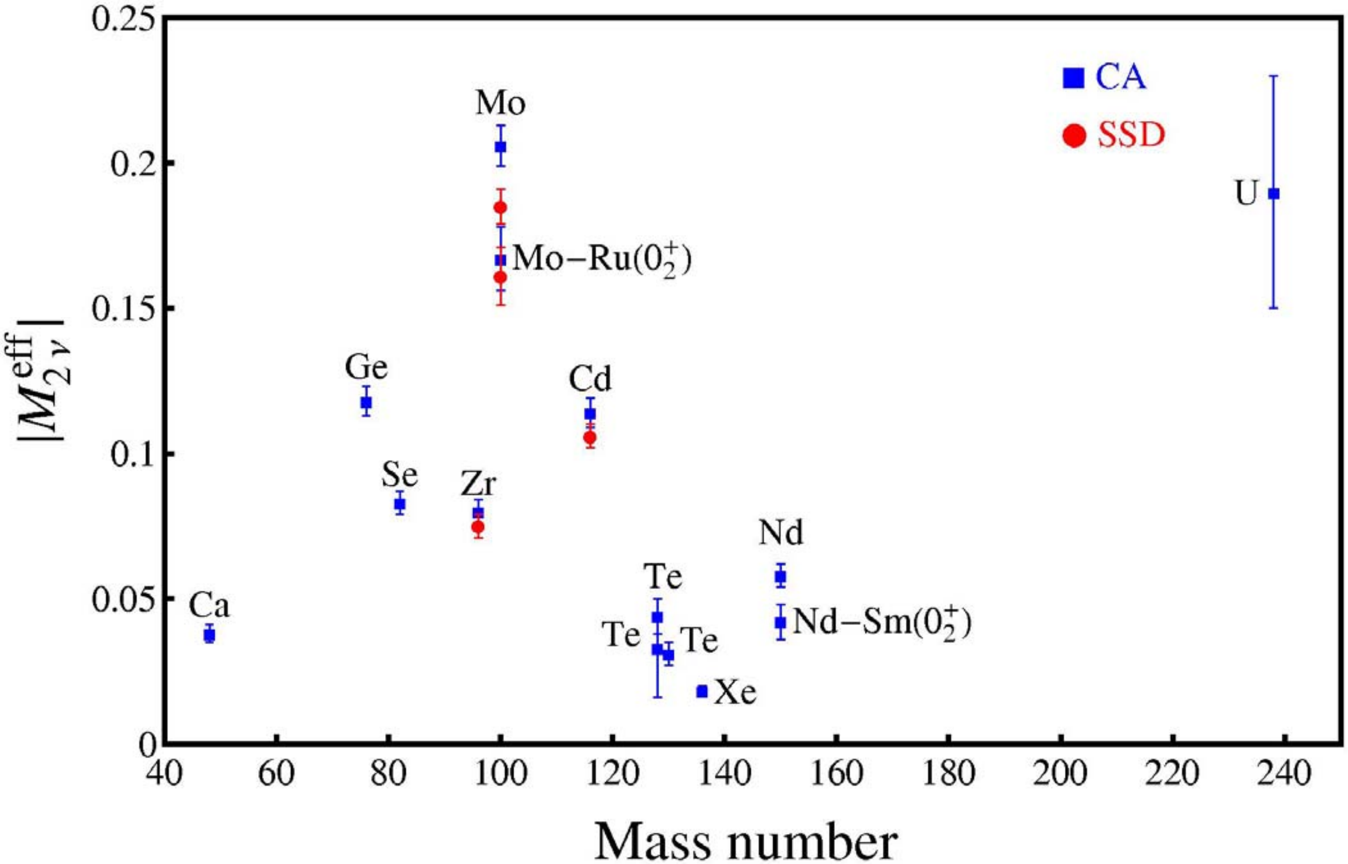
$$M_{2\nu}^{eff} = \left(\frac{g_{A,eff}}{g_A}\right)^2 M_{2\nu}$$

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

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.

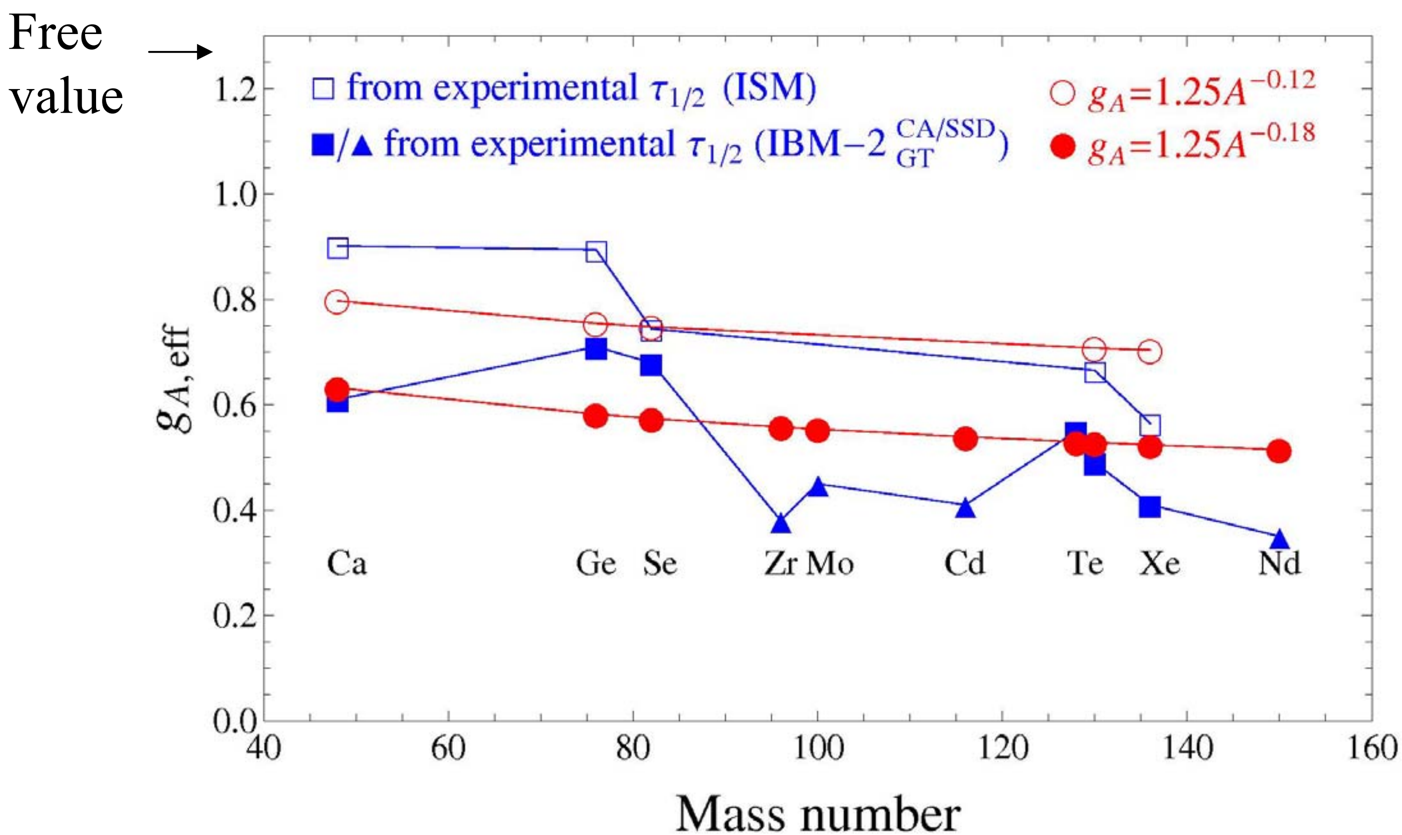
¶ J. Fujita and K. Ikeda, Nucl. Phys. 67, 145 (1965).
D.H. Wilkinson, Nucl. Phys. A225, 365 (1974).

Values of $|M_{2\nu}^{eff}|$ obtained from experimental half-lives ¶



¶ From a compilation by A.S. Barabash, Phys. Rev. C 81, 035501 (2010). For ^{136}Xe, N. Ackerman *et al.* (EXO Collaboration), Phys. Rev. Lett. 107, 212501 (2011).

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

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

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

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

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

$g_{A,eff}$, has been extracted also from single β/EC in QRPA, very recently by Suhonen and Civitarese (QRPA-Jy), $g_{A,eff}^{QRPA} \sim 0.8\text{-}0.4$ [§], and a few years ago by Faessler *et al*. (QRPA-Tü) ~ 0.7 [*].

[In some earlier (1989) QRPA papers[¶] , it is claimed that no renormalization of g_A is needed. However, this claim is based on results where the renormalization of g_A is transferred to a renormalization of the free parameter g_{pp} used in the calculation and adjusted to the experimental 2νββ half-life.]

§ J. Suhonen and O. Civitarese, Phys. Lett. B 725, 153 (2013).
* A. Faessler, G.L. Fogli, E. Lisi, V. Rodin, A.M. Rotunno, and F. Šimkovic, J. Phys. G: Nucl. Part. Phys. 35, 075104 (2008).

¶ K. Muto, E. Bender, H.V. Klapdor, Z. Phys. A334, 177 (1989); 187 (1989), as quoted by M. Hirsch (2014).

IMPACT OF THE RENORMALIZATION

The axial vector coupling constant, g_A, appears to the second power in the NME

$$M_{2\nu} = g_A^2 M^{(2\nu)}$$

$$M_{0\nu} = g_A^2 M^{(0\nu)}$$

$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$

and hence to the fourth power in the half-life!

Therefore, the results of the previous slides should be multiplied by 6-34 to have realistic estimates of expected half-lives. [See also, H. Robertson ¶, and S. Dell'Oro, S. Marcocci, F. Vissani#.]

¶ R.G.H. Robertson, Modern Phys. Lett. A 28, 1350021 (2013).

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

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

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).

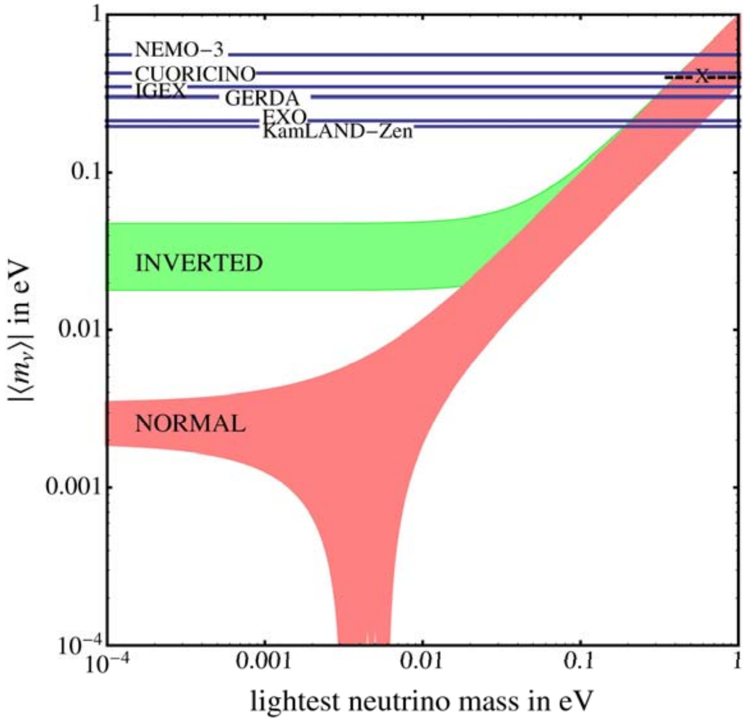
Another question is whether or not the vector coupling constant, g_V, is renormalized in nuclei.
Because of CVC, the mechanism (ii) omission of non-nucleonic degrees of freedom cannot contribute.
However, the mechanism (i), limited model space, can contribute, and, if so, the ratio g_V/g_A may remain the same as the non-renormalized ratio 1/1.269.
No experimental information is available, but is could be obtained by measuring with (^{3}He,t) and (d,^{2}He) reactions the F matrix elements to and from the intermediate odd-odd nucleus.
Also some novel experimental information could be obtained by double charge exchange reactions with heavy ions, (^{18}O,^{18}Ne) and (^{20}Ne,^{20}O) ¶ .

¶ F. Cappuzzello, C. Agodi, *et al.*, proposal NUMEN at LNS.

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.

Current (2015) limits on the neutrino mass from $0\nu\beta^-\beta^-$ (light neutrino exchange) with g_A=1.269, IBM-2 NME, and KI PSF:



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

With 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 EXO/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 EXO/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

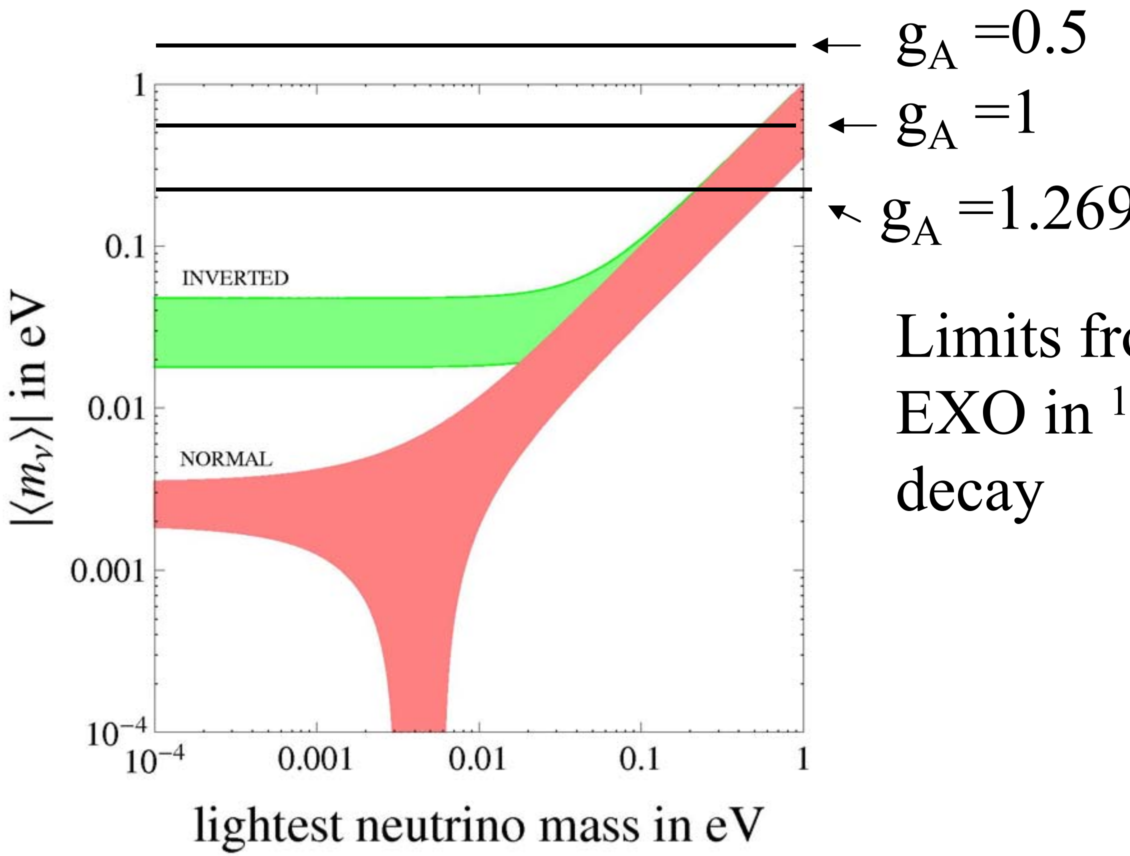
$$g_A = 1$$ ← Quark value

$$g_A = 1.269 A^{-0.18}$$ ← 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 ~0.8-0.5, all estimates for half-lives should be increased by a factor of ~6-34 and limits on the average neutrino mass should be increased by a factor ~2.5-6, making it impossible to reach in the foreseeable future even the inverted region.



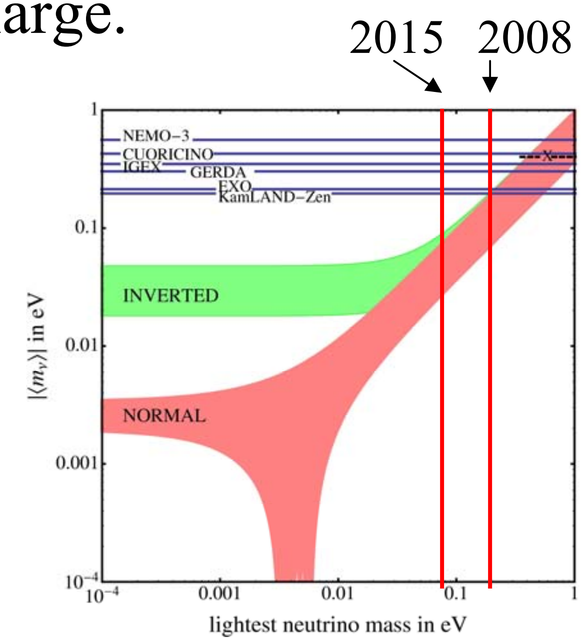
Limits from EXO in ^{136}Xe decay

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

This possibility will be in tension with the cosmological bound on the sum of the neutrino masses

$$\sum_i m_i \leq 0.6eV \qquad (2008)$$

$$\sum_i m_i \leq 0.230eV \qquad (2015)\ \text{Planck}\ ¶$$



¶ M. White for the Planck collaboration, private communication.

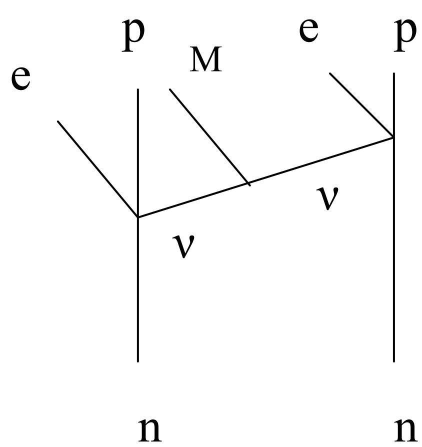
(2) Both mechanisms, light and heavy exchange, contribute simultaneously, are of the same order of magnitude, and interfere constructively.

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

This possibility requires a fine tuning which is quite unlikely.

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

3



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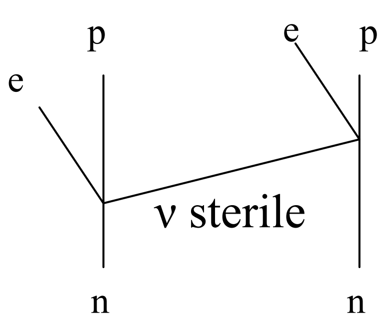


…

Scenario 3: MAJORON EMISSION

The inverse half-life for this scenario ($0\nu\beta\beta\varphi$ decay) is given by

$$\left[\tau_{1/2}^{0\nu\beta\beta\varphi}\left(0^+ \rightarrow 0^+\right)\right]^{-1} = G_{0\nu\varphi}\left|M_{0\nu}\right|^2 \left\langle g\right\rangle^2$$

effective Majoron coupling constant

NME are the same as for scenario 1 and 2.
PSF are being recalculated at the present time.

This scenario was suggested by H.M. Georgi, S.L. Glashow, and S. Nussinov, Nucl. Phys. B193, 297 (9181).

Scenario 4: STERILE NEUTRINOS

Another scenario is currently being discussed, namely the mixing of two or three additional "sterile" neutrinos, 4, 5 and 6, with masses in the keV-GeV range.
[The question on whether or not "sterile" neutrinos exist is an active areas of research at the present time with experiments planned at FERMILAB and CERN-LHC.]

NME for this scenario can be calculated by using a transition operator as in scenario 1 and 2 but with

$$f = \frac{m_{\nu I}}{m_e}$$

$$v(p) = \frac{2}{\pi} \frac{1}{\sqrt{p^2 + m_{\nu I}^2}\left(\sqrt{p^2 + m_{\nu I}^2} + \tilde{A}\right)}$$

Effective mass of the sterile neutrinos

NME in IBM-2 for this scenario are being calculated at the present time.

PSF are the same as in scenario 1 and 2 and are therefore already available.

Possible values of the sterile neutrino masses in the keV-GeV range have been suggested in T. Asaka and M. Shaposhnikov, Phys. Lett. B620, 17 (2005) and T. Asaka, S. Blanchet, and M. Shaposhnikov, Phys. Lett. B631, 151 (2005).

No matter what the mechanism of neutrinoless DBD is, its observation will answer the fundamental questions:

- What is the absolute neutrino mass scale?
- Are neutrinos Dirac or Majorana particles?
- How many neutrino species are there?

APPENDIX A: REFERENCES

PSF

$2\nu\beta^-\beta^-/0\nu\beta^-\beta^-$

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

$2\nu\beta^+\beta^+/0\nu\beta^+\beta^+$

J. Kotila and F. Iachello, Phys. Rev. C 87, 024313 (2013).

NME

$2\nu\beta^-\beta^-/0\nu\beta^-\beta^-$

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

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

J. Barea, J. Kotila and F. Iachello, Phys. Rev. C, in press (2015).

$2\nu\beta^+\beta^+/0\nu\beta^+\beta^+$

J. Barea, J. Kotila and F. Iachello, Phys. Rev. C87, 057301 (2013).

R0νECEC

J. Kotila, J. Barea, and F. Iachello, Phys. Rev. C 89, 064319 (2014).

APPENDIX B : RECENT IBM-2 RESULTS WITH ERROR FOR 0νββ (2015)

Decay	Light neutrino exchange	Heavy neutrino exchange
^{48}Ca	1.75(28)	47(13)
^{76}Ge	4.68(75)	104(29)
^{82}Se	3.73(60)	83(23)
^{96}Zr	2.83(45)	99(28)
^{100}Mo	4.22(68)	164(46)
^{110}Pd	4.05(65)	154(43)
^{116}Cd	3.10(50)	110(31)
^{124}Sn	3.19(51)	79(22)
^{128}Te	4.10(66)	101(28)
^{130}Te	3.70(59)	92(26)
^{134}Xe	4.05(65)	91(26)
^{136}Xe	3.05(59)	73(20)
^{148}Nd	2.31(37)	103(29)
^{150}Nd	2.67(43)	116(32)
^{154}Sm	2.82(45)	113(32)
^{160}Gd	4.08(65)	155(43)
^{198}Pt	2.19(35)	104(29)
^{232}Th	4.04(65)	159(45)
^{238}U	4.81(77)	189(53)

$^{76}Ge \rightarrow {}^{76}Se$

4.68 ± 0.75

GERDA

$^{130}Te \rightarrow {}^{130}Xe$

3.70 ± 0.59

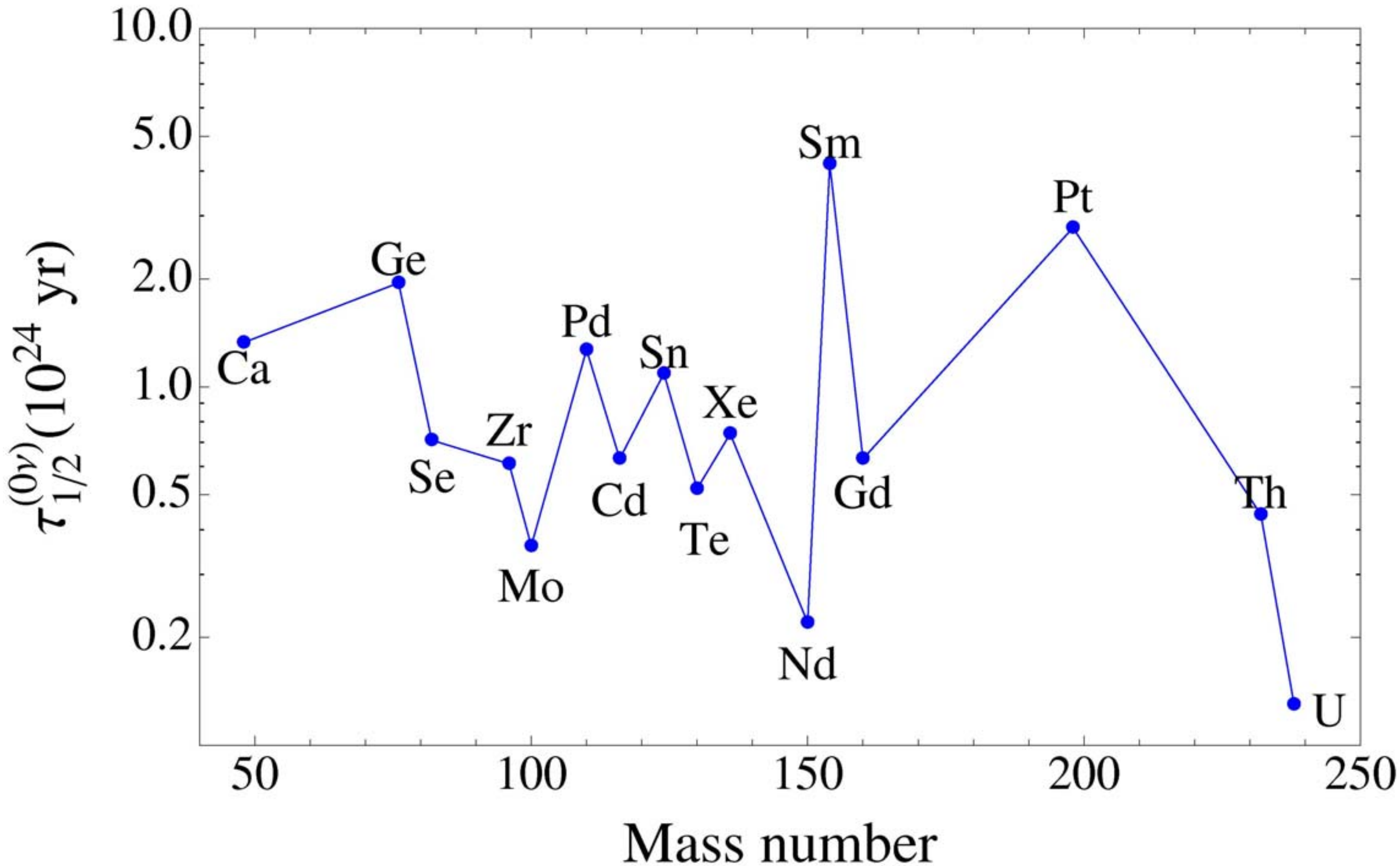
CUORE

$^{136}Xe \rightarrow {}^{136}Ba$

3.05 ± 0.59

EXO
KamLAND-Zen

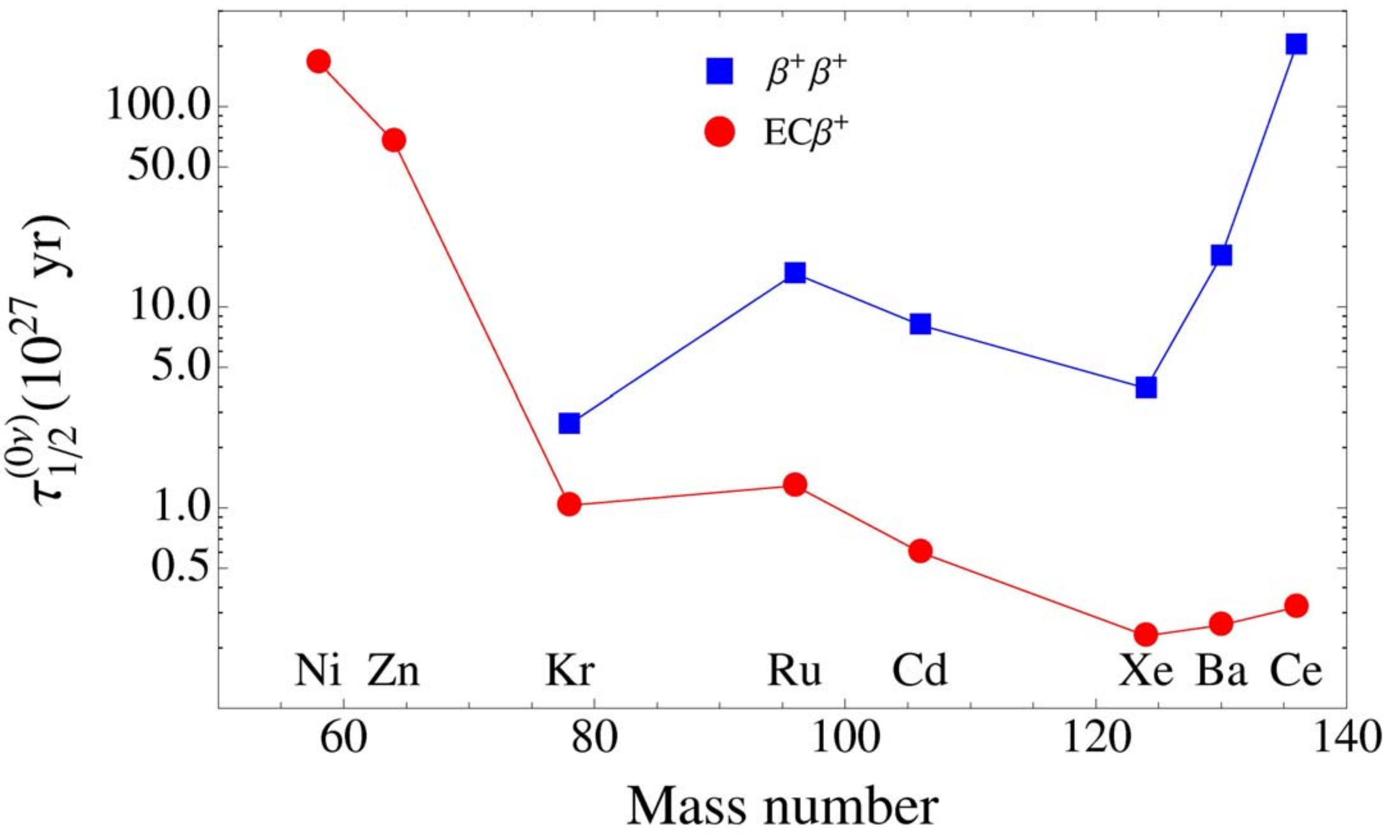
APPENDIX C: EXPECTED HALF-LIVES (2015) $0\nu\beta^-\beta^-$



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

$$g_A = 1.269$$

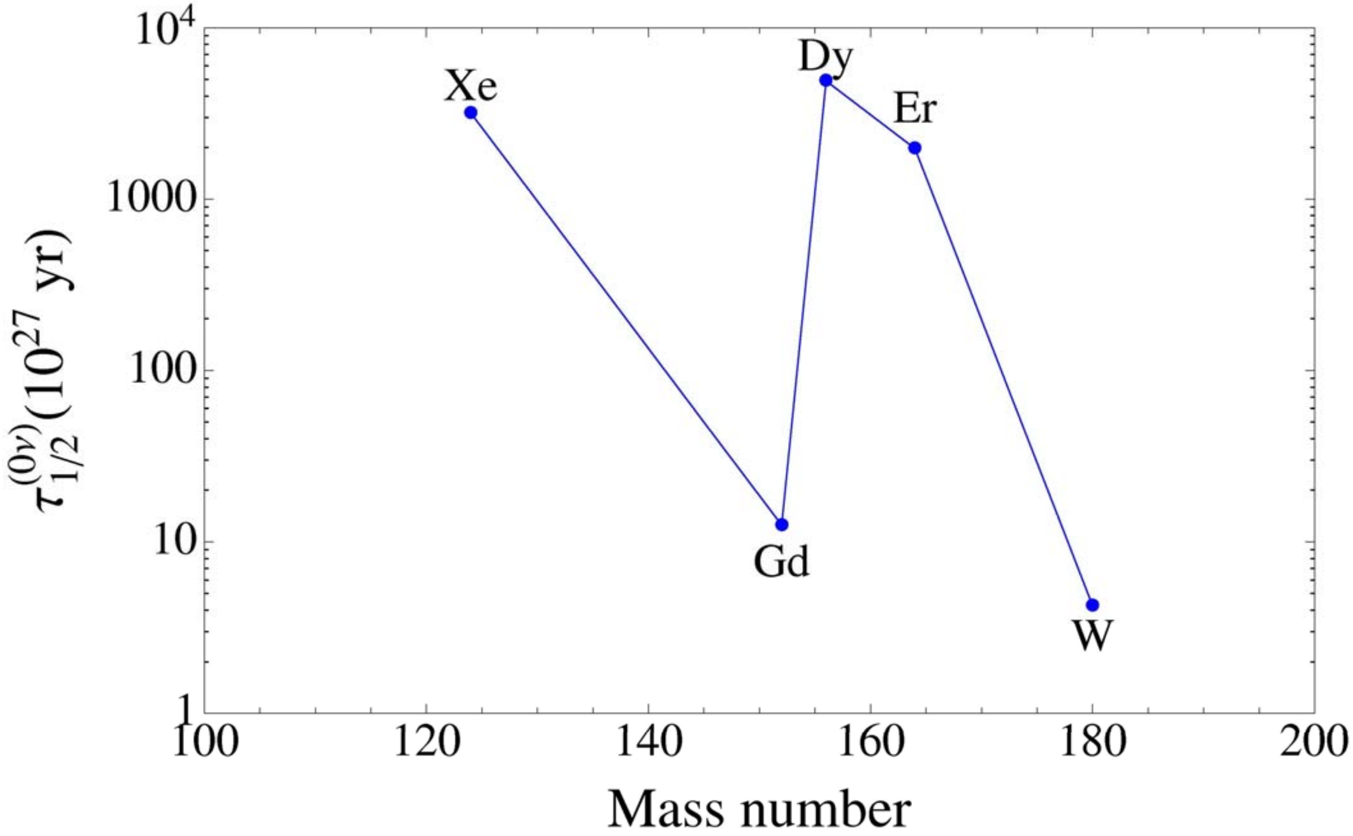
EXPECTED HALF-LIVES (2015) $0\nu\beta^+\beta^+/0\nu\beta^+EC$



$g_A=1.269$

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

EXPECTED HALF-LIVES (2015) R0νECEC



g_A=1.269

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

APPENDIX D: MATRIX ELEMENTS ALL

$g_A = 1.269$