$0\nu\beta\beta$ DECAY WITHOUT AND WITH MAJORON EMISSION

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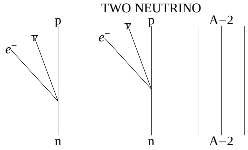
Motivation

- Short description of double beta decay: Nucleus (A, Z) decays to nucleus $(A, Z \pm 2)$ by emitting two electrons or positrons + other light particles

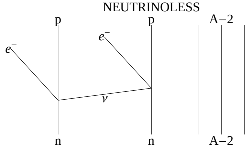


- For processes allowed by the standard model the half-life is

$$\left[\tau_{1/2}^{2\nu}\right]^{-1} = G_{2\nu} g_A^4 |m_e c^2 M^{(2\nu)}|^2$$

  - Observed in several nuclei with half-lives $\tau_{1/2}^{2\nu} > 10^{18}$yr

- and for neutrinoless modes

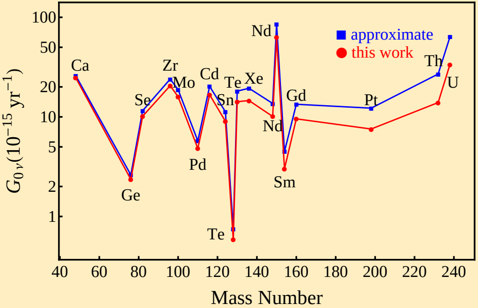


$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 |M^{(0\nu)}|^2 |f(m_i, U_{ei})|^2$$

- $G_{2\nu}$ and $G_{0\nu}$ are the phase space factors
- g_A is the axial vector coupling constant (effective value essentially model dependent)
- $M^{(2\nu)}$ and $M^{(0\nu)}$ are the nuclear matrix elements
- $f(m_i, U_{ei})$ contains the physics beyond standard model

Phase Space Factors

- The key ingredient for the evaluation of phase space factors (and thus also double beta decay) are the electron wave functions
- To simulate realistic situation, we take radial functions that satisfy Dirac equation and potential that takes into account the finite nuclear size and the electron screening



- Current $0\nu\beta^-\beta^-$ PSFs

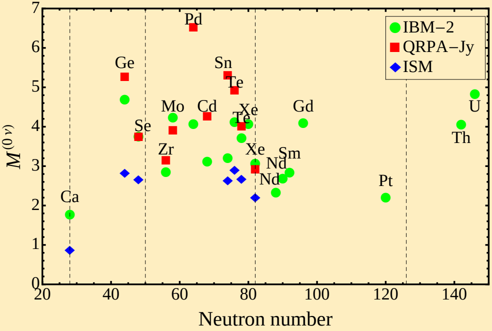
  Kotila *et al.* PRC **85**, 034316 (2012)

  (red) compared to previous calculations (blue)
- From PSF we also get single electron spectra, angular correlation, double differential rate (and summed electron spectra, triple differential rate)
- web site: nucleartheory.yale.edu

Nuclear Matrix Elements

COMPARISON OF IBM-2, QRPA, and ISM

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



IBM-2: J. Barea *et al.*, PRC **91**, 034304 (2015), QRPA-Jy: Suhonen *et al.*, PRC **91** 024613 (2015),ISM: J. Menendez *et al.*, NPA **818**, 139 (2009)

- IBM-2/QRPA/ISM similar trend
  - Larger values at the middle of the shell than at closed shells
- Isospin restoration reduces IBM-2 and QRPA matrix elements closer two ISM ones, where isospin is a good quantum number by construction
- Both the IBM-2 and QRPA are a factor of ∼2 larger than ISM in the lighter nuclei and the difference is smaller for heavier
  - Effective value of g_A?

Quenching of g_A

- It is well-known from single β decay/EC * and $2\nu\beta\beta$ that g_A is renormalized in models of nuclei. Reasons:
  - Limited model space
  - Omission of non-nucleonic degrees of freedom(Δ, N^*,...)
- The effective value of g_A can be
  - defined as

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

  - and obtained by comparing the calculated and measured half-lives for β/EC and/or for $2\nu\beta\beta$

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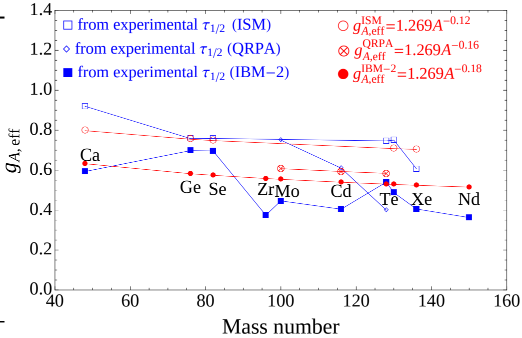
* J. Fujita and K. Ikeda, Nucl. Phys. 67, 145 (1965), D.H. Wilkinson. Nucl. Phys. A225, 365 (1974)

Quenching of g_A

Maximally quenched value from $2\nu\beta^-\beta^-$ experiments:

Nucleus	$\tau^{2\nu}_{1/2}(10^{18}$ yr) exp*
^{48}Ca	44^{+6}_{-5}
^{76}Ge	1650^{+140}_{-120}
^{82}Se	92 ± 7
^{96}Zr	23 ± 2
^{100}Mo	7.1 ± 0.4
^{100}Mo-^{100}Ru(0^+_2)	670^{+50}_{-40}
^{116}Cd	28.7 ± 1.3
^{128}Te	2000000 ± 300000
^{130}Te	690 ± 130
^{136}Xe	2110 ± 250
^{150}Nd	8.2 ± 0.9
^{150}Nd-^{150}Sm(0^+_2)	120^{+30}_{-20}
^{238}U	2000 ± 600

- $|M^{eff}_{2\nu}|^2 = \left[\tau^{2\nu}_{1/2} \times G_{2\nu}\right]^{-1}$
- $g_{A,eff} = g_A\sqrt{M^{eff}_{2\nu}/M_{2\nu}}$
- Extracted $g_{A,eff}$:
  - IBM-2$\sim 0.7 - 0.4$
  - QRPA$\sim 0.8 - 0.5$
  - ISM $\sim 0.9 - 0.6$



- Assumption: $g_{A,eff}$ is a smooth function of A
- Parametrization: $g_{A,eff} = 1.269A^{-\gamma}$
  - IBM-2: $\gamma = 0.18$
  - QRPA: $\gamma = 0.16$
  - ISM: $\gamma = 0.12$

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* A.S. Barabash, NPA **935**, 52 (2015).

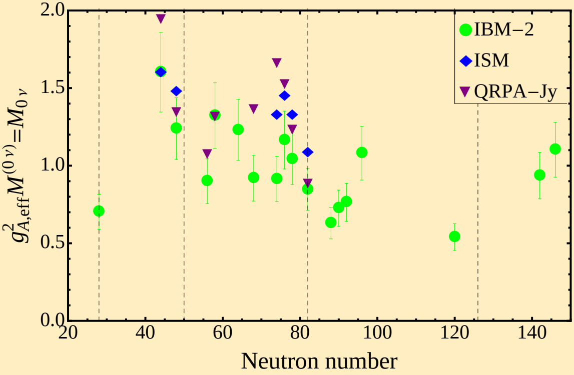
[a] ISM: E. Caurier *et al.*, PLB **711**, 61 (2012).

[b] QRPA: J. Suhonen *et al.*, PLB **725**, 153 (2013).

Quenching of g_A

Let's return to $0\nu\beta\beta$ NMEs:

$M_{0\nu} = g^2_{A,eff} M^{(0\nu)}$ for IBM-2, QRPA, and ISM



- Taking into account the 16% error estimate for IBM-2: Agreement quite good
- Looks promising...

Quenching of g_A

Effective value of g_A is work in progress, since:

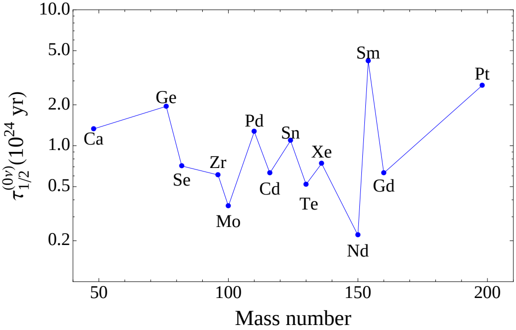
- Is the renormalization of g_A the same in $2\nu\beta\beta$ as in $0\nu\beta\beta$?
  - In $2\nu\beta\beta$ only the 1^+ (GT) multipole contributes. In $0\nu\beta\beta$ all multipoles 1^+, 2^-,...; 0^+, 1^-,... contribute. Some of which could be unquenched. However, also in $0\nu\beta\beta$, 1^+ intermediate states dominate
- How to estimate $g_{A,eff}$ more reliably?
  - Experiments: by measuring the matrix elements to and from the intermediate odd-odd nucleus in $\beta\beta$ decay [a]
  - Theoretical studies by using effective field theory (EFT) to estimate the effect of non-nucleonic degrees of freedom (two-body currents) [b]
- Half-life predictions with maximally quenched g_A are $\sim 6 - 34$ times longer due to the fact that g_A enters the equations to the power of 4!

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

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

Half-Life Predictions: $0\nu\beta^-\beta^-$

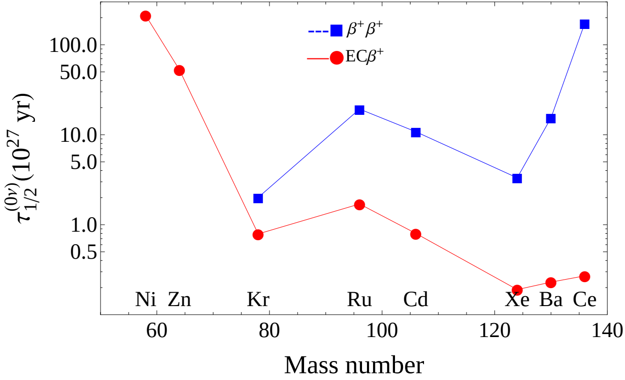
- Keep this in mind but for now predictions are calculated with g_A=1.269 (and $|\langle m_\nu \rangle| = 1$eV)



- Judging by the half-life, best candidates ^{150}Nd, ^{100}Mo, and ^{130}Te, where half-lives $\sim 10^{23}$yr

Half-Life Predictions: $\mathbf{0\nu\beta^+\beta^+}$ and $\mathbf{0\nu EC\beta^+}$

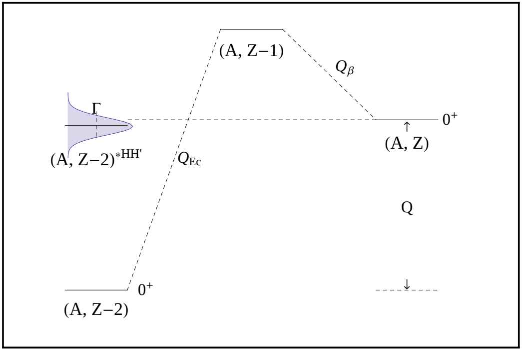
- $\beta^+\beta^+$, $\boldsymbol{EC\beta^+}$ available kinetic energy much smaller ⇒ much smaller phase space ⇒ much longer half-lives



- Best candidates $\mathbf{0\nu EC\beta^+}$ in $^{\mathbf{124}}$Xe, $^{\mathbf{130}}$Ba, and $^{\mathbf{136}}$Ce, where half-lives $\sim \mathbf{10^{26}}$ for g_A=1.269, $|\langle m_\nu\rangle| = \mathbf{1}eV$
  - Compared to $\mathbf{0\nu\beta^-\beta^-}$ hardly detectable

Half-Life Predictions: Resonantly Enhanced $0\nu ECEC$

- $0\nu ECEC$ available energy larger, but since all the energies are fixed, additional requirement that Q-value matches the final state energy
- Resonance enhancement:



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

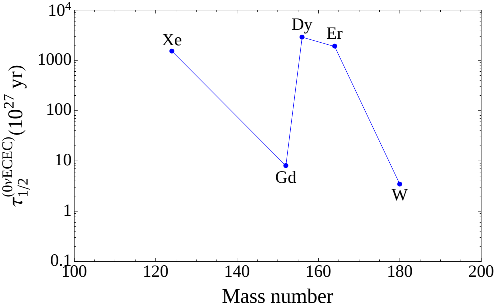
where $\Delta = |Q - B_{2h} - E|$ is the degeneracy parameter, and Γ is the two-hole width

- So in principle, if $\Delta \sim 0$ and $\Gamma \sim 1$eV we could obtain up to 10^6 enhancement
- Many candidates, such as ^{112}Sn, ^{130}Ba, and ^{136}Ce, ruled out by recent high precision Q-value measurements

Half-Life Predictions: Resonantly Enhanced $0\nu ECEC$

Decay	$G_{0\nu}^{ECEC}$ (10^{-19}yr^{-1})	$M^{(0\nu)}$	Δ (keV)	Γ (keV)	$(m_e c^2)$F	$\tau_{1/2}$ (10^{27})yr
^{124}Xe	2.57	0.30	1.86	0.0198	2.92	1520
^{152}Gd	1.46	2.45	0.91	0.023	14.38	8.03
^{156}Dy	0.27	0.31	0.54	0.0076	13.52	2890
^{164}Er	0.36	3.95	6.81	0.0086	0.095	1880
^{180}W	46.2	4.67	11.24	0.072	0.29	3.44

- Best candidates at the moment ^{152}Gd, and ^{180}W



- Half-lives $> 10^{27}$ for $|\langle m_\nu \rangle| = 1eV$ and $g_A = 1.269$
    - Compared to $0\nu\beta^-\beta^-$ hardly detectable

J. Kotila *et al. PRC 89, 064319 (2014)*

Limits on Average Neutrino Mass

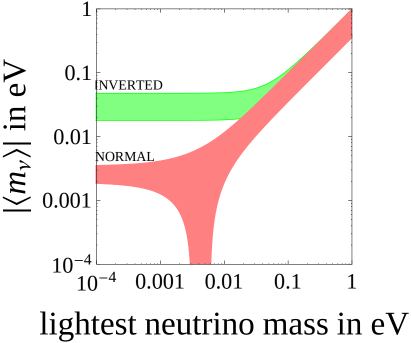
Reminder:

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 |M^{(0\nu)}|^2 |f(m_i, U_{ei})|^2$$

- Light neutrinos:

$$f(m_i, U_{ei}) = \frac{\langle m_\nu \rangle}{m_e} = \frac{1}{m_e} \sum_{k=light} (U_{ek})^2 m_k$$

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



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

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

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

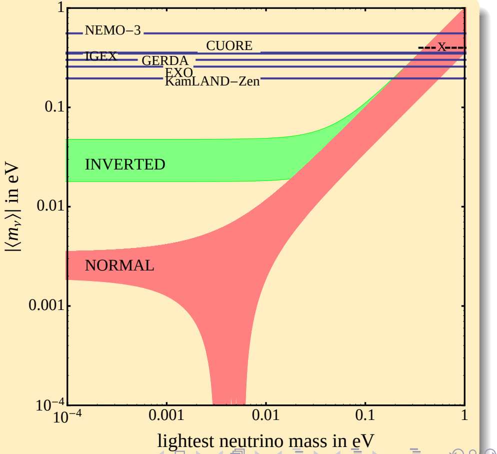
ϑ, δm, and Δm fitted to oscillation experiments,
φ varies $[0, 2\pi]$

Limits on Average Light Neutrino Mass

Current lower half-life limits coming from different experiments

Experiment	nucleus	$\tau_{1/2}$	$\langle m_\nu \rangle$
IGEX[a]	^{76}Ge	$> 1.57 \times 10^{25}$yr	< 0.35eV
GERDA[b]	^{76}Ge	$> 2.1 \times 10^{25}$yr	< 0.30eV
NEMO-3[c]	^{100}Mo	$> 1.1 \times 10^{24}$yr	< 0.56eV
CUORE[d]	^{130}Te	$> 4.0 \times 10^{24}$yr	< 0.35eV
EXO[e]	^{136}Xe	$> 1.1 \times 10^{25}$yr	< 0.25eV
Kamland-Zen[f]	^{136}Xe	$> 1.9 \times 10^{25}$yr	< 0.20eV

$$\tau_{1/2} \Rightarrow \langle m_\nu \rangle < \frac{m_e}{\sqrt{\tau_{1/2}^{exp} G_{0\nu} g_A^2}\,|M^{(0\nu)}|}$$



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[a] C. E. Aalseth *et al.*, PRD **65**, 092007 (2002),
[b] M. Agostini *et al.* PRL **111** 122503 (2013),
[c] R. Arnold, *et al.*, PRD **89**, 111101 (2014),
[d] K. Alfonso *et al.*, arXiv:1504.02454 [nucl-ex] (2015),
[e] M. Auger *et al.*, Nature 510, 229 (2014),
[f] A. Gando *et al.*, PRL **110**, 062502 (2013)

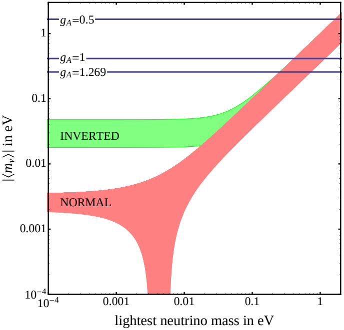
Limits on Average Neutrino Mass: Remarks

- If both light and heavy neutrino exchange contribute, the half-lives are given by

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

  - The two contributions could add or subtract depending on their relative phase

- The question of effective value of g_A is still open. Three suggested scenarios are
  - Free value: 1.269
  - Quark value: 1
  - Maximally quenched value: $1.269 A^{-0.18}$



- Consideration of other scenarios like Majoron emitting modes of DBD and new mechanisms like sterile neutrinos?

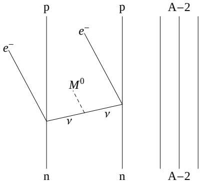
Majoron emitting $0\nu\beta\beta$

- This mechanism requires the emission of one or two additional bosons, Majorons

$$(A,Z) \rightarrow (A,Z{+}2){+}2e^{-}{+}\chi_0$$

or

$$(A,Z) \rightarrow (A,Z{+}2){+}2e^{-}{+}2\chi_0$$



- If Majorons exist, they could play a significant role in the history of the early Universe and in the evolution of stars
  - Dark matter, cosmological and astrophysical processes...
- Half-life

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = g_A^4 G^{(0)}_{m\chi_0 n} \left|\left\langle g_{\chi^M_{ee}}\right\rangle\right|^{2m} \left|M^{(m,n)}_{0\nu M}\right|^2$$

  - m is the number of emitted Majorons and n is the spectral index of the decay
  - $\langle g_{\chi^M_{ee}}\rangle$ is the majoron-neutrino coupling constant

Majoron emitting $0\nu\beta\beta$

single

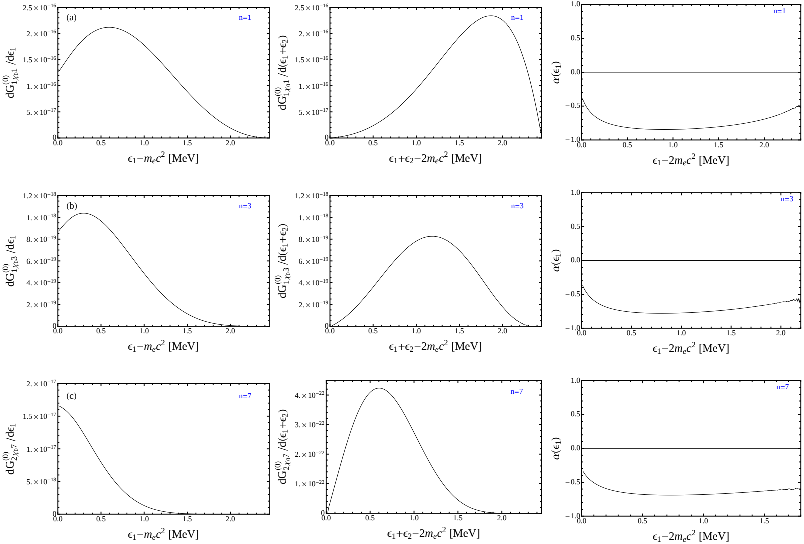
summed

α

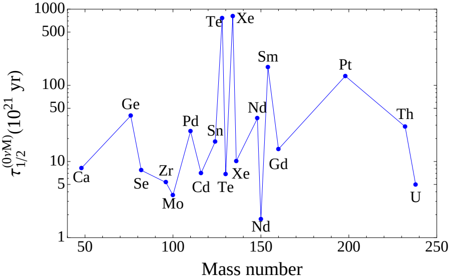
n=1

n=3

n=7



Majoron emitting $0\nu\beta\beta$



- Half-lives: Ordinary Majoron decay $m = 1, n = 1$, (with $\langle g_{ee}^{M} \rangle = 10^{-4}$)
- If the Majoron couples only to light neutrino, the NME needed to calculate the half-life are the same as for light neutrino exchange

Decay	$\tau_{1/2}^{0\nu M}(10^{21}$yr)	$\tau_{1/2,exp}^{0\nu M}$(yr)	$\langle g_{ee}^{M} \rangle$ (eV)
^{48}Ca$\rightarrow^{48}$Ti	8.19	$> 7.2 \times 10^{20}$	$< 3.4 \times 10^{-3}$
^{76}Ge$\rightarrow^{76}$Se	39.8	$> 6.4 \times 10^{22}$	$< 7.9 \times 10^{-4}$
^{82}Se$\rightarrow^{82}$Kr	7.68	$> 1.5 \times 10^{22}$	$< 7.2 \times 10^{-4}$
^{96}Zr$\rightarrow^{96}$Mo	5.32	$> 1.9 \times 10^{21}$	$< 1.7 \times 10^{-3}$
^{100}Mo$\rightarrow^{100}$Ru	3.62	$> 3.9 \times 10^{22}$	$< 3.0 \times 10^{-4}$
^{116}Cd$\rightarrow^{116}$Sn	7.06	$> 8 \times 10^{21}$	9.4×10^{-4}
^{128}Te$\rightarrow^{128}$Xe	765	$> 2 \times 10^{24}$	$< 6.2 \times 10^{-4}$
^{130}Te$\rightarrow^{130}$Xe	6.82	$> 1.6 \times 10^{22}$	$< 6.5 \times 10^{-4}$
^{134}Xe$\rightarrow^{134}$Ba	805		
^{136}Xe$\rightarrow^{136}$Ba	10.1	$> 2.6 \times 10^{24}$	$< 6.2 \times 10^{-5}$
		$> 1.2 \times 10^{24}$	$< 9.2 \times 10^{-5}$
^{148}Nd$\rightarrow^{148}$Sm	36.8		
^{150}Nd$\rightarrow^{150}$Sm	1.74	$> 1.5 \times 10^{21}$	$< 1.1 \times 10^{-3}$

J. Kotila *et al.*, *accepted to PRC*

Sterile neutrinos

- Another scenario, currently being extensively discussed, is the mixing of additional "sterile" neutrinos
- Several types of sterile neutrinos have been suggested
  - Light sterile neutrinos
    - Neutrino masses are $m_N \sim 1\text{eV}$
    - These neutrinos account for the reactor anomaly in oscillation experiments and for the gallium anomaly
  - Heavy sterile neutrinos
    - Neutrino masses are $m_N \gg 1\text{eV}$
    - keV mass range, MeV-GeV mass range, TeV mass range
    - Possible dark matter candidates
- Limits on possible sterile neutrino contributions in DBD are being calculated at the present time...

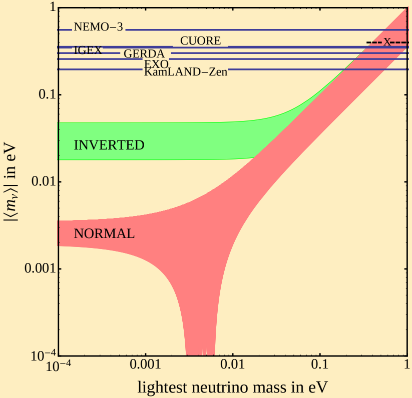
Summary

- We have studied several scenarios and mechanisms suggested to describe double beta decay
    - This includes two neutrino and neutrinoless decays, exhange of light and heavy neutrinos, majoron emitting $\beta\beta$, and decays to ground states as well as to first excited $\mathbf{0^+}$ states
- Concerning the mass mechanism, based on our results $\boldsymbol{0\nu\beta^-\beta^-}$ is the likeliest mode to be observed, even if $\boldsymbol{0\nu ECEC}$ is resonantly enhanced
- Effective value of $\boldsymbol{g_A}$ is work in progress and first results suggest considerable quenching

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

THANK YOU!



More information: nucleartheory.yale.edu

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