Description of neutrinoless double beta decay using IBM-2

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Challenges in the investigation of double charge-exchange nuclear reactions: towards neutrino-less double beta decay

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Contents

Motivation

- Although proposed more than 70 years ago to establish the nature of neutrinos, neutrinoless double beta decay remains the most sensitive probe to following open questions:
  - What is the absolute neutrino mass scale?
  - Are neutrinos Dirac or Majorana particles?
  - How many neutrino species are there?
- At the moment experiments are scanning half-lives of the order of $\mathbf{10^{25}}$yr:

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

- $\mathbf{f(m_i, U_{ei})}$ contains the physics beyond standard model and is different for different scenarios and mechanisms: exchange of light or heavy neutrino, emission of Majoron, exchange of sterile neutrino(s)...
- The fact that $\mathbf{0\nu\beta\beta}$-decay is a unique process, and there is no direct probe which connects the initial and final states other than the process itself makes the prediction challenging for theoretical models.
- The reliability of the used wave functions, and eventually $\mathbf{M^{(0\nu)}}$, has to be then tested using other available relevant data.

Different models, different assumptions

$\mathbf{M}^{(0\nu)}$ are calculated in nuclear models, such as:

- The Quasiparticle random phase approximation, QRPA, constructs ground state correlations by iterating two-quasiparticle excitations on top of a BCS or HFB vacuum. A quasiboson approximation is then imposed on the excitations. The calculations are performed in a large valence space including several major shells. The Hamiltonian is typically based on a realistic G matrix, but modified in the like-particle pairing and particle-hole channels to reproduce experimental pairing gaps and Gamow-Teller resonance energies. Results depend on fine-tuning of the interaction, especially near the spherical-deformed transition, for example ^{150}Nd.

- In the interacting shell model, ISM, the single-particle Hilbert space is small, typically a few valence orbits. However, the shell model includes all possible correlations within that space through direct diagonalization of the Hamiltonian. The valence-shell interaction usually comes from G-matrix perturbation theory or a renormalization-group treatment, but must be adjusted to reproduce spectra. ISM cannot address nuclei with many particles in the valence shells, for example ^{150}Nd, due to the exploding size of the Hamiltonian matrices ($> 10^9$).

Different models, different assumptions

- The idea that inspires the microscopic interacting boson model, IBM-2, is a truncation of the very large shell model space to states built from pairs of nucleons with $\mathbf{J = 0}$ and $\mathbf{2}$. These pairs are then assumed to be collective and are taken as bosons. The Hamiltonian is constructed phenomenologically and two- and four valence-nucleon states are generated by a schematic interaction. IBM-2 is known to be very successful in reproducing trends for spectra and E2 transitions involving collective states across isotopic and isotonic chains.
- Can be used in any nucleus and thus all nuclei of interest can be calculated within the same model.
- Realistic and well checked wave functions (excitation energies, B(E2) values and quadrupole moments, B(M1) values and magnetic moments, occupation probabilities, etc.).

Different models, different assumptions: IBM-2

- In the microscopic IBM the shell model $\mathbf{S}, \mathbf{D}$ pair states are mapped onto $\mathbf{s}, \mathbf{d}$ bosons as

$$S^{\dagger}_{\rho} = \sum_{j} \alpha_j \sqrt{\frac{\Omega_j}{2}} \left(a^{\dagger}_j \times a^{\dagger}_j\right)^{(0)} \longrightarrow s^{\dagger}_{\rho}$$

$$D^{\dagger}_{\rho} = \sum_{j \leq j'} \beta_{jj'} \frac{1}{\sqrt{1+\delta_{jj'}}} \left(a^{\dagger}_j \times a^{\dagger}_{j'}\right)^{(2)} \longrightarrow d^{\dagger}_{\rho},$$

  with $\Omega_j = j + 1/2$ and pair structure coefficients α_j and $\beta_{jj'}$, that are obtained by diagonalizing the surface delta interaction (SDI) in a chosen valence space.

- Following the method developed by Pittel, Duval and Barrett, $S^{\dagger}_{\rho}$ and $D^{\dagger}_{\rho}$ create the energetically-lowest 0^+ and 2^+ two-fermion states appropriate to the nucleus of interest. By using this method some possible renormalization (polarization) effects induced by the neutron-proton interaction are included approximately.

- The used single particle energies are taken from experiments.

- Isovector strength parameter A_1 value is fitted to reproduce the energy difference between the first 2^+ and the 0^+ ground state in the corresponding two-valence-particle or two-valence-hole nucleus.

Different models, different assumptions: IBM-2

- The bosonization method, when carried to all orders, produces results that are identical to the fermionic results. In $\beta\beta$-decay the fermion transition operator creates a pair of protons (neutrons) and annihilates a pair of neutrons (protons), so we need the mapping of the coupled pair operator:

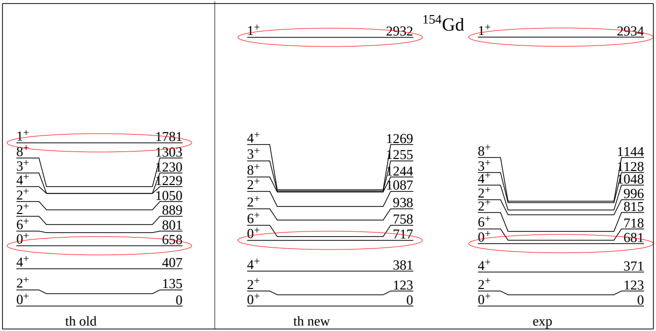
$$
\begin{aligned}
\left(\pi^\dagger_{j_\pi} \times \pi^\dagger_{j_\pi}\right)^{(0)} &\longmapsto A^{(01)}_{j_\pi} s^\dagger_\pi + A^{(11)}_{j_\pi} s^\dagger_\pi \left(d^\dagger_\pi \tilde{d}_\pi\right)^{(0)} + \ldots \\
\left(\pi^\dagger_{j_\pi} \times \pi^\dagger_{j'_\pi}\right)^{(2)} &\longmapsto B^{(01)}_{j_\pi j'_\pi} d^\dagger_\pi \\
&+ B^{(11)}_{j_\pi j'_\pi} s^\dagger_\pi \left(s^\dagger_\pi \tilde{d}_\pi\right)^{(2)} + B^{(12)}_{j_\pi j'_\pi} s^\dagger_\pi \left(d^\dagger_\pi \tilde{d}_\pi\right)^{(2)} \\
&+ \ldots \\
(\tilde{\nu}_{j_\nu} \times \tilde{\nu}_{j_\nu})^{(0)} &\longmapsto \tilde{A}^{(01)}_{j_\nu} \tilde{s}_\nu + \tilde{A}^{(11)}_{j_\nu} \tilde{s}_\nu \left(d^\dagger_\nu \tilde{d}_\nu\right)^{(0)} + \ldots \\
(\tilde{\nu}_{j_\nu} \times \tilde{\nu}_{j'_\nu})^{(2)} &\longmapsto \tilde{B}^{(01)}_{j_\nu j'_\nu} \tilde{d}_\nu \\
&+ \tilde{B}^{(11)}_{j_\nu j'_\nu} \left(d^\dagger_\nu \tilde{s}_\nu\right)^{(2)} \tilde{s}_\nu + \tilde{B}^{(12)}_{j_\nu j'_\nu} \left(d^\dagger_\nu \tilde{d}_\nu\right)^{(2)} \tilde{s}_\nu \\
&+ \ldots
\end{aligned}
$$

- The nuclear matrix elements of proper operators are then obtained between realistic wave functions obtained from IBM-2, which in addition to spherical nuclei is also capable of describing medium and heavy deformed nuclei as ^{150}Nd and ^{150}Sm

Some tests of wave functions

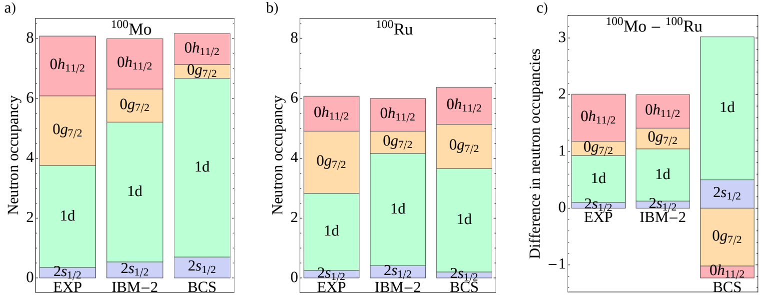
Case ^{154}Gd: Granddaughter of ^{154}Sm

- Shape transitional region ⇒ rapid changes of nuclear deformation
- Old calculation: No experimental information about $\mathbf{1^+}$ scissors mode
- New experimental data ⇒ parameters of Majorana operator can be fitted
  - Little effect on low-lying full-symmetric states
  - BUT significant effect on the mixed symmetry state wave function, like $\mathbf{0_2^+}$ ⇒ new $\mathbf{M^{0\nu}(0_2^+) = 0.37}$ (old $\mathbf{M^{0\nu}(0_2^+) = 0.02}$)



Some tests of wave functions

Occupation probabilities: A=100 system, neutrons

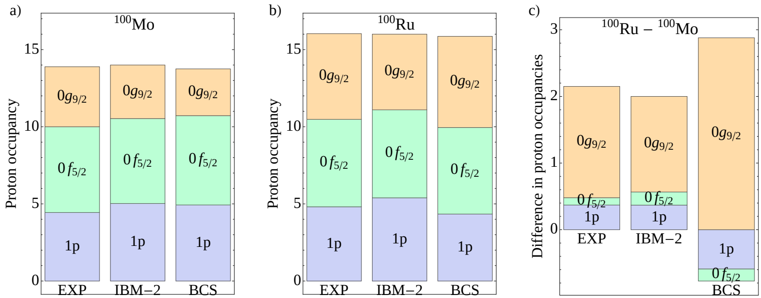


EXP: D. K Sharp at MEDEX'15; BCS: J. Suhonen and O. Civitarese, NPA **924** (2014) 1

- IBM-2: **1d** overfilled for both ^{100}Mo and ^{100}Ru
- The change appears to be dominated by the **1d** and $\mathbf{0h_{11/2}}$ orbitals with a small contributions from $\mathbf{2s_{1/2}}$ and $\mathbf{0g_{7/2}}$
- IBM-2: Agreement good with experiments
- BCS: more complex rearrangement of nucleons, differs both from experiments and IBM-2 results

Some tests of wave functions

Occupation probabilities: A=100 system, protons



EXP: D. K Sharp, a. MEDEX'15; BCS: J. Suhonen and O. Civitarese, NPA **924** (2014) 1

- Individual ^{100}Mo and ^{100}Ru proton occupancies, as well as the difference in proton occupancy are in proper agreement with the experiments
- Change is dominated by $\mathbf{0g_{9/2}}$ orbital, where **1p** orbitals play a lesser role, and $\mathbf{0f_{5/2}}$ orbital gives only a small contribution
- Comparison with BCS calculation reveals complex differences

∴ Overall agreement good between IBM-2 and experiments for $\mathbf{A = 100}$ system

Nuclear Matrix Elements

- Transition operator for $\beta\beta$ decay: $\mathbf{T(p) = H(p)f(m_i, U_{ei})}$, where

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

(in momentum space, including higher order corrections)

- Truncated transition operator in IBM-2

$$h_{IBM}^{F,GT,T} = h_{s-s}^{F,GT,T}\, s_\pi^\dagger\cdot\tilde{s}_\nu + h_{d-d}^{F,GT,T}\, d_\pi^\dagger\cdot\tilde{d}_\nu$$

where coefficients

$$\begin{aligned} h_{s-s}^{F,GT,T} &= -\sum_{j_\pi}\sum_{j_\nu} G^{F,GT,T}\left(j_\pi j_\pi j_\nu j_\nu; J=0\right) A_{j_\pi}^{(01)}\tilde{A}_{j_\nu}^{(01)} \\ h_{d-d}^{F,GT,T} &= -\frac{1}{2}\sum_{j_\pi j'_\pi}\sum_{j_\nu j'_\nu}\sqrt{1+\delta_{j_\pi j'_\pi}}\sqrt{1+\delta_{j_\nu j'_\nu}} \\ &\times\ G^{F,GT,T}\left(j_\pi j'_\pi j_\nu j'_\nu; J=2\right) B_{j_\pi j'_\pi}^{(01)}\tilde{B}_{j_\nu j'_\nu}^{(01)} \end{aligned}$$

Nuclear Matrix Elements

Using the above defined oprators we obtain some general trends:

- Shell effects: The matrix elements are smaller at the closed shells than in the middle of the shell
- Deformation effects always decrease the matrix elements
- Isospin restoration reduces matrix elements
  - The offending isospin violating NME is the Fermi NME in $2\nu\beta\beta$ which should be zero, since the Fermi part of the transition operator can not change isospin
  - Isospin restoration makes the Fermi NME vanish for $2\nu\beta\beta$ and for $0\nu\beta\beta$ is reduced by subtraction of the monopole term in the expansion of the matrix element multipoles

Nuclear Matrix Elements: : $0\nu\beta^-\beta^-$

ISOSPIN RESTORATION reduces matrix elements

	$\chi_F = (g_V/g_A)^2 M_F^{(0\nu)}/M_{GT}^{(0\nu)}$		
Decay	IBM-2	QRPA	ISM
^{48}Ca	-0.10(-0.39)	-0.32(-0.93)	
^{76}Ge	-0.09(-0.37)	-0.21(-0.34)	-0.12
^{82}Se	-0.10(-0.40)	-0.23(-0.35)	-0.11
^{96}Zr	-0.08(-0.08)	-0.23(-0.38)	
^{100}Mo	-0.08(-0.08)	-0.30(-0.30)	
^{110}Pd	-0.07(-0.07)	-0.27(-0.33)	
^{116}Cd	-0.07(-0.07)	-0.30(-0.30)	
^{124}Sn	-0.12(-0.34)	-0.27(-0.40)	
^{128}Te	-0.12(-0.33)	-0.27(-0.38)	-0.15
^{130}Te	-0.12(-0.33)	-0.27(-0.39)	-0.15
^{136}Xe	-0.11(-0.32)	-0.25(-0.38)	-0.15
^{148}Nd	-0.12(-0.12)		
^{150}Nd	-0.10(-0.10)		
^{154}Sm	-0.09(-0.09)		
^{160}Gd	-0.07(-0.07)		
^{198}Pt	-0.10(-0.10)		
^{232}Th	-0.08(-0.08)		
^{238}U	-0.08(-0.08)		

$0\nu\beta^-\beta^-$:

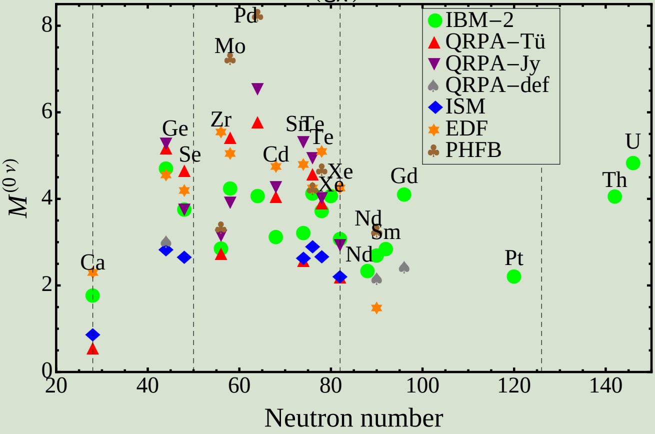
$\chi_F = (\frac{g_V}{g_A})^2 M_F^{(0\nu)}/M_{GT}^{(0\nu)}$ (old values in parentheses):

- Considerable reduction obtained!
- Isospin restored χ_F values very close to the ones obtained from ISM, where isospin is a good quantum number by construction
- Similar prescription has been used for QRPA (Simkovic *et al.*, PRC **87** 045501 (2013) and Suhonen *et al.*, PRC **91** 024613 (2015))

Nuclear Matrix Elements: : $0\nu\beta^-\beta^-$

- Light neutrino exchange: $v(p) = \frac{2}{\pi}\frac{1}{p(p+\tilde{A})}$, $f = \frac{\langle m_\nu \rangle}{m_e}$

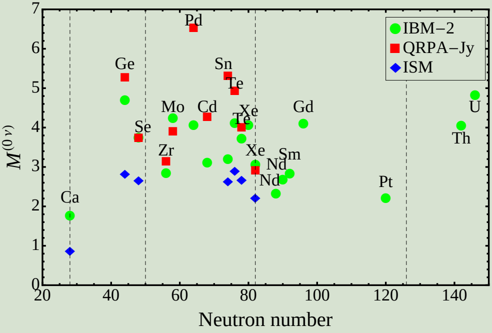
$$M^{(0\nu)} = M_{GT}^{(0\nu)} - \left(\frac{g_V}{g_A}\right)^2 M_F^{(0\nu)} + M_T^{(0\nu)}$$



IBM-2: J. Barea *et al.*, PRC **91**, 034304 (2015), QRPA-Tu: F. Simkovic *et al.* PRC **87**, 045501 (2013), QRPA-Jy: Suhonen *et al.*, PRC **91** 024613 (2015),QRPA-def: J:L. Fang *et al.*, PRC **83** 034320 (2011), ISM: J. Menendez *et al.*, NPA **818**, 139 (2009),PHFB: P.K. Rath *et al.*, PRC **82**, 064310 (2010), EDF: T.R. Rodriguez *et al.*, PRL **105**, 252503 (2008)

Nuclear Matrix Elements: : $0\nu\beta^-\beta^-$

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



- Comparison of IBM-2, QRPA, ISM NMEs for light neutrinos
- IBM-2/QRPA/ISM similar trend
- Larger values at the middle of the shell than at closed shells
- The ISM is a factor of $\sim$2 smaller than both the IBM-2 and QRPA in the lighter nuclei and the difference is smaller for heavier
  - Effective value of g_A?

IBM-2: J. Barea *et al.*, PRC **91**, 034304 (2015), QRPA-Tu: F. Simkovic *et al.* PRC **87**, 045501 (2013), QRPA-Jy: Suhonen *et al.*, PRC **91** 024613 (2015),QRPA-def: J:L. Fang *et al.*, PRC **83** 034320 (2011), ISM: J. Menendez *et al.*, NPA **818**, 139 (2009)

Nuclear Matrix Elements: : $\mathbf{0\nu\beta^-\beta^-}$

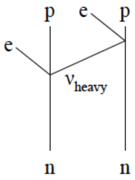
Estimate of error

- Sensitivity to input parameter changes
  - Single particle energies: 10%
  - Strengths of interactions: 5%
  - Oscillator parameter (SP wave functions): 5%
  - Closure energy in the neutrino potential: 5%
  - Nuclear radius (If NMEs in dimensionless units): 5%
- Sensitivity to model assumptions
  - Truncation to S-D space: 1% (spherical) - 10% (deformed)
  - Isospin purity: 2%
- Sensitivity to operator assumptions
  - Form of the transition operator: 5%
  - Finite nuclear size: 1%
  - Short range correlations (SRC): 5%

- The total error estimate is 16%

Nuclear Matrix Elements: : $0\nu_h\beta^-\beta^-$

- In heavy neutrino exchange scenario the transition operator has same form as for light neutrinos, but with



$$f \propto m_p \left\langle m_{\nu_h}^{-1} \right\rangle$$

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

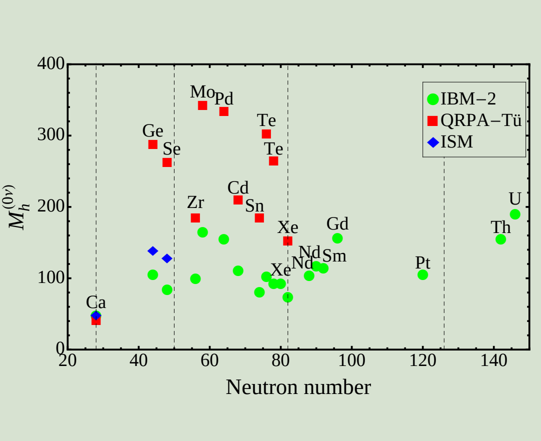
  - involves the mass eigenstates m_{k_h} of heavy neutrinos
  - and $m_{\nu_h} \gg 1$GeV
  - The Fourier transform of the neutrino "potential" is

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

    - Contact interaction in configuration space ⇒ strongly influenced by short range correlations

Nuclear Matrix Elements: : $\mathbf{0\nu_h\beta^-\beta^-}$

- Comparison of IBM-2, QRPA, and ISM matrix elements for heavy neutrinos

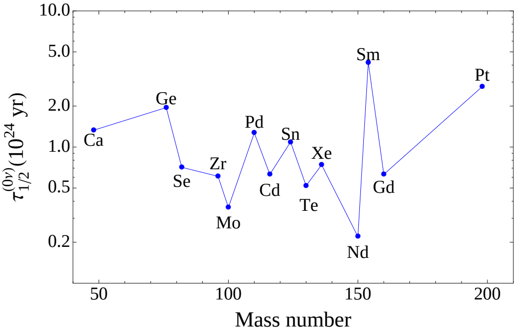


- IBM-2/QRPA/ISM similar trend, factor of ∼2 difference between IBM-2 and QRPA-Tü
- Comment: Ratio for QRPA-Jy/QRPA-Tü results varies from 1 up to 2.5, reason for this discrepancy is not clear
- Note: IBM-2 error estimate in this case is 56% mostly coming from SRC

IBM-2: J. Barea *et al.*, PRC **91**, 034304 (2015), QRPA-Tü: F. Simkovic *et al.* PRC **87**, 045501 (2013), QRPA-Jy: Suhonen *et al.*, PRC **91** 024613 (2015) ISM: A. Neacsu *et al.*,AHEP **2014**,724315(2014)

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

- Predictions calculated with g_A=1.269 (and $|\langle m_\nu \rangle| = 1$eV)

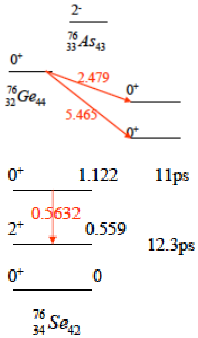


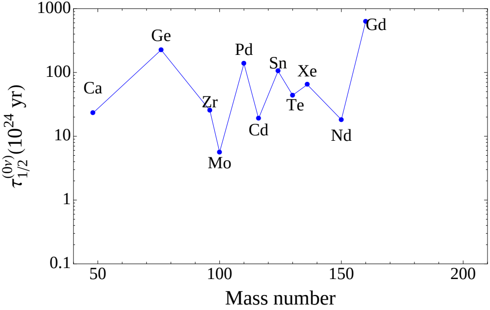
- Judging by the half-life, best candidates ^{150}Nd, ^{100}Mo, and ^{130}Te, where half-lives $\sim 10^{23}$yr

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

DECAYS TO FIRST EXCITED 0^+ STATES

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

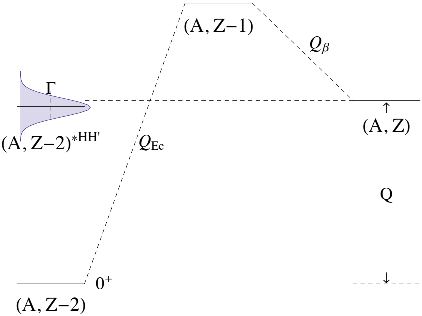




- Best candidates ^{100}Mo and ^{150}Nd, $\tau_{1/2}^{(0\nu)} \sim 10^{24}$yr
  - $2\nu\beta\beta$-decay observed to excited 0^+ state in these nuclei!

Comment about $\mathbf{0\nu\beta^+\beta^+}$, $\mathbf{0\nu EC\beta^+}$, and $\mathbf{R0\nu ECEC}$

- $\beta^+\beta^+$ and $\mathbf{0\nu EC\beta^+}$: available kinetic energy much smaller since
  $\mathbf{T_{\beta^+\beta^+} = M(A, Z) - M(A, Z-2) - 4m_e c^2}$ and
  $\mathbf{T_{EC\beta^+} = M(A, Z) - M(A, Z-2) - 2m_e c^2 - \epsilon_b}$
  $\Rightarrow$ much smaller phase space $\Rightarrow$ much longer $\tau_{1/2}^{(0\nu)} > 10^{26}$yr
- For $\mathbf{0\nu ECEC}$ available energy larger, but since all the energies are fixed, additional requirement that Q-value matches the final state energy



- Resonance enhancement:

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

  where $\mathbf{\Delta = |Q - B_{2h} - E|}$ is the degeneracy parameter, and $\mathbf{\Gamma}$ is the two-hole width
- So in principle, if $\mathbf{\Delta \sim 0}$ and $\mathbf{\Gamma \sim 1}$eV we could obtain up to $\mathbf{10^6}$ enhancement
  - Unfortunately this is not the case and $\tau_{1/2}^{(0\nu)} > 10^{27}$yr

Comment about Majoron emitting $0\nu\beta\beta$

- This mechanism requires the emission of one or two additional bosons, Majorons, so it has similarities with $2\nu\beta\beta$
- There are many different models, where $\mathbf{m}$, the number of emitted Majorons and $\mathbf{n}$, the spectral index of the decay take different values:

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

- Comparison with experimental limits on $\tau^{0\nu M}_{1/2,exp}$ gives information about $\langle g_{ee}^M \rangle$, the majoron-neutrino coupling constant
- Ordinary Majoron decay $\mathbf{m = 1, n = 1}$: If the Majoron couples only to light neutrino, the NME needed to calculate the half-life are the same as for light neutrino exchange
- There are cosmologic constraints on $\langle g_{ee}^M \rangle$, such as values $3 \times 10^{-7} \lesssim g_{ee}^M \lesssim 2 \times 10^{-5}$ or $g_{ee}^M \gtrsim 3 \times 10^{-4}$ are excluded by the observation of SN 1987A
  - The most stringent of the current limits are at these regions

Sterile neutrinos

- Another scenario, currently being extensively discussed, is the mixing of additional "sterile" neutrinos
- The NME for sterile neutrinos of arbitrary mass can be calculated using a transition operator as in ν_{light} and ν_{heavy} exchange but with

$$f = \frac{m_N}{m_e}, \qquad v(p) = \frac{2}{\pi}\frac{1}{\sqrt{p^2+m_N^2}\left(\sqrt{p^2+m_N^2}+\tilde{A}\right)},$$

  where m_N is the mass of the sterile neutrino
- The product

$$fv(p) = \frac{m_N}{m_e}\frac{2}{\pi}\frac{1}{\sqrt{p^2+m_N^2}\left(\sqrt{p^2+m_N^2}+\tilde{A}\right)}$$

  has the limits:
  $m_N \to 0 \qquad fv(p) = \frac{m_N}{m_e}\frac{2}{\pi}\frac{1}{p\left(p+\tilde{A}\right)}$
  $m_N \to \infty \qquad fv(p) = \frac{m_N}{m_e}\frac{2}{\pi}\frac{1}{m_N^2} = \frac{2}{\pi}\frac{1}{m_e m_N}$

Sterile neutrinos

- Several types of sterile neutrinos have been suggested.
  - Light sterile neutrinos
    - Neutrino masses are $\mathbf{m_N} \sim \mathbf{1}$eV
    - These neutrinos account for the reactor anomaly in oscillation experiments and for the gallium anomaly *
  - Heavy sterile neutrinos
    - Neutrino masses are $\mathbf{m_N} \gg \mathbf{1}$eV
    - keV mass range, MeV-GeV mass range, TeV mass range

- When the mass $\mathbf{m_N}$ is intermediate the factorization is not possible, and physics beyond the standard model is entangled with nuclear physics. In this case, the half-life can be written as

$$[\tau_{1/2}^{0\nu}]^{-1} = \mathbf{G_{0\nu}} \left| \sum_{\mathbf{N}} (\mathbf{U_{eN}})^2 \mathbf{M_{0\nu}}(\mathbf{m_N}) \frac{\mathbf{m_N}}{\mathbf{m_e}} \right|^2$$

Giunti, NEUTEL2015 conference proceedings

Sterile neutrinos

- The corresponding nuclear matrix elements can be written as

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

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

- The NMEs can be calculated exactly, but a simple formula

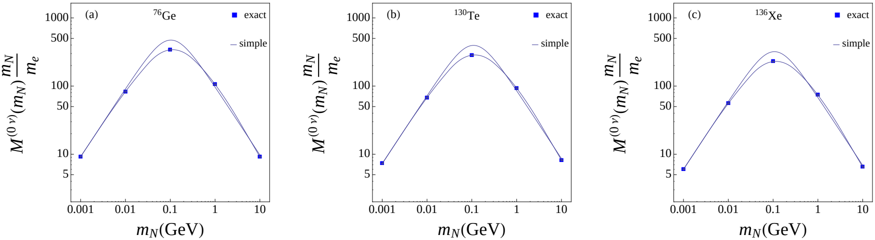
$$[\tau_{1/2}^{0\nu}]^{-1} = \mathbf{G_{0\nu} g_A^4 \left| M^{(0\nu_h)} \right|^2 \left| m_p \sum_N (U_{eN})^2 \frac{m_N}{\langle p^2 \rangle + m_N^2} \right|^2},$$

with

$$\langle \mathbf{p^2} \rangle = \frac{\mathbf{M^{(0\nu_h)}}}{\mathbf{M^{(0\nu)}}} \mathbf{m_p m_e},$$

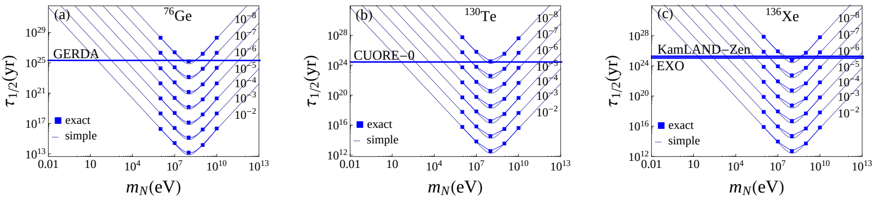
gives a very good approximation

Sterile neutrinos



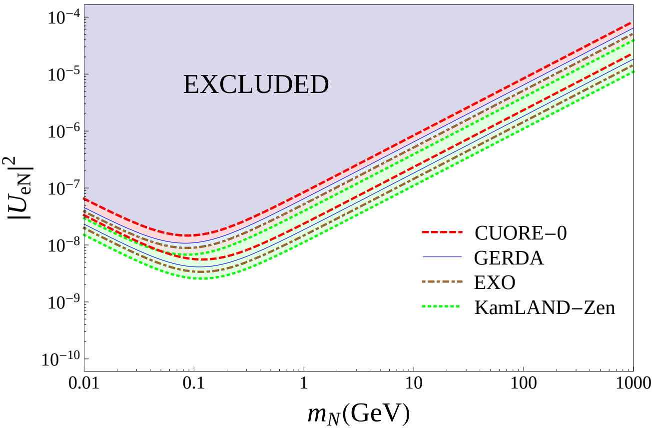
- IBM-2 NMEs for neutrinos of arbitrary mass plotted as a function of $\mathbf{m_N}$ in a) ^{76}Ge, b) ^{130}Te, and c) ^{136}Xe. Blue squares represent the exact calculation for $\mathbf{m_N = 0.001}$GeV, $\mathbf{0.01}$GeV, $\mathbf{0.1}$GeV, $\mathbf{1}$GeV, $\mathbf{10}$GeV, joined together by a Mathematica interpolating formula. The curve is obtained using the simple formula.
- The interesting aspect is that the curves peak at $\mathbf{m_N \sim 100}$MeV, the scale set by the nucleon Fermi momentum in the nucleus, $\mathbf{p_F}$. If sterile neutrinos of this mass exist, their contribution to the half-life is enhanced.

Sterile neutrinos



- Expected half-life for a single neutrino of mass $\mathbf{m_N}$ with coupling $\mathbf{U_{eN}^2 = 10^{-2} - 10^{-8}}$ and $\mathbf{g_A = 1.269}$ for a) ^{76}Ge, b) ^{130}Te, and c) ^{136}Xe. Blue squares represent the exact calculation for $\mathbf{m_N = 0.001}$GeV, $\mathbf{0.01}$GeV, $\mathbf{0.1}$GeV, $\mathbf{1}$GeV, $\mathbf{10}$GeV. The smooth curve is obtained using the simple formula. The experimental limits from GERDA, CUORE-0, KamLAND-Zen, and EXO are also shown. The excluded zone is that below these limits.

Sterile neutrinos



- Excluded values of $|\mathbf{U_{eN}}|^2$ and $\mathbf{m_N}$ in the $\mathbf{m_N}$-$|\mathbf{U_{eN}}|^2$ plane, for $\mathbf{g_A = 1.269}$. For each experiment, GERDA , CUORE-0, KamLAND-Zen, and EXO, a band of values is given, corresponding to our error estimate

Limits on Average Light Neutrino Mass

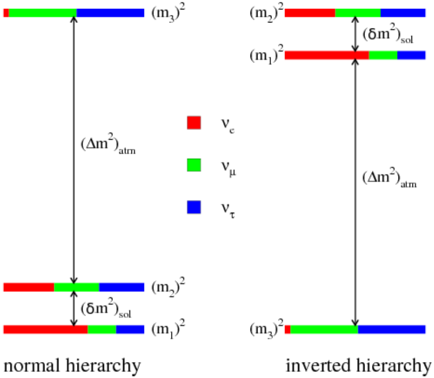
Reminder:

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

- Light neutrinos:

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

- The average light neutrino mass is now well constrained by atmospheric, solar, reactor and accelerator neutrino oscillation experiments
- Obtained information on mass differences and their mixing leaves two possibilities: Normal and inverted hierarchy



Limits on Average Light Neutrino Mass

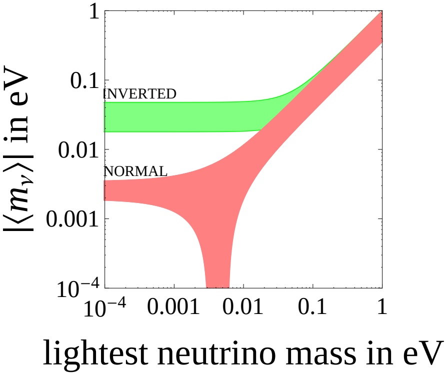
- The average light neutrino mass is then written as:

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

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

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

- $\theta_{12}, \theta_{13}, \theta_{23}$ and δm, Δm fitted to oscillation experiments*
- Phases φ_2 and φ_3 may vary from 0 to 2π



*$\sin^2\theta_{12} = 0.308$, $\delta m^2 = 7.54 \times 10^{-5}$ eV^2
NH: ($\Delta m^2 = 2.43 \times 10^{-3}$ eV^2, $\sin^2\theta_{13} = 0.0234$, $\sin^2\theta_{23} = 0.437$)
IH: ($\Delta m^2 = 2.38 \times 10^{-3}$ eV^2, $\sin^2\theta_{13} = 0.0240$, $\sin^2\theta_{23} = 0.455$)

Limits on Average Light Neutrino Mass

Current lower half-life limits coming from different experiments

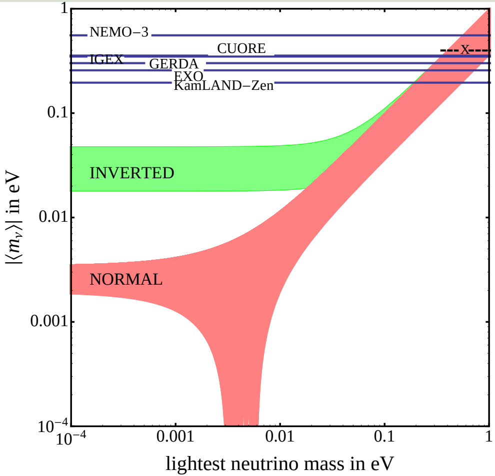
Experiment	nucleus	$\tau_{1/2}$	$\langle m_\nu \rangle$
IGEX	^{76}Ge	$> 1.57 \times 10^{25}$yr	< 0.35eV
GERDA	^{76}Ge	$> 2.1 \times 10^{25}$yr	< 0.30eV
NEMO-3	^{100}Mo	$> 1.1 \times 10^{24}$yr	< 0.56eV
CUORE	^{130}Te	$> 4.0 \times 10^{24}$yr	< 0.35eV
EXO	^{136}Xe	$> 1.1 \times 10^{25}$yr	< 0.25eV
Kamland-Zen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

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

IGEX: C. E. Aalseth *et al.*, PRD **65**, 092007 (2002), GERDA: M. Agostini *et al.* (GERDA collaboration) PRL **111** 122503 (2013), NEMO-3: R. Arnold, *et al.*, PRD **89**, 111101 (2014), CUORE: K. Alfonso *et al.*, PRL 115, 102502 (2015), EXO: M. Auger *et al.*, Nature 510, 229 (2014),KamLAND-Zen: A. Gando *et al.*, PRL. **110**, 062502 (2013)

Limits on Average Light Neutrino Mass

- Current limits to $\langle \mathbf{m}_\nu \rangle$ from CUORE, IGEX, NEMO-3, KamLAND-Zen, EXO, and GERDA $0\nu\beta\beta$ experiments for light neutrino exchange

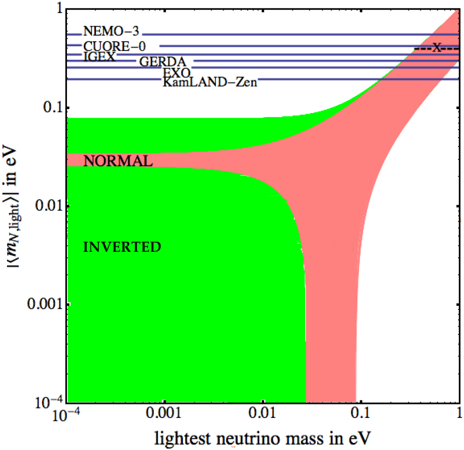


IGEX: C. E. Aalseth *et al.*, Phys. Rev. D **65**, 092007 (2002), NEMO-3: R. Arnold, *et al.*, Phys. Rev. D **89**, 111101 (2014), CUORE: K. Alfonso *et al.*, arXiv:1504.02454 [nucl-ex] (2015), KamLAND-Zen: A. Gando *et al.*, Phys. Rev. Lett. **110**, 062502 (2013), EXO: M. Auger *et al.*, Nature 510, 229 (2014)GERDA: M. Agostini *et al.* (GERDA collaboration) Phys. Rev Lett. **111** 122503 (2013), X: H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004),

Limits on Average Light Neutrino Mass

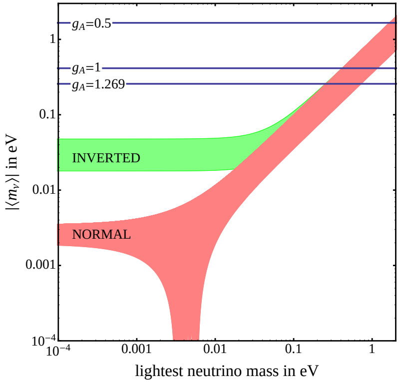
- If, however, there are sterile neutrinos, this picture is different
- Considering, for example, a suggested of a 4th neutrino with mass $\mathbf{m_4 = 1}$eV and $|\mathbf{U_{e4}}|^2 = \mathbf{0.03}$, we have

$$\langle \mathbf{m_{N,light}} \rangle = \sum_{k=1}^{3} \mathbf{U_{ek}^2 m_k + U_{e4}^2 e^{i\alpha_4} m_4}, \text{ with } \mathbf{0} \leq \alpha_4 \leq \mathbf{2}\pi$$



Limits on Average Light Neutrino Mass: Remarks

- We do not know what is the mechanisms of $0\nu\beta\beta$ -decay and several mechanisms may contribute with different relative phases
- The question of effective value of $\mathbf{g_A}$ is still open. Three suggested scenarios are
  - Free value: 1.269
  - Quark value: 1
  - Even stronger quenching: $\mathbf{g_{A,eff} < 1}$



Quenching of $\mathbf{g_A}$

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

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

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

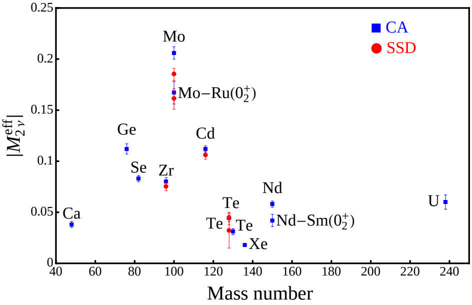
  - and obtained by comparing the calculated and measured half-lives for β/**EC** and/or for $\mathbf{2\nu\beta\beta}$

* 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	$\tau_{1/2}^{2\nu}(10^{18}$ y) 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



- $|\mathbf{M}_{2\nu}^{\rm eff}|^2$ is obtained from the measured half-life by

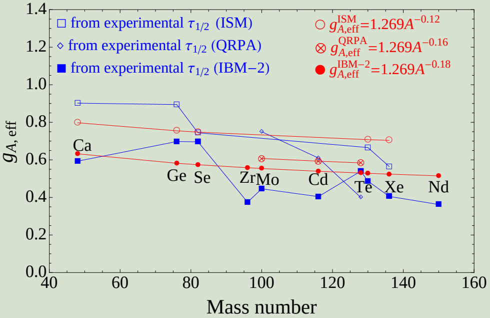
$$|\mathbf{M}_{2\nu}^{\rm eff}|^2 = \left[\tau_{1/2}^{2\nu} \times \mathbf{G}_{2\nu}\right]^{-1}$$

Smallest $\mathbf{M}_{2\nu}^{\rm eff}$ for ^{136}Xe, the newest one measured!

* A.S. Barabash, Nucl. Phys. A **935**, 52 (2015).

Quenching of g_A

$$g_{A,eff} = g_A \sqrt{M_{2\nu}^{eff}/M_{2\nu}}$$



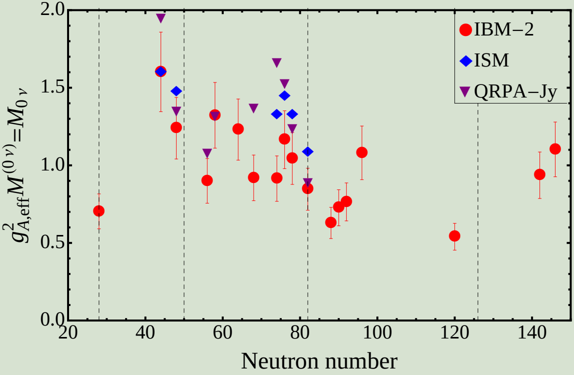
- Extracted $g_{A,eff}$:
  - IBM-2 $\sim$ **0.6 − 0.5**
  - QRPA $\sim$ **0.7 − 0.6**
  - ISM $\sim$ **0.8 − 0.7**
- Similar values found by analyzing β^-/**EC** for IBFM-2[a] and for QRPA[b]
- Assumption: $g_{A,eff}$ is a smooth function of **A**
- Parametrization: $g_{A,eff} = 1.269A^{-\gamma}$
  - IBM-2: $\gamma = 0.18$
  - QRPA: $\gamma = 0.16$
  - ISM: $\gamma = 0.12$

* ISM NMEs from E. Caurier *et al.*, Int. J. Mod. Phys. E **16**, 552 (2007).
a Yoshida and Iachello, PTEP **2013**, 043D01 (2013).
b QRPA results from J. Suhonen *et al.*, Phys. Lett. B **725**, 153 (2013).

Quenching of g_A

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

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



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

Quenching of $\mathbf{g_A}$

Effective value of $\mathbf{g_A}$ is a work in progress, since:

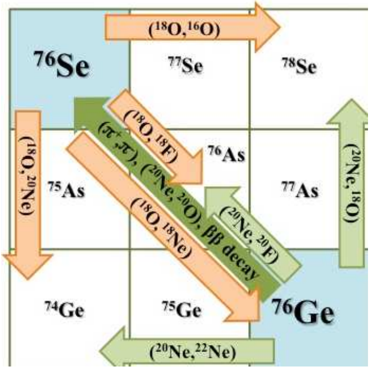
- Is the renormalization of $\mathbf{g_A}$ the same in $\mathbf{2\nu\beta\beta}$ as in $\mathbf{0\nu\beta\beta}$?
  - In $\mathbf{2\nu\beta\beta}$ only the $\mathbf{1^+}$ (GT) multipole contributes. In $\mathbf{0\nu\beta\beta}$ all multipoles $\mathbf{1^+}$, $\mathbf{2^-}$,...; $\mathbf{0^+}$, $\mathbf{1^-}$,... contribute. Some of which could be even unquenched.
  - This is a critical issue, since half-life predictions with maximally quenched $\mathbf{g_A}$ are $\sim \mathbf{6-34}$ times longer due to the fact that $\mathbf{g_A}$ enters the equations to the power of 4!
- Additional ways to study quenching of $\mathbf{g_A}$:
  - Theoretical studies by using effective field theory (EFT) to estimate the effect of non-nucleonic degrees of freedom (two-body currents)
  - Experimental and theoretical studies of single beta decay and single charge exchange reactions involving the intermediate odd-odd nuclei
  - Double charge exchange reactions

Double charge exchange reactions

A lot of similarities with $\mathbf{0\nu\beta\beta}$:

- Same initial and final states: Parent/daughter states of the $\mathbf{0\nu\beta\beta}$ = target/residual nuclei in the DCE
- Structure of the transition operator: Fermi, Gamow-Teller and rank-2 tensor present in both cases

- Large momentum transfer: A linear momentum transfer as high as 100 MeV/c or so is characteristic of both processes
- In-medium processes: both processes happen in the same nuclear medium, thus we can learn about quenching phenomena
- ...



Double charge exchange reactions

However, a simple relation between DCE cross sections and $\beta\beta$-decay half-lives is by no means trivial:

- DCE and $\mathbf{0\nu\beta\beta}$ processes are mediated by different interactions, so the comparison is not straightforward
- The theory of DCE is much more complicated than the theory of $\mathbf{0\nu\beta\beta}$-decay
- DCE reaction, to its leading order, is a two-step process involving projectile and target internal structure as well as the full nucleus-nucleus interaction and the details of the theory have not yet been fully worked out
- Both theoretical and experimental work is needed
- ...

In any case the involved nuclear matrix elements are connected, and valuable information about the reliability of NMEs and quenching of $\mathbf{g_A}$ may be learned from the study of DCE reactions

Conclusions

- 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 $\beta\beta$, decays to ground states as well as to first excited $\mathbf{0}^+$ states, and possible contributions of sterile neutrinos
- The next generation of experiments should be able to reach at least the inverted mass hierarchy. In case there are sterile neutrinos, the situation might be more complicated
  - With or without sterile neutrinos, the reliability of nuclear matrix elements as well as the quenching of $\mathbf{g_A}$ are becoming more and more important and the NUMEN project is expected to bring valuable information on these issues

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

- What is the absolute neutrino mass scale?
- What is the nature of neutrinos?
- How many neutrino species are there?

THANK YOU!

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