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Nuclear physics of non-standard neutrinoless double beta decay

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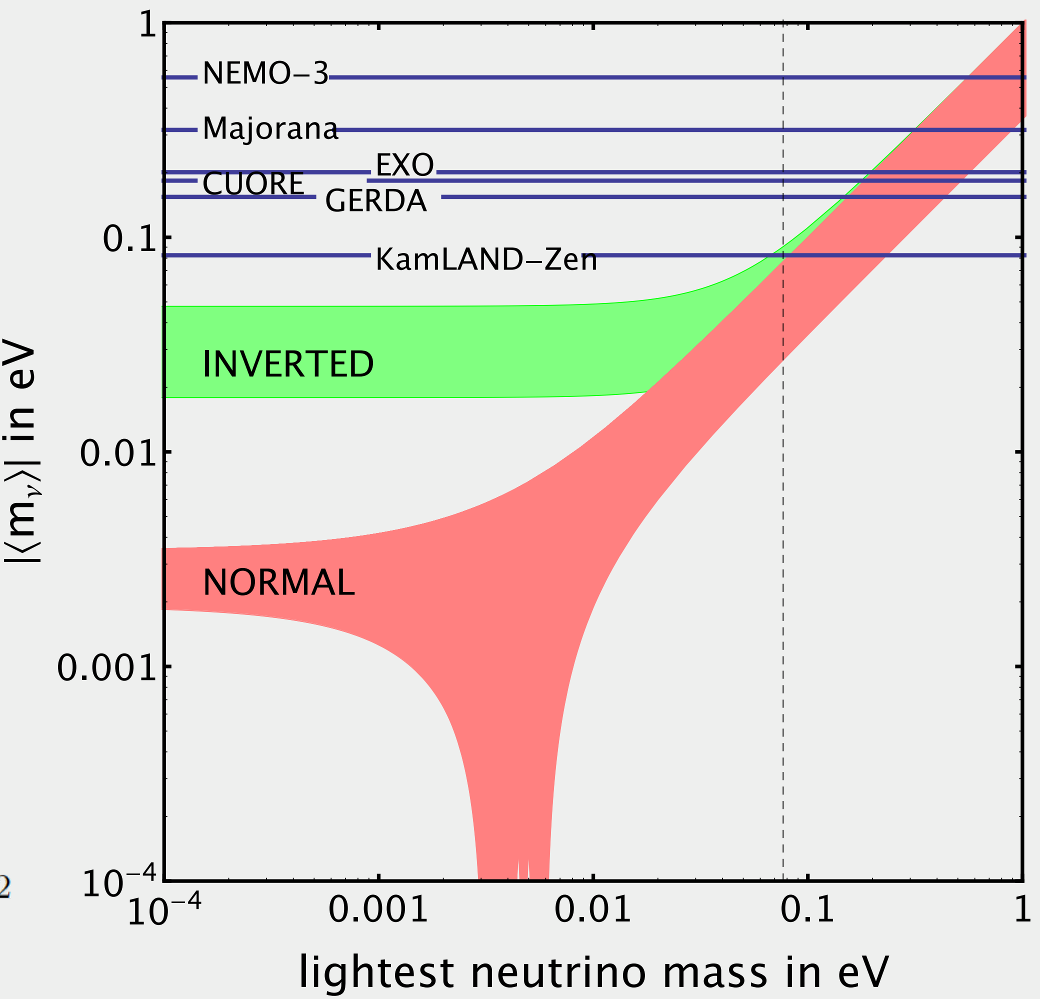
JYU. Since 1863.

Motivation

- In spite of several attempts by many groups $0\nu\beta\beta$-decay has not yet been observed
- This observation is crucial for understanding lepton number violation
- After the discovery of neutrino oscillations, attention has been mostly focused on the mass mechanism of $0\nu\beta\beta$-decay, wherein the three species of neutrinos have masses m_i and couplings to the electron neutrino U_{ei}. In this case, the inverse decay rate is given by

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



Experimental limits for $\tau_{1/2}$

Current lower half-life limits coming from different experiments:

Experiment	nucleus	$\tau_{1/2}$	$\langle m_\nu \rangle$
Majorana	^{76}Ge	$> 1.9 \times 10^{25}$yr	< 0.27eV
GERDA	^{76}Ge	$> 8 \times 10^{25}$yr	< 0.13eV
NEMO-3	^{100}Mo	$> 1.1 \times 10^{24}$yr	< 0.44eV
CUORE	^{130}Te	$> 1.5 \times 10^{25}$yr	< 0.19eV
EXO-200	^{136}Xe	$> 1.8 \times 10^{25}$yr	< 0.21eV
Kamland-Zen	^{136}Xe	$> 1.07 \times 10^{26}$yr	< 0.09eV

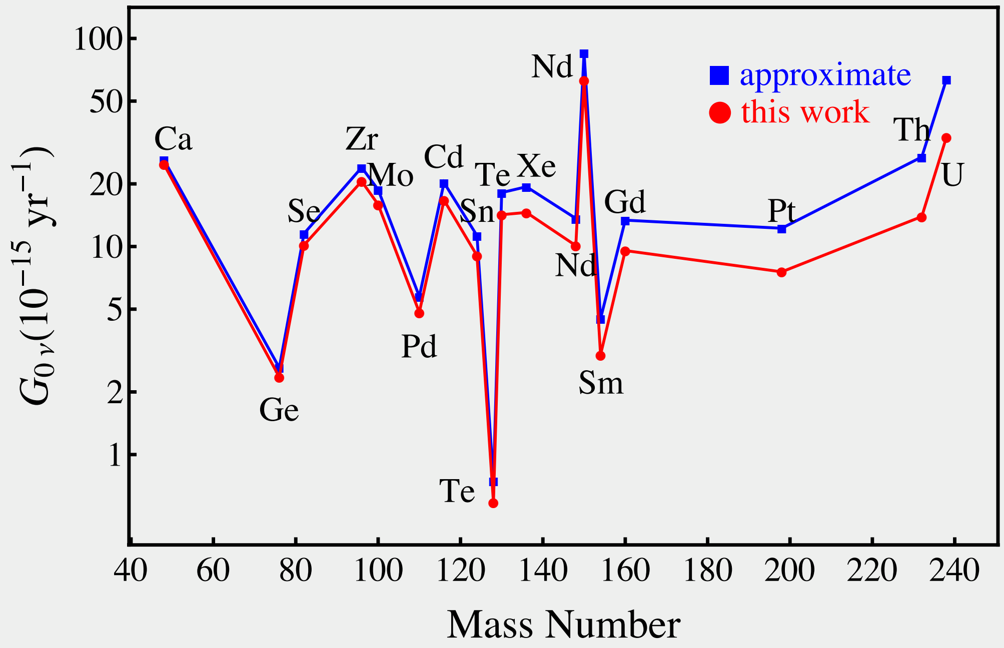
$$\tau_{1/2} \Rightarrow \langle m_\nu \rangle < \frac{m_e}{\sqrt{\tau_{1/2}^{exp} G_{0\nu} g_A^2}\,|M^{(0\nu)}|}$$

Majorana: C. E. Aalseth et al., PRL 120, 132502 (2018), GERDA: M. Agostini et al. PRL 120 132503 (2018),
NEMO-3: R. Arnold, et al., PRD 92, 072011 (2015),
CUORE: C. Alduino et al., PRL 120, 132501 (2018),
EXO: J.B. Albert et al., PRL 120 072701 (2018) , KamLAND-Zen: A. Gando etal., PRL. 117, 082503 (2016)

Calculation of PSF: Mass mechanism

- Two phase space factors to be calculated: $G^{(0)}$ and $G^{(1)}$
- Obtained using Dirac electron wave functions with electron screening
- From these one obtains half-life:

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



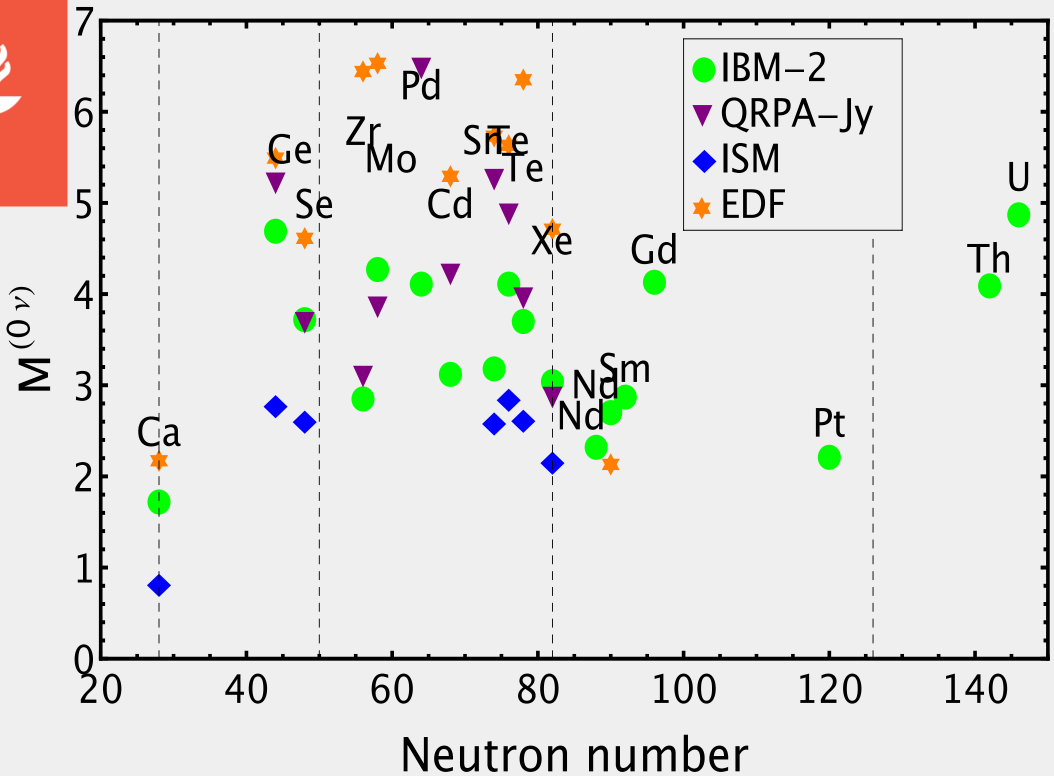
- Single electron spectrum:

$$\frac{dW_{0\nu}}{d\epsilon_1} = \mathcal{N}_{0\nu}\frac{dG_{0\nu}^{(0)}}{d\epsilon_1}$$

- Angular correlation:

$$\alpha(\epsilon_1) = \frac{f_{11}^{(1)}(\epsilon_1)}{f_{11}^{(0)}(\epsilon_1)} = \frac{dG_{0\nu}^{(1)}/d\epsilon_1}{dG_{0\nu}^{(0)}/d\epsilon_1}$$

- Our results [PRC 85 (2012) 034316] have been confirmed by independent calculations of Stoica et al. [PRC 88 (2013) 037303]



IBM-2: J. Barea et al., PRC91 (2015) 034304,
QRPA-Jy: J. Hyvärinen et al., PRC91 (2015) 024613,
ISM: J. Menendez et al., NPA818 (2009) 139,
EDF: N.L. Vaquero et al., PRL111 (2013) 142591

Calculation of NME: Mass mechanism

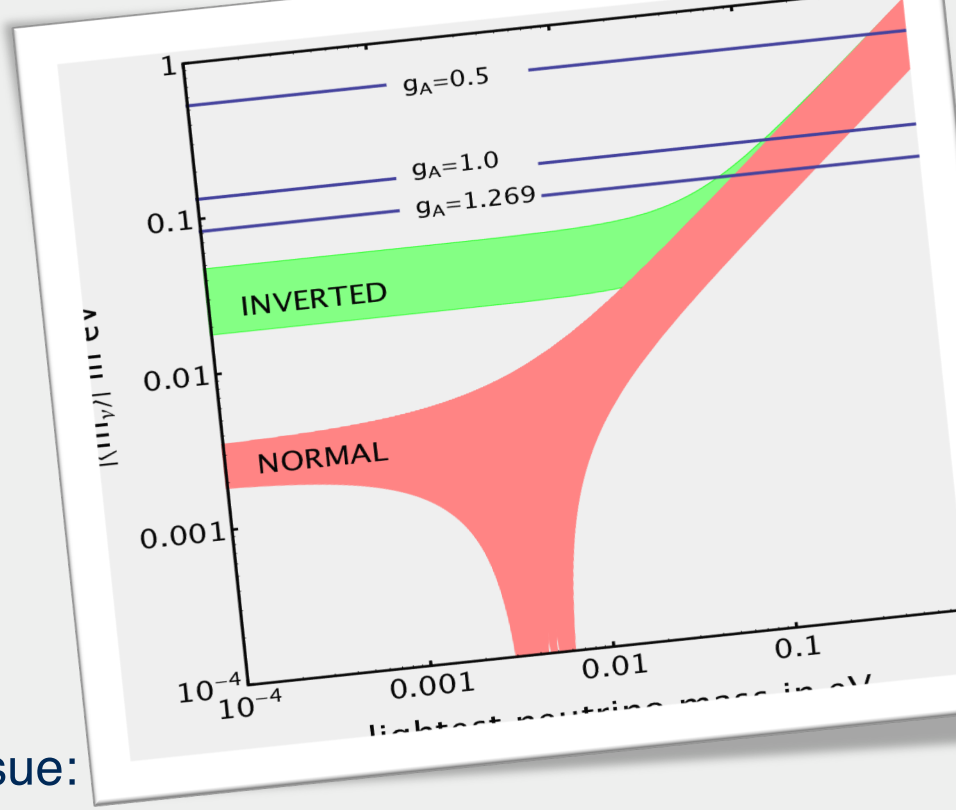
- **Challenging calculation: The fact that $0\nu\beta\beta$-decay is a unique process makes the prediction challenging for theoretical models.**
- **Still large differences between the different models but some of them can be explained by model dependent quenching of g_A**
- **When combined with PSFs can be directly compared with experimental half-life limits**

Cause of worry: Quenching of g_A

- It is well known from single beta decay and electron capture that g_A is renormalized in models of nuclei. Two reasons for this are:
  - The limited model space in which the calculations done, q_{Nex}
  - The omission of non-nucleonic degrees of freedom, q_{Δ}
- $2\nu\beta\beta$ may be used to get and idea of the quenching. But effective value of g_A is a work in progress:
  - 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 even unquenched.
    - → The two processes differ by the momentum transferred to leptons. In $2\nu\beta\beta$ this is of the order of few MeV, while in $0\nu\beta\beta$ it is of the order of 100 MeV.
- This is a critical issue, since half-life predictions with maximally quenched g_A are up to 6 times longer due to the fact that g_A enters the equations to the power of 4!

Quenching of g_A

- Three suggested scenarios are:
- Free value: 1.269
- Quark value: 1
- Even stronger quenching: $g_{A,eff} < 1$



- Various studies are addressing this issue:
  - Theoretical studies 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
  - Experimental program (NUMEN) to measure both single and double charge exchange reaction intensities with heavy ions. Useful information on the Fermi and Gamow-Teller matrix elements of interest in $0\nu\beta\beta$ and $2\nu\beta\beta$ decay will also be provided.

Non-standard $0\nu\beta\beta$-decay mechanisms

- On the other hand the underlying interaction does not have to be as simple as the standard neutrino mass mechanism
- The general Lagrangian of 0νββ-decay consists of long-range and short-range parts, corresponding to pointlike vertices at the Fermi scale ≈100 MeV

$$\mathcal{L}_{0\nu\beta\beta} = \mathcal{L}_{\mathrm{LR}} + \mathcal{L}_{\mathrm{SR}}$$

- The aim current work is:
  - To provide explicit formulas for the nuclear matrix elements (NMEs) and phase space factors (PSFs) from which the decay rate for one or combination of mechanisms can be calculated
  - To provide numerical values of the NMEs and PSFs obtained by making use of the interacting boson model for the NMEs and of exact Dirac wave functions for the PSFs

Short range mechanisms

- General effective Lagrangian for short range contributions can be schematically written as [Päs et al. PLB 498 (2001) 35]

$$\mathcal{L}_{\rm SR} = \frac{G_F^2}{2m_p} \sum_{\rm chiralities} [\epsilon_1^\bullet J_\circ J_\circ j_\circ + \epsilon_2^\bullet J_\circ^{\mu\nu} J_{\circ\mu\nu} j_\circ + \epsilon_3^\bullet J_\circ^\mu J_{\circ\mu} j_\circ + \epsilon_4^\bullet J_\circ^\mu J_{\circ\mu\nu} j^\nu + \epsilon_5^\bullet J_\circ^\mu J_\circ j_\mu]$$

  - The sum and the place holders ∘ indicate that the currents involved can have different chiralities and there is a separate effective coupling $\epsilon_i^\bullet$ for each such combination
  - The hadronic and leptonic currents read

$$J_{R/L} = \bar{u}(1 \pm \gamma_5)d, \qquad J^\mu_{R/L} = \bar{u}\gamma^\mu(1 \pm \gamma_5)d,$$
$$J^{\mu\nu}_{R/L} = \bar{u}\sigma_{\mu\nu}(1 \pm \gamma_5)d,$$

$$j_{R/L} = \bar{e}(1 \pm \gamma_5)e^c, \qquad j^\mu = \bar{e}\gamma^\mu\gamma_5 e^c,$$

Short range mechanisms

- Explicit expressions for NME corresponding to products of nucleon currents are (with g_S=1, g_{PS}=349, g_P=233, g_W=3.70):

$$\mathcal{M}_1 = g_S^2 \mathcal{M}_F \quad (+ \quad + \quad -) \; \frac{g_P^2}{12} \left(\mathcal{M}'^{PP}_{GT} - \mathcal{M}'^{PP}_{T} \right)$$

$$\mathcal{M}_2 = -2 g_{T_1}^2 \mathcal{M}^{T_1 T_1}_{GT}$$

$$\begin{aligned} \mathcal{M}_3 \; &= \; g_V^2 \mathcal{M}_F \quad (- \quad - \quad +) \; g_A^2 \mathcal{M}^{AA}_{GT} \quad (+ \quad + \quad -) \; \frac{g_A g_{P'}}{6} \left(\mathcal{M}'^{AP'}_{GT} + \mathcal{M}'^{AP'}_{T} \right) \\ &+ \; \frac{(g_V + g_W)^2}{12} \left(-2 \mathcal{M}'^{WW}_{GT} + \mathcal{M}'^{WW}_{T} \right) \quad (- \quad - \quad +) \; \frac{g_{P'}^2}{48} \left(\mathcal{M}''^{P'P'}_{GT} + \mathcal{M}''^{P'P'}_{T} \right) \end{aligned}$$

$$\mathcal{M}_4 = (- \quad - \quad + \; +) \; i g_A g_{T_1} \mathcal{M}^{AT_1}_{GT} \quad (+ \quad + \quad - \; -) \; i \frac{g_{P'} g_{T_1}}{12} \left(\mathcal{M}'^{P'T_1}_{GT} + \mathcal{M}'^{P'T_1}_{T} \right)$$

$$\begin{aligned} \mathcal{M}_5 \; &= \; g_S g_V \mathcal{M}_F \quad (+ \quad + \quad - \; -) \; \frac{g_A g_P}{12} \left(\tilde{\mathcal{M}}^{AP}_{GT} + \tilde{\mathcal{M}}^{AP}_{T} \right) \\ & \quad (- \quad - \quad + \; +) \; \frac{g_{P'} g_P}{24} \left(\mathcal{M}'^{q_0 P'P}_{GT} + \mathcal{M}'^{q_0 P'P}_{T} \right) \end{aligned}$$

- For the first three operators three sign possibilities correspond to combinations of chiralities : RR, LL and 1/2(RL + LR).
- For the fourth and fifth operator a row of four signs is shown, as in those cases the two hadronic currents have different Lorentz structures and all four possible combinations of chiralities have to be considered: RR, LL, RL and LR.

Form factors

- Fermi, Gamow-Teller and tensor NMEs are calculated with 6 different form factors (m_V=0.84GeV, m_A=1.09GeV, m_π=0.138GeV)

$$\tilde{h}_{VV}(q^2) = \frac{1}{(1+q^2/m_V^2)^4} ,$$

$$\tilde{h}_{AA}(q^2) = \frac{1}{(1+q^2/m_A^2)^4} ,$$

$$\tilde{h}_{AX}(q^2) = \frac{1}{(1+q^2/m_A^2)^2}\frac{1}{(1+q^2/m_V^2)^2} ,$$

$$\tilde{h}_{AP}(q^2) = \tilde{h}_{AP'}(q^2) = \frac{1}{(1+q^2/m_A^2)^4}\frac{1}{(1+q^2/m_\pi^2)} ,$$

$$\tilde{h}_{XP}(q^2) = \tilde{h}_{XP'}(q^2) = \frac{1}{(1+q^2/m_V^2)^2}\frac{1}{(1+q^2/m_A^2)^2}\frac{1}{(1+q^2/m_\pi^2)} ,$$

$$\tilde{h}_{PP}(q^2) = \tilde{h}_{P'P'}(q^2) = \tilde{h}_{PP'}(q^2) = \frac{1}{(1+q^2/m_A^2)^4}\frac{1}{(1+q^2/m_\pi^2)^2} ,$$

- The needed two-body transition operator is then constructed in momentum space as the product of the so-called neutrino potential times the form factors: $h(q) = v(q)\tilde{h}(q)$

F, GT, and tensor NMEs

- The NMEs of interest are (ordered as q^k):
  - k=0

$$\mathcal{M}_F = \langle h_{VV}(q^2) \rangle$$

$$\mathcal{M}_{GT}^{AA} = \langle h_{AA}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \rangle$$

$$\mathcal{M}_{GT}^{T_1T_1} = \langle h_{VV}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \rangle$$

$$\mathcal{M}_{GT}^{AT_1} = \langle h_{AX}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \rangle$$

- k=2, suppressed by a factor of O(0.01), enhanced by g_{PS}=349, g_P=233

$$\mathcal{M}_{GT}^{\prime P'P'} = \mathcal{M}_{GT}^{\prime P'P} = \mathcal{M}_{GT}^{\prime PP} = \left\langle \frac{q^2}{m_p^2} h_{PP}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \right\rangle$$

$$\mathcal{M}_{T}^{\prime P'P'} = \mathcal{M}_{T}^{\prime P'P} = \mathcal{M}_{T}^{\prime PP} = \left\langle \frac{q^2}{m_p^2} h_{PP}(q^2) S_{12} \right\rangle$$

$$\mathcal{M}_{GT}^{\prime AP'} = \mathcal{M}_{GT}^{\prime AP} = \left\langle \frac{q^2}{m_p^2} h_{AP}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \right\rangle$$

$$\mathcal{M}_{T}^{\prime AP'} = \mathcal{M}_{T}^{\prime AP} = \left\langle \frac{q^2}{m_p^2} h_{AP}(q^2) S_{12} \right\rangle$$

$$\mathcal{M}_{GT}^{\prime P'T_1} = \mathcal{M}_{GT}^{\prime PT_1} = \left\langle \frac{q^2}{m_p^2} h_{XP}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \right\rangle$$

$$\mathcal{M}_{T}^{\prime P'T_1} = \mathcal{M}_{T}^{\prime PT_1} = \left\langle \frac{q^2}{m_p^2} h_{XP}(q^2) S_{12} \right\rangle$$

F, GT, and tensor NMEs

- k=4, suppressed suppressed by a factor of O(10^{-4}), enhanced by g_P^2=233^2

$$\mathcal{M}_{GT}^{\prime\prime PP} = \left\langle \frac{q^4}{m_p^4} h_{PP}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \right\rangle$$
$$\mathcal{M}_{T}^{\prime\prime PP} = \left\langle \frac{q^4}{m_p^4} h_{PP}(q^2) S_{12} \right\rangle$$

- So called recoil terms, k=2 (approximation Q≅q)

$$\tilde{\mathcal{M}}_{GT}^{AP} = \left\langle \frac{\mathbf{Q}\cdot\mathbf{q}}{m_p^2} h_{AP}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \right\rangle$$
$$\tilde{\mathcal{M}}_{T}^{AP} = \left\langle \frac{\mathbf{Q}\cdot\mathbf{q}}{m_p^2} h_{AP}(q^2) S_{12} \right\rangle$$

- k=3 (approximation $q_0 / m_p \cong 0.01$)

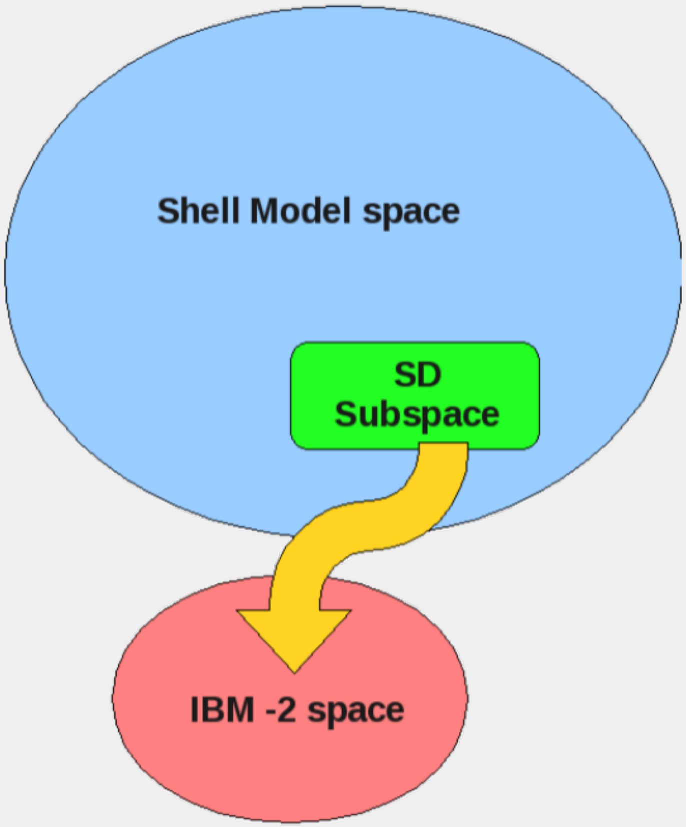
$$\mathcal{M}_{GT}^{\prime q_0 PP} = \left\langle \frac{q_0 q^2}{m_p^3} h_{PP}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \right\rangle$$
$$\mathcal{M}_{T}^{\prime q_0 PP} = \left\langle \frac{q_0 q^2}{m_p^3} h_{PP}(q^2) S_{12} \right\rangle$$

- k=2, with $h_{WW}(q^2) \equiv h_V(q^2)$

$$\mathcal{M}_{GT}^{\prime WW} = \left\langle \frac{q^2}{m_p^2} h_{WW}(q^2)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \right\rangle$$
$$\mathcal{M}_{T}^{\prime WW} = \left\langle \frac{q^2}{m_p^2} h_{WW}(q^2) S_{12} \right\rangle$$

Nuclear model: IBM-2

- In IBM-2 the very large shell model space is truncated to states built from pairs of nucleons with J = 0 and 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
- The fermion operators are mapped onto a boson space and the matrix elements of the mapped operators are then evaluated with realistic wave functions



Nuclear model: IBM-2

Single Particle Energies

↓

S.D.I Calculation

↓

Structure Coefficients of S and D pairs

↓

Mapping coefficients of the transition operator

Experimental data: spectra, EM transitions, ...

↓

IBM-2 wavefunctions

↓

Bosonic matrix elements:

$$\left\langle F \left| s_\pi^\dagger \cdot \tilde{s}_\nu \right| I \right\rangle$$

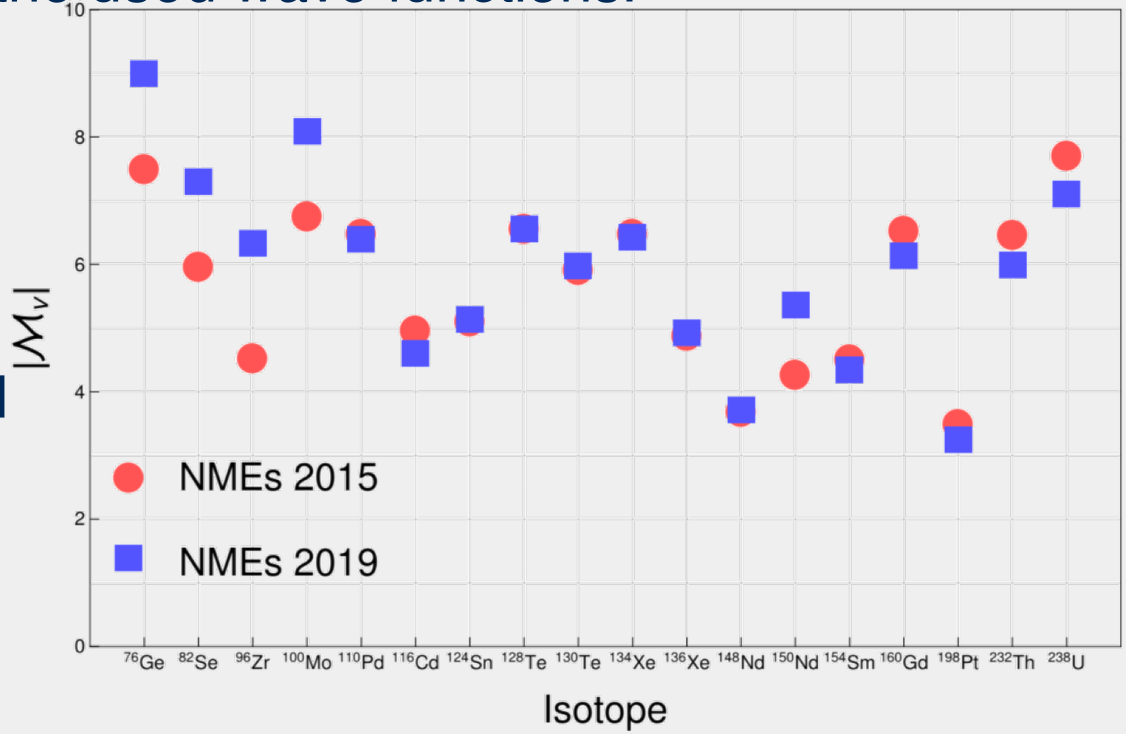
$$\left\langle F \left| d_\pi^\dagger \cdot \tilde{d}_\nu \right| I \right\rangle$$

$$\boxed{\left[\tau_{1/2}^{(0\nu)}\right]^{-1} \simeq G_{0\nu} \left|M_{0\nu}\right|^2 \left|f(m_i, U_{ei})\right|^2}$$

Nuclear model: IBM-2

- The single-particle and -hole energies and strengths of interaction were evaluated and discussed in detail in [PRC 94 (2016) 034320] where the occupancies of the single particle levels were calculated in order to satisfy a twofold goal:
  - asses the goodness of the single particle energies
  - check the reliability of the used wave functions.

  - Comparison of standard light NMEs with 2015 and updated SPEs:



Short-range mechanisms

- For short-range mechanisms neutrino potential is defined as

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

- Short-range transitions with no mediating particle lighter than ≈100 MeV.
- In this case $0\nu\beta\beta$-decay probes lepton number violating physics around the TeV scale
- The most prominent scenario where this kind of operator is generated is through the inclusion of heavy sterile neutrinos [Simkovic et al. PRC60 (1999) 055502]
- The cases where additional light states are either mediating the decay or are emitted in it (e.g., Majorons) are studied separately [e.g. PRC 91 (2015) 064310].

Short-range: NME numerics

- We have performed IBM-2 calculation for the needed 16 NMEs for 18 nuclei of interest

A	$\mathcal{M}_F$	$\mathcal{M}_{GT}^{VV}$	$\mathcal{M}_{GT}^{AA}$	$\mathcal{M}_{GT}^{A}$	$\mathcal{M}'_{GT}$	$\mathcal{M}'_{T}$	$\mathcal{M}'^{AP}_{GT}$	$\mathcal{M}'^{AP}_{T}$
^{76}Ge	−48.89	173.5	170.0	174.3	−1.927	−0.906	1.330	−0.184
^{82}Se	−41.22	143.6	140.7	144.3	−1.607	−0.859	1.107	−0.175
^{100}Mo	−51.96	188.6	181.9	188.1	−2.961	1.115	1.431	0.224
^{128}Te	−41.82	134.1	131.7	134.9	−1.401	−0.626	1.050	−0.125
^{130}Te	−38.05	121.9	119.7	122.6	−1.281	−0.568	0.954	−0.113
^{134}Xe	−39.45	127.2	124.7	127.8	−1.383	−0.580	0.985	−0.116
^{136}Xe	−29.83	96.09	94.18	96.56	−1.064	−0.437	0.742	−0.087
^{150}Nd	−30.18	103.1	100.0	103.2	−1.445	0.409	0.814	0.082
^{154}Sm	−31.83	110.9	107.1	110.7	−1.691	0.470	0.854	0.094
^{148}Nd	−31.71	105.8	103.0	106.0	−1.394	0.354	0.848	0.072
^{96}Zr	−35.31	128.8	124.3	128.5	−2.010	0.753	0.959	0.153
^{110}Pd	−43.52	157.0	151.2	156.5	−2.542	0.944	1.191	0.191
^{116}Cd	−32.45	115.2	110.5	114.6	−1.974	0.585	0.865	0.118
^{124}Sn	−33.19	106.1	104.2	106.7	−1.117	−0.506	0.832	−0.102
^{198}Pt	−31.87	109.0	104.4	108.4	−1.923	0.439	0.840	0.088
^{160}Gd	−41.43	148.6	142.9	148.0	−2.452	0.724	1.118	0.144
^{232}Th	−44.04	160.3	154.2	159.7	−2.650	0.851	1.196	0.167
^{238}U	−52.48	190.5	183.1	189.7	−3.205	0.998	1.419	0.196

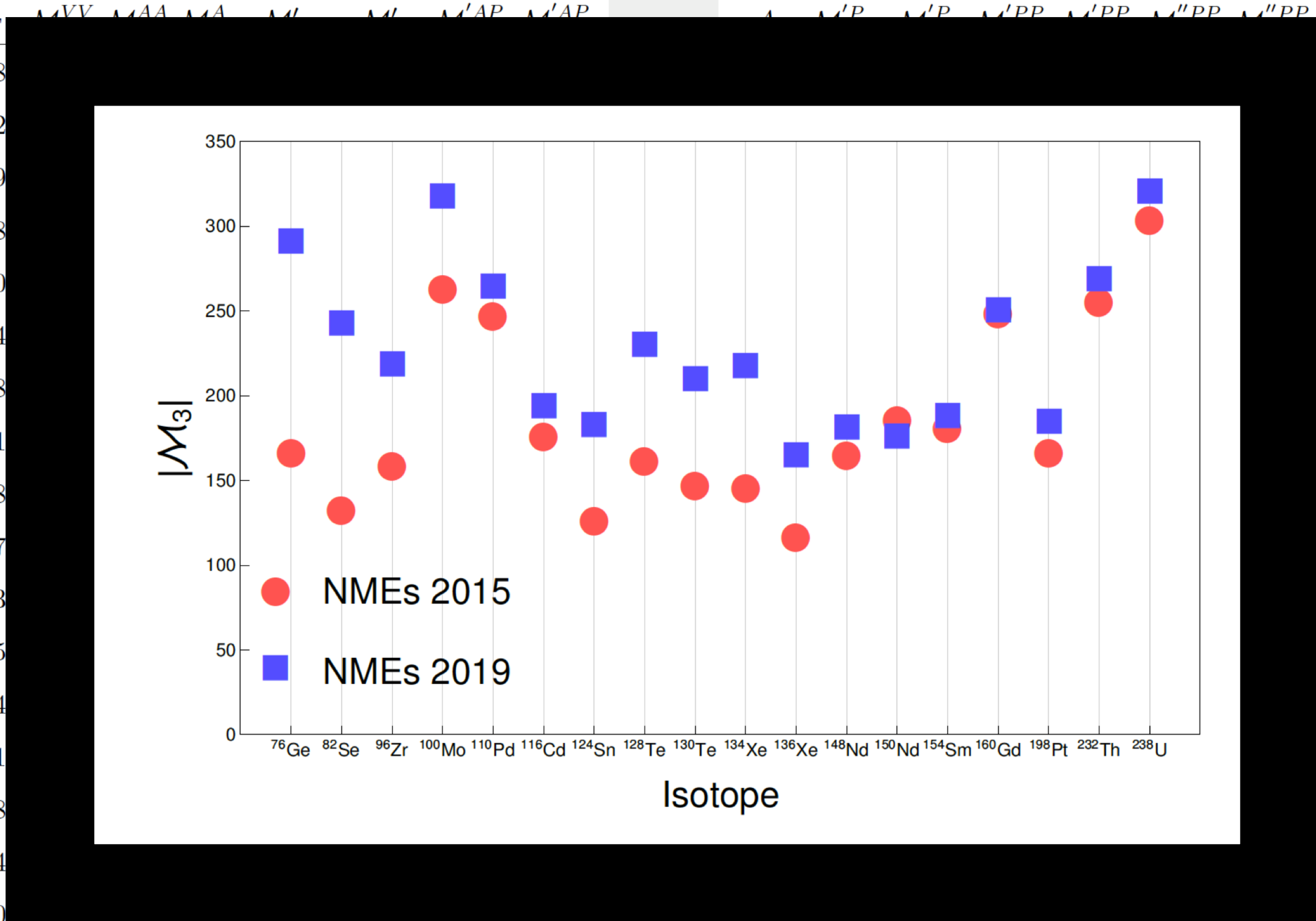
A	$\mathcal{M}'^{P}_{GT}$	$\mathcal{M}'^{P}_{T}$	$\mathcal{M}'^{PP}_{GT}$	$\mathcal{M}'^{PP}_{T}$	$\mathcal{M}''^{PP}_{GT}$	$\mathcal{M}''^{PP}_{T}$	$\mathcal{M}'^{q_0PP}_{GT}$	$\mathcal{M}'^{q_0PP}_{T}$
^{76}Ge	2.255	−0.263	0.798	−0.060	0.028	−0.005	0.009	−0.001
^{82}Se	1.878	−0.251	0.660	−0.058	0.024	−0.005	0.007	−0.001
^{100}Mo	2.464	0.318	0.910	0.071	0.029	0.006	0.010	0.001
^{128}Te	1.776	−0.178	0.617	−0.039	0.023	−0.003	0.007	0.000
^{130}Te	1.613	−0.161	0.561	−0.036	0.021	−0.003	0.006	0.000
^{134}Xe	1.669	−0.165	0.585	−0.036	0.021	−0.003	0.006	0.000
^{136}Xe	1.257	−0.124	0.442	−0.027	0.016	−0.002	0.005	0.000
^{150}Nd	1.392	0.116	0.497	0.026	0.017	0.002	0.005	0.000
^{154}Sm	1.467	0.134	0.536	0.030	0.018	0.003	0.006	0.000
^{148}Nd	1.445	0.102	0.508	0.023	0.018	0.002	0.005	0.000
^{96}Zr	1.652	0.219	0.613	0.051	0.020	0.004	0.007	0.001
^{110}Pd	2.055	0.272	0.762	0.060	0.024	0.005	0.008	0.001
^{116}Cd	1.497	0.169	0.565	0.038	0.017	0.003	0.006	0.000
^{124}Sn	1.407	−0.145	0.489	−0.032	0.018	−0.003	0.005	0.000
^{198}Pt	1.454	0.125	0.546	0.026	0.017	0.002	0.006	0.000
^{160}Gd	1.931	0.204	0.722	0.045	0.023	0.004	0.008	0.000
^{232}Th	2.067	0.236	0.783	0.051	0.024	0.005	0.008	0.001
^{238}U	2.456	0.278	0.932	0.060	0.029	0.005	0.010	0.001

Short-range: NME numerics

- We have performed IBM-2 calculation for the needed 16 NMEs for 18 nuclei of interest

A	$\mathcal{M}_F$	$\mathcal{M}^{VV}$	$\mathcal{M}^{AA}$	$\mathcal{M}^{A}$	$\mathcal{M}'$	$\mathcal{M}'$	$\mathcal{M}'^{AP}$	$\mathcal{M}'^{AP}$
^{76}Ge	−48.8							
^{82}Se	−41.2							
^{100}Mo	−51.9							
^{128}Te	−41.8							
^{130}Te	−38.0							
^{134}Xe	−39.4							
^{136}Xe	−29.8							
^{150}Nd	−30.1							
^{154}Sm	−31.8							
^{148}Nd	−31.7							
^{96}Zr	−35.3							
^{110}Pd	−43.5							
^{116}Cd	−32.4							
^{124}Sn	−33.1							
^{198}Pt	−31.8							
^{160}Gd	−41.4							
^{232}Th	−44.0							
^{238}U	−52.48	190.5	183.1	189.7	−3.205	0.998	1.419	0.196

A	$\mathcal{M}'^{P}$	$\mathcal{M}'^{P}$	$\mathcal{M}'^{PP}$	$\mathcal{M}'^{PP}$	$\mathcal{M}''^{PP}$	$\mathcal{M}''^{PP}$	$\mathcal{M}_{GT}'^{q_0 PP}$	$\mathcal{M}_{T}'^{q_0 PP}$
							0.009	−0.001
							0.007	−0.001
							0.010	0.001
							0.007	0.000
							0.006	0.000
							0.006	0.000
							0.005	0.000
							0.005	0.000
							0.006	0.000
							0.005	0.000
							0.007	0.001
							0.008	0.001
							0.006	0.000
							0.005	0.000
							0.006	0.000
							0.008	0.000
							0.008	0.001
^{238}U	2.456	0.278	0.932	0.060	0.029	0.005	0.010	0.001



Short-range: PSF

- The key ingredient for the evaluation of phase space factors 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
- We adopt the approximation of evaluating the electron wavefunction at the nuclear radius

$$f_{\pm 1}(E) \equiv f_{\pm 1}(E, R_A), \quad g_{\pm 1}(E) \equiv g_{\pm 1}(E, R_A).$$

- This choice reflects the fact that nucleons largely decay at the surface of the nucleus due to Pauli-blocking of inner states.

Short-range: PSF numerics

- Integrated PSFs are

$$G_{ij}^{(a)} = \frac{2C}{\ln 2}\frac{g_{ij}^{(a)}}{4R_A^2}\int_{m_e}^{Q_{\beta\beta}+m_e} dE_1 w(E_1) f_{ij}^{(a)}(E_1, Q_{\beta\beta}+2m_e-E_1)$$

- With 6 independent $f_{ij} \neq 0$:

$$f_{11\pm}^{(0)} = \pm|f^{-1-1}|^2 \pm |f_{11}|^2 + |f^{-1}{}_1|^2 + |f_1{}^{-1}|^2,$$

$$f_{66}^{(0)} = 16\left[|f^{-1-1}|^2 + |f_{11}|^2\right],$$

$$f_{16}^{(0)} = 4\left[|f_{11}|^2 - |f^{-1-1}|^2\right],$$

$$f_{11\pm}^{(1)} = -2\left[f^{-1}{}_1 f_1{}^{-1} \pm f^{-1-1} f_{11}\right],$$

$$f_{66}^{(1)} = 32\left[f^{-1-1} f_{11}\right],$$

$$f_{16}^{(1)} = 0.$$

- Our results agree with those of Päs et al. [PLB498 (2001) 35] and Tomoda [RPP 54 (1991) 53], except for the extra interference term between the left- and right handed scalar electron current

A	$G_{11}^{(0)}$	$G_{11-}^{(0)}$	$G_{66}^{(0)}$	$G_{16}^{(0)}$	$G_{11}^{(1)}$	$G_{11-}^{(1)}$	$G_{66}^{(1)}$	$G_{16}^{(1)}$
^{76}Ge	4.720	3.818	2.640	1.739	−3.908	0.000	1.954	0.000
^{82}Se	20.37	15.32	10.97	5.849	−18.16	0.000	9.079	0.000
^{100}Mo	31.82	23.77	16.96	8.913	−28.50	0.000	14.25	0.000
^{128}Te	1.170	1.054	0.741	0.626	−0.780	0.000	0.390	0.000
^{130}Te	28.40	21.79	15.34	8.733	−24.89	0.000	12.45	0.000
^{134}Xe	1.193	1.080	0.760	0.646	−0.788	0.000	0.394	0.000
^{136}Xe	29.11	22.41	15.75	9.048	−25.44	0.000	12.72	0.000
^{150}Nd	126.0	90.74	66.11	30.88	−115.7	0.000	57.83	0.000
^{154}Sm	6.010	5.144	3.544	2.677	−4.582	0.000	2.291	0.000
^{148}Nd	20.15	16.09	−2.788	−44.63	−28.38	0.000	8.493	0.000
^{96}Zr	41.16	30.20	−2.334	−87.08	−43.23	0.000	18.67	0.000
^{110}Pd	9.614	7.724	5.348	3.460	−8.028	0.000	4.014	0.000
^{116}Cd	33.38	25.19	−1.854	−71.50	−38.74	0.000	14.83	0.000
^{124}Sn	18.06	14.14	9.870	5.953	−15.52	0.000	7.760	0.000
^{198}Pt	15.03	12.76	8.818	6.555	−11.69	0.000	5.845	0.000
^{160}Gd	19.05	15.41	10.64	7.012	−15.83	0.000	7.917	0.000
^{232}Th	27.74	23.49	16.29	12.04	−21.83	0.000	10.91	0.000
^{238}U	66.89	54.19	37.62	24.92	−56.03	0.000	28.01	0.000

Short-range: Half-life

- Combining the PSFs and NMEs, the inverse 0νββ-decay half-life is then given by

$$T_{1/2}^{-1} = G_{11}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I \mathcal{M}_I \right|^2 + G_{66}^{(0)} \left| \sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right|^2 \mp G_{16}^{(0)} \mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I \mathcal{M}_I \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right]$$

- And for single mechanisms at a time

$$T_{1/2}^{-1} = |\epsilon_I|^2 G_I |\mathcal{M}_I|^2$$

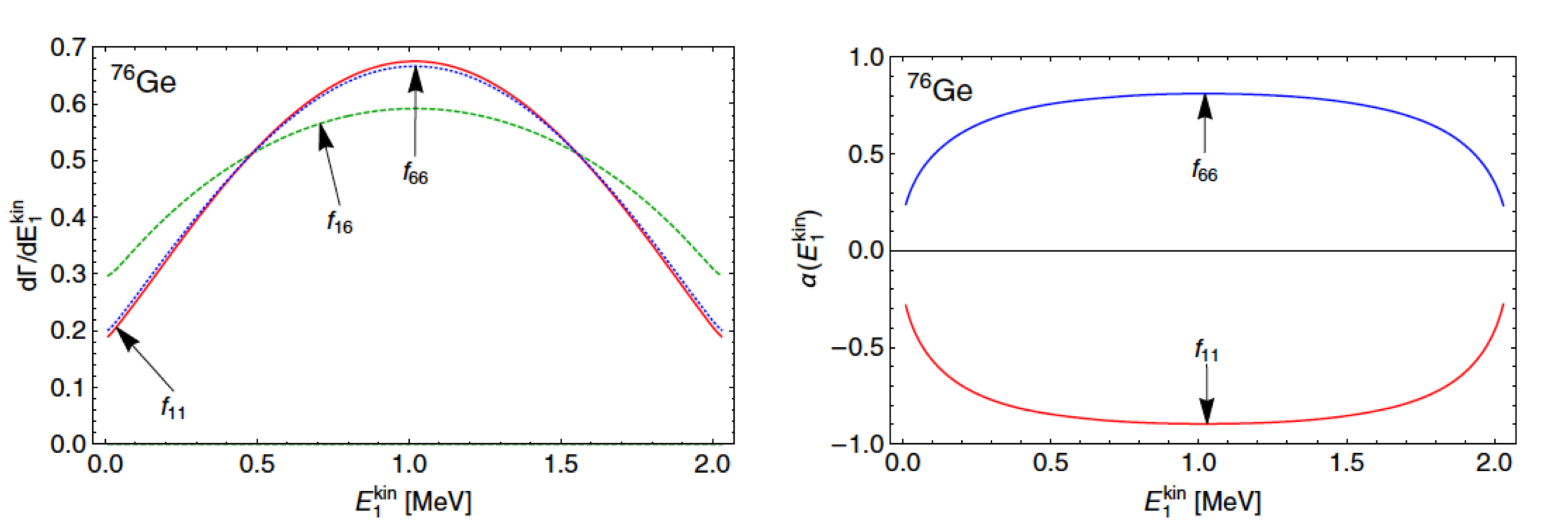
- We can also calculate the integrated angular correlation factors in the three different cases jk=11,66, and 16:

$$K_{jk} = \frac{B}{A} = \frac{G_{jk}^{(1)}}{G_{jk}^{(0)}}$$

- And energy-dependent angular correlation, as well as the single electron energy distribution

Short-range: Ses & Angular correlation

- Example of normalized single electron spectra and angular correlation



- The two electrons preferably share the available kinetic energy equally.
- Only a small difference between the f_{11} and f_{66} case, with the latter having a slightly flatter profile, that is unlikely to be distinguishable experimentally
- The term f_{16}, corresponding to an interference between i=1, 2, 3 and i=4, 5 mechanisms, has a more significantly flatter profile
- In view of the opposite sign for 11 and 66 measurements of the angular correlation would allow a discrimination of the two types of mechanisms

Long-range mechanisms

- Long-range transitions proceeding through the exchange of a light neutrino
  - This includes the standard neutrino mass mechanism via Majorana neutrinos
- Alternatively, in models with exotic interactions incorporating right-chiral neutrinos, no mass insertion is required
  - In the SM with only left-handed neutrinos, these operators violate $\Delta L=2$, and they incorporate a helicity flip through the inclusion of a Higgs field.
- The calculation of NMEs and PSFs for long-range mechanisms makes use of the NMEs and PSFs derived for short-range mechanisms
- BUT this calculation is more complicated since while for short-range only one hadronic and one leptonic matrix element need to be calculated, now there are three hadronic and three leptonic matrix elements that need to be calculated.

Long-range mechanisms

- The three terms that need to be calculated are identified by neutrino potential, v(q)
  - m_i terms

$$v_1(q) = \frac{2}{\pi}\frac{1}{q(q+\tilde{A})}$$

  - ω terms

$$v_3(q) = \frac{2}{\pi}\frac{1}{(q+\tilde{A})^2}$$

  - **k**-terms

$$v_4(q) = \frac{2}{\pi}\frac{q+2\tilde{A}}{q(q+\tilde{A})^2}$$

Long-range mechanisms

- Altogether there are 48 NMEs to be calculated for each double beta decay candidate nucleus
  - Done for ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te and ^{136}Xe
- Currents 1,2,3:
  - 11 PSFs
  - Our results correspond to the ones by Tomoda when approximate wavefunctions for electrons are used
- Currents 4,5:
  - 11 new PSFs
- Interference between i=1,2,3 and i=4,5
  - 12 new PSF

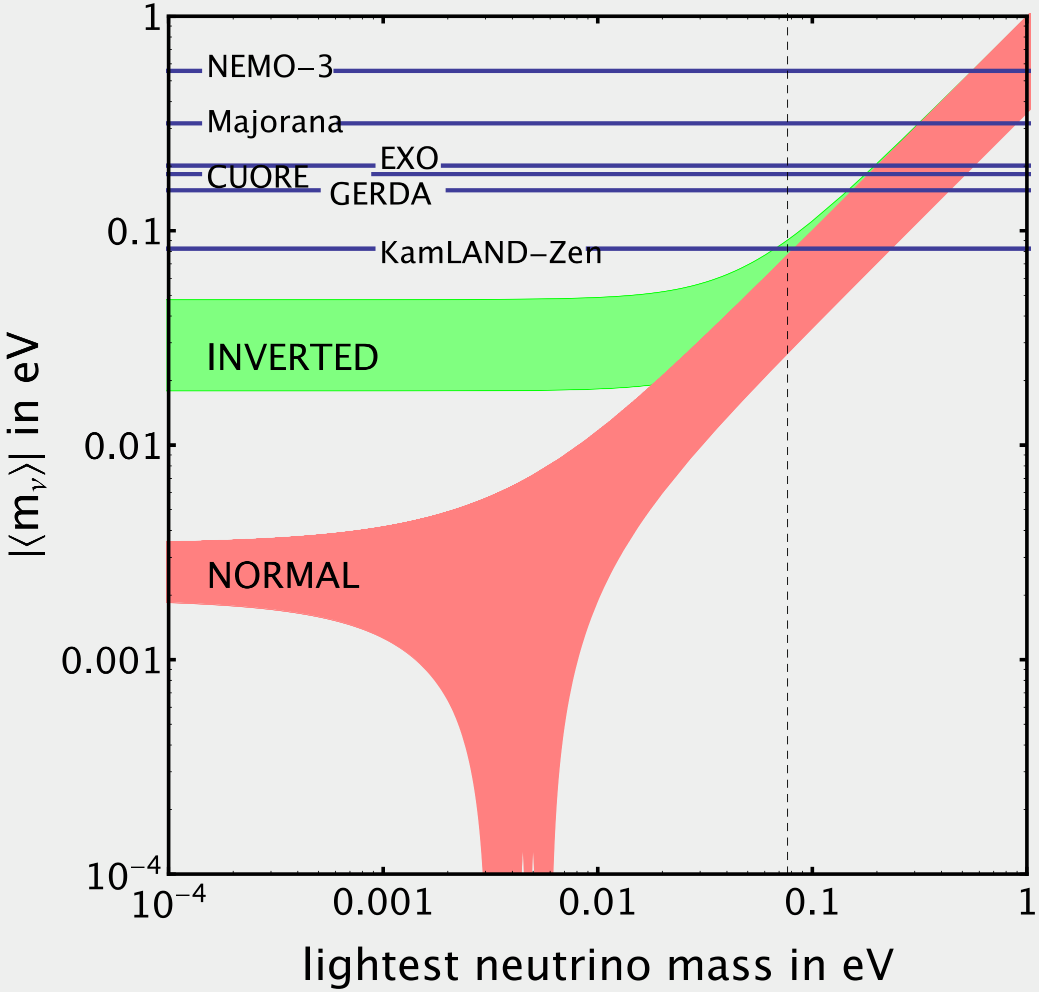
Long-range $0\nu\beta\beta$-decay mechanisms

- The derived formulas and the numerical calculations allow to study any non-standard long-range mechanism
- The form of the general problem in which all possible ε coefficients are present is very complicated and thus we have explicitly studied two classes of models:
  - LR models
    - → The differential rate for these models is obtained by combining matrix elements $\mathcal{M}_3$ with appropriate phase space factors
    - → The half-life depends on three parameters: $\frac{\langle m_\nu \rangle}{m_e}, \langle \lambda \rangle, \langle \eta \rangle$
  - SUSY models
    - → The differential rate for these models is obtained by combining the matrix elements $\mathcal{M}_4$ and $\mathcal{M}_5$ with appropriate phase space factors
    - → The half-life depends on four parameters: $\frac{\langle m_\nu \rangle}{m_e}, \langle \theta \rangle, \langle \tau \rangle, \langle \varphi \rangle$

Summary

- We have developed a general formalism for non-standard mechanisms contributing to neutrinoless double beta decay in an effective operator approach.
- We calculate all terms of the order of q^2/m_p^2 in the non-relativistic expansion of the combined nucleon currents
- Some of these terms play an important role, as, e.g., the pseudoscalar terms which are enhanced by a large value of g_{PS} or g_P
- Furthermore, we evaluate new phase space factors originating from the electron currents, including interference effects of different contributions.
- Using experimental bounds on half-lives we have calculated numerical limits on the effective new physics parameters ε
  - See Lukas' talk on Thursday!

Thank you!



1
0.1
0.01
0.001
10^{-4}
10^{-4}
0.001
0.01
0.1
1
NEMO−3
Majorana
EXO
CUORE
GERDA
KamLAND−Zen
INVERTED
NORMAL
$|\langle m_\nu \rangle|$ in eV
lightest neutrino mass in eV