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Probing BSM Physics with Non-Standard $0\nu\beta\beta$

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(1806.06058 + follow-up - to appear soon)

Progress and Challenges in $0\nu\beta\beta$, Trento, 2019

Outline

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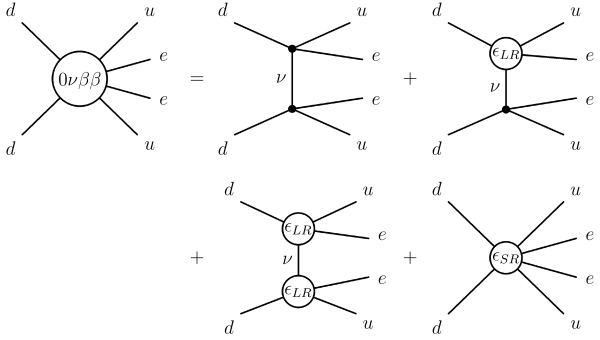
- non-standard neutrinoless double beta decay ($0\nu\beta\beta$) mechanisms - effectively description at low energy
- microscopic description of $0\nu\beta\beta$ - nuclear matrix elements (NMEs), nucleon form factors (NFFs) and phase-space factors (PSFs)
- $\rightarrow$ formulae for $0\nu\beta\beta$ half-life $+$ energy distribution & angular correlation of the outgoing electrons
- standard $+$ non-standard mechanisms - constraints on neutrino mass & new-physics couplings
- conclusions & outlook

Mechanisms of $0\nu\beta\beta$

- $\mathcal{L}_{0\nu\beta\beta} = \mathcal{L}_{LR} + \mathcal{L}_{SR}$, general Lagrangian in terms of effective couplings ϵ corresponding to the pointlike vertices at low energies



F. F. Deppisch, M. Hirsch, H. Päs: J. Phys. G **39** (2012), 124007

General Lagrangian for $0\nu\beta\beta$

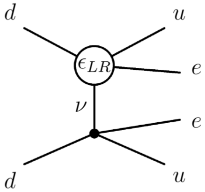
- long-range part: $\mathcal{L}_{LR} = \frac{G_F}{\sqrt{2}} \left[J^{\dagger}_{V-A\,\mu} j^{\mu}_{V-A} + \tilde{\sum}_{\alpha,\beta} \epsilon^{\beta}_{\alpha} J^{\dagger}_{\alpha} j_{\beta} \right]$,

  where $J^{\dagger}_{\alpha} = \bar{u} O_{\alpha} d$, $j_{\beta} = \bar{e} \mathcal{O}_{\beta} \nu$

  and $\mathcal{O}_{V\pm A} = \gamma^{\mu}(1 \pm \gamma_5)$,

  $\mathcal{O}_{S\pm P} = (1 \pm \gamma_5)$,

  $\mathcal{O}_{T_{R,L}} = \frac{i}{2}[\gamma_{\mu}, \gamma_{\nu}](1 \pm \gamma_5)$



- short range part:

$$\mathcal{L}_{SR} = \frac{G_F^2}{2m_p} \left[\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu} \right],$$

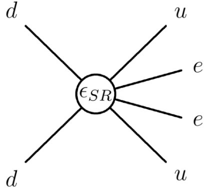
with $J = \bar{u}(1 \pm \gamma_5) d$,

$J^{\mu} = \bar{u} \gamma^{\mu} (1 \pm \gamma_5) d$,

$J^{\mu\nu} = \bar{u} \frac{i}{2} [\gamma^{\mu}, \gamma_{\nu}] (1 \pm \gamma_5) d$

$j = \bar{e}(1 \pm \gamma_5) e^C$

$j^{\mu} = \bar{e} \gamma^{\mu} (1 \pm \gamma_5) e^C$



H. Päs et. al.: Phys.Lett. B453 (1999) 194-198 and B498 (2001) 35-39

Mechanisms of $0\nu\beta\beta$

- connection to the experimental half-life - if only a single ϵ is considered to be non-zero at a time: $T_{1/2}^{-1} = |\epsilon|^2 G_i |M_i|^2$
- $\implies$ $0\nu\beta\beta$ half-life sets constraints on effective couplings
- accurate calculation of nuclear matrix elements (NMEs) and phase-space factors (PSFs) is crucial for this estimation
- main focus here: short-range $0\nu\beta\beta$ decay mechanisms & their interference with the standard mechanism

Mechanisms of $0\nu\beta\beta$

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- standard mass mechanism:

$$\Gamma_{m_\nu}^{0\nu\beta\beta} \sim m_\nu^2 G_F^4 m_F^2 Q_{\beta\beta}^5 \sim \left(\frac{m_\nu}{0.1\ \text{eV}}\right)^2 (10^{26}\ \text{y})^{-1}$$

- non-standard long-range mechanisms:

$$\Gamma_{\text{LR}}^{0\nu\beta\beta} \sim v^2 \Lambda_{O_7}^{-6} G_F^2 m_F^4 Q_{\beta\beta}^5 \sim \left(\frac{10^5\ \text{GeV}}{\Lambda_{O_7}}\right)^6 (10^{26}\ \text{y})^{-1}$$

- non-standard short-range mechanisms:

$$\Gamma_{\text{SR}}^{0\nu\beta\beta} \sim \Lambda_{O_9}^{-10} m_F^6 Q_{\beta\beta}^5 \sim \left(\frac{5\ \text{TeV}}{\Lambda_{O_9}}\right)^{10} (10^{26}\ \text{y})^{-1}$$

Mechanisms of $0\nu\beta\beta$

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- standard mass mechanism:

$$\Gamma^{0\nu\beta\beta}_{m_\nu} \sim m_\nu^2 G_F^4 m_F^2 Q_{\beta\beta}^5 \sim \left(\frac{m_\nu}{0.1\ \text{eV}}\right)^2 (10^{26}\ \text{y})^{-1}$$

- non-standard long-range mechanisms:

$$\Gamma^{0\nu\beta\beta}_{\text{LR}} \sim v^2 \Lambda_{O_7}^{-6} G_F^2 m_F^4 Q_{\beta\beta}^5 \sim \left(\frac{10^5\ \text{GeV}}{\Lambda_{O_7}}\right)^6 (10^{26}\ \text{y})^{-1}$$

- non-standard short-range mechanisms:

$$\Gamma^{0\nu\beta\beta}_{\text{SR}} \sim \Lambda_{O_9}^{-10} m_F^6 Q_{\beta\beta}^5 \sim \left(\frac{5\ \text{TeV}}{\Lambda_{O_9}}\right)^{10} (10^{26}\ \text{y})^{-1}$$

- due to the intrinsic helicity flip, non-standard long-range mechanisms in typical scenarios suppressed indirectly by neutrino mass

- e.g. L-R symmetric models: small y_ν $(y_\nu v = \sqrt{m_\nu M_N})$
  $\Longrightarrow$ $0\nu\beta\beta$ rate scales as $\Gamma^{0\nu\beta\beta}_{\text{LR}} \sim \left(\frac{m_\nu}{0.1\ \text{eV}}\right)\left(\frac{5\ \text{TeV}}{\Lambda_{\text{LR}}}\right)^5 (10^{26}\ \text{y})^{-1}$

J. C. Helo, M. Hirsch and T. Ota, JHEP 06, 006 (2016), [1602.03362]

Non-Standard Short-Range $0\nu\beta\beta$ Revisited

- $\mathcal{L}_{SR} = \frac{G_F^2}{2m_p}\left[\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu}j^\nu + \epsilon_5 J^\mu J j_\mu\right]$

- first: Is this formula complete?

- combination of left- and right-handed tensor currents $= 0$

- total number of independent low-energy $0\nu\beta\beta$ effective operators of dim. 9?

- Hilbert Series $\implies$ 24

  L. Lehman, A. Martin: 1503.07537, B. Henning, X. Lu, T. Melia, and H. Murayama: 1512.03433

- $+$ linear algebra $\implies$ indeed, $\mathcal{L}_{SR}$ contains 24 independent effective 9D operators triggering $0\nu\beta\beta$, in agreement with other literature (e.g. M. L. Graesser: 1606.04549)

Short-Range $0\nu\beta\beta$ Rate

- differential rate of $0\nu\beta\beta$ decay reads

$$d\Gamma = 2\pi\overline{|\mathcal{R}|^2}\delta(E_1 + E_2 + E_F - E_I)\frac{d^3\mathbf{p}_1}{(2\pi)^3}\frac{d^3\mathbf{p}_2}{(2\pi)^3},$$

with the full matrix element given symbolically as

$$\mathcal{R} = \frac{G_F^2}{2m_p}\sum_{K,\Xi}\epsilon_K \left\langle e_{\mathbf{p}_1 s_1}\middle| j_K^{\Xi} \middle| e^c_{\mathbf{p}_2 s_2}\right\rangle \left\langle \mathcal{O}_F^+\middle| J_K^{\Xi} J_K^{\prime\Xi} \middle|\mathcal{O}_I^+\right\rangle$$

- fully differential rate for $0^+ \to 0^+$ $0\nu\beta\beta$ decay

$$\frac{d^2\Gamma}{dE_1\, d\cos\theta} = C\, w(E_1)\,(a(E_1) + b(E_1)\cos\theta)\,,$$

where $C = \frac{G_F^4 m_e^2}{16\pi^5}$, $w(E_1) = E_1 E_2 p_1 p_2$

- quantites of interest: $a(E_1)$, $b(E_1)$

Nucleon Current Approximation

- considering nucleon isodoublet $\mathcal{N} = \binom{P}{N}$, the nucleon matrix elements of the quark currents are

$$
\begin{aligned}
\langle P(p)|\,\bar{u}(1\pm\gamma_5)d|N(p')\rangle &= \bar{\mathcal{N}}(p)\tau^+\left[F_S^{(3)}(q^2)\pm F_P^{(3)}(q^2)\gamma_5\right]\mathcal{N}(n),\\
\langle P(p)|\,\bar{u}\gamma^\mu(1\pm\gamma_5)d|N(p')\rangle &= \bar{\mathcal{N}}(p)\tau^+\left[F_V^{(3)}(q^2)\gamma^\mu - iF_W^{(3)}(q^2)\sigma^{\mu\nu}q_\nu\right]\mathcal{N}(n)\\
&\quad\pm\bar{\mathcal{N}}(p)\tau^+\left[F_A^{(3)}(q^2)\gamma^\mu\gamma_5 - F_P^{(3)}(q^2)\gamma_5 q^\mu\right]\mathcal{N}(n),\\
\langle P(p)|\,\bar{u}\sigma^{\mu\nu}(1\pm\gamma_5)d|N(p')\rangle &= \bar{\mathcal{N}}(p)\tau^+\left[J^{\mu\nu}\pm\frac{i}{2}\varepsilon^{\mu\nu\rho\sigma}J_{\rho\sigma}\right]\mathcal{N}(n),
\end{aligned}
$$

where we have defined:

$$J^{\mu\nu} = T_q^{(3)}(q^2)\sigma^{\mu\nu} + T_2^{(3)}(q^2)\frac{i}{m_p}(\gamma^\mu q^\nu - \gamma^\nu q^\mu) + T_3^{(3)}(q^2)\frac{1}{m_p^2}(\sigma^{\mu\rho}q_\rho q^\nu - \sigma^{\nu\rho}q_\rho q^\mu).$$

- form factors - from experiment or theoretical calculation (old: MIT bag model, new: LQCD)

NR Expansion of the Nucleon Currents

- non-relativistic limit then gives the resulting approximated nuclear bilinears

$$
\begin{aligned}
J_{S\pm P} &= \sum_a \tau_+^a \delta\left(\mathbf{x}-\mathbf{r}_a\right)\left(F_S^{(3)} \pm F_{PS}^{(3)} \frac{1}{2m_p}(\boldsymbol{\sigma}_a \cdot \boldsymbol{q})\right), \\
J^\mu_{V\pm A} &= \sum_a \tau_+^a \delta\left(\mathbf{x}-\mathbf{r}_a\right)\left\{g^{\mu 0}\left[F_V I_a \pm \frac{F_A}{2m_p}\left(\boldsymbol{\sigma}_a \cdot \boldsymbol{Q} - \frac{F_P}{F_A} q^0 \mathbf{Q}\cdot\boldsymbol{\sigma}_a\right)\right]\right. \\
&\qquad \left. + g^{\mu i}\left[\mp F_A (\boldsymbol{\sigma}_a)_i - \frac{F_V}{2m_p}\left(\mathbf{Q} I_a - \left(1 - 2m_p \frac{F_W}{F_V}\right) i\boldsymbol{\sigma}_a \times \mathbf{q}\right)_i\right]\right\}, \\
J^{\mu\nu}_{T\pm T_5} &= \sum_a \tau_+^a \delta\left(\mathbf{x}-\mathbf{r}_a\right) T_1^{(3)}\Big[(g^{\mu i} g^{\nu 0} - g^{\mu 0} g^{\nu i}) T_a^i + g^{\mu j} g^{\nu k} \varepsilon^{ijk} \sigma^{ai} \\
&\qquad \pm \frac{i}{2} \varepsilon^{\mu\nu\rho\sigma} (g_{\mu i} g_{\nu 0} - g_{\mu 0} g_{\nu i}) T_{ai} + g_{\mu m} g_{\nu n} \varepsilon_{mni} \sigma_{ai}\Big],
\end{aligned}
$$

where we have defined:

$$
T_a^i = \frac{i}{2m_p}\left[\left(1 - 2\frac{T_2^{(3)}}{T_1^{(3)}}\right) q^i I_a + (\boldsymbol{\sigma}_a \times \mathbf{Q})^i\right].
$$

Nucleon Form Factors

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- we consider the following q^2 dependence of the NFFs

$$F_S(q^2) = \frac{g_S}{\left(1+q^2/m_V^2\right)^2}, \qquad g_S = 1.0$$

$$F_{PS}(q^2) = \frac{g_{PS}}{\left(1+q^2/m_V^2\right)^2}\frac{1}{1+q^2/m_\pi^2}, \qquad g_{PS} = 349$$

$$F_V(q^2) = \frac{g_V}{\left(1+q^2/m_V^2\right)^2}, \qquad g_V = 1.0,$$

$$F_W(q^2) = \frac{g_W}{\left(1+q^2/m_V^2\right)^2}, \qquad g_W = 3.7,$$

$$F_A(q^2) = \frac{g_A}{\left(1+q^2/m_A^2\right)^2}, \qquad g_A = 1.27$$

$$F_P(q^2) = \frac{g_P}{\left(1+q^2/m_A^2\right)^2}\frac{1}{1+q^2/m_\pi^2} \qquad g_P = 4g_A\frac{m_p^2}{m_\pi^2}\left(1-\frac{m_\pi^2}{m_A^2}\right) = 231$$

$$F_{T_i}(q^2) = \frac{g_{T_i}}{\left(1+q^2/m_V^2\right)^2}, \qquad g_{T_{1,2,3}} = 1.0, -3.3, 1.34$$

($m_V = 0.84$ GeV, $m_A = 1.09$ GeV, $m_\pi = 0.138$ GeV)

Nuclear Matrix Elements

- $F_{PS}(q^2) = \frac{g_{PS}}{\left(1+q^2/m_{PS}^2\right)^2} \frac{1}{1+q^2/m_\pi^2}$

  $g_{PS} = 349$

  M. Gonzalez-Alonso, O. Naviliat-Cuncic and N. Severijns, Prog. Part. Nucl. Phys. 104, 165 (2019), [1803.08732].

- $F_P(q^2) = \frac{g_A}{\left(1+q^2/m_A^2\right)^2} \frac{1}{1+q^2/m_\pi^2} \times \frac{4m_p^2}{m_\pi^2}\left(1 - \frac{m_\pi^2}{m_A^2}\right)$

  $g_P = 231$

  F. Simkovic, G. Pantis, J. D. Vergados and A. Faessler, Phys. Rev. C60, 055502 (1999), [hep-ph/9905509]

  V. Bernard, L. Elouadrhiri, U.-G. Meissner, J. Phys. G28, R1 (2002), [hep-ph/0107088]

- enhanced values of pseudoscalar form factors $\implies$ additional NMEs taken into account

$$
\begin{aligned}
\mathcal{M}_1 &= g_S^2 \mathcal{M}_F \\
&\quad (+\ +\ -)\ \frac{g_{PS}^2}{12}\left(\mathcal{M}_{GT}'^{PP} - \mathcal{M}_T'^{PP}\right), \\
\mathcal{M}_2 &= -2 g_{T_1}^2 \mathcal{M}_{GT}, \\
\mathcal{M}_3 &= g_V^2 \mathcal{M}_F \\
&\quad (-\ -\ +)\ g_A^2 \mathcal{M}_{GT}^{AA} \\
&\quad (+\ +\ -)\ \frac{g_A g_P}{6}\left(\mathcal{M}_{GT}'^{AP} - \mathcal{M}_T'^{AP}\right) \\
&\quad + \frac{(g_V + g_W)^2}{12}\left(\mathcal{M}_{GT}' + \frac{1}{2}\mathcal{M}_T'\right) \\
&\quad (-\ -\ +)\ \frac{g_P^2}{48}\left(\mathcal{M}_{GT}''^{PP} - \mathcal{M}_T''^{PP}\right), \\
\mathcal{M}_4^\mu &= (-\ -\ +\ +)\ i g^{\mu 0} g_A g_{T_1} \mathcal{M}_{GT}^A \\
&\quad (+\ +\ -\ -)\ i g^{\mu 0} \frac{g_P g_{T_1}}{12}\left(\mathcal{M}_{GT}'^P - \mathcal{M}_T'^P\right), \\
\mathcal{M}_5^\mu &= g^{\mu 0} g_S g_V \mathcal{M}_F \\
&\quad (+\ +\ -\ -)\ g^{\mu 0} \frac{g_A g_{PS}}{12}\left(\tilde{\mathcal{M}}_{GT}^{AP} - \tilde{\mathcal{M}}_T^{AP}\right) \\
&\quad (-\ -\ +\ +)\ g^{\mu 0} \frac{g_P g_{PS}}{24}\left(\mathcal{M}_{GT}'^{q_0 PP} - \mathcal{M}_T'^{q_0 PP}\right).
\end{aligned}
$$

Nuclear Matrix Elements

- selection of the relevant NMEs involved in the non-standard short-range mechanisms
- pseudoscalar enhancement $\implies$ additional NMEs
- for $\mathcal{M}_3$ ('heavy neutrino exchange'):

NME	$\tilde{h}_\circ(q^2)$
$\mathcal{M}'^{WW}_{GT} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XX}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{XX}(q^2)$
$\mathcal{M}'^{WW}_{T} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XX}(q^2)\mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{XX}(q^2)$
$\mathcal{M}^{AA}_{GT} = \langle h_{AA}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \rangle$	$\tilde{h}_{AA}(q^2) = \frac{1}{\left(1+q^2/m_A^2\right)^4}$
$\mathcal{M}'^{AP}_{GT} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{AP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{AP}(q^2) = \frac{1}{\left(1+q^2/m_A^2\right)^4} \frac{1}{1+q^2/m_\pi^2}$
$\mathcal{M}'^{AP}_{T} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{AP}(q^2)\mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{AP}(q^2)$
$\mathcal{M}''^{PP}_{GT} = \left\langle \frac{\mathbf{q}^4}{m_p^4} h_{PP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b) \right\rangle$	$\tilde{h}_{PP}(q^2)$
$\mathcal{M}''^{PP}_{T} = \left\langle \frac{\mathbf{q}^4}{m_p^4} h_{PP}(q^2)\mathbf{S}_{ab} \right\rangle$	$\tilde{h}_{PP}(q^2)$

Nuclear Matrix Elements

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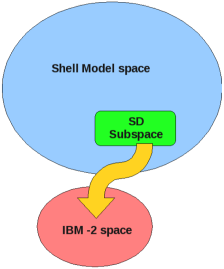
	NME	$\tilde{h}_\circ(q^2)$
$\mathcal{M}_1$	$\mathcal{M}_F = \langle h_{XX}(q^2)\rangle$	$\tilde{h}_{XX}(q^2) = \frac{1}{\left(1+q^2/m_V^2\right)^4}$
	$\mathcal{M}_{GT}^{\prime PP} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{PP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b)\right\rangle$	$\tilde{h}_{PP}(q^2) = \frac{1}{\left(1+q^2/m_A^2\right)^4}\frac{1}{(1+q^2/m_\pi^2)^2}$
	$\mathcal{M}_T^{\prime PP} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{PP}(q^2)\mathbf{S}_{ab}\right\rangle$	$\tilde{h}_{PP}(q^2)$
$\mathcal{M}_2$	$\mathcal{M}_{GT}^{T_1T_1} = \langle h_{XX}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b)\rangle$	$\tilde{h}_{XX}(q^2)$
$\mathcal{M}_4$	$\mathcal{M}_{GT}^{AT_1} = \langle h_{AX}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b)\rangle$	$\tilde{h}_{AX}(q^2) = \frac{1}{\left(1+q^2/m_V^2\right)^2}\frac{1}{\left(1+q^2/m_A^2\right)^2}$
	$\mathcal{M}_{GT}^{\prime PT_1} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b)\right\rangle$	$\tilde{h}_{XP}(q^2) = \frac{1}{\left(1+q^2/m_V^2\right)^2}\frac{1}{\left(1+q^2/m_A^2\right)^2}\frac{1}{1+q^2/m_\pi^2}$
	$\mathcal{M}_T^{\prime PT_1} = \left\langle \frac{\mathbf{q}^2}{m_p^2} h_{XP}(q^2)\mathbf{S}_{ab}\right\rangle$	$\tilde{h}_{XP}(q^2)$
$\mathcal{M}_5$	$\tilde{\mathcal{M}}_{GT}^{AP} = \left\langle \frac{\mathbf{Q}\cdot\mathbf{q}}{m_p^2} h_{AP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b)\right\rangle \approx \mathcal{M}_{GT}^{\prime AP}$	$\tilde{h}_{AP}(q^2)$
	$\tilde{\mathcal{M}}_T^{AP} = \left\langle \frac{\mathbf{Q}\cdot\mathbf{q}}{m_p^2} h_{AP}(q^2)\mathbf{S}_{ab}\right\rangle \approx \mathcal{M}_T^{\prime AP}$	$\tilde{h}_{AP}(q^2)$
	$\mathcal{M}_{GT}^{\prime q_0 PP} = \left\langle \frac{q_0\mathbf{q}^2}{m_p^3} h_{PP}(q^2)(\boldsymbol{\sigma}_a \cdot \boldsymbol{\sigma}_b)\right\rangle \approx 10^{-2}\mathcal{M}_{GT}^{\prime PP}$	$\tilde{h}_{PP}(q^2)$
	$\mathcal{M}_T^{\prime q_0 PP} = \left\langle \frac{q_0\mathbf{q}^2}{m_p^3} h_{PP}(q^2)\mathbf{S}_{ab}\right\rangle \approx 10^{-2}\mathcal{M}_T^{\prime PP}$	$\tilde{h}_{PP}(q^2)$

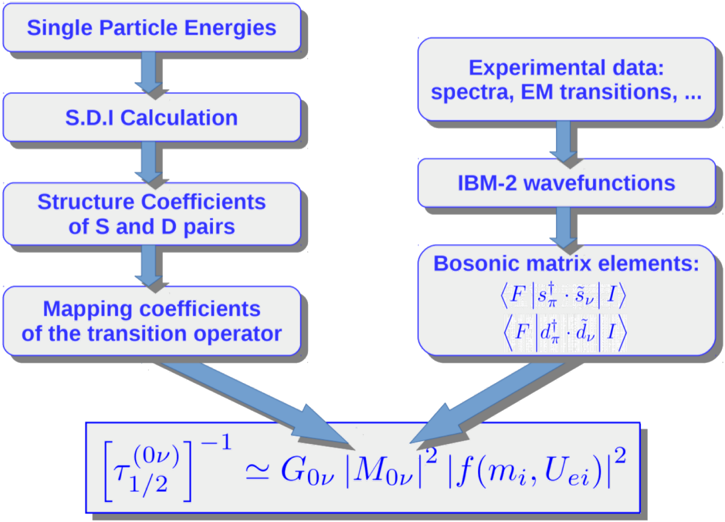
Nuclear Model: IBM-2

- IBM-2 - the very large shell model space truncated to states built from pairs of nucleons with $J = 0, 2$
- these pairs - bosons - are then assumed to be collective
- Hamiltonian constructed phenomenologically, two- and four valence-nucleon states generated by a schematic interaction
- fermion operators - mapped onto a boson space
- matrix elements of the mapped operators evaluated with realistic wave functions

J. Barea and F. Iachello, Phys. Rev. C79, 044301 (2009)



Nuclear Model: IBM-2



(figure from Jenni Kotila)

NMEs - Numerical Results

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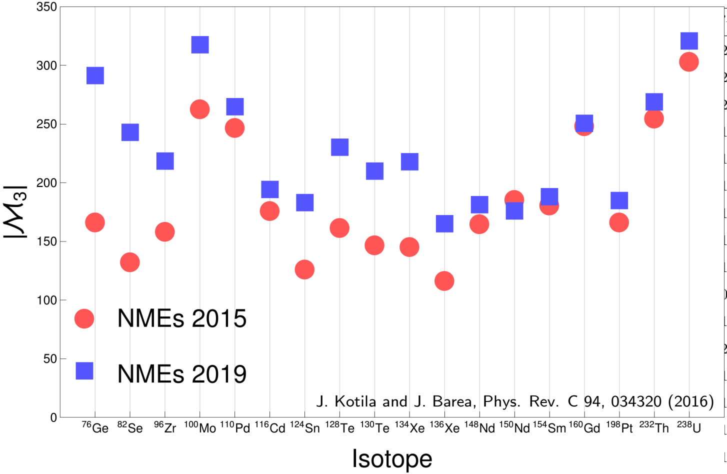
Isotope	$\mathcal{M}_F$	$\mathcal{M}_{GT}^{VV}$	$\mathcal{M}_{GT}^{AA}$	$\mathcal{M}_{GT}^{A}$	$\mathcal{M}_{GT}^{\prime WW}$	$\mathcal{M}_{T}^{\prime WW}$	$\mathcal{M}_{GT}^{\prime AP}$	$\mathcal{M}_{T}^{\prime AP}$	$\mathcal{M}_{GT}^{\prime P}$	$\mathcal{M}_{T}^{\prime P}$	$\mathcal{M}_{GT}^{\prime PP}$	$\mathcal{M}_{T}^{\prime PP}$	$\mathcal{M}_{GT}^{\prime\prime PP}$	$\mathcal{M}_{T}^{\prime\prime PP}$	$\mathcal{M}_{GT}^{\prime q_0 PP}$	$\mathcal{M}_{T}^{\prime q_0 PP}$
^{76}Ge	-48.89	173.5	170.0	174.3	-2.945	-6.541	2.110	-1.310	2.255	-1.183	0.798	-0.271	0.028	-0.022	0.008	-0.003
^{82}Se	-41.22	143.6	140.7	144.3	-2.456	-6.206	1.758	-1.249	1.878	-1.183	0.660	-0.259	0.024	-0.021	0.007	-0.003
^{100}Mo	-51.96	188.6	181.9	188.1	-4.590	8.055	2.273	1.590	2.464	1.128	0.910	0.317	0.029	0.027	0.009	0.003
^{128}Te	-41.82	134.1	131.7	134.9	-2.439	-4.519	1.667	-0.890	1.776	-1.433	0.617	-0.178	0.023	-0.015	0.006	-0.002
^{130}Te	-38.05	121.9	119.7	122.6	-1.951	-4.105	1.514	-0.807	1.613	-0.726	0.561	-0.160	0.021	-0.014	0.006	-0.002
^{134}Xe	-39.45	127.2	124.7	127.8	-2.111	-4.191	1.564	-0.823	1.669	-0.741	0.585	-0.163	0.021	-0.014	0.006	-0.002
^{136}Xe	-29.83	96.1	94.18	96.56	-1.625	-3.158	1.177	-0.620	1.257	-0.558	0.442	-0.123	0.016	-0.011	0.004	-0.001
^{150}Nd	-30.18	103.1	100.0	103.2	-2.230	2.955	1.292	0.581	1.392	0.523	0.497	0.116	0.017	0.010	0.005	0.001
^{154}Sm	-31.83	110.9	107.1	110.7	-2.618	3.397	1.356	0.668	1.467	0.601	0.536	0.135	0.018	0.012	0.005	0.001
^{148}Nd	-31.71	105.8	103.0	106.0	-2.145	2.557	1.346	0.510	1.445	0.460	0.508	0.104	0.018	0.009	0.005	0.001
^{96}Zr	-35.31	128.8	124.3	128.5	-3.116	5.436	1.523	1.090	1.652	0.984	0.613	0.228	0.020	0.019	0.006	0.002
^{110}Pd	-43.52	157.0	151.2	156.5	-3.945	6.816	1.892	1.356	2.055	1.223	0.762	0.271	0.024	0.023	0.008	0.003
^{116}Cd	-32.45	115.2	110.5	114.6	-3.069	4.222	1.374	0.843	1.497	0.760	0.565	0.169	0.017	0.015	0.006	0.002
^{124}Sn	-33.19	106.1	104.2	106.7	-1.701	-3.655	1.321	-0.723	1.407	-0.651	0.489	-0.146	0.018	-0.012	0.005	-0.001
^{198}Pt	-31.87	109.0	104.4	108.4	-2.992	3.172	1.334	0.626	1.454	0.564	0.546	0.119	0.017	0.011	0.005	0.001
^{160}Gd	-41.43	148.6	142.9	148.0	-3.808	5.231	1.776	1.023	1.931	0.920	0.722	0.205	0.023	0.018	0.007	0.002
^{232}Th	-44.04	160.3	154.2	159.7	-4.116	6.146	1.900	1.185	2.067	1.063	0.783	0.230	0.024	0.021	0.008	0.002
^{238}U	-52.48	190.5	183.1	189.7	-4.981	7.206	2.255	1.393	2.456	1.251	0.932	0.272	0.029	0.024	0.009	0.003

NMEs - Numerical Results



Isotope	$\mathcal{M}$													P	$\mathcal{M}_{GT}^{\prime q_0 PP}$	$\mathcal{M}_{T}^{\prime q_0 PP}$
^{76}Ge	-48.8													22	0.008	-0.003
^{82}Se	-41.2													21	0.007	-0.003
^{100}Mo	-51.9													27	0.009	0.003
^{128}Te	-41.8													15	0.006	-0.002
^{130}Te	-38.0													14	0.006	-0.002
^{134}Xe	-39.4													14	0.006	-0.002
^{136}Xe	-29.8													11	0.004	-0.001
^{150}Nd	-30.1													10	0.005	0.001
^{154}Sm	-31.8													12	0.005	0.001
^{148}Nd	-31.7													09	0.005	0.001
^{96}Zr	-35.3													19	0.006	0.002
^{110}Pd	-43.5													23	0.008	0.003
^{116}Cd	-32.4													15	0.006	0.002
^{124}Sn	-33.1													12	0.005	-0.001
^{198}Pt	-31.8													11	0.005	0.001
^{160}Gd	-41.4													18	0.007	0.002
^{232}Th	-44.04	160.3	154.2	159.7	-4.116	6.146	1.900	1.185	2.067	1.063	0.783	0.230	0.024	0.021	0.008	0.002
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Leptonic Matrix Elements

- the key ingredient for the phase space factors (PSFs): the electron wave functions
- position-dependent wavefunction of each electron can be expanded in terms of spherical waves

$$e_{\mathbf{p}s}(\mathbf{r}) = e_{\mathbf{p}s}^{S_{1/2}}(\mathbf{r}) + e_{\mathbf{p}s}^{P_{1/2}}(\mathbf{r}) + \dots$$

($\mathbf{p}$ is the asymptotic momentum of the electron at long distance and s denotes its spin projection)

$$e_{\mathbf{p}s}^{S_{1/2}}(\mathbf{r}) = \begin{pmatrix} g_{-1}(E,r)\chi_s \\ f_1(E,r)(\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})\chi_s \end{pmatrix}, \quad e_{\mathbf{p}s}^{P_{1/2}}(\mathbf{r}) = i\begin{pmatrix} g_1(E,r)(\boldsymbol{\sigma}\cdot\hat{\mathbf{r}})(\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})\chi_s \\ -f_{-1}(E,r)(\boldsymbol{\sigma}\cdot\hat{\mathbf{r}})\chi_s \end{pmatrix},$$

- $g_\kappa(E,r)$ and $f_\kappa(E,r)$ are the radial wavefunctions of the 'large' and 'small' components

Leptonic Matrix Elements

- realistical calculation: radial functions satisfying the Dirac equation with potential taking into account the finite nuclear size and the electron screening

  J. Kotila and F. Iachello, Phys. Rev. C85, 034316 (2012), [1209.5722]

- approximation: electron wavefunctions evaluated at the nuclear radius $r = R_A$ - nucleons decay largely at the surface due to Pauli-blocking of inner states

$$f_\pm(E) \equiv f_\pm(E, R_A), \quad g_\pm(E) \equiv g_\pm(E, R_A)$$

- 8 different leptonic matrix elements (6 independent ones)

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

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

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

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

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

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

$$f^{-1-1} = g_{-1}(E_1) g_{-1}(E_2)$$

$$f_{11} = f_1(E_1) f_1(E_2)$$

$$f^{-1}{}_1 = g_{-1}(E_1) f_1(E_2)$$

$$f_1{}^{-1} = f_1(E_1) g_{-1}(E_2)$$

Resulting Coefficients $a(E_1)$ and $b(E_1)$

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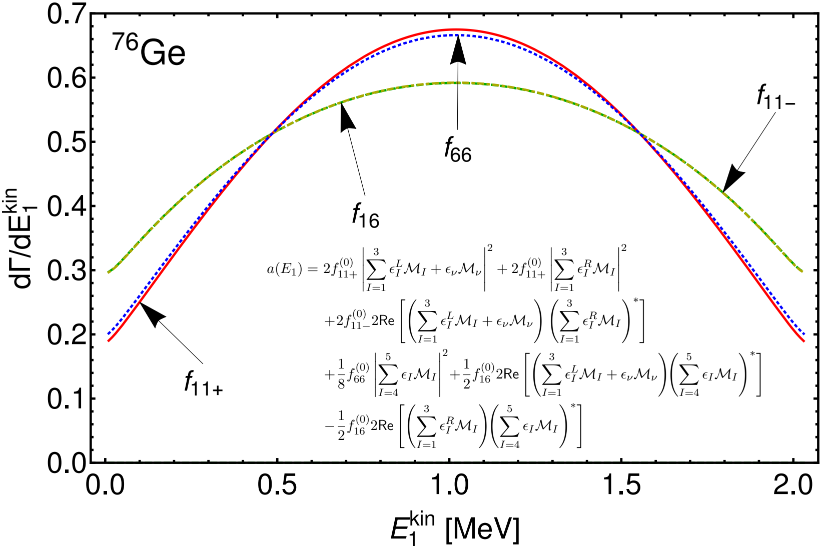
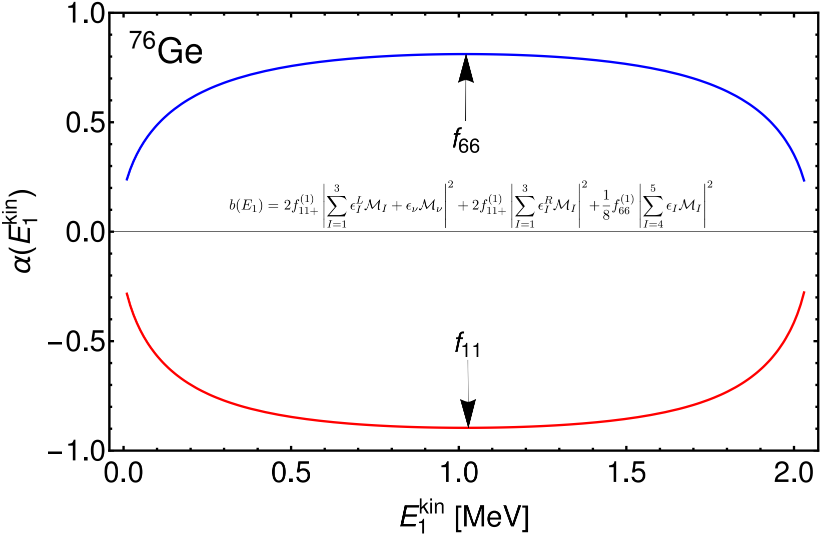
- considering $\mathcal{L}_{SR}$ + the mass mechanism $\to a(E_1)$ and $b(E_1)$ entering the fully differential rate for $0^+ \to 0^+ \; 0\nu\beta\beta$ decay:

$$
\begin{aligned}
a(E_1) = {} & 2f_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right|^2 + 2f_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right|^2 \\
& + 2f_{11-}^{(0)} \, 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right) \left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right)^* \right] \\
& + \frac{1}{8} f_{66}^{(0)} \left| \sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right|^2 + \frac{1}{2} f_{16}^{(0)} \, 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right] \\
& - \frac{1}{2} f_{16}^{(0)} \, 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right], \\
b(E_1) = {} & 2f_{11+}^{(1)} \left| \sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right|^2 + 2f_{11+}^{(1)} \left| \sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right|^2 + \frac{1}{8} f_{66}^{(1)} \left| \sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right|^2
\end{aligned}
$$

Energy Distribution



Angular Correlation



Integrated Phase-Space Factors

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- PSFs obtained by integration of the above leptonic matrix elements

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

which enters the half-life

$$T_{1/2}^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 G_\nu |\mathcal{M}_\nu|^2$$

- both distributions and integrated PSFs calculated for a wide range of isotopes
- results consistent with previous calculations

A	$G_{11}^{(0)}$	$G_{11-}^{(0)}$	$G_{66}^{(0)}$	$G_{16}^{(0)}$	$G_{11}^{(1)}$	$G_{66}^{(1)}$
^{76}Ge	4.720	−0.561	2.640	1.739	−3.908	1.954
^{82}Se	20.37	−1.425	10.90	5.849	−18.16	9.079
^{96}Zr	41.16	−2.379	21.76	10.81	−43.23	18.67
^{100}Mo	31.82	−2.105	16.96	8.913	−28.50	14.25
^{110}Pd	9.614	−1.083	5.348	3.460	−8.028	4.014
^{116}Cd	33.38	−2.375	17.88	9.685	−38.74	14.83
^{124}Sn	18.06	−1.685	9.870	5.953	−15.52	7.760
^{128}Te	1.170	−0.312	0.741	0.626	−0.780	0.390
^{130}Te	28.40	−2.284	15.34	8.733	−24.89	12.45
^{134}Xe	1.193	−0.327	0.760	0.646	−0.788	0.394
^{136}Xe	29.11	−2.395	15.75	9.048	−25.44	12.72
^{148}Nd	20.15	−2.168	11.16	7.096	−28.38	8.493
^{150}Nd	126.0	−6.250	66.11	30.88	−115.7	57.83
^{154}Sm	6.010	−1.078	3.544	2.677	−4.582	2.291
^{160}Gd	19.05	−2.258	10.64	7.012	−15.83	7.917
^{198}Pt	15.03	−2.610	8.818	6.555	−11.69	5.845
^{232}Th	27.74	−4.839	16.29	12.04	−21.83	10.91
^{238}U	66.89	−8.353	37.62	24.92	−56.03	28.01

General Half-Life Formula

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- considering $\mathcal{L}_{SR}$ + the mass mechanism
- $\implies$ general formula for half-life of $0\nu\beta\beta$ decay induced by the short-range mechanisms + the standard mechanism and their mutual interference:

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

Limits on Couplings

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- new NMEs + new PSFs + current exp. bounds on $T_{1/2}^{0\nu\beta\beta}$ $\Longrightarrow$ new limits on effective neutrino mass $\langle m_\nu \rangle$ and new-physics couplings ϵ_I (all ϵ limits $\times 10^{-10}$)

$\langle m_\nu \rangle = \sum U_{ei}^2 m_{\nu_i}$

	$T_{1/2}^{\rm exp}$ [y]	$\langle m_\nu \rangle$ [eV]
^{76}Ge	8×10^{25}	0.093
^{82}Se	2.4×10^{24}	0.32
^{96}Zr	9.2×10^{21}	4.2
^{100}Mo	1.1×10^{24}	0.34
^{116}Cd	2.2×10^{23}	1.3
^{130}Te	1.5×10^{24}	1.9
^{130}Te	1.5×10^{25}	0.13
^{136}Xe	1.07×10^{26}	0.059
^{150}Nd	2.0×10^{22}	1.9

$\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu$

	$T_{1/2}^{\rm exp}$ [y]	$\lvert\epsilon_1^{XX}\rvert$	$\lvert\epsilon_1^{LR}\rvert$	$\lvert\epsilon_2^{XX}\rvert$	$\lvert\epsilon_3^{XX}\rvert$	$\lvert\epsilon_3^{LR}\rvert$	$\lvert\epsilon_4^{XX,LR}\rvert$	$\lvert\epsilon_5^{XX}\rvert$	$\lvert\epsilon_5^{RL,LR}\rvert$
^{76}Ge	8×10^{25}	1.88	1.86	93.8	56.2	88.8	126	39.3	33.3
^{82}Se	2.4×10^{24}	6.24	6.17	315	188	299	435	131	111
^{96}Zr	9.2×10^{21}	90.7	89.5	3990	2370	3660	5220	2520	2000
^{100}Mo	1.1×10^{24}	6.32	6.24	283	169	263	371	174	139
^{116}Cd	2.2×10^{23}	22.0	21.7	1010	606	961	1330	619	493
^{130}Te	1.5×10^{24}	36.1	35.6	1780	1040	1720	2250	696	581
^{130}Te	1.5×10^{25}	2.54	2.51	126	73.6	121	172	53.0	44.3
^{136}Xe	1.07×10^{26}	1.20	1.18	59.0	34.7	57.2	80.3	25.4	21.2
^{150}Nd	2.0×10^{22}	41.9	41.4	1930	1140	1820	2580	1060	856

PRELIMINARY

- constraining the scale: $\frac{1}{\Lambda_{\rm NP}^5} = \frac{G_F^2}{2m_p}\epsilon_I$

Limits on Couplings

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- above: effective couplings at $\Lambda_{\text{QCD}} \approx 1$ GeV
- more correctly: new-physics scale $\Lambda_{\text{NP}} \approx 1$ TeV
- $\implies$ QCD running taken into account

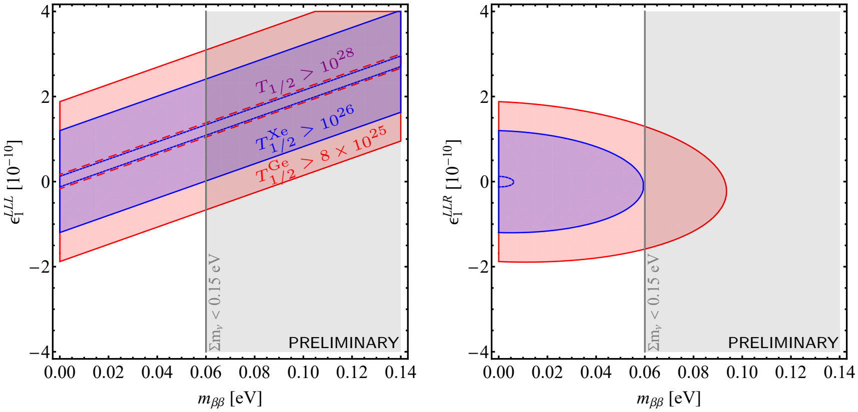
M. González, M. Hirsch and S. G. Kovalenko, Phys. Rev. D93, 013017 (2016), [1511.03945]

$$c_1\, JJj + c_2\, J^{\mu\nu} J_{\mu\nu} j + c_3\, J^{\mu} J_{\mu} j + c_4\, J^{\mu} J_{\mu\nu} j^{\nu} + c_5\, J^{\mu} J j_{\mu}$$

	$T_{1/2}^{\text{exp}}$ [y]	$\lvert c_1^{XX}\rvert$	$\lvert c_1^{LR}\rvert$	$\lvert c_2^{XX}\rvert$	$\lvert c_3^{XX}\rvert$	$\lvert c_3^{LR}\rvert$	$\lvert c_4^{XX}\rvert$	$\lvert c_4^{LR}\rvert$	$\lvert c_5^{XX}\rvert$	$\lvert c_5^{RL,LR}\rvert$
^{76}Ge	8×10^{25}	0.762	0.445	145	80.2	106	315	203	16.3	8.07
^{82}Se	2.4×10^{24}	2.53	1.48	478	268	356	1080	702	54.4	26.9
^{96}Zr	9.2×10^{21}	36.6	21.4	7530	3380	4360	14000	8410	1030	485
^{100}Mo	1.1×10^{24}	2.55	1.49	518	242	313	995	598	71.5	33.6
^{116}Cd	2.2×10^{23}	8.88	5.19	1770	866	1140	3570	2150	255	119
^{130}Te	1.5×10^{24}	14.6	8.53	2800	1490	2050	5620	3620	289	141
^{130}Te	1.5×10^{25}	1.03	0.602	197	105	144	429	277	22.0	10.7
^{136}Xe	1.07×10^{26}	0.485	0.283	93.0	49.5	68.1	202	129	10.5	5.12
^{150}Nd	2.0×10^{22}	17.0	9.91	3380	1630	2170	6810	4170	437	207

PRELIMINARY

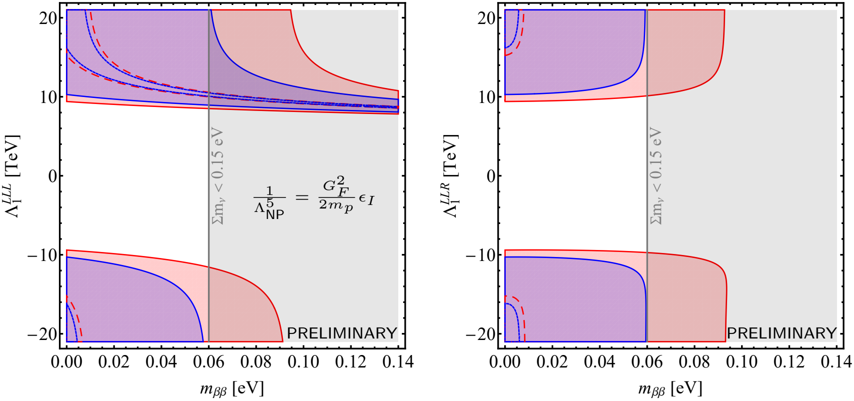
Interference with Mass Mechanism



$$T_{1/2}^{-1} = G_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right|^2$$

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

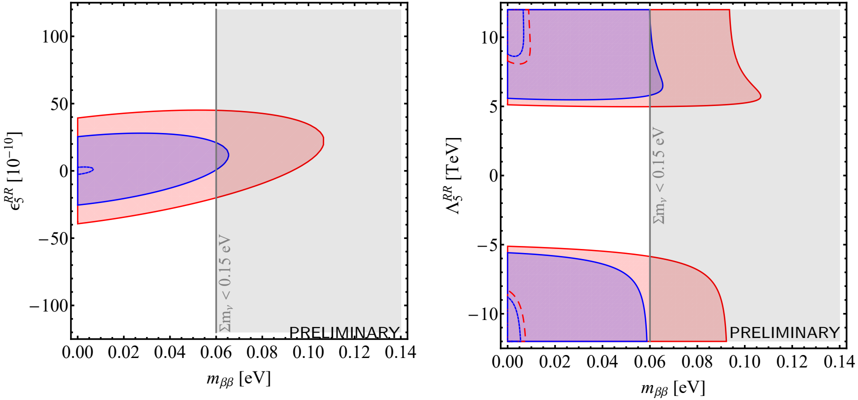
Interference with Mass Mechanism



$$T_{1/2}^{-1} = G_{11+}^{(0)} \left|\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu\right|^2$$

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

Interference with Mass Mechanism



Non-Standard Long-Range Mechanisms

- more complicated, nontrivial neutrino potential (from the neutrino propagator)

- terms proportional to neutrino mass, energy and momentum come with different neutrino potentials

$$v_m = \frac{1}{k_0 + A_1} + \frac{1}{k_0 + A_2},\ v_{k_0} = \frac{k_0(E_1 - E_2)}{(k_0 + A_1)(k_0 + A_2)},\ v_{\mathbf{k}} = \mathbf{k}\left(\frac{1}{k_0 + A_1} + \frac{1}{k_0 + A_2}\right)$$

- more combinations contributing to $0^+ \to 0^+$
  $\implies$ possibly additional/new relevant (non-negligible) terms, electron p-wave important

- additional PSFs entering the half-life formula

Discrimination of $0\nu\beta\beta$ Decay Mechanism

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- analysis of angular correlation between the emitted electrons
- in certain cases the operators correspond to a final state of opposite electron chiralities $\implies$ can be distinguished by SuperNEMO from the purely left-handed current interaction via the measurement of the decay distribution

  R. Arnold et al. (NEMO-3): Phys. Rev. D98 (2007), 232501
- some operators can be probed at the LHC
- comparison with related processes (capture or $0\nu\beta^+\beta^+$)
- another way: comparing ratios of half life measurements for different isotopes

  F. Deppisch, H. Päs: Phys. Rev. Lett. 89 (2014), 111101

Conclusions

- a number of different non-standard mechanisms can contribute to $0\nu\beta\beta$
- we provide a detailed description of the short-range scenarios $\leftrightarrow$ variety of NMEs calculated using IBM-2, combined with accurate PSFs, analysis of limits on BSM physics
- observation of $0\nu\beta\beta \rightarrow$ hint for the scale of the BSM physics
- outlook: revisiting long-range; comparison/connection with χEFT?, 'new' contributions?

Conclusions

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- a number of different non-standard mechanisms can contribute to $0\nu\beta\beta$
- we provide a detailed description of the short-range scenarios $\leftrightarrow$ variety of NMEs calculated using IBM-2, combined with accurate PSFs, analysis of limits on BSM physics
- observation of $0\nu\beta\beta$ $\rightarrow$ hint for the scale of the BSM physics $\rightarrow$ see also Frank's talk!
- outlook: revisiting long-range; comparison/connection with χEFT?, 'new' contributions?

Thank You for attention!