Double Beta Decay and its potential to explore beyond Standard Model physics

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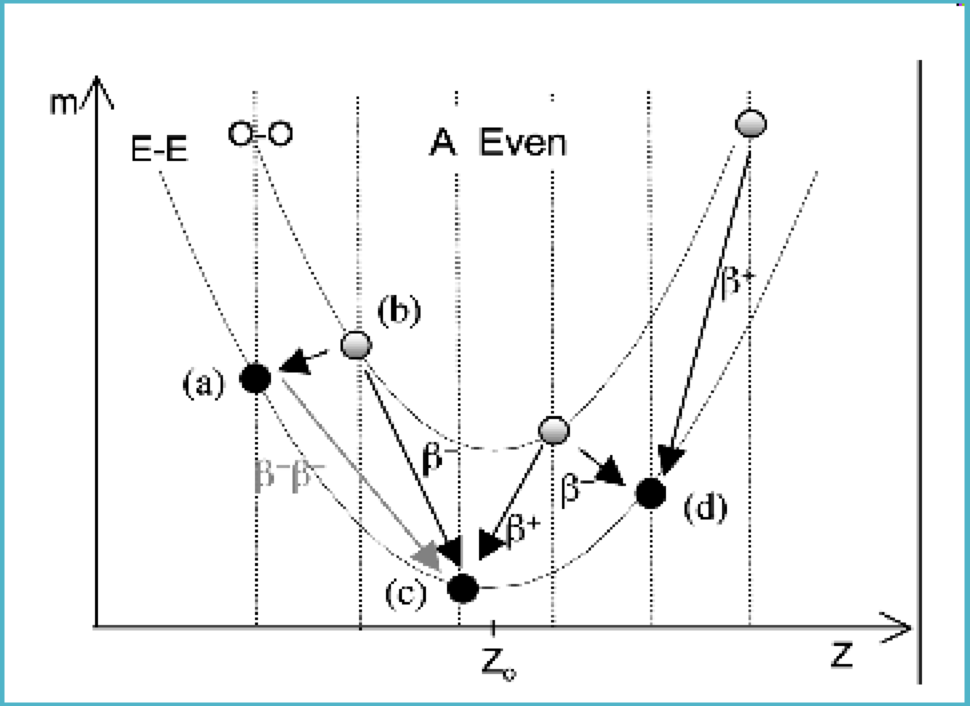
Outline

- *Introduction: Double beta decay – 2νββ, 0νββ*
- *Calculation of the nuclear matrix elements*
- *Calculation of the Phase space factors*
- *Exploration of BSM physics : constrains of BSM parameters*
- *Conclusions*

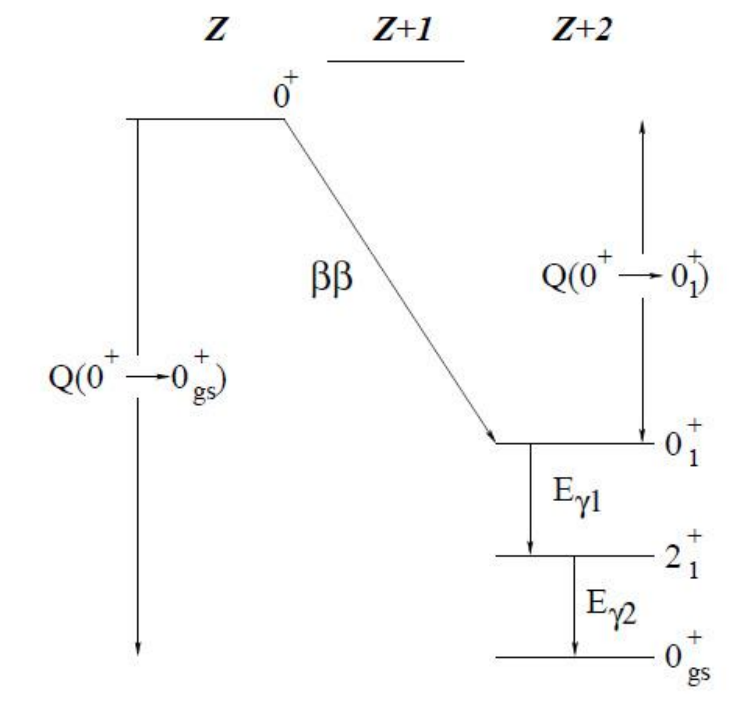
Double Beta Decay

The rarest spontaneous nuclear decay measured until now, by which an e-e nucleus transforms into another e-e nucleus with the same mass but with its nuclear charge changed by two units.

It occurs whatever single β decay can not occur due to energetical reasons or it is highly forbidden by angular momentum selection rules



(a) and **(d)** are stable against β decay, but unstable against β β decay: $\beta^-\beta^-$ for (a) and $\beta^+\beta^+$ for (d)

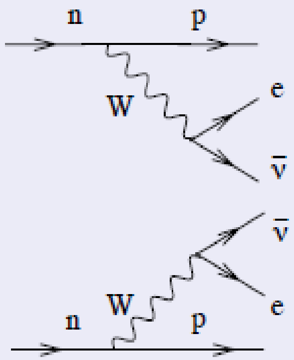


35 isotopes decaying $\beta^-\beta^-$ isotopes

Double Beta Decay processes

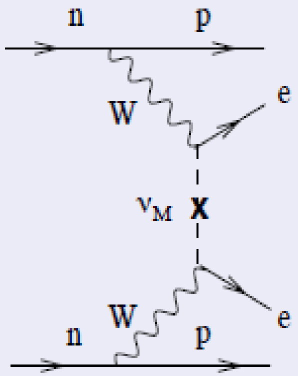
$2\nu\beta\beta$

- $(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e$
- $\Delta L = 0$
- $\left|T^{2\nu}_{1/2}\right|^{-1} = G^{2\nu}(Q_{\beta\beta},Z)\,|M_{2\nu}|^2 \sim \left|10^{20}\ \mathrm{y}\right|^{-1}$

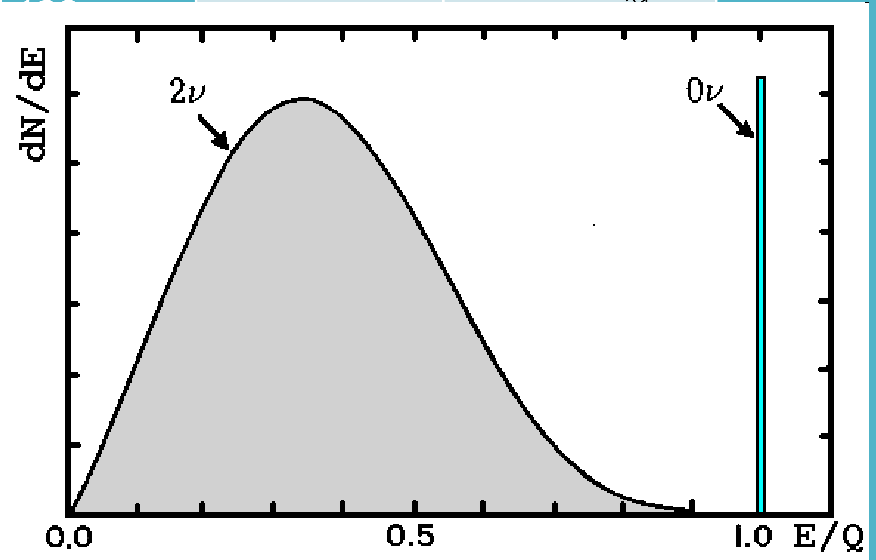


$0\nu\beta\beta$

- $(Z,A) \rightarrow (Z+2,A) + 2e^-$
- $\Delta L = 2$
- $\left|T^{0\nu}_{1/2}\right|^{-1} = G^{0\nu}(Q_{\beta\beta},Z)\,|M_{0\nu}|^2 \langle m^2_{\beta\beta}\rangle \sim \left|10^{25}\ \mathrm{y}\right|^{-1}$
- $\langle m_{\beta\beta}\rangle = \left|\sum_i U^2_{ei}\, m_i\right|$



Isotope	$Q_{\beta\beta}$ [KeV]	$T_{1/2}$ [yr]
^{48}Ca	4272	$4.40 \bullet 10^{19}$
^{76}Ge	2039	$1.65 \bullet 10^{21}$
^{82}Se	2995	$0.92 \bullet 10^{20}$
^{96}Zr	3350	$2.30 \bullet 10^{19}$
^{100}Mo	3034	$7.10 \bullet 10^{18}$
^{116}Cd	2813	$2.87 \bullet 10^{19}$
^{128}Te	866	$2.0 \bullet 10^{24}$
^{130}Te	2521	$6.90 \bullet 10^{20}$
^{136}Xe	2457	$2.19 \bullet 10^{21}$
^{150}Nd	3371	$8.20 \bullet 10^{18}$



Importance of the DBD study

Neutrino properties:	- character Dirac or Majorana? - mass scale (absolute mass) - mass hierarchy - how many flavors? Sterile neutrinos?
Check of some symmetries:	Lepton number, CP, Lorentz
Constrain beyond SM parameters:	associated with different mechanisms/scenarios that may contribute to the neutrinoless DBD occurrence

Positron emission decays

$2\nu\beta^+\beta^+$

$(A,Z) \rightarrow (A,Z-2) + 2e^+ + 2\nu$

$0\nu\beta^+\beta^+$

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

$2\nu EC\beta^+$

$(A,Z) + e^- \rightarrow (A,Z-2) + e^+ + 2\nu$

$0\nu EC\beta^+$

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

$2\nu ECEC$

$(A,Z) + 2e^- \rightarrow (A,Z-2) + 2\nu$

$0\nu ECEC$

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

0νββ decay: one of the most investigated process of physics: numerous experiments, in different stages:

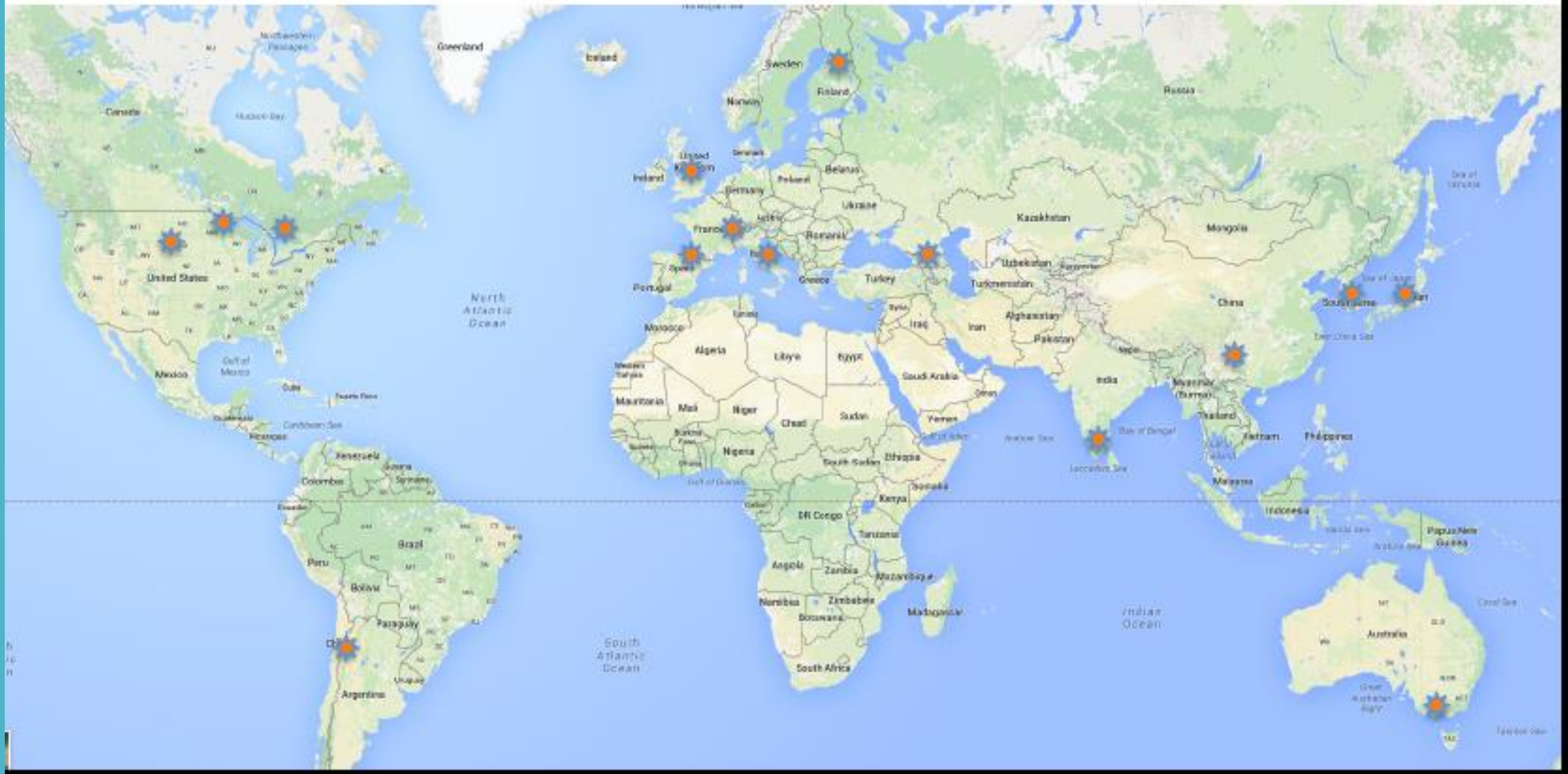
a) completed (Gotthard TPC, Heidelberg-Moscow, IGEX, NEMO1,2,3)

b) taking data (COBRA, CUORICINIO-CUORE, EXO, DCBA, GERDA, KamLAND-Zen, MAJORANA, XMASS)

c) proposed/future(CANDLES, MOON, AMoRE, LUMINEU, NEXT, SNO+, SuperNEMO, TIN.TIN)

They are running in underground laboratories and involve complex set-ups and large investments.

Underground laboratories



DBD lifetimes

2νββ $[T^{2\nu}]^{-1} = G^{2\nu}(E_0, Z) \times g_A^{\ 4} \times |m_e c^2\ M^{2\nu}|^2$

↓ ↓

$[yr^{-1}]$ $[yr^{-1}]$ dimensionless

0νββ $[T^{0\nu}]^{-1} = G^{0\nu}(E_0, Z) \times g_A^{\ 4} \times \Sigma_l\ [\ |M^{0\nu}{}_l|^2 \times <\eta_l>^2\ ]$

↓ ↓ ↓ ↓

$[yr^{-1}]$ $[yr^{-1}]$ dimensionless dimensionless

$G^{(2,0)\nu}(E_0, Z)$ phase space factors (PSF) $\Sigma_l = |M^{0\nu}|^2 (<m_\nu>/m_e)^2 + |M^{0\nu}{}_N|^2 <m_N>^2 + |M^{0\nu}{}_\lambda|^2\ <\eta_\lambda>^2 + |M^{0\nu}{}_q|^2\ <\eta_q>^2$

$M^{(2,0)\nu}$ = nuclear matrix elements (NME)

$$\langle m_\nu \rangle = \sqrt{\frac{m_e^2}{|M^{0\nu}|^2 G^{0\nu}} \left[T_{1/2}^{0\nu}\left(0_i^+ \to 0_f^+\right)\right]^{-1}}$$

$<\eta_l>$ = BSM parameter depending on the scenario by which 0νββ may occur

g_A = axial-vector constant

Challenging issues in double beta decay

1) **Theoretical :** - accurate calculation of the NME (a long standing problem, not yet resolved in spite of much progress) and PSF
- extraction of the information regarding the ν mass, mass hierarchy, etc.
- models for the 0νββ decay mechanisms, constrain BSM parameters

2) **Experimental:** - accurate measurements of 2νββ decay, including transitions to excited states, study of electron spectra, etc.
- search for 0νββ decay: improvements of experimental set-ups and techniques → large isotopically enriched sources; the reducing of background; detectors with high energy resolution, improved techniques of detection, etc.

- determination of the 0νββ decay mechanisms

Calculation of the nuclear matrix elements

2νββ

$$M_{GT}^{2\nu} = \sum_j \frac{\left\langle 0_f^+ | t_-\sigma || 1_j^+ \right\rangle \left\langle 1_j^+ || t_-\sigma | o_i^+ \right\rangle}{E_j + Q/2 + m_e - E_i}$$

0νββ

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

a) pnQRPA (different versions)

b) interacting Shell model (ISM)

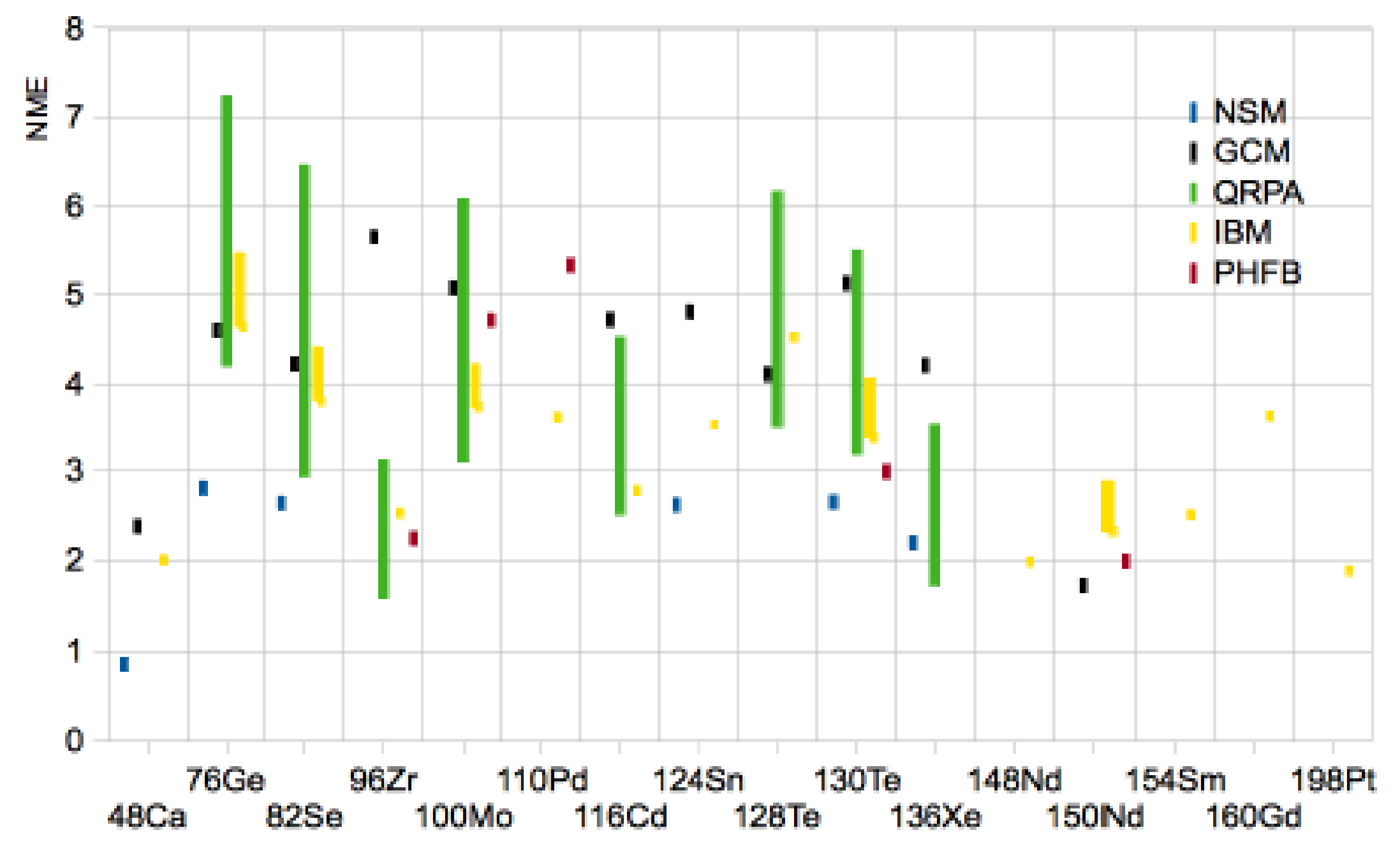
c) IBM-2

d) Generator coordinate method

e) Projected HFB

Origin of differences

- many-body theory (correlations)
- single-particle model space
- effective NN interaction
- Nuclear (input) parameters
  g_A , R, <E>, nuclear form factors


NME
0
1
2
3
4
5
6
7
8
48Ca
76Ge
82Se
96Zr
100Mo
110Pd
116Cd
124Sn
128Te
130Te
136Xe
148Nd
150Nd
154Sm
160Gd
198Pt
NSM
GCM
QRPA
IBM
PHFB

ShM calculations

Fast numerical code for computing the TBME

Horoi, Stoica, PRC81(2010); Neacsu, Stoica, Horoi, PRC 86(2012), Neacsu, Stoica, JPG 41(2014)

$$M_\alpha^{0\nu} = \sum_{j_p j_{p'} j_n j_{n'} J_\pi} \mathrm{TBTD}(j_p j_{p'}, j_n j_{n'}; J_\pi) \langle j_p j_{p'}; J_\pi \| \tau_{-1} \tau_{-2} O_{12}^\alpha \| j_n j_{n'}; S_\alpha J_\pi \rangle$$

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

The most difficult is the computation of radial part of $M^{0\nu}$ which contains ν potentials

$$\langle nl | H_\alpha | n'l' \rangle$$

$$H_\alpha(r) = \frac{2R}{\pi} \int_0^\infty j_i(qr) \frac{h_\alpha(q)}{\omega} \frac{1}{\omega + \langle E \rangle} q^2 \, \mathrm{d}q$$

Ingredients, which may differ from one computation to another:

SRC $\psi_{nl}(r) \rightarrow [1 + f(r)] \psi_{nl}(r)$

$$f(r) = -c \cdot \mathrm{e}^{-ar^2} (1 - br^2)$$

FNS $G_A(q^2) = g_A \left(\frac{\Lambda_A^2}{\Lambda_A^2 + q^2} \right)^2$

$$G_V(q^2) = g_V \left(\frac{\Lambda_V^2}{\Lambda_V^2 + q^2} \right)^2$$

$$\langle nl|H_\alpha(r)|n'l'\rangle = \int_0^\infty r^2\,\mathrm{d}r\,\psi_{nl}(r)\psi_{n'l'}(r)[1+f(r)]^2 \times \int_0^\infty q^2\,\mathrm{d}q V_\alpha(q) j_n(qr)$$

$$\langle nl|H_\alpha(r)|n'l'\rangle = \sum_{s=0}^{n+n'} A_{l+l'+2s}(nl,n'l')\mathcal{K}_\alpha(m)$$

This procedure reduces substantially the CPU time: ~ with a factor of 30 as compared with our older ShM code from ref. PRC81 (2010)

Other ingredients: the effective NN interaction(GXPF1A, KB3, GN28, GN50, etc.)

Input parameters: $R = r_0A^{1/3}$ (r_0 = 1.1, or 1.2 fm), $<E_N>$ = closure energy, g_A = 1.0, 1.25, 1.264, 1.272

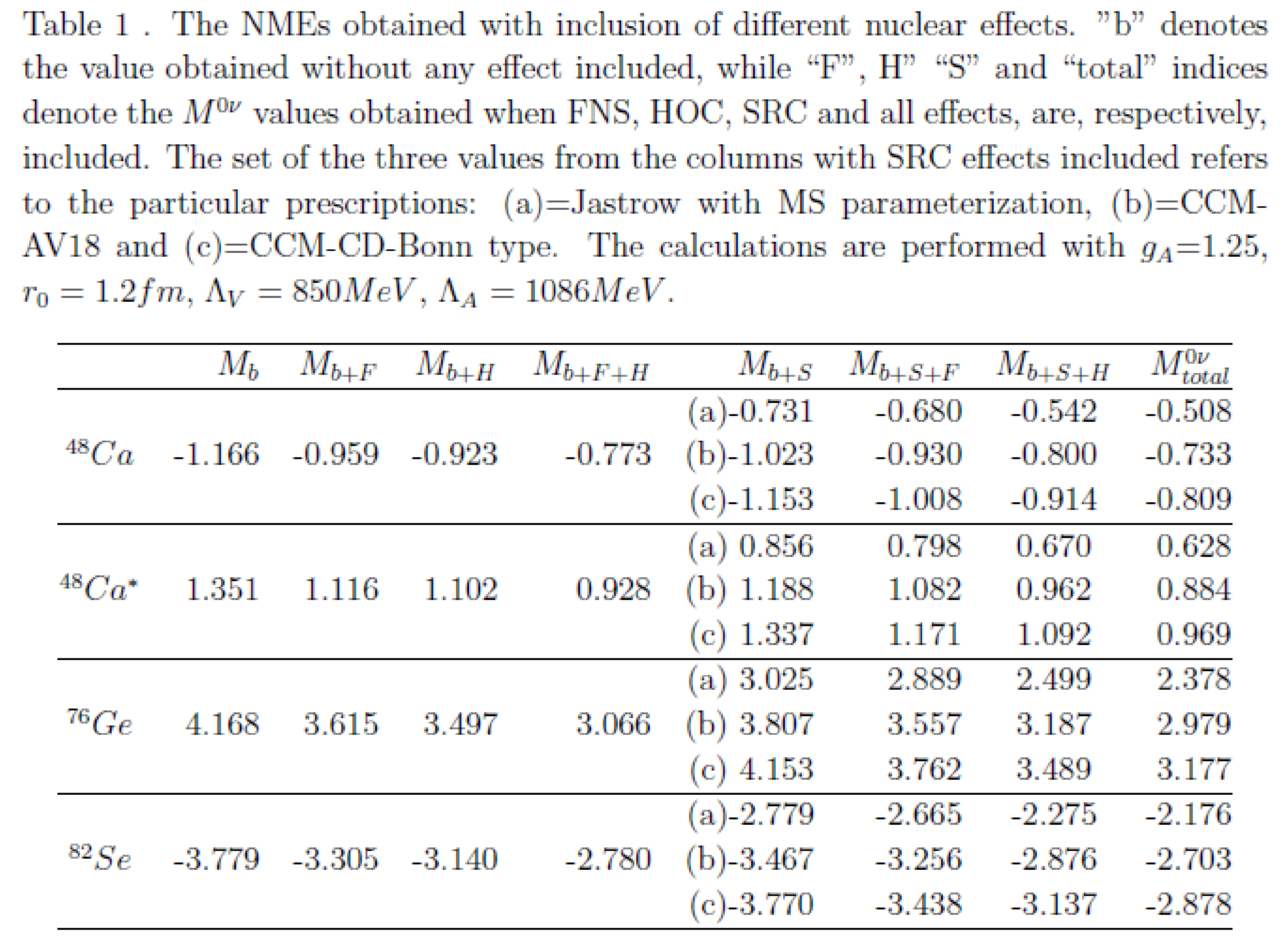


Table 1 . The NMEs obtained with inclusion of different nuclear effects. ”b” denotes the value obtained without any effect included, while “F”, H” “S” and “total” indices denote the $M^{0\nu}$ values obtained when FNS, HOC, SRC and all effects, are, respectively, included. The set of the three values from the columns with SRC effects included refers to the particular prescriptions: (a)=Jastrow with MS parameterization, (b)=CCM-AV18 and (c)=CCM-CD-Bonn type. The calculations are performed with g_A=1.25, $r_0 = 1.2fm$, $\Lambda_V = 850MeV$, $\Lambda_A = 1086MeV$.

	M_b	M_{b+F}	M_{b+H}	M_{b+F+H}	M_{b+S}	M_{b+S+F}	M_{b+S+H}	$M^{0\nu}_{total}$
^{48}Ca	-1.166	-0.959	-0.923	-0.773	(a)-0.731	-0.680	-0.542	-0.508
					(b)-1.023	-0.930	-0.800	-0.733
					(c)-1.153	-1.008	-0.914	-0.809
$^{48}Ca^*$	1.351	1.116	1.102	0.928	(a) 0.856	0.798	0.670	0.628
					(b) 1.188	1.082	0.962	0.884
					(c) 1.337	1.171	1.092	0.969
^{76}Ge	4.168	3.615	3.497	3.066	(a) 3.025	2.889	2.499	2.378
					(b) 3.807	3.557	3.187	2.979
					(c) 4.153	3.762	3.489	3.177
^{82}Se	-3.779	-3.305	-3.140	-2.780	(a)-2.779	-2.665	-2.275	-2.176
					(b)-3.467	-3.256	-2.876	-2.703
					(c)-3.770	-3.438	-3.137	-2.878

Study of the effect of different nuclear ingredients on NMEs

- their overall effect is to decrease the NME values

- SRC inclusion: J-MS prescription decreases significantly the NME value as compared with softer CCM prescriptions.

- however, NME values calculated with inclusion of only SRC by J-MS prescription, are close (within 10%) to the values calculated with SRC by CCM prescriptions and with the inclusion of other nuclear ingredients (FNS+HOC)→ a kind a compensation effect

- inclusion of HOC is important → correction up to ~ 20%

- tensor component: contribution of (4-9)% (has to be taken with correct sign)

- dependence of NN interactions: up to 17%

- dependence on input nuclear parameters:

  axial vector coupling constant g_A quenched/un-quenched – the largest uncertainty

  nuclear radius; $R = r_0 A^{1/3}$ (r_0=1.1fm or 1.2fm) ~ 7%

  nuclear form factors (Λ_A, Λ_V) ~ 8%;

  average energy used in closer approx. <E> - negligible

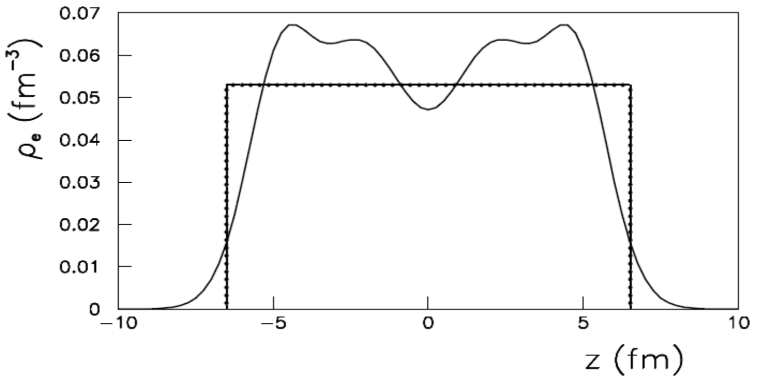
Calculation of the phase space factors for DBD

$$G^{\beta\beta}_{2\nu}(0^+ \rightarrow 0^+) = \frac{2\tilde{A}^2}{3\ln 2 g_A^4 (m_e c^2)^2} \int_{m_e c^2}^{Q^{\beta\beta}+m_e c^2} d\epsilon_1 \int_{m_e c^2}^{Q^{\beta\beta}+2m_e c^2-\epsilon_1} d\epsilon_2 \int_0^{Q^{\beta\beta}+2mc_e^2-\epsilon_1-\epsilon_2} d\omega_1 f_{11}^{(0)} w_{2\nu}(\langle K_N\rangle^2+\langle L_N\rangle^2+\langle K_N\rangle\langle L_N\rangle)$$

$$G^{\beta\beta}_{0\nu}(0^+ \rightarrow 0^+) = \frac{2}{4g_A^4 R_A^2 \ln 2} \int_{m_e c^2}^{Q^{\beta\beta}+m_e c^2} f_{11}^{(0)} w_{0\nu} d\epsilon_1$$

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

$$f^{-1-1} = g_{-1}(\epsilon_1)g_{-1}(\epsilon_2)\ ;\ f_{11} = f_1(\epsilon_1)f_1(\epsilon_2),$$
$$f^{-1}{}_1 = g_{-1}(\epsilon_1)f_1(\epsilon_2)\ ;\ f_1{}^{-1} = f_1(\epsilon_1)g_1(\epsilon_2)$$



$$\frac{dg_\kappa(\epsilon,r)}{dr} = -\frac{\kappa}{r}g_\kappa(\epsilon,r) + \frac{\epsilon - V + m_e c^2}{c\hbar}f_\kappa(\epsilon,r)$$
$$\frac{df_\kappa(\epsilon,r)}{dr} = -\frac{\epsilon - V - m_e c^2}{c\hbar}g_\kappa(\epsilon,r) + \frac{\kappa}{r}f_\kappa(\epsilon,r)$$

$$V(Z,r) = \begin{cases} -\frac{Z\alpha\hbar c}{r}, & r \geq R_A \\ -Z(\alpha\hbar c)\left(\frac{3-(r/R_A)^2}{2R_A}\right), & r < R_A \end{cases}$$

$$V(r) = \alpha\hbar c \int \frac{\rho_e(\vec{r'})}{\mid \vec{r} - \vec{r'} \mid} d\vec{r'}$$

$$\rho_e(\vec{r}) = 2\sum_i v_i^2 \mid \Psi_i(\vec{r}) \mid^2$$

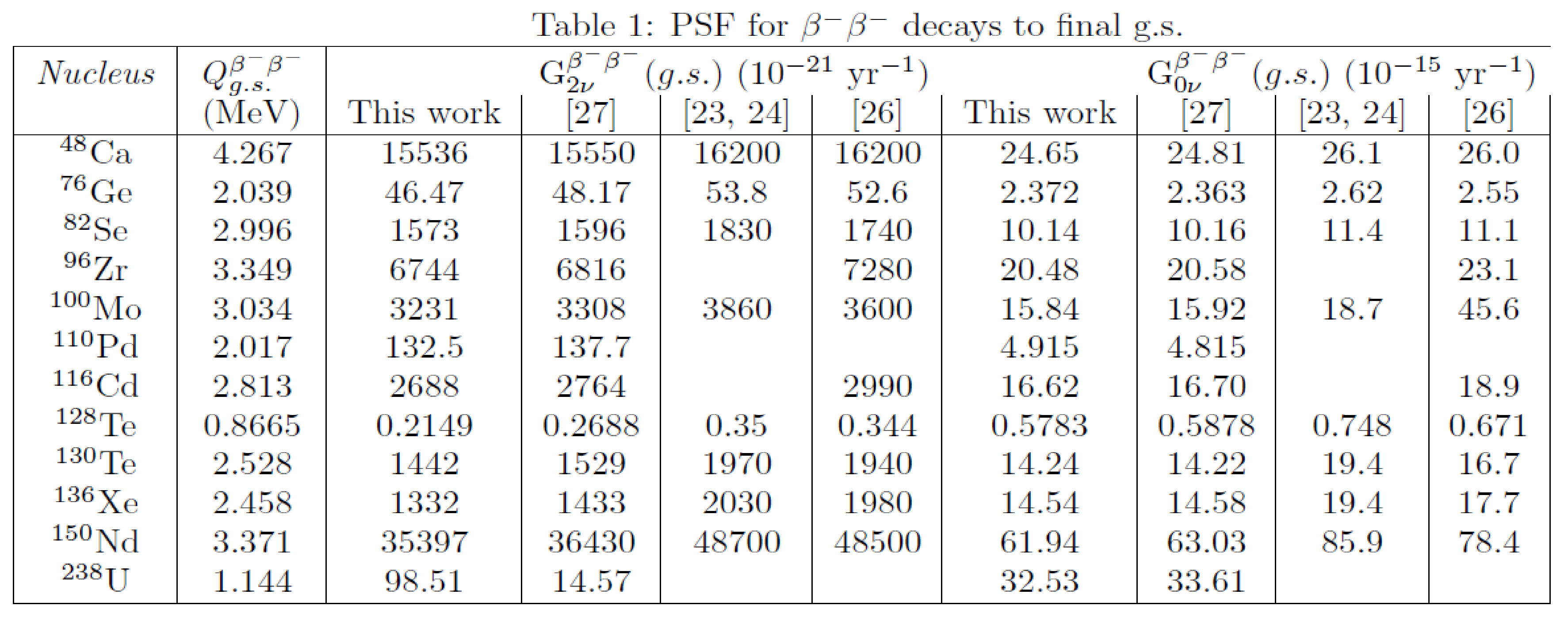
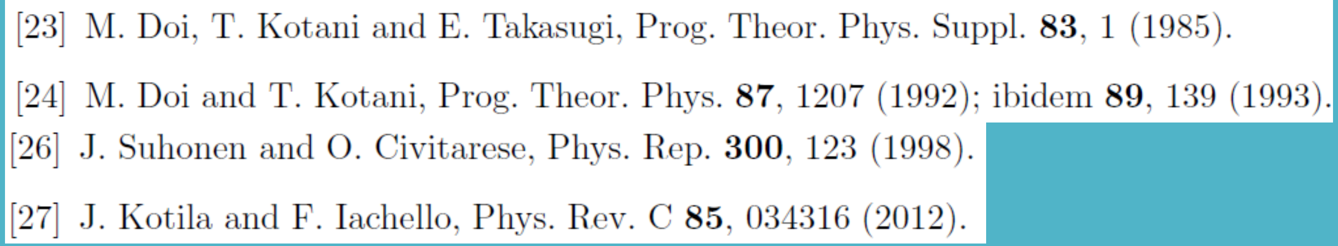


Table 1: PSF for $\beta^-\beta^-$ decays to final g.s.

Nucleus	$Q^{\beta^-\beta^-}_{g.s.}$ (MeV)	$G^{\beta^-\beta^-}_{2\nu}$ $(g.s.)$ $(10^{-21}$ yr$^{-1})$ This work	[27]	[23, 24]	[26]	$G^{\beta^-\beta^-}_{0\nu}$ $(g.s.)$ $(10^{-15}$ yr$^{-1})$ This work	[27]	[23, 24]	[26]
^{48}Ca	4.267	15536	15550	16200	16200	24.65	24.81	26.1	26.0
^{76}Ge	2.039	46.47	48.17	53.8	52.6	2.372	2.363	2.62	2.55
^{82}Se	2.996	1573	1596	1830	1740	10.14	10.16	11.4	11.1
^{96}Zr	3.349	6744	6816		7280	20.48	20.58		23.1
^{100}Mo	3.034	3231	3308	3860	3600	15.84	15.92	18.7	45.6
^{110}Pd	2.017	132.5	137.7			4.915	4.815		
^{116}Cd	2.813	2688	2764		2990	16.62	16.70		18.9
^{128}Te	0.8665	0.2149	0.2688	0.35	0.344	0.5783	0.5878	0.748	0.671
^{130}Te	2.528	1442	1529	1970	1940	14.24	14.22	19.4	16.7
^{136}Xe	2.458	1332	1433	2030	1980	14.54	14.58	19.4	17.7
^{150}Nd	3.371	35397	36430	48700	48500	61.94	63.03	85.9	78.4
^{238}U	1.144	98.51	14.57			32.53	33.61		



[23] M. Doi, T. Kotani and E. Takasugi, Prog. Theor. Phys. Suppl. **83**, 1 (1985).

[24] M. Doi and T. Kotani, Prog. Theor. Phys. **87**, 1207 (1992); ibidem **89**, 139 (1993).

[26] J. Suhonen and O. Civitarese, Phys. Rep. **300**, 123 (1998).

[27] J. Kotila and F. Iachello, Phys. Rev. C **85**, 034316 (2012).

– very good agreement with [27] both for $G^{2\nu}$ and $G^{0\nu}$ for the majority of nuclei
exceptions: 128Te(~20%) and 238U(factor of 7)

- in comparison with older calculations there are some notable differences

Stoica, Neacsu, AHEP 2014

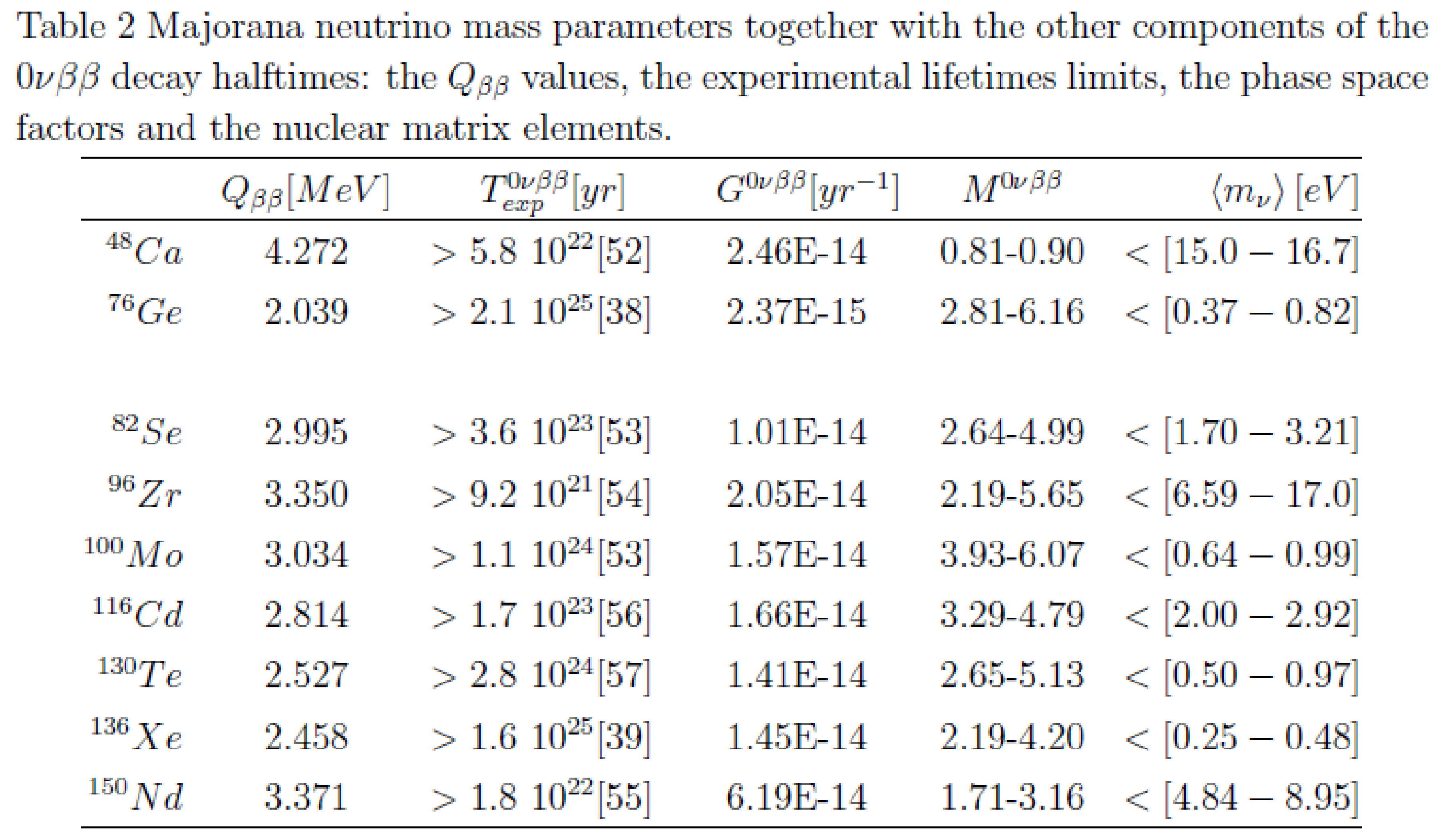
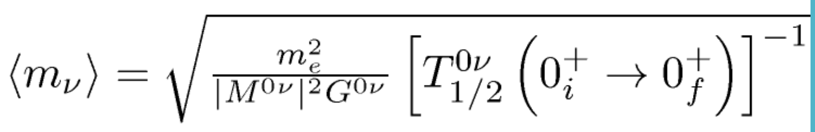


Table 2 Majorana neutrino mass parameters together with the other components of the $0\nu\beta\beta$ decay halftimes: the $Q_{\beta\beta}$ values, the experimental lifetimes limits, the phase space factors and the nuclear matrix elements.

	$Q_{\beta\beta}[MeV]$	$T^{0\nu\beta\beta}_{exp}[yr]$	$G^{0\nu\beta\beta}[yr^{-1}]$	$M^{0\nu\beta\beta}$	$\langle m_\nu \rangle$ $[eV]$
^{48}Ca	4.272	$> 5.8\ 10^{22}[52]$	2.46E-14	0.81-0.90	$< [15.0 - 16.7]$
^{76}Ge	2.039	$> 2.1\ 10^{25}[38]$	2.37E-15	2.81-6.16	$< [0.37 - 0.82]$
^{82}Se	2.995	$> 3.6\ 10^{23}[53]$	1.01E-14	2.64-4.99	$< [1.70 - 3.21]$
^{96}Zr	3.350	$> 9.2\ 10^{21}[54]$	2.05E-14	2.19-5.65	$< [6.59 - 17.0]$
^{100}Mo	3.034	$> 1.1\ 10^{24}[53]$	1.57E-14	3.93-6.07	$< [0.64 - 0.99]$
^{116}Cd	2.814	$> 1.7\ 10^{23}[56]$	1.66E-14	3.29-4.79	$< [2.00 - 2.92]$
^{130}Te	2.527	$> 2.8\ 10^{24}[57]$	1.41E-14	2.65-5.13	$< [0.50 - 0.97]$
^{136}Xe	2.458	$> 1.6\ 10^{25}[39]$	1.45E-14	2.19-4.20	$< [0.25 - 0.48]$
^{150}Nd	3.371	$> 1.8\ 10^{22}[55]$	6.19E-14	1.71-3.16	$< [4.84 - 8.95]$



$$\langle m_\nu \rangle = \sqrt{\frac{m_e^2}{|M^{0\nu}|^2 G^{0\nu}} \left[T^{0\nu}_{1/2} \left(0_i^+ \to 0_f^+ \right) \right]^{-1}}$$

Calculation of products PSF x NME

$$P^{2\nu} = G^{2\nu} \times |m_e c^2 M^{2\nu}|^2$$

$$[T^{2\nu}]^{-1} = (g^{2\nu}_{A,eff})^4 \times P^{2\nu}$$

$$P^{0\nu} = G^{0\nu} \times |M^{0\nu}_l|^2$$

$$[T^{0\nu}]^{-1} = (g^{0\nu}_{A,eff})^4 \times P^{0\nu} \times < \eta_l >$$

$$[T^{2\nu}] = [(g^{2\nu}_{A,eff})^4_m / (g^{2\nu}_{A,eff})^4_n] \times [P^{2\nu}_m / P^{2\nu}_n] \times [T^{2\nu}]_m$$

$$[T^{0\nu}] = [(g^{0\nu}_{A,eff})^4_m / (g^{0\nu}_{A,eff})^4_n] \times [P^{0\nu}_m / P^{0\nu}_n] \times [T^{0\nu}]_m$$

Nucleus	$T^{2\nu}$ [yr]	$P^{2\nu}$ [yr^{-1}]	$T^{0\nu}$ [yr]	$P_{\nu}^{0\nu}$ [yr^{-1}]
^{48}Ca	6.40×10^{19} [1]	123.81×10^{-21} $g_{A,eff} = 0.65/0.71$th[8]	$> 2.0 \times 10^{22}$ [1]	16.13×10^{-15}
^{76}Ge	1.92×10^{21} [2]	5.16×10^{-21} $g_{A,eff} = 0.56/0.60$th[7]	$> 5.3 \times 10^{25}$ [3]	23.94×10^{-15}
^{82}Se	0.92×10^{20} [2]	186.62×10^{-21} $g_{A,eff} = 0.49/0.60$th[7]	$> 3.6 \times 10^{23}$ [9]	83.99×10^{-15}
^{130}Te	8.20×10^{20} [4]	25.26×10^{-21} $g_{A,eff} = 0.47/0.57$th[7]	$> 4.0 \times 10^{24}$ [5]	64.00×10^{-15}
^{136}Xe	2.16×10^{21}[1]	20.30×10^{-21} $g_{A,eff} = 0.45/0.39$th[7]	$> 1.1 \times 10^{25}$ [6]	44.11×10^{-15}

[1] NEMO3, PRD **93**(2016); [2] Patrignani, C. et al. (PDG), China Phys. C **40**(2016);
[3] *GERDA II,* Nature, **544**(2017)*;* [4] CUORE, EPJ C **77**(2017) ; [5] CUORE, PRL**115** (2015);
[6] EXO, *Nature. **510**, 229 (2014)*; [7]Caurier, PLB**71**(2012); [8]Iwata et al., PRL**116**(2016);
[9] V.I. Tretyak, NEMO3, AIP Conf.Proc. 1417,125 (2011).

DBD potential to explore BSM physics

- Check of lepton number conservation (LNC): if $0\nu\beta\beta$ is discovered ➔ $\Delta L = 2$; still the most sensitive process

- Neutrino properties: Dirac or Majorana; still the most sensitive process

  limits for $m_{\nu e}$
  sterile $\nu_s \rightarrow$ limits for m_N
  hints for neutrino mass hierarchy

- Other BSM parameters : Majoron existence, SUSY particles, L-R theories, existence of RH currents in the WI

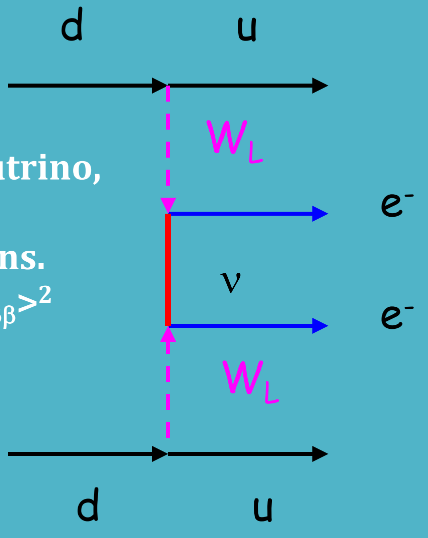
LNV: $(A, Z) \rightarrow (A, Z + 2) + 2\,e^- ;\ \Delta L = 2$

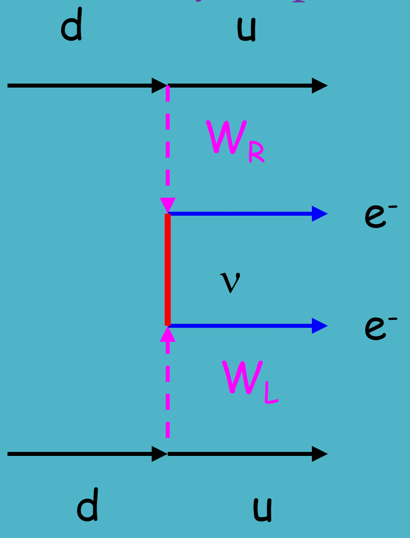
BSM parameters: $|T^{0\nu}|^{-1} = G^{0\nu}(E_0, Z) \times g_A^{\ 4} \times (|M^{0\nu}|^2 <m_\nu>^2 + |M^{0\nu}{}_N|^2 <m_N>^2 + |M^{0\nu}{}_\lambda|^2 <\eta_\lambda>^2 + |M^{0\nu}{}_q|^2 <\eta_q>^2)$

0νββ provides a broader potential to search for beyond SM physics: any ΔL=2 process can contribute to 0νββ

Diagrams that can contribute to the 0nbb decay amplitude

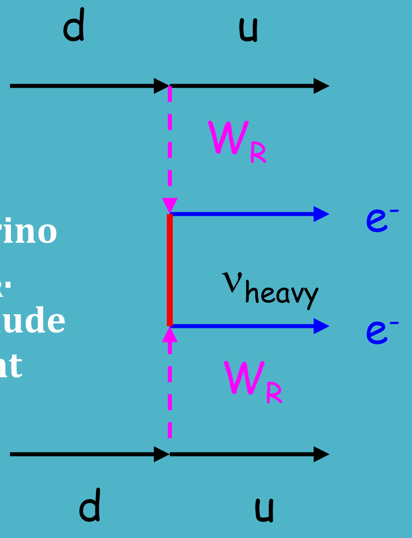
Light Majorana neutrino, only SM LH weak interactions. Decay rate ~$\langle m_{\beta\beta}\rangle^2$

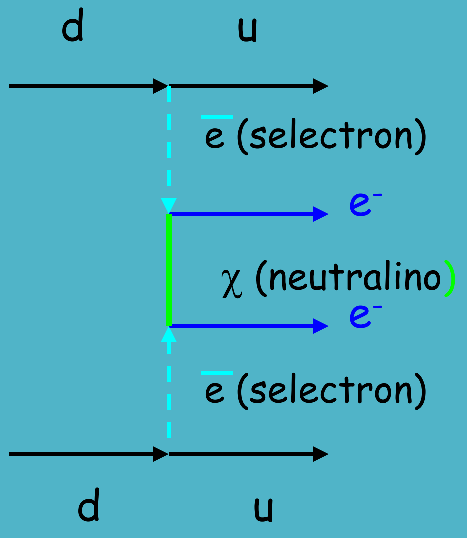




Light Majorana neutrinos. Model extended to include right-handed W_R. Mixing extended between the left and right-handed neutrinos. This is the mode where the rate ~λ^2 or η^2

Heavy Majorana neutrino interacting with W_R. Model extended to include right-handed current interactions.





Supersymmetry with R-parity violation. Many new particles invoked.

Results on neutrino mass and SUSY constraints

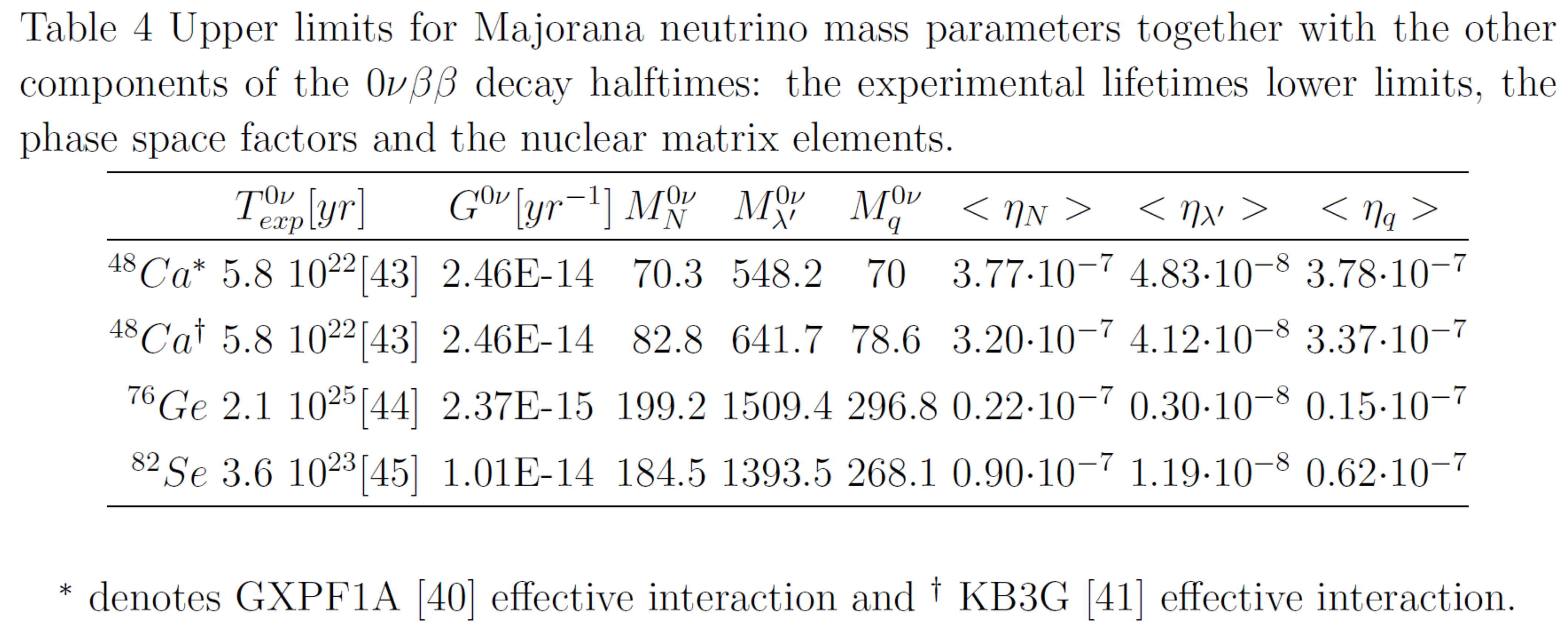


Table 4 Upper limits for Majorana neutrino mass parameters together with the other components of the $0\nu\beta\beta$ decay halftimes: the experimental lifetimes lower limits, the phase space factors and the nuclear matrix elements.

	$T^{0\nu}_{exp}[yr]$	$G^{0\nu}[yr^{-1}]$	$M^{0\nu}_N$	$M^{0\nu}_{\lambda'}$	$M^{0\nu}_q$	$< \eta_N >$	$< \eta_{\lambda'} >$	$< \eta_q >$
$^{48}Ca^*$	$5.8\ 10^{22}$[43]	2.46E-14	70.3	548.2	70	$3.77\cdot10^{-7}$	$4.83\cdot10^{-8}$	$3.78\cdot10^{-7}$
$^{48}Ca^\dagger$	$5.8\ 10^{22}$[43]	2.46E-14	82.8	641.7	78.6	$3.20\cdot10^{-7}$	$4.12\cdot10^{-8}$	$3.37\cdot10^{-7}$
^{76}Ge	$2.1\ 10^{25}$[44]	2.37E-15	199.2	1509.4	296.8	$0.22\cdot10^{-7}$	$0.30\cdot10^{-8}$	$0.15\cdot10^{-7}$
^{82}Se	$3.6\ 10^{23}$[45]	1.01E-14	184.5	1393.5	268.1	$0.90\cdot10^{-7}$	$1.19\cdot10^{-8}$	$0.62\cdot10^{-7}$

* denotes GXPF1A [40] effective interaction and † KB3G [41] effective interaction.

Lorentz violation in weak decays

- LV can also be investigated in β and ββ decays

- The general framework characterizing LV is the Standard Model Extension (SME)
- In minimal SME (operators dimension ≤ 4) there are operators that couples to ν_s and affect ν flavor oscillations, ν velocity or ν phase spaces (β, ββ decays)

- Until now, the most precise tests for LV involving ν_s are perform in ν oscillation experiments., but now deviations to Lorentz symmetry can be investigated in DBD experiments like EXO and NEMO3.

- There is a q-independent operator (countershaded operator), that doesn't affect ν oscillations, and hence can not be detected in LBL neutrino experiments, but can affect the electron energy sum spectrum or the one electron spectra (angular correlation) for experiments with tracking systems that can reconstruct the direction of the two emitted electrons.

The coupling of the ν to the countershaded operator modifies the neutrino momentum from the standard expression.

This, further, modifies the *2νββ transition amplitude, so the decay rate can be written as a sum of the standard term and a perturbation due to LVββ*

$\Gamma^{(2\nu)} = \Gamma_0^{(2\nu)} + d\Gamma^{(2\nu)}$

$\Gamma_0^{(2\nu)} = G_0^{2\nu}(E_0, Z) \text{ x } g_A^4 \text{ x } |m_e c^2 M^{2\nu}|^2$

$d\Gamma^{(2\nu)} = dG^{2\nu}(E_0, Z) \text{ x } g_A^4 \text{ x } |m_e c^2 M^{2\nu}|^2$

$G_0^{2\nu} = C \int_0^Q d\varepsilon_1 F(Z, \varepsilon_1) [\varepsilon_1(\varepsilon_1 +2)]^{1/2} (\varepsilon_1 +1) \int_0^{Q-\varepsilon 1} d\varepsilon_2 F(Z, \varepsilon_2) [\varepsilon_2(\varepsilon_2 +2)]^{1/2} (\varepsilon_2 +1)(Q- \varepsilon_1- \varepsilon_2)^5$

$dG^{2\nu} = 10å^{(3)}{}_{of}\, C \int_0^Q d\varepsilon_1 F(Z, \varepsilon_1) [\varepsilon_1(\varepsilon_1 +2)]^{1/2} (\varepsilon_1 +1) \int_0^{Q-\varepsilon 1} d\varepsilon_2 F(Z, \varepsilon_2) [\varepsilon_2(\varepsilon_2 +2)]^{1/2} (\varepsilon_2 +1)(Q- \varepsilon_1- \varepsilon_2)^4$

$C = (G_F{}^4 (\cos_\theta)^4 m_e)/240\pi^7$ $t_{1,2} = \varepsilon_{1,2} -1;$ J.S. Diaz, PRD**89**(2014), EXO collab., arXiv:1601.07266v2[nucl-ex]

$G_0^{2\nu}$, $dG^{2\nu}$ can be calculated in different approximations:

- $F(Z, \varepsilon) = (2\pi y)[1-\exp(- 2\pi y)]^{-1}$, $y = \pm\alpha Z\varepsilon/q$, Primakoff&Rosen, RPP**22**(1959)
- $F(Z, \varepsilon) = 4(2qR_A)^{2(\gamma-1)} |\Gamma(\gamma+iy)|^2\exp(\pi y) |\Gamma(2\gamma+1)|^{-2}$ Suhonen&Civitarese, PR**301**(1998)
- using exact electron functions obtained by solving Dirac equations Iachello,PRC**85**2012; Stoica, PRC**88**(2013); RRP63(2015)

Classification of the LNV processes

a) $dd \rightarrow uu\, W^{*-}W^{*-} \rightarrow uu\, e^-e^-$: $0\nu\beta\beta$

b) $\Sigma^- \rightarrow \Sigma^+ e^-e^-$; $\Xi^- \rightarrow p\, \mu^-\, \mu^-$: **hyperon decays**

$\Xi^+_{\mathbf{c}} \rightarrow \Xi$- $p\, \mu^+\, \mu^+$; $\Lambda_c^+ \rightarrow \Sigma^-\, \mu^+\, \mu^+$

c) $\tau^- \rightarrow l^+ M^-_1 M^-_2$ $\tau^- \rightarrow \mu^+\mu^-\mu^-$: **tau decays**

d) $M^\pm_1 \rightarrow l^\pm_1\, l^\pm_2\, M^{-/+}_2$: **rare meson decays (B, D, K,..)**

e) $t \rightarrow b\, l^+_1\, l^+_2\, W^-\, W^-$: **top-quark decay**

f) $pp \rightarrow l^+_1\, l^+_2\, X$: **same sign dileptonic production**

g) $H^{\pm\pm} \rightarrow l^\pm_1\, l^\pm_2\, X$: **double-charged Higgs decays**

Conclusions

- There is an extensive theoretical and experimental effort for studying DBD process, particularly the 0νββ decay mode.

- The interest comes from the information that this process can provide about fundamental properties of neutrinos, conservation of some symmetries (LNC, CP, LV) and strength of BSM parameters associated with possible scenarios of occurrence of 0uββ decay mode

- Theoretically the effort is focused to the accurately computation of the NME and PSF, mainly for 0νββ decay, and for understanding the mechanism of its occurrence

- The NME and PSF calculations enter now into a precision era and the goal is to provide experimentalists with values of these quantities within 30% errors. A progress could also come from the calculation at once the products NME x PSF.

- DBD study has a large potential to explore BSM physics

- DBD provides complementary information to that from neutrino physics (regarding neutrino properties) and HEP (LNV processes, sterile neutrinos, etc.)