Theoretical challenges in Double Beta Decay

Sabin Stoica

Horia Hulubei National Institute of Physics and Nuclear Engineering

Horia Hulubei Foundation

Outline

- ***Introduction: neutrino properties***
- ***Double beta decay – 2νββ, 0νββ***
- ***Calculation of the nuclear matrix elements***
- ***Calculation of the phase space factors***
- ***Results: NME, PSF, neutrino parameters***
- ***Connections with BSM physics***
- ***Neutrinoless decays at high energy (analysis at LHC/LHCb-CERN)***
- ***Conclusions***

Introduction

- **Neutrinos** play a key role in many physical processes from nuclear and particle physics, astrophysics and cosmology. In the same time, ν fundamental properties, like their absolute mass, their character (are they Dirac or Majorana particles?), mass hierarchy, the number of neutrino flavors, etc., are still unknown
- **Understanding ν properties** → deciphering of important issues: baryon asymmetry, DM composition (massive neutrinos are suitable candidates), stellar evolution, nucleosynthesis, BSM processes
- **Major discovery**: neutrinos oscillate and mix: this enters in conflict with the original SM formulation (*ν are* massless particles) and represented the first compelling exp. evidence for the incompleteness of the SM
- **Neutrino physics**: a priority domain of research→ one expects significant discoveries in the next future.
- **DBD-*0νββ***, a BSM process that occurs with LNV, is very appealing for investigating *ν properties*, since is able to decide on the *ν character(* Dirac or Majorana) and can provide info on the *ν* absolute mass and hierarchy, generating mechanism, existence of sterile *ν* etc.
- **LHC experiments** can analyze LNV processes at HE, with competitive sensitivity, providing same type of info
- **Study** of LNV processes opens an interesting direction of investigation at CERN.

Neutrino mixing matrix: Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

Relates weak states $\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$ with mass states

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

"Atmospheric" "Reactor" "Solar" "0νββ"

Neutrino properties: present status

What we know

- Neutrinos oscillate, have a mass and mix
- Squared mass differences between eigenstates
- Mixing angles (θ_{12}, θ_{23}, θ_{13} (?))

$\Delta m^2_{12} = \Delta m^2_{sol}$ ~ 7.58×10^{-5} eV^2;

$\tan^2 \theta_{12}$~0.484 → θ_{12}~35^0 : Solar experiments + KamLAND (r)

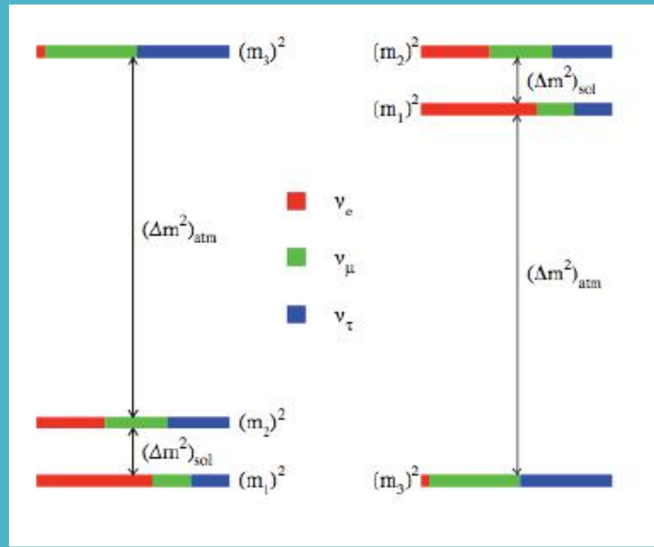
$|\Delta m^2_{32}| = \Delta m^2_{atm}$ ~ 2.40×10^{-3} eV^2;

$\sin^2 2\theta_{23}$~1.02 → θ_{23}~45^0 : Atm. expt. + K2K (r) + MINOS (acc)

$\sin^2 2\theta_{13}$ ~ 0.092; θ_{13} ~ 8.8^0: Daya Bay experiment (r)

Other measurements: Double-Chooz, T2K, RENO,…

Hierarchical mass schemes



normal **inverted**

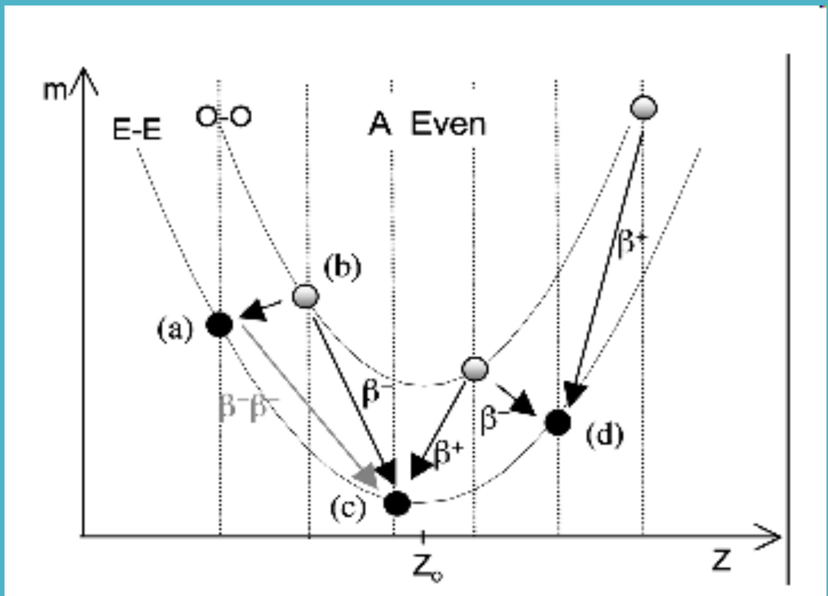
What we still do not know

- Mass scale and generating mechanism
- Mass hierarchy
- Majorana vs. Dirac
- Sterile neutrino(s)?
- CP violation in the lepton sector
- What is the SM extension responsible for m_ν?

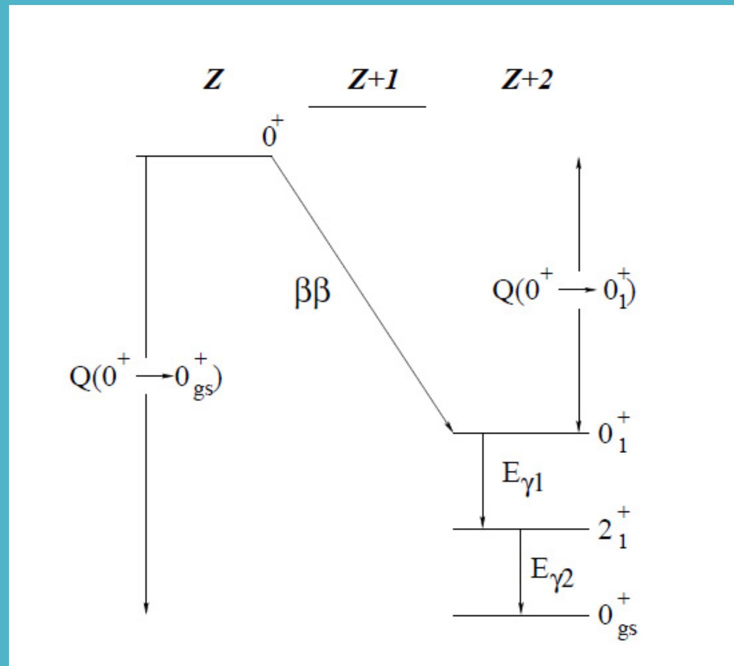
Double Beta Decay

The rarest spontaneous nuclear decay measured until now, by which an e-e nucleus transforms into another e-e nucleus 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 ββ decay: $\beta^-\beta^-$ for (a) and $\beta^+\beta^+$ for (d)

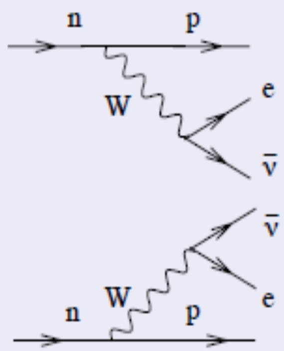


There are 35 ββ isotopes in nature

Double Beta Decay

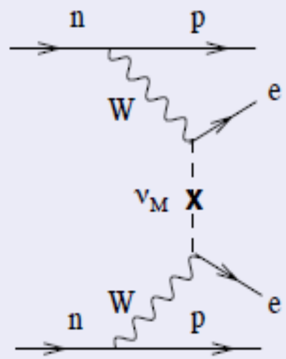
$2\nu\beta\beta$

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



$0\nu\beta\beta$

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



Positron decays

2νβ⁺β⁺

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

0νβ+β+

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

2νECβ⁺

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

0νECβ+

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

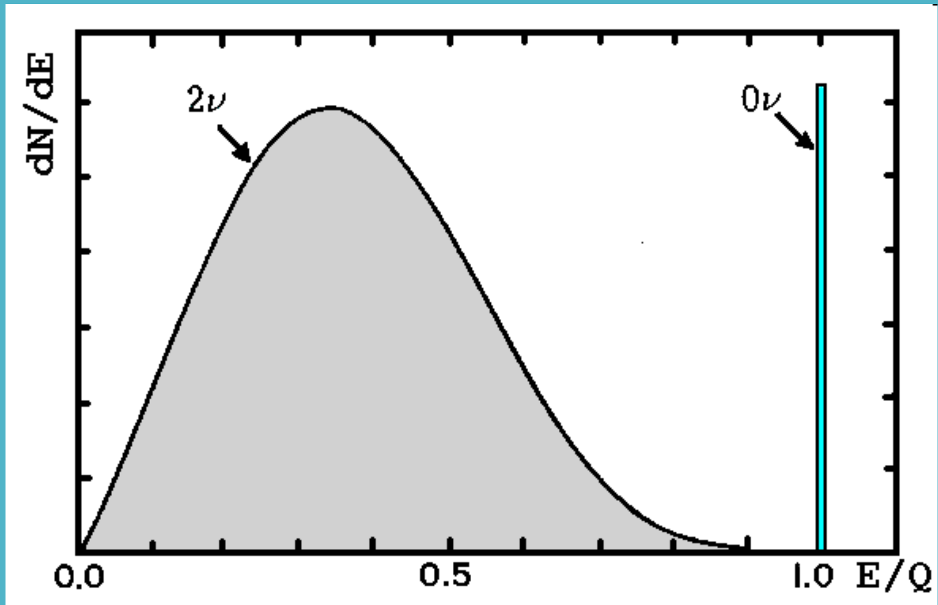
2νECEC

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

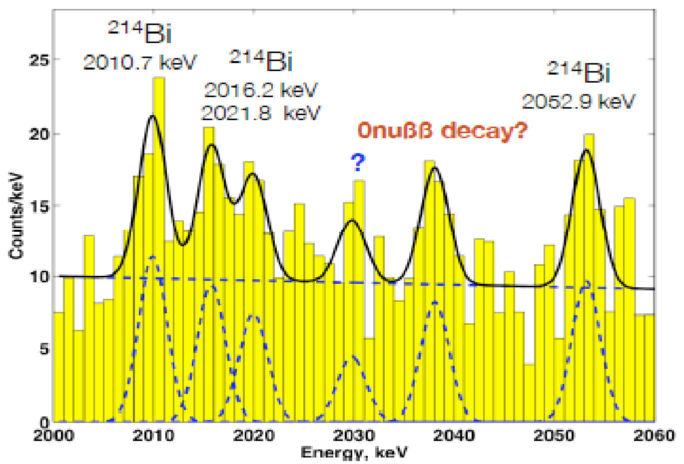
0νECEC

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

Experimentally, one can distinguish *2νββ, 0νββ* by measuring the sum electron energy



H.V.Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198



Isotope	$T^{2\nu}_{1/2}$ (yr)
^{48}Ca	$(4.2^{+2.1}_{-1.0}) \times 10^{19}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$
^{96}Zr	$(2.0 \pm 0.3) \times 10^{19}$
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$
^{116}Cd	$(3.0 \pm 0.2) \times 10^{19}$
^{128}Te	$(2.5 \pm 0.3) \times 10^{24}$
^{130}Te	$(0.9 \pm 0.1) \times 10^{21}$
^{150}Nd	$(7.8 \pm 0.7) \times 10^{18}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$

$0\nu\beta\beta$ decay: one of the most investigated process of physics: numerous experiments, in different stages:

a) completed (Gotthard, 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 very large investments.

Underground laboratories

Theoretical calculations for 0νββ lifetime

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\Sigma_k \left(\mid M_k^{0\nu} \mid^2\right) (\eta_k)^2$$

$$\mathcal{M}_\nu^{(0\nu)} = \mathcal{M}_{GT}^{0\nu} - (\frac{g_V}{g_A})^2 \mathcal{M}_F^{0\nu} - \mathcal{M}_T^{0\nu}$$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \left(\mid M_\nu^{0\nu} \mid < \eta_\nu > + \mid M_N^{0\nu} \mid < \eta_N > + \mid M_{\lambda'}^{0\nu} \mid < \eta_{\lambda'} > + \mid M_q^{0\nu} \mid < \eta_q > \right)^2$$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|\mathcal{M}_\nu^{0\nu}\right|^2 \cdot < m_\nu >^2$$

$$\langle m_\nu \rangle^2 = \left|\sum_i^N U_{ei}^2 m_i\right|^2 = \left|\sum_i^N |U_{ei}|^2 e^{\alpha_i} m_i\right|^2$$

$$\langle m_\nu \rangle = \frac{m_e}{\mid M^{0\nu} \mid \sqrt{T^{0\nu} \cdot G^{0\nu}}}$$

Precise calculations of PSF and NME are required to predict lifetimes, derive neutrino parameters, extract ν info

PSF: less attention has been paid, since were considered to be calculated with enough accuracy.

Kotila & Iachello (K&I) PRC2012; PRC872013 re-computed PSF for the DBD within an improved method (exact electron w.f.: Dirac eq. in a Coulomb with inclusion of finite nuclear size and screening effects. Found relevant differences as compared with the previous PSF values for some cases.

Our work: an independent computation of the PSF, improving further K&I's approach. New ingredients: Coulomb potential derived from a more realistic proton distribution inside the nucleus, up-dated $Q^{\beta\beta}$ (2012), routines with controlled, improved precision:Stoica, Mirea, PRC88 (2013), RRP66,68 (2014, 2015)

Calculation of NME carry the largest uncertainties, many works devoted to their calculations: different methods, different groups

pnQRPA (diff. versions);

Sh Model; IBM2;

Density functional method

PHFB

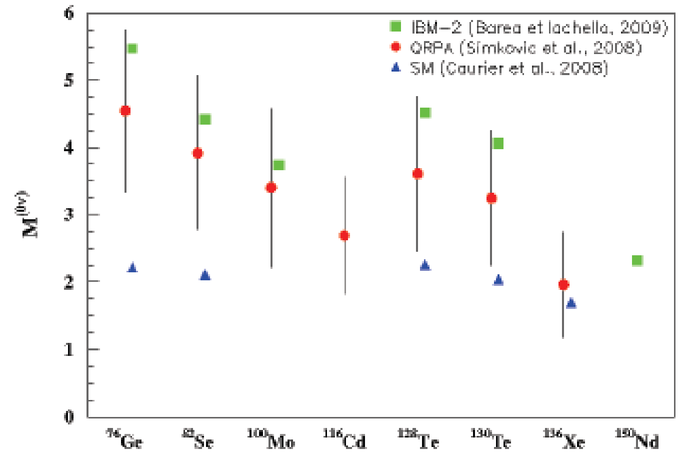
Three different methods for calculation:

Nuclear Shell Model (SM) Uses Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels

Quasi-Particle Random Phase Approximation (QRPA) Uses 3 parameters accounting for pairing, particle-particle and particle-hole interactions.

Interacting Boson Model (IBM) Bosons can interact through 1- and 2-body interactions giving rise to bosonic wave functions.

- QRPA and IBM (coincidentally?) in agreement
- SM a factor of 2 lower



Horoi, Stoica, PRC81, 024321 (2010)

Neacsu, Stoica, Horoi, PRC 86, 067304 (2012), Neacsu, Stoica, JPG 41, 015201 (2014)

Fast numerical code for computing the TBME

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

$$O_{12}^{GT} = \sigma_1 \cdot \sigma_2 H(r) \qquad O_{12}^F = H(r) \qquad O_{12}^T = \sqrt{\frac{2}{3}}\,[\sigma_1 \times \sigma_2]^2 \cdot \frac{r}{R} H(r) C^{(2)}(\hat{r})$$

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

$$h_F = G_V^2(q^2) \qquad h_{GT}(q^2) = \frac{G_A^2(q^2)}{g_A^2}\left[1 - \frac{2}{3}\frac{q^2}{q^2+m_\pi^2} + \frac{1}{3}\left(\frac{q^2}{q^2+m_\pi^2}\right)^2\right] + \frac{2}{3}\frac{G_M^2(q^2)}{g_A^2}\frac{q^2}{4m_p^2}$$

$$h_T(q^2) = \frac{G_A^2(q^2)}{g_A^2}\left[\frac{2}{3}\frac{q^2}{q^2+m_\pi^2} - \frac{1}{3}\left(\frac{q^2}{q^2+m_\pi^2}\right)^2\right] + \frac{1}{3}\frac{G_M^2(q^2)}{g_A^2}\frac{q^2}{4m_p^2}$$

$$G_A(q^2) = g_A\left(\frac{\Lambda_A^2}{\Lambda_A^2+q^2}\right)^2 \qquad G_V(q^2) = g_V\left(\frac{\Lambda_V^2}{\Lambda_V^2+q^2}\right)^2 \qquad G_M(q^2) = (\mu_p - \mu_n) G_V(q^2)$$

$$\langle nl \mid H_\alpha(r) \mid n'l' \rangle = \int_0^\infty r^2 dr \psi_{nl}(r) \psi_{n'l'}(r) \left[1 + f(r)\right]^2 \times \int_0^\infty q^2 dq V_\alpha(q) j_n(qr)$$

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

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

a, b, c parameters that take different balues for different methods of parameterization:

MS, CCM – AV18, CCM - CDBonn

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

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}	$M^{0\nu}_{total}$
					(a)-0.731	-0.680	-0.542	-0.508
^{48}Ca	-1.166	-0.959	-0.923	-0.773	(b)-1.023	-0.930	-0.800	-0.733
					(c)-1.153	-1.008	-0.914	-0.809
					(a) 0.856	0.798	0.670	0.628
$^{48}Ca^*$	1.351	1.116	1.102	0.928	(b) 1.188	1.082	0.962	0.884
					(c) 1.337	1.171	1.092	0.969
					(a) 3.025	2.889	2.499	2.378
^{76}Ge	4.168	3.615	3.497	3.066	(b) 3.807	3.557	3.187	2.979
					(c) 4.153	3.762	3.489	3.177
					(a)-2.779	-2.665	-2.275	-2.176
^{82}Se	-3.779	-3.305	-3.140	-2.780	(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 – (10-14)%

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

- nuclear form factors (🔍$_A$, 🔍$_V$) ~ 8%;

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

Calculation of the PSF

Relativistic treatment: the electron w.f. are expressed as a superposition of s and p Coulomb distorted spherical waves, solutions of the Dirac equation with a central (Coulomb) potential

$$\Psi^{+}_{\epsilon\kappa\mu}(r) = \begin{pmatrix} g_\kappa(\epsilon,r)\chi^{\mu}_{\kappa} \\ i f_\kappa(\epsilon,r)\chi^{\mu}_{-\kappa} \end{pmatrix}$$

for β⁻ decay

$$\Psi^{-}_{\epsilon\kappa\mu} = \begin{pmatrix} i f_\kappa(\epsilon,r)\chi^{-\mu}_{-\kappa} \\ -g_\kappa(\epsilon,r)\chi^{-\mu}_{\kappa} \end{pmatrix}$$

for β⁺ decay

$$\kappa = (l-j)(2j+1)$$

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

The positive/negative solutions of the radial Dirac eq. for a given V potential. They can be expanded in spherical w.f. s and p. They are normalized such that they have the asymptotic behavior:

$$\begin{pmatrix} g_k(\epsilon,r) \\ f_k(\epsilon,r) \end{pmatrix} \sim \frac{\hbar e^{-i\delta_k}}{pr} \begin{pmatrix} \sqrt{\frac{\epsilon+m_e c^2}{2\epsilon}}\sin(kr - l\frac{\pi}{2} - \eta\ln(2kr) + \delta_k) \\ \sqrt{\frac{\epsilon-m_e c^2}{2\epsilon}}\cos(kr - l\frac{\pi}{2} - \eta\ln(2kr) + \delta_k) \end{pmatrix} \quad (5)$$

k=is the electron wave number

$\eta = Ze^2/hv$, and δ_k = phase shift

v) Present work: taking into account the influence of the nuclear structure by determining a potential V(r) from a realistic proton density distribution in the daughter nucleus.
This was done by solving a Schrodinger equation for a Wood-Saxon potential well.

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

We obtained V (r) as:

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

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

Ψ_i = proton (WS) w.f. of the s.p. state i; v_i = its occupation amplitude

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

$$w_{0\nu} = \frac{g_A^4 (G\cos\theta_C)^4}{16\pi^5} (m_e c^2)^2 (\hbar c^2)(p_1 c)(p_2 c)\epsilon_1\epsilon_2$$

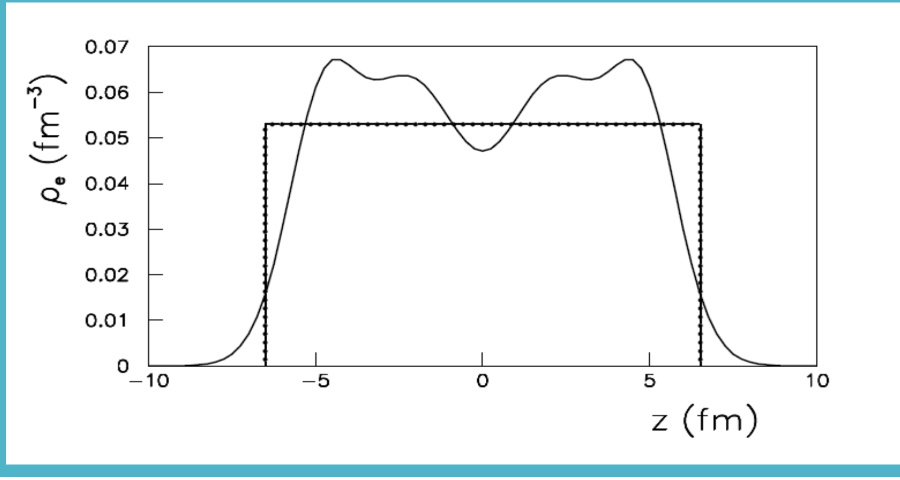


FIG. 1. Profile of the realistic proton density ρ_e for ^{150}Sm (thick line) compared with that given with the constant density approximation (dot-dashed line).

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 $G0^{\nu}$ for the majority of nuclei
exceptions: 128Te(~20%) and 238U(factor of 7)

- in comparison with older calculations there are some notable differences

S. Stoica, OCA-Nice, June 28, 2016

Table 2: PSF for $\beta^-\beta^-$ decays to final excited 0_1^+ states

Nucleus	$Q_{0_1^+}^{\beta^-\beta^-}$ (MeV)	$G_{2\nu}^{\beta^-\beta^-}(0_1^+)$ $(10^{-21}$ yr$^{-1})$ This work	[27]	[26]	$G_{0\nu}^{\beta^-\beta^-}(0_1^+)$ $(10^{-15}$ yr$^{-1})$ This work	[27]
^{48}Ca	1.270	0.3518	0.3627	0.376	0.3041	0.2989
^{76}Ge	0.9171	0.06129	0.06978	0.0769	0.1932	0.1776
^{82}Se	1.508	4.170		4.80	0.9440	
^{96}Zr	2.201	169.4	175.4	190	4.594	4.566
^{100}Mo	1.904	57.08	60.55	101	3.168	3.162
^{110}Pd	0.5472	3.3×10^{-3}	4.8×10^{-3}		0.1223	0.08844
^{116}Cd	1.056	0.7590	0.8737	0.89	0.7585	0.7163
^{130}Te	0.7335	0.05460	0.07566	18.6	0.3651	0.3086
^{136}Xe	0.8790	0.2823	0.3622	0.485	0.6746	0.6127
^{150}Nd	2.631	4116	4329	4850	26.96	27.27
^{238}U	0.2032	1.5×10^{-4}	4.6×10^{-4}		0.8229	0.7534

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

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

- several cases, especially for heavier nuclei, where the differences are of (10-40)%; again, for 238U our $G^{2\nu}$ value is 3 times smaller than KI result
- notable differences with older results

S. Stoica, OCA-Nice, June 28, 2016

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	$< [4.84 - 8.95]$

Stoica, Neacsu, AHEP2014

Computation of products

$[T^{0\nu}]_A^{-1} = G^{0\nu}{}_A \times |M^{0\nu}|^2{}_A \times \langle\eta\rangle$; $[T^{2\nu}]_A^{-1} = G^{2\nu}{}_A \times |M^{2\nu}|^2{}_A$

$[T^{0\nu}]_B^{-1} = G^{0\nu}{}_B \times |M^{0\nu}|^2{}_B \times \langle\eta\rangle$; $[T^{2\nu}]_B^{-1} = G^{2\nu}{}_B \times |M^{2\nu}|^2{}_B$

A measurement of the 0νββ decay rate combined with neutrino oscillation data and a reliable calculation of the NMEs, would yield insight into all three neutrino mass eigenstates.

Based on the present data one can extract limits for the neutrino mass scale.

NH: $m_1 < m_2 < m_3$

$$|\langle m_\nu \rangle| \simeq |c_{13}^2 s_{12}^2 \sqrt{\Delta m^2_{\mathrm{SUN}}} + s_{13}^2 \sqrt{\Delta m^2_{\mathrm{ATM}}} e^{-2i\alpha_2}$$
$$\leq 4 \cdot 10^{-3}\ \mathrm{eV}.$$

IH: $m_3 < m_1 < m_2$

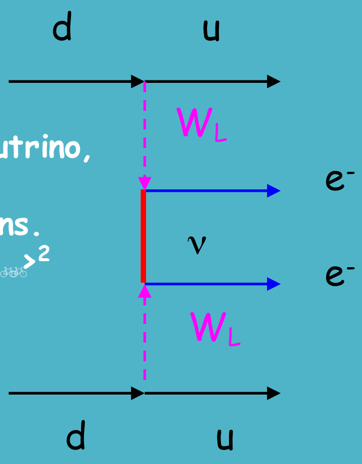
$$|\langle m_\nu \rangle| \simeq \sqrt{\Delta m^2_{\mathrm{Atm}}}\, c_{13}^2 (1 - \sin^2 2\theta_{12} \sin^2 \alpha_{12})^{\frac{1}{2}}$$

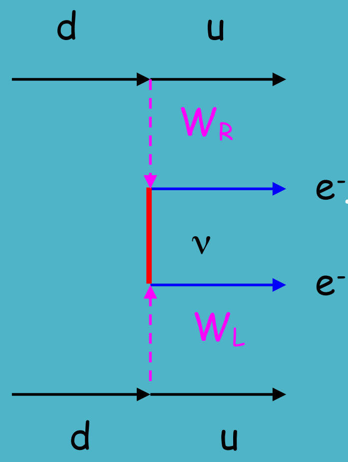
$$1.5 \cdot 10^{-2}\ \mathrm{eV} \leq |\langle m_\nu \rangle| \leq 5.0 \cdot 10^{-2}\ \mathrm{eV}$$

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

Diagrams that can contribute to the 0nbb decay amplitude

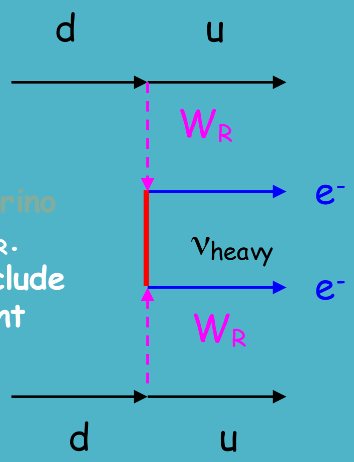
Light Majorana neutrino, only SM LH weak interactions. Decay rate ~<m>^{2}

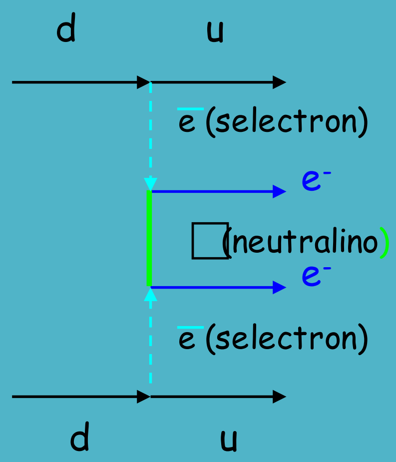




Light Majorana neutrinos. Model extended to include right-handed W_R. Mixing extended between the left and right-handed neutrinos. This is the mode where the rate ~^{2} or ^{2}

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





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

Search of LNV processes at high energy: like sign dilepton processes

Interest for searching LNV processes at hadron colliders

Motivation: i) pressing need to check BSM physics in the lepton sector→ complete the astroparticle road map (see ESPP12, Krakow)

ii) the increased luminosity of the present LHC experiments and future superB factories

Check: - lepton number violation

- neutrino character: Dirac or Majorana
- existence of heavy sterile neutrino(s): when the heavy mass is kinematically accessible, a LNV process may undergo a resonant production of the heavy and, at future luminosity of LHC experiments, there is a chance to be observed

Classification of the LNV processes

a) $dd \to uu\, W^{*-}W^{*-} \to uu\, e^-e^-$: 0[illegible]β

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

$\Xi^+_c \to \Xi^- p\, \mu^+ \mu^+$; $\Lambda_c^+ \to \Sigma^- \mu^+ \mu^+$

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

d) $M^{\pm}_1 \to l^{\pm}_1\, l^{\pm}_2\, M^{-/+}_2$: **rare meson decays (B, D, K,..)**

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

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

g) $H^{\pm\pm} \to l^{\pm}_1\, l^{\pm}_2\, X$: double-charged Higgs decays

Search of LNV processes @ LHC

Collider signatures:

CMS & ATLAS: search of isolated same-sign dilepton pairs in pp collisions

CMS has searched such events (production of **ee, eμ, μμ, μτ, ττ**) using an integrated luminosity of 35 pb^{-1} of pp collision data at a E_{CM} of 7 TeV. The observed numbers of events agree with the SM predictions, and no evidence for new physics was found.

JHEP 06 (2011) 077 [$pp \rightarrow l^+_1 \, l^+_2 \, X$; $l_{1,2} = e, \mu, \tau$]

ATLAS: similar search at an integrated luminosity of 34pb^{-1}.

JHEP 10 (2011) 107 [$pp \rightarrow l^+_1 \, l^+_2 \, X$; $l_{1,2} = e, \mu$]

LHCb: [$B^+ \rightarrow (\pi^-, K^-) \, \mu^+ \mu^+$] (PRL108, 2012)

[$B^- \rightarrow (D^{(*,0)+}_{(s)}, \pi^+) \, \mu^- \mu^-$] (PRD85, 2012); PLB **724**, 36 (2013)

[$\tau \rightarrow \mu^+\mu^-\mu^-$] PRL**112**, 131802 (2014)

One assumes: three active ν flavors (ν_e, ν_μ, ν_τ)

one (heavy) sterile ν flavor (N_4)

Theoretical approach

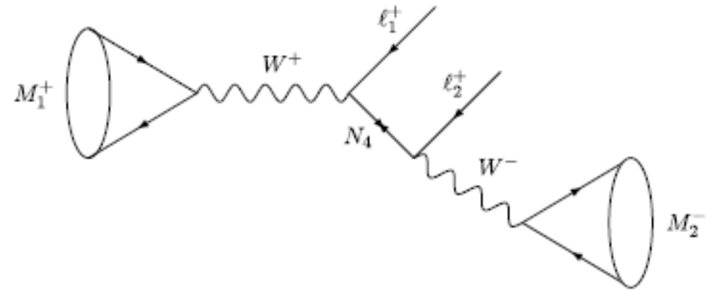


Fig. 2 Feynman diagram corresponding to the lepton-number violating decays $M_1^+(q_1) \to \ell_1^+(p_1)\ell_2^+(p_2)M_2^-(q_2)$

$$\Gamma(M \to M'\ell^+\ell^+) \approx \frac{1}{128\pi^2} G_F^4 f_M^2 f_{M'}^2 |V_{qQ}V_{q_2q_1}|^2 \frac{|U_{N\ell}|^4}{\sum_{\ell'} |U_{N\ell'}|^2} \frac{m_M m_\tau^5}{2\Gamma_\tau} \left(1 - \frac{m_{M'}^2}{m_N^2}\right)^2 \left(1 - \frac{m_N^2}{m_M^2}\right)^2$$

Goals: discover a LNV process → decide on the ν character (D or M)

put bounds on m_N mass and on the mixing parameters U_{Ne}, $U_{N\mu}$, $U_{N\tau}$

Strategy

- re-evaluate the bounds of the neutrino mixing parameters $|V_{\alpha 4}|$ from different actual low-energy measurements, including $0\nu\beta\beta$ decay recent developments

- use these bounds, through the corresponding decay rates/widths to constraint the Br.

- choose specific channels for analysis combining the Br predictions with particular experimental constraints

- get new limits for the neutrino mixing parameters and heavy neutrino mass

Conclusions

- Neutrinos play a key role in many processes from nuclear and particle physics, astrophysics and cosmology
- Neutrinos fundamental properties as: absolute masses and mechanism of generating them, mass hierarchy, character (Dirac or Majorana?), number of flavors (sterile neutrinos?), etc., are still unknown
- DBD- $0\nu\beta\beta$, a BSM process that occurs with LNV: very appealing to provide information on these issues
- Theoretically: NME and PSF are two important quantities entering the $0\nu\beta\beta$ lifetimes $\rightarrow$ need for precise calculations. Idea is to compute at once their product. Understanding the mechanisms of this decay.
- Experimentally: search of $0\nu\beta\beta$ is done in many UG Labs all over the world, involving large investments
- New opportunity: LNV processes are now searched at HE, as well, specially at LHC experiments. This is possible due to the present and future integrated luminosity, which make the analysis competitive to that from $0\nu\beta\beta$
- This is a new direction of research: to use data provided by the analysis of LNV processes at low- and high-energy to advance in understanding the neutrino properties

Thank you for your attention