Theoretical challenges in Double Beta Decay

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Outline

- Introduction: neutrino properties
- Double beta decay – $2\nu\beta\beta$, $0\nu\beta\beta$
- 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)

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Relates weak states with mass states

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

“Atmospheric” “Reactor” “Solar” “\(\bar{\nu}_\beta\beta\)"

S. Stoica, OCA-Nice, June 28, 2016
**Neutrino properties: present status**

### What we know

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

\[ \Delta m_{12}^2 = \Delta m_{\text{sol}}^2 \sim 7.58 \times 10^{-5} \text{ eV}^2; \]

\[ \tan^2 \theta_{12} \sim 0.484 \rightarrow \theta_{12} \sim 35^0: \] Solar experiments + KamLAND (r)

\[ |\Delta m_{32}^2| = \Delta m_{\text{atm}}^2 \sim 2.40 \times 10^{-3} \text{ eV}^2; \]

\[ \sin^2 2\theta_{23} \sim 1.02 \rightarrow \theta_{23} \sim 45^0: \] Atm. expt. + K2K (r) + MINOS (acc)

\[ \sin^2 2\theta_{13} \sim 0.092; \theta_{13} \sim 8.8^0: \] Daya Bay experiment (r)

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

### 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 $m_\nu$?
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 e-e 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+ decay: β-β for (a) and β+β for (d)

There are 35 ββ isotopes in nature
Double Beta Decay

$2\nu\beta\beta$

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

$0\nu\beta\beta$

- $(Z, A) \rightarrow (Z + 2, A) + 2e^-$
- $\Delta L = 2$
- $\left| T_{1/2}^{0\nu} \right|^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) |M_{0\nu}|^2 \langle m_{\beta\beta}^2 \rangle \sim |10^{25} \text{ yr}|^{-1}$
- $\langle m_{\beta\beta} \rangle = \left| \sum_i U_{e i}^2 m_i \right|$
### Positron Decays

<table>
<thead>
<tr>
<th>Type</th>
<th>Equation</th>
<th>Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\nu\beta^+\beta^+$</td>
<td>$(A,Z) \rightarrow (A,Z - 2) + 2e^+ + 2\nu$</td>
<td>$0\nu\beta+\beta^+$</td>
<td>$(A,Z) \rightarrow (A,Z - 2) + 2e^+$</td>
</tr>
<tr>
<td>$2\nu EC\beta^+$</td>
<td>$(A,Z) + e^- \rightarrow (A,Z - 2) + e^+ + 2\nu$</td>
<td>$0\nu EC\beta^+$</td>
<td>$(A,Z) + e^- \rightarrow (A,Z - 2) + e^+$</td>
</tr>
<tr>
<td>$2\nu ECEC$</td>
<td>$(A,Z) + 2e^- \rightarrow (A,Z - 2) + 2\nu$</td>
<td>$0\nu ECEC$</td>
<td>$(A,Z) + 2e^- \rightarrow (A,Z - 2)$</td>
</tr>
</tbody>
</table>
Experimentally, one can distinguish $2\nu\beta\beta$, $0\nu\beta\beta$ by measuring the sum electron energy.
0νββ 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, CUORICINO-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 $0\nu\beta\beta$ lifetime

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \sum_{k} \left( | M^{0\nu}_{k} |^2 \right) (\eta_{k})^2
\]

\[
\left( T_{1/2}^{0\nu} \right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \left( | M^{0\nu}_{\nu} | < \eta_{\nu} > + | M^{0\nu}_{N} | < \eta_{N} > + | M^{0\nu}_{\lambda} | < \eta_{\lambda} > + | M^{0\nu}_{q} | < \eta_{q} > \right)^2
\]

\[
\langle m_{\nu} \rangle^2 = \frac{\sum_{i=1}^{N} U_{ei}^2 m_i^2}{\sum_{i=1}^{N} U_{ei}^2 e^{\alpha_i} m_i}
\]

\[
\langle m_{\nu} \rangle = \frac{m_{e}}{| M^{0\nu} | \sqrt{T^{0\nu} \cdot G^{0\nu}}}
\]

Precise calculations of PSF and NME are required to predict lifetimes, derive neutrino parameters, extract $\nu$ 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.


S. Stoica, OCA-Nice, June 28, 2016
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
Fast numerical code for computing the TBME

\[
M^{0\nu}_{\alpha} = \sum_{j_p, j_p', j_n, j_n'} T B T D (j_p, j_p', j_n, j_n'; J_\pi) \langle j_p, j_p'; J_\pi \parallel \tau_{-1} \tau_{-2} O_{12}^{n} \parallel j_n, j_n'; S_\alpha J_\pi \rangle
\]

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

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

\[
h_F = G_V^2 (q^2)
\]

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

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

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

S. Stoica, OCA-Nice, June 28, 2016
\[ \langle nl | H_\alpha(r) | n'l' \rangle = \int_0^\infty r^2 dr \psi_{nl}(r) \psi_{n'l'}(r) \left[ 1 + f(r) \right]^2 \times \int_0^\infty q^2 dq V_\alpha(q) j_n(qr) \]

\[ \psi_{nl}(r) \rightarrow [1 + f(r)] \psi_{nl}(r) \quad \quad f(r) = -c \cdot e^{-ar^2} (1 - br^2) \]

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

MS, CCM – AV18, CCM - CDBonn

\[ \langle nl | H_\alpha(r) | n'l' \rangle = \sum_{s=0}^{n+n'} A_{l+l'+2s}(nl, n'l') K_\alpha(m) \]
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 $M^{\nu}$ 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 $g_A=1.25$, $r_0 = 1.2 fm$, $\Lambda_V = 850 MeV$, $\Lambda_A = 1086 MeV$.

<table>
<thead>
<tr>
<th></th>
<th>$M_b$</th>
<th>$M_{b+F}$</th>
<th>$M_{b+H}$</th>
<th>$M_{b+F+H}$</th>
<th>$M_{b+S}$</th>
<th>$M_{b+S+F}$</th>
<th>$M_{b+S+H}$</th>
<th>$M_{total}^{\nu}$</th>
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<tbody>
<tr>
<td>$^{48}Ca$</td>
<td>-1.166</td>
<td>-0.959</td>
<td>-0.923</td>
<td>-0.773</td>
<td>(a)-0.731</td>
<td>-0.680</td>
<td>-0.542</td>
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<td></td>
<td></td>
<td>(b)-1.023</td>
<td>-0.930</td>
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<td>-0.733</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(c)-1.153</td>
<td>-1.008</td>
<td>-0.914</td>
<td>-0.809</td>
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<tr>
<td>$^{48}Ca^*$</td>
<td>1.351</td>
<td>1.116</td>
<td>1.102</td>
<td>0.928</td>
<td>(a) 0.856</td>
<td>0.798</td>
<td>0.670</td>
<td>0.628</td>
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<td></td>
<td></td>
<td>(b) 1.188</td>
<td>1.082</td>
<td>0.962</td>
<td>0.884</td>
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<td></td>
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<td>(c) 1.337</td>
<td>1.171</td>
<td>1.092</td>
<td>0.969</td>
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<tr>
<td>$^{76}Ge$</td>
<td>4.168</td>
<td>3.615</td>
<td>3.497</td>
<td>3.066</td>
<td>(a) 3.025</td>
<td>2.889</td>
<td>2.499</td>
<td>2.378</td>
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<td></td>
<td></td>
<td>(b) 3.807</td>
<td>3.557</td>
<td>3.187</td>
<td>2.979</td>
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<td>(c) 4.153</td>
<td>3.762</td>
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<td>3.177</td>
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<td></td>
<td></td>
<td>(b)-3.467</td>
<td>-3.256</td>
<td>-2.876</td>
<td>-2.703</td>
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<td></td>
<td>(c)-3.770</td>
<td>-3.438</td>
<td>-3.137</td>
<td>-2.878</td>
</tr>
</tbody>
</table>
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; $R = r_0A^{1/3}$ ($r_0$=1.1fm or 1.2fm) ~ 7%
  - nuclear form factors ($\Omega_A, \Omega_V$) ~ 8%;
  - average energy used in closer approx. $<E>$ - negligible

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

\( \Psi^+_{\epsilon \kappa \mu}(r) = \left( \frac{g_\kappa(\epsilon, r)\chi^\mu_\kappa}{i f_\kappa(\epsilon, r)\chi^\mu_-\kappa} \right) \)

for \( \beta^- \) decay

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

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

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

\( \left( \frac{g_\kappa(\epsilon, r)}{f_\kappa(\epsilon, r)} \right) \sim \frac{\hbar e^{-i \delta_k}}{pr} \left( \frac{\sqrt{\frac{\epsilon + m_e e^2}{2\epsilon} \sin(kr - l \frac{\pi}{2} - \eta \ln(2kr) + \delta_k)}}{\sqrt{\frac{\epsilon - m_e e^2}{2\epsilon} \cos(kr - l \frac{\pi}{2} - \eta \ln(2kr) + \delta_k)}} \right) \)

k = is the electron wave number

\( \eta = Ze^2/\hbar v \), and \( \delta_k = \text{phase shift} \)

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:

Calculation of the PSF

S. Stoica, OCA-Nice, June 28, 2016
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 Schrödinger equation for a Wood-Saxon potential well.

We obtained $V(r)$ as:

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

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

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

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

$$G^{\beta \beta}_{00}(0^+ \rightarrow 0^+) = \frac{2}{4g_A^4 R_A^2 \ln 2} \int_{m_e c^2}^{Q^2 + m_e c^2} f_{11}^{(0)} w_{0\nu} \, d\epsilon_1$$

$$w_{0\nu} = g_A^4 (G \cos \theta_C)^4 \frac{1}{16\pi^5} (m_e c^2)^2 (\hbar c^2) (p_1 c)(p_2 c) \epsilon_1 \epsilon_2$$

FIG. 1. Profile of the realistic proton density $\rho_e$ 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.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$Q_{g.s.}^{\beta^-\beta^-} (\text{MeV})$</th>
<th>This work</th>
<th>$G_{2\nu}^{\beta^-\beta^-} (g.s.) \left(10^{-21} \text{ yr}^{-1}\right)$</th>
<th>$G_{0\nu}^{\beta^-\beta^-} (g.s.) \left(10^{-15} \text{ yr}^{-1}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{45}$Ca</td>
<td>4.267</td>
<td>15536</td>
<td>15550</td>
<td>16200</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>2.039</td>
<td>46.47</td>
<td>48.17</td>
<td>53.8</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>2.996</td>
<td>1573</td>
<td>1596</td>
<td>1830</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>3.349</td>
<td>6744</td>
<td>6816</td>
<td>7280</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>3.034</td>
<td>3231</td>
<td>3308</td>
<td>3860</td>
</tr>
<tr>
<td>$^{110}$Pd</td>
<td>2.017</td>
<td>132.5</td>
<td>137.7</td>
<td>2990</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>2.813</td>
<td>2688</td>
<td>2764</td>
<td>0.2149</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>0.8665</td>
<td>1442</td>
<td>1529</td>
<td>1970</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>2.528</td>
<td>1332</td>
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<td>2030</td>
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<tr>
<td>$^{136}$Xe</td>
<td>2.458</td>
<td>35397</td>
<td>36430</td>
<td>48700</td>
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<tr>
<td>$^{238}$U</td>
<td>1.144</td>
<td>98.51</td>
<td>14.57</td>
<td>32.53</td>
</tr>
</tbody>
</table>


– very good agreement with [27] both for $G^{2\nu}$ and $G^{0\nu}$ for the majority of nuclei exceptions: $^{128}$Te($\sim$20%) and $^{238}$U(factor of 7)
- in comparison with older calculations there are some notable differences
- 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

![Table 2: PSF for $\beta^{-}\beta^{-}$ decays to final excited $0^+_1$ states](image)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$Q^{\beta^{-}\beta^{-}}_{0^+_1}$ (MeV)</th>
<th>This work</th>
<th>$G^{\beta^{-}\beta^{-}}_{2\nu} (0^+_1) \times 10^{-21}$ yr$^{-1}$</th>
<th>[26]</th>
<th>$G^{\beta^{-}\beta^{-}}_{0\nu} (0^+_1) \times 10^{-15}$ yr$^{-1}$</th>
<th>[27]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>1.270</td>
<td>0.3518</td>
<td>0.3627</td>
<td>0.376</td>
<td>0.3041</td>
<td>0.2989</td>
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<tr>
<td>$^{76}$Ge</td>
<td>0.9171</td>
<td>0.06129</td>
<td>0.06978</td>
<td>0.0769</td>
<td>0.1932</td>
<td>0.1776</td>
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<tr>
<td>$^{82}$Se</td>
<td>1.508</td>
<td>4.170</td>
<td>175.4</td>
<td>190.0</td>
<td>4.594</td>
<td>4.566</td>
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<td>$^{90}$Zr</td>
<td>2.201</td>
<td>169.4</td>
<td>60.55</td>
<td>101.0</td>
<td>3.168</td>
<td>3.162</td>
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<tr>
<td>$^{100}$Mo</td>
<td>1.904</td>
<td>57.08</td>
<td>1.223</td>
<td>0.08844</td>
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<tr>
<td>$^{110}$Pd</td>
<td>0.5472</td>
<td>3.3 x 10$^{-3}$</td>
<td>4.8 x 10$^{-3}$</td>
<td>0.89</td>
<td>0.7585</td>
<td>0.7163</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>1.056</td>
<td>0.7590</td>
<td>0.8737</td>
<td>0.89</td>
<td>0.7585</td>
<td>0.7163</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>0.7335</td>
<td>0.05460</td>
<td>0.07566</td>
<td>18.6</td>
<td>0.3651</td>
<td>0.3086</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>0.8790</td>
<td>0.2823</td>
<td>0.3622</td>
<td>0.485</td>
<td>0.6746</td>
<td>0.6127</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>2.631</td>
<td>4116</td>
<td>4329</td>
<td>4850</td>
<td>26.96</td>
<td>27.27</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>0.2032</td>
<td>1.5 x 10$^{-4}$</td>
<td>4.6 x 10$^{-4}$</td>
<td>0.8229</td>
<td>0.7534</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>$Q_{\beta\beta}$ [MeV]</th>
<th>$T_\text{exp}^{0\nu\beta\beta}$ [yr]</th>
<th>$G^{0\nu\beta\beta}$ [yr$^{-1}$]</th>
<th>$M^{0\nu\beta\beta}$</th>
<th>$\langle m_\nu \rangle$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{45}Ca$</td>
<td>4.272</td>
<td>$&gt; 5.8 \times 10^{22}$ [52]</td>
<td>2.46E-14</td>
<td>0.81-0.90</td>
<td>&lt; [15.0 - 16.7]</td>
</tr>
<tr>
<td>$^{76}Ge$</td>
<td>2.039</td>
<td>$&gt; 2.1 \times 10^{25}$ [38]</td>
<td>2.37E-15</td>
<td>2.81-6.16</td>
<td>&lt; [0.37 - 0.82]</td>
</tr>
<tr>
<td>$^{82}Se$</td>
<td>2.995</td>
<td>$&gt; 3.6 \times 10^{23}$ [53]</td>
<td>1.01E-14</td>
<td>2.64-4.99</td>
<td>&lt; [1.70 - 3.21]</td>
</tr>
<tr>
<td>$^{96}Zr$</td>
<td>3.350</td>
<td>$&gt; 9.2 \times 10^{21}$ [54]</td>
<td>2.05E-14</td>
<td>2.19-5.65</td>
<td>&lt; [6.59 - 17.0]</td>
</tr>
<tr>
<td>$^{100}Mo$</td>
<td>3.034</td>
<td>$&gt; 1.1 \times 10^{24}$ [53]</td>
<td>1.57E-14</td>
<td>3.93-6.07</td>
<td>&lt; [0.64 - 0.99]</td>
</tr>
<tr>
<td>$^{116}Cd$</td>
<td>2.814</td>
<td>$&gt; 1.7 \times 10^{23}$ [56]</td>
<td>1.66E-14</td>
<td>3.29-4.79</td>
<td>&lt; [2.00 - 2.92]</td>
</tr>
<tr>
<td>$^{130}Te$</td>
<td>2.527</td>
<td>$&gt; 2.8 \times 10^{24}$ [57]</td>
<td>1.41E-14</td>
<td>2.65-5.13</td>
<td>&lt; [0.50 - 0.97]</td>
</tr>
<tr>
<td>$^{136}Xe$</td>
<td>2.458</td>
<td>$&gt; 1.6 \times 10^{25}$ [39]</td>
<td>1.45E-14</td>
<td>2.19-4.20</td>
<td>&lt; [0.25 - 0.48]</td>
</tr>
<tr>
<td>$^{150}Nd$</td>
<td>3.371</td>
<td>$&gt; 1.8 \times 10^{22}$ [55]</td>
<td>6.19E-14</td>
<td>1.71-3.16</td>
<td>&lt; [4.84 - 8.95]</td>
</tr>
</tbody>
</table>
Computation of products

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

\[ [T^{0\nu}]_B^{-1} = G^{0\nu}_B \times |M^{0\nu}|^2_B \times \langle \eta \rangle; \quad [T^{2\nu}]_B^{-1} = G^{2\nu}_B \times |M^{2\nu}|^2_B \]
A measurement of the $0\nu\beta\beta$ 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.

\[ |\langle m_\nu \rangle| \simeq |c_{13}s_{12}\sqrt{\Delta m_{\text{SUN}}^2 + s_{13}^2\Delta m_{\text{ATM}}^2}|e^{-2i\alpha_2} \leq 4 \times 10^{-3} \text{ eV}. \]

\[ |\langle m_\nu \rangle| \simeq \sqrt{\Delta m_{\text{Atm}}^2 c_{13}^2 (1 - \sin^2 2\theta_{12} \sin^2 \alpha_{12})} \]

\[ 1.5 \times 10^{-2} \text{ eV} \leq |\langle m_\nu \rangle| \leq 5.0 \times 10^{-2} \text{ eV} \]
$\beta\beta$ provides a broader potential to search for beyond SM physics: any $\Delta L=2$ process can contribute to $0n\beta b$.

Diagrams that can contribute to the $0n\beta b$ decay amplitude:

1. **Light Majorana neutrino**, only SM LH weak interactions. Decay rate $\sim <m_{\nu}>^2$.

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

3. **Model extended to include right-handed $W_R$. Mixing extended between the left and right-handed neutrinos. This is the mode where the rate $\sim \frac{1}{2}$ or $\frac{3}{2}$**.

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

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

S. Stoica, OCA-Nice, June 28, 2016
Classification of the LNV processes

a) \( dd \rightarrow uu \ W^+W^- \rightarrow uu \ e^+e^- \) : \( 0\beta \)

b) \( \Sigma^- \rightarrow \Sigma^+ e^-e^- ; \Xi^- \rightarrow p \bar{\nu} \bar{\nu} \) : hyperon decays
\( \Xi^+_c \rightarrow \Xi^- p \bar{\nu}^+ \bar{\nu}^+ ; \Lambda_c^+ \rightarrow \Sigma^- \bar{\nu}^+ \bar{\nu}^+ \)

c) \( \tau \rightarrow l^+ M^-_{1} M^-_{2} \rightarrow \mu^+\mu^-\mu^- \) : tau decays

d) \( M^{\pm_1} \rightarrow l^{\pm_1}_1 l^{\pm_2}_2 \ M^{-/2} \) : 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

S. Stoica, OCA-Nice, June 28, 2016
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 $ee$, $e^+\mu^-$, $\mu^+\mu^-$) using an integrated luminosity of 35 pb$^{-1}$ of pp collision data at an $E_{CM}$ 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**  
$[pp \rightarrow l_1^+ l_2^- X; l_{1,2} = e, \mu]$  

**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**:  
$[B^+ \rightarrow (\pi, K^+) l^+ l^-] \ (PRL108, 2012)$  
$[B^- \rightarrow (D^{*,0}+, \pi^+) l^- l^+] \ (PRD85, 2012); \ PLB \ 724, \ 36 \ (2013)$  
$[\mu^+\mu^-\mu^-] \ PRL112, \ 131802 \ (2014)$
One assumes: three active flavors ($\nu_e, \nu_m, \nu_t$), one (heavy) sterile flavor ($N_4$)

**Theoretical approach**

\[
\Gamma(M \rightarrow M'\ell^+\ell^+) \approx \frac{1}{128\pi^2} \frac{G_F^4 f_M^2 f_{M'}^2 |V_{qQ}V_{q2q1}|^2}{\sum_{\mu} |U_{N\mu}|^2} \frac{|U_{Ne}|^4}{2\Gamma_\tau} \frac{m_M m_{M'}^5}{m_N^2} \left( 1 - \frac{m_{M'}^2}{m_N^2} \right)^2 \left( 1 - \frac{m_N^2}{m_M^2} \right)^2
\]

**Goals:**
- discover a LNV process \( \rightarrow \) decide on the character (D or M)
- put bounds on \( m_N \) mass and on the mixing parameters \( U_{Ne}, U_{Nt}, U_{Nt} \)
Strategy

• re-evaluate the bounds of the neutrino mixing parameters $|V_{\alpha4}|$ 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

S. Stoica, OCA-Nice, June 28, 2016
Thank you for your attention