Neutrinoless Double Beta Decay and Particle Physics

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02/09/16

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

\[ m_\nu = m_L - m_D \left( M^2_R - m_D \right)^{-1} \]
Neutrinoless Double Beta Decay

\[ (A, Z) \rightarrow (A, Z + 2) + 2e^- \quad (0\nu\beta\beta) \Rightarrow \text{Lepton Number Violation} \]

- **Standard Interpretation** (neutrino physics)
- **Non-Standard Interpretations** (BSM \( \neq \) neutrino physics)

W.R., Int. J. Mod. Phys. **E20**, 1833-1930 (2011);

Why should we probe Lepton Number Violation?

- $L$ and $B$ *accidentally* conserved in SM
- effective theory: $\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_{\text{LNV}} + \frac{1}{\Lambda^2} \mathcal{L}_{\text{LFV, BNV, LNV}} + \ldots$
- baryogenesis: $B$ is violated
- $B, L$ often connected in GUTs
- GUTs have seesaw and Majorana neutrinos
- (chiral anomalies: $\partial_\mu J_{B,L}^\mu = c G_{\mu\nu} \tilde{G}^{\mu\nu} \neq 0$ with $J_{B,L}^\mu = \sum q_i \gamma_\mu q_i$ and $J_{L}^\mu = \sum \overline{\ell}_i \gamma_\mu \ell_i$)

⇒ Lepton Number Violation as important as Baryon Number Violation

$(0\nu\beta\beta$ is much more than a neutrino mass experiment)
Upcoming/running experiments: exciting time!!

best limit was from 2001, improved 2012

<table>
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<tr>
<th>Name</th>
<th>Isotope</th>
<th>Source = Detector; calorimetric with high $\Delta E$</th>
<th>Source = Detector; calorimetric with low $\Delta E$</th>
<th>Source $\neq$ Detector topology</th>
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Interpretation of Experiments

Master formula:

$$\Gamma^{0\nu} = G_x(Q, Z) |\mathcal{M}_x(A, Z) \eta_x|^2$$

- $G_x(Q, Z)$: phase space factor
- $\mathcal{M}_x(A, Z)$: nuclear physics
- $\eta_x$: particle physics
Interpretation of Experiments

Master formula:
\[ \Gamma^{0\nu} = G_x(Q, Z) \left| M_x(A, Z) \eta_x \right|^2 \]

- \( G_x(Q, Z) \): phase space factor; calculable
- \( M_x(A, Z) \): nuclear physics; problematic
- \( \eta_x \): particle physics; interesting
Standard Interpretation

Neutrinoless Double Beta Decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution.

Prediction of $(100 - \epsilon)\%$ of all neutrino mass mechanisms.
Amplitude proportional to coherent sum ("effective mass"): 

\[ |m_{ee}| ≡ |\sum U_{ei}^2 m_i| = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\alpha} + |U_{e3}|^2 m_3 e^{2i\beta} | \]

\[ = f (\theta_{12}, |U_{e3}|, m_i, \text{sgn}(\Delta m_{A}^2), \alpha, \beta) \]

7 out of 9 parameters of neutrino physics!
The usual plot
The usual plot

(life-time instead of $|m_{ee}|$)
Plot against other observables

Complementarity of \(|m_{ee}| = U^2_{ei} m_i\), \(m_\beta = \sqrt{|U_{ei}|^2 m^2_i}\) and \(\Sigma = \sum m_i\)
Neutrino Mass

\[ m(\text{heaviest}) \geq \sqrt{|m_3^2 - m_1^2|} \simeq 0.05 \text{ eV} \]

3 complementary methods to measure neutrino mass:

<table>
<thead>
<tr>
<th>Method</th>
<th>Observable</th>
<th>Now [eV]</th>
<th>Near [eV]</th>
<th>Far [eV]</th>
<th>Pro</th>
<th>Con</th>
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<tr>
<td>Kurie</td>
<td>( \sqrt{\sum</td>
<td>U_{ei}</td>
<td>^2 m_i^2} )</td>
<td>2.3</td>
<td>0.2</td>
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<td>Cosmo.</td>
<td>( \sum m_i )</td>
<td>0.5</td>
<td>0.2</td>
<td>0.05</td>
<td>best; NH/IH</td>
<td>systemat.; model-dep.</td>
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<tr>
<td>( 0\nu\beta\beta )</td>
<td>(</td>
<td>\sum U_{ei}^2 m_i</td>
<td>)</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
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</table>
Cosmological Limits

stacking more and more data sets on top of each other, limits become stronger
(needed to break degeneracies, but induces systematic issues)

including more and more parameters, limits become weaker

Riess *et al.*, Palanque-Delabrouille *et al.*, Hannestad,
1604.01424 1506.05976 PRL 95
(most extreme (1410.7244): at 1σ: \( \Sigma m_\nu \leq 0.08 \) eV, disfavors inverted ordering...
Sterile Neutrinos and $0\nu\beta\beta$

- LSND/MiniBooNE/gallium/reactor anomalies, $\Delta m^2 \simeq 1 \text{ eV}^2$, $U_{\alpha 4} \simeq 0.1$
- $|m_{ee}| = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2i\alpha} + |U_{e3}|^2 m_3 e^{2i\beta} + |U_{e4}|^2 m_4 e^{2i\Phi_1}$

- sterile contribution to $0\nu\beta\beta$:

$$|m_{ee}|^\text{st} \cong \sqrt{\Delta m_{\text{st}}^2} |U_{e4}|^2 \gg |m_{ee}|^\text{act}_{\text{NH}}$$

$$\cong |m_{ee}|^\text{act}_{\text{IH}}$$

$\Rightarrow |m_{ee}|_{\text{NH}}$ cannot vanish and $|m_{ee}|_{\text{IH}}$ can vanish!

$\Rightarrow$ usual phenomenology gets completely turned around!

Barry, W.R., Zhang, JHEP 1107; Giunti et al., PRD 87; Girardi, Petcov, Meroni, JHEP 1311
Usual plot gets completely turned around!

![Graph showing normal and inverted plots with different mass values](image)
Non-Standard Interpretations:
There is at least one other mechanism leading to Neutrinoless Double Beta Decay and its contribution is at least of the same order as the light neutrino exchange mechanism.

Clear experimental signature:
KATRIN and/or cosmology see nothing but $0\nu\beta\beta$ does.
Energy Scale:

Note: *standard amplitude* for light Majorana neutrino exchange:

\[ A_1 \simeq G_F^2 \frac{|m_{ee}|}{q^2} \simeq 7 \times 10^{-18} \left( \frac{|m_{ee}|}{0.5 \text{ eV}} \right) \text{GeV}^{-5} \simeq (2.7 \text{ TeV})^{-5} \]

if new heavy particles are exchanged:

\[ A_h \simeq \frac{c}{M^5} \]

⇒ for \( 0\nu\beta\beta \) holds:

\[ 1 \text{ eV} = 1 \text{ TeV} \]

⇒ Phenomenology in colliders, LFV

(cosmology limits decoupled from \( 0\nu\beta\beta \))
\[ T^{0\nu}(1 \text{ eV}) = T^{0\nu}(1 \text{ TeV}) \]

- RPV Supersymmetry
- left-right symmetry
- heavy neutrinos
- color octets
- leptoquarks
- effective operators
- extra dimensions
- ... 

⇒ need to solve the inverse problem...
Example: Left-right symmetric theories
Lindner, Queiroz, W.R., Yaguna, JHEP 1606

LHeC ↔ polarization and complementarity
Constraints from Lepton Flavor Violation

\[ \delta_{\mu e} = 3.5 \text{ TeV} \]
\[ \delta_{\mu e} = 2 \text{ TeV} \]
\[ \delta_{\mu e} = 1 \text{ TeV} \]

Barry, W.R., JHEP 1309
Surprising correlations in alternative scenarios

keV-$\nu$ in KATRIN
(RH interaction)

Barry, Heeck, W.R., JHEP 1407

excess events in IceCube
(RPV SUSY)

Dev, Ghosh, W.R., 1605.09743
QCD corrections

• naive size $\alpha_s/(4\pi) \ln \frac{M_W^2}{(100 \text{ MeV})^2} = 10\%$, true for standard interpretation

• but: creates in non $(V - A) \otimes (V - A)$ mechanisms color non-singlet operators, Fierz them and mix with new operators with different NMEs

• can give for alternative mechanisms large effect in either direction...

• (makes limit on right-handed diagrams slightly weaker)

Mahajan, PRL 112; Gonzalez, Kovalenko, Hirsch, PRD 93; Peng, Ramsey-Musolf, Winslow, PRD 93
Do Dirac neutrinos mean there is no Lepton Number Violation?

Model based on gauged $B - L$, broken by 4 units

$\Rightarrow$ Neutrinos are Dirac particles, $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed...
Do Dirac neutrinos mean there is no Lepton Number Violation?

Model based on gauged $B - L$, broken by 4 units

⇒ Neutrinos are Dirac particles, $\Delta L = 2$ forbidden, but $\Delta L = 4$ allowed...

⇒ observable: neutrinoless quadruple beta decay $(A, Z) \rightarrow (A, Z + 4) + 4 e^-$

Heeck, W.R., EPL 103
Candidates for neutrinoless quadruple beta decay

<table>
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<tr>
<th></th>
<th>$Q_{0\nu4\beta}$</th>
<th>Other decays</th>
<th>NA</th>
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<tr>
<td>$^{96}<em>{40}\text{Zr} \to ^{96}</em>{44}\text{Ru}$</td>
<td>0.629</td>
<td>$\tau_{1/2}^{2\nu2\beta} \approx 2 \times 10^{19}$</td>
<td>2.8</td>
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<tr>
<td>$^{136}<em>{54}\text{Xe} \to ^{136}</em>{58}\text{Ce}$</td>
<td>0.044</td>
<td>$\tau_{1/2}^{2\nu2\beta} \approx 2 \times 10^{21}$</td>
<td>8.9</td>
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<tr>
<td>$^{150}<em>{60}\text{Nd} \to ^{150}</em>{64}\text{Gd}$</td>
<td>2.079</td>
<td>$\tau_{1/2}^{2\nu2\beta} \approx 7 \times 10^{18}$</td>
<td>5.6</td>
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</table>

Heeck, W.R., EPL 103
Summary

- need to pursue all neutrino mass approaches
  - confirm 3 Majorana neutrino paradigm!
  - inconsistencies not unlikely
- LHC and $0\nu\beta\beta$ complementary
- distinguishing mechanisms necessary
Another extreme point of view: Quenching

\[ T_{1/2}^{0\nu} \propto g_A^{-4}, \text{ where in } 2\nu\beta\beta\text{-decay (Iachello)} \]

\[ g_A^{\text{IBM}} \simeq 1.27 A^{-0.18} = \begin{cases} 
0.58 & \text{Ge} \\
0.53 & \text{Te} \\
0.52 & \text{Xe}
\end{cases} \]

would shift lifetimes an order of magnitude (in wrong direction...)

- model-space truncation (A-dep.)/omission of \( N^* \), \( \Delta \) (not A-dep.)
- energy scale (no quenching for muon capture)/many multipolarities in 0\( \nu \)
- include 2 body currents (creation of 2p2h), weaker quenching in 0\( \nu \) (Engel, Simkovic, Vogel, PRC 89)

lots of nuclear theory work on the way, possibly no showstopper (20%?)
Inverted Ordering

Nature provides 2 scales:

\[ |m_{ee}|^{IH}_{\text{max}} \approx c_{13}^2 \sqrt{\Delta m^2_A} \quad \text{and} \quad |m_{ee}|^{IH}_{\text{min}} \approx c_{13}^2 \sqrt{\Delta m^2_A} \cos 2\theta_{12} \]

requires \( O(10^{26} \ldots 10^{27}) \) yrs

is the lower limit \( |m_{ee}|^{IH}_{\text{min}} \) fixed?
Current $3\sigma$ range of $\sin^2 \theta_{12}$ gives factor of $\sim 2$ uncertainty for $|m_{ee}|_{\text{IH min}}$

$\left(T_{1/2}^{0\nu}\right)^{-1} \propto a \varepsilon \sqrt{\frac{M t}{B \Delta E}} \Rightarrow$ need precision determination of $\theta_{12}$! ↔ JUNO

Dueck, W.R., Zuber, PRD 83; Ge, W.R., PRD 92
LHC vs. $0\nu\beta\beta$

- LHC assumptions: $M_N < M_{W_R}$, $\text{BR}(M_N \to ee) = 1$, $g_R = g_L$
- cuts result in weak sensitivities for low $M_N$
- background processes?
- QCD corrections?
- (LNV at LHC and baryogenesis)
Background

Helo et al., PRD 88

one should include e.g.

• “jet fake” (high-$p_T$ jet registered as electron)
• “charge flip” ($e^-$ from opposite sign pair transfer $p_T$ to $e^+$ via conversion)

Peng, Ramsey-Musolf, Winslow, 1508.04444
Background

one should include e.g.

- “jet fake” (high-$p_T$ jet registered as electron)
- “charge flip” ($e^-$ from opposite sign pair transfer $p_T$ to $e^+$ via conversion)

Peng, Ramsey-Musolf, Winslow, 1508.04444
Distinguishing Mechanisms

The inverse problem of $0\nu\beta\beta$

1.) Other observables (LHC, LFV, KATRIN, cosmology,...)

2.) Decay products (individual $e^-$ energies, angular correlations, spectrum,...)
   (SuperNEMO, EPJC 70; Horoi, Neascu, 1511.00670)

3.) Nuclear physics (multi-isotope, $0\nu$ECEC, $0\nu\beta^+\beta^+$,...)
   (Gehman, Elliott, JPG 34,35)
Complementarity!

- are already in era of complementarity
  - cosmology limits rule out that light neutrinos saturate $0\nu\beta\beta$-limits
    * strictest limits start to disfavor inverted ordering
  - $0\nu\beta\beta$ limits rule out that light neutrinos saturate Mainz/Troitsk limit

- interesting possibilities in case inconsistencies arise...
CP violation!
Dirac neutrinos!
something else does $0\nu\beta\beta$!
Distinguishing via decay products

Consider standard plus $\lambda$-mechanism

Arnold et al., EPJC 70
Distinguishing via decay products

\[ |m_{ee}| = 0.1 \text{ eV and} \]
\[ \frac{U_{ei} S_{ei}}{M_{WR}^2} = 0 \]
\[ \frac{U_{ei} S_{ei}}{M_{WR}^2} = 8 \cdot 10^{-6} \text{ TeV}^{-2} \]
\[ \frac{U_{ei} S_{ei}}{M_{WR}^2} = 3 \cdot 10^{-5} \text{ TeV}^{-2} \]

Horoi, Neascu, 1511.00670
Distinguishing via decay products

Defining asymmetries

\[ A_{\theta} = \frac{N_+ - N_-}{N_+ + N_-} \] and \[ A_E = \frac{N_+ - N_-}{N_+ + N_-} \]

Arnold et al., EPJC 70
Distinguishing via nuclear physics

Gehman, Elliott, JPG 34,35

3 to 4 isotopes necessary to disentangle mechanism
Left-right symmetry

\[
\begin{align*}
U_{ei}^2 m_i & \quad S_{ei}^2 \frac{M_i}{M} \\
\frac{U_{ei}^2 m_i}{M^2_{\Delta L}} & \quad \frac{V_{ei}^2 M_i}{M^4_{WR} M^2_{\Delta R}} \\
U_{ei} T_{ei} \tan \zeta & \quad \frac{U_{ei} T_{ei}}{M^2_{WR}}
\end{align*}
\]
Predictions of $SO(10)$ theories

Yukawa structure of $SO(10)$ models depends on Higgs representations

$10_H \leftrightarrow H$, $\overline{126}_H \leftrightarrow F$, $120_H \leftrightarrow G$

Gives relation for mass matrices:

$m_{\text{up}} \propto r(H + sF + it_u G)$

$m_{\text{down}} \propto H + F + iG$

$m_D \propto r(H - 3sF + it_D G)$

$m_\ell \propto H - 3F + it_\ell G$

$M_R \propto r^{-1}_R F$

Numerical fit including RG, Higgs, $\theta_{13}$

$10_H + \overline{126}_H$: 19 free parameters

$10_H + \overline{126}_H + 120_H$: 18 free parameters

20 (19) observables to be fitted
Predictions of $SO(10)$ theories

| Model                      | Fit | $|m_{ee}|$ [meV] | $m_0$ [meV] | $M_3$ [GeV] | $\chi^2$ |
|----------------------------|-----|----------------|-------------|-------------|----------|
| $10_H + \overline{126}_H$  | NH  | 0.49           | 2.40        | $3.6 \times 10^{12}$ | 23.0     |
| $10_H + \overline{126}_H + SS$ | NH  | 0.44           | 6.83        | $1.1 \times 10^{12}$ | 3.29     |
| $10_H + \overline{126}_H + 120_H$ | NH  | 2.87           | 1.54        | $9.9 \times 10^{14}$ | 11.2     |
| $10_H + \overline{126}_H + 120_H + SS$ | NH  | 0.78           | 3.17        | $4.2 \times 10^{13}$ | $6.9 \times 10^{-6}$ |
| $10_H + \overline{120}_H + 120_H$ | IH  | 35.52          | 30.2        | $1.1 \times 10^{13}$ | 13.3     |
| $10_H + \overline{120}_H + 120_H + SS$ | IH  | 24.22          | 12.0        | $1.2 \times 10^{13}$ | 0.6      |

Dueck, W.R., JHEP 1309
Recent Results

- $^{76}\text{Ge}$:
  - GERDA: $T_{1/2} > 2.1 \times 10^{25}$ yrs
  - GERDA + IGEX + HDM: $T_{1/2} > 3.0 \times 10^{25}$ yrs

- $^{136}\text{Xe}$:
  - EXO-200: $T_{1/2} > 1.1 \times 10^{25}$ yrs (first run with less exposure: $T_{1/2} > 1.6 \times 10^{25}$ yrs...)
  - KamLAND-Zen: $T_{1/2} > 2.6 \times 10^{25}$ yrs

Xe-limit is stronger than Ge-limit when:

$$T_{\text{Xe}} > T_{\text{Ge}} \frac{G_{\text{Ge}}}{G_{\text{Xe}}} \left| \frac{M_{\text{Ge}}}{M_{\text{Xe}}} \right|^2 \text{ yrs}$$
Current new limits on $|m_{ee}|$ (post KamLAND-Zen)

<table>
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<th>$^{136}$Xe</th>
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<td>GERDA</td>
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<tr>
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![Graph showing thermal decay half-lives for different models](image)
Imprint of keV neutrinos on β-spectrum

Mertens et al., 1409.0920
⇒ mixing down to $10^{-7}$ in reach!?
Focus for simplicity on

\[ \frac{d\Gamma/dE - (d\Gamma/dE)_{\text{std}}}{(d\Gamma/dE)_{\text{std}}} \simeq \left( a + b \frac{M}{E_0 - E} \right) \sqrt{1 - \frac{M^2}{(E_0 - E)^2}} \Theta(E_0 - E - M) \]

and assume keV neutrino with RH current
neglect interference term \( b \):

\[
\theta^2_{\text{eff}} \simeq |S_{ej}|^2 + 1.1 \times 10^{-6} |V_{ej}|^2 \left( \frac{2.5 \text{ TeV}}{m_{W_R}} \right)^4
\]

and note that \( M \) does 0\( \nu \)\( \beta \beta \) with amplitude \( \propto |V_{ej}|^2 \left( m_W/m_{W_R} \right)^4 M/q^2 \)

\[\Rightarrow \text{connection to } 0\nu\beta\beta \text{ constraints!}\]
connection to $0\nu\beta\beta$ constraints:

$$\theta_{\text{eff}}^2 = |S_{ej}|^2 + \frac{m_e}{M_j} \left[ |\mathcal{M}_{\nu}^{0\nu}|^{-2} \left( G_{01}^{0\nu} \right)^{-1} \left( T_{1/2}^{0\nu} \right)^{-1} - |S_{ej}^2 M_j/m_e|^2 \right]^{\frac{1}{2}}$$

Barry, Heeck, W.R., 1404.5955
How the additional interactions save the day

- double beta decay without RHC: $\theta^2 M = 7 \times 10^{-10}$ keV = 70 $\mu$eV
- double beta decay with RHC: $(m_{W_L}/m_{W_R})^4 |V_ei|^2 M = 8$ meV
- decay: $\frac{\Gamma_{RHC}(N_j \to \bar{\nu} \gamma)}{\Gamma_{SM}(N_j \to \nu \gamma)} \approx \frac{m_{W_L}^4 |S_ei|^2}{m_{W_R}^4 |T_ei|^2} \approx \frac{m_{W_L}^4}{m_{W_R}^4}$
- beta decay: $\theta_{eff}^2 \approx |S_{ej}|^2 + 1.1 \times 10^{-6} |V_{ej}|^2 \left(\frac{2.5 \text{ TeV}}{m_{W_R}}\right)^4 > |S_{ej}|^2$
Observation of LNV at LHC implies washout effects in early Universe!

Example TeV-scale $W_R$: leading to washout $e^\pm_R e^\pm_R \rightarrow W^\pm_R W^\pm_R$ and $e^\pm_R W^\mp_R \rightarrow e^\mp_R W^\pm_R$. Further, $e^\pm_R W^\mp_R \rightarrow e^\mp_R W^\pm_R$ stays long in equilibrium

(Frere, Hambye, Vertongen; Bhupal Dev, Lee, Mohapatra; U. Sarkar et al.)

More model-independent (Deppisch, Harz, Hirsch):

\[
\text{washout: } \log_{10} \frac{\Gamma_W(qq \rightarrow \ell^+\ell^+ qq)}{H} \gtrsim 6.9 + 0.6 \left( \frac{M_X}{\text{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\text{LHC}}}{\text{fb}}
\]

(TeV-0$\nu\beta\beta$, LFV and $Y_B$: Deppisch, Harz, Huang, Hirsch, Päs)

$\leftrightarrow$ post-Sphaleron mechanisms, $\tau$ flavor effects,...