Lepton Number Violation with Dirac Neutrinos

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based on
J.H., Werner Rodejohann,
EPL **103**, 32001 (2013), arXiv:1306.0580;
J.H.,
arXiv:1307.2241.

Baryon and Lepton Number

- B and L classically conserved in the Standard Model.
- $B - L$ globally conserved at quantum level.[1]
- $B - L$ locally conserved after adding three ν_R.
  $\Rightarrow$ Neutrinos massive!

Gauged $U(1)_{B-L}$ very well motivated by SM and $m_\nu \neq 0$.

Great, *but*:

- No fifth force coupled to $B - L$ observed.
- No B, L or $B - L$ breaking processes observed.

Fate of $B - L$ is an experimental question!

[1] But broken by quantum gravity, see e.g. E. Witten, hep-ph/0006332.

$B - L$ Landscape

Three possibilities for local $U(1)_{B-L}$:

1. Exact $B - L$: make Z'_{B-L} massive à la Stückelberg without breaking $B - L$.[2] Parameter space in $(g', M_{Z'})$ from weakly coupled long-range to strongly coupled short-range force.[3] Neutrinos are Dirac; baryogenesis via neutrinogenesis.[4]
2. Majorana $B - L$: break $B - L$ spontaneously with $\phi \sim 2$ at high scale. Majorana neutrinos via seesaw, thermal leptogenesis etc.
3. Dirac $B - L$: break $B - L$ spontaneously with $\phi \sim q \notin \{1, 2\}$. Leftover $\mathbb{Z}_q^L$ protects Dirac nature of neutrinos ($\Delta(B - L) = 2$ forbidden!), but still allows for $\Delta(B - L) = q$ violating processes.[5]

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[2] D. Feldman, P. Fileviez Perez, and P. Nath, JHEP **1201**, 038 (2012).
[3] M. Williams *et al.*, JHEP **1108**, 106 (2011).
[4] K. Dick, M. Lindner, M. Ratz, and D. Wright, PRL **84**, 4039 (2000).
[5] Also mentioned in M.-C. Chen *et al.*, Nucl. Phys. B **866**, 157 (2013).

Dirac $B - L$

- All fermions in SM$+\nu_R$ are odd under $B - L$
  $\Rightarrow$ only $\Delta(B - L) = 2n$ possible.
- Lowest order new processes: $\Delta(B - L) = 4$:

$$
\begin{aligned}
\mathcal{O}_{d=6}: &\quad \overline{\nu}_R^c \nu_R \, \overline{\nu}_R^c \nu_R \\
\mathcal{O}_{d=8}: &\quad |H|^2 \, \overline{\nu}_R^c \nu_R \, \overline{\nu}_R^c \nu_R \,, \quad (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, \overline{\nu}_R^c \nu_R \,, \quad F_Y^{\mu\nu} \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R \, \overline{\nu}_R^c \nu_R \\
\mathcal{O}_{d=10}: &\quad (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \,, \quad |H|^2 (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, \overline{\nu}_R^c \nu_R \,, \\
&\quad F_Y^{\mu\nu} (\overline{L}^c \tilde{H}^*) \sigma_{\mu\nu} (\tilde{H}^\dagger L) \, \overline{\nu}_R^c \nu_R \,, \quad F_Y^{\mu\nu} (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R \,, \\
&\quad W_a^{\mu\nu} (\overline{L}^c \tilde{H}^*) \sigma_{\mu\nu} (\tilde{H}^\dagger \tau^a L) \, \overline{\nu}_R^c \nu_R \,, \quad W_a^{\mu\nu} (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger \tau^a L) \, \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R \,, \\
&\quad (\overline{u}_R d_R^c)(\overline{d}_R \tilde{H}^\dagger L)(\overline{\nu}_R^c \nu_R) \,, \ldots
\end{aligned}
$$

Simple Model for $\Delta(B-L)=4$

- Gauged $B-L$ symmetry, three RHNs $\nu_R \sim -1$, one scalar $\phi \sim 4$ to break $B-L$, and one scalar $\chi \sim -2$ as a mediator.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'} - V(H,\phi,\chi) + \left(y_{\alpha\beta}\,\overline{L}_\alpha H \nu_{R,\beta} + \kappa_{\alpha\beta}\,\chi\,\overline{\nu}_{R,\alpha}\nu^c_{R,\beta} + \text{h.c.}\right).$$

- Neutrinos are Dirac (and $\Delta L = 2$ forbidden) if $\langle\chi\rangle = 0$.
- Scalar potential:

$$V(H,\phi,\chi) = \sum_{X=H,\phi,\chi} \left(\mu_X^2 |X|^2 + \lambda_X |X|^4\right) + \sum_{\substack{X,Y=H,\phi,\chi\\ X\neq Y}} \frac{\lambda_{XY}}{2}|X|^2|Y|^2 - \mu\left(\phi\chi^2 + \text{h.c.}\right).$$

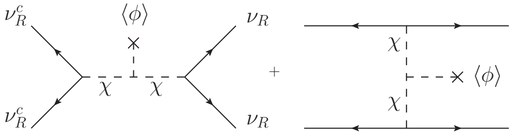
Scalar Potential

$$V(H,\phi,\chi) = \sum_{X=H,\phi,\chi} \left(\mu_X^2 |X|^2 + \lambda_X |X|^4\right) - \mu\left(\phi\chi^2 + \text{h.c.}\right) + \dots$$

- Choose $\mu_H^2, \mu_\phi^2 < 0 < \mu_\chi^2$ and small μ: $\langle H\rangle \neq 0 \neq \langle\phi\rangle$, $\langle\chi\rangle = 0$.
- μ term splits χ in two real fields $\chi = (\Xi_1 + i\,\Xi_2)/\sqrt{2}$:

$$m_1^2 = m_c^2 - 2\mu\langle\phi\rangle\,, \qquad m_2^2 = m_c^2 + 2\mu\langle\phi\rangle\,.$$

- Ξ_j mediate $\Delta L = 4$ processes! E.g. operator $\frac{\mu\langle\phi\rangle}{m_c^4}\,\overline{\nu}_R^c\nu_R\,\overline{\nu}_R^c\nu_R$:



Phenomenology

Quick summary:

- Even with Dirac neutrinos, we can have LNV.[6]
- Lowest order is then $\Delta(B-L) = \Delta L = 4$, via $\mathcal{O}_{d=6} = (\overline{\nu}_R^c \nu_R)^2/\Lambda^2$.

How to check for $\Delta L = 4$?

- Neutrinoless quadruple-beta decay $(A, Z) \to (A, Z+4) + 4\, e^-$.
- Collider process $e^- e^- \to W^- W^- W^- W^- \ell^+ \ell^+$.
- Rare meson decays etc.?

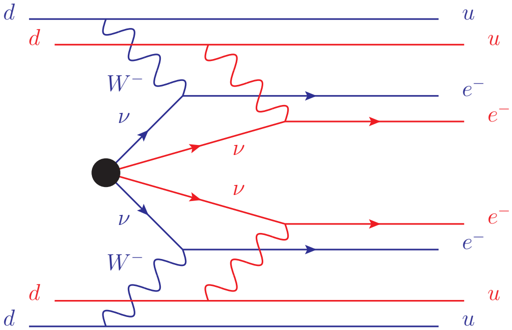
All tough, many particles in final state!

$\Delta L = 4$ can however easily be relevant in the early Universe
$\Rightarrow$ new Dirac leptogenesis mechanism.

[6]Famous unperturbative example: sphalerons with $\Delta(B+L) = 6$.

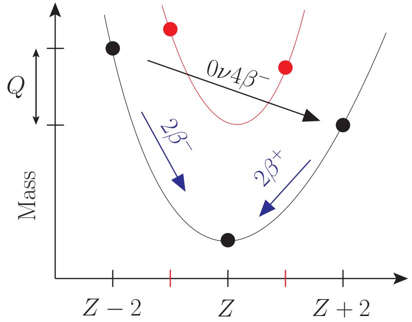
Neutrinoless Quadruple-Beta Decay $0\nu4\beta$

$(A, Z) \to (A, Z+4) + 4\, e^-$ via $\mathcal{O} = (\overline{\nu}_L^c \nu_L)^2/\Lambda^2$:



Candidate Nuclei

- Experimental aspects of $0\nu4\beta$ independent of underlying mechanism.
- Need beta-stable initial state:



- Decay modes: $0\nu4\beta$ and $2\nu2\beta$ ($0\nu2\beta$ forbidden by $\mathbb{Z}_4^L$).

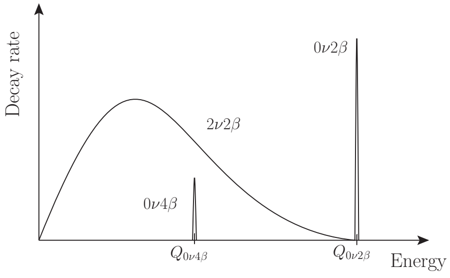
Candidates for Nuclear $\Delta L = 4$ Processes

	$Q_{0\nu 4\beta}$	Other decays	NA/%
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629 MeV	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{19}$ y	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044 MeV	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{21}$ y	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079 MeV	$\tau^{2\nu 2\beta}_{1/2} \simeq 7 \times 10^{18}$ y	5.6
	$Q_{0\nu 4\mathrm{EC}}$		
${}^{124}_{54}\mathrm{Xe} \to {}^{124}_{50}\mathrm{Sn}$	0.577 MeV	—	0.095
${}^{130}_{56}\mathrm{Ba} \to {}^{130}_{52}\mathrm{Te}$	0.090 MeV	$\tau^{2\nu 2\mathrm{EC}}_{1/2} \sim 10^{21}$ y	0.106
${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$	1.138 MeV	$\tau^{\alpha}_{1/2} \simeq 75$ y	—
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	2.063 MeV	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y	—
	$Q_{0\nu 3\mathrm{EC}\beta^+}$		
${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$	0.116 MeV	$\tau^{\alpha}_{1/2} \simeq 75$ y	—
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	1.041 MeV	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y	—
	$Q_{0\nu 2\mathrm{EC}2\beta^+}$		
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	0.019 MeV	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y	—

Best Candidate: Neodymium $^{150}_{60}\mathrm{Nd}$

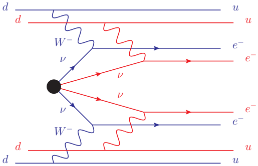
Decay channels:

- $^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$ via $2\nu 2\beta$ ($\tau_{1/2}^{2\nu 2\beta} \simeq 7\times 10^{18}\,\mathrm{y}$): two neutrinos and two electrons are emitted; the electrons have a continuous energy spectrum and total energy $E_{e,1}+E_{e,2} < 3.371\,\mathrm{MeV}$.
- $^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$ via $0\nu 4\beta$. Four electrons with continuous energy spectrum and summed energy $Q_{0\nu 4\beta} = 2.079\,\mathrm{MeV}$ are emitted. In this special case, the daughter nucleus is α-unstable with half-life $\tau^{\alpha}_{1/2}({}^{150}_{64}\mathrm{Gd} \to {}^{146}_{62}\mathrm{Sm}) \simeq 2\times 10^{6}\,\mathrm{y}$.



Neutrinoless Quadruple-Beta Decay $0\nu4\beta$

$(A, Z) \to (A, Z+4) + 4\,e^-$ via $\mathcal{O} = (\overline{\nu}_L^c \nu_L)^2/\Lambda^2$:



- Very naive comparison with competing channel $2\nu2\beta$:

$$\frac{\tau_{1/2}^{0\nu4\beta}}{\tau_{1/2}^{2\nu2\beta}} \simeq \left(\frac{Q_{0\nu2\beta}}{Q_{0\nu4\beta}}\right)^{11} \left(\frac{\Lambda^4}{q^{12} G_F^4}\right) \simeq 10^{46} \left(\frac{\Lambda}{\mathrm{TeV}}\right)^4,$$

  with $|q| \sim p_\nu \sim 1\,\mathrm{fm}^{-1} \simeq 100\,\mathrm{MeV}$.
- For $(\overline{\nu}_R^c \nu_R)^2/\Lambda^2$ additional mass-flip suppression $(m_\nu/q)^8$ or right-handed currents...
- Estimated rate in toy model unobservably small. Elaborate models with resonances overcome this?

Comments

- Background: electrons from $2\nu 2\beta$ kick out two more e^-.
  $\Rightarrow$ 4 e^- with $\sum E_i \sim Q_{0\nu 4\beta}$ possible.
- $0\nu 4\beta$ to excited state ${}^{150}_{64}\mathrm{Gd}^*$: Q reduced by $0.6\,\mathrm{MeV}$ (2^+) or $1.2\,\mathrm{MeV}$ (0^+), but more photons...
- Nuclear matrix elements impossible (?) to calculate.
  $\Rightarrow$ No way to extract fundamental couplings from $\tau_{0\nu 4\beta}$ (?)
- $0\nu 6\beta$ etc. all involve beta-unstable nuclei.
  $\Rightarrow$ $0\nu 2\beta$ and $0\nu 4\beta$ somewhat unique.
- Very different $\Delta(B-L) = 4$ decay: $4n \to 3p + 3e^-$, mimics $0\nu 3\beta$.
  Candidate:

$$ {}^{148}_{60}\mathrm{Nd} \xrightarrow{931.6\,\mathrm{MeV}} {}^{147}_{63}\mathrm{Eu} + 3e^- $$

$$ \hookrightarrow \quad {}^{147}_{62}\mathrm{Sm} \left(\tau^{\beta^+}_{1/2} \simeq 24\,\mathrm{d}\right) $$

Leptogenesis

$\Delta L = 4$ can be relevant in the early Universe: new Dirac leptogenesis.

1. Majorana $B-L$: heavy right-handed Majorana neutrinos decay into L, H and $\overline{L}, \overline{H}$, violating CP and $\Delta L = 2$. Sphalerons with $\Delta(B+L) = 6$ translate asymmetry to baryons: $Y_B = \frac{28}{79} Y_{B-L}$.
2. Exact $B-L$: *Neutrinogenesis*: new scalars decay to leptons so that $\Delta_{\ell_L} = -\Delta_{\ell_R}$. ν_R not thermalized (Yukawas too small), hidden from sphalerons. Only Δ_{ℓ_L} converted into baryon asymmetry.
3. Dirac $B-L$: heavy mediator scalars decay into $\nu_R \nu_R$ and $\overline{\nu}_R \overline{\nu}_R$, violating CP and $\Delta L = 4$. Second Higgs doublet translates Δ_{ν_R} to leptons, and sphalerons generate $Y_B = \frac{1}{4} Y_{B-L}$.

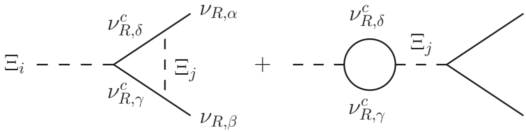
Leptogenesis with LNV Dirac Neutrinos

Add second copies of Higgs doublet and mediator scalar $\chi_{1,2} \sim -2$:

- Neutrinophilic H_2 with small VEV $\langle H_2 \rangle \sim 1\,\mathrm{eV}$
  $\Rightarrow$ Dirac neutrinos light with large Yukawas.
- $\chi_{1,2}$ split into four real scalars Ξ_j after $\phi \to \langle \phi \rangle$, with couplings

$$\mathcal{L} \supset \frac{1}{2} V^j_{\alpha\beta}\, \Xi_j \overline{\nu}_{R,\alpha} \nu^c_{R,\beta} + \frac{1}{2} \overline{V}^j_{\alpha\beta}\, \Xi_j \overline{\nu}^c_{R,\alpha} \nu_{R,\beta} \,.$$

- Lightest Ξ_i decays in $\nu_R \nu_R$ or $\nu^c_R \nu^c_R$:



$\Rightarrow$ *CP* asymmetry in ν_R:

$$Y_{\nu_R} \equiv \frac{n_{\nu_R}}{s} \sim \frac{1}{g_*} \frac{\Gamma(\Xi_i \to \nu_R \nu_R) - \Gamma(\Xi_i \to \nu^c_R \nu^c_R)}{\Gamma(\Xi_i \to \nu_R \nu_R) + \Gamma(\Xi_i \to \nu^c_R \nu^c_R)} \,.$$

Baryon Asymmetry

- RHN asymmetry Y_{ν_R} translated to left-handed leptons via second Higgs H_2.
- Partially converted to baryons via sphalerons ($Y_B = \frac{1}{4} Y_{B-L}$).

$\Rightarrow$ Very different from old Dirac leptogenesis (neutrinogenesis), very similar to standard leptogenesis!

- Necessary thermalization of $\nu_R \Rightarrow N_{\text{eff}} > 3$!
- $3.14 \lesssim N_{\text{eff}} \lesssim 3.29$ depending on H_2^+ mass and Yukawa coupling.
- Planck: $N_{\text{eff}} = 3.30 \pm 0.27$ at 68% C.L.
- Specific collider signatures of neutrinophilic H_2.[7]

[7] S. M. Davidson and H. E. Logan, PRD **80**, 095008 (2009).

Summary

- Lepton number violation not synonymous with Majorana neutrinos.
- If neutrinos are Dirac, $\Delta(B-L) = \Delta L = 4$ lowest order LNV.
- Hard to test: $0\nu 4\beta$ or $e^- e^-$ collider...
- Experimental limit on $\Delta L = 4$ from $^{150}\mathrm{Nd} \xrightarrow{2.079\,\mathrm{MeV}} {}^{150}\mathrm{Gd}$?
- New kind of Dirac leptogenesis possible, predicts $3.14 \lesssim N_{\mathrm{eff}}$.